DOUBLE AND SINGLE LEG LANDING BIOMECHANICS IN ADOLESCENT FEMALE ATHLETES WITH A HISTORY OF ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION AND THE EFFECTS OF VERBAL INSTRUCTIONS ON ACUTE ALTERATIONS IN LANDING

Rebecca Lynn Begalle

A dissertation submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Interdisciplinary Human Movement Science (School of Medicine).

Chapel Hill
2014

Approved by:

Darin A. Padua
J. Troy Blackburn
Stephen W. Marshall
Michael Lewek
Yvonne Golightly
Rebecca Lynn Begalle: Double and Single Leg Landing Biomechanics in Adolescent Female Athletes with a History of Anterior Cruciate Ligament Reconstruction and the Effects of Verbal Instructions on Acute Alterations in Landing (Under the direction of Darin A. Padua)

Young female athletes that return to sport following anterior cruciate ligament (ACL) injury and reconstruction (ACLR) are at great risk of secondary injury. Landing biomechanics in adolescent females following ACLR have not been studied and it is unknown if verbal instructions to acutely alter landing are effective in a previously injured population. The purpose of this study was to investigate trunk and bilateral lower extremity biomechanics in adolescent female athletes with and without a history of ACLR and to determine the effectiveness of verbal instructions in altering landing forces. Twenty-two ACLR (age=16.68 ± 1.55yrs, height=166.80 ± 6.04cm, mass=61.08 ± 8.78kg) and 25 control (CON; age=16.91 ± 1.23yrs, height=170.22 ± 7.40cm, mass=63.32 ± 7.59kg) participants completed this study. Participants performed a double-leg jump landing and single-leg double hop for biomechanical analysis. Verbal instructions conditions (soft landing or equal landing on both limbs) were provided to influence the jump-landing task in comparison to baseline. During the jump-landing, ACLR group participants relied on the contralateral Uninjured limb to absorb landing forces through greater sagittal plane displacement and larger internal joint moments and forces. The ACLR Injured limb utilized greater frontal plane hip motion compared to the Uninjured limb. During the single-leg hop, ACLR participants utilized less sagittal plane with greater frontal and transverse plane motion, and
reduced landing forces when compared to the Uninjured and CON participants. The verbal instructions interventions caused similar changes in the ACLR Injured limb and healthy CON limbs. However, the ACLR Uninjured limb demonstrated greater magnitude decreases in vertical ground reaction (VGRF) compared to the Injured and matched CON limb following the soft landing instructions and greater decreased in VGRF and anterior tibial shear forces following the equal landing instructions compared to the Injured limb. These results highlight asymmetrical biomechanics between the ACLR limbs and differences between the ACLR group and CON group, potentially placing the ACLR group participants at greater risk for secondary ACL injury. The results of this investigation provide significant evidence for the importance of evaluating quality of movement to aid in return to play decision-making.
ACKNOWLEDGEMENTS

There are so many people who have contributed to this journey both professionally and personally and I would like to whole-heartedly say this project would not have been possible without all of you. I am grateful for the guidance and support from my committee members, including Drs. Darin Padua, Troy Blackburn, Stephen Marshall, Michael Lewek, and Yvonne Golightly. I truly appreciate your time and effort in helping me succeed and providing guidance that has certainly made this project better. I feel honored to have had the opportunity to work with you and to learn from each and every one of you. Thank you.

I am especially thankful to Dr. Padua for allowing me the opportunity to join the Carolina family and achieve more than I thought I was capable of. I appreciate the subtle way in which you pushed me to be better while always finding ways to let me know I was enough. This was a personal journey for me and you were willing to be there for all the ups and downs. Thank you.

I am also grateful for my friend and mentor, Dr. Margie King, who was instrumental in my decision to pursue a doctoral degree. Thank you for your continued support and friendship.

I would also like to acknowledge the cohort of doctoral students that have been a part of this journey from start to finish. You have been wonderful classmates, office mates, role models, and friends. Returning to academia after working clinically for years was a challenge. I would not have survived my first two years of coursework without my core six, you know who you are. I am grateful for the lifelong friendships we have forged. Thank you.
To my Carolina family, thank you for your guidance, thank you for your support, and thank you for your friendship. The long journey of pursuing my PhD, but too short adventure of living in Carolina has come to a close. You have impacted my life more than I can ever express. Thank you.

I am eternally grateful for the love and support from my family. My parents, Jack and Kay Scanlon, thank you for your unyielding love and encouragement. My siblings, Kevin & Betsy, Chris & Jillian, thank you for your endless love and laughter. To Kate, thank you for being my sunshine on every rainy day. My in-laws, Dave and Jeri, thank you for loving me like a daughter and allowing your son to follow me in pursuit of my dreams. Last, none of this would have been possible without the unconditional love and support of my husband Scott. You have shown more sacrifice and understanding than I am probably worthy of, but I am forever grateful. I will never be able to thank you enough.
TABLE OF CONTENTS

LIST OF FIGURES ........................................................................................................... X

LIST OF TABLES ............................................................................................................. XI

CHAPTER ONE ..................................................................................................................... 1

1.1 BACKGROUND ........................................................................................................... 1
1.2 OPERATIONAL DEFINITIONS ................................................................................... 10
1.3 ASSUMPTIONS AND LIMITATIONS .......................................................................... 13
1.4 DELIMITATIONS ......................................................................................................... 14
1.5 INDEPENDENT VARIABLES ..................................................................................... 14
1.6 DEPENDENT VARIABLES ......................................................................................... 15
1.7 SPECIFIC AIMS .......................................................................................................... 16
1.8 RESEARCH HYPOTHESES ......................................................................................... 18
1.9 SIGNIFICANCE ........................................................................................................... 21

CHAPTER TWO .................................................................................................................. 22

2.1 ACL INJURY EPIDEMIOLOGY ..................................................................................... 22
2.2 CONSEQUENCES OF ACL INJURY: THE PROBLEM ................................................... 26
2.3 MECHANISM OF INJURY .......................................................................................... 31
2.4 FACTORS THAT INFLUENCE ACL LOADING ........................................................... 35
2.5 PROSPECTIVE ACL INJURY RISK FACTORS .......................................................... 39
2.6 FACTORS THAT CONTRIBUTE TO POOR OUTCOMES FOLLOWING ACLR ....... 41
LIST OF FIGURES

Figure 1: Depiction of Data Collection Procedures .................................................. 118
Figure 2: Depiction of Verbal Instructions Intervention ........................................... 119
Figure 3: Depiction of the Double Leg Jump Landing Task ................................... 120
Figure 4: Depiction of the Single-Leg Double Hop Task ........................................ 121
LIST OF TABLES

Table 1: Power Analyses for all Dependent Variables .................................................. 122
Table 2: Power Analyses for Verbal Instructions Intervention ...................................... 123
Table 3. Healthy Control Limb Group Assignment ......................................................... 124
Table 4. Descriptive Statistics for Participant Demographics ........................................ 125
Table 5. Injury History and Activity Level for each ACLR Group Participant ............ 126
Table 6. Trunk Kinematics during the Landing Phase of the Jump Landing ............. 127
Table 7. Initial Contact Kinematics during the Landing Phase of the Jump Landing ................................................................. 128
Table 8. Joint Displacement (DSP) Kinematics during the Landing Phase of the Jump Landing .................................................................................................................. 129
Table 9. Landing Phase Peak Kinetics during the Jump Landing .......................... 130
Table 10. Pushoff Phase Peak Kinetics during the Jump Landing .................. 131
Table 11. Initial Contact Kinematics during the Landing Phase of the Single-Leg Double Hop .................................................................................................................. 132
Table 12. Joint Displacement (DSP) Kinematics during the Landing Phase of the Single-Leg Double Hop ........................................................................................................ 133
Table 13. Landing Phase Peak Kinetics during the Single-Leg Double Hop .......... 134
Table 14. Pushoff Phase Peak Kinetics during the Single-Leg Double Hop ........... 135
Table 15. Summary Table of Statistically Significant Differences ......................... 136
Table 16. Descriptive Statistics for the Jump Landing Verbal Instructions Intervention ................................................................. 137
Table 17. Soft Landing Change Scores for the Jump Landing Verbal Instructions Intervention ........................................................................................................ 138
Table 18. Equal Landing Change Scores for the Jump Landing Verbal Instructions Intervention ................................................................. 139
CHAPTER ONE
INTRODUCTION

1.1 Background

Female participation in sport has increased drastically over the past three decades, resulting in an escalated number of musculoskeletal injuries. Of particular concern is injury to the anterior cruciate ligament (ACL), which occur more frequently in female athletes compared to male athletes participating in the same sports. The incidence of sport related ACL injuries in the adolescent population is on the rise, with female injury rates beginning to rise steadily by the age of twelve and peaking around age eighteen. ACL injuries incur a financial burden of approximately $2 billion per year. However, most debilitating are the long-term consequences these young female athletes face.

Widespread rehabilitation guidelines typically allow athletes to return to sport within 6-9 months of surgery, however follow-up studies suggest nearly 70% of ACL injured athletes no longer participate in sport in as little as three years after injury. Unfortunately, once an athlete has sustained an ACL injury, she is 10.4 times more likely to suffer a secondary injury to either leg especially when returning to sports requiring lateral sidestepping, cutting, and pivoting. Not surprisingly, the highest rates of secondary ACL injury within 1-2 years are reported in young active individuals who return to competitive sport. Overall, males and females are equally likely to sustain a secondary ACL injury, however females may be more apt to injure their contralateral (previously uninjured) ACL.
Of mounting concern is the growing evidence that a history of knee injury is one of the strongest predictors of knee osteoarthritis (OA), which is compounded by a concomitant meniscal or cartilage injury. More than 50% of all ACL injuries involve a concomitant meniscal injury, with reports ranging from 21-100% in young active individuals. Additionally, if a meniscal injury does not result initially, many patients go on to develop a meniscal tear within 1-2 years due to the chronic instability caused by injury to the ACL. In fact, 55.5% of one hundred twenty nine pediatric patients (< 19 years old) who received anterior cruciate ligament reconstruction (ACLR) greater than five months after the initial injury had a higher rate of meniscal tears than those who received reconstruction earlier following injury (37.8%). Surgical management in a young, potentially skeletally immature, population is often delayed due to the risk of growth-plate damage from tunnel placement and graft fixation during surgery. Some surgeons feel this delay in reconstruction is necessary to offset potential growth plate problems, however this may leave them at greater risk of concomitant injury. Limiting physical activity is one way to decrease the continued bouts of giving way and pain while awaiting surgical reconstruction in a young female population. However, limiting activity in this population can be a great challenge and potentially may not contribute to improved outcomes such as decreased incidence of osteoarthritis or secondary injury.

Therefore, female adolescents with a history of ACL injury are at substantial risk for suffering a secondary ACL injury to either knee compared to the general population, providing a strong rationale to investigate them in this research study. In fact, a recent report from the Swedish National ACL register revealed that 22% of female soccer players between the ages of 15-18 who suffered ACL injury suffered a secondary ACL injury within five
years, compared to 9% in adults. There is a gap in the research literature investigating this population following ACL injury and reconstruction (ACLR). Perhaps rehabilitation does not effectively address the original risk factors prior to returning an athlete to play or the lack of structured return to play guidelines is failing our young athletes. Due to the increased likelihood of secondary injury of the contralateral limb, females may adopt movement compensations that intensify their injury risk on the previously uninjured knee, perhaps by unloading the injured leg at the expense of the uninjured contralateral limb, creating potentially harmful asymmetries. Steps have to be taken to identify movement dysfunction and asymmetry in female adolescents post ACLR to improve rehabilitation and return to play criteria to ensure better long-term outcomes.

Biomechanical research utilizing human cadaver specimens has identified mechanisms that directly load the ACL. The ACL resists movement in all three planes of motion by minimizing forward translation of the tibia relative to the femur, preventing knee hyperextension, minimizing medial / lateral motion, and providing rotary stability. Therefore, combined loading states, rather than a single mechanism is most unfavorable to the ACL. The most direct loading mechanism on the ACL is a linear shear force at the proximal tibia, causing translation of the tibial plateau in an anterior direction relative to the femur. However, anterior tibial shear force combined with knee valgus (or varus) moment and tibial internal rotation moment, particularly when the knee is in a more extended position, have proven to further increase the strain on the ACL. The quadriceps, hamstrings, and gastrocnemius muscles directly cross the knee joint and play an important role in modifying or exacerbating the load placed on the ACL, which is largely dependent on knee flexion angle. Generally, ACL loading is greatly increased with isolated quadriceps activity,
particularly at small knee flexion angles (0-45 degrees).\textsuperscript{36-38} Isolated quadriceps contractions and inertial forces due to sudden accelerations or decelerations, such as taking off and landing from a jump, generate a large anterior tibial shear force.\textsuperscript{32}

Joint position, patterns of movement, and landing forces can directly influence the magnitude of ACL loading during dynamic tasks. An estimated 70-80\% of all sport related ACL injuries are due to non-contact or indirect contact mechanisms (NCIC) during landing, cutting, or deceleration.\textsuperscript{2, 39, 40} These injuries result from the athletes’ own movements being disturbed by physical or cognitive perturbations during or immediately before the injury event with no direct knee contact.\textsuperscript{41} In light of the greater risk of ACL injury in young female athletes, many gender and age comparison studies have been carried out to identify movement characteristics specific to females that may predispose them to NCIC ACL injury. Results suggest that a combination of excessive frontal plane movement at the knee and hip (valgus and adduction), lesser sagittal plane motion at the knee, greater vertical ground reaction forces, excessive quadriceps activation in comparison to the hamstrings, and poor neuromuscular control over the trunk and lower extremity, may be in large part responsible for NCIC ACL injuries in females.\textsuperscript{42-53} Females may also be more likely to experience an ACL injury during double-legged landings as opposed to single-leg landing and cutting maneuvers, in comparison to males.\textsuperscript{54} Results also suggest that prior to puberty males and females perform functional tasks similarly. However, differences in the way males and females move become more evident across maturation.\textsuperscript{55-59}

The average age of onset for puberty and associated growth spurts is at 10.5 years for females and 12.5 years for males and is typically complete by age of seventeen and twenty, respectively.\textsuperscript{60} It is believed that potentially males increase strength and neuromuscular
control throughout maturation to accommodate skeletal growth, whereas females may not adapt accordingly. Studying this population poses a challenge due to the potential for these females to be at different stages of maturation at the time of testing. Despite this challenge, we feel investigating females between the ages of 12-18 who have experienced an ACL injury is critical based on their heightened risk of secondary injury. Typically it is assumed that children will attain mastery of fundamental motor skills, such as optimal landing from a jump, by late childhood (10-12 years old). This time period is critical for the development and refinement of complex motor skills like those used in sport. Potentially, female athletes with a history of ACL injury during adolescence may not have attained mastery of these motor skills, which may have contributed to their injury.

Previous research utilizing prospective, case-control study designs, has observed individuals after experiencing an initial ACL injury and tracked them over time for instances of secondary injury. Interestingly, individuals who sustained a secondary injury on either leg demonstrated similar at risk movement characteristics as those reported for primary injury, but also displayed unique differences. Individuals who suffered a secondary injury also displayed greater hip flexion at initial ground contact, decreased knee extension moment at mid-stance, and greater overall knee flexion motion on the previously injured limb, suggesting significant quadriceps dysfunction in these individuals even after full rehabilitation. A single prospective study was carried out in adolescents after experiencing initial ACLR using three-dimensional motion analysis during a drop vertical jump and then tracking these athletes for one year. Thirteen of fifty-six athletes suffered a secondary ACL injury (age=15.77 ± 1.36 years), eleven of whom were females, and all but one experienced secondary injury on their contralateral limb. Adolescents that exhibited greater knee valgus
motion during the landing phase on the injured limb and greater hip internal rotation net moments on the uninjured limb were 3-8 times more likely to sustain a secondary ACL injury. Additionally, these adolescents displayed greater knee extension moment on the uninjured limb and lesser on the previously injured limb, suggesting greater bilateral asymmetry in absorbing landing forces. Similar asymmetries, in vertical ground reaction forces (VGRF) and knee extension moments have been observed in laboratory studies in adults post ACLR even after full return to physical activity and sport.

ACLR does not exactly replicate the normal anatomic complexity of the original ACL structure in the knee. Comparisons of lower extremity kinematics and kinetics have exposed a number of movement and landing adaptations in adults with a history of ACL injury and ACLR. Specifically, reports of asymmetrical ground reaction forces, asymmetrical knee extension moments, strength deficits, and abnormal movement patterns often ensue. Adults with a history of ACLR often rely more heavily on their previously uninjured limbs to absorb and produce landing forces in comparison to their injured limb. These asymmetries have been reported during the landing and takeoff phases of a double-leg jump as well as during single-leg hopping maneuvers. Quadriceps dysfunction in individuals post ACLR, including decreased muscle activation, decreased muscle strength, and decreased knee extension moment greatly exacerbates abnormal kinematics and asymmetrical lower extremity loading, potentially leading to future injury and the initiation and progression of knee OA.

The most common criteria used to return an athlete to sport following ACLR includes lower extremity muscle strength, lower limb symmetry while performing single-leg hopping tasks, and clinical knee exams (range of motion, effusion). However, altered movement
patterns during functional tasks have been shown to last beyond the time frame of when return to sport is often allowed. Standardized return to play guidelines do not exist making safe and effective return to sport challenging.

Most researchers and clinicians utilize some form of a limb symmetry index (LSI) for strength and performance measures to assess when the ability of the injured limb has returned to an acceptable level of the uninjured limb. Often this is calculated as the ‘injured limb’ divided by the ‘uninjured limb’ multiplied by 100 to attain a percentage. Normal LSI values of 85-90% are often used, based on the original findings of Noyes et al. in which 93% of healthy individuals performed a single leg hop with an LSI of 85% or greater. However, using an LSI value as the sole criterion for return to sport does not account for the crossover effects of strength and function loss often apparent in the uninjured limb. Moreover, female adolescents are suggested to be more prone to suffer ACL injury during sport, in comparison to similarly aged males, in large part due to their altered neuromuscular control during functional movements. Perhaps, returning the ACLR limb to the ability of the uninjured limb does not address the problem, as the contralateral limb may possess the same predisposing biomechanical alterations. In addition, unclear return to play guidelines focus on quantitative strength and performance measures, such as force output, jump height, and jump distance, but do not assess the overall quality of movement. The current study assesses lower extremity biomechanics during two commonly used functional tasks and compare outcomes bilaterally but also in comparison to healthy matched control subjects. This research project fulfills a large gap in the research because very little post ACLR biomechanical research has been carried out in an adolescent female population as they are
cleared to return to sport, therefore it is unknown if similar or entirely different movement characteristics and asymmetries are present.

Clinicians often utilize functional performance tests to determine when an athlete can progress and return to sport. Researchers utilize the same functional performance tests to analyze performance and seemingly not often enough, movement quality. Single-leg hopping tasks were first introduced to detect abnormal lower limb symmetry in hop performance and are widely used to discriminate performance of the injured and uninjured limbs. The double-leg jump landing has previously been validated as a clinical screening tool to identify lower extremity risk factors for non-contact indirect-contact knee injury. As mentioned previously, females often experience ACL injury during a similar double-leg jump landing maneuver. A double-leg jump landing and single-leg double hop for distance have been chosen for this study because they require efficient movement patterns and stability to absorb the generated impact forces efficiently and then immediately produce propulsive forces to jump vertically or horizontally, respectively. Both tasks are good representations of sport specific maneuvers, which are commonly related to ACL injuries. Most importantly, both tasks are capable of elucidating movement impairments and asymmetries.

Increased attention has been directed toward ACL injury prevention strategies, as researchers attempt to minimize risk factors that are believed to be modifiable. Injury prevention programs include components of muscle strengthening, flexibility, balance training, plyometrics, core stability, proprioceptive training, and often landing instructions (or movement awareness). These same components of training are also utilized in the rehabilitation setting following ACLR. Verbal instructions have been successful in influencing acute changes in ground reaction force variables and lower extremity kinematics.
in healthy children and adults.\textsuperscript{92-96} Single training sessions have been shown to be as effective as multiple sessions, as the magnitude of change was not greater with further opportunity to practice the skill.\textsuperscript{93} However, all research to date has investigated the effectiveness of verbal instructions in healthy, previously uninjured populations. There is a gap in the literature regarding the effectiveness of verbal instructions in pathologic populations, specifically female adolescents with a history of ACLR, who may have greater challenges in altering their neuromuscular control to change landing forces.

In summary, this project addresses biomechanical variables during the performance of two separate functional tasks, the double-leg jump landing and single-leg double hop for distance. Gender comparisons were not made in this study as male and female pubertal adolescents display inherent differences in the way they perform these types of tasks. An adolescent female population with a history of ACLR and healthy female control subjects matched by age, body mass, height, physical activity level, and sport participation were investigated. All previously injured females were a minimum of six months post ACLR with full medical clearance to return to sport. All females were assessed within the first year of fully returning to sport. Adolescent females have a higher sport related ACL injury rate in comparison to their male counterparts, but have not been studied for the quality of biomechanical movement following ACLR. The primary purpose of this study was to compare trunk and lower extremity biomechanics between adolescent females with a history of ACLR and healthy matched control subjects. Additionally, healthy adolescents have been able to reduce landing forces (VGRF) and make landing forces more symmetrical when given focused verbal instructions to do so. However, it is unknown if a previously injured female adolescent population can utilize similar verbal instructions to make the same
adjustments. Therefore, the secondary purpose of this research study was to investigate the effectiveness of simple verbal instructions in altering landing forces during the double-leg jump landing in ACLR female adolescents in comparison to the healthy control subjects.

1.2 Operational Definitions

**Adolescent**: Participants between the ages of 12-18 years.

**Dominant Leg**: The leg the subject would self-select to kick a soccer ball for maximal distance.

**Balance Leg**: The leg the subject would self-select to land on if they were to perform a single leg hop.

**ACLR Group**: Subjects meeting the inclusion criteria for the unilateral anterior cruciate ligament reconstruction. Subjects with concomitant meniscal injury will be included, however concomitant ligament injury will be an excluding factor.

**Control Group**: Subjects meeting the inclusion criteria for healthy active female adolescents with no prior history of knee injury. Right and left limbs randomly assigned to serve as the ‘Index’ or ‘Non-Index’ limb based on the distribution of ACL injuries to the right and left limbs in the ACLR group.

**Bilateral**: Testing including both limbs: injured and uninjured for the ACLR group and index and non-index for the control group.

**Passive Range of Motion**: Movement of a joint through its available range of motion by a single investigator until the point of first resistance, defined as the point where
the investigator felt resistance from tension in the muscle and other soft tissue structures.

**Double-Leg Jump landing (JL):** Double leg forward jump from a 30-cm box placed a distance of 50% of subjects’ standing height away from the landing surface (force plates), followed by an immediate maximal vertical jump.

**Single-leg double hop (SDH):** Two consecutive single leg forward hops, taking off and landing on the same leg, starting a standard 30-in (76-cm) from the forceplate. The goal is to land in the center of the forceplate (target) after the first hop and follow immediately with a maximal horizontal jump.

**Initial Contact:** The first time point during each trial of the jump landing and single leg double hop tasks where the vertical ground reaction force recorded by the force plate registers over 10N.

**Toe-off:** The first time point after initial contact, during each trial of the jump landing and single leg double hop tasks, where the vertical ground reaction force recorded by the force plate registers less than 10N.

**Stance phase:** The period of time between initial contact and toe-off, representing the period of time where the subject’s foot is in contact with the force plates during the jump landing and single leg double hop.

**Peak Knee Flexion:** Maximum knee flexion angle reached during the stance phase of the jump landing.

**Landing phase:** Time period from initial contact to peak knee flexion for the double leg jump landing, and the first 50% of total stance time for the single leg double hop, representing the period of time where the subject is absorbing the landing forces.
Pushoff phase: Time period from peak knee flexion to toe-off for the double leg jump landing, and the second 50% of total stance time for the single leg double hop, representing the propulsive period of time where the subject is preparing to take off into a subsequent vertical jump or forward hop.

Joint displacement (DSP): Overall joint motion during the landing phase, calculated by subtracting the joint angle at the time point of initial contact from the peak joint angle occurring during the landing phase.

Peak Vertical Ground Reaction Force: Peak vertical ground reaction force reached during the landing and pushoff phases of the jump landing and single leg double hop, normalized to body weight (N).

Segment angular position: The instantaneous angular position of the segment of interest relative to the world horizontal axis, expressed in degrees (°).

Knee extension moment: The combined contribution of the soft tissue surrounding the knee joint producing a moment in the direction of knee extension, normalized to the product of body weight and height (BW*Ht).

Knee valgus/varus moment: The combined contribution of the soft tissue surrounding the knee joint producing a frontal plane moment in the valgus or varus direction, normalized to the product of body weight and height (BW*Ht).

Anterior tibial shear force (ATSF): The maximum value of the net shear force directed anteriorly at the tibiofemoral joint causing the tibia to translate anterior relative to the femur, normalized to body weight (N).

Limb Symmetry Index (LSI): Asymmetry between limbs presented as the injured limb relative to the uninjured limb, calculated as [(Injured – Uninjured /
Injured)*100] for the ACLR group and [(Index – Non-Index / Index)*100] for the healthy control group. Negative value indicates asymmetry toward the Uninjured / Non-Index side and larger values indicate a larger magnitude asymmetry.

**Verbal instructions:** Verbal instructions providing an attention focus about how to perform the jump landing task to achieve a “softer landing” or “equal landing.”

**Change scores:** Calculated for Specific Aim 3 as the difference between the selected dependent variable with each verbal instruction condition minus the dependent variable during the baseline condition. (Soft Δ = Soft – Baseline / Equal Δ = Equal – Baseline)

**Isometric Muscle Strength:** The peak force output, recorded by a handheld dynamometer, during the selected strength assessments (knee extension, knee flexion, hip abduction) normalized to body mass using Allometric scaling (Sn = S / m^{2/3}).

### 1.3 Assumptions and Limitations

The following assumptions and limitations will apply to this study:

1. All participants gave their best effort in performing all of the testing protocols.
2. Subjects accurately reported surgical information, including date of injury, type of surgery, date of surgery, completion of rehabilitation.
3. Type of ACL graft and mechanisms of injury were not controlled for in subject inclusion criteria.
4. Segment kinematics calculated from the motion analysis system and biomechanical software were accurate and reliable.
5. Subjects accurately followed and attended to the verbal instructions provided for the jump-landing task intervention.

6. The results of this study only apply to adolescent females with an anterior cruciate ligament injury with subsequent reconstruction.

1.4 Delimitations

The following delimitations were made for this study.

1. The goal was to recruit 50 subjects (25 ACLR, 25 control) from the Raleigh/Durham/Chapel Hill community.

2. All subjects were between the ages of 12-18 years.

3. Control subjects were healthy with no history of lower extremity surgery, particularly knee surgery.

4. ACLR subjects will have had unilateral injury with one surgical intervention; therefore one limb was free of knee surgery.

5. All subjects were free from lower extremity musculoskeletal injury for six months prior to testing.

1.5 Independent Variables

The following independent variables were assessed in this study:

1. Group (2 Levels)
   a. ACLR
   b. Control

2. Limb (2 Levels)
   a. ACLR: Injured, Uninjured
b. Control: Index, Non-Index

   i. Control subjects limbs randomly allocated to Index and Non-Index limb in a manner to match the distribution of right and left limb injuries in the ACLR group

1.6 Dependent Variables

The following dependent variables were measured in this study:

Kinematic variables at Initial Contact (IC) for each task

- Trunk Sagittal Plane Position (flexion/extension)
- Trunk Frontal Plane Position (medial/lateral flexion)
- Hip Sagittal Plane Position (flexion/extension)
- Hip Frontal Plane Position (adduction / abduction)
- Hip Transverse Plane Position (internal rotation / external rotation)
- Knee Sagittal Plane Position (flexion / extension)
- Knee Frontal Plane Position (varus / valgus)
- Tibial Rotation Position (internal rotation / external rotation)

Kinematic Joint Displacement (DSP) Variables during the landing phase for each task

- Trunk Sagittal Plane DSP (flexion)
- Trunk Frontal Plane DSP (medial/lateral flexion)
- Hip Sagittal Plane DSP (flexion)
- Hip Frontal Plane DSP (adduction)
- Hip Transverse Plane DSP (internal rotation)
- Knee Sagittal Plane DSP (flexion)
- Knee Frontal Plane DSP (valgus)
- Knee Transverse Plane DSP (tibial rotation)

Kinetic variables during the Landing Phase and Pushoff Phase for each task

- Peak Vertical Ground Reaction Force (VGRF)
- Peak Anterior Tibial Shear Force (ATSF)
- Peak Knee Extension Moment (KEM)
- Peak Knee Valgus Moment (KVM)
1.7 Specific Aims

Specific Aim 1: Determine the effects of anterior cruciate ligament reconstruction in adolescent female athletes on measures of trunk and bilateral lower extremity biomechanics during a double leg jump landing compared to healthy controls with no history of ACL injury

1a: Compare trunk kinematics at *initial contact* and trunk *displacement* during the landing phase of the jump landing between the ACLR group and the healthy control group.

1b: Compare *initial contact* hip and knee kinematics of the ACLR Injured limb during the landing phase of the jump landing compared to the ACLR Uninjured limb and the Control Index limb.

1c: Compare *joint displacement* hip and knee kinematics of the ACLR Injured limb during the landing phase of the jump landing compared to the ACLR Uninjured limb and the Control Index limb.

1d: Compare peak VGRF, ATSF, KEM, and KVM of the ACLR Injured limb during the landing and pushoff phases of the jump landing to the ACLR Uninjured limb and Control Index limb.

Specific Aim 2: Determine the effects of anterior cruciate ligament reconstruction in adolescent female athletes on measures of trunk and bilateral lower extremity biomechanics during a single leg double hop compared to healthy controls with no history of ACL injury
2a: Compare trunk, hip, and knee kinematics at initial contact while performing the single leg double hop on the ACLR Injured limb compared to the ACLR Uninjured limb and the Control Index limb.

2b: Compare trunk, hip, and knee kinematic joint displacements during the landing phase while performing the single leg double hop on the ACLR Injured limb compared to the ACLR Uninjured limb and the Control Index limb.

2c: Compare peak VGRF, peak ATSF, peak KEM, and peak KVM while performing the single leg double hop on the ACLR Injured limb compared to the ACLR Uninjured limb and the Control Index limb during both the landing phase and pushoff phase.

Specific Aim 3: Determine the acute effects of verbal instructions on altering jump landing biomechanics in female adolescent athletes with a history of anterior cruciate ligament reconstruction and healthy controls with no history of ACL injury.

3a: Compare change scores of the ACLR Injured limb for knee flexion DSP, peak VGRF, peak KEM, peak KVM, and peak ATSF during the landing phase of the jump landing compared to the ACLR Uninjured limb and the Control Index limb for the ‘soft’ verbal instructions condition.

3b: Compare change scores of the ACLR Injured limb for knee flexion DSP, peak VGRF, peak KEM, peak KVM, and peak ATSF during the landing phase of the jump landing compared to the ACLR Uninjured limb and the Control Index limb for the ‘equal’ verbal instructions condition.
1.8 Research Hypotheses

Research Hypotheses for Specific Aim 1:

1a Hypothesis: There will be no difference in trunk kinematics at initial contact between the ACLR and healthy control group. However, there will be differences in trunk displacement during the landing phase, such that the ACLR group will demonstrate greater trunk flexion displacement compared to the control group.

1b Hypothesis: The ACLR Injured limb will demonstrate greater sagittal and frontal plane hip and knee joint angles at initial contact compared to the Uninjured limb and Control Index limb. There will be no differences in transverse plane initial contact angles.

1c Hypothesis: The ACLR Injured limb will display lesser sagittal plane motion, but greater frontal and transverse plane motion compared to their own Uninjured limb as well as the Control Index limb.

1d Hypothesis: The ACLR Injured limb will display lesser peak landing and pushoff forces (VGRF, ATSF) and less internal knee extension moment compared to their own Uninjured limb as well as the Control Index limb. The ACLR Injured will have greater peak knee valgus moment compared to the Control Index limb.
Research Hypotheses for Specific Aim 2:

2a Hypothesis: There will be no difference in trunk kinematics at initial contact between the ACLR and healthy control group. The ACLR group will demonstrate reduced sagittal plane flexion with greater frontal plane joint angles (hip and knee) when performing the single-leg double hop on the Injured limb compared to the Uninjured and healthy Control Index limb. There will be no differences in transverse plane joint angle at initial contact.

2b Hypothesis: The ACLR group will demonstrate greater forward and lateral trunk flexion when performing the single-leg double hop on their Injured limb in comparison to the Uninjured limb and the Control Index limb. The ACLR Injured limb will demonstrate less sagittal plane motion with greater frontal and transverse plane motion in comparison to their own Uninjured limb and the healthy Control Index limb.

2c Hypothesis: The ACLR Injured limb will display lesser peak landing and pushoff forces (VGRF, ATSF) and less internal knee extension moment compared to their own Uninjured limb as well as the Control Index limb. The ACLR Injured will have greater peak knee valgus moment compared to the Control Index limb.
Research Hypotheses for Specific Aim 3:

3a & 3b Hypotheses: Soft landing verbal instructions will affect the selected lower extremity kinematic and kinetic variables during the landing phase of the double-leg jump landing in both groups. However, the magnitude of change or direction of changes will be different.

• Post ‘soft landing’ instructions
  - Peak VGRF will decrease on all limbs following the soft landing instructions in comparison to baseline
  - Peak knee extension moment (KEM) will remain unchanged or increase slightly on the ACLR Injured limb and decrease on the ACLR Uninjured and Control Index limb in comparison to baseline.
  - Peak knee valgus moment will remain unchanged in all limbs compared to baseline.
  - Peak anterior tibial shear force will remain unchanged or increase slightly on the ACLR Injured limb and decrease on the ACLR Uninjured limb and Control Index limb in comparison to baseline.
  - Knee flexion displacement will increase on all limbs in comparison to baseline, but magnitude of change will be greater on the ACLR Injured limb

• Post ‘equal landing’ instructions
  - Peak VGRF will remain unchanged or increase slightly on the ACLR Injured limb, decrease on the ACLR Uninjured limb and remain unchanged on the Control Index limb in comparison to baseline.
  - Peak knee extension moment (KEM) will increase on the ACLR Injured limb but remain unchanged on the ACLR Uninjured and Control Index limb in comparison to baseline.
  - Peak knee valgus moment will remain unchanged in all limbs compared to baseline.
  - Peak anterior tibial shear force will increase on the ACLR Injured limb and remain unchanged on the ACLR Uninjured and Control Index limb in comparison to baseline.
  - Knee flexion displacement will increase on the ACLR Injured limb but remain unchanged on the ACLR Uninjured and Control Index limb in comparison to baseline.
1.9 Significance

Non-contact and indirect contact ACL injuries in adolescent females contribute to minimized sports participation, high risk of re-injury, and a lifetime of dysfunction due to the heightened risk of early onset and progression of knee OA. Elucidating movement characteristics and potential asymmetries in this population is important in the ongoing ambition to reduce injury rates and improve long-term outcomes. Additionally, the investigation of verbal instructions to improve the magnitude and symmetry of landing forces in a pathologic population will provide valuable insight into the effectiveness of using these techniques following injury or if these methods are only effective in healthy populations.

Ultimately, this research project aims to further understand the biomechanical impact of ACLR on adolescent females and use this information to work toward preventing secondary injury and protecting the long-term knee related quality of life in this population.
CHAPTER TWO
REVIEW OF THE LITERATURE

The purpose of this study was to examine the effect of ACL injury and surgical reconstruction (ACLR) on a sample of female adolescent athletes whom have fully return to sport. A secondary purpose was to investigate the acute effects of verbal instructions on landing biomechanics in this sample. This review of the available literature will indicate what additional information this study will provide to the current literature.

2.1 ACL Injury Epidemiology

More than 38 million children and adolescents participate in organized sports programs in the US alone.\textsuperscript{97} This is in large part due to the passage of Title IX in 1972, which sparked a significant increase in female participation. In fact, since the inception of Title IX, female participation in high school sports has increased \textit{904}\% over a 30-year time period.\textsuperscript{1} However, this has also resulted in an escalated number of musculoskeletal injuries. Of particular concern is injury to the anterior cruciate ligament (ACL), which is occurring at increasing rates in the young athlete population.\textsuperscript{4, 5, 24, 98} However, female athletes are more likely to sustain a sport related ACL injury at a younger age compared to males participating in the same sports.\textsuperscript{99, 2, 10, 100, 101}

In the general population, including all ages, an estimated 350,000 ACL reconstructions are performed annually in the United States.\textsuperscript{98} Recent estimates illustrate a
national increase of 67.8% over a ten-year period, from 1997-2006. The highest sport related ACL injury rates are seen in women’s basketball, soccer, and gymnastics, likely due to the continual cutting, decelerating, and landing movements, which are commonly thought to load the ACL.

An estimated 2.5 million adolescents visit emergency departments with sport related injuries annually. Upwards of 60% of these adolescent injuries are knee injuries requiring surgery, such as ACL reconstruction (ACLR). Roughly 30% of all sport related knee injuries reported are in persons between the ages of 12-20, with female rates beginning to rise by the age of 12 and peaking around 18 years of age. The average age of onset for puberty and associated growth spurts is around 10.5 years for females and 12.5 years for males, and puberty is typically completed by the age of seventeen and twenty, respectively. Many epidemiology studies report that sport related ACL injuries are more common in immature boys (< 12 years old), but after maturation, the risk and incidence in females is greater.

Prior to puberty there are no differences in physical ability between boys and girls, however once they enter puberty, strength and size differences seem to create distinction in their abilities. There are limited longitudinal research studies in this population that investigate changes in movement patterns in the same individuals across puberty. Quatman et al. completed a 2-year longitudinal study with subjects who were classified as pubertal (ages 12-13) during the first year and post-pubertal (ages 13-14) during the second year. At post-puberty, males had increased their vertical jump height and reduced their ground reaction forces during a drop vertical jump, whereas females had not. The only similarity was that both males and females had decreased loading rates with maturation. The majority of
research compares separate groups of adolescents at different stages of development, rather than tracking longitudinally through time. While there are inherent limitations with these studies, they do offer valuable information. During a drop landing, pre-pubescent females demonstrated greater peak ground reaction forces at initial contact and reached peak heel contact quicker in comparison to post-pubescent females.\textsuperscript{112} When comparing landing kinematics between children (age = 9 years, n=30, 15 female, 15 male) and adults (age = 24 years, n = 28, 14 female, 14 male), Swartz et al.\textsuperscript{56} discovered children landed with greater knee valgus, less hip flexion, and took longer to reach maximum vertical ground reaction force compared to adults. Gender comparisons in youth athletes has revealed that females in late or post-puberty (n=58, age=15.5 ± 1.5 yrs) had more medial knee motion in comparison to males (n = 30, 15.8 ± 1.7 yrs)\textsuperscript{57} and decreased sagittal plane hip and knee motion (n = 60, 30 female, 30 male, 11-16 yrs)\textsuperscript{59} in comparison to males during a drop vertical jump and stop jump, respectively. In addition, males in post-puberty had greater strength compared to males pre-puberty, whereas there were no differences between pre- and post-pubescent females.\textsuperscript{57} In summary, prior to puberty there are limited differences between boys and girls, however at the onset of puberty and maturation there are strength and movement characteristics that set them apart. Males adapt with strength and neuromuscular control across puberty, whereas females do not. In combination, changes occurring during this time period, contribute to rendering females four to six times more likely to suffer an ACL injury compared to males playing the same landing and cutting sports.\textsuperscript{2} The mechanisms of ACL injury and the theories behind the gender disparity in sport related ACL injuries are multi-factorial and will be discussed throughout this literature review.
Physical activity and sports participation at a young age provides many physical, mental, and emotional health benefits. The tendency to be physically active (or inactive) as an adult is directly related to the quality of physical activity experiences earlier in life. Today’s young athletes are starting to “specialize” in one sport at an earlier age, often in hopes of earning college scholarship funding. This typically means participating in one sport, year round, with little to no breaks. Unfortunately, this early specialization could theoretically contribute to injury due to the repetitive stresses and altered muscle balance, muscle recruitment, and human motion from a lack of well-rounded training. As will be discussed later, ACL injury often occurs due to altered neuromuscular control during sport specific movements. Long-term knee related quality of life is poor in adults that have suffered an ACL injury earlier in life, with diminished physical activity, high rates of re-injury and high rates of knee osteoarthritis (OA). It may be safe to conclude that the same or potentially worse outcomes would exist in children and adolescents, particularly females, suffering injury at such a young age. However, there is a lack of research in this population following ACLR, therefore the prognosis is relatively unknown.

Surprisingly, biomechanical research has not called attention to adolescent females following ACL injury and ACLR. Improved screening procedures for athletes at risk of primary or secondary injury and improved management of female adolescents with a history of ACLR should be a high priority to avoid the poor consequences later in life. In order to do so, we need to better understand the biomechanical consequences these females face as they progress through rehabilitation and prepare to return to sport. A recent consensus statement of leading ACL injury researchers emphasized the need to focus on the youth athlete in our injury-risk screening and injury-prevention strategies. It has also been suggested that
female and male adolescents should be evaluated separately due to the inherent differences in neuromuscular control and functional performance during this time period. Therefore, this study will focus on female adolescents with a history of ACLR due to the heightened injury rates these female athletes face.

The purpose of this study is to investigate landing biomechanics in adolescent females that have sustained an ACL injury with subsequent ACLR. Comparisons specific to their own asymmetries and in comparison to healthy control subjects will be made. A special focus will be placed on studying dynamic functional movements typically used to progress rehabilitation and make return to play decisions. In addition, we will study the effectiveness of verbal instructions on altering landing forces in adolescent females, with and without previous ACLR. This literature review provides a background and rationale for this study.

2.2 Consequences of ACL Injury: The Problem

The volume of short and long term consequences due to ACL injury and subsequent surgical reconstruction are vast. Many adolescent athletes identify themselves with the sports they play and the group of friends they attain through those sports. ACL injury typically results in a loss of an entire season, which can make the athlete feel excluded. Diminished academic performance, irrational or depressive thoughts, and other long-term disabilities are also possible. In addition to the personal and psychological impact, ACL injury carries a large financial burden. Conservative estimates of surgery and rehabilitation costs are approximately $17,000-$25,000 per injury. The overall cost to our health care system is estimated to be more than $2 billion annually. This does not even factor in the expenses
related to decrease or a total loss of potential scholarship funding and associated long-term disabilities.

There are surgical concerns specific to this population that need to be addressed. ACLR in a younger patient is concerning due to the potential for growth-plate injury from tunnel placement or graft fixation during repair.\textsuperscript{24-26, 119} Femoral or tibial bone overgrowth is possible with stimulation of an actively growing physis, therefore the occurrence of a growth spurt close to ACL reconstruction is problematic.\textsuperscript{24} Historically, a surgeon may opt to wait on surgery and treat the patient conservatively, leaving the knee ACL deficient, until any growth spurt has elapsed. However, adolescent athletes attempting to participate in sport with an ACL deficient knee may actually create a larger problem. The goal of treating an adolescent athlete conservatively, meaning no reconstruction, is to maintain stability, activity level, avoid re-injury, and maintain normal growth. Several studies have shown that ACL deficiency leads to further deterioration of the knee joint function, with the development of instability, poor control of muscle function and muscle weakness.\textsuperscript{120-122} The pressure to perform and compete often makes limiting activity nearly impossible and continued bouts of giving way and pain can certainly lead to subsequent injury to the menisci or articular cartilage, both of which are risk factors for developing knee osteoarthritis (OA).\textsuperscript{21, 123, 124} Therefore, most female adolescents who wish to return to sport requiring cutting, pivoting, and jumping need to undergo ACL reconstruction. Unfortunately, this does not ensure a successful outcome and return to sports participation at the desired level.

Rehabilitation guidelines typically allow adult athletes to return to sport within 6-9 months following surgery. However, follow-up studies suggest that up to 70% of ACL injured adults are no longer able to participate in the activity or sport that lead to their injury.
in as little as 3-years post.\textsuperscript{10, 125-130} A variety of reasons have been reported, including but not limited to ongoing knee issues, social reasons, and the fear of potential re-injury.\textsuperscript{128, 129, 131} Successful return to the same or higher level of sport activity in adults is largely dependent on the type of sport they are attempting to return to. A comparison of recreational and competitive level athletes undergoing ACLR found that only 38\% of competitive athletes, in comparison to 59\% of recreational athletes, were able to return to their pre-injury activity level.\textsuperscript{132} Obviously the level of activity for the recreational athletes was less both prior to and after surgery, therefore demonstrating a return to a lower level of activity may be possible. Similarly, adult soccer players treated surgically or conservatively for ACL injury were tracked over a 7-year time period. At three years post injury, regardless of treatment, only 30\% remained active in soccer. At seven years post injury, regardless of treatment, none of the injured players were active in soccer.\textsuperscript{10} Attention must be drawn again to the previously mentioned studies, as all of these researchers reported on the success and failure of ACL rehabilitation and return to sport in adults. A single retrospective study investigated a group of adolescents (females = 40, males = 15, age = 15.9 ± 1.65 years) who had undergone ACLR to track their time to quadriceps strength recovery and time of full return to activity.\textsuperscript{133} Overall, 32 patients (59\%) had achieved ≥ 85\% quadriceps strength, in comparison to their uninjured leg, within 6 months of their surgery.\textsuperscript{133} Of these patients, sixteen of them returned to full activity within 6 months, indicating only 29\% of the adolescent subject population was ready to return in this time frame. We do not know how long these adolescents were able to continue a full level of play after returning and the only return to play criteria considered was quadriceps strength, both of which are weaknesses to this study. Young, adolescent females that sustain an ACL injury are undoubtedly hoping to return to sport and have a career at the
level of competition they desire. However, we simply do not know appropriate return to play
timing for these adolescents to ensure longevity in their career and good long-term outcomes.
The rehabilitation and return to play components of ACLR will be discussed in greater detail
later in this review.

Some of the most devastating consequences of ACL injury are certainly the long-term
consequences, including re-injury and the onset of posttraumatic OA. Individuals with a
previous ACL injury are up to 15 times more likely to suffer a second ACL injury, to either
knee, in comparison to an otherwise healthy subject. An epidemiology study of elite
female soccer players showed the risk of suffering a new or secondary ACL injury was five
times higher in players with a previous ACL injury. The distinctive part of this study was
that the increased rate of re-injury for these women was only true for ACL injury, such that a
prior ankle sprain or knee sprain to another ligament did not put someone at greater risk of
suffering re-injury. ACL re-injury rates ranging from 3% at 2-years follow-up up to 33%
at 10-years follow-up have been reported. Even more significant to this study is the
alarming fact that the highest short-term re-injury rates, within 1-2 years, are in younger,
more active individuals, under the age of 20. In fact, a recent report from the Swedish
National ACL register revealed that 22% of female soccer players between the ages of 15-18
suffered a secondary ACL injury within five years, compared to 9% in the general adult
population. The type of sport one returns to and the time frame of return to play following
ACLR are both factors that influence re-injury rates. Young adults who return to sports
incorporating lateral side-stepping, cutting and jumping are 10.4 times more likely to sustain
a repeat ACL injury to either leg. Returning to these activities in less than seven months
compounds these risks. Females appear to be at no greater risk of repeat injury
compared to males. However females may be more likely to injure their previously uninjured knee (contralateral), while males may be more likely to injure their surgical graft (ipsilateral). This evidence draws three potential problems to mind, either we are returning young athletes to sport before they are ready, we are not addressing the original injury risk factors through rehabilitation, and/or females are adopting movement compensations following ACLR that elevate their risk of injury on the previously uninjured leg. The answers are currently unknown.

OA in the injured joint is caused by intra-articular pathogenic processes initiated at the time of injury, combined with long-term changes in dynamic joint loading. The incidence of OA after ACLR is disturbingly high, with approximately 50% of patients developing mild to moderate radiographic OA as early as 6 years post reconstruction, but most often at 10-15 years post injury. Knee OA can lead to a lifetime of pain and disability, often making it impossible for individuals who experience an ACL injury as an adolescent to continue any form of strenuous activity or sport through the lifespan. Twelve-years post ACL injury, female soccer players who had undergone ACLR (60%) or conservative treatment (40%) showed no differences between groups in knee symptoms. Both groups displayed a high prevalence of radiographic tibiofemoral knee OA (82%), pain (75%), and functional limitations at a mean age of 31 years, suggesting surgical reconstruction did not offer a better outcome. Currently, there is a lack of evidence to support the notion that reconstructive surgery can protect the knee against future OA development. Recent research has also revealed a link between ACLR and patellofemoral OA at roughly twelve years following reconstruction. Previous knee injury is one of the strongest risk factors for knee OA, such that ligament or meniscus injury alone
increases risk by 20%, menisectomy (partial removal of torn meniscus) increases risk by 40%, and combined ACL rupture with meniscal injury increases the risk by 70%. The loss of the meniscus in addition to the ACL may contribute to increased cartilage contact stress through decreased load distribution, shock absorption, and joint stability. More than 50% of all ACL injuries and nearly 100% of pediatric ACL injuries include a concomitant meniscal injury. Therefore, the risk of early onset of OA is massive in a female adolescent population.

With a greater understanding of the long-term consequences of ACL injury, suffering these injuries at an earlier age is frightening. An adolescent suffering an ACL injury could potentially face radiographic knee OA much earlier in life. In fact, post-traumatic knee OA has been reported in persons as young as 20 years old. Successful treatment options for long term function and comfort for this female adolescent population are challenging. Very limited research exists in females in this age range after ACL injury and subsequent ACLR; therefore there is a pronounced need to identify unsafe movement patterns and asymmetries in this population that could potentially be modified to improve these poor long-term outcomes.

2.3 Mechanism of Injury

The ACL serves to resist movement in all three planes of motion. It minimizes forward translation of the tibia relative to the femur, prevents knee hyperextension, and provides rotary stability. Injury to the ACL results from excessive loading and deformation due to a combination of joint forces, moments, and body movements. An estimated 70-80% of all sport related ACL injuries are due to non-contact mechanisms during landing, cutting,
pivoting, and sudden deceleration movements. Compared to males in the same sports, females between the ages of 13-18 years old are twice as likely to suffer a non-contact ACL injury in soccer and four times as likely in basketball, owed to inherent differences in the way females move. Through the years, variations in the operational definitions of ‘non-contact’ ACL injury have made interpretation and comparisons of some data challenging. Historically, non-contact injury mechanisms generally denoted no direct contact with another person or object (other than the ground) has occurred. However, indirect contact often occurs at the time of injury, indicating a physical perturbation by the athletes’ own movements or by contact with another player that slightly knocked them off balance. The key is that no direct contact with the knee has occurred in either situation. In combination, non-contact indirect contact (NCIC) mechanisms result from the athlete’s own movements, which typically are disturbed by a physical or cognitive perturbation either during or immediately before the injury event. Often times in team sports, athletes that suffer a NCIC ACL injury have had some interaction with the ball, often performing a task in rapid response to a game situation, which likely affects full body kinematics and knee moments. The intended motor play has to be rapidly updated due to this disruption and can be problematic for some individuals. This more focused and detailed description of NCIC injury will be utilized for the remainder of this review.

No single mechanism for NCIC ACL injuries exist, rather the literature is in agreement that multifactorial mechanisms lead to injury, including both extrinsic and intrinsic factors. Extrinsic risk factors include type of competition, footwear, playing surface, and environmental conditions. Intrinsic risk factors are commonly divided into four categories, including anatomical, hormonal, neuromuscular, and biomechanical
characteristics. These risk factor categories are somewhat theoretical because in most cases epidemiological risk factor identification has not been performed, however gender differences have been identified. Anatomical factors that have been identified as potential risk factors include increased posterior tibial slope, decreased femoral notch width, ACL geometry, excessive Q-angle, high body mass index (BMI), excessive foot pronation, large navicular drop, and increased generalized joint laxity. Hormonal influences are also potential risk factors as research has suggested greater knee laxity in females occurs during certain phases of the menstrual cycle regardless of oral contraceptive use. We acknowledge the importance of both anatomical and hormonal risk factors, and the potential influence these factors have on our participants, however this project will focus on the investigation of neuromuscular and biomechanical factors specific to altered movement patterns and joint loading that may predispose someone to primary or secondary ACL injury. All four categories will be discussed in greater detail due to their potential contribution to poor long-term outcomes after ACL reconstruction, with an emphasis on the neuromuscular and biomechanical factors.

Biomechanical research utilizing human cadaver specimens has worked towards describing mechanisms that directly load the ACL. The most direct loading mechanism on the ACL is a linear shear force at the proximal tibia, causing translation of the tibial plateau in an anterior direction relative to the femur. However, anterior tibial shear force in combination with knee valgus (or varus) moment and tibial internal rotation moment, particularly when the knee is more extended, further increases the ACL load.

In addition, computer modeling studies have created simulated loading situations to investigate the effects estimated loading placed on the ACL during a combination of loading.
Results have provided evidence for the role of a smaller patellar tendon insertion angle during deceleration on ACL strain during a single leg landing, as ACL deficient knees had smaller insertion angles compared to the contralateral limb.\textsuperscript{166} During simulated sidestep cutting tasks, McLean et al.\textsuperscript{167} concluded that ACL injury via a valgus loading mechanism is more likely to occur during sidestepping when landing at ground contact with a more extended posture. Pflum et al.\textsuperscript{168} described the force of the patellar tendon pull on the anterior tibia and the tibiofemoral compressive force as significant contributors to the magnitude of anterior tibial shear force experienced during simulated landing movements.

Video analyses of ACL injury events consistently reports joint posture at the time of initial foot contact (IC)\textsuperscript{39, 102, 145, 169, 170} as the time of injury onset is believed to be between 17-50ms after IC.\textsuperscript{54} Video evidence of females at the time of ACL injury shows they land in a relatively more extended position with valgus knee collapse and lateral flexion of the trunk, resulting in the center of mass moving outside of the base of support.\textsuperscript{39, 145, 169} Olsen et al.\textsuperscript{145} revealed female team handball players were injured while landing with the knee close to full extension combined with tibial rotation (external or internal) and a forceful knee valgus collapse. Hewett et al.\textsuperscript{169} noted that lateral trunk lean and knee abduction angles (valgus) were significantly higher in females while sustaining an ACL injury compared to males. In a more novel approach, Krosshaug et al.\textsuperscript{54} used model-based image matching techniques from multiple camera views of an injury event and found females actually landed with significantly more knee and hip flexion and were 5-times more likely to demonstrate valgus knee collapse than males when sustaining an ACL injury. Additionally, an opponent typically perturbed the athletes’ movement patterns, representing an NCIC mechanism, but no direct contact with the knee was made. Finally, a more recent video analysis study linked NCIC
ACL injury mechanisms with foot and ankle positioning at initial ground contact, suggesting landing flatfooted, or with minimal ankle plantar flexion, greater knee abduction (valgus) and increased hip flexion may be risk factors for ACL injury. Video based studies of ACL injury events provide valuable information, however there are some difficulties with interpreting these studies as methods and techniques are not standardized.

Based on cadaveric, computer modeling and video analysis research it is evident that a combination of loading states is most injurious to the ACL. Landing with greater frontal and transverse plane motion at the trunk, hip, and knee in conjunction with minimal sagittal plane motion may contribute to NCIC ACL injury in females. A more detailed discussion of the specific factors that increase loading on the ACL is helpful in order to better understand the impact of landing patterns on ACL injury. The following section will elaborate on these factors and then progress into the laboratory derived ACL injury risk factors derived from invaluable prospective case-control research studies.

### 2.4 Factors that Influence ACL Loading

The magnitude of loading placed on the ACL is influenced by body position and limb alignment. As mentioned previously, the ACL is injured through multi-directional loading as opposed to a single load. Cadaveric studies have identified three of the most likely mechanisms that pose a threat to the ACL; including anterior tibial translation, knee valgus, and tibial rotation. Knee flexion angle and muscles acting on the knee joint directly affect these mechanistic factors. It is necessary to discuss the importance of knee flexion angle and muscle function in greater detail to better understand how the ACL is loaded.
Additionally, this provides the background for the factors that contribute to a poor outcome following ACL injury that will be discussed in the future.

The quadriceps, hamstrings, and gastrocnemius muscles directly cross the knee joint and play an important role in increasing or potentially decreasing the loading placed on the ACL. Isolated quadriceps contractions and inertial forces due to sudden accelerations and decelerations generate anterior tibial shear force.\textsuperscript{28} Cadaveric\textsuperscript{171} and laboratory\textsuperscript{38} research has demonstrated greatly increased ACL loading from isolated quadriceps activity, particularly at small knee flexion angles ranging from 0 to 45 degrees.\textsuperscript{36, 172} The influence of quadriceps force on ACL loading is mediated by two factors directly related to the knee flexion angle; the patellar tendon insertion angle and the ACL elevation angle. When the knee is in a more extended position, the patellar tendon insertion angle with respect to the tibial longitudinal axis increases, thereby inducing an anteriorly-directed force on the tibia when the quadriceps contract.\textsuperscript{173} As the knee moves into greater flexion, the patellar tendon insertion angle decreases, thereby minimizing anterior tibial shear force with quadriceps contraction. Previous research has reported decreases in anterior tibial translation and subsequent shear force with greater knee flexion angles during real or simulated knee extension exercises.\textsuperscript{38, 174, 175} This is in agreement with the video analysis studies that observed the majority of injuries occurring with minimal knee flexion at initial ground contact.

The ACL elevation angle is also directly influenced by knee flexion angle during dynamic movement. The elevation angle is the angle of the ACL insertion with respect to the tibial plateau, decreasing with knee flexion so that the ACL is practically parallel to the tibial plateau when the knee is flexed to 90 degrees.\textsuperscript{173, 176} In a more flexed position, an anteriorly directed force on the tibia would produce a tensile force on the ACL as opposed to a shear
force, which is typically produced by anterior tibial translation at smaller knee flexion angles. Biomechanical properties of ligamentous tissue render them stronger under tensile forces and weaker under shear forces. Therefore, with respect to the ACL elevation angle, a greater amount of knee flexion is ideal.

The hamstring muscles are a synergist to the ACL, producing a posterior force on the tibia and potentially countering the anterior tibial shear force produced by the quadriceps. This potential protective mechanism is also dependent on knee flexion angle. The angle of hamstrings tendon insertions relative to the longitudinal axis of the tibia is increased as the knee moves into greater flexion. Hamstrings muscle activation at a larger knee flexion angle would produce a posteriorly-directed force on the tibia, whereas in a relatively more extended position these forces would be more compressive. Previous research has demonstrated that at knee flexion angles greater than 30 degrees, hamstring muscle activation is able to reduce the load on the ACL and reduce anterior tibial translation. In a cadaver study, More et al. found a 90N hamstrings load could decrease the load on the ACL by 40% when the knee was between 15-45 degrees of flexion. While Li et al. found an 80N hamstring load was capable of decreasing ACL loading by 30-44%.

Another influence on the magnitude of ACL loading is the combined co-contraction of the hamstrings and quadriceps muscles, which affects loading in all three planes of motion. The hamstrings not only aid in reducing anterior tibial shear forces, but they are capable of preventing knee valgus and limiting tibial internal rotation. Muscles surrounding the knee counteract knee valgus by producing a greater knee extension moment, knee flexion moment or a greater co-contraction prior to landing. The third muscle that crosses the knee joint is the gastrocnemius, which acts primarily as an ankle plantar flexor.
but also contributes to knee flexion. Computer modeling studies have demonstrated that both quadriceps and gastrocnemius muscle contractions load the ACL, but the impact is once again dependent on knee flexion angle.\textsuperscript{180, 181} Specially, at small knee flexion angles, between fifteen and thirty degrees of flexion, contraction of the gastrocnemius muscle increases strain on the ACL. Furthermore, gastrocnemius contraction in combination with quadriceps contraction at smaller knee flexion angles dramatically increases ACL strain.\textsuperscript{181}

Females demonstrate quadriceps dominant muscle activation patterns in comparison to males performing the same tasks, which may be one of many predisposing factors for higher ACL injury rates in female athletes. Quadriceps dominant activation increases anterior tibial shear force and is also capable of creating tibial internal rotation during knee extension, both of which magnify ACL loading.\textsuperscript{38, 175, 181} The timing of muscle activation between males and females also appears to be different. During a variety of sport specific tasks, including running, cutting and stop-jump, females repeatedly activated their quadriceps muscles prior to their hamstrings when making initial ground contact, whereas males activated their hamstrings muscles first.\textsuperscript{182, 183} Similar alterations in muscular relationships are seen in the medial and lateral musculature of the leg. Palmieri-Smith et al.\textsuperscript{184} calculated a co-activation ratio between the medial and lateral quadriceps and hamstrings during a single-leg forward hop and landing task. In general, females had less overall muscle activation during the landing phase in comparison to the males, but females also demonstrated less activation in the medial quadriceps (VMO) and medial hamstrings in comparison to the lateral, potentially contributing to knee valgus.

In summary, the ACL is ruptured when the load on the ACL exceeds the ability of the ligament to elongate and recover. During movement, combined anterior tibial translation,
knee valgus, and tibial internal rotation combined with low knee flexion angles are known to load the ACL. However, the identification of prospective risk factors, or variables that can be identified years before an ACL injury mechanism is experienced, are crucial to identifying individuals that are at risk so that interventions can be performed to reduce the risk of injury and re-injury. Undoubtedly, of primary concern are these adolescent females that have suffered an ACL injury and are at such a high risk for a secondary injury and the early onset of posttraumatic knee OA.

### 2.5 Prospective ACL Injury Risk Factors

Previous research utilizing prospective, case-control study designs, has identified risk factors for primary and secondary ACL injury.\(^ {17, 45, 52, 62}\) These types of studies are more challenging, as you need to assess a large number of individuals prospectively and then wait for subsequent injuries to occur. But they are the most valuable, as the identified risk factors can be used for screening purposes to detect individuals at greater risk of sustaining an ACL injury before it happens. A similarity to three of these studies is the use of a double leg jump landing (drop vertical jump) from a set height followed immediately by a maximal vertical jump, to elucidate these risk factors.\(^ {17, 45, 184}\) Padua and Marshall et al.\(^ {184}\) assessed 6000 cadets as they entered one of three military service academies and then tracked them throughout their tenure for subsequent NCIC ACL injuries. Individuals that went on to tear their ACL (n=98) landed from a jump landing task with greater hip external rotation, hip adduction, and knee valgus on their dominant limb at initial contact with greater overall hip flexion motion in comparison to subjects who did not go on to suffer an injury.\(^ {184}\) A separate study observed 20% higher vertical ground reaction forces (VGRF) in females who later went on to suffer an
ACL injury (n = 9) in comparison to females who did not. Finally, greater trunk repositioning error (more motion) after a sudden force release in males and females was predictive of later experiencing a general knee injury (n=25).

Recently, similar prospective, case-control, study designs were used to identify risk factors for secondary ACL injury. Individuals that were assessed during a jump landing after sustaining a primary ACL injury (n=150), that went on to suffer a secondary ACL injury (n=13), also demonstrated greater hip external rotation, hip adduction, and knee valgus at initial contact with greater overall hip flexion motion in comparison to those who did not suffer an injury. These movement characteristics are the same as the risk factors that were predictive of an initial ACL injury. However, these individuals also demonstrated greater hip flexion at initial ground contact, decreased knee extension moment at midstance, and greater overall knee flexion motion, suggesting significant quadriceps dysfunction exists following initial ACLR. Paterno et al. assessed adolescents post ACLR (N=56, female=35, male=21, 16.41 ± 2.97 years) using three-dimensional motion analysis during a drop vertical jump and then tracked these athletes for one year. Alarmingly, thirteen adolescent athletes went on to suffer a secondary ACL injury within one year. Eleven of the thirteen re-injuries were in females (85%) at a mean age of 15.77 ± 1.36 years. Furthermore, ten of the secondary ACL injuries were to the contralateral limb. Adolescents that went on to suffer a secondary injury displayed greater hip internal rotation net moments (initial 10% of stance) on the previously uninjured limb and greater knee valgus motion (angular displacement) on the previously injured limb. In addition, those that went on to suffer a secondary ACL injury had greater asymmetry in knee extension moment at initial ground contact, such that the previously uninjured limb was loaded more than the injured limb. Adolescents who
exhibited these movements were 3-8 times more likely to sustain a secondary ACL injury to either leg. Results from this study accentuate the need to study adolescent females post ACLR to identify movement characteristics at the trunk and both lower extremities that may set them up for future re-injury and work diligently to improve their movement and prevent secondary injury. The results of these studies suggest that some factors that are predictive of primary ACL injury are still present and predictive of a secondary injury. There are additional risk factors predictive of a secondary injury, including greater overall sagittal plane motion and asymmetrical loading, which could be potential compensations resulting from the initial injury and subsequent reconstruction.

2.6 Factors that Contribute to Poor Outcomes following ACLR

**Anatomical Factors**

As mentioned previously, anatomical or structural characteristics may contribute to an individual being at greater risk of experiencing ACL injury. Similarly, these same anatomical factors may contribute to the less than desirable outcomes following ACLR as they have likely not changed. Several studies have demonstrated that individuals with previous ACL injury, particularly females, had larger posterior tibial slope angles compared to matched controls. The geometry of the tibial plateau has a direct influence on the biomechanics of the tibiofemoral joint in terms of anterior tibial translation and the amount of shear force placed on the ACL. Larger angles indicate a steeper elevation of the anterior tibial plateau in comparison to the posterior plateau. A combination of a large (steep) posterior tibial slope and tibiofemoral compressive forces created during dynamic landing
movements, such as the jump landing, create an anteriorly directed shear force resulting in anterior translation of the tibia.\textsuperscript{148,150,187} Thus loading on the ACL is increased.

Another anatomical characteristic associated with ACL injury and potentially poor outcomes is the size of the intercondylar notch at the distal femur.\textsuperscript{155} The ACL sits in a vulnerable position in the confines of the notch and runs the risk of coming into contact with the medial margin of the lateral femoral condyle when the knee is flexed and the anterior part of the notch in extension. Intraoperative measurements have revealed that the intercondylar notch width is narrower in women in comparison to men, which is not surprising.\textsuperscript{151,188} However, when analyzed with height and weight as covariates\textsuperscript{150} or when solely comparing within gender,\textsuperscript{188} individuals with narrower notch widths were more likely to experience an ACL injury.\textsuperscript{151,188,152,155}

The geometry of the ACL is generally smaller in women compared to men even after normalization to body mass.\textsuperscript{7} This also is an anatomical characteristic that may be related to poorer outcomes, particularly in females. A smaller ACL in females results in lower tensile linear stiffness, less elongation ability, decreased energy absorption and decreased load resulting in failure in comparison to men.\textsuperscript{189,190}

Generalized joint laxity, often assessed through a variety of hyperextension assessments, has been shown to be a prospective risk factor for ACL injury.\textsuperscript{155,162} Assessments include a combination of small finger hyperextension, elbow hyperextension, knee hyperextension, and the ability to touch the thumb to the volar aspect of the forearm. Anterior knee joint laxity is assessed as the amount of anterior translation of the tibia relative to the femur, typically applied by an arthrometer to measure the laxity of the ACL. Generalized joint laxity\textsuperscript{136} and anterior knee laxity\textsuperscript{137} tend to be greater in women. At the
time of surgery and immediately following, knee joint laxity is typically restored to the same level of the contralateral knee or very close. However, within 1-2 years an increase in generalized knee joint laxity becomes apparent, regardless of accelerated or non-accelerated rehabilitation.\textsuperscript{161, 191} A recent literature review reports consistent increases in anterior knee joint laxity in females after ACLR when using a hamstring graft in comparison to males with a hamstring graft and both males and females with a patellar tendon graft.\textsuperscript{192} Ongoing knee laxity leads to further damage of the articular cartilage and menisci, contributing to re-injury and the onset of knee OA.\textsuperscript{193} Due to the prevalence of anterior-posterior knee laxity in females following ACLR, anterior displacement of the tibia relative to the femur will be assessed with the KT-1000 knee arthrometer (MEDmetric Inc., San Diego, CA). This measurement is not directly built into the specific aims of this project, however this information will be valuable in the interpretation of the results.

Finally, sex hormones certainly could affect the structure, metabolism and mechanical properties of the ACL even after reconstruction, however the specific causes are not fully understood and will not be addressed further in this study.

There is some debate as to the role of anthropometric measures, such as body mass index (BMI), height, weight, girth, or other body dimensions on ACL injury. High BMI may put someone at greater risk of non-contact indirect contact ACL injury,\textsuperscript{135} however some research has shown no effect on injury risk.\textsuperscript{194} Faude et al.\textsuperscript{135} prospectively tracked elite female soccer players (22.6 ± 4.9 years old) over the course of one season after collecting baseline anthropometric data. They found female soccer players, who were taller (>1 SD above the mean), had a significantly increased injury risk compared to those with intermediate height.\textsuperscript{135} Additionally, females with a higher body mass (>1 SD above the
mean) were more likely to sustain a non-contact injury, however these higher body mass females also played in significantly more games during the previous season. In another prospective study of West Point military cadets, a higher than normal BMI in women (mean 24.1 ± 1.2) was a significant predictor of sustaining a non-contact ACL injury, in comparison to the women who did not suffer an injury. Women with a BMI that was one standard deviation or more above the mean had a relative risk for noncontact ACL injury that was 3.5 times that of women with a lower BMI. However, these injuries occurred within four years of baseline testing and it is unknown what their BMI was at the time of injury. A very recent study retrospectively assessed concomitant meniscal and chondral injuries in pediatric patients that had experienced an ACL injury and underwent ACLR. Increased patient body mass (> 65 kg) in these pediatric patients was associated with an increased rate of medial (53%) and lateral (63.5%) meniscus tears. Concomitant meniscal injuries increase the risk of knee OA and will be addressed further in the following section. Regardless of the debate, it does seem plausible that females with a higher body mass or BMI could be at an increased risk of sustaining injury and re-injury. The ability to return to high intensity sports is a great challenge following ACLR and physical activity through the lifespan is often decreased. A decrease in physical activity could lead to higher body mass and higher BMI values and the risk of developing knee OA are strongly associated with BMI. Additional anthropometric measures such as triceps-skinfold thickness in men and waist-hip ratio in women have also been associated with knee OA.

In summary, structural and hormonal risk factors are not easy to correct, but it is important to understand them if we want to be able to identify those at increased risk of primary or secondary ACL injury. We acknowledge the impact these factors may have on
adolescent females, but will focus the direction of the current study on the more modifiable neuromuscular and biomechanical factors. While anthropometric data are not directly a part of our specific aims, height, body mass, and segment lengths will be recorded for the purposes of normalizing our data for comparisons. The thigh segment length will be measured from the hip greater trochanter to the line of application of the handheld dynamometer above the knee for hip abduction muscle testing, while the shank segment will be measured from the knee lateral joint line to the line of application of the handheld dynamometer at the ankle for knee flexion and extension muscle testing.

**Concomitant Injuries**

Another factor that contributes to the poor outcomes following ACLR are concomitant injuries to the menisci, chondral tissue, or collateral ligaments at the time of initial injury onset. A meager 20% of ACL injuries are isolated to the this structure alone. One study performed MRI’s on adults (non-athlete’s) after sustaining an injury with a suspected ACL rupture and found 38% of the eighty-nine confirmed injuries had an associated medial meniscal tear. However, in younger patients, reports ranging from 21-100% of patients have a concomitant meniscal injury. The medial and lateral menisci of the knee serve an important role in shock absorption, load transmission, joint nutrition, proprioception, and added stability within the joint. Traumatic injuries to the menisci typically occur in younger active individuals caused by a distinct knee trauma that causes the meniscus to become trapped between the two articulating bones. This trauma often occurs from a non-contact mechanism during a twisting motion on a partially fixed, weight bearing knee, similar to ACL injury mechanisms. If a meniscal injury does not result initially, many patients go on to develop a meniscal tear within 1-2 years due to the chronic
instability caused by injury to the ACL.\textsuperscript{21} The ability to preserve the menisci and other cartilage in the knee is certainly preferred over removal due to the large influence they have on preventing degenerative changes and pain in the knee. However, the course of action is dependent on the location of the tear. The outer peripheral portion of the meniscus is well vascularized, meaning there is adequate blood supply, which gives it the potential to heal. The inner most portion is lacking the blood supply and consequently is very unlikely to heal.\textsuperscript{203} At the time of ACL reconstruction, arthroscopic surgical techniques allow repair of the vascularized tissue when possible, but removal of the damaged portion (meniscectomy) is often necessary or preferred for a quicker recovery. Unfortunately, meniscectomy decreases the joint contact surface area and increases the stress on the tibia during loading.\textsuperscript{204} As mentioned previously, both ACL injury and partial meniscectomy are independent risk factors for the onset of knee OA.

Chondral fractures and subchondral bone bruising are additional concomitant injuries that can occur simultaneously with ACL injury. Chondral fractures are rarer, however subchondral bruising with intact cartilage surfaces is very common.\textsuperscript{205-207} The damage caused by these bruises can be very debilitating for months following injury and even reconstruction. The true long-term impact is unknown, but certainly it has been suggested that these lesions will eventually lead to knee OA. Simply put, combined injury to numerous structures in the knee increases the risk of permanent dysfunction and disability.

Due to the prevalence of concomitant meniscal injuries in a young athletic population, female adolescents with or without meniscal injury will be included in this study. However, additional ligament injuries will be considered exclusionary as the course of treatment, rehabilitation, and return to play would have been quite different.
Surgical Factors

Long-term outcomes following ACLR may also be reliant on several surgical factors. The primary goal of treating an ACL injury is to restore knee function, permit the patient to return to a desired level of physical activity without experiencing giving way, and reduce the risk of repeat injury and the risk of OA. Most athletes wish to return to high demand activities, which require surgical ACL reconstruction. The graft selection for repair may play a role in the long-term outcome, with pros and cons present for each.

Bone-patellar tendon-bone (B-PT-B) autografts are widely used for reconstruction due to its excellent initial fixation, biomechanical properties, durability, and reported success at long-term follow-up. However, excessive scar formation, shortening of the patellar tendon, loss of terminal knee extension, quadriceps dysfunction and chronic patellofemoral pain have been reported in numerous studies following reconstruction with this graft. Of particular interest to this study is the performance deficits during functional tasks, such as the vertical jump landing. Ernst and colleagues found at nine months post B-PT-B ACLR, subjects displayed significantly lower summated internal extensor moments on the injured limb during a single-leg landing in comparison to healthy control subjects. Results suggest quadriceps dysfunction and an inability to attenuate landing forces on the previously injured limb following ACLR with a patellar tendon graft, which consequently would contribute to future re-injury.

Hamstrings autografts, specifically semitendinosus and gracilis tendon (ST-G) grafts, may preserve the vitality of the patellar tendon and knee extensor unit, however hamstring strength deficits after reconstruction have also been reported. Strength deficits have been reported in generating knee flexion as well as tibial internal rotation. The
hamstrings muscles are bi-articular, crossing both the knee and hip, therefore weakness or dysfunction could actually affect the hip extensor mechanism as well. Vairo et al.\textsuperscript{63} investigated landing neuromechanics during a single-leg drop landing on the surgical limb in adults who received a hamstrings (ST-G) autograft in comparison to their uninjured limb and healthy matched control subjects. Isokinetic strength assessments of the hamstrings revealed no differences between the reconstructed limb of the ACLR group and the healthy limb of the control group. However, the reconstructed limb demonstrated decreased peak ground reaction forces and decreased hip flexion at initial ground contact as well as greater peak hip, knee, and ankle flexion during landing in comparison to their uninjured limb and the healthy control subjects.\textsuperscript{63} In addition, greater quadriceps and hamstrings co-activation with less gastrocnemius activation was present in the ACLR limb in comparison to the healthy control subjects. Results suggest altered functional performance after ACLR with a hamstrings graft as a means of stabilizing the knee during landing and attenuating landing forces. Increased hamstrings graft failure rates have been reported in women compared with men.\textsuperscript{217} But as reported earlier, contralateral ACL rupture, regardless of graft, may be more likely in women.\textsuperscript{192, 218}

Allograft harvesting from cadaveric specimens is an alternative to minimize the effects of graft harvesting from the patient. Overall, allograft healing is somewhat delayed in comparison to autograft repairs and encompasses a potential increased risk for graft failure if a patient returns to high level sports.\textsuperscript{219, 220} This is significant for young athletes who desire a full return to the high level competitive sport. Disease transmission, potential immune reactions, and altered mechanical properties caused by sterilization of the tissue when developing the graft are also concerns.\textsuperscript{219-222} A newer technique using a double bundle graft
has shown some promise regarding decreased rotational laxity that is often times still present after reconstruction. However, there is no concrete evidence that this technique improves long-term outcomes at this point. Additionally, this surgical technique is more technically demanding and may require greater experience and skill by the surgeon.

In a recent 15-year follow up study, survival of the ACL graft was less favorable in adult men than women, but not different between the hamstrings or patellar tendon autograft.\textsuperscript{218} Evidently, the selection of an ACL graft is not clear-cut. A patellar tendon autograft may be a more suitable choice for women. An autograft, as opposed to an allograft, may be more suitable for younger patients, particularly if they wish to return to sports involving cutting, pivoting, and jumping. When making a graft decision, the patient’s knee morphology and anatomy should be considered so that the native anatomy of the knee can be replicated as close as possible by the surgeon, as well as the patient’s requirements for returning to function.\textsuperscript{223} With similar long-term outcomes regardless of graft type, ongoing research is necessary.

Possibly more important than the graft type, is the elapsed time from the onset of injury to surgery. In a younger population, surgical reconstruction is sometimes delayed to avoid potential growth plate injury. Unfortunately, allowing the knee to remain ACL deficient may lead to repetitive trauma from minor translation and giving way episodes, resulting in increased cartilage and meniscal damage.\textsuperscript{224} In fact, the odds of articular cartilage injury has been shown to increase by 1\% for every month the reconstructive surgery is delayed.\textsuperscript{223} A delay of greater than six months from injury to surgery is associated with a significant increase in the prevalence of medial meniscus tears.\textsuperscript{23, 225, 226} Dumont et al.\textsuperscript{23} found that 53.5\% of pediatric patients treated with ACLR greater than six months after injury
onset had medial meniscus tears, versus 37.8% in those treated in less than six months. As mentioned previously, a concomitant meniscal injury greatly increases the likelihood of early onset knee OA.21 However, a clear consensus on the optimal timing of surgery does not exist. It is generally believed that the patient should demonstrate normal knee motion, ‘sufficient’ strength bilaterally, and little to no joint effusion prior to surgery. On average these guidelines are met after three to six weeks of pre-surgery rehabilitation, however each case needs to be evaluated on an individual basis by the surgeon.

Another surgical factor that may contribute to the poor long-term outcomes after ACL reconstruction is related to the overall frequency of cases performed by both the surgeon and the hospital. A recent review demonstrated a surgeon volume with fewer than 52 cases per year was a predictor of a patient needing re-admission into the hospital within 90-days and the patient requiring another knee surgery within one year.22 Subsequent surgeries in this case incorporated subsequent ACL reconstruction, removal of adhesions, and/or a follow-up meniscectomy. Somewhat frightening, is one report that states a total of 85% of orthopedic surgeons do fewer than 10 ACL reconstructions per year.227 Additionally, a hospital with a volume of fewer than 125 cases per year was a significant predictor of a patient requiring a subsequent ACL reconstruction.22 Not surprisingly, a less experienced surgeon and hospital could lead to less than desirable outcomes.

In light of the literature regarding surgical influences on long-term outcomes, subjects (and parents/guardians) will complete a questionnaire to report these details pertaining to their ACL injury. We will not control for surgery type, physician, or postsurgical rehab protocol in our recruitment process due to the nature of the recruitment process and time
constraints. Surgical characteristics, particularly the graft type and time from injury to surgery, will be documented but not analyzed directly for this study.

2.7 Neuromuscular Factors affected by ACLR

Neuromuscular deficits following ACLR play an immense role in recovery and long-term outcomes. Knee joint proprioception, postural stability, joint range of motion, muscle activation, and biomechanics during dynamic movements are all impacted by ACL injury and subsequent ACLR.

The somatosensory system is influenced greatly by injury to the knee joint and the associated skin, muscle, tendon, and ligament damage. Proprioception plays a key role in muscular control influencing both movement and stability. Mechanoreceptors within the knee and the ACL respond to mechanical pressure, or distortion, and provide information about joint position back to the central nervous system. Research has demonstrated that the knee joints of patients with ACLR have diminished proprioception detected both actively and passively. Several studies have reported decreased ability to actively reposition the knee of an ACL deficient leg to a specified joint angle following ACL injury, with these deficits persisting long after ACLR. In addition, the ability to passively detect joint position is also diminished in patients after ACLR. Katayama et al. found associations between poor active joint repositioning and performance measures, such as decreased vertical jump height and decreased single-leg hop distance in patients with ACL deficiency. Most of the research in this area has been performed on ACL deficient subjects with limited evidence suggesting that ACLR patients also suffer from these proprioceptive deficits. These results are somewhat controversial within the literature as there are a variety
of methods used to assess proprioception and other factors, such as instability and pain, which could affect the results. To our knowledge proprioception has not been assessed in adolescents post ACLR and will not be a focus of the current research project.

Postural stability, or balance, is defined as the ability of an individual to maintain their center of mass over their base of support. Athletic maneuvers challenge postural stability by causing deviations of ones’ center of mass away from the base of support, which certainly contributes to potentially injurious lower extremity alignment. Deficits in single-leg postural stability on the ACL reconstructed limb was also identified as a prospective risk factor for a secondary ACL injury in adolescent athletes. However, there appears to be no difference in static balance during double-leg stance among ACLR patients compared with healthy controls. Deficits in postural stability during single-leg static stance on an ACL deficient knee have been more widely reported, but results are conflicting in ACLR patients when compared to healthy controls. Balance measures following a perturbation may be a better indicator of function compared with static measures because they better represent sporting demands that are typically placed on the neuromuscular system. Decreased ability to maintain balance following a perturbation has been reported in ACLR patients in comparison to healthy controls. Redirecting attention back to the definition of NCIC ACL injury, physical or cognitive perturbations are often present at the time of ACL injury insult. Therefore, evaluating dynamic sport specific movements on a single leg with perturbations created by the trunk and limbs may be important, particularly if evaluating the quality of movement and not simply the success of performance.

In addition to proprioception and stability, the loss of normal range of motion following ACLR can adversely affect outcome measures. The prevalence of radiographic
knee OA at long-term follow-up after ACLR is much higher in patients who do not regain or maintain normal knee range of motion, regardless of concomitant injuries. Several studies have found adults with a history of ACLR that had a loss of full knee extension (knee flexion contracture) or knee flexion at follow-up sessions, ranging from 7-13 years, had a higher incidence of radiographic OA. The loss of normal knee flexion and knee extension is also associated with weaker quadriceps strength, which in turn could alter characteristics of muscle activation and biomechanical movement leading to asymmetry and dysfunction. Recent evidence has brought to light the importance of evaluating passive knee hyperextension as part of a regular knee range of motion exam, in addition to traditional knee flexion and extension. Some degree of knee hyperextension is present in 95% of people, with normal values ranging from 5-6 degrees in males and females, respectively. This additional extension motion must be factored in when comparing differences in range of motion between limbs as the abnormalities may be compounded. According to the International Knee Documentation Committee (IKDC) criteria, normal knee extension is considered with 2 degrees of the opposite knee, and normal flexion is considered to be within 5 degrees of the opposite knee. Shelbourne et al. found 92% of patients at 10 years post ACLR had some degree of knee hyperextension ranging from 1°-14° in the previously injured limb. Hyperextension contributed to the abnormal knee extension between patients with definite signs of radiographic OA and those without. Regaining knee flexion and extension following ACLR, with consideration of the degree of hyperextension, is crucial in improving long-term outcomes.

Ankle range of motion, both passive and active, may also influence outcomes following ACLR particularly in terms of dynamic movement characteristics. As previously
mentioned, the gastrocnemius muscle crosses the knee joint and plays a role in both ankle plantar flexion and knee flexion. Previous research has demonstrated the importance of the ankle plantar flexors (gastrocnemius, soleus) in absorbing impact forces during landing.\cite{242,243}

Diminished ankle dorsiflexion displacement capabilities during landing have been linked with less hip and knee flexion,\cite{191,244} greater frontal plane knee motion,\cite{245-247} greater transverse plane hip motion,\cite{195} and greater peak landing forces.\cite{191,248,249} Essentially, if an individual has soft tissue or arthrokinematic restrictions that are not conducive to dorsiflexion displacement upon landing, the lower extremity will potentially compensate by absorbing the impact forces in other planes of motion. Additional evidence has shown that less passive ankle dorsiflexion range of motion, assessed prior to a movement task, was associated with less knee flexion during landing as well as larger ground reaction forces.\cite{250} There are many methods of assessing ankle dorsiflexion range of motion, both weight bearing and non-weight bearing. A recent unpublished study conducted in our laboratory found individuals with greater dorsiflexion range of motion during a weight bearing lunge were able to utilize greater knee flexion and ankle dorsiflexion during double-leg and single-leg squatting tasks. This may seem intuitive but it was the first study to classify individuals based on weight-bearing or non-weight bearing ankle dorsiflexion range of motion, and then compare how they performed on these tasks. Without doubt, range of motion influences lower extremity performance during dynamic movement. Abnormal range of motion seems to be related to radiographic joint changes following ACLR in follow-up studies. Although the focus of the current project is on biomechanical measures, we feel it is important to assess passive knee flexion, knee extension, hyperextension, and a weight-bearing lunge in our female
adolescents with and without a history of ACLR in order to capture the full scope of factors that may impact their outcome.

To comprehend the full neuromuscular impact of ACLR, we must investigate how proximal and distal neuromuscular control deficits can influence knee joint biomechanics and their role in ACL injury mechanisms and poor outcomes. This includes understanding the influence of trunk, hip, knee and ankle kinematics. The specific alterations in movement patterns are the emphasis of this study and will be discussed in greater detail.

Quadriceps dysfunction is a very common consequence of ACL injury and ACLR. In combination, quadriceps dysfunction incorporates decreased muscle activation, decreased muscle strength, and decreased knee extension moment on the previously injured limb. Over time, altered muscle function leads to static and dynamic malalignments, which in turn alters the length-tension and force-couple relationships of working muscles. This altered muscle function causes abnormal movement patterns and inefficient neuromuscular control, and likely continued breakdown and injury. As mentioned previously, in a large prospective study after initial injury, ACLR patients that went on to suffer a secondary ACL injury displayed greater hip flexion at initial ground contact, decreased internal knee extension moment, and an increased overall hip flexion displacement on their dominant limb. Quadriceps dysfunction in these patients most likely exacerbated changes in dynamic alignment and faulty movement patterns. An inability to activate the quadriceps to absorb landing forces and decelerate the body leads to necessary adjustments in these individuals. Specifically during landing, greater hip flexion would be accompanied by an anterior tilt of the pelvis, thereby causing the posterior pelvis to migrate superiorly. The length of the posterior muscles (gluteus maximus and hamstrings) would increase with the
altered pelvic positioning, changing the length-tension relationship of the muscle fibers, and contributing to a decreased force production capability. This altered recruitment and force production of the gluteus maximus and hamstrings, leads to compensation and substitution by the hip adductors (synergists), and to some extent the hip internal rotators, to decelerate the large amount of hip flexion that is occurring. This concept is known as synergistic dominance, defined as the process by which a synergist muscle(s) compensates for a prime mover to maintain force production.\(^{253}\) Unfortunately, the synergistic dominance of the hip adductors and internal rotators would contribute to increased hip adduction and internal rotation moment. Greater internal moments in the direction of hip adduction and internal rotation direction would lead to body positioning with greater hip adduction, internal rotation, and potentially knee valgus collapse. In combination, repetitive landing with greater hip flexion angle and displacement could influence movement patterns characteristics of prospective risk factors for ACL injury and re-injury. Additionally, research has demonstrated a link between poor neuromuscular function and knee OA.\(^{13, 19, 136, 139, 184}\)

Lower extremity muscle weakness, particularly in the quadriceps, is frequently reported following ACLR. Decreased strength is often attributed to a decrease in muscle activation and/or a decrease in the overall amount of motor unit firing.\(^{87, 254, 255}\) Evidence suggests that both arthrogenic muscle inhibition (AMI) and muscle atrophy could be responsible for persistent muscle weakness. AMI is an inability to completely activate the muscle surrounding a joint, even if that muscle itself was not injured.\(^{256}\) The damage to the mechanoreceptors within the ACL causes a disruption in the ligament-muscle reflex between the ACL and the quadriceps, leading to an inability to actively recruit and sustain a quadriceps muscle contraction.\(^{77}\) Following a traumatic injury, AMI serves as a protective
mechanism, however it can become a severe hindrance during the rehabilitation process contributing to stubborn quadriceps strength deficits.\textsuperscript{76} Unfortunately, bilateral quadriceps inhibition in cases of unilateral ACLR have been reported, suggesting a crossover effect does exist.\textsuperscript{86, 87} Many athletes return to sport with lingering strength deficits and neuromuscular deficiencies,\textsuperscript{75, 77} contributing to inefficient movement and an inability to absorb and produce forces necessary for sport. These compensatory movement patterns serve as a protective mechanism following ACL injury and ACLR, but may also contribute to re-injury.

Muscle strengthening is often an integral component of rehabilitation both prior to and following ACLR. Furthermore, decisions regarding exercise progression and return to sport are largely based on strength measurements, typically assessed with an isokinetic dynamometer and compared bilaterally.\textsuperscript{82} Following ACL injury and ACLR, accounts of quadriceps strength deficits in the ACLR limb compared to the uninjured limb range from 5-30\%,\textsuperscript{70, 235, 257-261} with hamstrings deficits ranging from 9-13\%.\textsuperscript{259-261} Typically, these percentages are derived from a limb symmetry index (LSI), representing the strength of the injured limb in relation to the ‘healthy’ uninjured limb presented as a percentage. Isokinetic strength deficits have been vastly reported following ACLR in comparison to the subjects uninjured limb\textsuperscript{11, 235, 262, 263} but also in comparison to healthy control subjects.\textsuperscript{63, 83, 211, 235, 262, 264} The largest deficits are typically seen within 6-12 months of surgery and may improve over time,\textsuperscript{211} however deficits as high as 18\% have been reported 5-15 years following ACLR and rehabilitation.\textsuperscript{69-71} Bilateral, or crossover, deficits in strength have been observed in individuals with unilateral ACL injury and ACLR in comparison to healthy controls.\textsuperscript{211, 259, 265} Bilateral strength deficits in individuals with unilateral injury clearly suggest that returning the strength of the injured limb to that of the uninjured limb may not be suitable
criteria for someone to be ready to compete in sport against an individual with no history of injury. Comparisons to healthy, normative data, should be performed

Appropriate strength and function of the hamstring muscles are crucial to performing sport specific movements, but as alluded to earlier, may be affected by ACLR more than originally thought. The hamstrings muscles contract both eccentrically and concentrically to allow for controlled deceleration and proper force attenuation when landing. Until recently, many studies had reported no clear deficits in hamstring strength following ACLR. When assessed concentrically, hamstring deficits are often not perceived with bilateral limb comparisons. However, eccentric muscle testing of the hamstrings has exposed asymmetric bilateral deficits of 15% in adults with ACL deficient knees, but only an 8% deficit when assessed concentrically.\textsuperscript{266} This particular group would have been classified as ‘normal’ based on many guidelines of reaching 85% symmetry in muscle strength if only assessed through concentric means. Hamstrings weakness has also been reported more commonly after ACLR procedures that utilized a hamstrings (semitendinosus-gracilis) graft.\textsuperscript{211}

In summary, isokinetic quadriceps and hamstrings strength deficits following ACLR are a concern. One of the most widely used objective return to play criteria for athletes following ACLR is a limb symmetry value of 90% or higher on isokinetic quadriceps strength tests.\textsuperscript{82} It is necessary to consider how these open-chain isokinetic strength assessments relate to functional performance on field when an athlete returns to sport. Research studies that have investigated the relationship between isokinetic strength measures and closed-chain functional performance have found only low to moderate correlations, both in healthy subjects\textsuperscript{267-269} and in those with a history of ACLR.\textsuperscript{212} This suggests that isokinetic
strength is not a greater indicator of functional performance and should not be evaluated as an isolated guide for return to play decisions.

Muscle power, or the ability to produce a high force over a short period of time, is more indicative of functional performance and may be a more important factor for sports performance and injury prevention. The time required to develop muscular strength in athletic activities is considerably less (0-200 ms) than the time required to achieve maximal contraction strength (≥ 300 ms). The ability to generate strength quickly is relevant to both performance and protection against injury. In fact, the most recent American College of Sports Medicine (ACSM) position stand promotes muscle power development as having a “greater impact on sports performance than traditional strength training alone.” If athletes are reaching ‘normal’ levels of isokinetic strength prior to returning to activity, but are unable to return to the level of play they desire and are experiencing secondary injuries, power is likely another factor that should be considered. Open and closed chain leg power development was recently investigated in a group of adults six months after ACL injury and another group of adults six months after ACLR. Measurements of knee extension, knee flexion, and leg press power were evaluated. Patients were instructed to go through the motion as quickly and forcefully as possible, while the distance the weight traveled and time it took to do so was recorded. When considering all three tests of lower extremity power, 90% of patients were identified as having abnormal or decreased leg power on the injured or reconstructed side in comparison to the uninjured. It is unknown if these patients would be classified as having ‘normal’ strength as these measures were not reported. However, the battery of power tests had good sensitivity in identifying deficits that would be problematic had the patient returned to the playing field at this time point.
Rate of force development (RFD), or rate of force production, is one means of quantifying the ability of a muscle to produce force quickly. Angelozzi et al. measured isometric RFD during a single-limb leg press in male soccer players as part of standard baseline pre-season testing. Forty-five males were brought back in for repeat testing after incurring an ACL injury (but prior to reconstruction) and then tested two more times at six and twelve months post ACLR. Maximal isometric strength returned to 97% of the pre-injury values at six months post reconstruction. Based on strength values alone, these athletes’s may be considered ready to return to play. However, RFD assessed at 30%, 50%, and 90% of maximal isometric voluntary contraction (MVIC) revealed the injured limb was only 80%, 77%, and 63% of the pre-injury values, respectively at the same time period. RFD was severely diminished on the injured limb when the required force production was increased. This same study went on to implement a rehabilitation program focused on muscle power, resulting in the same patients returning to 90% of their pre-injury levels on all assessments. Therefore, RFD appears to be modifiable in a pathologic population, which is very promising considering the impact this may have on a safe return to sport.

ACL injuries typically occur at the time of initial ground contact or very shortly after landing, which is the same time period when a large amount of force needs to be produced very quickly in order to absorb the landing forces. Sports require dynamic neuromuscular control including both power generation and absorption in order to be successful. Perhaps from a more functional perspective, calculating RFD during landing (loading rate) may be a great adjunct to traditional strength assessments and movement analyses. During landing, the RFD is calculated as the slope of the VGRF-time curve ($\Delta$ VGRF / $\Delta$ time) during the landing phase, defined as the time period from initial ground contact to its peak.
al.\textsuperscript{66} identified similar magnitudes of VGRF, but longer loading rates during a drop vertical jump in ACLR limbs in comparison to healthy control subjects. More specifically, these patients landed in a more extended position at the hip, knee, and ankle, which may have afforded them more time to absorb the landing forces but could set them up for injury in a true sport setting. These landing mechanics also place more load on the ACL as discussed previously. Paterno et al.\textsuperscript{64} observed bilateral asymmetry in females post ACLR during a drop vertical jump, with reduced VGRF and longer loading rates on the surgical side in comparison to the uninjured. This would indicate that more of the landing forces were absorbed on the uninjured limb, and at a greater rate. This could provide theory behind the increased contralateral limb injury rates observed in females.

2.8 Biomechanical Outcomes following ACLR

ACLR does not exactly replicate the normal anatomic complexity of the original ACL structure in the knee. Comparisons of lower extremity kinematics and kinetics have exposed a number of movement and landing adaptations in adults with a history of ACL injury and ACLR. Specifically, reports of asymmetrical ground reaction forces, asymmetrical knee extension moments, strength deficits, and abnormal movement patterns often ensue. Adults with a history of ACLR often rely more heavily on their previously uninjured limb to absorb and produce landing forces in comparison to their injured limb. There is a growing body of literature with an ever-growing range of methodologies and means of classifying movement impairments and asymmetries.

A comparison of lower extremity kinematics and kinetics in adults has exposed a number of movement and landing adaptations following ACLR. Previous research has
investigated both between limb and between group comparisons during a variety of dynamic tasks. Unfortunately, very little biomechanical research post ACLR has been performed on an adolescent athlete population and none focusing on females. There is a large gap in the literature regarding adolescent females post ACLR.

Group comparisons between ACLR subjects and healthy control subjects during landing tasks has revealed differences in sagittal, frontal, and transverse plane landing kinematics. Several studies have reported ACLR subjects landed with greater ankle plantar flexion, less hip and knee flexion, and greater knee abduction (valgus) at initial contact in comparison to the healthy control group. Greater overall hip adduction and hip internal rotation displacement during the landing phase has also been reported in comparison to the healthy control group. In short, post ACLR adults landed more erect and demonstrated more frontal and transverse plane movement at the hip and knee, which we know to be problematic for the ACL. However, reports of greater hip flexion at initial contact during a single leg landing task and double leg jump landing (Padua) have also occurred. Vairo et al. observed greater hip flexion at initial contact as well as greater peak hip, knee and ankle flexion at the time point of peak VGRF in subject’s 21-months post reconstructive surgery using a hamstrings autograft. The ACLR injured limb had greater sagittal plane displacement in comparison to the uninjured limb and in comparison to a healthy control group. These results are similar to the prospective risk factors for secondary injury that were discussed earlier, as those that went on to suffer a secondary injury had displayed greater overall hip flexion in comparison to those that did not.

Similarly, kinetic differences have been reported between ACLR subjects and healthy matched control groups. Typically, reduced VGRF during landing reduced VGRF during
takeoff,\textsuperscript{64} reduced loading rates,\textsuperscript{64, 66} and reduced knee extension moments\textsuperscript{66-68} have been reported in the ACLR group in comparison to the healthy control group. In contrast, some studies have observed no differences between groups on measures of landing VGRF\textsuperscript{66, 67} and extension moments particularly during takeoff.\textsuperscript{68} Kinematic and kinetic results allude to a definite asymmetry in the way ACLR patients perform functional landing tasks, which needs to be discussed in greater detail.

Methodological differences in task selection and matching procedures could contribute to the somewhat inconsistent findings with between group comparisons. Particularly in athletes, tasks should be challenging enough to draw out any dysfunction or asymmetry and ideally some consistency should exist on how we are matching the injured limb to a control subject. Variations in procedures include matching the ACLR limb to the control subjects by limb stiffness,\textsuperscript{66} limb dominance,\textsuperscript{64, 67, 84, 277} or simply by using an equal number of right and left limbs from the control group as surgically reconstructed limbs.\textsuperscript{68, 83} ACLR limbs have been matched to the dominant limb\textsuperscript{64, 67, 84, 277} as well as to the non-dominant or ‘non-preferred’ limb.\textsuperscript{65} To muddy the waters even further, dominant limb has been operationally defined as (1) the limb with the furthest single leg hop distance,\textsuperscript{67} (2) the limb preferred to perform a single leg hop for distance,\textsuperscript{42, 84, 277} and (3) the limb not selected to lead off the box when performing a drop jump task.\textsuperscript{65} At the very least, one should take note of each studies operational definitions to clearly interpret the results. For the purposes of the current study, the healthy control limbs will be randomly assigned to serve as the Index or Non-Index limb using randomization so as to match the distribution of injured right and left limbs in the ACLR group. For example, if five ACLR subjects injured their right limb,
then five control subjects would be randomly selected to have their right limb designated as the Index limb.

2.9 Asymmetries Post ACLR

Consistently, landing force asymmetries in VGRF and lower extremity extension moments, particularly knee extension, have been reported from bilateral comparisons in the ACLR group. Specifically, lower VGRF\textsuperscript{63-65} and lower internal knee extension moments\textsuperscript{67, 68} are commonly observed on the surgical limb in comparison to the uninjured. Lower VGRF on the surgical side has been reported during double leg squatting,\textsuperscript{264, 278} as well as the landing and takeoff phases of a double leg jump landing.\textsuperscript{64} Likewise, internal knee extension moments on the surgical side have been reported to be lower during squatting,\textsuperscript{279} lateral step down,\textsuperscript{68} stair climbing,\textsuperscript{280} and single-leg hopping or jumping maneuvers\textsuperscript{63, 67, 68, 73, 74} in comparison to the uninjured limb. It appears, when performing single limb tasks, the injured limb may land slightly more extended and then move through a greater sagittal plane range of motion (displacement) compared to the uninjured limb performing the same task.

While the large majority of ACLR research is in adults, Paterno et al.\textsuperscript{65} investigated kinetic differences (VGRF) during a drop vertical jump from a 31-cm height between side (injured, uninjured), group (ACLR, control) and sex (male, female) within four weeks of full return to sport (6.9±1.7 months) in adolescent males and females. Results indicated that both males and females demonstrated bilateral asymmetries in VGRF at the time of return to sport, even after completing supervised progressive rehabilitation. More specifically, the injured limb displayed significantly lower peak VGRF’s compared to the uninjured limb and both limbs of the control subjects.\textsuperscript{65} Limb-to-limb asymmetries within the ACLR subjects
may be of prime concern because they are excessively loading their ‘healthy’ knee and unloading their reconstructed.

Kinematic asymmetries during landing tasks have also been reported. During a single leg forward hop landing, Deneweth et al.\textsuperscript{281} investigated bilateral landing mechanics four months post surgery. With a very small sample size (n=9), significant differences in sagittal and transverse plane kinematics were observed at initial contact and maximum joint angles between limbs.\textsuperscript{281} The injured limb displayed a position of greater overall extension, tibial external rotation, and medial tibial translation at the time point of initial contact. The injured limb also reached a greater maximum knee flexion, tibial external rotation and maximum anterior tibial translation position compared to the uninjured limb.\textsuperscript{281}

Finally, strength and range of motion asymmetries are also apparent but were discussed in greater detail previously. In summary, strength deficits in the injured limb compared to the uninjured are present sometimes as far as 5-15 years following reconstruction and extensive rehabilitation.\textsuperscript{69-71} Additionally, a loss of full knee extension or flexion on the injured knee in comparison to the uninjured is common, which contributes to weaker quadriceps\textsuperscript{240, 241} and the future onset and progression of radiographic OA.\textsuperscript{238}

\textbf{Quantifying Asymmetry}

Some degree of asymmetry between limbs is normal, even in healthy subjects while performing functional tasks.\textsuperscript{264} However, reduced loading on the surgical side can be problematic because the body will struggle to recover quadriceps function and will need to compensate and adapt to perform. Not to mention the excessive loading the previously uninjured side now faces. People will find a way to perform tasks that are necessary or desired, however eventual negative consequences of these compensations are imminent. In
theory, as clinicians, we should be able to visualize asymmetries in movement and even weight bearing. However, one challenge in attempting to visualize asymmetries during movement is that the non-surgical side can often compensate for, or mask, the effects of asymmetrical loading on performance. Therefore, performance may or may not be affected especially when observing a double leg task. A large body of literature has been able to use a variety of single-leg hop or jump tasks to determine functional deficits in jump height or horizontal hopping distance between limbs and in comparison to healthy controls. In light of this, many clinicians use single-leg hop performance to gauge progress in rehabilitation and often return to sport. If the surgical limb has reduced vertical force or internal extension moments during landing or takeoff, it’s not surprising that deficits would become apparent during single leg tasks because the ability to compensate with the uninjured limb has been taken away. Single-leg hopping tasks were first introduced to detect abnormal lower limb symmetry in hop performance and are now widely used to discriminate between the hop performance of the injured and uninjured limbs. Asymmetries may subside over time, however some asymmetries in higher demand activities persist long after full return to sport. Studies by Paterno et al. highlighted the ongoing loading asymmetry during vertical drop landings in females 2-years post ACLR and in adolescents at the time of full return to sport, respectively.

The limb symmetry index (LSI) is the most commonly reported criterion used to quantify performance such as quadriceps strength, jump height, and hopping distance. The purpose of this calculation is to ensure that the injured side reaches an acceptable ability level in comparison to the healthy limb during rehabilitation. Clinicians use these values as a guide for rehabilitation and return to play, while researchers may use these values to compare the
amount of asymmetry in an injured group compared to what is considered normal. Normal LSI values of $\geq 85$-$90\%$ are often used,\textsuperscript{70, 71, 85, 268} based on the original findings of Noyes et al.\textsuperscript{255} in which 93\% of healthy individuals performed a single leg hop with an LSI of 85\% or greater. Recent research has questioned if these values are stringent enough. Gustavsson et al.\textsuperscript{89} suggested a combined battery of functional tests, such as the vertical jump, single leg hop for distance, and side hop be used to discriminate asymmetries in hop performance. Using this test battery, only one out of ten patients had restored sufficient hop performance on all three tests following injury and reconstruction. Additionally, Thomee et al.\textsuperscript{271} suggests an LSI $> 100\%$ should be required for knee extensor and flexor strength if the patient is returning to sports requiring cutting, pivoting, and contact. Most importantly, using an LSI strength or performance value as objective criterion for return to sport does not account for the crossover effects in the uninjured limb, resulting in biomechanical and neuromuscular changes.\textsuperscript{86, 87, 289} Decreased asymmetry over time could be the result of an improvement on the surgical side or a decline on the non-surgical side. Moreover, female adolescents are more prone to suffer ACL injury in large part due to their altered neuromuscular control during functional movements. Perhaps, returning the ACLR limb to the ability of the uninjured limb is not addressing the problem. Finally, unclear return to play guidelines focus on quantitative strength and performance measures as discussed here, but do not assess the overall quality of movement (biomechanics). The current study will assess lower extremity biomechanics during two commonly used functional tasks in adolescent females whom have already passed all clinical return to play measures and compare outcomes bilaterally, but also in comparison to healthy matched control subjects.
The long-term goal of our research is to enhance clinical practice by identifying movement impairments and asymmetries after injury and developing means of correcting these impairments to improve outcomes. However, the immediate need is to utilize tasks that have been previously validated, such as a double-leg jump landing and single-leg hopping, with more advanced measures of motion analysis in female adolescents to better understand the movement compensations following ACLR. The double-leg jump landing task has previously been utilized and validated as a clinical screening tool that reliably allows identification of individuals that are at increased risk of ACL injury. The same task was used in prospective, case-control, study designs to identify predictors of ACL injury. Plus, females often experience ACL injury during a similar double-leg jump landing maneuver, more so than males. A variety of single-leg hopping tasks have been used successfully to distinguish bilateral and group differences in performance (hop distance). More specifically, two studies found the single-leg triple hop to be among the most sensitive tests to detect performance differences between limbs and in comparison to healthy control subjects. For these reasons, we feel the double-leg jump landing and single-leg triple hop (for distance) tasks are valuable movement patterns to investigate in this study population. Both tasks require efficient movement patterns and stability to absorb the generated impact forces and then immediately produce propulsive forces to jump vertically or horizontally, respectively. However, we have modified the triple hop into a double-hop task. The goal of repetitive forward hopping remains the same, but the potential bias introduced by varied hop distances is removed. The distance hopped prior to hitting the forceplate directly influences the kinematics and kinetics calculated for each individual. If the control group is capable of hopping farther, it is possible that we would be biasing the ACLR groups’ data. Therefore, to
analyze and compare kinematic and kinetic variables effectively we feel it is necessary to modify the single-leg triple hop. This study will focus on trunk, hip and knee biomechanics throughout the landing and takeoff phases of these tasks. Performance characteristics will be recorded but not analyzed for the purposes of this study.

2.10 Rehabilitation Considerations

Knee function prior to surgical reconstruction is very important in dictating the final outcome following surgery. Rehabilitation prior to surgery, or ‘prehab’, focuses on regaining full range of motion, minimizing or eliminating joint effusion, and minimizing bilateral limb differences in strength before surgical reconstruction is performed. Research has also suggested perturbation training along with aggressive quadriceps strengthening to reduce bilateral differences. 241

Rehabilitation after ACL reconstruction has similar goals; restore knee function and work towards getting the patient or athlete back to physical activity. Initial goals are to minimize pain, maintain (or regain) full range of motion, and limit potential arthrogenic muscle inhibition. The most common complication immediately following surgery is the failure to regain full knee extension, which contributes significantly to poorer long-term outcomes. 240 Specific rehabilitation exercises focus on regaining or maintaining complete knee extension and knee flexion, cardiorespiratory fitness, postural stability, muscle strength, muscle endurance, muscle power, and functional sport specific ability. 290 These goals are achieved through progressions of open kinetic chain, closed kinetic chain, and integrated functional exercises. Neuromuscular training should be used to help restore knee joint stability and smooth coordinated movement patterns. 89
At this point, the standard of care for ACLR rehabilitation does not call for different protocols for males and females. However, we do know that after puberty males and females have distinct differences in the way they perform the same sport specific tasks. Females have often displayed decreased knee and hip flexion at initial contact,\textsuperscript{59, 291, 292} greater knee valgus,\textsuperscript{45, 59, 291, 292} and higher ground reaction forces\textsuperscript{45, 55} in comparison to males performing the same tasks. All of which contribute to the higher incidence rates of ACL injury in females. Children and adults perform sport specific tasks very differently, such that children land in a more extended posture and display greater knee valgus compared to adults.\textsuperscript{56} Rehabilitation considerations based on development should be considered in an adolescent population because both physical and physiological maturity is different than adults. As discussed earlier, prior to puberty there are no differences in physical ability between males and females. Both males and females tend to have a rapid increase in size during puberty, however females seem to lack the increase in strength and neuromuscular control that males possess. Therefore, possibly the most essential objective of end phase rehabilitation and ACL injury prevention, regardless of age and gender, is advanced neuromuscular training (re-training) especially if desiring a return to high-risk sports.

\textbf{2.11 Return to Sport Considerations}

The ability to make a successful return to sport is largely dependent on the level of activity one is returning to. A recent meta-analysis found that 82\% of adults post ACLR were able to return to some physical activity, 63\% to their pre-injury levels, but only 44\% of adults were able to return to a competitive level of play.\textsuperscript{127} Younger patients may be more capable of returning initially to a higher level of sport, however we know that ACLR athletes are
forced to retire at a much higher rate. So the question remains, what is causing these athletes to retire early and why are the rates of re-injury so high.

Guidelines in the final phases of rehabilitation and transition back to sport are not standardized. The overall goal is to transition the athlete from the ability to perform activities of daily living to proficiency with higher-level sport-related activities. A recent systematic review discovered that only 13% of all research publications regarding return to play decisions after ACLR had noted specific objective criterion that were used. The most commonly reported return to sport criterion are 1) isokinetic lower extremity muscle strength, 2) single-limb hop symmetry, and 3) knee examination (range of motion, effusion). Within this systematic review, 57% had used one of these criteria, 38% had used two, and only 4% had used all three criterion measures for allowing an athlete to return to sport. The most commonly used was isokinetic quadriceps strength, requiring a limb symmetry value ranging from 80-90%. However, no consistency in testing velocity was utilized or able to be recommended by the authors following this review. As discussed previously, adolescent females are more apt to suffer an ACL injury largely due to pre-existing neuromuscular and biomechanical characteristics. Returning the injured limb to the level of the uninjured limb, whether it be strength or hop performance characteristics, may not be adequate to determine readiness for the playing field. As surgeons and clinicians, we often pride ourselves on returning a young athlete to sport within 6-9 months, but these decisions should be made based on comprehensive ability rather than a set time frame.

The best soccer players in the world, those participating in the Union of European Football Associations (UEFA) Champions League, on average need 7 months to return to initial training, 10 months to return to full training, and 12 months to return to match play.
Granted, the demands upon them when they return to play are much higher. But, they are also working with the highest-level surgeons and therapists, often for hours a day. If the most elite athletes are taking this long to effectively get back on the playing field, how could a ‘mediocre’ athlete with definite neuromuscular control deficits by comparison, be ready to compete in a shorter time frame? A joint effort between clinicians and researchers is necessary to better understand at risk movement profiles that are present following ACLR and then work towards developing evidence based return to play criterion to protect our athletes’ careers and long-term function.

2.12 ACL Injury Prevention

Increased attention has been directed toward ACL injury prevention strategies, as researchers attempt to minimize risk factors that are believed to be modifiable. Injury prevention programs include components of muscle strengthening, flexibility, balance training, plyometrics, core stability, proprioceptive training, and often landing instructions (or movement awareness training). ACL injury prevention programs can be effective if implemented appropriately and have good compliance. Researchers have developed intervention programs that have been successful in decreasing the incidence of non-contact indirect contact ACL injury in a variety of sports. Most recently, Walden et al. cluster randomized female soccer players, between the ages of 12-17, to either the ‘Knee Control Program’ group (n=2479) or the control group (n=2085) and tracked their ACL injuries across one season. The ‘Knee Control Program’ was a 15-minute warm-up focused on core stability, balance, and proper knee alignment, carried out twice per week. In the end, seven players in the intervention group and fourteen in the control group suffered an ACL
injury, resulting in a decreased incidence in the intervention group of 64%\.^302 In summary, there is strong evidence to support a beneficial effect of ACL injury prevention programs, with pooled estimates suggesting a 52% risk reduction in females and an 85% risk reduction in males.\(^303\) The overall risk reduction is great news, however the disparity between males and females is still alarming.

Overall, injury incidence has been shown to decrease with the performance of a neuromuscular training program. However, similar programs in a younger population have not been overly successful in altering the lower extremity kinematics during landing, which are related to the incidence of ACL injury. An eight-week neuromuscular training program, similar to what has been successful in adults, was unsuccessful in altering lower extremity kinematics or jump height ability in pre-pubescent adolescents between the ages of 9-11.\(^304\) DiStefano et al.\(^305\) developed two separate intervention programs aimed at improving medial knee displacement and toe out stance during a jump landing task in 10-17 year old male and female soccer players. All players were evaluated with the landing error scoring system (LESS) while performing the double-leg jump landing, prior to and after the completion of the program. Subjects that performed “poorly” at pre-testing testing did show improvement in their jump landing score, however no differences were observed between programs. DiStefano et al.\(^306\) then developed and implemented a specific pediatric program providing more feedback, more progressions, and greater variety in exercises in a group of 9-11 year old soccer players. Results of this study demonstrated reduced knee external rotation at initial contact after the 9-week program, however no other changes were evident.

In summary, neuromuscular training has been successful in lowering the incidence rate of ACL injury in a variety of sports, and recently in adolescent female soccer players.
While promising, there is a gender disparity in the effectiveness of these programs and we may not be truly changing the biomechanics. The rationale for Walden et al.\textsuperscript{302} in designing their program was the common lateral trunk displacement and dynamic knee valgus present in females when sustaining ACL injuries. Therefore, they focused on trunk and core stabilization in addition to proper knee alignment and landing technique in their program design. The primary outcome measure was injury incidence, therefore we do not know what their quality of movement looked like before or after the intervention. It remains unclear what is most effective in encouraging altered movement in adolescent females, particularly in adolescent females with a prior history of ACLR. It may be important to break down problematic characteristics of movement into smaller parts, so that we can identify how to alter each component most effectively.

One characteristic of landing in females that contributes to ACL loading is increased vertical ground reaction forces in comparison to females who did not suffer an ACL injury.\textsuperscript{45} Additionally, adolescent athletes\textsuperscript{17, 242} and adults\textsuperscript{164, 238} with a history of ACLR have demonstrated asymmetrical knee extension moments and vertical ground reaction forces during landing. Verbal instructions have been successful in influencing acute changes in ground reaction force variables and lower extremity kinematics in healthy children and adults.\textsuperscript{92, 93, 95} However, research has not looked at this feedback to improve landing forces or symmetry of VGRF during landing in pathologic population.

\textbf{2.13 Verbal Instructions Intervention}

Neuromuscular training programs often attempt to minimize the risk of incurring injury while landing from a jump by offering verbal instructions on how to better perform the
movement. Verbal instructions, in combination with expert demonstration or video feedback, have resulted in acute changes in double-leg landing mechanics, including decreased peak vertical ground reaction forces\textsuperscript{307-310} and general increases in sagittal plane displacement.\textsuperscript{95} With the exception of one study,\textsuperscript{281} these changes in landing mechanics were in healthy college aged individuals. Other studies have found verbal instructions in isolation were capable of altering landing mechanics as well.\textsuperscript{92-94, 311} Verbal instructions are often technical, describing in great detail how one would like the individual to land. Examples include, “position yourself on the balls of your feet with bent knees just prior to landing. On landing, lower the heels slowly to the ground and bend the knees until well after the landing.”\textsuperscript{92-94} These specific instructions have been successful in acutely reducing vertical ground reaction forces in adults\textsuperscript{279, 286} and children.\textsuperscript{280} However, once again all subjects were healthy with no prior history of knee ligament injury. Mizner et al.\textsuperscript{287} investigated the relationship between lower extremity strength and the ability to change landing patterns given verbal instructions in a group of healthy collegiate female athletes (19.5 ± 1.2 years old). They found that their verbal instructions were successful in acutely decreasing peak vertical ground reaction forces, but lower extremity strength was not a significant predictor of this change. The general landing instructions were, “try to land as softly as you can,” but were also instructed to increase bending in their knees, land on toes, keep chest over knees, keep knees over toes, and avoid knee valgus during landing.” This dosage of instructions was successful in reducing ground reaction forces, but it is unclear which instruction(s) were beneficial. A recent study set out to avoid using multiple instructions (or overly technical instructions) in an attempt to clarify if a single simple verbal instruction could result in an immediate change in knee biomechanics during landing. Milner et al.\textsuperscript{96} investigated the
effects of three separate verbal instructions, in a counterbalanced order, on acute knee landing biomechanics during a countermovement jump. The separate instructions were to land “1) with knees over your toes, 2) with equal weight distribution on both your feet, and 3) as softly as possible.” Results indicated that the instructions specific to ‘land softly’ reduced peak vertical ground reaction forces and increased peak knee flexion in comparison to the control condition.\(^6\) The instructions specific to ‘land with equal weight’ reduced the asymmetry of peak vertical ground reaction force compared to the control condition.\(^6\) The novelty of this study is that it demonstrated instructions can and likely should be simple. However, as with the previous studies discussed, this population consisted of a small sample (n=12) of healthy female recreational athletes with no history of ACL injury.

Previous research has demonstrated that landing forces, specifically vertical ground reaction forces, can be modified via simple verbal instructions. Acute changes in landing mechanics have been observed in healthy adults and children. The same effects have not been tested in female adolescents with a history of ACLR. However, similar verbal instructions are utilized in rehabilitation and injury prevention settings in attempt to improve neuromuscular control and landing mechanics. Therefore, a secondary purpose of the current project is to investigate the effects of simple verbal instructions, focused on soft and symmetrical landings, on landing biomechanics in this population. The double-leg jump landing task will be performed at baseline, with no specific landing instructions or demonstration, and then repeated with verbal instructions in a counterbalanced order. A single-session repeated measures design should be sufficient to discern acute changes as previous work found that providing more than one session with instructions did not improve the magnitude of the changes observed in children.\(^{280}\)
2.14 Summary of Literature Review

The purpose of this study is to investigate lower extremity biomechanics in adolescent females with a history of ACLR. The previously injured limb will be compared to both the uninjured limb and both limbs of the health control group. In addition, acute verbal instructions will be provided in a counterbalanced order to investigate the effects each has on landing biomechanics during the double-leg jump landing.

The variables selected for this project were based off of previous research and pilot work investigating male and female adults with a history of non-contact ACL injury with reconstruction.
CHAPTER THREE
METHODOLOGY

3.1 Experimental Design

This study utilized a cross-sectional research design for Specific Aims 1 and 2, investigating previously injured adolescent females (ACLR) and healthy matched controls (Control). A quasi-experimental, repeated measures cross-over design, was utilized for Specific Aim 3 to investigate the effectiveness of simple verbal instructions on altering variables during the double-leg jump landing. The purpose of the current study was to investigate trunk and lower extremity biomechanical differences between 1) the injured and uninjured limbs of the ACLR female adolescents and 2) the injured and uninjured limbs of the ACLR participants compared to those of the healthy control participants while performing a double leg jump landing and single leg double hop. Furthermore, we aimed to determine if simple verbal instructions were capable of altering landing strategies during the double leg jump landing within the ACLR group and between both limbs of the healthy control group for selected kinematic and kinetic variables between conditions. A depiction of data collection procedures is located in Figure 1.

3.2 Participants

Forty-seven female adolescent athletes (22 ACLR, 25 Control) were recruited to participate in this research study. All subjects were between the ages of 12-18 years and were
recruited from local schools, physical therapy clinics, orthopedic practices, and sports organizations via emails, flyers and personal contact. This adolescent age range is known to incorporate the average onset and time period of puberty, which is associated with growth spurts and neuromuscular changes in both males and females. Athletes in this age range are participating in organized sports programs in greater numbers, but also sustaining increasing rates of ACL injuries. To be included in the study, all subjects were required to satisfy the following criteria:

- Female between the ages of 12-18 years
- Physically active (sport participation 2-3 times per week)
- No history of ankle, hip, spine, or knee (contralateral only for ACLR group) injury in the past 6 months
- No history of lower extremity surgery or fracture (other than unilateral ACLR)
- No known neurological disorder that would prevent them from completing testing

To be included in the study, female ACLR subjects needed to satisfy the following criteria:

- Unilateral ACL reconstruction (with no more than one surgical intervention)
- At least 6 months post ACLR and released for full sports participation by physician (not longer than 2 years post ACLR)
- Completed supervised rehabilitation following surgical reconstruction
- With or without concomitant meniscal injury
- No concomitant posterior cruciate ligament (PCL), medial collateral ligament (MCL), or lateral collateral ligament (LCL) injuries that would alter the timeline of rehabilitation
All previously injured subjects had been fully cleared by their operating physician and therapist/athletic trainer, having returned to organized competitive sport. All subjects were tested within two years of fully returning to sport. Healthy female subjects were matched by age, body mass, height, physical activity level, and sport participation to the ACLR cohort.

**Power Analyses**

An *a priori* power analysis, using pilot data and previously published data, was performed for each dependent variable (Table 1-2). For Specific Aims 1 and 2, the analysis revealed that a sample size of 25 per group would allow the investigators to detect a minimum 20% difference in the majority of primary dependent variables with power of 0.80 and $\alpha=0.05$. Previous research has detected group differences of greater than 20% on these measures with smaller sample sizes.$^{72, 277}$ Differences of greater than 20% have been demonstrated in VGRF, knee extension moment, knee valgus moment, and ATSF between ACLR and healthy groups.$^{42, 45, 65}$

For Specific Aim 3, the analysis revealed that a sample size of 25 per group would allow the investigators to detect a minimum 20% change in all dependent variables with power of 0.70 and $\alpha=0.05$. Previous research using verbal instructions in healthy adolescent females has shown a reduction in VGRF larger than 20%.$^{92, 93, 96}$
3.3 Instrumentation

Three-Dimensional Motion Capture System

A Vicon MX-40 infrared seven-camera motion analysis system (Vicon Systems, Centennial, CO) was used to collect segment kinematic data during the jump landing and single leg double hop tasks. The capture volume was approximately 2m x 2m x 2m and was calibrated prior to data collection following manufacturer guidelines. Kinematic data was collected at a sampling frequency of 120 Hz. A global axis system was defined for the laboratory capture volume, and local coordinate systems for each body segment were aligned such that the positive X-axis points in the direction the subject is facing along the anterior-posterior axis, the positive Y-axis was aligned to the subject’s left along the medial-lateral axis, and the positive Z-axis was aligned vertically along the superior-inferior axis. Digital camera data was imported into Vicon Nexus data collection software (Vicon Systems, Centennial, CO) for integration with the forceplate data and marker identification.

Force Plates

Two Bertec force plates (Type 4060-08, Bertec Corporation, Worthington, OH) embedded in the laboratory floor were used to collect ground reaction force data during the jump landing and single leg double hop. The axis systems of both forceplates was aligned to the global coordinate system of the laboratory defined by the motion capture system. Analog data was sampled at 1200 Hz and passed through an A/D board prior to being imported and synchronized with the segment kinematic data within the Vicon Nexus software.

A digital scale and stadiometer were used to assess body mass and height demographics, respectively.
**Pubertal Maturation Observational Scale**

This survey tool is a scale used to classify adolescents into developmental stages. Questions pertain to secondary sex characteristics, such as rate of height changes, breast development, menarche, body hair, acne, sweating and muscle development in order to determine the adolescent’s stage of development relative to puberty. If an adolescent has zero or one of the characteristics on the checklist, the adolescent is considered pre-pubertal. If four to five characteristics are present, including a growth spurt, the adolescent is considered pubertal. Finally, if at least six characteristics are present, the adolescent is considered post-pubertal. This scale was necessary to confirm successful matching of our healthy and previously injured female adolescents. Females between the ages of 12-18 were primarily categorized as post-pubertal. It was imperative that we account for maturational phase so that group differences observed are attributable to injury states as opposed to developmental stage.

**Skeletal Maturity Scale**

A non-invasive skeletal maturity estimate was used to predict each subject’s mature height, presented as a percentage of his or her predicted adult height. The Pubertal Maturation Observational Scale listed above asks additional questions specific to the height of the subject’s biological mother and father, if available. The subject’s current height, weight, and midparents height \[(\text{mother’s height} + \text{father’s height}) / 2\] was used to predict mature height with the Khamis-Roche protocol.\textsuperscript{312} This method has been used previously and has shown moderate associations with more invasive skeletal age assessments.\textsuperscript{313}
Health History and Activity Level Questionnaire

This questionnaire was designed to collect specific details regarding the injury, including 1) date of injury, 2) date of surgery, 3) duration of rehabilitation, 4) type of rehabilitation, 5) date of return to sport, 6) current activity level, and 7) concomitant injuries that may have occurred. The Marx activity rating scale was also embedded within this questionnaire to adequately assess physical activity level.

Marx Activity Rating Scale

The Marx activity rating scale quantifies physical activity in knee-injured patients and is typically completed in less than one minute. The scale measures specific components of function, rather than type of sport, and is scored out of a total of 16 points. For example, a 12 out of 16 points on this scale indicates they perform running, cutting, deceleration, and pivoting activities two to three times per week. Results were used to confirm similar physical activity levels between groups. The Marx scale is a valid and reliable assessment tool in the knee injured population.314, 315

3.4 Procedures

Consent & Subjective Questionnaires

Once a subject was identified and scheduled for data collection, University Institutional Review Board approved materials were e-mailed to the subject and their parent/guardian. Subjects and parents/guardians were asked to take the time to read all materials to fully understand all procedures and potential risks/benefits involved in
participating in this study. Materials in this packet included relevant Institutional Review Board approved consent documents; adult consent form (age 18), adolescent assent form (ages 15-17), minor assent form (ages 12-14), and the parental consent form for any subject under the age of eighteen. Once parents and subjects understood the procedures and agreed to participate they signed their respective forms and continued to fill out the pubertal maturational observation scale and the detailed health history and physical activity questionnaire (Appendix A). The purpose of sending the materials ahead of time was threefold, (1) to allow the parent/guardian and subject ample time to read and review all materials, (2) to allow the parent/guardian and subject ample time to accurately fill out the questionnaires with details of their injury and recovery, and (3) to shorten their overall time commitment once they reported to the laboratory for data collection. If at anytime while completing these materials they decided not to participate in this study, they were able to keep their own informational materials and had no need to report to the laboratory where they may feel slight pressure to participate. In addition, the cover letter attached to the informational materials included the primary investigator’s contact information (telephone and email) so that she could be contacted at any time to answer any and all questions. Subjects and parents/guardians worked together on completing all necessary paperwork prior to the scheduled testing session. They were then asked to bring all forms to their testing session and were provided ample time to ask any remaining questions that they had prior to data collection.

Subjects reported to the Sports Medicine Research Laboratory for a single testing session lasting approximately two hours. Subjects were asked to wear their own dark colored spandex shorts and a fitted tank top (or sports bra) with their own running shoes for testing.
A running shoe was required in an attempt to standardize the type of shoe each subject wore. Therefore, no turf shoes, court shoes, or certainly cleats were allowed. However, there was still some variation in the type of running shoe each participant wore. If any subject did not have the appropriate clothing, it was provided for them and returned at the completion of testing. Dark colored clothing was necessary for better marker reflection during motion analysis testing. Fitted and minimal clothing was necessary to minimize marker movement during motion analysis.

Anthropometric data was assessed prior to warm-up. Demographic height (cm), body mass (kg), and bilateral limb segment length (m) was recorded. Bilateral segment length was measured from the location of handheld dynamometer placement to the axis of rotation for both the thigh and shank segments. This data was recorded for potential use in calculating torque from force measurements.

A five-minute warm-up was then performed on a stationary bicycle ergometer at an estimated rating of perceived exertion (RPE) of 12 followed by self-selected lower extremity stretching. Following warm-up, biomechanical analysis was performed. All data were collected bilaterally and the order of limb tested was counterbalanced between subjects.

**Biomechanical Analysis**

The double leg jump landing (JL) and the single leg double hop (SDH) were performed within the calibration volume of the infrared camera system. All subjects performed the tasks in this order as a typical progression from double leg to single leg hopping activities. A custom 34-point marker set was used for all three-dimensional motion analysis data collection. Retroreflective markers were placed bilaterally on each subject in
the following locations: tip of the acromion process, anterior superior iliac spine (ASIS), greater trochanter, anterior thigh, medial femoral epicondyle, lateral femoral epicondyle, anterior tibia, medial malleolus, lateral malleolus, calcaneus, head of the 5th metatarsal, and head of the 1st metatarsal. Additional markers were placed over the seventh cervical vertebra (C7), second thoracic vertebra (T2), eight thoracic vertebra (T8), tenth thoracic vertebra (T10), most caudal point of the sternum (PX), deepest point of the suprasternal notch (IJ), L4-L5 lumbar vertebrae, and a customized marker cluster containing three markers was placed over the sacrum (sacrum, left PSIS, right PSIS). The medial femoral epicondyle and medial malleolus markers were used for static subject calibration to calculate hip, knee, and ankle joint centers during processing. The location for each retroreflective marker was identified through palpation and the skin was cleaned with isopropyl rubbing alcohol. Adhesive spray was applied and allowed to let fully dry. The markers were affixed with double sided tape, pre-wrap, and white athletic tape as necessary. A calibration trial was then recorded with the subject standing with the feet shoulder-width apart, one foot on each force plate pointing straight ahead, and the arms abducted 90 degrees. This position was maintained for 1-2 seconds while marker positions were recorded. The medial static calibration markers were then removed.

To perform the double leg jump landing (Figure 3), participants stood atop a 30-cm box that was placed a horizontal distance of 50% of their height behind the leading edge of the force plates. They jumped forward from the box to a double leg landing with one foot in the center of each force plate before jumping vertically for maximal height. Instructions given to the subjects were to “focus on jumping forward into the target area with both feet and immediately jump straight up as high as you can.” No demonstration was given, however
all subjects performed three practice trials prior to data collection. Subjects then completed three successful trials, with 30 seconds of rest between. A trial was deemed successful if they left the jump box with both feet at the same time, landed on the forceplates, and immediately jumped straight up for maximal height. If subjects lead with one foot more while leaving the box or forgot to jump straight up for maximal height, trials were discarded and new trials were recorded.

The single leg double hop (Figure 4) is a series of two consecutive hops that require using a single leg to propel the body forward, and absorb impact forces upon landing, while maintaining stability to repeat the movement. The goal was to hop from the standardized starting position to the forceplate before jumping horizontally for maximum distance. Subjects started on the test leg in a semi-crouched position directly in front of the forceplate at a distance of 30 inches (76.2cm). They were instructed to “hop forward to the forceplate, landing safely on the same limb, and immediately jump forward as far as you can on the same leg, holding the second landing”. Upon landing a piece of tape was placed on the floor behind the heel in order to mark the distance hopped. Distance was measured and recorded for all trials from the start line marked on the laboratory floor to the location marked on the ground where the heel landed. Subjects were allowed to use their arms for a counter movement and complete three successful trials on each leg having 30 seconds of rest between trials and two minutes of rest between legs.\textsuperscript{316} All subjects performed three practice trials on each limb, followed by one minute of rest, prior to data collection. The starting distance for this task was a standard position of 30-inches (76.2cm) from the front edge of the forceplate. The Centers for Disease Control and Prevention (CDC) has estimated the average height of teenage girls between the ages of 12-17 to be between 62-64 inches.\textsuperscript{317} Accounting for the
lower end, we chose a starting position of slightly less than half of that distance from the forceplate as a challenging but realistic distance for this population. Three trials were collected on each leg with a minimum of 30-seconds of rest between trials.

**Verbal Instructions Intervention**

Following the completion of the initial jump landing and single leg double hop tasks; the verbal instructions intervention was carried out for all subjects in a repeated measures, cross-over, design. The initial three trials of the jump landing task were used as the baseline assessment for the intervention. All subjects performed an additional set of three jump landing trials for each of two verbal instructions conditions in a counter balanced order. The goal of the verbal instruction conditions was to shift the focus of the subjects to decreasing landing forces (soft instruction) or making landing forces more symmetrical between limbs (equal instructions). A washout of two different squatting tasks was performed in between the verbal instruction conditions to shift the subjects’ focus away from what they had done previously. A depiction of the verbal instructions jump landing intervention is located in Figure 2. The verbal instructions script utilized during data collection is located in APPENDIX B.

The squatting tasks for the wash out block included a double leg and single leg squat performed bilaterally. To perform the overhead squat, subjects stood on the forceplates with legs shoulder-width apart and toes facing forward. Arms were extended and maintained vertically above their head for the duration of the task. They were instructed to lower into a squat to maximal comfortable knee flexion and then return to the initial upright posture. Subjects performed one set of five consecutive squats at a slow controlled cadence of
approximately 2-seconds down and 2-seconds up. Subjects rested for 2-minutes after the completion of the double leg squat prior to performing the single-leg squats.

To perform the single leg squat, subjects stood on the forceplate on their test leg with toes facing forward. Both hands were placed and maintained on their hips with the non-stance leg raised approximately 5-10cm off the ground. They were instructed to lower into a squat to maximal comfortable knee flexion and then return to the initial upright posture. Subjects performed one set of five consecutive squats at a slow controlled cadence of approximately 2-seconds down and 2-seconds up. Each subject performed one set of five consecutive squats on each leg with 2-minutes rest between. The same task was repeated on the contralateral limb.

**Soft Landing Instructions**

Verbal instructions were given prior to the first jump landing trial in this condition and were repeated in an abbreviated form prior to the start of the remaining trials. Subjects performed three trials within this condition, with 30-seconds of rest between each. Instructions stated: “This time when you perform the jump landing I want you to focus on landing as soft as you can.” Abbreviated Instructions stated: “Focus on landing as soft as you can.”

**Equal Landing Instructions**

Verbal instructions were given prior to the first jump landing trial in this condition and were repeated in an abbreviated form prior to the start of the remaining trials. Subjects performed three trials within this condition, with 30-seconds of rest between each.
Instructions stated: “This time when you perform the jump landing I want you to focus on landing with equal weight under each foot.” Abbreviated instructions stated: “Focus on landing with equal weight under each foot.” After the completion of the second condition, motion analysis testing was complete and all retroreflective markers were removed.

Similar verbal instructions were provided to healthy children, with no prior involvement in jumping sports before performing a double leg landing and were successful in reducing landing ground reaction forces. These authors also found that increasing the duration of these sessions beyond the initial ‘training’ was not any more effective in altering the magnitude of change occurring from the instructions. Therefore, we felt this will be an effective means of comparing ACLR and control group responses to verbal instructions in relation to altering landing biomechanics.

3.5 Data Sampling, Processing and Reduction

**Biomechanical Data Reduction**

Kinematic and kinetic data were recorded using The Vicon Nexus software program and was time synchronized to 1200 Hz using linear interpolation. All retroreflective markers (34 calibration/static trial, 30 for movement trials) were identified and labeled using a predefined labeling template. Any missing marker trajectories were filled using a Woltring smoothing spline function provided by the Vicon Nexus software. Extra reflections in the field of view were deleted following marker identification and trajectory processing. These data, along with the synchronized ground reaction force data were saved as a .c3d files.

Marker and ground reaction force data were imported into The Motion Monitor biomechanical data analysis software package (Innsport Inc, Chicago, IL). The three-
dimensional local coordinates of the medial femoral epicondyles and medial malleoli were estimated from the coordinates of markers on the shank in the standing trial. The three-dimensional coordinates of the hip joint centers were estimated from the three-dimensional coordinates of the reflective markers on the right and left ASIS and L4-L5 joint using the Bell method. The knee and ankle joint centers were defined as the mid-point between the medial and lateral femoral epicondyle and medial and lateral malleoli, respectively. The coordinates of the right and left acromion processes and the L5 marker defined the trunk reference frame. The coordinates of the sacral cluster, including the sacrum and right and left PSIS markers, defined the pelvis. The tibia reference frame was defined by the coordinates of the knee and ankle joint centers and medial and lateral malleoli, whereas the femur reference frame will be defined by the coordinates of the knee and hip joint centers and medial and lateral femoral epicondyles. The three-dimensional coordinates of the 1st and 5th metatarsal heads and the calcaneus defined the foot reference frame. The trunk angles were determined as Euler angles of the trunk reference frame relative to the pelvis frame rotated in an order of (1) flexion-extension (y-axis), (2) lateral flexion (x-axis), and (3) rotation (z-axis). The hip joint angles were determined as Euler angles of the femur reference frame relative to the pelvis reference frame rotated in an order of (1) flexion-extension (y-axis), (2) abduction-adduction (x-axis), (3) internal-external rotation (z-axis). The knee joint angles were determined as Euler angles of the tibia reference frame relative to the femur reference frame rotated in an order of (1) flexion-extension (y-axis), (2) valgus-varus (x-axis), (3) internal-external rotation (z-axis).

Kinematic and kinetic data were exported into a customized MATLAB software program (Mathworks, Natick, MA, version 11.0) for data reduction. Kinematic data were
filtered using a 4th order zero-phase-lag Butterworth low-pass filter at a 12 Hz cutoff frequency. Ground reaction forces and anterior tibial shear force data were normalized to body weight (N) and internal joint moment data were normalized to the product of body weight (N) and height (m). The vertical ground reaction force data was used to define the landing phase, pushoff phase, and total stance phase of both the jump landing and single leg double hop tasks. Initial contact was defined as the first time point during each trial that the vertical ground reaction force exceeded 10N, and toe-off was defined as the first time point during each trial that the vertical ground reaction force dropped below 10N. The total stance phase was defined as the time period from initial contact to toe-off. For the jump landing task, the landing phase was defined as the time period from initial contact to the time point of peak knee flexion, whereas the pushoff (propulsive) phase was defined as the time period from peak knee flexion to toe-off. For the single leg double hop, the landing phase was defined as the first 50% of the stance phase defined by the VGRF data. The takeoff phase was defined as the second 50% of the stance phase defined by the VGRF data. Kinematic variables were assessed as the value at the time point of initial contact and overall joint displacements calculated during the landing phase. The following kinematic variables were collected: trunk flexion angle, trunk lateral flexion angle, hip flexion angle, hip adduction angle, hip internal rotation angle, knee flexion angle, knee valgus angle, and tibial rotation angle. The kinetic variables were assessed as peak values during the landing phase and during the takeoff phase of each jumping task. The following kinetic variables were calculated and analyzed: peak vertical ground reaction force (VGRF), peak anterior tibial shear force (ATSF), peak knee extension moment, and peak knee valgus/varus moment. Joint
moments were calculated and presented as internal moments. Joint moments and anterior tibial shear force were calculated using standard inverse dynamic procedures.\textsuperscript{319}

Joint displacements (DSP) reflecting overall lower extremity joint motion during the landing phase of the jump landing and single leg double hop were calculated for each kinematic variable by subtracting joint angles at the time point of initial contact from peak joint angles reached during the landing phase (DSP = Peak Angle – IC Angle).

3.6 Statistical Analysis

An \textit{a priori} alpha level of 0.05 was set to determine statistical significance for all statistical analyses performed. All statistical analyses were performed using IBM SPSS Statistics (IBM Corp., Armonk, NY, v.21.0) software package. Prior to completion of all statistical analyses, each dependent variable was assessed for statistical outliers and to ensure normal distribution. Independent samples t-tests were also performed to compare subject demographic data for age (years), body mass (kg), and height (cm) to ensure groups were similar aside from injury status.

\textit{Specific Aim 1:} Determine the effects of anterior cruciate ligament reconstruction in adolescent female athletes on measures of trunk and bilateral lower extremity biomechanics during a double leg jump landing compared to healthy controls with no history of ACL injury.

\textit{Statistical Procedure Aim 1a:} A linear regression model with generalized estimating equations (GEE) to account for correlated data were performed for each trunk kinematic
variable (6) for the double leg jump landing to determine the differences between the ACLR group and healthy control group.

*Statistical Procedure Aim 1b-1d:* A linear regression model with generalized estimating equations (GEE) to account for correlated data were performed with two factors (Group, Limb) for each dependent variable. Three pairwise comparisons were evaluated for each variable of interest: 1) Injured * Uninjured, 2) Injured * Index, and 3) Uninjured * Non-Index.

*Specific Aim 2:* Determine the effects of anterior cruciate ligament reconstruction in adolescent female athletes on measures of trunk and bilateral lower extremity biomechanics during a single leg double hop compared to healthy controls with no history of ACL injury.

*Statistical Procedure Aim 2a-2c:* A linear regression model with generalized estimating equations (GEE) to account for correlated data were performed with two factors (Group, Limb) for each dependent variable during the single leg double hop. Three pairwise comparisons were evaluated for each variable of interest: 1) Injured * Uninjured, 2) Injured * Index, and 3) Uninjured * Non-Index.
**Specific Aim 3:** Determine the acute changes in double leg jump landing biomechanics with two separate verbal instruction conditions in female adolescent athletes with a history of anterior cruciate ligament reconstruction compared to healthy controls with no history of ACL injury.

**Statistical Procedure 3a-3b:** Change scores were calculated for each dependent variable by subtracting the value at baseline from the value with each verbal instruction condition. A linear regression model with generalized estimating equations (GEE) to account for correlated data were performed with two factors (Group, Limb) for each dependent variable change score. Three pairwise comparisons were evaluated for each variable of interest: 1) Injured * Uninjured, 2) Injured * Index, and 3) Uninjured * Non-Index.

### 3.7 Additional Measures

Additional clinical measures were performed during each testing session that were not directly included in the aims of the current project. There were two additional survey instruments embedded within the questionnaire, including the knee injury and osteoarthritis outcome score (KOOS) and the shortened version of the Tampa scale of kinesiophobia (TSK-11). Additional clinical measures of knee laxity, joint range of motion and isometric strength of selected muscles were also performed. Each additional assessment is described in detail below.
**Knee Injury and Osteoarthritis Outcome Score (KOOS)**

The knee injury and osteoarthritis outcome score (KOOS) is an instrument to assess the patient’s opinion about her knee and associated problems such as symptoms, stiffness, pain, function, and knee related quality of life. This instrument was developed for knee injuries that can result in post-traumatic osteoarthritis (OA) (i.e. ACL injury, meniscus injury) and has been shown to be valid and reliable for use in adults with ACL injuries. We acknowledge this instrument has not been previously used in an adolescent population, however this form was likely completed with the assistance of a parent or guardian as parental consent is warranted, therefore we feel safe that the questions were interpreted and answered accurately.

**Tampa Scale of Kinesiophobia (TSK-11)**

The TSK-11 assesses psychometric properties of chronic pain, which could lend insight to movement avoidance behaviors after ACLR. This tool has been used previously in an adult ACLR population, to pinpoint potential fear of movement and or re-injury. This survey asks eleven questions that are scored on a 4-point likert scale ranging from ‘strongly disagree’ to ‘strongly agree.’ An example question reads, “I am afraid I might injure myself if I exercise…” Again, we do acknowledge this instrument has not been previously used in an adolescent population, however this form was likely completed with the assistance of a parent or guardian as parental consent was warranted, therefore we feel safe that the questions were interpreted and answered accurately. The score from this tool will not be directly used in our statistical analyses, however we felt it would be valuable information to potentially help explain our results.
**Anterior-Posterior Knee Laxity**

Knee laxity was assessed bilaterally for all subjects, defined as the amount of anterior tibial displacement relative to the femur at 133N, measured by a KT-1000 knee arthrometer (MEDmetric Corp, San Diego, CA). Subjects were positioned supine with the knee flexed 20-30 degrees and supported by a bolster behind the popliteal space. The subject’s ankles were placed in a cradle and a thigh strap was added to control rotation of the thighs. After proper subject positioning, the KT-1000 was placed on the anterior shank, aligned with the joint line, and secured to the lower limb using Velcro straps. The primary investigator applied an anterior force that resulted in anterior displacement of the tibia. Two practice trials were used to ensure that the subject was fully relaxed and the KT-1000 was aligned and secured properly. Three trials were recorded on each limb. High intrarater reliability was established prior to data collection (ICC (3,1) = 0.995, SEM = 0.22 mm). Knee laxity was not directly used in our statistical analyses, however anterior knee laxity is often present following ACLR, particularly in females, and is a standard measure taken my clinicians and researchers. We felt it was valuable information and necessary to collect.

**Lower Extremity Range of Motion**

Following the warm-up period, passive range of motion (PROM) was measured bilaterally for each subject, with order of assessments randomized, to prevent a potential order effect. All PROM measurements were taken with a standard goniometer or digital inclinometer (The Saunders Group, Chaska, MN). For each muscle group, a single investigator passively moved the associated joint through its available range of motion from
a neutral position to the point of first resistance. The point of first resistance was defined as the point where the investigator felt resistance from tension in the muscle and other soft tissue structures, or the subject vocalized discomfort. The measurements were selected based on previous literature that has demonstrated abnormal knee extension (hyperextension) and abnormal knee flexion following ACL reconstruction are significant factors related to the presence of knee OA on radiographs. There has also been recent evidence that restricted ankle dorsiflexion range of motion is associated with landing strategies known to put an individual at risk of ACL injury, as adequate ankle dorsiflexion during weight bearing is necessary for the performance of functional tasks. High intrarater reliability was established prior to data collection (WBLT ICC \( (3,k) = 0.996, \text{ SEM } = 0.037^\circ \); Knee Hyperextension ICC \( (3,k) = 0.992, \text{ SEM } = 0.01^\circ \); Knee Flexion ICC \( (3,k) = 0.996, \text{ SEM } = 0.10^\circ \); Ankle Dorsiflexion Flx ICC \( (3,k) = 0.998, \text{ SEM } = 0.49^\circ \); Ankle Dorsiflexion Straight ICC \( (3,k) = 0.996, \text{ SEM } = 0.09^\circ \)). Three trials of each measurement were performed bilaterally.

- **Weight Bearing Lunge**: The subject was asked to stand with their foot perpendicular to the wall. The researcher zeroed the digital inclinometer ot the vertical and placed the superior tip on the distal border of the tibial tuberosity resting on the anterior surface of the shank. The subject was then be asked to bend the test knee and lunge forward as far as possible while keeping their foot in the same position with the heel on the ground. The angle of the tibial shaft from the vertical position was measured using a digital inclinometer. Three trials were performed bilaterally and results were recorded and averaged.

- **Knee hyperextension**: The subject was positioned supine, both legs fully extended with the heel elevated on a bolster to allow the knee to go into hyperextension if
present. The subject was instructed to completely relax and knee range of motion was measured with the axis of the standard goniometer over the lateral epicondyle of the femur, proximal arm aligned with the midline of the lateral femur and the distal arm aligned with the shaft of the fibula.\textsuperscript{325} Three trials were recorded and the same procedure was repeated on the contralateral leg.

- **Knee Flexion:** Quadriceps range of motion of each subject was determined by measuring knee flexion while positioned supine. The goniometer was aligned with the axis over the lateral epicondyle of the femur, proximal arm aligned with the midline of the lateral femur and the distal arm aligned with the shaft of the fibula. The investigator passively flexed the knee, bringing the heel toward the gluteals, until resistance was met and the angle was recorded.\textsuperscript{325} Three trials were recorded and the same procedure was repeated on the contralateral leg.

- **Ankle dorsiflexion:** The length of the gastrocnemius and soleus were determined by measuring the amount of passive ankle joint dorsiflexion with the knee extended and again with the knee flexed to 90°, respectively. The subject was positioned supine with the knee fully extended (gastrocnemius) and the ankle/lower leg positioned on a bolster for support. The proximal arm of the goniometer was aligned with the shaft of the fibula using the lateral malleolus as a guide, and the distal arm aligned with the lateral midline of the foot.\textsuperscript{326} The investigator passively dorsiflexed the talocrural joint until first restriction was met, and the angle was recorded. Three trials were recorded and the same test procedure was repeated with the knee flexed to 90 degrees to assess the soleus muscle.\textsuperscript{327} Both procedures were repeated on the contralateral leg.
**Lower Extremity Isometric Strength**

Peak isometric force was assessed using a handheld dynamometer by a single examiner (Catillon CSD 300, Amtek, Inc., Largo, FL) in standardized testing positions. Subjects performed three separate 5-second maximal voluntary isometric contractions (MVIC) for knee extension (quadriceps), knee flexion (hamstrings), and hip abduction (gluteus medius) in a randomized order. The same assessment order was repeated on both limbs. Subjects were instructed to use the first two seconds to build up to their maximal contraction and then sustain that for three additional seconds. Verbal encouragement was used to promote maximal effort. Subjects were given one minute of rest in between each trial to minimize the risk of fatigue. Peak force in Newtons (N) was recorded for three separate trials that each lasted five seconds. The mean of these measurements was calculated and normalized using the allometric scaling method based on the principle of geometric similarity. Specifically, dividing strength by the body size variable raised to an appropriate power has been theorized to eliminate the effects of body size. This procedure normalizes force measured by the dynamometer and takes into account variations in muscle cross-sectional area as a function of body mass (kg). The equation used for normalization in this study was $S_n = S/m^{2/3}$, where $S_n$ is the normalized strength value, $S$ is the force (N) measured by the hand-held dynamometer, and $m$ is body mass (kg). High intrarater reliability was established prior to data collection (Knee Extension ICC $^{(3,1)} = 0.999$, SEM = 2.08 N; Knee Flexion ICC $^{(3,1)} = 0.996$, SEM = 1.12N; Hip Abduction ICC $^{(3,1)} = 0.998$, SEM = 3.18N).
Knee extension (quadriceps): Subjects were positioned prone on the treatment table with their knee flexed to 90 degrees. The investigator applied manual resistance with the handheld dynamometer to the test limb just proximal to the anterior ankle in the direction of knee flexion. The subject was instructed to push against the resistance with maximal effort. Three trials were collected on each leg.

Knee Flexion (hamstrings): Subjects were positioned prone on the treatment table with their knee flexed to 90 degrees. The investigator applied manual resistance with the handheld dynamometer to the test limb just proximal to the posterior ankle in the direction of knee extension. The subject was instructed to pull against the resistance with maximal effort. Three trials were collected on each leg.

Hip abduction (gluteus medius, tensor fascia latae): Subjects were positioned sidelying with their back, gluteals, and heel of the test leg against the wall to prevent rotation. The investigator applied manual resistance to the test limb just above the knee on the lateral aspect of the thigh in the direction of hip adduction. The subject was instructed to push up against the resistance, keeping their leg straight, with maximal effort. Three trials were collected on each leg.
CHAPTER FOUR
SUMMARY OF RESULTS

4.1 Introduction

The purpose of this chapter is to provide a synthesis of the results for this project and is organized to address each specific aim separately. A brief summary of major findings will be included. A more detailed presentation of the results for Specific Aim 1, 2, and 3 is provided in manuscripts attached to this document as appendices. Manuscript 1 (Appendix C) will address Specific Aim 1, Manuscript 2 (Appendix D) will address Specific Aim 2, and Manuscript 3 (Appendix E) will address Specific Aim 3. This chapter will provide a more detailed presentation of results concerning Specific Aims 1 and 2 regarding the push-off phase biomechanics as they were not included in the associated manuscripts. A more detailed presentation of results concerning Specific Aim 3 will include four additional dependent variables that were not included in the respective manuscript.

4.2 Overview of Participant Demographics

Forty-nine participants were enrolled in this research study over a recruitment period of 14 months. Twenty-four participants had a history of unilateral ACLR and returned to their primary sport. Of this group, 1 was identified as being ACL deficient at the time of testing having never undergone reconstructive surgery thereby not fitting our inclusion criteria. One participant’s data was not useable due to an error in data collection. Twenty-five
healthy control participants, matched by age, height, body mass, and primary sport also participated in this study.

The bilateral limbs of the previously injured group (ACLR) were referred to as the ‘Injured’ and ‘Uninjured’ limb. The bilateral limbs of the healthy control group (CON) were referred to as the ‘Index’ and ‘Non-Index’ limb. Right and left CON limbs were randomly allocated to serve as the Index limb to match the distribution of right (n=8) and left (n=14) limb injuries in the ACLR group (Table 3).

Overall, there were a total of 47 participants (22 ACLR, 25 CON) with data available to address Specific Aims 1, 2, and 3. All ACLR group participants had returned to their primary sport with an average time of 8.18 ± 2.48 months post surgery. The mean time from surgery to participation was 14.52 ± 8.62 months. All injuries were due to noncontact or indirect contact mechanisms during their primary sport such that no direct contact with the knee occurred. All participants completed supervised rehabilitation following ACLR and prior to full return to sport, however individual rehabilitation progressions and return to sport criteria was unknown.

Healthy CON group participants were matched by age, height, body mass, and sport participation. There was an equal distribution of ACLR and CON participants competing in each sport, including soccer, basketball, lacrosse, volleyball, softball, and gymnastics. The limbs of the CON group participants were randomly allocated to serve as the Index or Non-Index limb based on the distribution of right and left limb ACL injuries as described previously. This limb allocation procedure also resulted in similar distributions of dominant kicking limbs that were Injured in the ACLR group (n=12) or assigned as the Index in the CON group (n=10). However, matching based primarily on kicking limb dominance, as in

103
previous research, was not possible due to the lack of left limb kicking dominant participants in the CON group. Detailed information regarding participant inclusion criteria and demographics are provided in each subsequent manuscript.

A pubertal maturation observation scale and skeletal maturity checklist were used to classify development stages and estimate skeletal maturity in the female adolescent participants, respectively. All participants in both groups reported at least six characteristics on the pubertal maturation scale were present, indicating all participants would be categorized, as post-pubertal. The participant’s current height, weight, and midparents height \([(\text{mother’s height} + \text{father’s height}) / 2]\) was used to predict mature height with the Kharmis-Roche protocol. All participants were an average of 99% of their mature height at the time of testing. When investigating a younger adolescent population it is important to account for pubertal and skeletal maturation as developmental stages can certainly vary in two individuals who are the same age. There were no differences between the ACLR and CON groups on measures of pubertal or skeletal maturation and no further classification of participants was necessary. Therefore, age, height, body mass and primary sport participation was emphasized as group characteristics in the manuscripts. Group demographics and descriptive data of each ACLR group participant are provided in Tables 4-5.

4.3 Results

4.3.1 Results Specific Aim 1

The purpose of this Aim was to determine the effect of ACLR in an adolescent female athlete population on trunk and lower extremity biomechanics during a double-leg jump landing. Kinematics at the time point of initial contact and overall joint displacements
(DSP) during the landing phase were compared between limbs in the ACLR group and between the matched limbs of the ACLR group participants and the healthy CON group participants. Kinetic variables were compared as peak values during the Landing phase and Pushoff phase. Descriptive statistics for all biomechanical variables analyzed for Specific Aim 1 are presented in Tables 6-10.

**Initial Contact:** The ACLR Injured limb demonstrated greater knee flexion at the time point of initial contact in comparison to the Uninjured limb ($p = 0.008$) and the CON Index limb ($p = 0.005$). The contralateral Uninjured limb demonstrated greater hip abduction at the time point of initial contact in comparison to the matched Non-Index limb ($p = 0.047$). No other statistically significant differences were observed in hip and knee initial contact kinematics ($p > 0.05$). Additionally, no statistically significant differences in sagittal or frontal plane trunk kinematics at initial contact were observed between groups ($p > 0.05$).

**Joint Displacement (DSP):** The ACLR Injured limb demonstrated significantly less hip flexion DSP ($p = 0.002$) and knee flexion DSP ($p < 0.001$) during the landing phase compared to the contralateral Uninjured limb, indicating asymmetrical movement during landing. The ACLR Injured limb also demonstrated greater hip adduction DSP during the landing phase in comparison to the contralateral Uninjured limb ($p = 0.034$). There were no significant differences between the ACLR group’s Uninjured limb and the matched Non-Index limb ($p > 0.05$). No other statistically significant differences in joint DSP kinematics were observed ($p > 0.05$).

**Landing Phase:** The ACLR Injured limb demonstrated significantly less internal peak knee extension moment ($p = 0.002$), peak knee varus moment ($p = 0.040$), and peak vertical ground reaction force ($p < 0.001$) during the landing phase in comparison to the contralateral
Uninjured limb. The ACLR Injured limb also demonstrated significantly less peak anterior tibial shear force during landing in comparison to the Uninjured limb \((p < 0.001)\) and CON Index limb \((p = 0.010)\). The ACLR Uninjured limb also demonstrated significantly greater knee valgus moment \((p = 0.048)\) and vertical ground reaction force \((p = 0.013)\) in comparison to the matched Non-Index limb. Therefore, during the double-leg jump landing, the ACLR Uninjured limb was loaded to a greater extent during the landing phase in comparison to the previously Injured limb and the matched healthy CON limb.

*Pushoff Phase*: Comparison of select peak kinetic variables during the Pushoff Phase of the jump landing are not included in the accompanying manuscripts, and will be presented in detail here. During pushoff, we observed significantly less internal peak knee varus moment on the Injured limb compared to the contralateral Uninjured limb \((p = 0.002)\). The ACLR Injured limb displayed lesser peak vertical ground reaction force compared to the Uninjured \((p < 0.001)\) and CON Index limb \((p = 0.017)\) during the pushoff phase of the jump landing. We also observed less peak anterior tibial shear force on the ACLR Injured limb in comparison to the Uninjured \((p < 0.001)\) and CON Index limb \((p < 0.001)\). There were no significant differences between the ACLR group’s Uninjured limb and the matched Non-Index limb \((p > 0.05)\). During the pushoff phase of the double-leg jump landing, the ACLR group’s contralateral Uninjured limb was loaded to a greater extent than the ACLR Injured limb, but not more so than the matched CON Non-Index limb. We did not observe statistically significant differences in internal peak knee extension moments or peak knee valgus moments within the ACLR group, between the ACLR Injured and CON Index limbs, or between the ACLR Uninjured and CON Non-Index limbs \((p > 0.05)\).
4.3.2 Results Specific Aim 2

The purpose of this Aim was to determine the effect of ACLR in an adolescent female athlete population on trunk and lower extremity biomechanics during a single-leg double hop task. Kinematics at the time point of initial contact and overall joint displacements (DSP) during the landing phase were compared within the ACLR group and between the ACLR Injured limb and matched CON Index limb. Kinetic variables were compared as peak values during the Landing phase and Pushoff phase. Descriptive statistics for all biomechanical variables analyzed for Specific Aim 2 are presented in Tables 11-14.

Initial Contact: The ACLR Injured limb demonstrated significantly less knee flexion at initial contact during the single-leg double hop in comparison to the contralateral Uninjured limb \((p < 0.001)\), indicating within group differences in knee sagittal plane strategy. No other statistically significant differences were observed at initial contact for trunk, hip, or knee kinematics within the ACLR group, between the ACLR Injured and CON Index limb, or between the ACLR groups’ Uninjured and CON Non-Index limbs \((p > 0.05)\).

Joint Displacement (DSP): The ACLR Injured limb demonstrated significantly less knee flexion DSP during the landing phase in comparison to the contralateral Uninjured limb \((p = 0.007)\) when performing the single-leg double hop. The ACLR Injured limb also demonstrated greater hip frontal plane DSP and knee transverse plane DSP in comparison to the Uninjured and CON Index limbs. Specifically, the ACLR Injured limb displayed greater hip adduction DSP compared to the Uninjured \((p < 0.001)\) and CON Index limb \((p = 0.003)\) as well as greater knee internal rotation DSP compared to the Uninjured \((p < 0.001)\) and CON Index limb \((p = 0.011)\). These differences indicate statistically significant differences in frontal and transverse plane DSP at the hip and knee, respectively, compared to their own...
contralateral limb and the healthy matched control limb. However, no differences were observed between the ACLR group’s contralateral Uninjured limb and the matched CON Non-Index limb ($p > 0.05$).

*Landing Phase:* The ACLR Injured limb demonstrated significantly less internal peak knee extension moments during the landing phase of the single-leg double hop compared to the contralateral Uninjured limb ($p < 0.001$). We also observed between group differences, such that the ACLR Injured limb demonstrated significantly larger peak knee valgus moment compared to the CON Index limb ($p = 0.017$). Finally, we observed lesser peak anterior tibial shear force on the ACLR Injured limb compared to both the Uninjured limb ($p = 0.001$) and CON Index limb ($p = 0.043$) during the landing phase of the single-leg double hop. The ACLR group’s contralateral Uninjured limb demonstrated greater knee extension moment ($p < 0.001$) and greater vertical ground reaction force ($p = 0.004$) in comparison to the matched CON Non-Index limb.

*Pushoff Phase:* Comparison of select peak kinetic variables during the Pushoff Phase of the single-leg double hop are not included in the accompanying manuscripts, and will be presented in detail here. We observed differences within the ACLR group, such that the ACLR Injured limb had significantly less internal peak knee extension moment ($p < 0.001$) and peak anterior tibial shear force ($p = 0.005$) during the Pushoff phase. The ACLR Injured limb displayed greater internal peak knee valgus moment in comparison to the CON Index limb ($p = 0.049$). Finally, the ACLR group’s contralateral Uninjured limb also had significantly greater knee extension moment compared to the matched CON Non-Index limb ($p = 0.012$). Therefore, during a single-leg double hop the ACLR group’s contralateral Uninjured limb had greater sagittal plane force production in comparison to their previously
Injured limb and the matched healthy control limb. The ACLR Injured limb also had greater frontal plane knee moment compared to the matched healthy control limb. No statistically significant differences were observed in peak vertical ground reaction force within or between groups during the Pushoff phase \((p > 0.05)\).

A summary table of statistically significant differences during the double leg jump landing and single leg double hop is presented in Table 15. This table also incorporates dependent variables that were added to the associated manuscripts, but were not part of the primary specific aims. Namely, hip extension moment and ankle plantarflexion moment are presented for both the landing and pushoff phases. It is interesting because the biomechanical profiles of the ACLR group participants were slightly different when performing a double leg versus a single leg task. It appears that the ability to utilize the contralateral Uninjured limb to absorb landing forces encourages the ACLR group participant to rely more heavily on the contralateral limb. When performing a single leg landing task the same strategy is not possible. The ACLR Injured and Uninjured limbs perform the single leg double hop with distinct biomechanical differences, but with similar performance outcomes.

4.3.3 Results Specific Aim 3

The purpose of this Aim was to determine the acute effects of two different simple verbal instructions on select kinematic and kinetic variables during the double-leg jump landing task. The dependent variables were (1) knee flexion DSP, (2) peak knee extension moment, (3) peak knee valgus moment, (4) peak anterior tibial shear force (ATSF), and (5) peak vertical ground reaction force (VGRF). Change scores were calculated by subtracting the mean value at baseline from the mean value within each verbal instruction condition. Change scores were compared to evaluate the magnitude of change influenced by verbal
instruction conditions within the ACLR group and between the ACLR Injured limb and CON Index limb. Manuscript 3 focuses on the change scores of peak VGRF, however all variables will be presented here. Descriptive statistics for all biomechanical variables analyzed for Specific Aim 3 are presented in Tables 16-18.

**Soft Landing Instructions:** There was no statistically significant difference in the amount of change in knee flexion DSP, knee extension moment, knee valgus moment, or ATSF following the *soft landing instructions* between limbs in the ACLR group, between the ACLR Injured limb and the CON Index limb, or between the ACLR contralateral Uninjured limb and the CON Non-Index limb ($p > 0.05$). Generally, all limbs demonstrated a similar increase in knee flexion DSP following the soft landing instructions. No change occurred in knee extension moment, knee valgus moment, or ATSF following the *soft landing instructions* as the 95% confidence interval of the change scores crossed zero on all limbs.

There was no statistically significant difference between the ACLR Injured and CON Index limbs in the amount of change in VGRF ($p=0.554$). Both the ACLR Injured and CON Index limb experienced similar reductions in VGRF. However, in the ACLR group’s contralateral Uninjured limb the magnitude of change in VGRF was greater than that of the ACLR Injured limb ($p = 0.033$) and the CON Non-Index limb ($p = 0.043$). Thus, the magnitude of change with *soft landing instructions* appears to be greater on the contralateral Uninjured limb as it experienced a greater overall reduction in VGRF than the Injured limb and matched CON limb.

**Equal Landing Instructions:** There was no statistically significant difference in the amount of change in knee flexion DSP, knee extension moment or knee valgus moment following the *equal landing instructions* within the ACLR group, between the ACLR Injured
limb and CON Index limb, or between the ACLR group’s contralateral Uninjured limb and the CON Non-Index limb ($p > 0.05$). Generally, all limbs demonstrated a slight increase in knee flexion DSP, but remained unchanged on knee extension moment and knee valgus moment as once again the 95% confidence intervals of the change scores crossed zero on all limbs.

The *equal landing instructions* did not change VGRF or ATSF in the ACLR Injured limb as the 95% confidence interval of the change score crosses zero. Similarly, there was no change in VGRF or ATSF in the CON Index limb or CON Non-Index limb. However, there was a statistically significant difference in the magnitude of change in the ACLR contralateral Uninjured limb compared to the ACLR Injured limb for VGRF ($p = 0.041$) and ATSF ($p = 0.033$). The ACLR group’s contralateral Uninjured limb experienced a reduction in VGRF and a reduction in ATSF following the *equal landing instructions*. Thus, the magnitude of change with *equal landing instructions* appears to be asymmetrical in the ACLR group participants as the contralateral Uninjured limb experienced a greater overall reduction in VGRF and ATSF than the Injured limb. However, this asymmetrical response to the verbal instructions did contribute to an improvement in loading symmetry.
CHAPTER V
DISCUSSION OF RESULTS

5.1 Introduction

Results not discussed in the manuscripts will be discussed in this chapter. Specifically, this includes Peak Kinetics during the Pushoff Phase of the double-leg jump landing and single-leg double hop for Specific Aims 1 and 2, respectively. Dependent variables not included in the manuscript for Specific Aim 3 will be discussed, including knee flexion displacement, peak knee extension moment, peak knee valgus moment, and peak anterior tibial shear force. Pushoff phase kinetics for the double-leg and single-leg tasks will be discussed together followed by the discussion of the verbal instructions intervention.

5.2 Pushoff Phase Kinetics

Muscle strengthening is often an integral component of rehabilitation both prior to and following ACLR. Decisions regarding exercise progression and return to sport are largely based on strength measurements in conjunction with functional performance measures. Appropriate strength and function of the quadriceps and hamstring muscles are crucial to performing sport specific movements, and may be affected by ACLR. Many athletes return to sport with lingering strength deficits and neuromuscular deficiencies, likely contributing to inefficient movement and an inability to absorb and produce forces necessary for sport. Muscle power, or the ability to produce a high force over a short period
of time has been touted to be more indicative of functional performance\textsuperscript{73, 270, 316}. The time required to develop muscular strength in athletic activities is considerably less (0-200 ms) than the time required to achieve maximal contraction strength ($\geq 300$ ms).\textsuperscript{272} Therefore, the ability to generate strength quickly is relevant to both performance and protection against injury.\textsuperscript{273, 274} The tasks selected for biomechanical analysis in this research study specifically focused on double-leg and single-leg land and go maneuvers, such that the participants had to quickly decelerate and absorb landing forces while immediately producing force to pushoff into a maximum vertical jump (jump landing) or a maximum forward hop (single-leg double hop).

During the pushoff phase of the \textit{double-leg jump landing}, asymmetrical force production was present in the ACLR group participants. The ACLR Injured limb displayed less peak VGRF and less peak ATSF in comparison to the Uninjured limb, but also in comparison to the healthy matched CON limb. There were no differences between the ACLR group’s contralateral Uninjured limb in comparison to its’ healthy matched CON limb. This result highlights the asymmetry in force production in ACLR group participants even after full return to their primary sport. In combination, minimal limb loading on the ACLR Injured limb during the pushoff phase points to altered neuromuscular ability due to quadriceps dysfunction. Our results are similar to previous research in adult female recreational athletes who had undergone unilateral ACLR, $27.4 \pm 13.8$ months prior.\textsuperscript{64} During the takeoff phase (pushoff) of a double-leg drop vertical jump females demonstrated significantly lower VGRF on the previously Injured limb in comparison to the Uninjured as well as both limbs of the healthy control participants.\textsuperscript{64} Double-leg tasks provide the opportunity for an individual with a history of ACLR to load the previously Uninjured limb to a greater extent to compensate
for the inability of the Injured limb to produce enough force. This force development pattern on the Uninjured limb may be placing these individuals at greater risk of suffering a secondary ACL injury, particularly to the contralateral limb.

During the pushoff phase of the *single-leg double hop* task, ACLR group participants demonstrated a number of differences within and between groups. Interestingly, during the pushoff phase there were no differences in peak VGRF within the ACLR group or in comparison to the healthy CON group. However, the ACLR group’s contralateral Uninjured limb generated significantly greater internal knee extension moment when performing this task in comparison to the Injured limb and the matched CON limb. Orishimo et al.\(^7^3\) identified similar results in a small sample of adults who had undergone ACLR, 4-12 months prior to testing, with no control group comparison. The Involved limb (Injured) in their study had reduced peak VGRF and peak knee extension moments that were 40% lower in comparison to the Noninvolved (Uninjured) limb.\(^7^3\) When performing a single-leg hopping task, individuals with a history of ACLR demonstrate less internal knee extension moment in comparison to when they perform the same task on their Uninjured limb. Previous research has identified a shifting of internal joint moment production among the hip, knee, and ankle in those with a history of ACLR. Less internal knee extension moment has been accompanied by greater hip extensor and ankle plantar flexor moment during the landing phase\(^6^8, ^{3^3}\) and pushoff phase.\(^7^3\) This likely helps to explain our results as the ACLR group likely utilized more of a hip and ankle strategy to perform the task and achieve success.

We also observed greater peak knee valgus moment on the Injured limb compared to the CON Index limb during the pushoff phase. In combination, diminished ability to produce rapid force and greater frontal plane knee loading on the previously Injured limb place this
ACLR group at high risk of suffering a subsequent injury. These female adolescents had already returned to full sport participation and were competing in activities requiring quick acceleration movements after changes of direction. Results from this study provide further evidence that performance outcomes alone, such as distance hopped, are not adequate in determining an athlete’s readiness to compete. Quality of movement should be considered.

5.3 Verbal Instructions Intervention

The primary finding of the verbal instructions intervention was that the ACLR Injured limb changed in a similar manner as healthy CON participants following verbal instructions, but the magnitude of change in landing forces was asymmetrical within the ACLR group. The ACLR group’s contralateral Uninjured limb changed following both sets of verbal instructions with a greater reduction in VGRF compared to the Injured limb and matched CON limb following the soft landing instructions, and a greater reduction in ATSF compared to the Injured limb following the equal landing instructions. No statistically significant differences in magnitude of change were apparent for other variables investigated: knee flexion DSP, knee extension moment, and knee valgus moment. A full discussion of the change in VGRF is included in Manuscript 3, therefore will not be discussed here. Rather this section will focus on the discussion of the difference in magnitude of change of ATSF and the lack of difference in the other variables.

All limbs responded similarly to both sets of verbal instructions with an increase in knee flexion DSP. This result was expected given the goal of the soft landing instructions was to improve energy absorption during landing by increasing sagittal plane flexion. However, the magnitude of change was not different within the ACLR group or between the
ACLr group and the healthy matched CON group. Previous research utilizing similar verbal instructions has also observed an increase in knee flexion during a double-leg drop vertical jump and countermovement jump. Mizner et al. also found a decrease in external knee abduction moment in an adult female athlete population, while we did not observe a change in frontal plane knee loading. The verbal instructions utilized in the previous authors study were more in depth, instructing the participant to “increase bending in your knees, land on your toes, keep your chest over your knees, keep your knees over your toes, and avoid knee valgus.” Our verbal instructions were focused on minimizing loading in the sagittal plane and did not include prompts to alter frontal plane loading, therefore our finding was not surprising.

The soft landing instructions did not prompt a decrease in ATSF in the ACLR group or the CON group. Similarly, the equal landing instructions did not prompt a decrease in ATSF in the ACLR Injured limb or the CON group. However, the ACLR Uninjured limb did experience a decrease in ATSF following the equal landing instructions. Inspection of the normalized mean values of ATSF at baseline reveals a clear separation of confidence intervals between the ACLR Injured limb and Uninjured limb. The Uninjured limb had larger ATSF at baseline, therefore in an attempt to land with equal weight under each foot the Uninjured limb decreased the magnitude of ATSF in attempt to become more symmetrical. While this may have improved symmetry slightly, the ATSF mean values following the equal landing instructions were still distinctly different within the ACLR group, depicted by separation of the confidence intervals. It is not surprising that the ACLR Injured limb did not change following either set of instructions as the ATSF loading was already minimized on that limb. Previous research investigated the use of video feedback with or without additional
strength-training over a 9-week time period on landing biomechanics in healthy female
recreational athletes. These authors identified a decrease in peak ATSF in the participants
who received both strength training and video feedback. While difficult to make a
comparison between studies due to the use of a healthy population and a very different
intervention, it speaks to the ability to alter ATSF by improving landing technique. ATSF is a
direct loading mechanism for the ACL and may contribute to ACL injury in females who
also demonstrate greater VGRF during landing. However, it appears that individuals with a
history of ACLR minimize loading on the previously Injured limb already and do not need to
reduce loading on this side. The emphasis should be on protecting and improving the loading
on the contralateral Uninjured limb, especially with contralateral secondary ACL injury rates
being so prevalent following return to sport. The asymmetrical performance
characteristics within the ACLR group, even with verbal instructions, is of concern for future
injury.
**FIGURES**

**ENROLLMENT**

1. Assess Eligibility and Schedule Testing Session
2. E-Mail Forms to Subjects (Parents / Guardians)
3. Report for Testing Session Review Completed Paperwork

**TESTING PROTOCOL**

- **Anthropometric Assessments**
  - Body Mass
  - Height
  - Limb Length
  - Warm-Up

- **Motion Analysis Assessments**
  - Jump Landing
  - SL Hop$^*$

- **Verbal Instructions Intervention**
  - 'Soft'
  - 'Symmetric'
  - 1) Condition 1$^*$
  - 2) OHS, SLS
  - 3) Condition 2$^*$

* Counterbalanced

**Figure 1:** Depiction of Data Collection Procedures
Figure 2: Depiction of Verbal Instructions Intervention

ACLR & Control (Counterbalanced)

Condition 1
(Soft or Symmetric)

3 Jump Landing Trials
*Instructions prior to each trial

Active Washout
• Overhead Squat
• Single-Leg Squat

Condition 2
(Soft or Symmetric)

3 Jump Landing Trials
*Instructions prior to each trial
Figure 3. Depiction of the Double Leg Jump Landing Task
Figure 4. Depiction of the Single-Leg Double Hop Task
Table 1: Power Analyses for all Dependent Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Grand Mean</th>
<th>Standard Deviation</th>
<th>Proposed n (per group)</th>
<th>% Change</th>
<th>Numeric Change</th>
<th>Power</th>
<th>% Change</th>
<th>Numeric Change</th>
<th>Power</th>
<th>% Change</th>
<th>Numeric Change</th>
<th>Power</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk Flexion IC</td>
<td>24.90</td>
<td>13.32</td>
<td>25</td>
<td>20</td>
<td>4.98</td>
<td>0.47</td>
<td>15</td>
<td>3.74</td>
<td>0.29</td>
<td>10</td>
<td>2.49</td>
<td>0.15</td>
<td>Begalle 2012, unpublished</td>
</tr>
<tr>
<td>Trunk Lateral Flexion IC</td>
<td>-1.90</td>
<td>1.78</td>
<td>25</td>
<td>20</td>
<td>-0.38</td>
<td>0.19</td>
<td>15</td>
<td>-0.29</td>
<td>0.13</td>
<td>10</td>
<td>-0.19</td>
<td>0.08</td>
<td>Begalle 2012 unpublished</td>
</tr>
<tr>
<td>Hip Flexion IC</td>
<td>23.60</td>
<td>6.58</td>
<td>25</td>
<td>20</td>
<td>4.72</td>
<td>0.95</td>
<td>15</td>
<td>3.54</td>
<td>0.77</td>
<td>10</td>
<td>2.36</td>
<td>0.43</td>
<td>Vairo 2008</td>
</tr>
<tr>
<td>Hip Abduction/Adduction IC</td>
<td>-6.90</td>
<td>5.90</td>
<td>25</td>
<td>20</td>
<td>-1.38</td>
<td>0.21</td>
<td>15</td>
<td>-1.04</td>
<td>0.14</td>
<td>10</td>
<td>-0.69</td>
<td>0.08</td>
<td>Brown 2009</td>
</tr>
<tr>
<td>Hip Internal Rotation IC</td>
<td>-5.80</td>
<td>4.45</td>
<td>25</td>
<td>20</td>
<td>-1.16</td>
<td>0.26</td>
<td>15</td>
<td>-0.87</td>
<td>0.16</td>
<td>10</td>
<td>-0.58</td>
<td>0.10</td>
<td>Delahunt 2012</td>
</tr>
<tr>
<td>Knee Flexion IC</td>
<td>16.10</td>
<td>3.80</td>
<td>25</td>
<td>20</td>
<td>3.22</td>
<td>0.99</td>
<td>15</td>
<td>2.42</td>
<td>0.89</td>
<td>10</td>
<td>1.61</td>
<td>0.56</td>
<td>Gokeler 2010</td>
</tr>
<tr>
<td>Knee Abduction/Adduction IC</td>
<td>8.90</td>
<td>4.17</td>
<td>25</td>
<td>20</td>
<td>1.78</td>
<td>0.57</td>
<td>15</td>
<td>1.34</td>
<td>0.36</td>
<td>10</td>
<td>0.89</td>
<td>0.19</td>
<td>Delahunt 2012, Brown 2009</td>
</tr>
<tr>
<td>Knee (tibial) rotation IC</td>
<td>6.02</td>
<td>4.59</td>
<td>25</td>
<td>20</td>
<td>1.20</td>
<td>0.26</td>
<td>15</td>
<td>0.90</td>
<td>0.16</td>
<td>10</td>
<td>0.60</td>
<td>0.10</td>
<td>Deneweth 2010</td>
</tr>
<tr>
<td>Trunk Flexion_DSP</td>
<td>35.00</td>
<td>11.00</td>
<td>25</td>
<td>20</td>
<td>7.00</td>
<td>0.89</td>
<td>15</td>
<td>5.25</td>
<td>0.67</td>
<td>10</td>
<td>3.50</td>
<td>0.36</td>
<td>Blackburn 2008, Parsons 2012</td>
</tr>
<tr>
<td>Trunk Lateral Flexion_DSP</td>
<td>9.23</td>
<td>7.15</td>
<td>25</td>
<td>20</td>
<td>1.85</td>
<td>0.25</td>
<td>15</td>
<td>1.38</td>
<td>0.18</td>
<td>10</td>
<td>0.92</td>
<td>0.09</td>
<td>Begalle 2012, unpublished</td>
</tr>
<tr>
<td>Hip Flexion_DSP</td>
<td>48.00</td>
<td>11.30</td>
<td>25</td>
<td>20</td>
<td>9.60</td>
<td>0.99</td>
<td>15</td>
<td>7.20</td>
<td>0.89</td>
<td>10</td>
<td>4.80</td>
<td>0.57</td>
<td>Yamazaki 2010</td>
</tr>
<tr>
<td>Hip Adduction_DSP</td>
<td>-10.30</td>
<td>0.85</td>
<td>25</td>
<td>20</td>
<td>-2.06</td>
<td>0.99</td>
<td>15</td>
<td>-1.55</td>
<td>0.99</td>
<td>10</td>
<td>-1.03</td>
<td>0.99</td>
<td>Webster 2012</td>
</tr>
<tr>
<td>Hip IR_DSP</td>
<td>9.10</td>
<td>0.85</td>
<td>25</td>
<td>20</td>
<td>1.82</td>
<td>0.99</td>
<td>15</td>
<td>1.37</td>
<td>0.99</td>
<td>10</td>
<td>0.91</td>
<td>0.99</td>
<td>Webster 2012</td>
</tr>
<tr>
<td>Knee Flexion_DSP</td>
<td>66.20</td>
<td>9.90</td>
<td>25</td>
<td>20</td>
<td>13.24</td>
<td>0.99</td>
<td>15</td>
<td>9.93</td>
<td>0.99</td>
<td>10</td>
<td>6.62</td>
<td>0.99</td>
<td>Yamazaki 2010</td>
</tr>
<tr>
<td>Knee Abduction/Adduction_DSP</td>
<td>3.90</td>
<td>0.57</td>
<td>25</td>
<td>20</td>
<td>0.78</td>
<td>0.99</td>
<td>15</td>
<td>0.59</td>
<td>0.99</td>
<td>10</td>
<td>0.39</td>
<td>0.93</td>
<td>Webster 2012</td>
</tr>
<tr>
<td>Knee (tibial) rotation_DSP</td>
<td>19.80</td>
<td>4.80</td>
<td>25</td>
<td>20</td>
<td>3.96</td>
<td>0.98</td>
<td>15</td>
<td>2.97</td>
<td>0.87</td>
<td>10</td>
<td>1.98</td>
<td>0.54</td>
<td>McLean 2005</td>
</tr>
<tr>
<td>Peak Vertical Ground Reaction Force</td>
<td>5.11</td>
<td>1.07</td>
<td>25</td>
<td>20</td>
<td>1.02</td>
<td>0.99</td>
<td>15</td>
<td>0.77</td>
<td>0.95</td>
<td>10</td>
<td>0.51</td>
<td>0.66</td>
<td>Vairo 2008</td>
</tr>
<tr>
<td>Peak Anterior Tibial Shear Force</td>
<td>12.00</td>
<td>3.67</td>
<td>25</td>
<td>20</td>
<td>2.40</td>
<td>0.90</td>
<td>15</td>
<td>1.80</td>
<td>0.69</td>
<td>10</td>
<td>1.20</td>
<td>0.37</td>
<td>Deneweth 2010</td>
</tr>
<tr>
<td>Peak Knee Extension Moment</td>
<td>1.91</td>
<td>0.45</td>
<td>25</td>
<td>20</td>
<td>0.38</td>
<td>0.99</td>
<td>15</td>
<td>0.29</td>
<td>0.90</td>
<td>10</td>
<td>0.19</td>
<td>0.56</td>
<td>Ernst 2000</td>
</tr>
<tr>
<td>Peak Knee Valgus Moment</td>
<td>0.44</td>
<td>0.15</td>
<td>25</td>
<td>20</td>
<td>0.09</td>
<td>0.85</td>
<td>15</td>
<td>0.07</td>
<td>0.65</td>
<td>10</td>
<td>0.04</td>
<td>0.27</td>
<td>Brown 2009</td>
</tr>
</tbody>
</table>
## Table 2: Power Analyses for Verbal Instructions Intervention

<table>
<thead>
<tr>
<th>Verbal Instructions Intervention</th>
<th>Grand Mean</th>
<th>Standard Deviation</th>
<th>Proposed n (per group)</th>
<th>% Change</th>
<th>Numeric Change</th>
<th>Power</th>
<th>% Change</th>
<th>Numeric Change</th>
<th>Power</th>
<th>% Change</th>
<th>Numeric Change</th>
<th>Power</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak VGRF_Landing</td>
<td>1104.90</td>
<td>396.20</td>
<td>25</td>
<td>20</td>
<td>220.98</td>
<td>0.80</td>
<td>15</td>
<td>165.74</td>
<td>0.74</td>
<td>10</td>
<td>110.49</td>
<td>0.45</td>
<td>Miner 2011</td>
</tr>
<tr>
<td>Peak ATSF_Landing</td>
<td>0.44</td>
<td>0.18</td>
<td>25</td>
<td>20</td>
<td>0.09</td>
<td>0.71</td>
<td>15</td>
<td>0.07</td>
<td>0.69</td>
<td>10</td>
<td>0.04</td>
<td>0.33</td>
<td>Herman 2009</td>
</tr>
<tr>
<td>Peak KEM_Landing</td>
<td>1.85</td>
<td>0.29</td>
<td>25</td>
<td>20</td>
<td>0.37</td>
<td>0.99</td>
<td>15</td>
<td>0.28</td>
<td>0.99</td>
<td>10</td>
<td>0.19</td>
<td>0.97</td>
<td>Mizner 2008</td>
</tr>
<tr>
<td>Knee Flexion DSP_Landing</td>
<td>42.30</td>
<td>5.10</td>
<td>25</td>
<td>20</td>
<td>8.46</td>
<td>0.99</td>
<td>15</td>
<td>6.35</td>
<td>0.99</td>
<td>10</td>
<td>4.23</td>
<td>0.99</td>
<td>Gokeler 2010</td>
</tr>
<tr>
<td>Frequency (n)</td>
<td>ACLR (n=22)</td>
<td>Control (n=25)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
<td>----------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Injured</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>Left</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>Left</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4. Descriptive Statistics for Participant Demographics

<table>
<thead>
<tr>
<th></th>
<th>ACLR (n=22) Mean ± SD</th>
<th>Control (n=25) Mean ± SD</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>16.68 ± 1.55</td>
<td>16.91 ± 1.23</td>
<td>0.58</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>166.80 ± 6.04</td>
<td>170.22 ± 7.40</td>
<td>0.09</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>61.08 ± 8.78</td>
<td>63.32 ± 7.59</td>
<td>0.35</td>
</tr>
<tr>
<td>Predicted Height (%)</td>
<td>99.80 ± 1.09</td>
<td>99.68 ± 1.10</td>
<td>0.73</td>
</tr>
</tbody>
</table>
Table 5. Injury History and Activity Level for each ACLR Group Participant (N=22)

<table>
<thead>
<tr>
<th>Injured Limb</th>
<th>Injured Dominant Kicking Limb</th>
<th>Injured Dominant Balance Limb</th>
<th>Primary Sport</th>
<th>MOI</th>
<th>Graft</th>
<th>Meniscus Injury</th>
<th>Marx Activity Rating Score Pre</th>
<th>Marx Activity Rating Score Pre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Softball</td>
<td>NC</td>
<td>Hamstrings</td>
<td>Yes</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>Yes</td>
<td>Volleyball</td>
<td>IC</td>
<td>Hamstrings</td>
<td>No</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>Yes</td>
<td>Soccer</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Lacrosse</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>No</td>
<td>16</td>
<td>13</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Soccer</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>No</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>Yes</td>
<td>Soccer</td>
<td>NC</td>
<td>Hamstrings</td>
<td>Yes</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>Yes</td>
<td>Lacrosse</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Soccer</td>
<td>IC</td>
<td>Patellar Tendon Allograft</td>
<td>Yes</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Soccer</td>
<td>IC</td>
<td>Hamstrings</td>
<td>No</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>Yes</td>
<td>Lacrosse</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>No</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>Left</td>
<td>Yes</td>
<td>Yes</td>
<td>Basketball</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>Yes</td>
<td>Soccer</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>No</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Soccer</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Volleyball</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>7</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>Yes</td>
<td>Basketball</td>
<td>NC</td>
<td>Hamstrings</td>
<td>Yes</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Basketball</td>
<td>IC</td>
<td>Hamstrings</td>
<td>Yes</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Soccer</td>
<td>IC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>No</td>
<td>Basketball</td>
<td>NC</td>
<td>Hamstrings</td>
<td>No</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Left</td>
<td>Yes</td>
<td>No</td>
<td>Soccer</td>
<td>IC</td>
<td>Hamstrings</td>
<td>No</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Volleyball</td>
<td>NC</td>
<td>Hamstrings</td>
<td>Yes</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Left</td>
<td>Yes</td>
<td>Yes</td>
<td>Gymnastics</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>No</td>
<td>Soccer</td>
<td>IC</td>
<td>Hamstrings</td>
<td>No</td>
<td>16</td>
<td>8</td>
</tr>
</tbody>
</table>

NC = Noncontact Mechanism of ACL Injury / IC = Indirect Contact Mechanism of ACL Injury
Dominant Kicking Limb = Preferred Limb to Kick a Soccer Ball for Maximum Distance
Dominant Balance Limb = Preferred Limb to Land from a Single-Leg Jump
Table 6. Trunk Kinematics during the Landing Phase of the Jump Landing (Means, SE, 95% CI)

<table>
<thead>
<tr>
<th>Variables</th>
<th>ACLR (n=22)</th>
<th>Control (n=25)</th>
<th>Group P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SE</td>
<td>Mean ± SE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>95% CI</td>
<td>95% CI</td>
<td></td>
</tr>
<tr>
<td><strong>IC Kinematics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk Sagittal IC</td>
<td>27.70 ± 1.75</td>
<td>24.69 ± 1.41</td>
<td>0.181</td>
</tr>
<tr>
<td>(24.27, 31.13)</td>
<td>(21.93, 27.45)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk Frontal IC</td>
<td>0.92 ± 0.52</td>
<td>1.31 ± 0.61</td>
<td>0.623</td>
</tr>
<tr>
<td>(-0.10, 1.04)</td>
<td>(0.11, 2.51)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Joint Displacements</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk Flexion DSP</td>
<td>17.19 ± 1.70</td>
<td>15.32 ± 1.10</td>
<td>0.357</td>
</tr>
<tr>
<td>(13.86, 20.52)</td>
<td>(13.17, 14.48)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk Side Bend Left DSP</td>
<td>-1.83 ± 0.35</td>
<td>-1.55 ± 0.27</td>
<td>0.528</td>
</tr>
<tr>
<td>(-2.51, -1.15)</td>
<td>(-2.09, -1.02)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk Side Bend Right DSP</td>
<td>2.17 ± 0.32</td>
<td>2.06 ± 0.30</td>
<td>0.810</td>
</tr>
<tr>
<td>(1.53, 2.80)</td>
<td>(1.47, 2.65)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 7. Initial Contact Kinematics during the Landing Phase of the Jump Landing (Means, SE, 95% CI)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean ± SE</th>
<th>CI</th>
<th>Mean ± SE</th>
<th>CI</th>
<th>Inj * Uninj P-Value</th>
<th>Inj * Index P-Value</th>
<th>Uninj * Non P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip Sagittal Plane IC</td>
<td>-25.47 ± 1.71</td>
<td>(-29.83, -22.11)</td>
<td>-24.31 ± 1.59</td>
<td>(-27.43, -21.20)</td>
<td>0.168</td>
<td>0.067</td>
<td>0.141</td>
</tr>
<tr>
<td>Control</td>
<td>-21.76 ± 1.08</td>
<td>(-23.88, -19.63)</td>
<td>-21.62 ± 0.90</td>
<td>(-23.39, -19.84)</td>
<td>0.147</td>
<td>0.210</td>
<td>0.047</td>
</tr>
<tr>
<td>Hip Frontal Plane IC</td>
<td>-7.56 ± 0.73</td>
<td>(-8.98, -6.13)</td>
<td>-9.12 ± 0.55</td>
<td>(-10.21, -8.04)</td>
<td>0.047</td>
<td>0.273</td>
<td>0.458</td>
</tr>
<tr>
<td>Control</td>
<td>-8.84 ± 0.72</td>
<td>(-10.25, -7.43)</td>
<td>-7.32** ± 0.72</td>
<td>(-8.74, -5.89)</td>
<td>0.416</td>
<td>0.335</td>
<td>0.696</td>
</tr>
<tr>
<td>Hip Transverse Plane IC</td>
<td>4.83 ± 1.51</td>
<td>(1.86, 7.80)</td>
<td>4.18 ± 1.75</td>
<td>(0.76, 7.60)</td>
<td>0.147</td>
<td>0.210</td>
<td>0.047</td>
</tr>
<tr>
<td>Control</td>
<td>3.17 ± 0.84</td>
<td>(1.52, 4.81)</td>
<td>3.42 ± 0.84</td>
<td>(1.77, 5.07)</td>
<td>0.416</td>
<td>0.335</td>
<td>0.696</td>
</tr>
<tr>
<td>Knee Sagittal Plane IC</td>
<td>26.00 ± 0.93</td>
<td>(24.19, 27.82)</td>
<td>23.53* ± 1.11</td>
<td>(21.35, 25.72)</td>
<td>0.008</td>
<td>0.005</td>
<td>0.177</td>
</tr>
<tr>
<td>Control</td>
<td>21.87* ± 1.15</td>
<td>(19.61, 24.13)</td>
<td>21.71 ± 0.76</td>
<td>(20.21, 23.20)</td>
<td>0.843</td>
<td>0.273</td>
<td>0.458</td>
</tr>
<tr>
<td>Knee Frontal Plane IC</td>
<td>4.62 ± 0.88</td>
<td>(2.91, 6.35)</td>
<td>4.41 ± 0.72</td>
<td>(2.30, 5.82)</td>
<td>0.416</td>
<td>0.335</td>
<td>0.696</td>
</tr>
<tr>
<td>Control</td>
<td>3.27 ± 0.87</td>
<td>(1.56, 4.98)</td>
<td>3.57 ± 0.88</td>
<td>(1.84, 5.29)</td>
<td>0.416</td>
<td>0.335</td>
<td>0.696</td>
</tr>
<tr>
<td>Knee Transverse Plane IC</td>
<td>-15.16 ± 2.21</td>
<td>(-19.49, -10.83)</td>
<td>-16.11 ± 1.95</td>
<td>(-19.94, -12.28)</td>
<td>0.685</td>
<td>0.888</td>
<td>0.464</td>
</tr>
<tr>
<td>Control</td>
<td>-14.77 ± 1.69</td>
<td>(-18.08, -11.46)</td>
<td>-14.28 ± 1.55</td>
<td>(-17.32, -11.24)</td>
<td>0.685</td>
<td>0.888</td>
<td>0.464</td>
</tr>
</tbody>
</table>

* Indicates Significant Difference in Comparison to the ACLR Injured limb (p < 0.05)
** Indicates Significant Difference in Comparison to the ACLR Uninjured limb (p < 0.05)
Table 8. Joint Displacement (DSP) Kinematics during the Landing Phase of the Jump Landing (Means, SE, 95% CI)

<table>
<thead>
<tr>
<th>Group</th>
<th>Injured / Index</th>
<th>Uninjured / Non-Index</th>
<th>Inj * Uninj</th>
<th>Inj * Index</th>
<th>Uninj * Non</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SE</td>
<td>CI</td>
<td>Mean ± SE</td>
<td>CI</td>
<td>P-Value</td>
</tr>
<tr>
<td>Hip Flexion DSP</td>
<td>ACLR</td>
<td>-36.67 ± 1.99</td>
<td>(-40.57, -34.85)</td>
<td>-39.01* ± 2.12</td>
<td>(-43.17, -34.85)</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>-32.54 ± 2.70</td>
<td>(-37.99, -27.09)</td>
<td>-32.52 ± 0.41</td>
<td>(-38.30, -26.74)</td>
</tr>
<tr>
<td></td>
<td>ACLR</td>
<td>4.67 ± 0.73</td>
<td>(3.24, 6.09)</td>
<td>2.83* ± 0.51</td>
<td>(1.83, 3.84)</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>4.25 ± 0.74</td>
<td>(2.80, 5.69)</td>
<td>4.27 ± 0.57</td>
<td>(3.16, 5.38)</td>
</tr>
<tr>
<td>Hip Adduction DSP</td>
<td>ACLR</td>
<td>16.34 ± 1.38</td>
<td>(13.64, 19.04)</td>
<td>18.82 ± 1.68</td>
<td>(15.53, 22.12)</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>14.94 ± 1.75</td>
<td>(11.51, 18.37)</td>
<td>14.45 ± 1.97</td>
<td>(10.58, 18.31)</td>
</tr>
<tr>
<td>Hip Internal Rotation DSP</td>
<td>ACLR</td>
<td>60.34 ± 2.68</td>
<td>(55.09, 65.59)</td>
<td>66.66* ± 2.73</td>
<td>(61.30, 72.02)</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>62.73 ± 2.13</td>
<td>(58.56, 66.90)</td>
<td>62.67 ± 2.42</td>
<td>(57.93, 67.42)</td>
</tr>
<tr>
<td>Knee Flexion DSP</td>
<td>ACLR</td>
<td>-2.30 ± 0.72</td>
<td>(-3.73, -0.88)</td>
<td>-2.30 ± 0.53</td>
<td>(-3.34, -1.26)</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>-2.63 ± 0.49</td>
<td>(-3.59, -1.68)</td>
<td>-2.36 ± 0.56</td>
<td>(-3.46, -1.26)</td>
</tr>
<tr>
<td>Knee Valgus DSP</td>
<td>ACLR</td>
<td>10.46 ± 1.13</td>
<td>(8.25, 12.67)</td>
<td>11.24 ± 1.82</td>
<td>(7.68, 14.81)</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>8.14 ± 1.30</td>
<td>(5.59, 10.68)</td>
<td>8.15 ± 1.23</td>
<td>(5.74, 10.56)</td>
</tr>
</tbody>
</table>

* Indicates Significant Difference Compared to the ACLR Injured Limb (p < 0.05)
Table 9. Landing Phase Peak Kinetics during the Jump Landing; Internal Joint Moments (Nm/BWxBH), ATSF (N/BW), and VGRF (N/BW) (Mean, SE, 95% CI)

<table>
<thead>
<tr>
<th>Group</th>
<th>Injured / Index</th>
<th>Uninjured / Non-Index</th>
<th>Inj * Uninj P-Value</th>
<th>Inj * Index P-Value</th>
<th>Uninj * Non Index P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SE CI</td>
<td>Mean ± SE CI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Extension Mom</td>
<td>-0.159 ± 0.010 (-0.179, -0.140)</td>
<td>-0.191* ± 0.013 (-0.216, -0.165)</td>
<td>0.002</td>
<td>0.862</td>
<td>0.054</td>
</tr>
<tr>
<td>ACLR</td>
<td>-0.161 ± 0.010 (-0.180, -0.143)</td>
<td>-0.161 ± 0.008 (-0.177, -0.144)</td>
<td>0.946</td>
<td>0.097</td>
<td>0.048</td>
</tr>
<tr>
<td>Control</td>
<td>-0.020 ± 0.004 (-0.031, -0.013)</td>
<td>-0.019** ± 0.005 (-0.030, -0.009)</td>
<td>0.040</td>
<td>0.241</td>
<td>0.878</td>
</tr>
<tr>
<td>Knee Valgus Mom</td>
<td>0.047 ± 0.006 (0.035, 0.059)</td>
<td>0.073* ± 0.011 (0.051, 0.095)</td>
<td>0.040</td>
<td>0.241</td>
<td>0.878</td>
</tr>
<tr>
<td>ACLR</td>
<td>0.058 ± 0.007 (0.045, 0.071)</td>
<td>0.071 ± 0.011 (0.049, 0.092)</td>
<td>&lt; 0.001</td>
<td>0.010</td>
<td>0.112</td>
</tr>
<tr>
<td>Control</td>
<td>0.920* ± 0.031 (0.86, 0.98)</td>
<td>1.006* ± 0.044 (0.92, 1.09)</td>
<td>&lt; 0.001</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>Knee Varus Mom</td>
<td>2.253 ± 0.107 (2.044, 2.462)</td>
<td>2.929* ± 0.137 (2.660, 3.198)</td>
<td>&lt; 0.001</td>
<td>0.112</td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>2.530 ± 0.138 (2.260, 2.799)</td>
<td>2.492** ± 0.109 (2.278, 2.707)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Indicates Significant Difference Compared to the ACLR Injured Limb (p < 0.05)
** Indicates Significant Difference in Comparison to the ACLR Uninjured limb (p < 0.05)
Table 10. Pushoff Phase Peak Kinetics during the Jump Landing: Internal Joint Moments (Nm/BWxBH), ATSF (N/BW), and VGRF (N/BW) (Mean, SE, 95% CI)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean ± SE</th>
<th>CI</th>
<th>Mean ± SE</th>
<th>CI</th>
<th>Inj * Uninj P-Value</th>
<th>Inj * Index P-Value</th>
<th>Uninj * Non P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Extension Mom</td>
<td>ACLR -0.074 ± 0.002 (-0.088, -0.060)</td>
<td>-0.084 ± 0.005 (-0.094, -0.074)</td>
<td>0.070</td>
<td>0.377</td>
<td>0.967</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Control -0.082 ± 0.005 (-0.092, -0.071)</td>
<td>-0.084 ± 0.007 (-0.097, -0.070)</td>
<td>0.328</td>
<td>0.661</td>
<td>0.764</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Valgus Mom</td>
<td>ACLR -0.021 ± 0.004 (-0.028, -0.013)</td>
<td>-0.016 ± 0.003 (-0.023, -0.010)</td>
<td>0.002</td>
<td>0.051</td>
<td>0.206</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Control -0.018 ± 0.003 (-0.025, -0.012)</td>
<td>-0.015 ± 0.004 (-0.022, -0.008)</td>
<td>0.638*</td>
<td>0.216</td>
<td>0.580</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Varus Mom</td>
<td>ACLR 0.013 ± 0.002 (0.010, 0.016)</td>
<td>0.022* ± 0.002 (0.017, 0.026)</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>0.135</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Control 0.023 ± 0.004 (0.014, 0.031)</td>
<td>0.028 ± 0.005 (0.019, 0.037)</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>0.135</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior Tibial Shear Force</td>
<td>ACLR 0.549 ± 0.019 (0.512, 0.586)</td>
<td>0.638* ± 0.216 (0.596, 0.580)</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>0.135</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Control 0.875* ± 0.029 (0.618, 0.731)</td>
<td>0.700 ± 0.036 (0.630, 0.770)</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>0.135</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical Ground Reaction Force</td>
<td>ACLR 1.044 ± 0.027 (0.991, 1.097)</td>
<td>1.138* ± 0.027 (1.084, 1.191)</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>0.135</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Control 1.158* ± 0.040 (1.080, 1.237)</td>
<td>1.201 ± 0.047 (1.109, 1.293)</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>0.135</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Indicates Significant Difference Compared to the ACLR Injured Limb (p < 0.05)
Table 11. Initial Contact Kinematics during the Landing Phase of the Single-Leg Double Hop (Means, SE, 95% CI)

<table>
<thead>
<tr>
<th>Group</th>
<th>Injured / Index</th>
<th>Uninjured / Non-Index</th>
<th>Inj * Uninj P-Value</th>
<th>Inj * Index P-Value</th>
<th>Uninj * Non P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SE</td>
<td>Mean ± SE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk Sagittal Plane IC</td>
<td>27.60 ± 1.76</td>
<td>27.04 ± 1.65</td>
<td>(24.35, 31.25)</td>
<td>(23.42, 30.66)</td>
<td>0.501</td>
</tr>
<tr>
<td>ACLR</td>
<td>Control</td>
<td>24.99 ± 1.25</td>
<td>25.10 ± 1.31</td>
<td>(22.55, 27.44)</td>
<td>(22.53, 27.68)</td>
</tr>
<tr>
<td></td>
<td>-0.52 ± 1.17</td>
<td>2.45 ± 1.50</td>
<td>(-2.82, 1.77)</td>
<td>(-0.49, 5.38)</td>
<td>0.193</td>
</tr>
<tr>
<td>Hip Sagittal Plane IC</td>
<td>-28.36 ± 2.06</td>
<td>-29.48 ± 1.91</td>
<td>(-32.40, -24.32)</td>
<td>(-33.22, -25.74)</td>
<td>0.320</td>
</tr>
<tr>
<td>ACLR</td>
<td>Control</td>
<td>1.12 ± 1.03</td>
<td>1.92 ± 1.23</td>
<td>(-0.91, 3.15)</td>
<td>(-0.48, 4.32)</td>
</tr>
<tr>
<td></td>
<td>-0.52 ± 1.17</td>
<td>2.45 ± 1.50</td>
<td>(-2.82, 1.77)</td>
<td>(-0.49, 5.38)</td>
<td>0.193</td>
</tr>
<tr>
<td>Hip Frontal Plane IC</td>
<td>-27.00 ± 1.24</td>
<td>-27.93 ± 1.31</td>
<td>(-29.44, -24.56)</td>
<td>(-30.50, -25.35)</td>
<td>0.501</td>
</tr>
<tr>
<td>ACLR</td>
<td>Control</td>
<td>-6.55 ± 0.89</td>
<td>-4.95 ± 1.07</td>
<td>(-8.29, -4.82)</td>
<td>(-7.05, -2.86)</td>
</tr>
<tr>
<td></td>
<td>6.34 ± 0.91</td>
<td>7.12 ± 0.93</td>
<td>(4.56, 8.11)</td>
<td>(5.30, 8.94)</td>
<td></td>
</tr>
<tr>
<td>Hip Transverse Plane IC</td>
<td>8.57 ± 1.26</td>
<td>8.10 ± 1.43</td>
<td>(6.09, 11.05)</td>
<td>(5.29, 1.91)</td>
<td>0.735</td>
</tr>
<tr>
<td>ACLR</td>
<td>Control</td>
<td>14.63 ± 0.93</td>
<td>15.49 ± 1.03</td>
<td>(12.80, 16.45)</td>
<td>(13.47, 17.52)</td>
</tr>
<tr>
<td></td>
<td>6.50 ± 1.40</td>
<td>17.78* ± 1.24</td>
<td>(11.80, 17.30)</td>
<td>(15.35, 20.22)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Knee Sagittal Plane IC</td>
<td>14.63 ± 1.26</td>
<td>15.49 ± 1.03</td>
<td>(12.80, 16.45)</td>
<td>(13.47, 17.52)</td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>Control</td>
<td>6.34 ± 1.44</td>
<td>7.12 ± 0.93</td>
<td>(4.56, 8.11)</td>
<td>(5.30, 8.94)</td>
</tr>
<tr>
<td></td>
<td>14.63 ± 0.93</td>
<td>15.49 ± 1.03</td>
<td>(12.80, 16.45)</td>
<td>(13.47, 17.52)</td>
<td></td>
</tr>
<tr>
<td>Knee Frontal Plane IC</td>
<td>2.10 ± 0.83</td>
<td>2.50 ± 0.74</td>
<td>(0.47, 3.72)</td>
<td>(1.06, 3.94)</td>
<td>0.670</td>
</tr>
<tr>
<td>ACLR</td>
<td>Control</td>
<td>14.63 ± 0.93</td>
<td>15.49 ± 1.03</td>
<td>(12.80, 16.45)</td>
<td>(13.47, 17.52)</td>
</tr>
<tr>
<td></td>
<td>6.50 ± 1.40</td>
<td>17.78* ± 1.24</td>
<td>(11.80, 17.30)</td>
<td>(15.35, 20.22)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Knee Transverse Plane IC</td>
<td>-11.29 ± 1.13</td>
<td>-10.69 ± 1.79</td>
<td>(-15.31, -7.26)</td>
<td>(-14.19, -7.79)</td>
<td>0.767</td>
</tr>
<tr>
<td>ACLR</td>
<td>Control</td>
<td>-10.55 ± 1.44</td>
<td>-10.81 ± 1.60</td>
<td>(-13.37, -7.73)</td>
<td>(-13.94, -7.68)</td>
</tr>
</tbody>
</table>

* Indicates Significant Difference Compared to the ACLR Injured Limb (p < 0.05)
Table 12. Joint Displacement (DSP) Kinematics during the Landing Phase of the Single-Leg Double Hop (Means, SE, 95% CI)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean± SE</th>
<th>Injured / Index CI</th>
<th>Uninjured / Non-Index CI</th>
<th>Inj * Uninj P-Value</th>
<th>Inj * Index P-Value</th>
<th>Uninj * Non P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk Flexion DSP</td>
<td>ACLR</td>
<td>11.24 ± 0.77 (9.73, 12.75)</td>
<td>12.11 ± 0.90 (10.36, 13.87)</td>
<td>0.161</td>
<td>0.091</td>
<td>0.276</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>12.99 ± 0.70 (11.63, 14.36)</td>
<td>13.47 ± 0.86 (11.78, 15.16)</td>
<td>0.122</td>
<td>0.969</td>
<td>0.917</td>
</tr>
<tr>
<td>Trunk Side Bend Away DSP</td>
<td>ACLR</td>
<td>-6.6 ± 1.17 (-8.90, -4.30)</td>
<td>-3.46 ± 0.95 (-5.32, -1.59)</td>
<td>0.122</td>
<td>0.969</td>
<td>0.917</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>-6.66 ± 1.17 (-8.95, -4.37)</td>
<td>-3.33 ± 0.80 (-4.89, -1.76)</td>
<td>0.122</td>
<td>0.969</td>
<td>0.917</td>
</tr>
<tr>
<td>Trunk Side Bend Twrd DSP</td>
<td>ACLR</td>
<td>3.99 ± 1.25 (1.54, 6.43)</td>
<td>5.42 ± 0.92 (3.63, 7.22)</td>
<td>0.486</td>
<td>0.763</td>
<td>0.756</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>4.47 ± 1.02 (2.48, 6.46)</td>
<td>5.83 ± 0.92 (4.02, 7.63)</td>
<td>0.486</td>
<td>0.763</td>
<td>0.756</td>
</tr>
<tr>
<td>Hip Flexion DSP</td>
<td>ACLR</td>
<td>-6.44 ± 1.40 (-9.18, -3.69)</td>
<td>-7.76 ± 1.32 (-10.36, -5.17)</td>
<td>0.051</td>
<td>0.248</td>
<td>0.080</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>-4.42 ± 1.04 (-6.46, -2.38)</td>
<td>-4.86 ± 1.00 (-6.82, -2.89)</td>
<td>0.051</td>
<td>0.248</td>
<td>0.080</td>
</tr>
<tr>
<td>Hip Adduction DSP</td>
<td>ACLR</td>
<td>16.94 ± 1.04 (14.89, 18.98)</td>
<td>13.24* ± 0.97 (11.34, 15.15)</td>
<td>&lt; 0.001</td>
<td>0.003</td>
<td>0.918</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>13.19* ± 0.71 (11.79, 14.59)</td>
<td>13.39 ± 0.99 (11.45, 15.32)</td>
<td>0.600</td>
<td>0.969</td>
<td>0.703</td>
</tr>
<tr>
<td>Hip Internal Rotation DSP</td>
<td>ACLR</td>
<td>3.28 ± 0.68 (1.95, 4.60)</td>
<td>2.95 ± 0.64 (1.69, 4.20)</td>
<td>0.007</td>
<td>0.069</td>
<td>0.820</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>3.31 ± 0.54 (2.25, 4.36)</td>
<td>3.25 ± 0.47 (2.32, 4.17)</td>
<td>0.007</td>
<td>0.069</td>
<td>0.820</td>
</tr>
<tr>
<td>Knee Flexion DSP</td>
<td>ACLR</td>
<td>30.06 ± 1.54 (33.05, 39.08)</td>
<td>39.33* ± 1.76 (35.87, 41.78)</td>
<td>&lt; 0.001</td>
<td>0.011</td>
<td>0.882</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>39.70 ± 1.28 (37.20, 41.20)</td>
<td>38.80 ± 1.51 (35.84, 41.75)</td>
<td>&lt; 0.001</td>
<td>0.011</td>
<td>0.882</td>
</tr>
<tr>
<td>Knee Valgus DSP</td>
<td>ACLR</td>
<td>-4.72 ± 0.73 (-6.14, -3.29)</td>
<td>-3.79 ± 0.79 (-5.33, -2.24)</td>
<td>0.194</td>
<td>0.398</td>
<td>0.477</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>-3.92 ± 0.60 (-5.10, -2.73)</td>
<td>-4.53 ± 0.69 (-5.88, -3.19)</td>
<td>0.194</td>
<td>0.398</td>
<td>0.477</td>
</tr>
<tr>
<td>Knee Internal Rotation DSP</td>
<td>ACLR</td>
<td>8.36 ± 1.29 (5.83, 10.89)</td>
<td>5.02* ± 0.96 (3.14, 6.91)</td>
<td>&lt; 0.001</td>
<td>0.011</td>
<td>0.882</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>4.58* ± 0.73 (3.15, 6.00)</td>
<td>4.84 ± 0.78 (3.30, 6.38)</td>
<td>&lt; 0.001</td>
<td>0.011</td>
<td>0.882</td>
</tr>
</tbody>
</table>

* Indicates Significant Difference Compared to the ACLR Injured Limb (p < 0.05)
Table 13. Landing Phase Peak Kinetics during the Single-Leg Double Hop; Peak Internal Joint Moments (Nm/BWxBH), ATSF (N/BW), VGRF (N/BW) (Means, SE, 95% CI)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean</th>
<th>SE</th>
<th>CI</th>
<th>Mean</th>
<th>SE</th>
<th>CI</th>
<th>Inj * Uninj P-Value</th>
<th>Inj * Index P-Value</th>
<th>Uninj * Non P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Extension Mom</td>
<td>ACLR</td>
<td>-0.169</td>
<td>± 0.016 (-0.201, -0.137)</td>
<td>-0.238*</td>
<td>± 0.014 (-0.265, -0.211)</td>
<td>&lt; 0.001</td>
<td>0.580</td>
<td>&lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>-0.181</td>
<td>± 0.016 (-0.212, -0.150)</td>
<td>-0.160**</td>
<td>± 0.016 (-0.191, -0.128)</td>
<td>0.574</td>
<td>0.017</td>
<td>0.169</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Valgus Mom</td>
<td>ACLR</td>
<td>-0.068</td>
<td>± 0.009 (-0.086, -0.050)</td>
<td>-0.062</td>
<td>± 0.007 (-0.076, -0.048)</td>
<td>0.001</td>
<td>0.043</td>
<td>0.832</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>-0.042*</td>
<td>± 0.006 (-0.054, -0.030)</td>
<td>-0.049</td>
<td>± 0.006 (-0.060, -0.038)</td>
<td>1.105</td>
<td>± 0.039</td>
<td>1.029, 1.181</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior Tibial Shear Force</td>
<td>ACLR</td>
<td>1.013</td>
<td>± 0.049 (0.917, 1.109)</td>
<td>1.118*</td>
<td>± 0.048 (1.024, 1.211)</td>
<td>0.004</td>
<td>0.547</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>1.134*</td>
<td>± 0.034 (1.067, 1.200)</td>
<td>1.105</td>
<td>± 0.039 (1.029, 1.181)</td>
<td>2.650</td>
<td>± 0.062</td>
<td>2.529, 2.771</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical Ground Reaction</td>
<td>ACLR</td>
<td>2.650</td>
<td>± 0.062 (2.529, 2.771)</td>
<td>2.669</td>
<td>± 0.053 (2.565, 2.774)</td>
<td>0.484</td>
<td>0.547</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>2.596</td>
<td>± 0.064 (2.470, 2.722)</td>
<td>2.589**</td>
<td>± 0.062 (2.467, 2.710)</td>
<td>2.569</td>
<td>± 0.053</td>
<td>2.565, 2.774</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Indicates Significant Difference Compared to the ACLR Injured Limb (p < 0.05)
** Indicates Significant Difference in Comparison to the ACLR Uninjured limb (p < 0.05)
Table 14. Pushoff Phase Peak Kinetics during the Single-Leg Double Hop; Peak Internal Joint Moments (Nm/BWxBH), ATSF (N/BW), VGRF (N/BW) (Means, SE, 95% CI)

<table>
<thead>
<tr>
<th></th>
<th>Group</th>
<th>Injured / Index</th>
<th>Uninjured / Non-Index</th>
<th>Inj * Uninj P-Value</th>
<th>Inj * Index P-Value</th>
<th>Uninj * Non P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Extension Mom</td>
<td>ACLR</td>
<td>-0.145 ± 0.012</td>
<td>-0.202* ± 0.014</td>
<td>&lt; 0.001</td>
<td>0.177</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>-0.169 ± 0.014</td>
<td>-0.152** ± 0.014</td>
<td>0.754</td>
<td>0.049</td>
<td>0.255</td>
</tr>
<tr>
<td>Knee Valgus Mom</td>
<td>ACLR</td>
<td>-0.035 ± 0.005</td>
<td>-0.033 ± 0.006</td>
<td>0.005</td>
<td>0.065</td>
<td>0.795</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>-0.022* ± 0.006</td>
<td>-0.025 ± 0.004</td>
<td>0.452</td>
<td>0.472</td>
<td>0.738</td>
</tr>
<tr>
<td>Anterior Tibial Shear Force</td>
<td>ACLR</td>
<td>0.978 ± 0.044 (0.891, 1.064)</td>
<td>1.058* ± 0.049 (0.962, 1.155)</td>
<td>0.005</td>
<td>0.065</td>
<td>0.795</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>1.082 ± 0.035 (1.013, 1.150)</td>
<td>1.075 ± 0.038 (0.999, 1.150)</td>
<td>0.452</td>
<td>0.472</td>
<td>0.738</td>
</tr>
<tr>
<td>Vertical Ground Reaction Force</td>
<td>ACLR</td>
<td>1.927 ± 0.069 (1.791, 2.062)</td>
<td>1.955 ± 0.081 (1.795, 2.114)</td>
<td>0.005</td>
<td>0.065</td>
<td>0.795</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>1.898 ± 0.535 (1.885, 2.094)</td>
<td>1.988 ± 0.058 (1.874, 2.102)</td>
<td>0.452</td>
<td>0.472</td>
<td>0.738</td>
</tr>
</tbody>
</table>

* Indicates Significant Difference Compared to the ACLR Injured Limb (p < 0.05)
** Indicates Significant Difference in Comparison to the ACLR Uninjured limb (p < 0.05)
Table 15. Summary Table of Statistically Significant Differences during the Double Leg Jump Landing and Single Leg Double Hop Tasks

<table>
<thead>
<tr>
<th></th>
<th>Double Leg Jump Landing</th>
<th>Single Leg Double Hop</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial Contact Kinematics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Flexion IC</td>
<td>Injured &gt; Uninjured, Index</td>
<td>Uninjured &gt; Injured</td>
</tr>
<tr>
<td>Hip Abduction IC</td>
<td>Uninjured &gt; Non-Index</td>
<td>...</td>
</tr>
<tr>
<td><strong>Joint Displacement</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip Flexion DSP</td>
<td>Uninjured &gt; Injured</td>
<td>...</td>
</tr>
<tr>
<td>Hip Adduction DSP</td>
<td>Injured &gt; Uninjured</td>
<td>Uninjured &gt; Injured, Index</td>
</tr>
<tr>
<td>Knee Flexion DSP</td>
<td>Uninjured &gt; Injured</td>
<td>Uninjured &gt; Injured</td>
</tr>
<tr>
<td>Knee Internal Rotation DSP</td>
<td>...</td>
<td>Injured &gt; Uninjured, Index</td>
</tr>
<tr>
<td><strong>Peak Kinetics - Landing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip Extension Moment</td>
<td>Uninjured &gt; Injured</td>
<td>Injured &gt; Uninjured</td>
</tr>
<tr>
<td>Knee Extension Moment</td>
<td>Uninjured &gt; Injured</td>
<td>Uninjured &gt; Injured, Non-Index</td>
</tr>
<tr>
<td>Knee Valgus Moment</td>
<td>Uninjured &gt; Non-Index</td>
<td>Injured &gt; Index</td>
</tr>
<tr>
<td>Knee Varus Moment</td>
<td>Uninjured &gt; Injured</td>
<td>...</td>
</tr>
<tr>
<td>Ankle Plantarflexion Moment</td>
<td>Uninjured &gt; Injured</td>
<td>Injured &gt; Uninjured</td>
</tr>
<tr>
<td>ATSF</td>
<td>Uninjured, Index &gt; Injured</td>
<td>Uninjured, Index &gt; Injured</td>
</tr>
<tr>
<td>VGRF</td>
<td>Uninjured &gt; Injured, Non-Index</td>
<td>Uninjured &gt; Non-Index</td>
</tr>
<tr>
<td><strong>Peak Kinetics - Pushoff</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip Extension Moment</td>
<td>...</td>
<td>Injured &gt; Uninjured</td>
</tr>
<tr>
<td>Knee Extension Moment</td>
<td>...</td>
<td>Uninjured &gt; Injured, Non-Index</td>
</tr>
<tr>
<td>Knee Varus Moment</td>
<td>Uninjured &gt; Injured</td>
<td>Injured &gt; Index</td>
</tr>
<tr>
<td>Ankle Plantarflexion Moment</td>
<td>Index &gt; Injured</td>
<td>Injured &gt; Uninjured</td>
</tr>
<tr>
<td>ATSF</td>
<td>Uninjured, Index &gt; Injured</td>
<td>Uninjured &gt; Injured, Non-Index</td>
</tr>
<tr>
<td>VGRF</td>
<td>Uninjured, Index &gt; Injured</td>
<td>...</td>
</tr>
</tbody>
</table>
Table 16. Descriptive Statistics for the Jump Landing Verbal Instructions Intervention (Means, SE, 95% CI)

<table>
<thead>
<tr>
<th></th>
<th>ACLR Group (n=22)</th>
<th>Control Group (n=25)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Injured</td>
<td>Uninjured</td>
</tr>
<tr>
<td></td>
<td>Mean ± SE</td>
<td>CI</td>
</tr>
<tr>
<td>K Flx DSP - Baseline</td>
<td>60.34 ± 2.68</td>
<td>(55.09, 65.59)</td>
</tr>
<tr>
<td>K Flx DSP - Soft</td>
<td>66.61 ± 3.07</td>
<td>(60.60, 72.63)</td>
</tr>
<tr>
<td>K Flx DSP - Equal</td>
<td>63.19 ± 2.90</td>
<td>(57.51, 68.87)</td>
</tr>
<tr>
<td>KEM - Baseline</td>
<td>-0.16 ± 0.01</td>
<td>(-0.18, -0.14)</td>
</tr>
<tr>
<td>KEM - Soft</td>
<td>-0.13 ± 0.01</td>
<td>(-0.14, -0.11)</td>
</tr>
<tr>
<td>KEM - Equal</td>
<td>-0.16 ± 0.01</td>
<td>(-0.18, -0.14)</td>
</tr>
<tr>
<td>KVM - Baseline</td>
<td>-0.03 ± 0.01</td>
<td>(-0.05, -0.02)</td>
</tr>
<tr>
<td>KVM - Soft</td>
<td>-0.03 ± 0.01</td>
<td>(-0.04, -0.02)</td>
</tr>
<tr>
<td>KVM - Equal</td>
<td>-0.03 ± 0.01</td>
<td>(-0.04, -0.02)</td>
</tr>
<tr>
<td>ATSF - Baseline</td>
<td>0.81 ± 0.03</td>
<td>(0.75, 0.87)</td>
</tr>
<tr>
<td>ATSF - Soft</td>
<td>0.78 ± 0.03</td>
<td>(0.80, 1.00)</td>
</tr>
<tr>
<td>ATSF - Equal</td>
<td>0.80 ± 0.03</td>
<td>(0.74, 0.87)</td>
</tr>
<tr>
<td>VGRF - Baseline</td>
<td>2.25 ± 0.11</td>
<td>(2.04, 2.46)</td>
</tr>
<tr>
<td>VGRF - Soft</td>
<td>1.83 ± 0.09</td>
<td>(1.65, 2.02)</td>
</tr>
<tr>
<td>VGRF - Equal</td>
<td>2.28 ± 0.11</td>
<td>(2.07, 2.50)</td>
</tr>
</tbody>
</table>

K Flx DSP = Knee flexion displacement  
KEM = Peak knee extension moment  
KVM = Peak knee valgus moment  
ATSF = Peak anterior tibial shear force  
VGRF = Peak vertical ground reaction force
Table 17. Soft Landing Change Scores for the Jump Landing Verbal Instructions Intervention (Means, SE, 95% CI)

<table>
<thead>
<tr>
<th>Soft Landing Change Scores</th>
<th>Group</th>
<th>Injured / Index</th>
<th>Uninjured / Non-Index</th>
<th>Inj * Uninj P-Value</th>
<th>Inj * Index P-Value</th>
<th>Uninj * Non P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Flexion DSP Δ</td>
<td>ACLR</td>
<td>6.27 ± 1.48</td>
<td>5.57 ± 1.17</td>
<td>0.547</td>
<td>0.225</td>
<td>0.253</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>3.69 ± 1.53</td>
<td>3.39 ± 1.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Extension Moment Δ</td>
<td>ACLR</td>
<td>0.03 ± 0.01</td>
<td>0.04 ± 0.01</td>
<td>0.248</td>
<td>0.998</td>
<td>0.298</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>0.03 ± 0.01</td>
<td>0.03 ± 0.01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Valgus Moment Δ</td>
<td>ACLR</td>
<td>0.01 ± 0.01</td>
<td>0.01 ± 0.01</td>
<td>0.873</td>
<td>0.516</td>
<td>0.258</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior Tibial Shear Force Δ</td>
<td>ACLR</td>
<td>-0.03 ± 0.03</td>
<td>-0.06 ± 0.04</td>
<td>0.431</td>
<td>0.553</td>
<td>0.375</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>-0.05 ± 0.02</td>
<td>-0.02 ± 0.03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical Ground Reaction Force Δ</td>
<td>ACLR</td>
<td>-0.42 ± 0.09</td>
<td>-0.76* ± 0.11</td>
<td>0.005</td>
<td>0.268</td>
<td>0.043</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>-0.56 ± 0.10</td>
<td>-0.50** ± 0.07</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Indicates Significant Difference Compared to the ACLR Injured Limb (p < 0.05)
** Indicates Significant Difference in Comparison to the ACLR Uninjured limb (p < 0.05)
(-) Value indicates a decrease / (+) Value indicates an increase in dependent variable
Table 18. Equal Landing Change Scores for the Jump Landing Verbal Instructions Intervention (Means, SE, 95% CI)

<table>
<thead>
<tr>
<th>Equal Landing Change Scores</th>
<th>Group</th>
<th>Injured / Index Mean ± SE CI</th>
<th>Uninjured / Non-Index Mean ± SE CI</th>
<th>Inj * Uninj P-Value</th>
<th>Inj * Index P-Value</th>
<th>Uninj * Non P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Flexion DSP Δ</td>
<td>ACLR</td>
<td>2.85 ± 1.65 (-0.39, 6.09)</td>
<td>1.67 ± 1.45 (-1.17, 4.50)</td>
<td>0.258</td>
<td>0.577</td>
<td>0.287</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>4.05 ± 1.39 (1.33, 6.78)</td>
<td>3.85 ± 1.33 (1.24, 6.46)</td>
<td>0.341</td>
<td>0.490</td>
<td>0.306</td>
</tr>
<tr>
<td>Knee Extension Moment Δ</td>
<td>ACLR</td>
<td>0.00 ± 0.01 (-0.02, 0.02)</td>
<td>0.01 ± 0.01 (-0.01, 0.03)</td>
<td>0.981</td>
<td>0.470</td>
<td>0.174</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>-0.01 ± 0.01 (-0.03, 0.01)</td>
<td>0.00 ± 0.01 (-0.02, 0.01)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Valgus Moment Δ</td>
<td>ACLR</td>
<td>0.00 ± 0.01 (-0.01, 0.01)</td>
<td>0.00 ± 0.01 (-0.01, 0.01)</td>
<td>0.981</td>
<td>0.470</td>
<td>0.174</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>0.00 ± 0.00 (-0.01, 0.00)</td>
<td>-0.01 ± 0.00 (-0.02, 0.00)</td>
<td>0.035</td>
<td>0.402</td>
<td>0.227</td>
</tr>
<tr>
<td>Anterior Tibial Shear Force Δ</td>
<td>ACLR</td>
<td>0.00 ± 0.03 (-0.05, 0.05)</td>
<td>-0.07* ± 0.02 (-0.11, -0.02)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>-0.03 ± 0.02 (-0.08, 0.02)</td>
<td>-0.03 ± 0.02 (-0.07, 0.01)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical Ground Reaction Force Δ</td>
<td>ACLR</td>
<td>0.03 ± 0.08 (-0.12, 0.18)</td>
<td>-0.29* ± 0.13 (-0.56, -0.03)</td>
<td>0.041</td>
<td>0.554</td>
<td>0.363</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>-0.04 ± 0.10 (-0.25, 0.16)</td>
<td>-0.15 ± 0.08 (-0.30, -0.01)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Indicates Significant Difference Compared to the ACLR Injured Limb (p < 0.05)
(-) Value indicates a decrease / (+) Value indicates an increase in dependent variable
APPENDIX A: PARTICIPANT QUESTIONNAIRE

Previous Knee Injury 2012

HEALTH HISTORY & ACTIVITY QUESTIONNAIRE

1. Today’s date: [ ] [ ] [ ] 1 2

2. What is your date of birth?

<table>
<thead>
<tr>
<th>Month</th>
<th>Day</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan.</td>
<td>01</td>
<td>1993</td>
</tr>
<tr>
<td>Feb.</td>
<td>02</td>
<td>1994</td>
</tr>
<tr>
<td>March</td>
<td>03</td>
<td>1995</td>
</tr>
<tr>
<td>April</td>
<td>04</td>
<td>1996</td>
</tr>
<tr>
<td>May</td>
<td>05</td>
<td>1997</td>
</tr>
<tr>
<td>June</td>
<td>06</td>
<td>1998</td>
</tr>
<tr>
<td>July</td>
<td>07</td>
<td>1999</td>
</tr>
<tr>
<td>Aug.</td>
<td>08</td>
<td>2000</td>
</tr>
<tr>
<td>Sept.</td>
<td>09</td>
<td>2001</td>
</tr>
<tr>
<td>Oct.</td>
<td>10</td>
<td>2002</td>
</tr>
<tr>
<td>Nov.</td>
<td>11</td>
<td>2003</td>
</tr>
<tr>
<td>Dec.</td>
<td>12</td>
<td>2004</td>
</tr>
</tbody>
</table>

3. How old are you?
   - 12 years old
   - 13 years old
   - 14 years old
   - 15 years old

4. Gender:
   - Male
   - Female

5. If you were going to kick a ball for maximum distance, which leg would you use?
   - Right
   - Left

6. If you were going to jump and land on a single leg, which leg would you use?
   - Right
   - Left

7. Part 1 - History of ACL Injury
   These next questions refer to ACL knee injuries and details of that injury.

1. Have you injured your ACL?  If yes, go to Question 15
   - No
   - Yes

2. If yes to ACL injury, which knee(s)?
   - Right
   - Left
   - Both

3. When (what year or years) did the injury occur?
   - 2012
   - 2013
   - 2014
   - 2015
   - 2016
   - 2017
   - 2018
   - 2019
   - 2020
   - 2021
   - 2022
   - 2023
   - 2024
   - 2025
   - 2026
   - 2027
   - 2028
   - 2029
   - 2030

4. What type of surgical graft did you have for reconstruction?
   - Patellar Tendon
   - Hamstrings Tendon
   - Allograft

5. Did you complete rehabilitation prior to surgery?
   - No
   - Yes

6. How long after injury did you have surgery?
   - < 3 weeks
   - 3-6 weeks
   - > 6 months
   - 7-12 weeks
   - > 9 months

7. How long after surgery until full clearance to return to sport?
   - 4 mos
   - 6 mos
   - 9 mos
   - 12 mos
   - > 14 mos

8. Did you injury your meniscus at the time of injury?
   - No
   - Yes

8a. If yes, which knee(s)?
   - Right
   - Left
   - Both

8b. Which side was your meniscus injury on?
   - Medial
   - Lateral

8c. Did this injury (or injuries) require surgery? If so, which one?
   - No
   - Repair
   - Removal

8d. Was the surgery performed at the same time as an ACL repair?
   - No
   - Yes
PART I - HISTORY OF ACL INJURY (cont.)
This section asks for details about how your ACL injury occurred.

9. Which mechanism of best describes how your injury occurred?
   ○ Non-Contact
     No contact with another player, ball or object. Injury happened while running, cutting, landing on your own.
   ○ Indirect Contact
     Contact with the ball or another player causing imbalance, but no direct contact was made to the knee
   ○ Direct Contact
     Another player or object directly hit the knee, causing injury
   ○ Other
     Injury occurred during a non-sport activity

10. If sport activity was involved, what sport was it?

11. What playing surface were you on when injury occurred?
    ○ Wooden Court
    ○ Sport Court (rubberized)
    ○ Grass Field
    ○ Artificial Turf Field
    ○ Other

12. What were the weather conditions when injury occurred?
    ○ Dry (indoors)
    ○ Wet (outdoor field)
    ○ Dry (outdoor field)
    ○ Hot Humid
    ○ Cold

13. What type of competition were you in when injury occurred?
    ○ Recreation ○ Organized Practice ○ Game

14. Were you wearing any sort of brace or protective equipment when injury occurred?
    ○ No ○ Yes

PART II - HISTORY OF INJURY

15. Have you ever had an injury to the Medial Collateral Ligament (MCL)?
    ○ No If No, Go to Question 16.
    ○ Yes

15a. If yes to MCL injury, which knee(s)?
    ○ Right ○ Left ○ Both

15b. Did this MCL injury (or injuries) require surgery?
    ○ No ○ Yes

16. Have you ever had an injury to the Lateral Collateral Ligament (LCL)?
    ○ No If No, Go to Question 17.
    ○ Yes

16a. If yes to LCL injury, which knee(s)?
    ○ Right ○ Left ○ Both

16b. Did this LCL injury (or injuries) require surgery?
    ○ No ○ Yes

17. Have you ever had a Posterior Cruciate Ligament (PCL) injury?
    ○ No If No, Go to Question 18.
    ○ Yes

17a. If yes to PCL injury, which knee(s)?
    ○ Right ○ Left ○ Both

17b. Did this PCL injury (or injuries) require surgery?
    ○ No ○ Yes
18. Have you had knee surgery, within the past 5 years, other than that listed in the previous questions? (Other than ACL surgery)
   - No  If No, Go to Question 19.
   - Yes

   18a. If yes, which knee(s)?
      - Right  Left  Both

19. Have you had some other lower limb bone fracture within the past six months?
   - No  If No, Go to Question 20.
   - Yes

   19a. If yes, which leg(s)?
      - Right  Left  Both

20. Have you ever had a lower limb stress fracture?
   - No  If No, Go to Question 21.
   - Yes

   20a. If yes, which leg(s)?
      - Right
      - Left
      - Please specify location
      - Upper Leg, Hip
      - Lower Leg
      - Foot
      - What year did it occur?

21. Within the past six months, have you had episode(s) of severe pain in your knee(s) that lasted for a day or more?
   - Severe means pain that would make you stop what you were doing or limit or interfere with your activities.
   - No  If No, Go to Question 22.
   - Yes

   21a. If yes, which knee(s)?
      - Right  Left  Both

21b. Was it worse when you exercised?
   - No  Yes

21c. Do you currently have this problem, or has it resolved?
   - Still a problem
   - Pain has resolved

22. Are you currently experiencing any symptoms (pain, redness, swelling, stiffness) of any lower extremity joint, lower extremity muscle, or low back?
   - No
   - Yes

   22a. If yes, which side(s)?
      - Right  Left  Both

22b. Which body part is experiencing symptoms?
23. Have you had patellofemoral pain (severe knee pain, or runner’s knee) within the past six months?
   ○ No  If No, go to Question 24.
   ○ Yes
      ▼
   23a. If yes, which knee(s)?
      ○ Right  ○ Left  ○ Both

24. Have you had swelling, clicking, popping, or feeling of the knee giving way within the past six months?
   ○ No  If No, go to Question 25.
   ○ Yes
      ▼
   24a. If yes, which knee(s)?
      ○ Right  ○ Left  ○ Both

24b. If yes, does it currently interfere with any physical activity?
   ○ No  ○ Yes

25. In the past six months, have you used a training program that involves repeated jumping? (Such programs are sometimes referred to as plyometric exercises.)
   ○ No  If No, go to Question 26.
   ○ Yes
      ▼
   25a. If yes, how many months, out of the past six, have you been doing this program?
      ○ <1 month  ○ 4 months
      ○ 1 month  ○ 5 months
      ○ 2 months  ○ 6 months
      ○ 3 months

26. In the past six months, have you been doing a training program designed to reduce the risk of repeat ACL injury?
   ○ No
   ○ Yes
      ▼
   26a. If yes, how many months, out of the past six, have you been doing this program?
      ○ <1 month  ○ 4 months
      ○ 1 month  ○ 5 months
      ○ 2 months  ○ 6 months
      ○ 3 months

26b. What is the name of the program, or its developer? (Mark all that apply.)
   ○ My coach
   ○ My physical therapist
   ○ My athletic trainer
   ○ Other (Specify):

26c. How many days per week did you do the program, on average?
   ○ <1 day/wk  ○ 4 days/wk
   ○ 1 day/wk  ○ 5 days/wk
   ○ 2 days/wk  ○ 6 days/wk
   ○ 3 days/wk  ○ 7 days/wk
PART 3 - GENERAL HEALTH

1. In general, are you currently in good health?  ○ No  ○ Yes

2. Have you ever been diagnosed with any cardiac condition (such as tachycardia, bradycardia, fibrillation, heart murmur, etc.)?  ○ No  ○ Yes

3. Have you ever been diagnosed with any neurologic condition (such as brain injury, spinal cord injury, Parkinson's disease, multiple sclerosis, epilepsy, etc.)?  ○ No  ○ Yes

4. Have you ever had asthma?  ○ No  ○ Yes

5. Do you have diabetes?  ○ No  ○ Yes

6. Have you ever felt dizzy or fainted during exercise?  ○ No  ○ Yes

7. Are you currently taking any medications (prescription or non-prescription)?  ○ No  ○ Yes
PART 4 - KNEE SYMPTOMS (KOOS KNEE SURVEY)

**Symptoms**

These questions should be answered thinking of your INJURED knee symptoms during the last week.

<table>
<thead>
<tr>
<th>Question</th>
<th>Never</th>
<th>Rarely</th>
<th>Sometimes</th>
<th>Often</th>
<th>Always</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1. Do you have swelling in your knee?</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>S2. Do you feel grinding, hear clicking or any other type of noise when your knee moves?</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>S3. Does your knee catch or hang up when moving?</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

**Stiffness**

The following questions concern the amount of joint stiffness you have experienced in your INJURED knee during the last week. Stiffness is a sensation of restriction or slowness in the ease with which you move your joints.

<table>
<thead>
<tr>
<th>Question</th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>S6. How severe is your joint stiffness after first waking in the morning?</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>S7. How severe is your joint stiffness after sitting, lying or resting later in the day?</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

P1. How often do you experience knee pain?

<table>
<thead>
<tr>
<th>Question</th>
<th>Never</th>
<th>Monthly</th>
<th>Weekly</th>
<th>Daily</th>
<th>Always</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2. Twisting/pivoting on your RIGHT knee</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>P3. Straightening knee fully</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>P4. Bending knee fully</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>P5. Walking on flat surface</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>P6. Going up or down stairs</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>P7. At night while in bed</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>P8. Sitting or lying</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>P9. Standing upright</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>
The following questions concern your physical function. By this we mean your ability to move around and to look after yourself. For each of the following activities please indicate the degree of difficulty you have experienced in the last week due to your INJURED knee.

<table>
<thead>
<tr>
<th>Activity</th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1. Descending stairs</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>A2. Ascending stairs</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>A3. Rising from sitting</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>A4. Standing</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>A5. Bending to floor/picking up an object</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>A6. Walking on flat surface</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>A7. Getting in/out of car</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>A8. Going shopping</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>A9. Putting on socks/stockings</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>A10. Rising from bed</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>A11. Taking off socks/stockings</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>A12. Lying in bed (turning over, maintaining knee position)</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>A13. Getting in/out of bath</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>A14. Sitting</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>A15. Getting on/off toilet</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

For each of the following activities please indicate the degree of difficulty you have experienced in the last week.

<table>
<thead>
<tr>
<th>Activity</th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>A16. Heavy domestic duties (shoveling snow, scrubbing floors, etc)</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>A17. Light domestic duties (cooking dusting etc)</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>
**Function, sports and recreational activities**

The following questions concern your physical function when being active on a higher level. The questions should be answered thinking of what degree of difficulty you have experienced during the last week.

<table>
<thead>
<tr>
<th>Activity</th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP1. Squatting</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>SP2. Running</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>SP3. Jumping</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>SP4. Twisting/pivoting on your right knee</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>SP5. Kneeling</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

**Quality of Life**

<table>
<thead>
<tr>
<th>Question</th>
<th>Never</th>
<th>Monthly</th>
<th>Weekly</th>
<th>Daily</th>
<th>Constantly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1. How often are you aware of knee problems?</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Q2. Have you modified your lifestyle to avoid potentially damaging activities to your knees?</td>
<td>Not at all</td>
<td>Mildly</td>
<td>Moderately</td>
<td>Severely</td>
<td>Totally</td>
</tr>
<tr>
<td>Q3. How much are you troubled with lack of confidence in your knees?</td>
<td>Not at all</td>
<td>Mildly</td>
<td>Moderately</td>
<td>Severely</td>
<td>Totally</td>
</tr>
<tr>
<td>Q4. In general, how much difficulty do you have with your knees?</td>
<td>None</td>
<td>Mild</td>
<td>Moderate</td>
<td>Severe</td>
<td>Extreme</td>
</tr>
</tbody>
</table>
### PART 5 - ACTIVITY (MARX ACTIVITY RATING SCALE)

5a. PRIOR TO ACL KNEE INJURY (Skip to 5b. if you are a healthy subject)

*Please indicate how often you performed each activity in your healthiest and most active state, prior to your knee injury.*

<table>
<thead>
<tr>
<th>Activity Description</th>
<th>Less than one time in a month</th>
<th>One time in a month</th>
<th>One time in a week</th>
<th>2 or 3 times in a week</th>
<th>4 or more times in a week</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1. Running: running while playing a sport or jogging</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
</tr>
<tr>
<td>M2. Cutting: changing directions while running</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
</tr>
<tr>
<td>M3. Decelerating: coming to a quick stop while running</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
</tr>
<tr>
<td>M4. Pivoting: turning your body with your foot planted while playing a sport; For example: skiing, skating, kicking, throwing, hitting a ball (golf, tennis, squash), etc.</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
</tr>
</tbody>
</table>

5b. POST ACL KNEE INJURY

*Please indicate how often you perform each activity in your current and healthiest most active state.*

<table>
<thead>
<tr>
<th>Activity Description</th>
<th>Less than one time in a month</th>
<th>One time in a month</th>
<th>One time in a week</th>
<th>2 or 3 times in a week</th>
<th>4 or more times in a week</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1. Running: running while playing a sport or jogging</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
</tr>
<tr>
<td>M2. Cutting: changing directions while running</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
</tr>
<tr>
<td>M3. Decelerating: coming to a quick stop while running</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
</tr>
<tr>
<td>M4. Pivoting: turning your body with your foot planted while playing a sport; For example: skiing, skating, kicking, throwing, hitting a ball (golf, tennis, squash), etc.</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
</tr>
</tbody>
</table>
PART 6 (TSK-11)
Please indicate how much you 'agree' or 'disagree' with the following statements.

1. I am afraid I might injured myself if I exercise
   ○ Strongly Disagree ○ Disagree ○ Agree ○ Strongly Agree

2. If I were to overcome it, my pain would increase
   ○ Strongly Disagree ○ Disagree ○ Agree ○ Strongly Agree

3. My body is telling me I have something dangerously wrong
   ○ Strongly Disagree ○ Disagree ○ Agree ○ Strongly Agree

4. People are not taking my medical condition serious enough
   ○ Strongly Disagree ○ Disagree ○ Agree ○ Strongly Agree

5. My injury has put my body at risk for the rest of my life
   ○ Strongly Disagree ○ Disagree ○ Agree ○ Strongly Agree

6. Pain always means I have injured my body
   ○ Strongly Disagree ○ Disagree ○ Agree ○ Strongly Agree

7. Simply being careful that I do not make unnecessary movements is the safest thing I can do to prevent my pain from worsening
   ○ Strongly Disagree ○ Disagree ○ Agree ○ Strongly Agree

8. I would not have this much pain if there was not something potentially dangerous going on in my body
   ○ Strongly Disagree ○ Disagree ○ Agree ○ Strongly Agree

9. Pain lets me know when to stop exercising so that I do not injury myself
   ○ Strongly Disagree ○ Disagree ○ Agree ○ Strongly Agree

10. I can not do all the things normal people do because it is too easy for me to get injured
    ○ Strongly Disagree ○ Disagree ○ Agree ○ Strongly Agree

11. No one should have to exercise when he/she is in pain
    ○ Strongly Disagree ○ Disagree ○ Agree ○ Strongly Agree
APPENDIX B. VERBAL INSTRUCTIONS SCRIPT

IRB#: 12-1885

Verbal Instructions
Intervention Script

The order of verbal instruction conditions will be counterbalanced between subjects. Therefore, the script should begin with whichever condition is first and then continue with the second. The squatting tasks (overhead, single-leg) are to be performed in between Condition 1 and Condition 2.

Record order of conditions here:
Condition 1: _______________________
Condition 2: _______________________

‘Soft’ Landing Verbal Instructions

Prior to Trial 1:
“This time when you perform the jump landing I want you to focus on landing as softly as you can.”

Prior to Trials 2-3:
“Focus on landing as softly as you can.”

‘Equal’ Landing Verbal Instructions

Prior to Trial 1:
“This time when you perform the jump landing I want you to focus on landing with equal weight under each foot.”

Prior to Trials 2-3:
“Focus on landing with equal weight under each foot.”
Background: Adolescent females are at a high-risk of suffering sport related anterior cruciate ligament (ACL) injury and secondary ACL injury upon full return to sport. However, a focused investigation of landing biomechanics in a sample of adolescent females after ACL injury and subsequent reconstruction (ACLR) has not been performed.

Purpose: To evaluate trunk and lower extremity biomechanics during a double-leg jump landing in adolescent females with a history of ACLR that have fully returned to sport and those without a history of ACL injury.

Study Design: Laboratory Cross-Sectional Design

Methods: Trunk, hip, knee, and ankle kinematics along with selected kinetic variables of forty-seven adolescent females (ACLR = 22, Control = 25) were analyzed during a double-leg jump landing task using a motion analysis camera system interfaced with two force plates. Trunk and lower extremity kinematics were calculated at the time point of initial contact (IC) and displacement (DSP) during the landing phase, peak kinetics were calculated during the landing phase. A linear regression model using generalized estimating equations (GEE) were performed to analyze differences between the previously injured limb and all other limbs.

Results: At IC, the ACLR Injured limb displayed greater knee flexion than the Uninjured (p = 0.008) and CON Index (p = 0.005) with lesser ankle plantar flexion compared to the Uninjured (p = 0.009). The Uninjured limb displayed greater hip abduction at IC compared to the CON Non-Index limb (p = 0.047). However, the ACLR Injured limb moved through less
sagittal plane DSP (hip flexion, $p = 0.002$; knee flexion, $p < 0.001$; ankle dorsiflexion, $p = 0.006$) and greater hip adduction DSP ($p = 0.034$) in comparison to the Uninjured limb. Asymmetrical landing forces, including lesser peak vertical ground reaction force (Uninjured, $p < 0.001$), lesser anterior tibial shear force (Uninjured, $p < 0.001$; Index, $p = 0.010$), and lesser hip extension (Uninjured, $p = 0.002$), knee extension (Uninjured, $p = 0.002$), and ankle plantarflexion (Uninjured, $p < 0.001$; Index, $p = 0.009$) moments were observed on the Injured limb. The Injured limb also had less peak knee varus moment during landing compared to the Uninjured ($p = 0.040$). The Uninjured limb had greater peak VGRF ($p = 0.013$) and peak knee valgus moment ($p = 0.048$) compared to the CON Non-Index limb.

**Conclusion:** After full return to sport, we observed adolescent female athletes with a history of ACLR performed a double-leg jump landing task using avoidance strategies to limit the loading on the previously Injured limb and increase loading on the contralateral, or previously Uninjured limb.
INTRODUCTION

Young female athletes are at an increased risk of suffering an anterior cruciate ligament (ACL) injury during sport in comparison to males competing at the same level.\(^1\) Primary mechanisms of injury most often include a non-contact or indirect contact mechanism, such that the injury occurs due to the athlete’s own movements and no direct contact was made with the knee.\(^2,3\) Typically, young female adolescents have a strong desire to return to sport following ACL injury and surgical reconstruction (ACLR), but can be precluded by the occurrence of a secondary ACL injury.\(^4-6\)

Long-term consequences of ACLR include a decrease in physical activity through the lifespan and an early onset of knee osteoarthritis (OA).\(^7,8\) Younger patients returning to strenuous sports that integrate landing, cutting, pivoting, and deceleration movements are at a substantially increased risk of experiencing a secondary ACL injury.\(^4-6,11-13\) Webster et al.\(^6\) observed 29% of their sample of patients, younger than 20-years old, who had undergone primary ACLR suffered a subsequent graft or contralateral ACL injury within 3-years, equating to 1 in every 3.4 cases in this age group. The Swedish National ACL register reported 22% of female soccer players between the ages of 15-18 suffered a secondary ACL injury within five years, compared to only 9% in the general population.\(^14\) The long-term rates of secondary ACL injury to the contralateral, or previously uninjured knee, may be double that of experiencing a rupture to the ACL graft.\(^11,15,16\) Overall, males and females are equally likely to sustain a secondary ACL injury,\(^13\) however females may be more apt to injure their contralateral ACL.\(^4,17\) It is very concerning that adolescent female athletes whom experience an ACL injury and undergo surgical ACLR, complete supervised rehabilitation,
and pass return to sport criteria in their associated clinics are experiencing further injury to
this degree.

ACLR does not exactly replicate the normal anatomic complexity of the original ACL
structure in the knee. Comparisons of lower extremity kinematics and kinetics have exposed
a number of movement and landing adaptations in adults with a history of ACLR. Adults
with a history of ACLR rely more heavily on their previously uninjured limb to absorb
landing forces in comparison to their injured limb demonstrating asymmetries in ground
reaction forces,\textsuperscript{18, 19} knee extension moments,\textsuperscript{20-22} anterior tibial shear force,\textsuperscript{22} and three-
dimensional movement patterns.\textsuperscript{23, 24-26}

The most direct loading mechanism on the ACL is a linear shear force at the proximal
tibia, causing translation of the tibial plateau in an anterior direction relative to the femur.\textsuperscript{27}
Larger vertical ground reaction forces (VGRF) during landing have been identified as a
prospective risk factor for primary ACL injury in females.\textsuperscript{28} Previous research has
established a link between greater peak VGRF during a stop jump task and greater peak
anterior tibial shear force (ATSF) as well as greater peak knee extension moment (KEM) in
healthy physically active college students.\textsuperscript{29} The asymmetry in these variables between limbs
in those with a history of ACLR can be detrimental to ACL loading and potential secondary
injury risk.

While the large majority of ACLR research is in adults, Paterno et al.\textsuperscript{30} investigated
vertical ground reaction forces (VGRF) during a drop vertical jump in adolescents following
ACLR within four weeks of full return to sport. Male and female adolescents (age=16.2 ± 6.4
years) displayed bilateral asymmetries in VGRF, such that the injured limb had lower peak
VGRF values compared to the uninjured limb and both limbs of the control subjects.\textsuperscript{30}
Additionally, these authors\textsuperscript{31} tracked male and female adolescent athletes (age=16.60 \pm 3.29 years) after returning to sport following ACLR. Thirteen adolescents suffered a secondary ACL injury within one year, 11 were females and 10 occurred on the contralateral, previously uninjured limb. Adolescents that went on to suffer a second ACL injury displayed greater knee valgus motion on the injured limb, greater asymmetry in knee extension moment at initial contact, as well as greater hip internal rotation net moments (initial 10\% of stance) on the previously uninjured limb.\textsuperscript{31}

Unfortunately, very little biomechanical research post ACLR has been performed on an adolescent athlete population and none focusing on adolescent females. Proximal trunk and distal ankle biomechanics are theorized to influence knee loading, however no investigations have focused on the complete connection of trunk and lower extremity kinematics in this previously injured adolescent female population. Furthermore, the asymmetries in knee extension moment, knee valgus (varus) moment, and VGRF in adults and adolescents post ACLR requires ongoing investigation in this focused study. The direct link between ATSF and landing biomechanics that increase ACL loading provide rationale for the investigation of this variable as well. There is a pronounced need to identify unsafe movement patterns and loading asymmetries in this population that could potentially be modified to improve poor long-term outcomes.

The double-leg jump landing has previously been utilized and validated as a clinical screening tool to identify individuals displaying biomechanical profiles associated with increased ACL loading and injury mechanisms.\textsuperscript{32} This task requires efficient movement patterns and stability to absorb the generated impact forces and immediately produce propulsive forces to jump vertically for maximum height. It requires the participants to
control trunk and lower extremity joint motion while dissipating large landing forces in a similar manner to what they experience during sport, thereby an ideal task for this study.

Due to the increased likelihood of secondary injury on the contralateral limb, females may adopt movement compensations that emphasize their injury risk on the previously uninjured knee, perhaps by unloading the injured leg at the expense of the uninjured, creating potentially harmful asymmetries. Therefore, the purpose of our study was to compare (1) three-dimensional trunk and lower extremity kinematics at the time point of initial contact and displacement during the landing phase and (2) select peak kinetic variables during the landing phase between adolescent females with and without a history of ACLR. Within group comparisons of the Injured and Uninjured limb served as an indicator of asymmetry, while the between group comparison highlights differences between those with a history of ACLR and the healthy control. We hypothesized that adolescent females with a history of ACLR would display biomechanical asymmetries between their injured and uninjured limb that may make their previously uninjured limb more vulnerable to secondary injury and differences would exist between the ACLR injured limb and the matched healthy control limb.

METHODS

The current study utilized a cross-sectional design to investigate differences in landing biomechanics between limbs in the ACLR group and between the ACLR Injured limb and healthy matched control limb. The limbs of the previously injured group (ACLR) were referred to as the ‘Injured’ and ‘Uninjured’ limb. The limbs of the healthy control group (CON) were referred to as the ‘Index’ and ‘Non-Index’ limb. Right and left CON limbs were
randomly allocated to serve as the Index or Non-Index limb to match the distribution of right (n=8) and left (n=14) limb injuries in the ACLR group (Table 1). Participants reported to the research laboratory for a single data collection session.

Participants

Twenty-two ACLR (age = 16.68 ± 1.55 yrs, height = 166.80 ± 6.04 cm, mass = 61.08 ± 8.78 kg) and 25 healthy control (CON; age = 16.91 ± 1.23 yrs, height = 170.22 ± 7.40, mass = 63.32 ± 7.59 kg) adolescent female athletes participated in this study. All participants were high school or collegiate athletes between the ages of 12-18. All ACLR group participants had returned to their primary sport with an average time of 8.18 ± 2.48 months post surgery (range 6-12 months). The mean time from surgery to participation was 14.52 ± 8.62 months (range 6-24 months). All injuries were due to noncontact or indirect contact mechanisms during their primary sport such that no direct contact was made with the knee. Participants with concomitant meniscal injury (56%) that had been surgically addressed at the time of ACLR were not excluded given the high incidence of concomitant ACL and meniscus injuries. However, associated ligament injury to the medial collateral, lateral collateral, or posterior cruciate ligaments was considered exclusionary. Other exclusion criteria for the ACLR group included more than one surgical intervention and musculoskeletal injury affecting either lower extremity, other than the primary ACL injury. All participants completed supervised rehabilitation following ACLR and prior to full return to sport, however individual return to sport criteria were unknown. Table 2 describes ACL injury history and activity levels for the ACLR group participants in greater detail.
Healthy CON participants were matched by age, height, body mass, and sport participation to the ACLR group. The participant’s height, weight, and mid-parents height \([(\text{mother’s height} + \text{father’s height}) / 2]\) were used to predict mature height with the Khamis-Roche protocol. The ACLR group (99.80% ± 1.09) and the CON group (99.68% ±1.10) had reached their estimated mature height at the time of testing. Pubertal maturation was estimated using the pubertal maturation observation scale, whereby all participants were post pubertal at the time of testing. There was an equal distribution of ACLR and CON participants from each sport, including soccer, basketball, lacrosse, volleyball, softball, and gymnastics. The limbs of the CON group participants were randomly assigned to serve as the Index or Non-Index limb based on the distribution of right and left limb ACL injuries as described previously. This limb allocation procedure also resulted in similar distributions of dominant kicking limbs that were injured in the ACLR group (n=12) or assigned as the Index in the CON group (n=10). However, matching based primarily on kicking limb dominance, as in previous research, was not possible due to the lack of left limb kicking dominant participants in the CON group. All participants had no history of other significant lower extremity injuries.

**Data Collection**

Prior to testing all participants and their parent/guardian read and signed appropriate Institutional Review Board approved consent and assent forms. Participants and their parent/guardian completed a subjective questionnaire to obtain details pertaining to their healthy history and ACL injury, while also completing the Marx activity rating scale to quantify physical activity. ACLR participants completed two scales, one considering how
often they performed each activity in their healthiest and most active state prior to knee injury and one considering how often they performed each activity at the time of testing. The control participants completed the form considering their activity level at the time of testing only. Results were used to confirm similar physical activity levels between groups. The Marx activity scale is a valid and reliable assessment tool in the knee injured population.\textsuperscript{35, 36}

Participants wore dark colored spandex shorts and sports bra with their own running shoes for testing. No turf shoes, court shoes, or cleats were allowed. Anthropometric data, including height and body mass, were recorded prior to a five-minute warm-up on a stationary cycle ergometer at an estimated rating of perceived exertion (RPE) of 12 followed by self-selected lower extremity stretching.

After the warm-up, 29 reflective markers were placed on each participant in the following locations: bilaterally on the tip of the acromion process, anterior superior iliac spine (ASIS), greater trochanter, anterior thigh, medial femoral epicondyle, lateral femoral epicondyle, anterior tibia, medial malleolus, lateral malleolus, calcaneus, head of the 5\textsuperscript{th} metatarsal, and head of the 1\textsuperscript{st} metatarsal. Additional markers were placed over the seventh cervical vertebra, L4-L5 lumbar vertebrae, and a customized cluster containing three markers was placed over the sacrum (sacrum, left PSIS, right PSIS).

Marker coordinate data were captured using a seven-camera motion analysis system with a sampling frequency of 120 Hz (Vicon Systems, Centennial, CO). Ground reaction force data were captured with two floor embedded force plates with a sampling frequency of 1200 Hz (Bertec Corporation, Worthington, OH). A global coordinate system was defined for the laboratory capture volume, and local coordinate systems for each body segment were aligned such that the positive X-axis was oriented forward/anteriorly, the positive Y-axis was
oriented leftward/medially, and the positive Z-axis was oriented upward/superior. The ankle joint center and knee joint centers were estimated as the midpoint between the malleoli and femoral epicondyles, respectively. The hip joint center was estimated based on the location of the anterior superior iliac spines according to the Bell method. The axis systems of both force plates were aligned to the global coordinate system of the laboratory defined by the motion capture system. Digital camera data were imported in Vicon Nexus software for integration with the force plate data and marker identification. Following a static standing trial, participants performed the jump landing task.

To perform the jump landing task, participants stood atop a 30-cm box that was placed a horizontal distance of 50% of their height behind the leading edge of the force plates. They jumped forward from the box to a double leg landing with one foot in the center of each force plate before jumping vertically for maximal height. Instructions given to the subjects were to “focus on jumping forward into the target area with both feet and immediately jump straight up as high as you can.” No demonstration was given, but subjects performed three practice trials prior to data collection. Three successful trials of the jump landing were recorded with 30 seconds of rest between. A trial was deemed successful if the subject left the jump box with both feet at the same time, landed on the force plates, and immediately jumped straight up for maximal height. If participants did not meet these criteria, the jump-landing task was repeated.

**Data Reduction**

Prior to data exportation using The Motion Monitor biomechanical data analysis software (Innsport Inc., Chicago, IL), three-dimensional kinematic data of the trunk, hip,
knee, and ankle were defined using an Euler angle sequence Y’, X’’, Z’’’. Trunk angles were calculated as the trunk reference frame relative to the pelvis. Hip angles were calculated as the femur reference frame relative to the pelvis. Knee angles were calculated as the tibia reference frame relative to the femur. Ankle angles were calculated as the foot reference frame relative to the tibia. Internal joint moments were calculated using inverse dynamics. 

Raw kinematic and kinetic data were exported into a customized MATLAB software program for data reduction (Mathworks, Natick, MA, version 11.0). Kinematic data were filtered at 12 Hz using a 4th order zero-phase-lag low-pass Butterworth filter. All internal joint moments were normalized to the product of body height (m) and body weight (N). All ground reaction force and anterior tibial shear force data were normalized to body weight (N). Vertical ground reaction force data were used to define the landing phase of the jump landing, defined as the interval between initial contact (IC = vertical ground reaction force > 10N) to peak knee flexion on the right limb. Kinematic dependent variables included three-dimensional trunk, hip, and knee angles as well as ankle plantarflexion / dorsiflexion at the time point of IC and joint displacements (DSP) during the landing phase (i.e. peak landing phase angle – IC angle). Select kinetic variables included peak internal hip extension moment (HEM), knee extension moment (KEM), knee valgus/varus moment, ankle plantarflexion moment, anterior tibial shear force (ATSF), and vertical ground reaction force (VGRF) during the landing phase. The average of three trials was used for statistical analyses.

LSI was calculated for select loading variables (VGRF, ATSF) as previous research has demonstrated asymmetry on these measures in previously injured populations. LSI values were calculated for the ACLR group as [((Injured – Uninjured) / Injured)*100] and for the CON group as [((Index – Non-Index) / Index)*100].
Statistical Analyses

Independent samples t-tests were performed to compare subject demographic data for age (years), height (cm), and body mass (kg) between groups. A Mann-Whitney U test for non-parametric analyses was conducted to evaluate the Marx activity rating scores between groups prior to and after injury. The purpose of these tests was to ensure groups were similar aside from injury status at the time of testing. Independent samples t-tests were performed to compare peak VGRF LSI values and peak ATSF LSI values between groups.

Linear regression models using generalized estimating equations (GEE) were utilized to investigate biomechanical differences while adjusting for potential correlations with bilateral limb comparisons. A one-factor model (Group) was performed for each trunk kinematic variable to identify group differences at IC and overall DSP during the landing phase. A two-factor model (Group, Limb) with pairwise comparisons was performed for each lower extremity IC and DSP kinematic variable as well as peak kinetic variables during the landing phase to investigate differences between the 1) ACLR Injured * ACLR Uninjured, 2) ACLR Injured * CON Index limbs, and 3) ACLR Uninjured * CON Non-Index limbs. An a priori alpha level of 0.05 was utilized to determine statistical significance for all analyses performed. All statistical analyses were performed using IBM SPSS Statistics (IBM Corp., Armonk, NY, v.21.0).

All GEE analyses were initially performed with the dominant balance limb as a covariate. Dominant kicking limb could not be entered as a covariate as there were no CON participants who self-reported left limb kicking dominance. Results were not influenced by dominant balance limb so it was removed from the model for reporting.
RESULTS

Participant Demographics

There were no significant differences between groups on measures of age ($t_{45} = -0.56$, $p = 0.58$), height ($t_{45} = 1.72$, $p = 0.09$), body mass ($t_{45} = 0.94$, $p = 0.35$), or Marx activity rating scores pre- or post- ACLR (Pre $z = -1.48$, $p = 0.14$; Post $z = -1.69$, $p = 0.09$) indicating groups were similar at the time of testing on these measures. Additionally, all participants were post pubertal at the time of testing and had achieved estimated mature height.

Limb Symmetry

The ACLR group demonstrated greater asymmetry in peak VGRF (-34.70 ± 37.92, CON = -2.36 ± 24.03, $p = 0.002$) and peak ATSF (-27.41 ± 28.87, CON = -0.94 ± 16.41, $p = 0.001$) compared to the CON group during the jump landing. Negative values indicate greater loading toward the Uninjured or Non-Index limb in the ACLR and CON groups, respectively. Larger numbers indicate a greater magnitude of asymmetry.

Kinematics

At initial contact, we observed greater knee flexion on the ACLR Injured limb compared to the Uninjured limb ($p = 0.008$) and the CON Index limb ($p = 0.005$). We also observed less ankle plantar flexion at IC on the Injured limb compared to the Uninjured limb ($p = 0.009$). The ACLR Uninjured limb demonstrated greater hip abduction at initial contact compared to the CON Non-Index limb ($p = 0.047$).
We observed less sagittal plane DSP and greater frontal plane DSP in the ACLR Injured limb compared to the Uninjured limb indicating asymmetrical movement. Specifically, the ACLR Injured limb displayed less hip flexion DSP ($p = 0.002$), knee flexion DSP ($p < 0.001$), and ankle dorsiflexion DSP ($p = 0.006$) compared to the Uninjured limb, but greater hip adduction DSP compared to the Uninjured limb ($p = 0.034$). There were no statistically significant differences between DSP kinematics in the ACLR Uninjured and CON Non-Index limbs ($p > 0.05$).

No statistically significant differences were observed in trunk kinematics at IC or DSP during landing ($p > 0.05$). Descriptive statistics (Means, SE, 95% CI) for trunk and lower extremity IC and joint DSP kinematics are presented in Tables 3-5.

**Peak Landing Kinetics**

We observed considerably less loading on the Injured limb when compared to the Uninjured limb, indicating asymmetrical loading. The ACLR Injured limb had lesser net internal peak hip extension moment ($p = 0.002$), peak knee extension moment ($p = 0.002$), peak knee varus moment ($p = 0.040$), peak ankle plantarflexion moment ($p < 0.001$), peak VGRF ($p < 0.001$), and peak ATSF ($p < 0.001$) compared to the Uninjured limb. The ACLR Injured limb also displayed lesser peak ATSF ($p = 0.010$) and ankle plantarflexion moment ($p = 0.009$) compared to the CON Index limb. The ACLR Uninjured limb demonstrated greater peak knee valgus moment ($p = 0.048$) and peak VGRF ($p = 0.013$) compared to the CON Non-Index limb. Descriptive statistics (Means, SE, 95% CI) for peak internal joint moments and peak landing forces are presented in Table 6.
There were no statistical differences between the limbs of the control group for any dependent variable analyzed ($p > 0.10$); therefore the asymmetrical movement was unique to the ACLR group participants.

**DISCUSSION**

The primary, and perhaps most important finding of this investigation is that after full return to sport this adolescent female athlete population still performed a double-leg jump landing task using avoidance strategies to limit the loading on the previously injured limb creating asymmetries that place a greater load on the contralateral uninjured limb. These findings may provide insight into explaining the higher risk of secondary ACL injury to the contralateral knee in females after returning to sport.

We observed a number of kinematic and kinetic differences between limbs in the ACLR group, between the ACLR injured limb and the CON Index limb, as well as between the ACLR uninjured limb and the CON Non-Index limb. However, the majority of observed differences were between limbs in the ACLR group, indicating asymmetrical movement and loading. The same asymmetries were not present in the CON group. Somewhat surprising, we did not observe differences in trunk kinematics between the two groups. The magnitude of VGRF was greater on the contralateral uninjured limb compared to both the injured limb and the CON Non-Index limb, suggesting the excessive kinetic loading on the uninjured limb is likely driving much of the lower extremity kinematic profile that we observed in our ACLR group participants.
Peak Landing Kinetics

Within the ACLR group, peak internal knee extensor moments at the hip, knee, and ankle as well as knee varus moment, peak VGRF and ATSF loading were significantly less on the Injured limb in comparison to the contralateral Uninjured limb. It is important to note that only ATSF and ankle plantarflexion moment differed between the ACLR Injured and CON Index limb, with the ACLR Injured limb displaying significantly less in both variables. Generally, loading on the Injured limb was similar to that of the CON Index limb. Therefore, loading was greater on the contralateral Uninjured limb, which likely drives the differences observed in the ACLR group as opposed to diminished loading on the Injured limb. These same asymmetries were not present in the CON group. The Uninjured limb also displayed greater peak VGRF loading and knee valgus moment in comparison to the CON Non-Index limb, further explaining the potential severity of the magnitude of loading on the Uninjured limb.

Our findings agree with previous research in adults\textsuperscript{18, 23} and adolescents\textsuperscript{30, 31} during a similar double-leg landing task that identified reduced VGRF on the injured or involved limb at varying time points after ACLR. In two separate studies, Paterno et al.\textsuperscript{18, 30} revealed asymmetrical VGRF loading in recreational athletes following ACLR with no differences between the involved limb (previously injured) and either limb of the control participants. Similarly, Decker et al.\textsuperscript{23} observed similar VGRF in the ACLR injured limb in comparison to a healthy control limb during a 60-cm vertical drop landing. These authors did not conduct a between group comparison in the ACLR participants, so it is unknown if there were asymmetries present. In combination, these results point to the overreliance on the previously Uninjured limb during dynamic sport specific landing tasks. Additionally, a prospective
investigation in females who later experienced an ACL injury compared to females who did not, identified 20% larger VGRFs in females that suffered an ACL injury during a similar jump landing task. The difference between ACLR group limbs in our sample exceeds that 20% difference, likely placing the contralateral Uninjured limb at high risk of secondary ACL injury. Unfortunately, three participants in the current study did experience a contralateral ACL injury within several months of testing which further supports our findings.

Greater proximal anterior tibial shear force and knee extension moment, are known to directly load the ACL in cadaveric models. The ACLR group produced greater knee extension moment and anterior tibial shear force loading on the contralateral Uninjured limb compared to the Injured limb. The CON Index Limb also demonstrated greater anterior tibial shear force loading compared to the ACLR Injured limb. Internal knee extension moment is the torque produced by the quadriceps muscle group (knee extensors) in response to the external forces applied by the ground during landing that cause the body’s center of mass to flex the knee. Greater peak VGRF during landing is associated with peak knee extension moment and peak anterior tibial shear force such that an increase in one contributes to an increase in all. The ACLR group participants utilized an avoidance strategy to minimize loading on the Injured limb largely in comparison to the contralateral Uninjured limb but also in comparison to the CON Index limb on measures of peak anterior tibial shear force, which is the most direct loading mechanism for the ACL.

Numerous studies have reported deficiencies in knee extension moment in the Injured limb in comparison to the contralateral Uninjured limb during the loading phase of walking, single-leg hopping, and double leg landing in subjects with ACL deficient
or ACLR knees. These prior studies investigated differences within a previously injured ACLR group only; no between groups comparisons were made. We observed similar disparities between the Injured and Uninjured limb, but differences between the ACLR Injured limb and the healthy control group may suggest that this is not a deficiency in the Injured limb but, rather, represents excessive loading on the Uninjured limb. However, some studies have identified lower knee extension moments in the Injured limb in comparison to both the previously Uninjured and a healthy control group. Paterno et al. identified greater asymmetry in knee extension moment at initial contact in adolescents who went on to suffer a secondary ACL injury in comparison to adolescent athletes who did not. While we analyzed our kinetics as peak values during the landing phase, our findings generally agree with previous research. Future research is needed to investigate the influence of asymmetrical peak internal knee extension moment on future ACL injury risk in this population.

Frontal plane knee loading is deleterious to the ACL and has been implicated in ACL injury events and as a contributor to substantial combined loading placed on the ACL in cadaveric models. We observed greater peak internal knee varus moment on the Uninjured limb in comparison to the Injured limb within the ACLR group. Frontal plane hip motion was different within the ACLR group, likely contributing to this finding. Excessive hip adduction during dynamic weight bearing tasks can affect the kinematics and kinetics of the entire lower extremity. Hip adduction motion can cause the knee joint center to move medially relative to the foot, contributing to dynamic knee valgus. Theoretically, the ground reaction force vector would pass more medially compared to the knee joint center and the body would counteract this external force by producing an internal knee varus moment.
Excessive loading in the frontal plane (in either direction) is problematic for the ACL; therefore these results further indicate the contralateral Uninjured limb is at high risk of ACL injury.

**Kinematics**

The ACLR Injured limb contacted the ground with greater knee flexion and less ankle plantar flexion (more dorsiflexion), but proceeded to move through a smaller amount of sagittal plane DSP at the hip, knee, and ankle. The Injured limb also demonstrated greater frontal plane DSP at the hip. Primarily these differences occurred between limbs in the ACLR group, however the Injured limb also displayed greater knee flexion at IC compared to the CON Index limb. The Uninjured limb displayed greater hip abduction at IC compared to the CON Non-Index limb. Landing with greater knee and ankle flexion in the Injured limb may be a compensatory strategy to prevent larger ground reaction forces associated with stiff landings at ground contact.\(^{47}\) However, reduced sagittal plane DSP on the Injured limb compared to the Uninjured indicates asymmetrical energy absorption, which agree with the kinetic differences previously discussed.

Our initial contact results differ from those reported by Decker et al.\(^{23}\) who investigated landing adaptations after ACLR in male and female recreational adults (age = 27.3 years), observing less hip and knee flexion with greater ankle plantar flexion at initial contact on the Injured limb in comparison to the control subjects. They utilized a double-leg drop vertical jump task with a drop height of 60-cm, but analyzed unilateral data and no within group comparisons were made. This task differed from the jump landing used in the
current study as we incorporated more of a forward hop from the box to the force plate (50% of participants height), rather than a straight drop onto the force plate and we used a box with a height of 30-cm. Perhaps the differences can partially be attributed to the different drop heights, as the maximum forward and downward velocity of the body’s center of mass when reaching the force plates would differ. Peak VGRF would be larger when dropping from a larger height and would therefore influence kinetic variables calculated based on VGRF.

Greater lower extremity motion in the sagittal plane during landing has been associated with smaller VGRF.\textsuperscript{48, 49} Theoretically, greater knee flexion at IC on the Injured limb would be protective to the ACL. However, the differences within the ACLR group participants is concerning. It seems counter-intuitive that the Injured limb could have less sagittal plane DSP, but also have smaller VGRF, anterior tibial shear force, and knee extension moment. It appears the previously Uninjured limb moves through greater sagittal plane DSP at the hip, knee, and ankle in an attempt to lessen the impact forces it sustains due to the overreliance on that limb. However, the greater DSP does not lessen the burden on the previously Uninjured limb, as it is experiences greater loading. This is not a favorable situation for the Uninjured limb, as these loading factors are associated with primary\textsuperscript{28} and secondary\textsuperscript{31} ACL injury. Quadriceps dysfunction in these ACLR group participants likely contributes to the dynamic alignment and the movement patterns observed.

Neuromuscular alterations following joint injury may play a role in altering lower extremity biomechanics. Quadriceps dysfunction is a neuromuscular consequence of ACL injury and ACLR.\textsuperscript{50} In combination, quadriceps dysfunction encompasses decreased voluntary muscle activation, decreased muscle strength, and decreased knee extension moment on the previously injured limb.\textsuperscript{51, 52} However, these deficits in quadriceps function
have also been observed bilaterally following unilateral injury.\textsuperscript{53} It is unknown whether these neuromuscular alterations are a result of injury or are a predisposing factor to primary ACL injury. Potentially, an inability in our ACLR group participants to activate the quadriceps to produce a large breaking force during the jump landing contributed to excessive loading on the previously Uninjured limb. These compensatory movements may be beneficial in the short term to permit performance of a given task, but the asymmetries and deficiencies may contribute to future injury.

Model-based image matching techniques from videos of actual ACL injury events revealed females actually landed with significantly more knee and hip flexion when sustaining an ACL injury in comparison to males.\textsuperscript{44} There is often a distinct difference between biomechanical mechanisms known to increase ACL loading identified during cadaver studies and biomechanical risk factors we prospectively identify from screening tests to distinguish those at greater risk of suffering an ACL injury. Potentially, the movements we deem to be high risk are those that are carried out to avoid mechanisms of ACL loading during dynamic movement. However, Padua et al.\textsuperscript{54} identified prospective ACL injury risk factors in roughly 6,000 military cadets who went on to rupture their ACLs (n=98), which included greater overall hip flexion motion in comparison to those who did not experience an injury. The male and female cadets who suffered an ACL injury also displayed greater hip external rotation, hip adduction, and knee valgus at initial contact on the dominant (instrumented) limb.\textsuperscript{54} The adolescent females with a history of ACLR in the current study made contact with the ground on the Injured limb in greater knee flexion compared to the Uninjured (knee, ankle) and control limbs (hip, knee). However, the Uninjured limb demonstrated greater overall sagittal plane displacement in comparison to the Injured (hip,
knee, ankle) with lesser hip adduction displacement. These kinematic landing strategies may place these adolescent females at greater risk of suffering secondary ACL injury, particularly to the Uninjured or contralateral limb. It is unknown if this landing strategy contributed to their primary ACL injury or if this was an adaptation following ACL injury and subsequent ACLR.

Hip adduction displacement was significantly greater on the ACLR Injured limb in comparison to the previously Uninjured limb. Excessive hip adduction has been theorized to play a role in ACL injury, particularly in females. More recently, greater hip adduction during the stance phase of running was identified as a prospective risk factor in females who later went on to develop patellofemoral pain. Our findings are consistent with a recent study by Goerger et al. that assessed lower extremity biomechanics during the same jump landing task both pre- and post- ACL injury in a group of military cadets. The ACL Injured group demonstrated an increase in hip adduction angle at initial contact from baseline testing to follow-up testing (approximately 3 years later), while the control group did not change. Delahunt et al. assessed landing kinematics in adult female athletes just over four years following ACLR in comparison to a control group. The females with a history of ACLR displayed greater peak hip adduction as well as greater hip adduction over the first 200-ms of stance in comparison to the control group. In the current study, there were no differences between the Injured limb and the matched CON Index limb on measures of frontal plane hip motion. In fact, hip adduction DSP was quite similar between the Injured (4.67°) and the Index limb (4.25°). We theorize the greater hip adduction displacement observed on the Injured limb is largely due to the asymmetrical sagittal plane motion. The Uninjured limb moved through greater sagittal plane flexion and as such the pelvis and hip on that side
would dip lower than on the previously Injured side, which would be registered as greater hip adduction motion of the thigh relative to the pelvis.

Return to sport criteria most often reported in the literature include isokinetic lower extremity muscle strength, clinical knee examination, and single leg hop symmetry. The goal of late phase rehabilitation is to progress the athlete from the ability to perform activities of daily living to higher-level athletic function and a safe transition back to competitive sport. A large focus in functional ability is placed on the performance of single-leg hopping activities for concern that double-leg movements may mask deficits of the injured limb that persist into later phases of rehabilitation. Athletes will find a way to achieve success in any task you throw at them, likely through a variety of compensations. While we agree that single-leg hopping is important and provides valuable information, it is also crucial to revisit double-leg activities with our patients to ensure they are loading both limbs. Double-leg exercises afford them the opportunity to unload the Injured limb, and it appears most will subconsciously take advantage. We acknowledge costly motion analysis instrumentation is often not available in the clinical setting. However, shifting of body weight toward the previously uninjured side was visually apparent during real time performance of the jump landing in this sample, therefore providing optimism for the clinical applicability of these results.

There were several limitations of the current study. Only female adolescent athletes were included in the current study due to their high risk of ACL injury and secondary injury after full return to sport. Results are not generalizable outside of this population. The reporting of injury and surgery characteristics was all self-report by the participant and their parent or guardian. No surgical reports were acquired from physicians. We did not perform
subgroup analysis of reconstruction method or graft type. However, the natural breakdown of procedures was fairly split between bone-patellar tendon-bone autograft and hamstring autograft procedures with only one patellar tendon allograft. All participants with a history of ACLR had completed supervised rehabilitation prior to full return to sport and subsequent testing in our lab. However, rehabilitation was not standardized and we have no record of their individual rehabilitation protocols or specific return to sport criteria that was used by their clinicians.
REFERENCES


Table 1. Results of Healthy Control Limb Random Allocation

<table>
<thead>
<tr>
<th>Frequency (n)</th>
<th>ACLR (n=22)</th>
<th>Control (n=25)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Injured</td>
<td>Index</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>Right</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>Left</td>
</tr>
<tr>
<td>8</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>14</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>
Table 2. Anterior Cruciate Ligament Injury History and Activity Level for each Participant (N=22)

<table>
<thead>
<tr>
<th>Injured Limb</th>
<th>Injured Dominant</th>
<th>Injured Dominant</th>
<th>Primary Sport</th>
<th>MOI</th>
<th>Graft</th>
<th>Meniscus Injury</th>
<th>Marx Activity Rating Score Pre</th>
<th>Marx Activity Rating Score Pre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Softball</td>
<td>NC</td>
<td>Hamstrings</td>
<td>Yes</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>Yes</td>
<td>Volleyball</td>
<td>IC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>Yes</td>
<td>Soccer</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>No</td>
<td>16</td>
<td>13</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Lacrosse</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>No</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>Yes</td>
<td>Soccer</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>Yes</td>
<td>Lacrosse</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Soccer</td>
<td>IC</td>
<td>Patellar Tendon Allograft</td>
<td>Yes</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Soccer</td>
<td>NC</td>
<td>Hamstrings</td>
<td>No</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>Yes</td>
<td>Lacrosse</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>No</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>Left</td>
<td>Yes</td>
<td>Yes</td>
<td>Basketball</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>No</td>
<td>Soccer</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>No</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Soccer</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Volleyball</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>7</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>Yes</td>
<td>Basketball</td>
<td>NC</td>
<td>Hamstrings</td>
<td>Yes</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Basketball</td>
<td>IC</td>
<td>Hamstrings</td>
<td>Yes</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Soccer</td>
<td>IC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>No</td>
<td>Basketball</td>
<td>NC</td>
<td>Hamstrings</td>
<td>No</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Left</td>
<td>Yes</td>
<td>No</td>
<td>Soccer</td>
<td>IC</td>
<td>Hamstrings</td>
<td>No</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Volleyball</td>
<td>NC</td>
<td>Hamstrings</td>
<td>Yes</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Left</td>
<td>Yes</td>
<td>Yes</td>
<td>Gymnastics</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>No</td>
<td>Soccer</td>
<td>IC</td>
<td>Hamstrings</td>
<td>No</td>
<td>16</td>
<td>8</td>
</tr>
</tbody>
</table>

NC = Noncontact Mechanism of ACL Injury  
IC = Indirect Contact Mechanism of ACL Injury  
Dominant Kicking Limb = Preferred Limb to Kick a Soccer Ball for Maximum Distance  
Dominant Balance Limb = Preferred Limb to Land from a Single-Leg Jump
Table 3. Descriptive Statistics for Trunk Kinematics (°) during the Jump Landing (Means, SE, 95% CI)

<table>
<thead>
<tr>
<th>IC Kinematics</th>
<th>ACLR (n=22)</th>
<th>Control (n=25)</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SE 95% CI</td>
<td>Mean ± SE 95% CI</td>
<td></td>
</tr>
<tr>
<td>Trunk Sagittal IC</td>
<td>27.70 ± 1.75 (24.27, 31.13)</td>
<td>24.69 ± 1.41 (21.93, 27.45)</td>
<td>0.181</td>
</tr>
<tr>
<td>Trunk Frontal IC</td>
<td>0.92 ± 0.52 (-0.10, 1.04)</td>
<td>1.31 ± 0.61 (0.11, 2.51)</td>
<td>0.623</td>
</tr>
<tr>
<td>Trunk Transverse IC</td>
<td>-2.01 ± 0.81 (-3.60, -0.43)</td>
<td>-2.36 ± 0.72 (-3.77, -0.94)</td>
<td>0.753</td>
</tr>
</tbody>
</table>

Joint Displacements

<table>
<thead>
<tr>
<th>Joint Displacements</th>
<th>ACLR (n=22)</th>
<th>Control (n=25)</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SE 95% CI</td>
<td>Mean ± SE 95% CI</td>
<td></td>
</tr>
<tr>
<td>Trunk Flexion DSP</td>
<td>17.19 ± 1.70 (13.86, 20.52)</td>
<td>15.32 ± 1.10 (13.17, 14.48)</td>
<td>0.357</td>
</tr>
<tr>
<td>Trunk Side Bend Left DSP</td>
<td>-1.83 ± 0.35 (-2.51, -1.15)</td>
<td>-1.55 ± 0.27 (-2.09, -1.02)</td>
<td>0.528</td>
</tr>
<tr>
<td>Trunk Side Bend Right DSP</td>
<td>2.17 ± 0.32 (1.53, 2.80)</td>
<td>2.06 ± 0.30 (1.47, 2.65)</td>
<td>0.810</td>
</tr>
<tr>
<td>Trunk Rotation Left DSP</td>
<td>3.62 ± 0.85 (1.95, 5.28)</td>
<td>4.60 ± 0.60 (3.43, 5.78)</td>
<td>0.344</td>
</tr>
<tr>
<td>Trunk Rotation Right DSP</td>
<td>-2.78 ± 0.61 (-3.99, -1.58)</td>
<td>-1.52 ± 0.61 (-2.19, -0.86)</td>
<td>0.073</td>
</tr>
</tbody>
</table>

(+) Flexion, Right Side Bend, Left Rotation
Table 4. Descriptive Statistics for Initial Contact Kinematics (°) during the Jump Landing (Means, 95% CI)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean ± SE</th>
<th>Inj / Index CI</th>
<th>Mean ± SE</th>
<th>Uninjured / Non-Index CI</th>
<th>Inj * Uninj P-Value</th>
<th>Inj * Index P-Value</th>
<th>Uninj * Non P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip Sagittal Plane IC</td>
<td>ACLR</td>
<td>-25.47 ± 1.71</td>
<td>(-29.83, -22.11)</td>
<td>-24.31 ± 1.59</td>
<td>(-27.43, -21.20)</td>
<td>0.168</td>
<td>0.067</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>-21.76 ± 1.08</td>
<td>(-23.88, -19.63)</td>
<td>-21.62 ± 0.90</td>
<td>(-23.39, -19.84)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip Frontal Plane IC</td>
<td>ACLR</td>
<td>-7.56 ± 0.73</td>
<td>(-8.98, -6.13)</td>
<td>-9.12 ± 0.55</td>
<td>(-10.21, -8.04)</td>
<td>0.147</td>
<td>0.210</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>-8.84 ± 0.72</td>
<td>(-10.25, -7.43)</td>
<td>-7.32** ± 0.72</td>
<td>(-8.74, -5.89)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip Transverse Plane IC</td>
<td>ACLR</td>
<td>4.83 ± 1.51</td>
<td>(1.86, 7.80)</td>
<td>4.18 ± 1.75</td>
<td>(0.76, 7.60)</td>
<td>0.416</td>
<td>0.335</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>3.17 ± 0.84</td>
<td>(1.52, 4.81)</td>
<td>3.42 ± 0.84</td>
<td>(1.77, 5.07)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Sagittal Plane IC</td>
<td>ACLR</td>
<td>26.00 ± 0.93</td>
<td>(24.19, 27.82)</td>
<td>23.53* ± 1.11</td>
<td>(21.35, 25.72)</td>
<td>**0.008</td>
<td>**0.005</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>21.87* ± 1.15</td>
<td>(19.61, 24.13)</td>
<td>21.71 ± 0.76</td>
<td>(20.21, 23.20)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Frontal Plane IC</td>
<td>ACLR</td>
<td>4.62 ± 0.88</td>
<td>(2.91, 6.35)</td>
<td>4.41 ± 0.72</td>
<td>(2.30, 5.82)</td>
<td>0.843</td>
<td>0.273</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>3.27 ± 0.87</td>
<td>(1.56, 4.98)</td>
<td>3.57 ± 0.88</td>
<td>(1.84, 5.29)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Transverse Plane IC</td>
<td>ACLR</td>
<td>-15.16 ± 2.21</td>
<td>(-19.49, -10.83)</td>
<td>-16.11 ± 1.95</td>
<td>(-19.94, -12.28)</td>
<td>0.685</td>
<td>0.888</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>-14.77 ± 1.69</td>
<td>(-18.08, -11.46)</td>
<td>-14.28 ± 1.55</td>
<td>(-17.32, -11.24)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ankle Sagittal Plane IC</td>
<td>ACLR</td>
<td>34.69 ± 1.28</td>
<td>(32.19, 37.19)</td>
<td>38.11* ± 1.18</td>
<td>(35.79, 40.43)</td>
<td>**0.009</td>
<td>0.052</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>38.15 ± 1.24</td>
<td>(35.73, 40.58)</td>
<td>37.82 ± 1.60</td>
<td>(34.68, 40.96)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Indicates Significant Difference in Comparison to the ACLR Injured (reference) limb (p < 0.05)
** Indicates Significant Difference in Comparison to the ACLR Uninjured limb (p < 0.05)
(+) Hip Extension, Adduction, Internal Rotation / Knee Flexion, Varus, Internal Rotation / Ankle Plantarflexion
Table 5. Descriptive Statistics for Joint Displacement (DSP) Kinematics (°) during the Jump Landing (Means, SE, 95% CI)

<table>
<thead>
<tr>
<th>Group</th>
<th>Injured / Index</th>
<th>Uninjured / Non-Index</th>
<th>Inj * Uninj P-Value</th>
<th>Inj * Index P-Value</th>
<th>Uninj * Non P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip Flexion DSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>-36.67 ± 1.99</td>
<td>(-40.57, -34.85)</td>
<td>-39.01* ± 2.12</td>
<td>(-43.17, -34.85)</td>
<td>0.002</td>
</tr>
<tr>
<td>Control</td>
<td>-32.54 ± 2.78</td>
<td>(-37.99, -27.09)</td>
<td>-32.52 ± 0.41</td>
<td>(-38.30, -26.74)</td>
<td>0.226</td>
</tr>
<tr>
<td>Hip Adduction DSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>4.67 ± 0.73</td>
<td>(3.24, 6.09)</td>
<td>2.83* ± 0.51</td>
<td>(1.83, 3.84)</td>
<td>0.034</td>
</tr>
<tr>
<td>Control</td>
<td>4.25 ± 0.74</td>
<td>(2.80, 5.69)</td>
<td>4.27 ± 0.57</td>
<td>(3.16, 5.38)</td>
<td>0.074</td>
</tr>
<tr>
<td>Hip Internal Rotation DSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>16.34 ± 1.38</td>
<td>(13.64, 19.04)</td>
<td>18.82 ± 1.68</td>
<td>(15.53, 22.12)</td>
<td>0.002</td>
</tr>
<tr>
<td>Control</td>
<td>14.94 ± 1.75</td>
<td>(11.51, 18.37)</td>
<td>14.45 ± 1.97</td>
<td>(10.58, 18.31)</td>
<td>0.226</td>
</tr>
<tr>
<td>Knee Flexion DSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>60.34 ± 2.68</td>
<td>(55.09, 65.59)</td>
<td>66.66* ± 2.73</td>
<td>(61.30, 72.02)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Control</td>
<td>62.73 ± 2.13</td>
<td>(58.56, 66.90)</td>
<td>62.67 ± 2.42</td>
<td>(57.93, 67.42)</td>
<td>0.684</td>
</tr>
<tr>
<td>Knee Valgus DSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>-2.30 ± 0.72</td>
<td>(-3.73, -0.88)</td>
<td>-2.30 ± 0.53</td>
<td>(-3.34, -1.26)</td>
<td>0.034</td>
</tr>
<tr>
<td>Control</td>
<td>-2.63 ± 0.49</td>
<td>(-3.59, -1.68)</td>
<td>-2.36 ± 0.56</td>
<td>(-3.46, -1.26)</td>
<td>0.705</td>
</tr>
<tr>
<td>Knee Internal Rotation DSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>10.46 ± 1.13</td>
<td>(8.25, 12.67)</td>
<td>11.24 ± 1.82</td>
<td>(7.68, 14.81)</td>
<td>0.656</td>
</tr>
<tr>
<td>Control</td>
<td>8.14 ± 1.30</td>
<td>(5.59, 10.68)</td>
<td>8.15 ± 1.23</td>
<td>(5.74, 10.56)</td>
<td>0.177</td>
</tr>
<tr>
<td>Ankle Dorsiflexion DSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>-38.94 ± 1.65</td>
<td>(-42.16, -35.71)</td>
<td>-41.65* ± 1.48</td>
<td>(-44.56, -38.74)</td>
<td>0.006</td>
</tr>
<tr>
<td>Control</td>
<td>-43.40 ± 1.64</td>
<td>(-46.64, -40.17)</td>
<td>-43.49 ± 1.74</td>
<td>(-46.89, -40.09)</td>
<td>0.055</td>
</tr>
</tbody>
</table>

* Indicates Significant Difference in Comparison to the ACLR Injured (reference) limb (p < 0.05)
(-) Hip Flexion, Knee Valgus, Ankle Dorsiflexion
Table 6. Descriptive Data for Peak Internal Joint Moments (Nm/BHxBW), ATSF (N/BW), and Peak VGRF (N/BW) during the Jump Landing (Means, 95% CI)

| Group                  | Injured / Index | Uninjured / Non-Index | | | |
|------------------------|-----------------|-----------------------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|
|                        | Mean ± SE       | CI                    | Mean ± SE        | CI              | P-Value         | Inj * Uninj P-Value | Inj * Index P-Value | Uninj * Non P-Value |
| Hip Extension Mom      |                 |                       |                  |                 |                 |                  |                  |                  |                  |                   |
| ACLR                   | 0.302 ± 0.021   | (0.261, 0.344)        | 0.373* ± 0.030   | (0.315, 0.431)  | 0.002           | 0.192            | 0.324            |                  |                  |                   |
| Control                | 0.350 ± 0.030   | (0.291, 0.410)        | 0.336 ± 0.023    | (0.291, 0.381)  |                  |                  |                  |                  |                  |                   |
| Knee Extension Mom     |                 |                       |                  |                 |                 |                  |                  |                  |                  |                   |
| ACLR                   | -0.159 ± 0.010  | (-0.18, -0.14)        | -0.191* ± 0.013  | (-0.22, -0.17)  | 0.002           | 0.862            | 0.054            |                  |                  |                   |
| Control                | -0.162 ± 0.010  | (-0.18, -0.14)        | -0.161 ± 0.008   | (-0.18, -0.14)  |                  |                  |                  |                  |                  |                   |
| Ankle Plantarflexion Mom |             |                       |                  |                 |                 |                  |                  |                  |                  |                   |
| ACLR                   | 0.151 ± 0.015   | (0.122, 0.181)        | 0.220* ± 0.020   | (0.182, 0.259)  | < 0.001         | 0.009            | 0.594            |                  |                  |                   |
| Control                | 0.208* ± 0.016  | (0.177, 0.238)        | 0.208 ± 0.013    | (0.182, 0.233)  |                  |                  |                  |                  |                  |                   |
| Knee Valgus Mom        |                 |                       |                  |                 |                 |                  |                  |                  |                  |                   |
| ACLR                   | -0.035 ± 0.005  | (-0.05, -0.02)        | -0.035 ± 0.007   | (-0.05, -0.02)  | 0.946           | 0.097            | 0.048            |                  |                  |                   |
| Control                | -0.023 ± 0.004  | (-0.03, -0.01)        | -0.019** ± 0.005 | (-0.03, -0.01)  |                  |                  |                  |                  |                  |                   |
| Knee Varus Mom         |                 |                       |                  |                 |                 |                  |                  |                  |                  |                   |
| ACLR                   | 0.047 ± 0.006   | (0.04, 0.06)          | 0.073* ± 0.011   | (0.05, 0.10)    | 0.040           | 0.241            | 0.878            |                  |                  |                   |
| Control                | 0.058 ± 0.007   | (0.05, 0.07)          | 0.071 ± 0.011    | (0.05, 0.09)    |                  |                  |                  |                  |                  |                   |
| ATSF                   |                 |                       |                  |                 |                 |                  |                  |                  |                  |                   |
| ACLR                   | 0.806 ± 0.031   | (0.75, 0.87)          | 1.006* ± 0.044   | (0.92, 1.09)    | < 0.001         | 0.010            | 0.112            |                  |                  |                   |
| Control                | 0.920* ± 0.031  | (0.86, 0.98)          | 0.917 ± 0.034    | (0.85, 0.99)    |                  |                  |                  |                  |                  |                   |
| vGRF                   |                 |                       |                  |                 |                 |                  |                  |                  |                  |                   |
| ACLR                   | 2.253 ± 0.107   | (2.04, 2.46)          | 2.929* ± 0.137   | (2.66, 3.20)    | < 0.001         | 0.112            | 0.013            |                  |                  |                   |
| Control                | 2.530 ± 0.138   | (2.26, 2.80)          | 2.492** ± 0.109  | (2.28, 2.71)    |                  |                  |                  |                  |                  |                   |

* Indicates Significant Difference in Comparison to the ACLR Injured limb (p < 0.05)

** Indicates Significant Difference in Comparison to the ACLR Uninjured limb (p < 0.05)

(-) Knee Extension, Knee Valgus
APPENDIX D: MANUSCRIPT TWO
Altered Single-Leg Landing Mechanics in ACL-Reconstructed Adolescent Females after Full Return to Sport (Medicine & Science in Sports & Exercise)

Purpose: Young female athletes are at great risk of suffering a subsequent anterior cruciate ligament (ACL) injury, to either leg, following return to sport after surgical reconstruction (ACLR). Single-leg hop movements are often used in rehabilitation to help determine readiness to return to sport. A focus on performance outcome overweighs a biomechanical understanding of how athletes achieve success with these movements. Biomechanics during a single-leg hop in female adolescents has not been performed.

Methods: The aim of this study was to identify biomechanical differences within the previously injured (ACLR) and between the healthy control (CON) groups on measures of strength, performance, and biomechanics during a single-leg double hop. Biomechanics were analyzed at the time of initial contact (IC) with the ground and joint displacement (DSP) during landing. Statistical differences between the ACLR Injured and Uninjured as well as between the ACLR Injured and both CON limbs were analyzed using a two-factor (Group, Limb) Generalized Estimating Equations.

Results: The ACLR Injured limb demonstrated statistically significant deficits in quadriceps strength \(p = 0.020\), hamstrings strength \(p < 0.001\), and hop distance \(p < 0.001\). However, clinical differences were not evident as limb symmetry indices were within current clinical guidelines \(\geq 90\%). The ACLR Injured limb had less knee flexion at IC \(p < 0.001\) and DSP \(p = 0.007\) compared to the Uninjured limb. The ACLR Injured limb displayed greater hip adduction DSP (Uninjured, \(p < 0.001\); Index, \(p = 0.003\)) and knee internal rotation DSP (Uninjured, \(p < 0.001\); Index, \(p = 0.011\)) compared to the Uninjured and CON Index limbs.
The contralateral Uninjured limb displayed greater peak knee extension (Injured, $p < 0.001$; Non-Index, $p < 0.001$), and lesser hip extension (Injured, $p = 0.038$; Non-Index, $p = 0.032$) and ankle plantarflexion (Injured, $p = 0.002$; Non-Index, $p = 0.004$) moments compared to the Injured limb and the CON Non-Index limbs. The Injured limb also displayed greater peak knee valgus moment (Index, $p = 0.017$) and less anterior tibial shear force (Uninjured, $p = 0.001$; Index, $p = 0.043$). No statistically significant differences in vertical ground reaction force were observed.

**Conclusions:** Current return to sport guidelines following ACLR often utilize performance measures presented as a symmetry index relative to the previously Uninjured limb. Evaluating the quality of movement during functional performance tests may be an important enhancement to these guidelines for determining readiness for return to sport.
INTRODUCTION

Rupture to the anterior cruciate ligament (ACL) is a devastating injury for a young adolescent athlete. Females in particular have a substantially increased risk of ACL injury from participation in sport. Unfortunately, failure to return to pre-injury activity levels,\(^1,2\) future onset of osteoarthritis,\(^3,4\) and the occurrence of subsequent ACL injury\(^5\) are imminent.

Widespread rehabilitation guidelines typically allow athletes to return to sport within 6-9 months of surgery. The most commonly cited return to sport criterion include; (1) lower extremity muscle strength, (2) lower limb performance symmetry, and (3) knee exam of range of motion and effusion.\(^6\) Single-leg functional hop tests are often used to evaluate symmetrical performance after ACLR because they are simple and quick to use in a clinical setting, do not involve expensive equipment, and use the opposite limb as a control.\(^7\) Single-leg hop symmetry, calculated as a limb symmetry index (LSI), greater than or equal to 85-90% is often cited as satisfactory.\(^6,8\) However, the relationship between functional test performance and future athletic success (performance) is not well established.\(^9\)

Single-leg functional hop tests were initially developed to fill the void in existing rehabilitation guidelines, traditionally assessing strength, laxity, and range of motion for returning a patient to sport. Symmetry indices were designed to assess strength and confidence in the involved leg, while signaling patients who may be at greatest risk for giving way during functional activities.\(^10\) Previous research has demonstrated the ability of single-leg hop tests to detect differences between the Injured and Uninjured legs.\(^7,11-14\) However, even at the inception, Noyes et al.\(^7\) advised that normal scores on functional hop tests did not eliminate a patient from the risk of giving way during actual sport situations.
Quadriceps strength deficits in the injured leg have been identified as far as fifteen years following ACLR in comparison to the previously uninjured leg. Quadriceps strength has been positively associated with single-leg hop performance in those with a history of ACLR, such that greater strength is related to greater hop distance. Deficits in the ACLR injured limb in both isokinetic quadriceps strength (120°/s, 240°/s) and single-leg hop distance have been identified nearly two years following ACLR in comparison to the uninjured limb and a healthy matched control limb. The authors did not report LSI values for hop distance, which equate to approximately 89.8% in the ACLR group and 100.9% in the control group. While statistically different, using current clinical standards these symmetry values would actually be considered clinically acceptable (≥ 85%) regardless of the differences in hop distance.

Until more recently, the quality of movement during single-leg functional hop tests had not been considered. Rates of subsequent ACL injury in adolescent female athletes after full return to sport are upwards of 29% within the first two to three years. Younger patients are more likely to suffer a subsequent injury and females may be more apt to experience a subsequent ACL injury on their contralateral, or previously uninjured leg. Biomechanical deficits and asymmetries persist in adolescents following ACLR during double-leg landing tasks, such that they are over reliant on the previously uninjured limb to absorb landing forces. Reductions in vertical ground reaction force (VGRF) and internal knee extension moment (KEM) as well as altered movement profiles have been identified. Removing the ability to rely on the previously uninjured limb for support during landing by introducing a single-leg task, compels the ACLR injured limb to find a way to achieve success. However, single-leg hop performance (distance) seems to be disconnected from
successful return to sport, evidenced by the subsequent injury rate. To our knowledge previous research has not investigated the quality of movement (biomechanics) in female adolescents, after full return to sport following ACLR, while performing single-leg functional hop tests that were likely a portion of criterion they passed to achieve full clearance for sport.

Biomechanical differences in adults (ages 22-33 years) have been identified on the ACLR injured limb during a variety of single-leg hop tests. Landing with less sagittal plane flexion at the knee,\textsuperscript{24-26} less internal knee extension moment,\textsuperscript{27-29} and less vertical ground reaction force\textsuperscript{30} highlights the quadriceps dysfunction likely still present following ACLR. Greater internal extensor moments at the hip and ankle may accompany the diminished knee extensor moment on the injured limb as compensation to effectively perform a single-leg hop.\textsuperscript{29,31} The inability to efficiently absorb and produce forces on the previously injured limb likely places it at greater risk of injury during sport and creates a dependence on the previously uninjured limb. These compensations may work in a controlled laboratory setting or even on the playing field for a period of time, but future injury may be looming.

Other studies have identified differences in tibial rotation and proximal anterior tibial displacement,\textsuperscript{24} which are known to be direct ACL loading mechanisms through cadaveric research.\textsuperscript{32} Poor trunk neuromuscular control has been identified as a prospective risk factor for knee injury in females.\textsuperscript{33,34} Greater forward trunk flexion has been associated with reduced knee extension moment\textsuperscript{35} and vertical ground reaction forces during landing,\textsuperscript{36} therefore may be a movement compensation in those with ACLR to reduce loading on the previously injured knee. Due to this link between trunk flexion and landing forces, Ernst et al.\textsuperscript{31} investigated the relationship in adults post ACLR during a single-leg vertical jump.
Internal knee extension moment was less on the injured limb compared to the uninjured and control, but there were no correlations between trunk flexion angle and knee extension moment. Nevertheless, it is unknown if these differences in biomechanical variables will be similar in an adolescent female population after returning to competitive sport. There is a distinct difference between the demands of recreational physical activity and competitive sport participation. Perhaps the differences even themselves out through the inherent training involved with their associated teams, but more likely differences are present as have been demonstrated in other tasks.

High-risk female adolescent athletes with a history of ACLR have not been evaluated during single-leg hop functional test for quality of movement (biomechanics) and performance outcomes. We were interested in investigating female adolescents (ages 12-18) after full return to competitive sport with a history of unilateral ACLR in relation to age and activity matched healthy controls. The purposes of the current study were threefold; (1) evaluate lower extremity isometric strength, (2) evaluate hop performance (distance), and (3) investigate kinematics and kinetics during a single-leg double hop for distance. We hypothesized; ACLR group participants would achieve clinically acceptable levels of strength and hop distance symmetry but demonstrate within and between group differences in landing biomechanics potentially placing them at risk for subsequent injury.

METHODS

The current study utilized a cross-sectional design to investigate differences in strength, hop performance, and single-leg landing biomechanics within the ACLR group and between the ACLR Injured limb and healthy matched control limb. The bilateral limbs of the
previously injured group (ACLR) group were referred to as the ‘Injured’ and ‘Uninjured’ limb, whereas the bilateral limbs of the healthy control group (CON) were referred to as the ‘Index’ and ‘Non-Index’ limb. Right and left CON limbs were randomly assigned to serve as the Index or Non-Index limb to match the distribution of right (n=8) and left (n=14) limb injured in the ACLR group.

**Subjects**

Twenty-two female adolescents with a history of unilateral ACLR and 25 healthy matched controls participated in this study. All subjects were high school or collegiate athletes between the ages of 12-18 years. All ACLR subjects were at least six months post ACLR and had fully returned to her primary sport prior to testing (mean = 8.18 ± 2.48 months). Surgical grafts utilized for reconstruction varied and subjects with concomitant meniscal injuries that had been surgically addressed at the time of ACLR were allowed to participate given the high incidence of concomitant ACL and meniscus injuries. Thirteen participants (56%) had concomitant meniscal injury, however associated ligament injury to the medial collateral, lateral collateral, or posterior cruciate ligaments were considered exclusionary criteria for this study. Other exclusion criteria for the ACLR group included more than one surgical intervention and musculoskeletal injury affecting either lower extremity, other than the primary ACL injury. All subjects completed supervised rehabilitation following ACLR and prior to full return to sport, however individual return to sport criteria are unknown. Anecdotally, subjects reported a variety of open and closed kinetic chain exercises with double- and single- leg hopping exercises towards the end of their rehabilitation progressions.
Healthy control subjects (CON) were matched by age, height, body mass, and sport participation to the ACLR group. The participant’s current height, weight, and mid-parents height was used to predict mature height with the Khamis-Roche protocol. The ACLR group (99.80% ± 1.09) and the CON group (99.68% ±1.10) had reached their estimated mature height at the time of testing. Pubertal maturation was estimated using the pubertal maturation observation scale, whereby all participants were post pubertal at the time of testing. There was an equal distribution of ACLR and CON participants competing in a variety of sports, including soccer, basketball, lacrosse, volleyball, softball, and gymnastics. The limbs of the CON group were randomly assigned to serve as the Index (‘Injured’) or Non-Index (‘Uninjured’) limb in a manner that matched the distribution of ACL injury on the right and left limbs of the ACLR group as described previously. This limb assignment procedure also resulted in similar distributions of dominant kicking limbs that were Injured in the ACLR group (n=12) or assigned as the Index limb in the CON group (n=10). However, matching based primarily on kicking limb dominance was not possible due to the lack of left limb kicking dominant participants in the CON group. CON subjects had no history of lower extremity surgery or other musculoskeletal injury to either lower extremity or trunk within the past six months. The study protocol was approved by the University’s Institutional Review Board, and informed consent, minor or adolescent assent, and parental consent (subjects < 18 yrs) was obtained from all subjects and parent/guardian prior to data collection. Subjects reported to the research laboratory for a single data collection session.
Procedures

Subjects completed a health history and physical activity questionnaire, with the help of a parent/guardian when necessary, prior to testing. The subjective questionnaire obtained details pertaining to the subjects’ health history and specifically the ACL injury in the previously injured group. Subjects also completed the Marx activity rating scale, which quantifies physical activity. The scale measures specific components of function, rather than type of sport, and is scored out of a total of 16 points. A twelve out of 16 points on this scale would indicate they perform running, cutting, deceleration, and pivoting activities two to three times per week. ACLR subjects completed two scales, one considering how often they performed each activity in their healthiest and most active state prior to knee injury and one considering how often they perform each activity currently. Results were used to confirm similar physical activity levels between groups. The Marx scale is a valid and reliable assessment tool in the knee injured population.\(^{39,40}\)

Subjects wore dark colored spandex shorts and sports bra with their own running shoes for testing. No turf shoes, court shoes, or cleats were allowed. Anthropometric data, including height and body mass, were recorded prior to warm-up. A five-minute warm-up was performed on a stationary bicycle at an estimated rating of perceived exertion (RPE) of 12 followed by self-selected lower extremity stretching. Single-leg landing biomechanics were captured first followed by lower extremity isometric strength testing.

Single-Leg Landing Biomechanics

After the warm-up, 29 reflective markers were placed on each participant in the following locations: bilaterally on the tip of the acromion process, anterior superior iliac
spine (ASIS), greater trochanter, anterior thigh, medial femoral epicondyle, lateral femoral epicondyle, anterior tibia, medial malleolus, lateral malleolus, calcaneus, head of the 5th metatarsal, and head of the 1st metatarsal. Additional markers were placed over the seventh cervical vertebra, L4-L5 lumbar vertebrae, and a customized cluster containing three markers was placed over the sacrum (sacrum, left PSIS, right PSIS).

Marker coordinate data were captured using a seven-camera motion analysis system with a sampling frequency of 120 Hz (Vicon Systems, Centennial, CO). Ground reaction force data was captured with two floor embedded force plates with a sampling frequency of 1200 Hz (Bertec Corporation, Worthington, OH). A global axis system was defined for the laboratory capture volume, and local coordinate systems for each body segment were aligned such that the positive X-axis was oriented in the direction the participant was facing, the positive Y-axis was oriented to the participants left, and the positive Z-axis was oriented superior. The ankle joint center and knee joint centers were estimated as the midpoint between the malleoli and femoral epicondyles, respectively. The hip joint center was estimated based on the location of the anterior superior iliac spines according to the Bell method.41 The axis systems of both force plates were aligned to the global coordinate system of the laboratory defined by the motion capture system. Digital camera data were imported in Vicon Nexus software for integration with the force plate data and marker identification. Following a static standing trial, subjects performed the SDH.

**Single-Leg Double Hop**

The single-leg double hop task is a hybrid of the single-leg hop for distance and a single-leg triple hop for distance.7,13 The goal was to incorporate a land and go maneuver
that would require quick stabilization followed immediately by a maximal hop to best allow us to discriminate between limbs, but also to maintain the subject in the motion analysis capture volume. Therefore, to perform the single-leg double hop (SDH), the subject stood on a single leg, performed two consecutive forward hops in an attempt to cover as much distance as possible (Figure 1).

The start position was standardized so that all subjects started 30-inches (76.2 cm) from the force plate. We standardized the start distance so that the horizontal velocity of the center of mass would be similar for each subject as they reached the force plate and not influence our biomechanical calculations. This start distance was selected based on reports from the Centers for Disease Control and Prevention (CDC) estimating the average height of teenage girls between the ages of 12-17 to be between 62-64 inches. Through pilot testing, we chose a distance slightly half the average height as a challenging but safe distance for this population.

Subjects started in a semi-crouched position directly in line with the force plate. They were instructed to “hop forward to the force plate and immediately hop forward again as far as you can on the same leg.” Subjects were required to hold the second landing just long enough that their heel position could be marked on the floor for later measurement. Distance was measured and recorded for all trials from the toe position at the start line (marked on the laboratory floor) to just behind the heel upon landing from the second hop. Arm movement was not restricted for this task. All subjects performed three successful trials on each leg with 30 seconds of rest between trials and two minutes of rest between legs. Limb test order was counterbalanced between subjects. All subjects performed a standard three practice trials on
each leg, followed by one minute of rest prior to data collection. The arithmetic mean of hop distance for three SDH trials on each leg was calculated and used for statistical analysis.

**Isometric Strength Testing**

Peak isometric force was assessed bilaterally on all subjects using a handheld dynamometer (Catillon CSD 300, Amtek, Inc., Largo, FL) by the primary examiner (RLB) in standardized testing positions. Subjects performed three separate 5-second maximal voluntary isometric contractions (MVIC) for knee extension (quadriceps), knee flexion (hamstrings), and hip abduction (gluteus medius) on each leg. Knee extension was assessed with the subject positioned prone on the treatment table with their knee flexed to 90 degrees. The investigator applied manual resistance with the handheld dynamometer to the test limb just proximal to the anterior ankle in the direction of knee flexion. Knee flexion was also assessed with the subject positioned prone on the treatment table with their knee flexed to 90 degrees. The investigator applied manual resistance with the handheld dynamometer to the test limb just proximal to the posterior ankle in the direction of knee extension. Two straps were secured over the low back and proximal thigh to ensure no compensation was occurring during these two tests. Hip abduction was assessed with the subject positioned sidelying on the treatment table. The investigator applied manual resistance to the test limb just above the knee on the lateral aspect of the thigh in the direction of hip adduction. Attention was paid to maintain shoulder, hip, and limb alignment with slight hip internal rotation to isolate the gluteus medius muscle. The subject was instructed to maintain the position and push against the resistance with maximal effort.
Isometric strength testing order was randomized and the same assessment order was repeated on both limbs. The Uninjured or Non-Index Limb performed each assessment first. Verbal encouragement was used to promote maximal effort. Subjects were given one minute of rest between each trial to minimize the risk of fatigue. Peak force in Newtons (N) was recorded for each of the three trials. The arithmetic mean of three trials was calculated and normalized using an allometric scaling method based on the principle of geometric similarity.\textsuperscript{45, 46} Specifically, dividing strength by the body size variable raised to an appropriate power has been theorized to eliminate the effects of body size. This procedure normalizes force measured by the dynamometer and takes into account variations in muscle cross-sectional area as a function of body mass (kg). The equation used for normalization in this study was $S_n = S/m^{2/3}$, where $S_n$ is the normalized strength value, $S$ is the force (N) measured by the hand-held dynamometer, and $m$ is the body mass (kg). High intrarater reliability was established prior to data collection for all measures (Knee Extension ICC \((3,1) = 0.999\), SEM = 2.08N; Knee Flexion ICC \((3,1) = 0.996\), SEM = 1.12N; Hip Abduction ICC \((3,1) = 0.998\), SEM = 3.18N).

**Biomechanical Data Reduction**

Three-dimensional kinematic data of the trunk, hip, knee, and ankle were defined using an Euler angle sequence $Y', X'', Z''$; such that the first rotation was defined about the y-axis, second rotation about the x-axis, and third rotation about the z-axis.\textsuperscript{47} Trunk angles were calculated as the trunk reference frame relative to the pelvis. Hip angles were calculated as the femur reference frame relative to the pelvis. Knee angles were calculated as the tibia reference frame relative to the femur. Ankle angles were calculated as the foot reference
frame relative to the tibia. Internal joint moments were calculated using a traditional inverse dynamics approach.\textsuperscript{48}

Raw kinematic and kinetic data were exported into a customized software program for data reduction (Mathworks, Natick, MA, version 11.0). Kinematic data were filtered using a low-pass Butterworth 4\textsuperscript{th}-order filter at 12 Hz cutoff frequency. All internal joint moments were normalized to the product of body height (m) and body weight (N). All ground reaction force and anterior tibial shear force data were normalized to body weight (N). Initial contact (IC) was defined as the first time point during each trial that the vertical ground reaction force exceeded 10N and toe-off was defined as the first time point during each trial that the vertical ground reaction force dropped below 10N. The total stance phase was defined as the time period from IC to toe-off. The landing phase was defined as the first 50\% of the stance phase. Kinematic variables were evaluated at the time point of IC and joint displacements (DSP) were calculated during the landing phase. DSP was calculated for each kinematic variable by subtracting joint angles at IC from peak joint angles during the landing phase (DSP = Peak – IC). The kinematic dependent variables included two-dimensional trunk, three-dimensional hip and knee, as well as sagittal plane ankle angles. The kinetic dependent variables were assessed as peak values during the landing phase and included peak sagittal plane extensor moments at the hip, knee, and ankle along with peak knee valgus moment, peak vertical ground reaction force (VGRF), and peak anterior tibial shear force (ATSF).
**Statistical Analyses**

Independent samples t-tests were performed to compare subject demographic data for age (years), height (cm), and body mass (kg) between groups. Non-parametric Mann-Whitney U analyses were performed to assess Marx activity rating scores between groups prior to and after injury. The purpose of these analyses was to ensure groups were similar at testing aside from injury status.

Differences in single-leg hop distance, lower extremity strength, trunk kinematics, and lower extremity kinematics and kinetics were assessed via linear regression models using generalized Estimating Equations (GEE). The GEE model adjusts for potential unknown correlations when investigating limbs bilaterally. Separate two-factor (Group, Limb) GEE models were performed for each dependent variable. Three pairwise comparisons were evaluated (1) ACLR Injured * ACLR Uninjured, (2) ACLR Injured * CON Index, and (3) ACLR Uninjured * CON Non-Index limbs. An *a priori* alpha level of 0.05 was utilized to determine statistical significance for all analyses performed. All statistical analyses were performed using IBM SPSS Statistics (IBM Corp., Armonk, NY, v.21.0).

Analyses for the SDH task were initially performed with the dominant balance limb as a covariate. Results were not influenced by dominant balance limb so it was removed from the model for reporting. Dominant kicking limb could not be utilized as a covariate as there were no CON subjects who self-reported left limb kicking dominance.
RESULTS

Subject Demographics

There were no significant differences between groups on measures of age ($t_{45} = -0.56$, $p = 0.58$), height ($t_{45} = 1.72$, $p = 0.09$), body mass ($t_{45} = 0.94$, $p = 0.35$), or Marx activity rating scores pre- or post- ACLR (Pre $z = -1.48$, $p = 0.14$; Post $z = -1.69$, $p = 0.09$), indicating groups were similar at the time of testing on these measures. Subject demographics and group characteristics are reported in Table 1.

Performance Measures

We observed significantly greater hop distance on the ACLR Uninjured limb in comparison to the previously Injured limb ($p < 0.001$), indicating asymmetrical performance. However, there were no differences between the ACLR Injured limb and the CON Index limb ($p = 0.535$) or between the ACLR Uninjured limb and the CON Non-Index limb ($p = 0.386$) for hop distance, indicating similar performance compared to a healthy control subject.

We also observed significantly greater strength on the ACLR Uninjured limb in comparison to the Injured limb for measures of isometric quadriceps (mean difference = 1.23 N/kg, $p = 0.020$) and hamstrings strength (mean difference = 2.83 N/kg, $p < 0.001$). The ACLR Uninjured limb also demonstrated greater isometric quadriceps strength (mean difference = 1.43 N/kg, $p = 0.024$) compared to the CON Non-Index limb. However, there were no statistically significant differences between the ACLR Injured limb and the CON Index limb on any strength measure, indicating the Injured limb was not strength deficient in
comparison to a healthy CON population, but ACLR subjects were asymmetrical in quadriceps and hamstrings strength. No differences were observed on measures of hip abductor strength ($p > 0.05$). Descriptive data for performance measures; including hop distance and isometric strength (Mean, SE, 95% Confidence Intervals) are presented in Table 2.

**Landing Biomechanics**

At initial contact, the ACLR subjects were asymmetrical in their knee flexion as the Injured limb displayed less knee flexion in comparison to the Uninjured limb ($p < 0.001$). There were no other significant findings for kinematics at initial contact ($p > 0.05$). Thus, while ACLR subjects were asymmetrical in knee flexion at initial contact, their knee flexion at initial contact was similar to healthy control subjects. There were no differences between the ACLR Uninjured limb and the CON Non-Index limb at IC ($p > 0.05$).

During the landing phase, we again observed asymmetrical knee flexion motion as the ACLR Injured limb displayed less knee flexion displacement (DSP) compared to the Uninjured limb ($p = 0.007$). In the frontal plane, performing the single-leg double hop on the ACLR Injured limb resulted in greater hip adduction DSP in comparison to the Uninjured ($p < 0.001$) and CON Index ($p = 0.003$) limbs. A similar pattern was observed in the transverse plane as the ACLR Injured limb demonstrated greater knee internal rotation DSP in comparison to the Uninjured ($p < 0.001$) and CON Index ($p = 0.001$) limbs. Thus, hip adduction and knee internal rotation DSP in ACLR subjects was asymmetrical between limbs and also significantly altered compared to healthy control subjects. While it did not reach statistical significance, the ACLR Injured limb was trending towards less hip flexion DSP in
comparison to the Uninjured limb \((p = 0.051)\). There were no significant differences between the ACLR Uninjured limb and CON Non-Index limb \((p > 0.05)\). Descriptive statistics for all kinematic variables analyzed (means, SE, 95% confidence intervals) are reported in Tables 3 and 4.

Knee joint loading was largely asymmetrical between the Injured and Uninjured limbs of ACLR subjects. The Injured limb demonstrated greater internal hip extension moment \((p < 0.038)\) and ankle plantar flexion moment \((p = 0.002)\) with lesser internal knee extension moment \((p < 0.001)\) and anterior tibial shear force \((p = 0.043)\) compared to the Uninjured limb. The Injured limb also demonstrated greater internal knee valgus moment \((p = 0.017)\) and lesser anterior tibial shear force \((p = 0.001)\) in comparison to the CON Index limb. The ACLR Uninjured limb was also different in comparison to the CON Non-Index limb, such that the ACLR Uninjured limb demonstrated lesser internal hip extension moment \((p = 0.032)\) and ankle plantar flexion moment \((p = 0.004)\) with greater internal knee extension moment \((p = 0.017)\) compared to the CON Non-Index limb. Table 5 displays descriptive statistics for all kinetic variables analyzed (means, SE, 95% confidence intervals).

**DISCUSSION**

The primary findings of this study were that the ACLR group participants did demonstrate asymmetry in hop distance and lower extremity strength, such that the previously Uninjured Limb outperformed the Injured limb. However, the ACLR Injured limb was not different than the healthy CON group on any performance measure, suggesting that the primary difference is triggered by the Uninjured limb. This finding is supported by the greater quadriceps strength on the Uninjured limb when compared to the CON Non-Index limb.
limb. Regardless of performance, important biomechanical differences were observed within and between groups that could potentially place the ACLR group participants at risk of suffering a subsequent injury. A better understanding of movement compensations in this high-risk population is essential.

Younger athletes may be more likely to return to sport following ACLR, but the longevity of participation is not fully understood. Recently, a large sample of patients (n=561) who had undergone ACLR, with a minimum 3-year follow-up, were questioned about the incidence of ACLR graft rupture or contralateral ACL rupture. The highest incidence of subsequent ACL injury occurred in patients who were younger than 20 years old at the time of surgery. In this age group, 29% had experienced a subsequent injury and those that returned to cutting/pivoting sports were 5-times more likely to rupture the contralateral ACL. The subjects in our current study were a mean age of 16.68 years old at the time of data collection. However, the mean time from surgery to testing was approximately 1.5 years, thereby these subjects were even younger at the time of surgery. All subjects had been cleared for full sports participation and had returned to playing their primary sports. Unfortunately, they are at a substantially increased risk of suffering a subsequent ACL injury. Our hope is that the findings of the current research study provide valuable information to clinicians, coaches, and parents about the importance of quality of movement evaluation in conjunction with performance measures when determining overall readiness to return to sport.

Adolescent females are more apt to suffer a primary ACL injury largely due to pre-existing neuromuscular and biomechanical characteristics. Returning the Injured limb to the level of the Uninjured limb may not be an adequate comparison to determine readiness for
the playing field. Our results show the previously Injured limb did perform to the level of the healthy CON participants with no prior history of ACLR. Clinically, the ACLR group subjects would be considered symmetrical for quadriceps strength (93.98% ± 13.53) and hop distance (95.24% ± 5.21) according to current guidelines of normal ≥ 85-90%. However, we identified statistically significant differences within the ACLR group on both measures indicating they are asymmetrical. Hamstrings strength in the ACLR group participants would be considered clinically asymmetrical (72.60% ± 19.91) and was also statistically different in our sample. A standard LSI value that falls below the normal level may lead many to believe the Injured limb is deficient and need to improve when in some cases it may actually be the previously Uninjured limb is overloaded as evidenced by the greater quadriceps strength on the Uninjured limb when compared to the CON Non-Index limb as well. Healthy CON group comparisons are important to elucidate the full picture. Biomechanical assessments of movement help to clarify this argument.

We acknowledge that we do not have detailed information on individual rehabilitation protocols or return to sport criterion for the subjects. We also acknowledge the importance of quantifying performance during functional tasks for a variety of reasons. Quantifying outcomes of an exercise can be a great motivational tool for a patient. Athletes are inherently competitive and this may aid in keeping rehabilitation exciting and giving them something specific to work towards. These numbers may aid in improving the psychological readiness to return to sport, allowing the athlete to believe they can compete. Performance measures are also important for coaches and parents and even physicians to understand progress. However, the quality of movement should move up the reins in value so that we can better understand how they achieve their functional performance outcomes.
The remainder of the discussion is organized such that biomechanical differences by plane of motion, including sagittal, frontal, and transverse plane characteristics will be addressed separately.

**Sagittal Plane**

Interestingly, differences in sagittal plane kinematics and kinetics were mostly observed between the ACLR Injured and Uninjured limbs. Aside from anterior tibial shear force, there were no between group differences on sagittal plane biomechanical measures.

The ACLR Uninjured limb landed with the knee in a more flexed position and moved through more overall sagittal plane DSP in comparison to the previously Injured limb. The Injured limb performed the task with a similar degree of knee flexion compared to the healthy CON group. Our findings are in agreement with previously published research in adults, which demonstrated less knee flexion at initial contact and during stance on the Injured limb compared to the Uninjured during a single-leg forward hop. Orishimo et al. also found a clinically acceptable hop distance symmetry (93%) in their sample of adults (age = 33±10 years), 7-months post ACLR, whom also demonstrated differences in landing strategy.

Knee flexion angle and muscles acting on the knee joint directly affect the mechanisms that pose a threat to the ACL. Based on cadaveric studies, anterior tibial translation, knee valgus, and tibial rotation are the three most likely mechanistic factors that directly load the ACL. Previous research has demonstrated increased ACL loading at small knee flexion angles (0-45°) during dynamic movement, largely due to quadriceps activity. In the current study, the mean difference between the Injured and Uninjured limbs
was approximately 3° of knee flexion at initial contact. The Injured limb knee flexion angle was similar to that of the CON Index limb. While statistically significant, the clinical relevance is questionable due to the small difference between limbs. Females have often displayed decreased knee flexion at IC with the ground compared to males performing the same tasks,\textsuperscript{51} \textsuperscript{52}, \textsuperscript{53} which is theorized to contribute to greater ACL injury incidence.\textsuperscript{54} In our adolescent female sample, knee flexion angle at initial contact ranged from 15-18 degrees on all limbs, which is a relatively extended knee position and the slightly increased flexion observed on the Uninjured limb may not be protective to the ACL. However, the single-leg double hop task may not require a large amount of knee flexion due to the quick land-and-go nature of the maneuver.

Sagittal plane internal extensor moments also differed between the ACLR Injured and contralateral Uninjured limb as well as between the ACLR Uninjured and the CON Non-Index limbs. These results suggest an altered strategy by the contralateral Uninjured limb to perform the task. The ACLR Uninjured limb displayed greater peak knee extension moment during landing in comparison to the Injured and Non-Index limbs, while utilizing lesser hip extension and ankle plantar flexion moments to decelerate the forward momentum of the body. We also identified lesser peak anterior tibial shear force on the Injured limb compared to the Uninjured and the CON Index limb. Lower knee extensor moments on the ACLR Injured limb have been reported during gait,\textsuperscript{55}, \textsuperscript{56} double-leg landing,\textsuperscript{23} as well as single-leg landing in adults.\textsuperscript{27-29, 31} Oberlander et al.\textsuperscript{29} identified a similar pattern of extensor moments, such that the ACLR Injured limb utilized less knee extension with greater hip extension and ankle plantar flexion moments during a single-leg forward hop. However, they found the ACLR patients were able to reduce the knee moments by flexing their trunk to a greater
degree before ground contact, thereby shifting the body’s center of mass anterior, and encouraging greater hip and ankle extensor moments.\textsuperscript{23} We did not observe a difference in sagittal plane trunk motion in our subjects. Ernst et al.\textsuperscript{31} evaluated a group of young adult patients, 9-months post ACLR, during a single-leg vertical jump. These authors were interested in determining if reduced production of extensor moments at the knee would be compensated for by the hip and ankle, and to determine if forward trunk lean was associated with overall knee extensor moment. Similar to the current findings, knee extension moment and summated extension moment (hip, knee, ankle) was less on the previously Injured limb, alluding to greater contribution from the hip and ankle extensors during landing.\textsuperscript{23} However, no correlation between forward trunk lean and knee extensor moment was found.\textsuperscript{23} While our results are similar to previous research when comparing the ACLR Injured and Uninjured limbs, the comparison to the CON Index and Non-Index limbs presents a clearer picture. The ACLR Injured limb performed similarly to the CON Index limb. However, the same differences identified between the ACLR limbs were present between the Uninjured and CON Non-Index limbs. Perhaps the compensatory strategies in the sagittal plane while performing this task are in the Uninjured limb. It is challenging to interpret because performance strategies prior to injury are unknown. Quadriceps dysfunction during landing in the Injured limb likely contributed to reduced knee extensor moments and thereby reduced anterior tibial shear forces when compared to the Uninjured limb. The ACLR group subjects were successful with this task in terms of hop distance, however they shifted sagittal plane moment production to absorb and redirect landing forces to achieve success.
Frontal Plane

Frontal plane differences in kinematics and kinetics were present within the ACLR group participants, but also in comparison to the healthy CON group. Greater frontal plane hip displacement and greater frontal plane knee moment on the ACLR Injured limb were identified.

Neuromuscular control at the hip\textsuperscript{54} likely influences knee loading and potential ACL injury. We observed greater hip adduction DSP on the ACLR Injured limb in comparison to the Uninjured and CON Index limbs; therefore this difference was not driven by the Uninjured limb. Excessive hip joint adduction has been speculated to play a role in ACL injury, especially in females.\textsuperscript{54} Our results are similar to previous work in adult females with a history of ACLR. During a double-leg landing, adult females post ACLR demonstrated greater peak hip adduction on the Injured limb, at ground contact and over early stance, in comparison to healthy control subjects.\textsuperscript{57} The subjects were an older sample (age = 23 years), but were approximately 4-years removed from surgery, making many of them adolescents when surgery was performed. This speaks to the improbability of these movement patterns going away through time and likely demonstrates movement impairments that will continue if not addressed. Greater hip adduction during the stance phase in female runners has recently been identified as a prospective risk factor for developing patellofemoral pain syndrome (PFP), which is a debilitating chronic injury.\textsuperscript{58} These authors found an average peak hip adduction angle during the first 50% of running stance to be approximately 14° in females that later developed PFP. Our adolescent females with ACLR demonstrated approximately 17° of hip adduction DSP after landing in a slightly abducted position.
We also observed greater knee valgus moment on the ACLR Injured limb in comparison to the CON Index limb only. Knee valgus moment was similar between both limbs of the ACLR group. While not statistically significant, the Injured limb made initial contact with the ground with slightly more hip abduction and knee varus compared to the CON Index limb. This landing pattern would shift the vertical ground reaction force vector laterally in comparison to the knee joint center. An internal knee valgus moment would act to pull the knee in a more medial direction as the individual moves through the landing phase. Greater knee abduction moment (valgus) has previously been identified as a predictor of ACL injury in females.\textsuperscript{59} The combined hip adduction DSP and internal knee valgus moment on the Injured limb is likely a high-risk movement profile for these adolescent females.

**Transverse Plane**

Finally, the ACLR Injured limb demonstrated greater knee transverse plane DSP in the direction of internal rotation (IR) compared to the Uninjured and CON Index. As mentioned prior, tibial rotation combined with minimal knee flexion and frontal plane loading can impart an injurious load on the ACL.\textsuperscript{32} At initial contact with the ground, the mean transverse plane knee angle on the Injured limb was slightly more externally rotated (not significant) compared to the other limbs. The limb moved through significantly greater IR DSP, resulting in a less externally rotated knee during landing.

Our result did not agree with Deneweth et al.\textsuperscript{24} who found the ACLR tibia remained more externally rotated, extended, and anteriorly displaced in comparison to the Uninjured limb at initial contact and during the first 250-ms of the stance phase. There were several differences in methodology that may contribute to the dissimilarities. They analyzed a single-
hop to stabilization task over a shorter distance (30-cm), which also incorporated a small obstacle (4-cm). They utilized a very small sample of nine adults (age = 28.8±12.8 years) and tested them once the physician cleared them to begin light sports activity, which was typically 4-5 months after surgery. It is unknown if the subjects would present differently at a similar time point post surgery, therefore making direct comparison challenging.

Recent conference proceedings from the annual meeting of The American Orthopaedic Society for Sports Medicine revealed that military cadets with greater than 5 degrees of tibial internal rotation during a double-leg jump landing were 2-4 times more likely to experience a tibial stress fracture, when compared to those with neutral or external knee rotation alignment. The ACLR Injured limb in our subjects remained in a slightly externally rotated position, but less so than all other limbs analyzed. The degree of transverse plane movement during landing and the smaller external rotation likely place this limb in a position of greater ACL loading.

There were several limitations of the current study. The reporting of injury and surgery characteristics was self-report by the subject and their parent or guardian. Surgical reports, detailed rehabilitation guidelines, and individual return to sport criteria were not obtained. Only female adolescent athletes were included in this study due to their high risk of ACL injury and subsequent injury after full return to sport. Results cannot be generalized to a male adolescent athlete population. We did not perform subgroup analyses based on surgical reconstruction procedure due to sample size. However, future research will be performed. The single-leg double hop utilized in this study was a hybrid of two well-known functional tests utilized clinically and in research. The slight differences in the task may make direct comparison to other research challenging.
Clinical Relevance

Adolescent female athletes with a history of ACLR displayed clinically acceptable levels of lower extremity strength and single-leg hop distance, while clearly displaying biomechanical movement profiles that may be problematic for future injury. Findings from this study emphasize the need to evaluate both the quality of movement and performance characteristics in our patients as return to sport is being considered.

This adolescent female population utilized less knee flexion and more of a hip and ankle strategy in producing internal joint moments on the Injured limb to decelerate landing forces. Whereby, they demonstrated greater knee flexion and more of a knee strategy in producing internal joint moment Uninjured limb. They also demonstrated more frontal plane side-to-side movement and greater rotation at the knee in comparison to healthy control athletes. These movement characteristics are readily identifiable by the human eye while patients perform single-leg functional tasks. Over several repetitions of a task, a clinician can focus on the trunk mechanics, hip mechanics, and lower limb mechanics separately to identify movement patterns that would indicate an inability to control the body’s momentum in a safe manner. Fortunately, these movement qualities may be modifiable through continued strengthening and neuromuscular training.
REFERENCES


214


Figure 1. Depiction of the Single-Leg Double Hop (SDH) Task
Table 1. Subject Characteristics for each Group

<table>
<thead>
<tr>
<th></th>
<th>ACLR Group (n=22)</th>
<th>Control Group (n=25)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>16.68 ± 1.55</td>
<td>16.91 ± 1.23</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>166.80 ± 6.04</td>
<td>170.22 ± 7.40</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>61.08 ± 8.78</td>
<td>63.32 ± 7.59</td>
</tr>
<tr>
<td>Injured Side (n)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>8</td>
<td>...</td>
</tr>
<tr>
<td>Left</td>
<td>14</td>
<td>...</td>
</tr>
<tr>
<td>Mechanism of Injury (n)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-Contact</td>
<td>16</td>
<td>...</td>
</tr>
<tr>
<td>Indirect Contact</td>
<td>6</td>
<td>...</td>
</tr>
<tr>
<td>Surgical Graft Procedure (n)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Patellar Tendon Autograft (BPTB)</td>
<td>11</td>
<td>...</td>
</tr>
<tr>
<td>Hamstring Autograft</td>
<td>10</td>
<td>...</td>
</tr>
<tr>
<td>Patellar Tendon Allograft</td>
<td>1</td>
<td>...</td>
</tr>
<tr>
<td>Concomitant Meniscus Injury (n)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meniscal Repair</td>
<td>9</td>
<td>...</td>
</tr>
<tr>
<td>Partial Menisectomy</td>
<td>4</td>
<td>...</td>
</tr>
<tr>
<td>Time from Surgery to Full Return to Sport (mo)</td>
<td>8.18 ± 2.48</td>
<td>...</td>
</tr>
<tr>
<td>Time from Surgery to Testing (mo)</td>
<td>14.52 ± 8.62</td>
<td>...</td>
</tr>
<tr>
<td>Dominant Kicking Limb (n)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td>Left</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Dominant Balance Limb (n)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>16</td>
<td>21</td>
</tr>
<tr>
<td>Left</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Primary Sport Participation (n)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soccer</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Basketball</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Lacrosse</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Volleyball</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Softball</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Gymnastics</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Marx Activity Rating Scale (High = 16)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre_ACLR (Injured group only)</td>
<td>15.32 ± 1.64</td>
<td>15.32 ± 1.64</td>
</tr>
<tr>
<td>Post_ACLR (Time of testing)</td>
<td>11.64 ± 4.92</td>
<td>13.76 ± 3.28</td>
</tr>
<tr>
<td>Maturity Estimations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skeletal Maturity Predicted Height (%)</td>
<td>99.80 ± 1.09</td>
<td>99.68 ± 1.10</td>
</tr>
<tr>
<td>Pubertal Maturation Observation Scale</td>
<td>Post Puberty</td>
<td>Post Puberty</td>
</tr>
<tr>
<td>Group</td>
<td>Mean ± SE</td>
<td>CI</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Hamstring (N/kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>8.22 ± 0.76</td>
<td>(6.74, 9.70)</td>
</tr>
<tr>
<td>Control</td>
<td>9.62 ± 0.29</td>
<td>(9.05, 10.19)</td>
</tr>
<tr>
<td>Quadriceps (N/kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>18.34 ± 0.75</td>
<td>(16.88, 19.81)</td>
</tr>
<tr>
<td>Control</td>
<td>17.89 ± 0.45</td>
<td>(17.00, 18.78)</td>
</tr>
<tr>
<td>Hip Abductors (N/kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>15.42 ± 0.46</td>
<td>(14.52, 16.31)</td>
</tr>
<tr>
<td>Control</td>
<td>14.48 ± 0.44</td>
<td>(13.61, 15.35)</td>
</tr>
<tr>
<td>Hop Distance (cm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>256.17 ± 5.26</td>
<td>(245.86, 266.47)</td>
</tr>
<tr>
<td>Control</td>
<td>260.69 ± 5.07</td>
<td>(250.75, 270.64)</td>
</tr>
</tbody>
</table>

* Indicates Significant Difference in comparison to ACLR Injured limb (P < 0.05)
** Indicates Significant Difference in Comparison to the ACLR Uninjured limb (p < 0.05)
<table>
<thead>
<tr>
<th>Group</th>
<th>Injured / Index</th>
<th>Uninjured / Non-Index</th>
<th>Inj * Uninj P-Value</th>
<th>Inj * Index P-Value</th>
<th>Uninj * Non P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SE</td>
<td>CI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk Sagittal IC</td>
<td>27.80 ± 1.76</td>
<td>(24.35, 31.25)</td>
<td>27.04 ± 1.85</td>
<td>(23.42, 30.66)</td>
<td>0.501</td>
</tr>
<tr>
<td>ACLR</td>
<td>Control</td>
<td>24.99 ± 1.25</td>
<td>(22.55, 27.44)</td>
<td>25.10 ± 1.31</td>
<td>(22.53, 27.68)</td>
</tr>
<tr>
<td></td>
<td>-0.52 ± 1.17</td>
<td>(-2.82, 1.77)</td>
<td>2.45 ± 1.50</td>
<td>(-0.49, 5.38)</td>
<td>0.197</td>
</tr>
<tr>
<td>Control</td>
<td>1.12 ± 1.03</td>
<td>(-0.91, 3.15)</td>
<td>1.92 ± 1.23</td>
<td>(-0.48, 4.32)</td>
<td>0.394</td>
</tr>
<tr>
<td></td>
<td>2.93 ± 2.99</td>
<td>(-2.92, 8.78)</td>
<td>2.46 ± 5.39</td>
<td>(-8.10, 13.02)</td>
<td>0.945</td>
</tr>
<tr>
<td></td>
<td>-1.42 ± 3.06</td>
<td>(-7.42, 4.58)</td>
<td>-2.82 ± 2.48</td>
<td>(-7.67, 2.03)</td>
<td>0.193</td>
</tr>
<tr>
<td>Hip Sagittal IC</td>
<td>-28.36 ± 2.06</td>
<td>(-32.40, -24.32)</td>
<td>-29.48 ± 1.91</td>
<td>(-33.22, -25.74)</td>
<td>0.320</td>
</tr>
<tr>
<td></td>
<td>-27.00 ± 1.24</td>
<td>(-29.44, -24.56)</td>
<td>-27.93 ± 1.31</td>
<td>(-30.50, -25.35)</td>
<td>0.374</td>
</tr>
<tr>
<td></td>
<td>-7.70 ± 1.15</td>
<td>(-9.95, -5.45)</td>
<td>-5.58 ± 0.89</td>
<td>(-7.32, -3.83)</td>
<td>0.069</td>
</tr>
<tr>
<td></td>
<td>-6.55 ± 0.89</td>
<td>(-8.29, -4.82)</td>
<td>-4.95 ± 1.07</td>
<td>(-7.05, -2.86)</td>
<td>0.653</td>
</tr>
<tr>
<td></td>
<td>8.57 ± 1.26</td>
<td>(6.09, 11.05)</td>
<td>8.10 ± 1.43</td>
<td>(5.29, 1.91)</td>
<td>0.735</td>
</tr>
<tr>
<td>Hip Transverse IC</td>
<td>6.34 ± 0.97</td>
<td>(4.56, 8.11)</td>
<td>7.12 ± 0.93</td>
<td>(5.30, 8.94)</td>
<td>0.779</td>
</tr>
<tr>
<td></td>
<td>14.55 ± 1.40</td>
<td>(11.80, 17.30)</td>
<td>15.78* ± 1.24</td>
<td>(15.35, 20.22)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Knee Sagittal IC</td>
<td>14.63 ± 0.93</td>
<td>(12.80, 16.45)</td>
<td>15.49 ± 1.03</td>
<td>(13.47, 17.52)</td>
<td>0.156</td>
</tr>
<tr>
<td></td>
<td>2.10 ± 0.83</td>
<td>(0.47, 3.72)</td>
<td>2.50 ± 0.74</td>
<td>(1.06, 3.94)</td>
<td>0.734</td>
</tr>
<tr>
<td>Knee Frontal IC</td>
<td>2.05 ± 0.66</td>
<td>(0.76, 3.34)</td>
<td>2.15 ± 0.72</td>
<td>(0.74, 3.56)</td>
<td>0.964</td>
</tr>
<tr>
<td></td>
<td>-12.29 ± 1.13</td>
<td>(-15.31, -7.26)</td>
<td>-10.69 ± 1.79</td>
<td>(-14.19, -7.79)</td>
<td>0.960</td>
</tr>
<tr>
<td></td>
<td>-10.55 ± 1.44</td>
<td>(-13.37, -7.73)</td>
<td>-10.81 ± 1.60</td>
<td>(-13.94, -7.68)</td>
<td>0.770</td>
</tr>
<tr>
<td>Ankle Sagittal IC</td>
<td>12.77 ± 1.13</td>
<td>(10.56, 14.98)</td>
<td>11.03 ± 1.90</td>
<td>(7.30, 14.76)</td>
<td>0.742</td>
</tr>
<tr>
<td></td>
<td>13.73 ± 1.46</td>
<td>(10.87, 16.58)</td>
<td>10.18 ± 1.76</td>
<td>(6.73, 13.62)</td>
<td>0.605</td>
</tr>
</tbody>
</table>

* Indicates Significant Difference in comparison to ACLR Injured limb (p < 0.05)  
** Indicates Significant Difference in Comparison to the ACLR Uninjured limb (p < 0.05)  
(−) Trunk Left Side Bend, Hip Flexion, Hip Abduction, Knee External Rotation
Table 4. Descriptive Statistics for Displacement Kinematics (*) during the Single-Leg Double Hop (Means, SE, 95% CI)

<table>
<thead>
<tr>
<th>Group</th>
<th>Injured / Index</th>
<th>Uninjured / Non-Index</th>
<th>Inj * Uninj P-Value</th>
<th>Inj * Index P-Value</th>
<th>Uninj * Non P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SE</td>
<td>CI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk Flexion DSP</td>
<td>11.24 ± 0.77</td>
<td>(9.73, 12.75)</td>
<td>12.11 ± 0.90</td>
<td>(10.35, 13.87)</td>
<td>0.161</td>
</tr>
<tr>
<td></td>
<td>Injured</td>
<td>12.99 ± 0.70</td>
<td>(11.63, 14.36)</td>
<td>13.47 ± 0.86</td>
<td>(11.78, 15.16)</td>
</tr>
<tr>
<td></td>
<td>Uninjured</td>
<td>-6.66 ± 1.17</td>
<td>(-8.95, -4.37)</td>
<td>-3.33 ± 0.80</td>
<td>(-4.89, -1.76)</td>
</tr>
<tr>
<td>Trunk Lateral Away DSP</td>
<td>3.99 ± 1.25</td>
<td>(1.54, 6.43)</td>
<td>5.42 ± 0.92</td>
<td>(3.63, 7.22)</td>
<td>0.486</td>
</tr>
<tr>
<td></td>
<td>Injured</td>
<td>-4.47 ± 1.02</td>
<td>(2.48, 6.46)</td>
<td>5.83 ± 0.92</td>
<td>(4.02, 7.63)</td>
</tr>
<tr>
<td></td>
<td>Uninjured</td>
<td>-6.60 ± 1.17</td>
<td>(-8.90, -4.30)</td>
<td>-3.46 ± 0.95</td>
<td>(-5.32, -1.59)</td>
</tr>
<tr>
<td>Trunk Lateral Toward DSP</td>
<td>4.47 ± 1.02</td>
<td>(2.48, 6.46)</td>
<td>5.83 ± 0.92</td>
<td>(4.02, 7.63)</td>
<td>0.486</td>
</tr>
<tr>
<td></td>
<td>Injured</td>
<td>-4.44 ± 1.40</td>
<td>(-9.18, -3.69)</td>
<td>-7.76 ± 1.32</td>
<td>(-10.36, -5.17)</td>
</tr>
<tr>
<td></td>
<td>Uninjured</td>
<td>-3.33 ± 0.92</td>
<td>(-4.89, -1.76)</td>
<td>-5.32 ± 0.95</td>
<td>(-7.33, -3.32)</td>
</tr>
<tr>
<td>Hip Flexion DSP</td>
<td>-4.42 ± 1.04</td>
<td>(-6.62, -2.38)</td>
<td>-6.66 ± 1.17</td>
<td>(-8.90, -4.30)</td>
<td>0.486</td>
</tr>
<tr>
<td></td>
<td>Injured</td>
<td>-16.94 ± 1.04</td>
<td>(14.89, 18.98)</td>
<td>13.24* ± 0.97</td>
<td>(11.34, 15.15)</td>
</tr>
<tr>
<td></td>
<td>Uninjured</td>
<td>13.19* ± 0.71</td>
<td>(11.79, 14.59)</td>
<td>13.39 ± 0.99</td>
<td>(11.45, 15.32)</td>
</tr>
<tr>
<td>Hip Adduction DSP</td>
<td>-4.42 ± 1.04</td>
<td>(-6.62, -2.38)</td>
<td>-6.66 ± 1.17</td>
<td>(-8.90, -4.30)</td>
<td>0.486</td>
</tr>
<tr>
<td></td>
<td>Injured</td>
<td>16.94 ± 1.04</td>
<td>(14.89, 18.98)</td>
<td>13.24* ± 0.97</td>
<td>(11.34, 15.15)</td>
</tr>
<tr>
<td></td>
<td>Uninjured</td>
<td>13.19* ± 0.71</td>
<td>(11.79, 14.59)</td>
<td>13.39 ± 0.99</td>
<td>(11.45, 15.32)</td>
</tr>
<tr>
<td>Hip Internal Rotation DSP</td>
<td>16.34 ± 1.38</td>
<td>(13.64, 19.04)</td>
<td>18.82 ± 1.68</td>
<td>(15.53, 22.12)</td>
<td>0.124</td>
</tr>
<tr>
<td></td>
<td>Injured</td>
<td>14.94 ± 1.75</td>
<td>(11.51, 18.37)</td>
<td>14.45 ± 1.97</td>
<td>(10.58, 18.31)</td>
</tr>
<tr>
<td>Knee Valgus DSP</td>
<td>-3.92 ± 0.60</td>
<td>(-5.10, -2.73)</td>
<td>-4.53 ± 0.69</td>
<td>(-5.88, -3.19)</td>
<td>0.194</td>
</tr>
<tr>
<td></td>
<td>Injured</td>
<td>36.06 ± 1.54</td>
<td>(33.05, 39.08)</td>
<td>39.33* ± 1.76</td>
<td>(35.87, 41.78)</td>
</tr>
<tr>
<td></td>
<td>Uninjured</td>
<td>39.70 ± 1.28</td>
<td>(37.20, 41.20)</td>
<td>38.80 ± 1.51</td>
<td>(35.84, 41.75)</td>
</tr>
<tr>
<td>Knee Valgus DSP</td>
<td>-4.72 ± 0.73</td>
<td>(-6.14, -3.29)</td>
<td>-3.79 ± 0.79</td>
<td>(-5.33, -2.24)</td>
<td>0.194</td>
</tr>
<tr>
<td></td>
<td>Injured</td>
<td>-3.92 ± 0.60</td>
<td>(-5.10, -2.73)</td>
<td>-4.53 ± 0.69</td>
<td>(-5.88, -3.19)</td>
</tr>
<tr>
<td></td>
<td>Uninjured</td>
<td>8.36 ± 1.29</td>
<td>(5.83, 10.89)</td>
<td>5.02* ± 0.96</td>
<td>(3.14, 6.91)</td>
</tr>
<tr>
<td>Knee Internal Rotation DSP</td>
<td>4.58* ± 0.73</td>
<td>(3.15, 6.00)</td>
<td>4.84 ± 0.78</td>
<td>(3.30, 6.38)</td>
<td>0.882</td>
</tr>
<tr>
<td>Ankle Dorsiflexion DSP</td>
<td>-20.16 ± 1.44</td>
<td>(-22.99, -17.33)</td>
<td>-21.27 ± 1.01</td>
<td>(-23.26, -19.28)</td>
<td>0.418</td>
</tr>
<tr>
<td></td>
<td>Injured</td>
<td>-23.54 ± 1.49</td>
<td>(-26.45, -20.63)</td>
<td>-23.22 ± 1.44</td>
<td>(-26.03, -20.40)</td>
</tr>
<tr>
<td></td>
<td>Uninjured</td>
<td>-23.54 ± 1.49</td>
<td>(-26.45, -20.63)</td>
<td>-23.22 ± 1.44</td>
<td>(-26.03, -20.40)</td>
</tr>
</tbody>
</table>

* Indicates Significant Difference in comparison to ACLR Injured limb (P < 0.05)
** Indicates Significant Difference in Comparison to the ACLR Uninjured limb (p < 0.05)
Table 5. Descriptive Statistics for Peak Internal Joint Moments (Nm/BHxBW), ATSF (N/BW), and Peak VGRF (N/BW) during the Single-Leg Double Hop (Means, SE, 95% CI)

<table>
<thead>
<tr>
<th>Group</th>
<th>Injured / Index</th>
<th>Uninjured / Non-Index</th>
<th>Inj * Uninj P-Value</th>
<th>Inj * Index P-Value</th>
<th>Uninj * Non P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip Extension Mom</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>0.247 ± 0.018</td>
<td>0.220* ± 0.018</td>
<td>0.038</td>
<td>0.474</td>
<td>0.032</td>
</tr>
<tr>
<td>Control</td>
<td>0.263 ± 0.013</td>
<td>0.271** ± 0.016</td>
<td>&lt; 0.001</td>
<td>0.580</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Knee Extension Mom</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>-0.169 ± 0.016</td>
<td>-0.160** ± 0.016</td>
<td>0.574</td>
<td>0.017</td>
<td>0.169</td>
</tr>
<tr>
<td>Control</td>
<td>-0.181 ± 0.016</td>
<td>-0.160** ± 0.016</td>
<td>0.002</td>
<td>0.742</td>
<td>0.004</td>
</tr>
<tr>
<td>Knee Valgus Mom</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>-0.068 ± 0.009</td>
<td>-0.062 ± 0.007</td>
<td>0.001</td>
<td>0.043</td>
<td>0.832</td>
</tr>
<tr>
<td>Control</td>
<td>-0.042* ± 0.006</td>
<td>-0.049 ± 0.006</td>
<td>0.547</td>
<td>0.547</td>
<td>0.322</td>
</tr>
<tr>
<td>Ankle Plantarflexion Mom</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>0.114 ± 0.016</td>
<td>0.074* ± 0.013</td>
<td>0.135* ± 0.017</td>
<td>0.101</td>
<td>0.170</td>
</tr>
<tr>
<td>Control</td>
<td>0.121 ± 0.015</td>
<td>0.074* ± 0.013</td>
<td>1.118* ± 0.048</td>
<td>1.024</td>
<td>1.211</td>
</tr>
<tr>
<td>Anterior Tibial Shear Force</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>1.013 ± 0.049</td>
<td>0.135** ± 0.017</td>
<td>0.001</td>
<td>0.043</td>
<td>0.832</td>
</tr>
<tr>
<td>Control</td>
<td>1.134* ± 0.034</td>
<td>1.105 ± 0.039</td>
<td>0.584</td>
<td>0.547</td>
<td>0.322</td>
</tr>
<tr>
<td>Vertical Ground Reaction Force</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR</td>
<td>2.650 ± 0.062</td>
<td>2.669 ± 0.053</td>
<td>0.484</td>
<td>0.547</td>
<td>0.322</td>
</tr>
<tr>
<td>Control</td>
<td>2.598 ± 0.064</td>
<td>2.589 ± 0.062</td>
<td>(2.529 ± 2.771)</td>
<td>(2.470 ± 2.722)</td>
<td></td>
</tr>
</tbody>
</table>

* Indicates Significant Difference in comparison to ACLR Injured limb (P < 0.05)
** Indicates Significant Difference in Comparison to the ACLR Uninjured limb (p < 0.05)
APPENDIX E: MANUSCRIPT THREE
Effect of Verbal Instructions in Acutely Altering Landing Forces in Adolescent Females with and without a History of Anterior Cruciate Ligament Reconstruction
(Clinical Journal of Sports Medicine)

**Background:** The effect of verbal instructions in acutely altering landing forces in adolescent females with a history of anterior cruciate ligament (ACL) injury and reconstruction (ACLR) is currently unknown. This information may inform rehabilitation and return to play guidelines, while reducing the risk for subsequent injury.

**Aim:** Determine the effects of two different verbal instructions on changing vertical ground reaction force (VGRF) during a double-leg jump landing in adolescent female athletes with and without a history of ACLR.

**Methods:** Bilateral landing forces were recorded during three blocks of jump landing trials with baseline, soft landing, or equal landing verbal instructions. Twenty-two adolescent females with unilateral ACLR and full return to sport and 25 healthy matched controls (CON) participated. Change scores within ACLR limbs (Injured, Uninjured) and CON limbs (Index, Non-Index) were calculated from baseline to each verbal instruction condition. We compared peak VGRF change scores and limb symmetry index (LSI) within and between groups.

**Results:** No difference in VGRF change was observed between the ACLR Injured and CON Index limbs following the soft landing instructions ($p=0.268$), both had similar reductions. The ACLR Uninjured limb had a greater magnitude reduction in VGRF following the soft landing (Injured, $p = 0.005$; Non-Index, $p = 0.043$) and equal landing instructions (Injured, $p=0.041$). Equal landing instructions did not result in VGRF change in the ACLR Injured or CON Index limbs. A significant main effect for Group LSI ($p=0.001$) revealed the ACLR
group had greater asymmetry across all conditions. A main effect for Condition LSI 
($p=0.034$) revealed the equal landing instructions significantly reduced asymmetry compared 
to baseline ($p=0.018$), regardless of group. No group x limb interaction was present.

**Conclusions:** The ACLR Injured limb responded to verbal instructions in a manner that was
similar to the CON group. However, the ACLR group participants had greater loading 
asymmetry between limbs across all conditions compared to the CON group demonstrating a
disparity between groups.
INTRODUCTION

The incidence of sport related anterior cruciate ligament (ACL) injuries in the adolescent population is on the rise,\textsuperscript{1-4} with female injury rates increasing by age twelve and peaking near age eighteen.\textsuperscript{5, 6} Double-leg jump landings have been implicated as a primary action in females when sustaining an ACL injury,\textsuperscript{7} likely due to large impact forces that are generated during landing. Greater peak vertical ground reaction force (VGRF) during landing has been observed in female athletes who later went on to suffer an ACL injury in comparison to those who did not.\textsuperscript{8} Greater VGRF is strongly correlated with greater anterior tibial acceleration,\textsuperscript{9, 10} which directly loads the ACL.\textsuperscript{11} A softer landing, moving through larger sagittal plane range of motion allows the muscles to absorb energy, thereby decreasing VGRF.

ACL injury prevention programs strive to improve neuromuscular control and minimize knee loading. The most successful reduction in VGRF has been observed when injury prevention programs incorporate verbal instructions and feedback on proper movement technique.\textsuperscript{12} Verbal instructions are a form of augmented feedback, providing supplemental information to the individual, beyond the information that is naturally available to them.\textsuperscript{13} Verbal instructions, in conjunction with expert demonstration or video feedback, have resulted in acute changes in double-leg landing mechanics, including decreased VGRF in healthy individuals.\textsuperscript{14-17} Verbal instructions alone have also shown success in decreasing landing forces in healthy individuals.\textsuperscript{18-21} Mizner et al.\textsuperscript{21} investigated the relationship between lower extremity strength and the ability to change landing patterns given verbal instructions in a group of healthy collegiate female athletes (19.5±1.2 yrs). Peak VGRF was reduced with verbal instructions, but lower extremity strength was not a significant predictor
of the change. The general landing instructions were “try to land as softly as you can,” but were also to “increase bending in the knees, land on toes, keep chest over knees, keep knees over toes, and avoid knee valgus during landing.” While the dosage was successful, it is unclear which instruction(s) was beneficial. Verbal instructions are often technical, describing in great detail how one would like the individual to land. Recently, Milner et al. investigated the effects of three different simple verbal instructions on acute knee biomechanics in healthy female athletes during a double-leg countermovement jump. The simple instructions were to land “(1) with knees over your toes, (2) with equal weight distribution on both of your feet, or (3) as softly as possible.” Results indicated that the instructions specific to ‘land softly’ reduced peak VGRF and the instructions specific to ‘land with equal weight’ reduced the asymmetry of peak VGRF compared to the control condition. The novelty of this study was that it demonstrated instructions can and likely should be simple and evaluated symmetry between limb loading. However, previous research has solely investigated the acute effects of verbal instructions in healthy active individuals, therefore it is unknown if similar instructions are effective in those with a history of ACL injury.

Young female athletes with a history of ACL injury and surgical reconstruction (ACLR) are at substantially increased risk of suffering a subsequent injury when returning to sport. Muscle activation during landing allows the mass of the body segments to decelerate over a longer period of time, or softer, in order to decrease VGRF. Following ACLR, reduced knee flexion when performing double- and single-leg landing activities has been observed on the previously injured limb in comparison to the uninjured limb and healthy control participants. Adults and adolescents post ACLR rely more heavily on their
previously uninjured limb to absorb landing forces, demonstrating asymmetries in VGRF. This landing pattern would expose the previously uninjured limb to higher forces, which have been associated with ACL injury. Quadriceps dysfunction following knee injury may play a role in altering biomechanical performance in ACL injured populations. Therefore, it is unknown if adolescent female athletes with a history of ACLR would be able to attend to simple verbal instructions and effectively change their landing forces in a similar manner to previously investigated healthy populations.

Therefore, the purpose of this study was to determine the effects of two different simple verbal instructions on VGRF during a double-leg jump landing in adolescent female athletes with and without a history of ACLR. We were particularly interested in investigating adolescent females whom had fully returned to sport following ACLR as they are known to be at increased risk of subsequent injury to either limb. Differences between conditions and groups were evaluated utilizing both change scores between conditions and limb symmetry index values at baseline and following “soft landing” instructions and “equal landing” instructions. We hypothesized that all participants would decrease VGRF and improve symmetry in VGRF with instructions, but the magnitude of change would be greater in the healthy control participants.

METHODS

The current study employed a quasi-experimental, repeated measures, cross-over design to investigate the effectiveness of two different verbal instruction conditions on altering landing forces in adolescent females during a jump landing task. All participants received each set of verbal instructions within a single testing session in a counterbalanced
order with an active washout period between each condition. Additional functional tasks were utilized as the active washout to distract each participant from the prior instructions. The limbs of the previously injured group (ACLR) were referred to as the ‘Injured’ and ‘Uninjured’ limb. The limbs of the healthy control group (CON) were referred to as the ‘Index’ and ‘Non-Index’ limb. Right and left CON limbs were randomly assigned to serve as the Index or Non-Index limbs to match the distribution of right (n=8) and left (n=14) limb injuries in the ACLR group (Table 1).

Participants

Twenty-two adolescent female athletes with a history of unilateral ACLR (age = 16.68 ± 1.55 yrs, height = 166.80 ± 6.04 cm, mass = 61.08 ± 8.78 kg) and 25 healthy matched control participants (age = 16.91 ± 1.23 yrs, height = 170.22 ± 7.40 cm, mass = 63.32 kg) took part in this study. All participants were high school or collegiate athletes competing in sports requiring landing, cutting, and pivoting maneuvers.

All ACLR group participants had returned to their primary sport with an average time of 8.18 ± 2.48 months (range 6-12 months) post surgery. The mean time from surgery to participation was 14.52 ± 8.62 months (range 6-24 months). Pubertal maturation was estimated using the pubertal maturation observation scale, whereby all participants were post pubertal at the time of testing. Participants with concomitant meniscal injury (56%) that had been surgically addressed at the time of ACLR were allowed to participate given the high incidence of concomitant ACL and meniscus injuries. However, associated ligament injury to the medial collateral, lateral collateral, or posterior cruciate ligaments was considered exclusionary if it altered the course of rehabilitation. All injuries were due to noncontact or
indirect contact mechanisms during their primary sport.\textsuperscript{33} Other exclusion criteria for the ACLR group included more than one surgical intervention and musculoskeletal injury affecting either lower extremity, other than the primary ACL injury. All participants completed supervised rehabilitation following ACLR and prior to full return to sport, however individual return to sport criteria was unknown. \textbf{Table 2} describes ACL injury history and activity levels for the ACLR group participants in greater detail.

Healthy control participants (CON) were matched by age, height, body mass, pubertal maturation, and sport participation. The participant’s current height, weight, and mid-parents height $[(\text{mother’s height} + \text{father’s height}) / 2]$ was used to predict mature height with the Khamis-Roche protocol.\textsuperscript{34} The ACLR group (99.80% ± 1.09) and the CON group (99.68% ±1.10) had reached their estimated mature height at the time of testing. There was an equal distribution of ACLR and CON participants from each sport, including soccer, basketball, lacrosse, volleyball, softball, and gymnastics. The limbs of the CON group participants were randomly allocated to serve as the Index or Non-Index limb based on the distribution of right and left limb ACL injuries as described previously. This limb allocation procedure also resulted in similar distributions of dominant kicking limbs that were injured in the ACLR group (n=12) or assigned as the Index in the CON group (n=10). However, matching based primarily on kicking limb dominance, as in previous research, was not possible due to the lack of left limb kicking dominant participants in the CON group.

\textbf{Procedures}

Participants wore dark colored spandex shorts and sports bra for testing with their own running shoes. No turf shoes, court shoes, or cleats were permissible. All participants
(parent/guardian) read and signed appropriate Institutional Review Board approved consent and assent forms prior to testing. They also completed subjective questionnaires to provide health history and physical activity level information. The Marx Activity Scale was utilized to capture the physical activity level of each ACLR group participant in reference to her healthiest and most active state prior to ACL injury and at the time of testing. The CON group participants completed the same scale considering their current activity level only. Results were used to confirm similar physical activity levels between groups. The Marx activity scale is a valid and reliable assessment tool in the knee injured population.35,36

Each participant performed three blocks of double-leg jump landing maneuvers receiving difference verbal instructions each time. Similar jump landing maneuvers have been previously used to identify prospective risk factors for initial8 and subsequent37 ACL injury, and verbal instructions have acutely altered landing forces in healthy female17, 21, 22 and adolescent18 populations during similar tasks. The goal of the verbal instruction conditions was to shift the focus of the participants to decreasing landing forces (soft instruction) or making landing forces more symmetrical between limbs (equal instruction). Active rest was utilized in between blocks of jump landing trials to detract the participants’ focus away from the jump landing and prior instructions. Active rest activities included bilateral single-leg forward hops after baseline, and double- and single-leg squats following condition one. Thirty seconds of rest between each trial and 2-minutes of rest between each task was provided.
Baseline Jump Landing Trials

To perform the jump landing, participants stood atop a 30-cm box placed a horizontal distance of 50% of their height from the leading edge of two force plates. They jumped forward from the box to land with one foot in the center of each force plate before immediately jumping vertically for maximal height. Standardized verbal instructions specified, “Focus on jumping forward into the target area with both feet and immediately jump straight up as high as you can.” No demonstration was provided. All participants performed a standard three practice trials prior to data collection. Three successful trials were captured with 30-seconds of rest between each trial. A trial was deemed successful if the subject left the jump box with both feet at the same time, landed on the force plates, and immediately jumped for maximal vertical height. This first block of three trials served as the Baseline for the ensuing verbal instructions intervention.

Verbal Instructions Intervention

Verbal instructions were given prior to the first jump landing trial within the condition and were reinforced through abbreviated form prior to each subsequent trial. Participants performed three successful trials within each condition, with 30-seconds rest between. The verbal instructions from the baseline condition were always stated first to remind the participant how to perform the task, followed by the specific instructions for each condition.

The standardized verbal instructions for the soft landing condition stated “This time when you perform the jump landing, I want you to focus on landing as soft as you can.” Abbreviated instructions prior to each subsequent trial included, “Focus on landing as soft as
you can.” The standardized verbal instructions for the equal landing condition stated “This time when you perform the jump landing, I want you to focus on landing with equal weight under each foot.” Abbreviated instructions associated with this condition included, “Focus on landing with equal weight under each foot.” The same investigator (RLB) provided all standardized verbal instructions.

Biomechanical data were collected using a seven-camera motion capture system (Vicon Systems, Centennial, CO) integrated with two floor-embedded force plates (Bertec Corporation, Worthington, OH). Prior to data collection, 29 reflective markers were placed on each participant in the following locations: bilaterally on the tip of the acromion process, anterior superior iliac spine (ASIS), greater trochanter, anterior thigh, medial femoral epicondyle, lateral femoral epicondyle, anterior tibia, medial malleolus, lateral malleolus, calcaneus, head of the 5th metatarsal, and head of the 1st metatarsal. Additional markers were placed over the seventh cervical vertebra, L4-L5 lumbar vertebrae, and a customized cluster containing three markers was placed over the sacrum (sacrum, left PSIS, right PSIS). Three-dimensional marker coordinate data were captured to identify the time point of peak knee flexion to define the landing phase of the jump landing. The knee joint center was estimated as the midpoint between the femoral epicondyles. Knee joint angles were defined as the tibia position relative to the thigh and were calculated using an Euler angle sequence with the first rotation defining flexion/extension.

**Data Analysis**

Marker coordinate data were sampled at 120 Hz and ground reaction force data were sampled at 1200 Hz. Kinematic data were filtered using a fourth order, low pass, Butterworth
filter with a 12 Hz cutoff frequency. All biomechanical data were collected using Vicon Nexus Software and exported using The Motion Monitor software package (Innsport Inc., Chicago, Illinois, USA). The dependent variable of interest, peak VGRF during the landing phase, was identified using a customized MATLAB program (Mathworks, Inc, Natick, Massachusetts, USA). Initial contact was defined as the first time point during each trial that the VGRF exceeded 10N. The landing phase was defined as the time period from initial contact to the time point of peak knee flexion. Therefore, peak VGRF was identified as the peak value during the landing phase. The arithmetic mean of three trials for each participant within each condition was averaged and normalized to participant’s body weight (N). Change scores and limb symmetry indices (LSI) were calculated from the normalized values for statistical analyses.

Change scores were calculated from normalized peak VGRF data by subtracting the mean value at baseline from the mean value within each verbal instruction condition. Soft change scores (Peak VGRF Soft – Peak VGRF Baseline) and Equal change scores (Peak VGRF Equal – Peak VGRF Baseline) were analyzed to evaluate the magnitudes of change influenced by verbal instruction condition within and between groups.

LSI were also calculated to compare the overall loading symmetry between conditions and groups. LSI values were calculated for the ACLR group as [((Injured – Uninjured) / Injured)*100] and for the CON group as [((Index – Non-Index) / Index)*100]. Negative values indicate greater loading of the Uninjured limb in ACLR participants or the Non-Index limb in CON participants. Larger numbers indicate a greater magnitude of asymmetry.
Participant demographics were compared using an Independent samples t-test or Mann-Whitney U test for normal and non-normally distributed variables, respectively. Changes in peak VGRF were assessed via linear regression models using generalized Estimating Equations (GEE) with two-factors (Group, Limb), to adjust the standard error and associated significance level for the comparison of bilateral limbs with unknown correlations. Change scores for three pairwise comparisons were evaluated: (1) ACLR Injured * ACLR Uninjured, (2) ACLR Injured * CON Index, (3) ACLR Uninjured * CON Non-Index.

Limb symmetry in peak VGRF was assessed via a two-factor (Group x Condition) mixed model ANOVA with group as the fixed factor and condition as a repeated measure. Tukey post-hoc analyses were performed to identify the location of differences when more than two levels were involved. An a priori alpha level of 0.05 was utilized for all statistical analyses.

RESULTS

Participant Demographics

No statistically significant differences were observed between groups on measures of age ($t_{45} = -0.56$, $p = 0.58$), height ($t_{45} = 1.72$, $p = 0.09$), mass ($t_{45} = 0.94$, $p = 0.35$), or Marx activity rating scores pre- or post- ACLR (Pre $z = -1.48$, $p = 0.14$; Post $z = -1.69$, $p = 0.09$), indicating groups were similar at the time of testing on these measures.

Change Scores

There was no statistically significant difference between the ACLR Injured and CON Index limbs in the amount of change in VGRF following the soft landing instructions ($p = \ldots$)
0.268). Both the ACLR Injured and CON Index limb experienced similar reductions in VGRF. However, in the ACLR Uninjured limb the magnitude of change in VGRF was greater than that of the ACLR Injured limb ($p = 0.005$) and the CON Non-Index limb ($p = 0.043$). Thus, the magnitude of change with soft landing instructions was asymmetrical in the ACLR group participants as the Uninjured limb experienced a greater overall reduction in VGRF than the Injured limb. The magnitude of change was also greater on the Uninjured limb in comparison to the healthy CON Non-Index limb.

The equal landing instructions did not change VGRF in the ACLR Injured limb as the 95% confidence interval of the change scores crossed zero. Similarly, there was no change in VGRF in the CON Index limb. However, there was a significant difference in the magnitude of change in the ACLR Uninjured limb compared to the ACLR Injured limb ($p = 0.041$). The ACLR Uninjured limb experienced a reduction in VGRF following the equal landing instructions. Descriptive statistics for normalized mean values and change scores (means, SE, 95% CI) are reported in Tables 3-4, respectively.

**Limb Symmetry Index**

A significant main effect for Group ($p = 0.001$) and a significant main effect for Condition ($p = 0.034$) were observed. However, we did not observe a statistically significant Group x Condition interaction ($p = 0.207$). The ACLR group had greater limb asymmetry regardless of verbal instruction condition when compared to the CON group ($p = 0.001$). Post-hoc analyses revealed that limb asymmetry was significantly reduced in all participants following the equal landing instructions in comparison to the baseline condition, regardless of group ($p = 0.018$). However, asymmetry was not altered following the soft landing
instructions ($p > 0.05$). Descriptive statistics for calculated LSI values and the significant Main Effects for Group and Condition are presented (Means, SE, 95% CI) in Table 5.

**DISCUSSION**

The primary finding of this study was that the ACLR Injured limb changed in a similar manner as healthy CON participants following instructions, but the magnitude of asymmetry between limbs in the ACLR group remained significantly larger than the CON group across all conditions. Additionally, the ACLR Uninjured limb changed following both sets of verbal instructions with a greater reduction in VGRF compared to the Injured limb and CON Non-Index limbs. The results demonstrate a distinct difference between adolescent females with a history of ACLR and adolescent female athletes free from injury, even after full return to sport.

The soft landing verbal instructions prompted a decrease in peak VGRF in the ACLR group and the CON group, however the magnitude of decrease was greater on the ACLR Uninjured limb compared to the Injured and Non-Index limbs. This observation is not surprising as the Uninjured limb was loaded to a greater extent at baseline in comparison to the Injured, therefore had more capacity to decrease. However, the magnitude of asymmetry in the ACLR group was not significantly improved following soft landing instructions. While not significant, the asymmetry value increased slightly in the CON group following the soft landing instructions. Based on previous research, we did expect to see a decrease in VGRF following the soft landing instructions. Milner et al.\textsuperscript{22} observed a 23% decrease in peak VGRF utilizing the same instructions in a small sample of recreationally active female adults. The authors analyzed peak VGRF during the landing phase of a double-leg countermovement
jump, which is a slightly different task. Larger VGRF during double-leg landing has previously been identified as a prospective risk factor in females who later sustained an ACL injury. Verbal instructions cueing movers to land as soft as possible are commonly used in a clinical and injury prevention setting. While we observed a reduction in VGRF, large asymmetry between limbs was still present in the ACLR group. We feel these instructions may not be as beneficial as the equal landing instructions, particularly in isolation, in a previously injured population.

The equal landing instructions focused the participants’ attention toward landing with equal weight under each foot. These instructions are quick and easy to dispense with exercise prescription and significantly improved limb symmetry compared to baseline in all participants, regardless of group. The healthy CON participants essentially had a shifting of their body weight absorption, and thereby peak VGRF, to the opposite side compared to baseline. The magnitude of asymmetry in the CON group from baseline (-2.36) to the equal landing condition (2.94) was very similar, just in opposite directions. These values are quite small and generally represent symmetrical loading between the CON limbs. Comparatively, the ACLR group participants remained very asymmetrical even after receiving the equal landing instructions.

The ACLR group became more symmetrical after the equal landing instructions during the jump landing. The symmetry was certainly better in comparison to the baseline condition, however the magnitude remained quite large. Looking specifically at the mean values for peak VGRF from baseline to the equal landing condition it becomes apparent that it was not necessarily diminished loading on the Injured limb driving the asymmetry, as the Injured limb had similar loading compared to the CON limbs. We were pleased to see the
acute improvement in asymmetry after a single session of administering the instructions. However, the disparity in asymmetry between adolescent females with and without a history of ACLR and those without in the current study remains quite large. Chmielewski et al. found that both ACL deficient and ACLR group participants, very early after surgery (1.5-3 months), could achieve equal weight bearing between limbs during squatting tasks when given verbal cues to do so. The equal landing instructions may demonstrate promise for continued improvement if used from early rehabilitation all the way through return to sport. Based on our findings, we do not know if continued use of the instructions would affect greater improvements or if the improvements would persist over time. We also do not know if the improvements would impact performance, particularly on the playing field. We theorize that continued use of verbal instructions drawing attention to the movers symmetry in loading may be beneficial in addressing some of these deficiencies. Continued research is necessary and warranted based on these initial findings in a previously injured population.

Young athletes with a history of ACLR who return to competitive sports requiring landing, cutting, and pivoting movements are at great risk of suffering a subsequent ACL injury. A recent systematic review showed the risk of suffering a subsequent ACL injury on the contralateral limb, or previously uninjured, is double that of rupturing the ACL graft. Webster et al. recently found 29% of patients younger than 20-years old at the time of ACLR incurred a secondary ACL injury within 3-years. Additionally, returning to cutting/pivoting sports in this younger population increased the odds of an ACL graft rupture by a factor of 3.9 and contralateral ACL injury by a factor of 5. This information is alarming and highlights the necessity to identify effective methods to decrease secondary injury rates upon returning to sport. It seems apparent that the continued unloading of the Injured and
excessive loading of the previously uninjured limb would contribute to the high rates of contralateral ACL injury in young active female populations.

This study is not without limitations. We utilized a single-session of testing to investigate the acute of verbal instructions on landing forces in previously injured adolescent female population. It would be beneficial to examine the longitudinal effects of similar instructions in a previously injured population. Perhaps with additional practice we may see continued improvement. Additionally, the results of the current study are generalizable only to an athletic adolescent female population with and without a history of ACLR. We did not control for or analyze differences in surgical graft types and procedures utilized by the operating physicians. We also do not have specific information on the individual rehabilitation protocols or return to sport guidelines used for our individual participants.

In conclusion, our observations indicate that adolescent female athletes with a history of ACLR respond similarly to healthy females when provided verbal instructions that attempt to shift focus to decreasing landing forces (soft) or making landing forces more symmetrical (equal) during a jump landing. However, the magnitude of loading asymmetry within the females with ACLR remained disproportionately larger than the healthy participants. Asymmetrical loading places those with previous ACL injury at a greater risk of experiencing a secondary injury during sport.
REFERENCES


<table>
<thead>
<tr>
<th></th>
<th>ACLR (n=22)</th>
<th>Control (n=25)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Injured</td>
<td>Index</td>
</tr>
<tr>
<td>Frequency (n)</td>
<td>Right 8</td>
<td>Right 10</td>
</tr>
<tr>
<td></td>
<td>Left 14</td>
<td>Left 15</td>
</tr>
</tbody>
</table>
Table 2. Anterior Cruciate Ligament Injury History and Activity Level for each Participant (N=22)

<table>
<thead>
<tr>
<th>Injured Limb</th>
<th>Injured Dominant Kicking Limb</th>
<th>Dominant Balance Limb</th>
<th>Primary Sport</th>
<th>MOI</th>
<th>Graft</th>
<th>Meniscus Injury</th>
<th>Marx Activity Rating Score Pre</th>
<th>Marx Activity Rating Score Pre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Softball</td>
<td>NC</td>
<td>Hamstrings</td>
<td>Yes</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>Yes</td>
<td>Volleyball</td>
<td>IC</td>
<td>Hamstrings</td>
<td>No</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>Yes</td>
<td>Soccer</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Lacrosse</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>No</td>
<td>16</td>
<td>13</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Soccer</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>No</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>Yes</td>
<td>Soccer</td>
<td>NC</td>
<td>Hamstrings</td>
<td>Yes</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>Yes</td>
<td>Lacrosse</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Soccer</td>
<td>IC</td>
<td>Patellar Tendon Allograft</td>
<td>Yes</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Soccer</td>
<td>NC</td>
<td>Hamstrings</td>
<td>Yes</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>Yes</td>
<td>Lacrosse</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>No</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>Left</td>
<td>Yes</td>
<td>Yes</td>
<td>Basketball</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>No</td>
<td>Soccer</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>No</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Soccer</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Volleyball</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>7</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>Yes</td>
<td>Basketball</td>
<td>NC</td>
<td>Hamstrings</td>
<td>Yes</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Basketball</td>
<td>IC</td>
<td>Hamstrings</td>
<td>Yes</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Left</td>
<td>No</td>
<td>No</td>
<td>Soccer</td>
<td>IC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>No</td>
<td>Basketball</td>
<td>NC</td>
<td>Hamstrings</td>
<td>No</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Left</td>
<td>Yes</td>
<td>No</td>
<td>Soccer</td>
<td>IC</td>
<td>Hamstrings</td>
<td>No</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>No</td>
<td>Volleyball</td>
<td>NC</td>
<td>Hamstrings</td>
<td>Yes</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Left</td>
<td>Yes</td>
<td>Yes</td>
<td>Gymnastics</td>
<td>NC</td>
<td>Bone-Patellar Tendon-Bone</td>
<td>Yes</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>Right</td>
<td>Yes</td>
<td>No</td>
<td>Soccer</td>
<td>IC</td>
<td>Hamstrings</td>
<td>No</td>
<td>16</td>
<td>8</td>
</tr>
</tbody>
</table>

NC = Noncontact Mechanism of ACL Injury  
IC = Indirect Contact Mechanism of ACL Injury  
Dominant Kicking Limb = Preferred Limb to Kick a Soccer Ball for Maximum Distance  
Dominant Balance Limb = Preferred Limb to Land from a Single-Leg Jump.
Table 3. Descriptive Statistics for Peak Vertical Ground Reaction Force (N/BW) during all Conditions of the Jump Landing (Means, 95% CI)

<table>
<thead>
<tr>
<th>Condition</th>
<th>ACLR Group (n=22)</th>
<th>Control Group (n=25)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Injured</td>
<td>Uninjured</td>
</tr>
<tr>
<td></td>
<td>Mean ± SE</td>
<td>Mean ± SE</td>
</tr>
<tr>
<td></td>
<td>CI</td>
<td>CI</td>
</tr>
<tr>
<td>VGRF_Baseline</td>
<td>2.25 ± 0.11</td>
<td>2.93 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>(2.04, 2.46)</td>
<td>(2.66, 3.20)</td>
</tr>
<tr>
<td>VGRF_Soft</td>
<td>1.83 ± 0.09</td>
<td>2.17 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>(1.65, 2.02)</td>
<td>(1.98, 2.35)</td>
</tr>
<tr>
<td>VGRF_Equal</td>
<td>2.28 ± 0.11</td>
<td>2.64 ± 0.16</td>
</tr>
<tr>
<td></td>
<td>(2.07, 2.50)</td>
<td>(2.32, 2.95)</td>
</tr>
</tbody>
</table>
Table 4. Change Score Descriptive Statistics for Peak Vertical Ground Reaction Force (VGRF) during each Condition (Means, SE, 95% CI)

<table>
<thead>
<tr>
<th>Peak VGRF</th>
<th>Injured / Index</th>
<th>Uninjured / Non-Index</th>
<th>Inj * Uninj P-Value</th>
<th>Inj * Index P-Value</th>
<th>Uninj * Non P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Δ ± SE CI</td>
<td>Mean Δ ± SE CI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft LandingACL</td>
<td>-0.41 ± 0.09 (-0.59, -0.25)</td>
<td>-0.76* ± 0.11 (-0.97, -0.55)</td>
<td>0.005</td>
<td>0.268</td>
<td>0.043</td>
</tr>
<tr>
<td>Control</td>
<td>-0.56 ± 0.10 (-0.75, -0.37)</td>
<td>-0.50** ± 0.07 (-0.65, -0.36)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equal Landing</td>
<td>0.03 ± 0.08 (-0.12, 0.18)</td>
<td>-0.29* ± 0.13 (-0.56, -0.03)</td>
<td>0.041</td>
<td>0.554</td>
<td>0.363</td>
</tr>
<tr>
<td>Control</td>
<td>-0.04 ± 0.10 (-0.25, 0.16)</td>
<td>-0.15 ± 0.08 (-0.30, -0.01)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Indicates significant difference in magnitude of change compared to ACLR Injured Limb (p ≤ 0.05)

** Indicates Significant Difference in Comparison to the ACLR Uninjured limb (p < 0.05)

(Negative value indicates a reduction in VGRF on that limb)
Table 5. Descriptive Statistics for Calculated VGRF Limb Symmetry Indices (LSI) Demonstrating the Main Effects for Group and Condition (Means, SE)

<table>
<thead>
<tr>
<th></th>
<th>Baseline LSI</th>
<th></th>
<th>Soft LSI</th>
<th></th>
<th>Equal LSI</th>
<th></th>
<th>Group</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SE</td>
<td>CI</td>
<td>Mean ± SE</td>
<td>CI</td>
<td>Mean ± SE</td>
<td>CI</td>
<td>Mean ± SE</td>
<td>CI</td>
</tr>
<tr>
<td>ACLR Group</td>
<td>-34.7 ± 6.67</td>
<td>(-48.14, -21.27)</td>
<td>-22.93 ± 6.56</td>
<td>(-36.13, -9.72)</td>
<td>-16.97 ± 5.14</td>
<td>(-27.33, -6.61)</td>
<td>-24.87 ± 4.94</td>
<td>(-34.82, -14.92)</td>
</tr>
<tr>
<td>Control Group</td>
<td>-2.36 ± 6.26</td>
<td>(-14.96, 10.25)</td>
<td>-5.06 ± 6.15</td>
<td>(-17.45, 7.33)</td>
<td>2.94 ± 4.83</td>
<td>(-6.77, 12.66)</td>
<td>-1.49* ± 4.64</td>
<td>(-10.83, 8.85)</td>
</tr>
<tr>
<td>Condition</td>
<td>-18.53 ± 4.57</td>
<td>(-27.74, -9.32)</td>
<td>-13.99 ± 4.50</td>
<td>(-23.05, -4.94)</td>
<td>-7.01** ± 3.53</td>
<td>(-14.12, 0.09)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Indicates Significant Difference compared to ACLR Group Mean (p < 0.05)
** Indicates Significant Difference compared to Baseline Condition Mean (p < 0.05)
REFERENCES


259


264


143. Graf BK, Lange RH, Fujisaki CK, Landry GL, Saluja RK. Anterior cruciate ligament tears in skeletally immature patients: meniscal pathology at presentation and after


246. Begalle RL, Walsh MC, McGrath ML, Boling MC, Blackburn JT, Padua DA. Sagittal Plane Ankle Motion Affects Frontal and Transverse Plane Motion at the Knee and


292. McLean SG, Walker KB, van den Bogert AJ. Effect of gender on lower extremity kinematics during rapid direction changes: an integrated analysis of three sports


