CHANGE OF DIRECTION AND PSYCHOLOGICAL RESPONSE TO INJURY AS RISK FACTORS FOR SECOND ACL INJURY

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ABSTRACT

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Integration into sport is an important milestone after anterior cruciate ligament reconstruction (ACLR); however, only 65% of individuals with ACLR will return to sport. After integrating into sport, the risk of a second ACL injury is 6 times greater in individuals with ACLR than in individuals without a history of ACL injury. Common obstacles to return to sport (RTS) and risks factors for second ACL injury like functional deficits, patient demographics, and psychological response to injury have been identified. Return to sport (RTS) criteria has been proposed to mitigate the risk of a second ACL injury, but has been criticized for insufficiently identifying individuals at heightened risk of ACL injury and for lack of relevance to sport related movement. More vigorous functional assessments are needed to identify individuals with ACLR at increased risk of a second ACL injury. Individuals with ACLR exhibit high-risk biomechanics during change of direction (COD) and it is commonly reported as a fear-evoking task in those with ACLR. Psychological response to injury after ACLR may negatively affect lower extremity biomechanics during COD and contribute to a second ACL injury due to increased muscle tension and decreased focus. However, limited research has been conducted in this area. Omission of COD assessment from RTS criteria is a major limitation in the current approach to identifying those prepared to integrate into sport after ACLR. Vigorous testing representative of sport demands in addition to nonmodifiable risk factors are needed to identify at risk individuals. The purpose of this study was to assess modifiable and nonmodifiable risk factors for second ACL injury and obstacles to RTS. Our central hypothesis is that demographic information, surgical characteristics, patient-reported outcome measures, and lower extremity biomechanics during fear-evoking tasks will identify individuals with ACLR at risk for a second injury.

Ninety-one individuals with ACLR were assessed within 1-year of surgery on functional assessments, and patient-reported outcome measures. Follow-up interviews were collected 2-years after ACLR to collect return to sport status and second ACL injury status. Separate logistic regressions were used to assess the relationship between assessments collected 1-year after ACLR and return to sport status and incidence of second ACL injury. Older age, male sex, and meniscal procedure at the time of ACLR were predictive of return to sport status. Our models were unable to predict second ACL injury. Models for both outcomes were not enhanced with the addition of psychological outcome measures or functional data. Our results contribute to the growing concern that current RTS criteria does not adequately identify those at risk for a second ACL injury or those prepared to return to sport after ACLR.

To identify unique demands during COD, 48 individuals with ACLR were assessed using a 3D motion capture system while performing a single leg drop vertical jump (SLV) currently used in RTS criteria and a single leg crossover hop (SLC), a COD task. Spearman's Rho Correlation revealed moderate correlations between tasks during the amortization and acceleration phase. Deceleration and amortization time were longer during the COD task implying more time was needed to stabilize the knee and rotate the trunk toward the new trajectory, consistent with increased risk of ACL injury. COD did impose unique demands to suggest it should be assessed as part of RTS criteria.

To assess the relationship between psychological response to injury and lower extremity biomechanics after ACLR, 46 individuals with ACLR were assessed on 3 psychological response to injury outcome measures and lower extremity biomechanics were assessed during a SLC using a 3D motion capture system. Spearman's Rho Correlations showed positive psychological response to injury was associated with safer lower extremity biomechanics. Correlations in this study were weak and further investigation into the relationship between psychological response to injury and lower extremity biomechanics is warranted.

This dissertation is dedicated to my family and friends.
You have held me up, supported me and loved me through it all.

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INTRODUCTION

STATEMENT OF THE PROBLEM

Anterior cruciate ligament (ACL) rupture is a traumatic knee injury that results in a neurophysiological cascade of adverse changes in the joint and inhibits neuromuscular function.[1–7] In the past two decades, the number of ACL injuries per year has grown by 1.3-2.5% annually amongst individuals under 20 years old.[8] This has resulted in 121±19 injuries per 100,000 person-years and 130,000 total ACL reconstructions (ACLR) per year in the United States.[8,9] Following ACLR, only 65% of individuals who participated in sport prior to ACLR successfully return to pre-injury level of sport participation within two years and 55% of these individuals will return to any level of competitive sport.[10] Returning to pre-injury level of activity is an important milestone during recovery; however, individuals with ACLR are at an outsized risk of a second ACL injury after returning to sport. More than 30% of young individuals with a history of ACLR will sustain another ACL injury to the involved or contralateral limb within 2 years after returning to sport.[11] This is a 4 times greater risk of injury than an individual with no previous ACL injury over the same period of time.[11] Evidence suggests that risk of re-injury is lower among individuals with ACLR that meet evidence-based clinical criteria before returning to sport.[12] However, a low number of individuals meet these criteria before formal rehabilitation ends,[13–15] contributing to the outsize risk of re-injury in this population.

Common obstacles for return to pre-injury levels of sport and risk factors for a second ACL injury include persistent functional deficits,[16] poor patient-reported function,[2] and negative psychological response to injury.[15] Additionally female sex, younger age (<20 years old), and meniscal procedure at the time of primary ACLR are risk factors for a second ACL injury and associated with return to sport status.[17–19] Clinical adoption of criteria including patient-reported and objective assessments to guide the decision-making process around the appropriate time for return to sport (RTS) can help to mitigate the risk of a second injury. Currently, evidence-based RTS testing commonly includes assessments of isometric or isokinetic quadriceps strength, functional testing via a series of single leg hop tests, and assessments of patient-reported function.[12] While RTS testing is recommended in the literature and is increasingly adopted clinically,[20,21] concerns have been voiced about the validity of such assessments including the quality of available evidence supporting their ability to identify individuals at elevated risk of injury[22] and the lack of sport-related movements included in the current assessment paradigm. These assessments include uniplanar motions in a controlled environment that do not mirror physical or mental demands of sport, and they are not indicative of restoration of the individual's athletic profile and preparedness to participate in sport.

Rapid change of direction (COD) are strategic maneuvers in sport used to engage and avoid obstacles or opponents.[23–26] During COD individuals execute a preplanned movement to change trajectories and avoid an obstacle. COD is a leading cause of ACL injury,[27,28] because the foot becomes fixed to the ground forcing the tibia to internally rotate while the hip externally rotates increasing the valgus force on the knee and leading to an ACL injury. Individuals with ACLR exhibit high-risk biomechanics during planned COD tasks associated with ACL injury compared to the healthy contralateral limb nine months after surgery.[29,30] Recently, psychological well-being after ACLR has gained traction as an important indicator of recovery after ACLR. The Stress and Injury model presents a framework to suggest that individuals with a history of stressors like ACLR undergo a stress response including a cognitive appraisal of stressful situations that can result in a negative physiological response (i.e., increased muscle tension and decreased attention) that increases the risk of injury.[31] COD is frequently reported as a fear-evoking task in individuals with ACLR,[32] yet limited research has been conducted to study the influence of psychological response to injury on lower extremity biomechanics during COD that may increase the risk of a second ACL injury. COD is not assessed as part of RTS criteria despite its potential to cause an injury,[33,34] which is a major limitation of the current approach to RTS among young individuals who desire RTS to pre-injury levels of participation. Clear evidence that individuals with ACLR that meet RTS criteria can safely execute COD maneuvers has not been established, which is a major limitation in mitigating the risk of secondary ACL injury.

STATEMENT OF THE PURPOSE

Clinical assessments used to identify individuals at risk for a second ACL injury following a primary ACL injury and subsequent ACLR do not mirror the physical or mental demands of competitive sport participation. Due to such limitations in current RTS testing, individuals may be cleared to make a return to vigorous activity before they are physically or mentally prepared to do so under the guise that full knee function has been restored. It is hypothesized that the disconnect between testing characteristics and the demands of sport may contribute to outsized risk of second ACL injury after primary ACLR. Development and implementation of vigorous testing that is representative of sport demands in addition to nonmodifiable risk factors such as age and sex are needed to identify at risk individuals and to design targeted rehabilitation strategies to address functional deficits. Therefore, the purpose of this study was to assess modifiable and nonmodifiable risk factors for second ACL injury and obstacles to RTS. Our central hypothesis is that demographic information, surgical characteristics, patient-reported outcome measures, and lower extremity biomechanics during fear-evoking tasks will identify individuals with ACLR at risk for a second injury.

OPERATIONAL DEFINITIONS

Agility: A rapid, unanticipated change of direction in response to a stimulus.[35]

Anterior cruciate ligament reconstruction (ACLR): A surgical procedure in which the ruptured native ACL is replaced using a graft strung through a portal drilled into the posterior lateral aspect of the femur and the anteromedial aspect of the tibia. Common graft sources include the middle third of the patellar tendon, the semitendinosus tendon, the quadriceps tendon, and cadaveric allograft.[36–38]

Change of direction (COD): A rapid, anticipated motion which requires the individual to decelerate in the current direction of motion and then accelerate in new direction.[23]

Crossover Drop Vertical Jump (SLC): A drop vertical jump performed from a 30-cm box placed 40 cm away from the middle of the force plate during which the participant stands on a single leg jumps to the force plate then hops off the force plate at a 45° angle in the opposite direction of the working leg.

Single Leg Drop Vertical Jump (SLV): A drop vertical jump performed from a 30-cm box placed 40 cm away from the middle of the force plate during which the participant stands on a single leg jumps to the force plate then performs a vertical jump from the floor for maximal height.

Limb Symmetry Index: Performance difference between limbs expressed as a percentage of healthy limb performance on a functional assessment. The ACL limb performance is divided by that of the healthy limb and multiplied by 100.

Equation 1. $LSI = \frac{ACLR\ Limb\ Performance}{Contralateral\ Limb\ Performance} \times 100$

Return to Sport (RTS): Reintegration into preinjury sport and level of competition (i.e. high school, college, recreation, professional) after ACLR.[12]

Return to Sport Criteria: Evidence-based standards used to identify individuals at an increased risk of a second ACL injury after ACLR.[12,39] Limb symmetry indices (LSI) were calculated using the equation in Equation 1. RTS criteria for this project will include:

- Symmetrical (≥90% LSI) isometric and isokinetic quadriceps strength
- Symmetrical (≥90% LSI) single leg hop performance
- A score of ≥90 on the International Knee Documentation Subjective Knee Function Scale (IKDC)

Reactive Strength Index (RSI): A measurement of plyometric loading calculated as the ratio of jump height to ground contact time during a drop vertical jump.[40,41]

Equation 2. $RSI = \frac{Jump\ height\ (m)}{Ground\ Contact\ Time\ (s)}$

RESEARCH QUESTIONS AND EXPERIMENTAL HYPOTHESES

Manuscript One:

Primary Purpose 1.1

To determine the association between demographic information, surgical characteristics, patient-reported function, and objective strength and hopping outcomes collected within 1-year post-ACLR with the incidence of second ACL injury assessed 2 years after ACLR.

Secondary Purpose 1.2

To determine the association between demographic information, surgical characteristics, patient-reported function, and objective strength and hopping outcomes collected within 1-year post-ACLR with return to pre-injury level of sport assessed 2 years after ACLR.

Hypothesis 1.1

We hypothesize that female sex, younger patient age, involved limb quadriceps strength, and negative psychological response to injury will predict second ACL injury 2 years after ACLR.

Hypothesis 1.2

We hypothesize that male sex, younger age, involved limb quadriceps strength, and positive psychological response to injury will predict return to pre-injury level of sport 2 years after ACLR.

Manuscript Two

Primary Purpose 2.1

To compare biomechanical (i.e. ground contact time, reactive strength index, and peak vertical ground reaction time) outcomes during a traditional single leg drop vertical jump and a single leg crossover hop involving COD among individuals with a history of unilateral ACLR.

Secondary Purpose 2.2

To assess the relationship between biomechanical outcome measures (i.e. ground contact time, RSI, vGRF, acceleration time, and deceleration) between the single leg drop jump and single leg crossover hop.

Hypothesis 2.1

We hypothesize ground contact time will be shorter and vGRF will be lesser when assessed during the traditional single leg drop vertical jump as compared to the single leg crossover hop among individuals with a history of unilateral ACLR.

Hypothesis 2.2

We hypothesize there will be a strong correlation between biomechanical outcomes (peak vGRF, VIF, and deceleration time) during deceleration and weak to moderate correlations in biomechanical outcomes (VIF, amortization time, and acceleration time) during the amortization and acceleration phase between tasks.

Manuscript Three

Primary Purpose 3.1

To assess the association between measures of psychological response to injury (i.e., psychological readiness for return to sport, kinesiophobia, and fear-avoidance beliefs) and lower extremity biomechanics during a single leg crossover hop among individuals with a history of unilateral ACLR.

Hypothesis 3.1

We hypothesize that high TSK-11 and AFAQ scores and low ACL-RSI score will be associated with stiffer jump landing (low knee and hip sagittal plane excursion), greater knee abduction angle, and longer ground contact time during single leg crossover hop.

SIGNFICANCE OF THE STUDY

Rehabilitation clinicians that work with patients who are attempting to return to competitive sport must merge evidence-based rehabilitative care with an understanding of the physical and mental demands placed on patients when they return to competitive sport. There is a key limitation in the ability of clinicians to assess physical readiness for RTS because the most commonly utilized RTS criteria do not mirror the demands of competitive sport. Clinicians may be able to more effectively identify individuals who are prepared for RTS through the integration of more demanding tasks involving COD and assessment of psychological response to injury in addition to traditional RTS criteria. COD tasks are representative of critical component of sport and consistent with a common mechanism of ACL injury. Psychological response to injury is an important indicator of recovery after ACLR which may affect lower extremity biomechanics and contribute to the outsized risk of second ACL injury in this population. To understand the potential benefits of incorporating COD assessments and psychological response to injury into the RTS decision making process, it is essential to first characterize performance on these tasks among individuals who would be categorized as ready or not ready for RTS using traditional RTS criteria at a time period during which patients have been historically cleared to participate in sport after ACLR. Based on our findings, clinicians will be able to apply a more demanding, sport-related criteria to determine readiness for RTS and identify those with a negative psychological response to injury to mitigate the risk of second injury upon patients' re-integration into competitive sport.

REVIEW OF LITERATURE

INTRODUCTION

Individuals who experience an ACL injury and opt to undergo ACL reconstruction are at a 4-6 times greater risk of subsequent ACL injury when compared to individuals who do not have a history of knee injury.[10,42] A second ACL injury after primary ACL reconstruction (ACLR) is a meaningful health risk to young, physically active individuals. The current clinical strategy to mitigate risk of second ACL injury is to rehabilitate the individual while biological healing occurs and to delay sports participation until the individual demonstrates adequate strength and function to protect the knee when exposed to intensive physical activity.[12] In 2016, the First World Congress in Sports Physical Therapy (WCSPT) released a consensus statement that recommended 5 domains of evaluation or treatment when returning a patient back to sports: (1) use of a test battery, (2) inclusion of open tasks, (3) inclusion of tasks that require reactive decision-making, (4) assess psychological readiness to return to sport, and (5) monitor internal and external workload.[43]

The most commonly described criteria for return to sport (RTS) after ACLR include limb performance symmetry (≥90%) on single leg hop and quadriceps strength assessments, and time since surgery (≥9 months).[12,39] However, these criteria may not adequately identify individuals at elevated risk of second ACL injury following ACLR.[14,22,44] Additionally, these measures have been shown to overestimate knee function[45–47] since they do not mimic sport related movements, or the neurocognitive demand associated with competition.[48,49] Consistent with this finding, it has also been reported that the current RTS criteria does not include open tasks or reactive decision-making in compliance with the WCSPT recommendations. As a result, individuals with ACLR may be cleared for RTS by rehabilitation clinicians who utilize common before they are physical or mentally prepared to do so, resulting in increased risk of a second ACL injury. A logical step toward improving the RTS process is to assess movements known to cause ACL injury.

An ACL injury is not only a disruption to the mechanical stability of the knee but causes neurophysiological changes throughout the musculoskeletal and nervous system that negatively affect motor control and stabilization of the knee.[1,2,50] Change of direction (COD) and agility maneuvers are common evasion tactics in sport and they are leading causes of ACL injury.[27,34,51] Evasion tactics require the individual to decelerate the body, plant on a single leg and push off to accelerate in the chosen direction. Under planned and unanticipated conditions, healthy individuals, and those with ACLR display high risk joint angles and moments that can increase the risk of ACL injury.[52–56] Despite their relation to ACL injury and recommendations to include open tasks and reactive decision-making tasks, COD and agility assessments have not been integrated into commonly utilized RTS criteria. Omission of COD and agility assessments from RTS criteria can partially be attributed to the lack of research documenting progression COD and agility performance after ACLR. To improve shortcomings of RTS criteria, it is important to understand the persistent dysfunction, its sources, and the clinical manifestations of the dysfunction that individuals with ACLR face. Therefore, the two primary areas of focus in this literature review are functional recovery after ACLR and change of direction performance.

ANTERIOR CRUCIATE LIGAMENT (ACL) ANATOMY

The knee is a modified hinge joint that flexes and extends in the sagittal plane and limited rotation through the transverse plane. The femur, tibia, fibula, and the patella are the boney structures of the knee. The passive stabilizing structures of the knee includes the joint capsule and two extracapsular ligaments the medial (MCL) and lateral collateral ligament (LCL) and two intracapsular ligaments, the anterior (ACL) and posterior cruciate ligaments (PCL). The MCL and LCL provide mechanical stabilization in the frontal plane, while the ACL and PCL stabilize the knee in the sagittal plane. The ACL is the main stabilizing ligament of the knee and prevents anterior translation of the tibia on the femur.[57] Its origin is on the posterolateral aspect of the femoral condyle and the insertion is on the anteromedial intercondylar area of the tibial plateau. The ligament is approximately 38 mm long and 11 mm wide.[58] The ACL is divided into the anteromedial and posterolateral bundle and it is 90% type I collagen and 10% type III collagen.[58]

The quadriceps and hamstrings provide dynamic stabilization to the knee and they are primary the primary extensors and flexors. Rectus femoris is the large quadriceps muscle on the anterior aspect of the thigh and originates on the anterior inferior iliac spine and superior margin of the acetabulum. Vastus medialis originates on the intertrochanteric line of the femur and vastus lateralis originates on the linea aspera and greater trochanter of the femur. Vastus intermedius originates on the anterior surface of the femur. The quadriceps muscles converge to form the quadriceps tendon, which houses the patella over the femoral condyle where it becomes the patellar tendon and inserts on the tibial tuberosity. The hamstrings consist of the biceps femoris, semimembranosus, and the semitendinosus. The long head of the biceps femoris, semimembranosus and semitendinosus share a common origin on the ischial tuberosity. The short head of the biceps femoris originates on the linea aspera and lateral supracondylar line of the femur. Semitendinosus and semimembranosus cross the knee and insert at the medial surface of the knee and the medial tibial condyle, respectively. The two heads of the biceps femoris converge inferior to the origin and share a common tendon that inserts on the lateral head of the fibula.

EPIDEMIOLOGY OF ANTERIOR CRUCIATE LIGAMENT INJURY

An estimated 250,000 ACL injuries occur each year in the United States, resulting in 100,000 ACLR.[9] From 2002 to 2014 the rate of ACL injuries increased 22% from 61.4 per 100,000 person-years to 74.6 per 100,000 person years.[59] Most notably, during this same time period, the rate of ACL reconstruction (ACLR) was highest amongst individuals 13 to 17 years old.[59] This is of particular concern because young individuals will experience the impact of ACLR on their health over a greater portion of their lifespan. Neuromuscular, sensorimotor, and patient-reported consequences of ACL injury remain unresolved for several decades after surgery and inhibit many individuals from integrating back into vigorous forms of physical activity. Approximately 65% of individuals will return to pre-injury level of sport within two years after ACLR, but only 55% return to any level of sport.[10] Broadly, 15% of those individuals that undergo ACLR will sustain a second ACL injury;[44] however 30% individuals that return to sport will sustain a second ACL injury to either limb within two years after their return.[11] Second ACL injury rates are higher in individuals under 25 years old (~20%) for both graft failure and contralateral ACL injury particularly for those individuals that participate in higher levels of activity.[17] Several factors contribute to second ACLR injuries including early termination of rehabilitation services that leaves the individual unprepared physically to integrate into sport participation.[20,21] To compound the problem, RTS criteria used to identify individuals at an increased risk of ACL injury are insufficient in doing so,[60] and few individuals are meeting that criteria at the time of return to sports. [15,22,61,62]

MECHANISMS OF ACL INJURY

ACL injury can be caused by a direct contact or non-contact mechanism. The ultimate load to failure of the ACL is 2160±157 N regardless of injury mechanism.[27] A contact injury typically involves a blow to the lateral aspect of the knee forcing the knee into hypervalgus resulting in tearing of the ACL.[63] Risk of ACL injury increases in sports involving contact, particularly for female athletes.[34] Non-contact injuries occur more frequently than contact injuries and account for approximately 72% of ACL injuries.[34] Even in high collision sports like American football (72.5%)[63] and Australian football (56%),[33] non-contact ACL injuries are more prevalent. Concomitant injury to the MCL and meniscus are common, occurring in 20-40%[64,65] and 60% of ACL injuries[66] respectively. The MCL is attached to the medial meniscus, as the valgus force on the knee increases the MCL is stressed and pulls on the medial meniscus.[66] Lateral menisci injuries can also occur due to joint space narrowing on the lateral aspect of the knee under valgus force and have reported to occur in approximately 70% of ACL injuries.[66] Meniscal injuries increase the risk of degenerative disease like osteoarthritis (OA). Approximately 50% of patients that undergo meniscectomy with ACLR develop radiographic OA.[67]

Kobayashi et al.[34] described three prevalent lower extremity dynamic positions that lead to non-contact ACL injuries during sport participation. The first position was described as 'knee in and toe out.'[34] In this position, the knee is abducted, the tibia is internally rotated, and the femur is externally rotated. The first position was the most common mechanism of injury for males (49.5%) and for females (47.8%).[34] In position two, 'knee out and toe in,' the knee is adducted, the tibia is internally rotated and the hip is externally rotated. Position two accounted for a much smaller portion of non-contact injuries, 8.9% in males and 9.0% in females.[34] The third positioned the knee was hyperextended, which accounted for 6.1% of non-contact ACL injuries in males, and 7.6% in females.[34] Video analysis of ACL injuries during rugby,[68] soccer,[69] and American football[63] have also shown the positions described by Kobayashi et al[34] to be leading causes of ACL injury in sport. Aside from lower extremity kinematics, context affects the risk of ACL injury. Most ACL injuries occur during competition,[70,71] when attention is split between game scenarios and executing proper movement patterns.[72,73] To accurately describe knee function after ACLR, a battery of tests is necessary to assess the individual's ability to stabilize the knee in multiple planes of motion and react to environmental changes.[74]

RISK FACTORS FOR ACL INJURY

It is important to understand and identify risk factors that make an individual more susceptible to ACL injury. Risk factors are categorized as intrinsic or extrinsic.[19] Intrinsic risk factors are unique to the individual and are further categorized as modifiable and non-modifiable.[19] Modifiable risk factors include jump landing mechanics and muscular strength or other risk factor that can be mitigated through intervention. Non-modifiable risk factors cannot be altered through intervention and generally include factors outside the control of the individual such as knee joint structure.[19] Extrinsic factors include factors outside the individual's control like weather conditions or playing surface. Modifiable intrinsic risk factors are common targets for injury prevention programs.[75–77]

Sex

Title IX was passed in 1972 creating more opportunities for women to participate in sports at the scholastic and collegiate level,[78] which has also led to a greater number of female athletes sustaining ACL injuries. Female athletes are 2-8 times more likely to sustain an ACL injury than their male counterparts.[71,79] Contributing risk factors are lower extremity biomechanics,[80,81] hormonal changes throughout the menstrual cycle,[82–84] and anatomical differences in the architecture of the knee.[85,86] Anterior knee laxity is greater during the follicular phase of the menstrual cycle which is related to greater knee valgus during COD and landing from a jump compared to performing the same activities during the luteal phase.[82,87] During menses females land from a jump with greater vertical ground reaction forces (vGRF) and greater tibial internal rotation at initial contact and greater hip internal rotation moment.[84,88,89] At ovulation estradiol-β-17 (t=-1.9, p=0.009) and progesterone (t=-3.4, p=0.03) are higher than during menses as are knee-valgus moment (Z=-2.6, p=0.01) and hip internal rotation (t=-2.1, *p*=0.047) while landing from a jump.[84] Therefore, it has been hypothesized that this combination of factors are related to increased amounts of estradiol-β-17 and progesterone that increase ligament laxity and decrease muscle stiffness.[84]

Knee Anatomy

Structural differences in the architecture of the knee increase the risk of ACL injury among females. Anatomical risk factors include shorter femoral condyle height, smaller distances of the flattened surface of the femoral condyle, smaller anteroposterior tibial plateau distance.[85] In males, risk factors include shorter femoral condyle height, anteroposterior distance of the femur's lateral condyle, tibial plateau anteroposterior distances, smaller tibial slope.[86] Increased posterior femoral condylar depth (lateral femoral condyle ratio) is associated with increased risk of ACL injury.[86] Regardless of sex, the femur's diaphysis anteroposterior distance, the distance of anteroposterior flattened surface of the femoral lateral condyle, the anteroposterior distance of the tibial plateau, and the distance from the posterior lateral femoral condyle to posterior cortical and to the anterior cortical can identify 97% of individuals with an ACL injury.[85]

Age

Age is a risk factor for primary and second ACL injury.[17,90] From 1994 to 2006 the number of ACL injuries for individuals under 20 years old rose from 12.22 per 100,000 to 17.97 per 100,000.[9] During this time, the average age individuals undergoing ACLR was 29±13 years old, but this number is misleading as 41% (53,653) of those injured in 2006 were under 20 years old.[9] That is more than double the number of ACLR performed on individuals 20-29 years (26,815) old or 30-39 years (20,846).[9] Risk of a second ACL injury in younger individuals is related to returning to sports after ACLR,[90] as older individuals are less likely to do so.[17,91] The revision risk for individuals under 21 years old is 7.76 times higher than older patients.[90]

Risk Factors for Second ACL Injury

Following primary ACLR one of the main goals is to return to pre-injury levels of activity and prevent a second ACL injury to the ipsilateral or contralateral limb. Multiple risk factors have been identified that increase the risk of a second ACL injury. Individuals that have sustained an ACL injury are 5 times more likely to sustain another ACL injury within 2 years of RTS compared to someone who has never been injured.[42] High risk individuals fit one of two profiles described by Paterno et al.[42] described in Table 2.1. Fear of reinjury or fear of movement (kinesiophobia) are related to second ACL injury which is related to knee function after primary ACLR. Individuals that report greater fear on the Tampa Scale of Kinesiophobia (TSK-11) are 4 times (OR= 3.73; 95%CI, 0.98-14.23) more likely to be less active after ACLR; 7 times (OR=7.1; 95%CI, 1.5-33.0) more likely to have asymmetrical hop distance and 6 times (OR=6.0; 95%CI, 1.3-27.8) more likely to have asymmetrical quadriceps strength at the time of RTS.[92] Quadriceps strength symmetry is a strong predictor of second ACL injury. For every 1% increase in quadriceps strength symmetry, there is a 3% reduction in rate of second ACL injury.[12] Aside from functional recovery, biological healing must also occur following ACLR. It has been proposed that RTS should be delayed 9-24 months[12,93] after ACLR to allow for adequate healing time. During the first 9 months after ACLR, for every month RTS is delayed, there is a 51% reduction in the rate of reinjury.[12] It is not practical to withhold an individual from integrating back into sport for 2 years, but this time frame would allow for more healing of bone bruises associated with 80% of cases[94] and graft re-ligamentization.[95]

Table 2.1: Indicators of High Risk for Second ACL Injury after Returning to Sport[92]

Profile 1	Profile 2
<19 years old	< 19 years old
Triple hop distance 1.34 -1.9 times height	Triple hop distance > 1.34 times height
Triple hop distance LSI > 98.5%	Triple hop distance LSI > 98.5%
	Female
	High knee-related confidence

LSI= Limb symmetry Index

Lower Extremity Biomechanics

Biomechanical risk factors for ACL injury have been identified at the trunk, hip, and knee during several athletic movements.[96–99] The common thread between movements is that individuals at an increased risk of ACL injury display limited hip and knee flexion with large knee abduction moments that increase valgus force at the knee leading to injury.[100–102] Joint angles at initial contact and peak joint angle are important in force absorption.[103,104] Female basketball and floorball athletes were assessed while performing a drop vertical jump (DVJ) using 3D motion capture and their match and training exposure was tracked for 1 to 3 years.[103,104] The study found that when landing from a jump, for every 10° increase in hip flexion when landing from a jump, the hazard ratio decreases by 0.61, for every 10 Nm increase in knee flexion moment, the hazard ratio decreases 1.21,[104] and for each 10° increase in knee flexion the hazard ratio decreases 0.55.[103] Stiff jump landings in which the knees and hips do not flex adequately, result in higher vertical ground reaction forces (vGRF), which can damage articulating surfaces of the knee and increase the risk of ACL injury.[100,105] Individuals with high energy absorption at initial contact during a single leg jump landing experience higher knee extension moments and greater anterior tibial shear force.[100,105] The forces and joint angles experienced during different athletic movements vary between tasks and under anticipated and unanticipated conditions.

Commonly studied tasks in ACLR research include the DVJ and the countermovement jump (CMJ). The DVJ is performed by jumping off a box 30-60 cm high onto a force platform then performing a vertical jump for maximum height. The CMJ is translatable to in sport jumping. It is performed from the floor by swinging the hands from above the head down toward the waist while descending into a squatting position. The arms then swung forcefully upward as the individual attempts to jump as high as possible. Sagittal and frontal kinematics and vGRF during the DVJ and CMJ are risk factors for ACL injury. Jump landing mechanics are predictive of ACL injury in healthy individuals[96,106] and in those with a history of ACLR.[107] When landing from a jump, decreased knee flexion with increased hip and trunk flexion, increases the angle of the posterior tibial plateau that increases the anterior tibial sheer force at the ACL.[98] Landing with less knee and hip flexion increases vertical ground reaction forces (vGRF) and knee flexion moment that adds undue stress to the ACL.[96] Knee abduction moment at initial contact after a drop jump predicts ACL injury with 73% specificity and 78% sensitivity.[96] Hewett et al monitored 205 healthy female athletes over the course of two competitive seasons, individuals that sustained an ACL injury during the surveillance period displayed a 2.5 times greater knee abduction moment and 20% greater vGRF during pre-injury jump landing assessments.[96] It should be noted that these studies were conducted without a neurocognitive load such as a game scenario or other stimulus that would elicit a response. Neuromuscular control and subsequently lower extremity biomechanics are altered under neurocognitive load,[72,73] meaning individuals with ACLR will respond differently in a competitive scenario than they will in a clinical or laboratory setting.

Males and females display different biomechanics when performing identical tasks such as jump landing and cutting. Females tend to use movement patterns with less knee and hip flexion[108] and greater knee valgus and knee abduction angle[80,109] During a vertical stop-jump task, females have less knee flexion and more knee internal rotation during the landing phase.[108] Despite similar hip flexion angles at the beginning of the flight phase, females have less knee flexion than males.[108] During the landing phase, females' hips are abducted less than the males.[108] Despite intrinsic, non-modifiable risk factors like hormonal changes through the menstrual cycle and anatomical differences in females that can impact lower extremity biomechanics and lead to ACL injury, biomechanics can be improved through targeted neuromuscular training and injury prevention programs in to mitigate risk of ACL injury.[77,110,111]

Though jump landings pose a substantial risk to the ACL, there are clinical[112,113] and laboratory[114,115] means of assessing them. Additionally, progression of DVJ performance after ACLR has been documented up to two years after surgery.[116] Single leg hop assessments are used as a clinically friendly option for assessing knee function after ACLR,[12,15,74] but they are rarely assessed for high risk biomechanics. Use of 3D motion capture has shown that individuals after ACLR can hop symmetrical distances between limbs, but ACLR limb exhibits less hip extension during takeoff and less energy absorption while landing.[29] On the triple hop, symmetrical performance showed no agreement with knee flexion symmetry or peak internal knee extension moment.[46] When compared to healthy controls nine months after ACLR, those that had undergone ACLR exhibited greater knee valgus moment, greater hip extension moment, and less knee flexion, despite the lack of difference in hop distance.[29] COD and agility performance has not been prospectively documented after ACLR, despite research showing greater ACL loading during these tasks in comparison to jump landing.[30,117,118] Based on the relationship between COD and ACL injury risk, it is a logical step to examine progression of COD performance after ACLR to better under the return to knee function in this population and mitigate second ACL injury risk.

CHANGE OF DIRECTION AND AGILTY

A velocity-angle trade off exists in COD and agility tasks,[118,119] the greater the angle of COD the slower the approach speed must be to execute the COD. Slower approach velocity requires greater braking force from the hamstrings and greater hip and knee flexion to maintain the COM over the base of support.[120–123] Conversely, greater propulsion force is needed to reaccelerate in the new directions.[121,122,124,125] This relationship is important for two reasons, first higher velocities and sharper angles place greater load on the ACL that can cause injury;[118,119] second it further illustrates the need to assess COD and agility after ACLR in addition to assessing jump landing mechanics. Performing a jump landing under a neurocognitive load like reacting to a stimulus or a game scenario can exacerbate high-risk biomechanics.[72,73] The same phenomenon occurs during COD, but regardless of neurocognitive load, the ACL experiences greater loads during COD than during other athletic movements.[117,126] No studies have directly linked COD and agility biomechanics to ACL injury. However, several studies have shown that the same high-risk biomechanics that can lead to an ACL injury during jump landing, are experienced when making a COD.[117,126–128]

Healthy individuals and those with ACLR perform faster on COD tasks with lower risk biomechanics when they are asked to perform a task in isolation without additional neurocognitive load like reacting to a stimulus.[72,129–131] A well-executed movement pattern during a controlled and isolated task is an important indicator of improved neuromuscular control after ACLR, but these task constraints are not representative of the conditions (i.e. forces and velocities) encountered during sport. Therefore, controlled and isolated tasks may not be an adequate representation of performance in a competitive setting.[48,49] Consequently, and consistent with WCSPT recommendations, unanticipated COD should be assessed before returning to sport after ACLR because it used to react to an opponent or obstacle.[43] During an unanticipated COD in which the individual must perform a sidestep cut at 45° angle or pivot

180° in response to a stimulus, both COD tasks resulted in higher peak vGRF compared to the DVJ.[126] Participants experienced greater varus-valgus moment during the sidestep cut (0.261±0.044 N) and the pivot (0.128±0.075 N) compared to the DVJ (0.029±0.027).[126] Additionally, at peak vGRF knee valgus angle was greater during the sidestep cut (-2.9±10.0°) and the pivot (-7±10.7°) than during the DVJ (3.7±6.4°).[126] Unanticipated sidestepping at a 45° angle, increases ACL loading by 13% compared to planned execution of the same task in recreationally active females and peak sagittal plane ACL loading occurs within 30 ms after initial contact during an unanticipated sidestep.[52] The time to peak sagittal plane loading is important because ACL injuries can occur within 50 ms of initial contact.[132] This is of particular concern for young female athletes who experience less time between peak knee valgus and peak vGRF during cutting tasks that may increase risk of ACL injury.[29]

COD and agility performance are deficient for years after ACLR.[133,134] Individuals performed anticipated and unanticipated 90° side cut with less symmetrical vGRF and knee flexion angle than healthy controls nine months after ACLR.[29] At the same time point, there were no differences in completion time between limbs on anticipated and unanticipated 90° side cut, but the ACLR limb displayed less knee extension moment and less knee flexion and lower knee valgus moment.[30] Individuals with ACLR (average time since surgery=28.11±19.30 months) had slower completion times on the T-test, a field based agility assessment than healthy controls, but there were not between group differences on two hopping based agility assessments.[133] Individuals with ACLR (average time since surgery=46.3±39.7 months), performed sidestep cutting (45°) with greater knee abduction angle than healthy controls.[134] Persistent deficits in COD and agility performance and poor lower extremity biomechanics are possible risk factors for a second ACL injury.[29,30,117,134] Based on the demands of COD and agility and their ubiquitous nature in sport, it is logical to believe these skills need to be assessed before an individual integrates back into sport after ACLR.

Muscle Function and Change of Direction

Stabilization and force production at a joint are dependent on the characteristics of the surrounding musculature. The quadriceps and hamstrings are the primary knee flexors and extensors, but hip muscles and the muscle of the lower leg aid in maintaining lower extremity alignment during dynamic movements to stabilize and protect the knee. Muscular strength has multiple characteristics that contribute to force production and joint stabilization. Peak torque (PT) produced during an isokinetic or isometric strength assessment is one of the most common strength characteristics studied in ACLR research because of its relationship to muscle function.[50,135–140] Approximately 300 ms from contraction onset is needed to achieve PT,[141] therefore it cannot be expected that PT will be the protective mechanism that prevents an ACL injury. Rather, the rate at which force can be generated within the first 50 ms of initial contact will stabilize the knee. Rate of torque (RTD) development is the change torque from the onset of contraction until peak torque is achieved.[142] RTD is more sensitive to underlying changes neurological drive to the muscle than PT, particularly during the first 100 ms after contraction onset.[143] In anticipation of volitional contraction and in preparation to absorb ground reaction forces during movement, pre-activation of the muscle aids in generating force to stabilize the knee.[144] A muscle's ability to generate force volitionally and resist external loads is related to its morphological make-up. The musculotendinous unit's resistance to lengthening is quantified as stiffness (Nm/kg). Greater muscle stiffness is related to improved breaking power and force absorption during jump landing and COD.[121,123,144]

During COD, the knee abducts, and experiences loads that can injury the ACL. To stabilize the knee in this position the semimembranosus and semitendinosus must contract to counteract the valgus moment exerted on the knee.[121,123,144] In healthy female athletes, those with low EMG pre-activity in the semitendinosus and high EMG pre-activity in the vastus lateralis during a side cutting maneuver sustained an ACL injury within 2 playing seasons.[144]

Hamstring strength is important to reducing anterior tibial sheer,[102] decelerating during COD,[123] and force absorption[102] when landing from a jump. Low hamstring strength has been identified as a risk factor for ACL injury.[102] Healthy Individuals with greater hamstring stiffness have larger knee flexion angles at peak internal knee varus moment, peak internal knee-extension moment, and at peak anterior tibial shear force that reduces the load on the ACL.[145,146] Greater hamstring stiffness reduces internal knee varus moments that in turn reduces the valgus loading at the knee.[102,144] Hip external rotators and abductors partner with the quadriceps and hamstrings to reduce knee valgus.[147] Low hip external rotation and abduction strength are predictors of ACL injury in male and female athletes involved in cutting sports like soccer and basketball.[147]

In a study on ski racers 14-19 years old core strength, quadriceps and hamstring strength, and reactive strength index (RSI) were predictors of ACL injury.[148] RSI is the ratio of jump height to ground contact time during a DVJ used to quantify plyometric performance. It has been found to be predictive of triple hop distance after ACLR,[149] and could be related to COD and agility performance as ground contact time is a determinant of both measures.[122,125,150–152] Core strength is a risk factor for ACL injury,[148,153] and may have some implications for COD performance after ACLR. In healthy adults, less trunk rotation toward the new direction and greater hip adduction moment explained 81% of the variance in internal knee varus (external knee valgus moment) moment during sidestep cutting.[99] This may stem from decreased trunk strength and inadequate braking force from the hamstrings causing the body's inertia to carry the COM in the original trajectory and overloading the stance leg as the individual attempts to COD.

ACL RECONSTRUCTION

ACLR is an arthroscopic surgery used to restore the mechanical stability of the knee by replacing the ruptured native ACL with autograft or allograft tissue. The native ACL has a tensile strength of 2160±157 N and stiffness of 242±28 N/mm,[154] meaning that the graft must have similar qualities to adequately stabilize the knee. The patellar tendon, semitendinosus tendon, and quadriceps tendon are commonly used autograft sources for ACLR as they offer similar levels of strength and stiffness when compared to the native ligamentous tissue.[155–157] Though there is no gold standard surgical approach or graft source selection, surgeons commonly use the patient's age, pre-injury activity level, and number of previous ACL injuries to guide the decision.[158,159] Autografts are generally preferred over allografts because there is a lower rate of graft failure[157,160] and a lower rate of infection when using the patient's own tissue,[161] but allograft tissue may be appropriate for older individuals or those that have had multiple ACL injuries and graft failures.[158,159] It is important to understand the differences between graft sources when choosing a graft to mitigate risk of graft failure and evaluating the role it may play in determining clinical outcomes.

Bone-Patellar-Tendon-Bone Autograft

The bone-patellar-tendon-bone (BPTB) autograft is harvested from the middle third of the patellar tendon with bone plugs extracted from the patella and the tibial tuberosity. The BPTB autograft was introduced by Kenneth Jones in 1963[36] and was considered the gold standard for reestablishing mechanical stability to the knee for several decades. This graft source offers several advantages over other soft tissue auto- and allograft sources including the maintenance of bone blocks from the tibia and the patella at either end of the graft that integrate into the femoral and tibial graft sockets.[38] Additionally, the patellar tendon's strength and stiffness are greater than that of the native ACL.[37] Such advantages were the basis for the idea that the BPTB autograft was the gold standard for ACLR.

Clinically, there are advantages and weakness that should be evaluated when considered BPTB autograft for ACLR. Graft failure occurs less frequently in individuals with BPTB graft in comparison to a hamstring[155] or allograft.[162] However, anterior knee pain and decreased quadriceps strength are common after ACLR with BPTB graft.[163] Five years after ACLR, there is no difference between individuals with BPTB and hamstring grafts in self-reported function or in number of patients that returned to pre-injury level of activity,[37] but those with a hamstring graft have greater joint laxity.[164] At ten years post-ACLR, individuals with BPTB grafts have a higher rate of patellofemoral osteoarthritis and are more likely to report pain with strenuous activity in comparison to those with a hamstring graft.[155] Despite no significant differences in quadriceps strength symmetry 12 months after ACLR between individuals with BPTB autograft (71.9±24.4%) and those with hamstring autografts (73.9±26.0),[163] the BPTB autograft may be a more suitable option for athletes returning to cutting sports like soccer or basketball because it does not compromise the integrity of the hamstrings. Braking forces are exerted by the hamstrings to decelerate the body in preparation to COD and medial hamstring muscles stabilize the medial aspect of the knee to reduce knee valgus during stance phase of COD.[123,144]

Hamstring Autograft

The hamstring graft is harvested from the semitendinosus and the gracilis. Double and quadruple bundle hamstring grafts are used to increase graft width to the necessary 8 mm. Hamstring autografts have a higher type III collagen which makes them more elastic than the BPTB graft.[57,165] Hamstring grafts are slower to incorporate due to the bone to tendon healing and there is an increased risk of tunnel widening. However, the tensile strength of the graft is approximately 2330±452 N, exceeding the strength of the native ACL and rivaling the strength of the BPTB autograft.[165]

Quadriceps strength is more symmetrical 6 months post-surgery in individuals with a hamstring autograft compared to those with a BPTB autograft, but hamstring strength is less symmetrical.[166] Two and five-year outcomes for quality of life, return to pre-injury level of activity, and self-reported function are similar between the hamstring graft and the BPTB graft.[164,167] The hamstring graft has a 10-year survival rate of 86% (95%CI=79%-98%), compared to the BPTB graft that has a survival rate of 92% (95%CI=86%-98%).[155] Ten year outcomes show no significant difference in the number of graft failures between BPTB and hamstring grafts; however there were more hamstring grafts failures, but more ACL injuries to the contralateral limb in those with BPTB.[155] It is important to note, that 10 years after ACLR there is a significant decline in physical activity regardless of graft source.[17,155] The hamstring graft is appealing to young athletes attempting to return to sport because they can regain symmetrical quadriceps strength earlier in their recovery, which is a key indicator of reduced risk of a second ACL injury.[12] It must also be considered that the hamstrings are vital to COD and agility performance. Athletes returning to cutting sports maybe exchanging one strength related risk factor for another when choosing a hamstring graft in attempt to reduce the recovery time after ACLR.

Quadriceps Tendon Autograft

The quadriceps tendon is a relatively new graft source option compared to the hamstrings and BPTB grafts. It does offer several anatomical and biomechanical advantages. The quadriceps tendon is approximately 1.8 times thicker than the patellar tendon and can withstand approximately 1.36 times the load to failure of the patellar tendon.[168] The quadriceps tendon has 20% more collagen than the patellar tendon and higher fibroblast density.[169] The quadriceps tendon autograft is more narrow in comparison to the BPTB graft which aids in greater preservation of the knee extensor mechanism and reduces quadriceps strength loss.[156]

There are mixed results regarding graft laxity and failures rates when comparing the quadriceps tendon to other graft sources;[170–172] however a systematic review found that using the quadriceps tendon resulted in less knee laxity and lower failure rate.[156] At 6 months post-surgery, on MRI the quadriceps tendon has less water content signifying graft maturity and more healing in comparison to the hamstring grafts at the same time points.[173] A year after ACLR, individuals with a quadriceps tendon graft had lower isokinetic quadriceps strength compared to individuals with a hamstring graft.[172] The hamstring to quadriceps (H/M) ratio was higher in the quadriceps tendon (72.3±15.2; 95%CI=68.-76.2) group compared to the hamstring tendon group (63.7±12.4; 95%CI=60.6-66.8),[172] that may mean the more stability at the knee because the hamstrings are not compromised due to graft harvest. Two years after ACLR, there is no difference in self-reported function or activity level between individuals with hamstring and quadriceps tendon grafts,[163] but those with quadriceps tendon had significantly greater hamstring strength. A higher H/M ratio, preservation of quadriceps strength, and no disruption to the hamstring muscle are reasons to consider the use of a quadriceps tendon for athletes return to cutting sports. However, it should be noted that the quadriceps tendon autograft has only recently gained popularity and there are limited high quality clinical outcome data available.

Allograft

Allografts are less popular graft sources for young, active individuals and their use has been identified as a risk factor for a second ACL injury in this population.[17,157] Freezing and chemical processing are used to preserve and sanitize allografts to reduce the risk of infection, but these processes weaken the graft and they have been linked to higher failure rates.[161] One study has found that the infection rate when using an allograft that has not been treated chemically is approximately 0.15%,[161] which may indicate chemical treatments are unnecessary and discontinuing use could potentially improve ACLR outcomes. Allografts are not without merit. Individuals with an allograft experience do not experience donor site pain and there is less scarring.[95,157,174] Allograft maybe a suitable option for those with recurrent ACL injuries or patients that will not return to sports.[158,159]

One study found within 2 years of ACLR using an allograft, young individuals (average age=19.6±6.6 years old) have 5.2 times greater odds of graft failure were 5.2 times greater than those that had a BPTB.[17] The odds of an allograft failure are lower in less active adults 31-40 years.[90] It should be noted that higher levels of activity and younger age are risk factors for graft failure, but the odds are higher when using an allograft.[17,158]

ACL RECONSTRUCTION SURGICAL TECHNIQUES

To place the graft, tunnels are drilled through the lateral femoral condyle at the 10 o'clock position[175] and through the inferior anteromedial tibial plateau. A tibial drill guide is aimed at a 60° angle through the ACL anatomical footprint to place a guide pin. Along the guide pin, the surgeon drills a 10 mm tibial tunnel.[176] In skeletally immature individuals a physeal-sparring technique is used in attempt to prevent growth disruptions.[177–179] A 7 mm offset femoral guide is used to drill the femoral tunnel. To place the femoral tunnel, the knee is placed in 90° of flexion and the tibia is pulled anteriorly and a varus force is applied while the lower leg is externally rotated.[176] A femoral guide pin is then inserted to drill the femoral tunnel. The tunnel must be 10 mm in diameter and 20-25 mm long.[176] In the event a bone block is attached to the graft like a BPTB or quadriceps tendon autograft, the bone block is inserted into the femoral tunnel and secured using a metal interference screw.[176] Within 6-12 weeks the bone block will integrate into the socket.[95,174,180] A bioabsorbable screw is used to secure the tendinous end of the graft. The tibial tunnel may increase in diameter during the first 6 weeks after surgery, but the bone block will be integrated into the bone by week 12.[95] Tunnel placement must be precise for the graft to take on the mechanical properties of the native ACL and resist anterior tibial translation. A femoral tunnel that is placed too vertically as in the 11 o'clock position does not mimic the posterior bundle of the native ACL, which reduces the graft's ability to resist anterior tibial translation.[175]

PERIPHERAL AND CENTRAL ADAPTATIONS TO ACLR

ACL injury and ACLR consistently result in deleterious neurophysiological effects like localized somatosensory adaptions at the knee joint and up-stream adaptations within the Central Nervous System (CNS). The ACL is innervated by an intricate system of mechanoreceptors including Pacinian corpuscles, Ruffini endings, Golgi tendon organs (GTO).[181,182] The same mechanoreceptors can be found in the subsynovial connective tissue. Most of the mechanoreceptors are located at the distal end of the ACL near the tibia, which has a higher concentration of Pacinian corpuscles and GTO than Ruffini endings.[181,182] The Pacinian corpuscles and the GTO are reflexogenic and act to stabilize the knee. The fast adapting Pacinian corpuscles are involved with quick movements and respond to the initiation and cessation of movement.[181,182] The GTO are located within the ligament and sense tension and joint position.

The primary mechanical goal of ACLR is to establish static and dynamic knee joint stability in the hope of facilitating a return to function following structured rehabilitation. Unfortunately, a consequence of ACLR, the native tissue, and therefore the mechanoreceptors that innervate the native ACL are lost. Complicating this issue, these mechanoreceptors do not regenerate in the autograft or allograft tissue utilized during the reconstructive procedure and therefore, do not innervate the newly implanted graft tissue. The additional tissue damage caused by ACLR, increases femoral nerve afference from the articular structures innervated by the femoral and saphenous nerves.[183] Post-surgery swelling and effusion inhibit the capsular nerve afference and in concert with the increased femoral afference cause pre- and post-synaptic inhibition at the spinal level. In short term, this results in inhibited reflexive quadriceps activation that eventually causes corticospinal inhibition and neuroplastic changes in the brain that diminish voluntary quadriceps activation.[1,3,183] Needle et al.[1] has proposed a model (Figure 2.1.) demonstrating the effect of peripheral joint injury on the CNS structure and function.[1]

Symptoms associated with ligamentous injury (i.e. pain or inflammation) disrupt sensory feedback and cause a cyclical pattern of altered motor control followed by inhibited afferent signaling from the joint back to the peripheral and central nervous system.[1] Over time, this pattern causes neuroplastic changes to occur in the brain[184] and the descending cortical pathways degenerate.[3]

Though no direct insult has occurred to the CNS, persistent inhibition of the reflexive pathways and increased femoral afference contribute to structural and functional changes that further exacerbate functional deficits observed in individuals with ACLR.[1,3,185] Functional deficits may manifest as reduced muscle function and decreased force output or during movements like walking, hopping, and COD. Understanding the manifestation and clinical presentations of functional deficits after ACLR is important in choosing appropriate assessments to quantifying functional deficits and tracking progression over time.

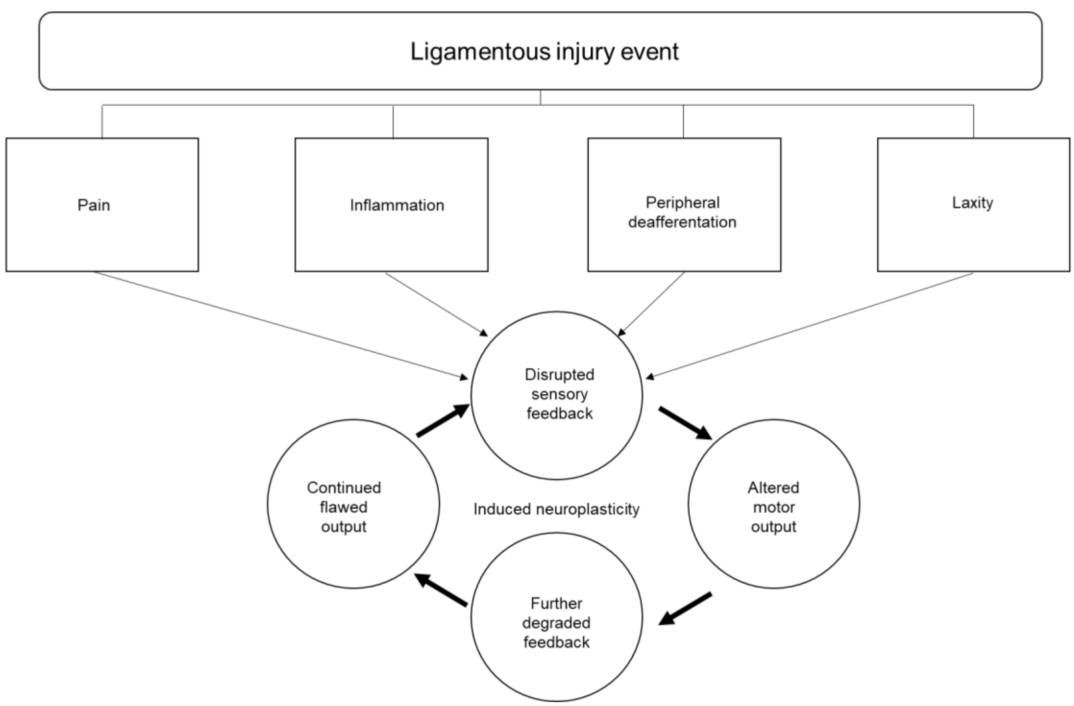

Figure 2.1: Model of Induced Neuroplasticity after Ligamentous Injury Adapted from Needle et al.[1]

Morphological Adaptions

ACL injury and subsequent reconstruction negatively impact quadriceps size, morphology, and histology. These changes are linked to systemic reflex inhibition called arthrogenic muscle inhibition (AMI),[186] the effects of which are compounded in those with concomitant meniscal, capsular injuries or multiple ligament injures.[187] After a total knee arthroplasty, AMI explained twice the variance in quadriceps strength compared to atrophy.[188] Rice and McNair[189] designed a model (Figure 2.2), to illustrate effects of joint damage on the central and peripheral nervous system that lead to long term AMI and decreased quadriceps activation. As shown in Figure 2.2, post-injury inflammation, swelling, and receptor damage inhibit spinal reflex pathways. This includes Group I nonreciprocal (Ib) interneurons that receive input predominantly from the GTO and also includes the γ-loop between muscle spindles and the α-motorneuron.[189] Inhibition of the Ib interneurons and the γ-loop decrease quadriceps motorneuron excitability, and contribute to AMI.[189] Inhibited afferent signaling results in decreased motor recruitment and under loading of the muscle resulting in atrophy and decreased force production.[1,190]

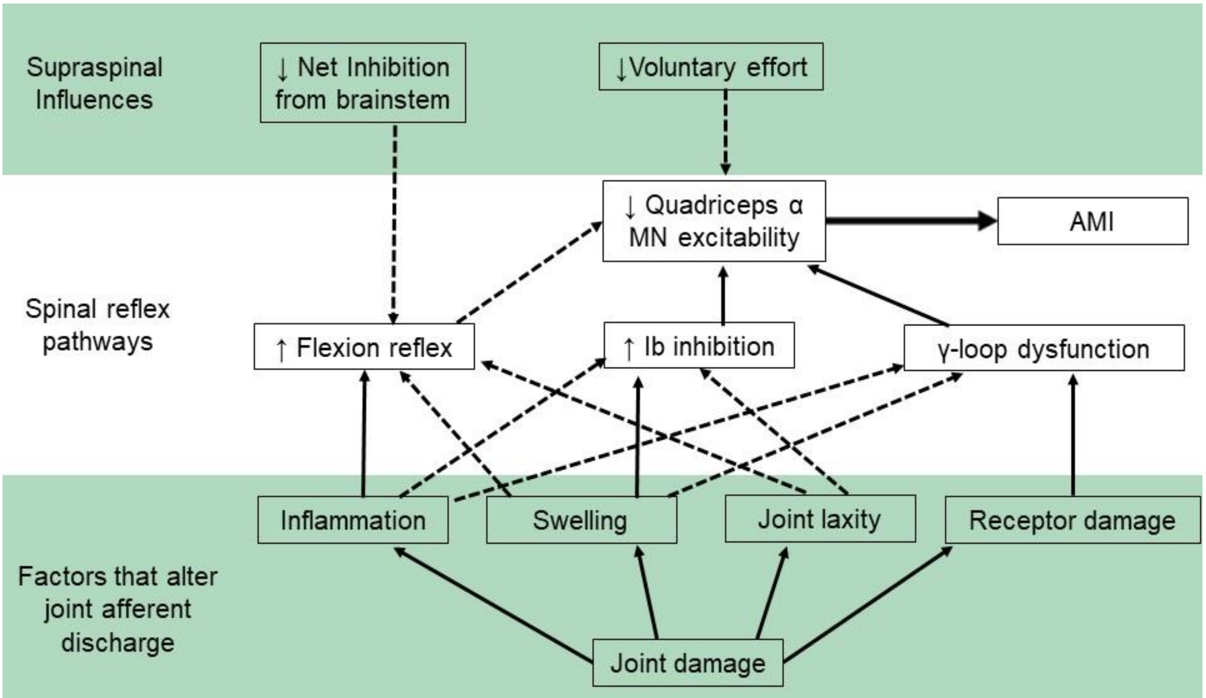

Figure 2.2: Model of Quadriceps Arthrogenic Muscle Inhibition After Joint Damage Solid lines indicate stronger evidence to support pathway. Adapted from Rice and McNair 2010

Low resistance exercises during rehabilitation insufficiently loads the muscle to improve quadriceps strength characteristics.[21] Structurally, the quadriceps experiences increased fibrosis and intramuscular fat infiltration and atrophy of Type II muscle fibers.[191–193] A negative regulator of muscle mass and satellite/progenitor cell differentiation called myostatin is activated after ACL injury.[6,7,194] Myostatin inhibits satellite cell function and prevents muscle regeneration by causing a negative myofiber protein balance and myofiber atrophy.[7] In turn, myostatin also acts upon fibroapidogenic (FAP) cells, undifferentiated stem cells, to differentiate into fibrotic tissue and adipose tissue.[6,7] Intramuscular fat infiltration and fibrosis reduces contractile tissue available for force production, decreasing quadriceps force production. Reduction in quadriceps strength in this population is attributed to atrophied Type IIa and Type IIx muscle fibers, that are responsible for rapid, high force generation, while still maintaining Type I muscle fiber health.[191,193]

It should be noted that atrophy may not be as significant a contributor to persistent quadriceps dysfunction among individuals with ACL injury and ACLR as previously thought. A recent systematic review found that only 36% of the included studies that compared quadriceps muscle size based on cross-sectional area (CSA) or muscle volume reported a meaningful difference between the ACLR and contralateral limbs and the effects sizes were small.[195] Additionally, magnitude of torque is not the only strength characteristic vital to recovery after ACLR, a high rate of force production is needed to perform athletic movements like jumping and COD. The changes in muscle morphology described above alter muscle function in a way that compromises the individual's ability to stabilize the knee during athletic movement. A better understanding of the interplay between muscle morphology, muscle strength characteristics and COD performance is needed to improve the rehabilitation process and find assessments that will adequately describe knee function after ACLR.

Arthrogenic Muscle Inhibition

Systematic inhibition and loss of mechanoreception after ACLR further exacerbate loss of quadriceps force generating capacity and coordination. Arthrogenic muscle inhibition (AMI) is a reflex response that occurs due to joint injury that reduces volitional contraction of the musculature despite a lack of structural damage to the muscle or innervating nerve.[186] AMI can be measured using supramaximal, percutaneous electrical technique or a interpolated twitch technique[196] to quantify the ratio of the strength of volitional contraction compared to the strength of contraction induced by electrical stimulation, called the central activation ratio (CAR).[50,197] Individuals with a CAR >95% have been described as achieving full muscle activation, those below are considered to have activation failure.[186,197] Individuals with ACLR have CAR of approximately 86.5% (95%CI= 78.1, 94.9), a meaningful difference from healthy controls that have a CAR of 98.3% (95%CI= 97.2, 99.4).[190] In the first year (7.4±1.2 months) after ACLR, CAR has been reported as low as 81.39%±8.96%.[139] Quadriceps strength has a moderate to strong correlation with self-reported knee function, psychological readiness to return to sport, and psychological response to injury at the time of return to sport;[2,139,198] surprisingly, CAR has a weak relationship with all of these variables. Recently, MRI analysis has revealed evidence of neuroplastic changes in the brain[184] and structural changes to the corticospinal tract[3] as well as alterations in corticospinal[198–200] excitability which has shifted our understanding of AMI and the long term effects of ACL injury.

The Hofmann reflex (H-reflex) is an electrically induced reflex that by-passes the muscle spindle,[201] used to assess modulation of monosynaptic reflex activity.[202] The H-reflex is measured using electromyography (EMG) coupled with an stimulating electrode over the femoral nerve and dispersive pad positioned on the hamstring of the ipsilateral leg. Electrical impulses are then used to cause a contraction to achieve a maximal peak-to-peak amplitude H-reflex. This value is the number of motor neurons available in a given state.[202] More simply put, the H-reflex reflects motorneuron pool excitability while considering the sources of pre- and post-synaptic inhibition ongoing within an individual. The motor wave (M-wave) is elicited in the same exogenous stimulation, its value represents the efferent activation of the entire motor-neuron pool for the muscle.[202] The H-reflex and M-wave values create a ratio (H:M ratio), which is the proportion of the total motor-neuron pool that available be recruited in the current physiologic state.[202,203] Unlike AMI or corticospinal excitability, spinal reflex excitability follows a different timeline and appears to resolve within 3-6 months post-surgical.[204,205] Between the time of ACL injury and two weeks post-ACLR, spinal-reflex excitability significantly decreases in the reconstructed and contralateral limb, but then exceeds pre-injury values 6 months after ACLR.[204]

Deficits in spinal reflex excitability are attributed to pain and swelling in the joint following injury. Temporary inhibition of the spinal-reflexive pathways has been recreated by injecting the knee with saline to mimic post-injury swelling.[206] The swelling affects afferent signals to the

CNS which can functionally manifest as decreased quadriceps strength. Evidence suggest that applying cryotherapy or transcutaneous electrical neuromuscular stimulation (TENS) while the patient performs rehabilitation exercises can alleviate the inhibitory effects of pain and swelling allowing for greater muscle recruitment and higher force production.[207,208] Despite resolution of spinal reflex inhibition within 6 months of ACLR, corticospinal excitability remains inhibited for several years.[50,140,204,209] Persistent inhibition forces reliance on secondary sensorimotor areas to contribute to coordinated movement.[1] In turn, proprioception and neuromuscular control are altered and reduce the individual's ability to respond to unpredicted stimuli and joint loads.[72,73] Such alterations in lower extremity neuromuscular control and biomechanics may increase the risk of ACL injury during COD or agile maneuver.

Quadriceps Strength and Voluntary Activation

Restoration of quadriceps strength and strength symmetry are important clinical indicators of recovery after ACLR and preparedness to resume physical activity. Peak torque during a maximal voluntary isometric contraction (MVIC) or during an isokinetic assessment are the most reported quadriceps strength characteristics. A clinical threshold of 3.0 Nm/kg during a MVIC has been establish in two independent studies as a predictor of clinically acceptable patient reported knee function after ACLR.[210] However, many individuals do not fully regain quadriceps strength after ACLR. A recent meta-analysis on quadriceps strength after ACLR revealed that when compared to healthy controls and compared to the contralateral limb, the ACLR limb is weaker after rehabilitation.[211] Persistent quadriceps weakness is caused by neurological inhibition[50,137,140,198] and atrophy of the muscle.[195,212,213] Though a recent systematic review found small to moderate effect sizes for muscle atrophy between limbs after ACLR,[195] changes in muscle size have a strong correlation with quadriceps strength in this population.[213] Understanding the progression of quadriceps strength after ACLR is important to understanding the functional limitations these individuals face and to selecting appropriate assessments to determine when to RTS. Quadriceps strength increases significantly from pre-surgery (2.09±0.56 Nm/kg) to 6 months after surgery (2.58±069 Nm/kg), but it remains significantly lesser than healthy matched controls participants (3.57±1.02),[204].[210] At 9 months post-ACLR, the minimal recommend time to RTS, 40.3% of young individuals (24.2±6.2 years old) with ACLR exhibit quadriceps strength less than 3.0 Nm/kg and 53.2% have asymmetrical quadriceps strength.[15] This pattern persists at two years[214,215] post-ACLR with individuals exhibiting persistent deficits in quadriceps strength, which is also related to lower self-reported knee function at the same time point in young athletes (16.9±3.4 years old).[216]

As a clinical indicator, quadriceps strength after ACLR is predictive of several other clinical outcomes. Quadricep strength during a MVIC predicts self-reported knee function (AUC=0.76; 95%CI [0.66,0.86]) and individuals with quadriceps strength greater than 3.1 Nm/kg have 8.15 (3.09-21.55) times higher odds of high self-reported knee function.[217] Individuals with quadriceps strength symmetry greater than 95% after ACLR have a 2.78 (1.16-6.64) times higher odds of high self-reported knee function.[217] At the time of return to sports (28.3±2.9 weeks post-surgery), quadriceps strength and pain predicts 74% of the variance in self-reported knee function in young individuals (20.9±4.4 years) after ACLR and quadriceps strength alone predicts 36% of the variance in psychological readiness to return to sport.[2] For every 1% increase in quadriceps strength symmetry, there is a 3% reduction in second ACL injury rate among individuals that return to sport participation.[12] Though peak torque is an important indicator of recovery after ACLR, other strength characteristic like rate of torque development (RTD) are more beneficial to athletic performance,[218] and may be critical in the prevention of a second ACL injury after returning to sport.

Evidence is growing that RTD during the first 200 ms after the onset of contraction, is an important clinical outcome following ACLR.[149,219,220] For example, 6-months after ACLR, professional male soccer players regain 97% of pre-injury quadriceps peak torque, but only

63% of preinjury RTD.[219] Peak torque is a measure of gross quadriceps function and neurological drive and has a strong relationship with decreased risk of injury; however, it can take almost 300 ms to generate peak torque.[142,143] Individuals with ACLR take significantly (1.94±0.82 s) longer to reach peak torque than healthy controls (1.37±0.83 s),[137] impeding their ability to stabilize the knee. An ACL injury occurs in approximately 50 ms after initial contact with the ground,[132] therefore it is critical to generate force quickly to stabilize the knee and avoid injury. RTD is the change in torque over time and it is measured from the onset of contraction to peak torque.[142,221] The torque-time curve is further divided into the first 100 ms (RTD_{100}) and from 100 ms to 200 ms after onset of contraction (RTD_{200}). Early and late phase RTD are dependent on different neuromuscular characteristics, to make a comprehensive evaluation of changes in RTD it is important to examine the phases of RTD independently. RTD_{100} is associated with neurological drive to the quadriceps and muscle fiber type.[202–204] Decreased RTD_{100} is attributed to less neurological signal reaching the quadriceps and atrophied Type II muscle fibers responsible for rapid force production.[141–143]

RTD_{200} is associated with peripheral nervous propagation of signals from the CNS and muscular strength.[141–143], these findings may indicate that Type II muscle fibers responsible for rapid force production, are still atrophied and require targeted RTD-based rehabilitation. After 90 ms from the onset of contraction, peak torque explains 52-81% of the variance in RTD.[222] After ACLR, RTD is slower during MVIC and treadmill walking.[223] Higher active motor threshold (AMT) is associated with slower late phase RTD indicating that individuals with ACLR need greater cortical excitability to generate force rapidly.[200] RTD has strong correlations with functional performance such as triple hop distance[149] and indicators of ideal knee joint biomechanics such as greater knee flexion angle at initial contact during a cross over hop,[224] however it has a weak association with self-reported knee function.[220,225] RTD is a relatively new measurement in the ACLR literature and no longitudinal studies have described its progression after surgery. The existing literature shows a correlation between RTD and functional performance which aligns with other studies in human performance that have found RTD is related to vertical jump performance[226] and other measures of athletic performance.[218] One study found that males exhibit faster RTD_{100} and RTD_{200} during the first year after ACLR than their female counterparts.[227] Despite the lack of longitudinal evidence supporting RTD as an important clinical indicator after ACLR, its relation to athletic performance has been established in other disciplines. Early phase RTD (≤100 ms) has a strong negative correlation (r=-0.54 to -0.63) with acceleration while sprinting. Late phase RTD (>100 ms) has a strong, positive correlation (r=0.51 to 0.61) with vertical jump height.[218] In male volleyball players, RTD predicts 70% of the variance in squat jump height.[228] This maybe an indication that RTD needs to be assessed to determine restoration of the individual's athletic profile after ACLR.[229]

Structural and functional neuroplastic changes have been documented in individuals after ACLR. Based on temporal brain activity, such adaptations have been suspected for the last two decades,[230] but spatial confirmation of neuroplastic change has only recently been found via functional magnetic resonance imaging (fMRI).[184] Cross sectional data from individuals with ACLR show atrophy in the hemisphere responsible for the ACLR limb control (left ACLR, right hemisphere atrophy), and decreased frontal anisotropy and higher diffusivity.[3] The latter two findings indicate increased water diffusion and degeneration in the microstructure of the brain's white matter.[3] Such changes in the white matter are associated with age, disuse, and pathology. Congruent with the model presented by Needle et al.[1] neuroplastic changes in the brain may explain in part the downstream changes in knee function after traumatic injury. Nerve regeneration is not possible in the CNS, therefore preservation of the neural pathways within the brain and of the descending cortical pathways will be pivotal improving long term outcomes after ACLR. Additionally, there is evidence that individuals that eventually sustain an ACL injury show differences in brain function before the injury.[231,232] Healthy individuals that later sustain an ACL injury do not perform as well on neurocognitive assessments[231,233] and have weaker functional connections between cortical sensory-motor regions of the brain and the cerebellum.[232] In high school aged American football players, individuals that sustained an ACL injury had less connectivity between somatosensory cortices and motor cortices compared to sex, age, and sport matched controls who did not sustain an ACL injury over the same time period.[232] Though a promising area, to date there has not been a longitudinal study describing progression of degenerative changes in the brain after ACLR or whether rehabilitation can attenuate those changes.

Corticospinal Excitability

The intensity of transcranial magnetic stimulation (TMS) or direct current stimulation needed to cause the neurons in the primary motor cortex to depolarize is called the motor threshold (MT) and it is used to quantify corticospinal excitability.[1,234] MT can be measured at rest (RMT) or activity during an isometric task (AMT) such as a quadriceps strength assessment.[1] A higher MT indicates lower motor cortex excitability meaning that greater cortical excitability is required to cause an action potential. A motor evoked potentials (MEP) is a representation of the magnitude of the stimulus caused by an action potential able to be transmitted down the corticospinal tract.[1,234] MEPs are measured using EMG recordings and evaluated based on the peak-to-peak amplitude of the muscle's response to TMS. A low amplitude MEP indicates less stimulus can be transmitted through the motor pathways thus decreasing the motor output at the muscle. High AMT indicates that greater effort is needed to excite the corticospinal tract and low MEP indicates that the excitation produced may not be sufficient to fire the motorneurons in the targeted muscle and achieve maximal force generation. In combination with quadriceps atrophy, changes in corticospinal excitability result in persistent quadriceps dysfunction.[50,140,204] Persistent inhibition causes degeneration of the corticospinal architecture[3] and contributes to reduced activation of the quadriceps.[200] While further research is warranted, decreased motor cortex excitability is experienced in both limbs after ACLR, which implies a functional reorganization of the motor networks. The functional reorganization may affect lower extremity biomechanics and in part explain the increased risk of a contralateral ACL injury after primary ACLR.

AMT significantly increases from pre-surgical to 6 months post-surgery,[204] and elevated AMT, as compared to healthy controls, persists for several years.[140,209] Conversely, from pre-surgical to 6 months post-surgical, MEP does not significantly change, but because AMT continues to rise during this time more corticospinal excitability is required to cause an action potential.[204] High AMT is negatively associated with early phase rate of torque development (0-50 ms).[200] This may be significant to injury prevention, as ACL injuries can occur in the same short amount of time. Fast force production enables earlier knee stabilization to attenuate external forces and preserve the integrity of the ACL graft.[219] Unpredictable stimuli that cause the individual to change direction diverts attention away from conscious control of the lower extremity at a time when greater cortical excitation is needed to generate force to stabilize and protect the knee.

Intracortical facilitation is studied using a paired-TMS paradigm by administering a subthreshold conditioning stimulus followed by a suprathreshold stimulus.[235,236] Inhibition occurs when the conditioning stimulus is administered for 1-4 ms while facilitation occurs when the suprathreshold stimulus is administer for 8-15 seconds.[235,237] Intracortical excitability is regulated by γ-Aminobutyric acid (GABA), the main inhibitory neurotransmitter in the primary motor cortex.[238] GABA has two receptor subtypes $GABA_A$ and $GABA_B$. Short-interval intracortical inhibition (SICI) is assessed to measure postsynaptic $GABA_A$ receptor mediated M1 intracortical inhibition.[237,238] Long-interval intracortical inhibition (LICI) is assessed to measure postsynaptic $GABA_B$ activity. SICI and LICI are measures of intracortical excitability. GABA optimizes corticomotor output during functional tasks and therefore it has been hypothesized GABA function may be affected after ACLR.[205] Limited studies have examined intracortical excitability following musculoskeletal injuries; however two studies have found there are no differences between limbs in individuals with ACLR[239] nor are there differences compared to healthy controls.[205,239] One study did find a strong, positive relationship (r=0.502, p=0.008) between CAR and intracortical inhibition in the ACLR limb, but did not find the same relationship in the contralateral limb (r=0.202, p=0.313). Despite these findings, there were no significant differences in intracortical inhibition between the ACLR limb (0.59±0.24) and the contralateral limb (0.68±0.37), nor were there significant differences in intracortical limb facilitation (ACLR=1.21±0.54, contralateral=1.09±0.42).[235] The findings indicate that intracortical inhibition does influence voluntary activation of the quadriceps in this population and maybe a viable therapeutic target during rehabilitation.

Somatosensory Cortex Excitability

The ACL is innervated by free nerve endings including Ruffini endings, Pacinian corpuscles, and Golgi tendon organs which can detect speed, acceleration, movement direction, and joint position.[240] After ACLR, the native mechanoreceptors may not regenerate to innervate the ACL graft.[181,182] Early work in patients with chronic ankle instability showed that mechanical instability following ligamentous sprain accounted for a small portion of those reporting ‘giving way’ at the joint, indicating that peripheral deafferentation of the mechanoreceptors maybe a root cause of repeated injury.[241] Peripheral deafferentation compromises ability to reactively stabilize the joint and increases the risk of a second injury.[1,241,242] Much of what is currently understood about the interaction between ACLR and somatosensory cortical activation has been found using electroencephalography (EEG),[243] but recently an fMRI study revealed increased activation of the secondary somatosensory areas of the brain.[184] These findings in combination with EEG studies provide temporal (EEG) and spatial (fMRI) evidence of neuroplastic changes following ACLR.

Use of EEG allows for temporal quantification of the brain’s electrical activity in response to sensorimotor stimuli and functional tasks. Commonly studied brain waves include delta waves associated with conscious awareness and cortical integration;[244] theta waves which are associated with memory tasks requiring short-term memory necessary for action-based perceptions;[245] and alpha waves that are associated with cortical inhibition. One study examined differences in frontal and parietal cortex delta and theta power during walking, running, and landing in individuals that were ACL deficient (ACLD) and healthy controls. In all three tasks, individuals with ACLD demonstrated increased delta and theta power in both areas.[246] Their results may imply that after ACL injury, greater awareness and conscious effort is needed to execute motions that are otherwise autonomously controlled in healthy individuals. Two EMG studies conducted on individuals with ACLR found increased theta power in the frontal cortex and higher Alpha-2 power in the parietal cortex.[243,247] In the first study, participants were asked to reproduce a joint angle by extending the knee from 90° of flexion to 40° of flexion.[247] Individuals with ACLR performed the task with the ACLR limb with greater error and increased Theta power in the frontal lobe compared to the healthy controls.[247] These differences were not present when comparing the uninjured limb in the ACLR group to the healthy controls.[247] Increased frontal lobe Theta power occurs when engaging in complex tasks with high attentional demand. The findings of this study indicate that individuals with ACLR have an altered sense of joint position due to peripheral deafferentation and increase reliance on the frontal lobe to position the knee during a simple, single-planar task. During complex tasks such as those performed during sport, greater Theta power in the frontal lobe is needed to maintain knee posture and protect the joint from injury. Additionally, those with ACLR exhibited lower Alpha-2 power when reproducing the joint angle, which is reflective of differences in sensory information processing in the somatosensory cortex.[247] These changes may also be attributed to peripheral deafferentation as altered neural input from the injured limb would elicit differences in the somatosensory cortex. In a follow-up study using a similar design using a force matching task, individuals with ACLR once again demonstrated greater Theta activation in the frontal lobe than did the healthy controls.[243] The authors concluded that their results increased activation in the anterior cingulate cortex (ACC) and increased reliance on secondary somatosensory cortex. The ACC is part of the attentional system and controls target selection, error detection, and monitors performance.[248] Greater activation of the ACC may indicate compensation for altered afferent signals from the knee in individuals with ACLR and greater reliance on cortical activation to stabilize the knee during athletic movements. Similar results were found using fMRI during a supine knee extension task, in which individuals with ACLD exhibited increased activation of the presupplementary motor area, the contralateral posterior secondary somatosensory area, and the ipsilateral posterior inferior temporal gyrus contralateral to the ACLD limb.[249] The posterior inferior temporal gyrus is part of the visual cortex and aids in recognizing movement.[250] Increased activation of this area maybe a result of peripheral deafferentation that limits proprioceptive information reaching the CNS and causing the individual to rely on motion vision for feedback on joint position. These findings were supported by a second fMRI study in individuals with ACLR,[184] that found increased activation of the secondary somatosensory[184] area responsible for integrating sensory stimuli and addressing painful stimuli.[251,252] During complex tasks like a competitive game with several external stimuli, diverting additional focus to joint position may distract the individual from opponents or obstacles that need to be avoided.[253] Likewise, drawing attention toward an opponent or obstacle may jeopardize the individual's ability to stabilize the knee and increase risk of a secondary injury.[72,73]

FUNCTIONAL ADAPTATIONS AFTER ACL RECONSTRUCTION

The adaptations described above manifest in several ways affecting the individual's behavior and movement patterns. Individuals with ACLR may adopt different movement patterns to compensate for the neuromuscular changes that have occurred due to their injury and surgery.[100,105,224,254] Post-injury and post-ACLR adaptions occur in gait speed and gait biomechanics during running and walking,[56,255,256] as well as during jumping,[257] hopping,[46] and COD.[30,258] In choosing assessments to determine RTS status, it is important to understand the individual's functional limitations during movements in multiple planes since uniplanar assessments, such as a single leg hop, may not be adequate to describe the individual's ability to stabilize the knee when performing a multiplanar or sport-related movement.

Reaction Time

Evidence suggests neuromuscular inhibition and peripheral deafferentation contribute to neuroplastic changes in the brain after ACLR.[184,249] One of the functional neuroplastic changes to occur is increased activation of the lingual gyrus and the primary motor cortex after ACLR. The lingual gyrus is involved in processing congruent visual and sensory feedback in three key areas: limb positioning,[259,260] sensory-visual spatial navigation,[261] and kinesthetic awareness.[260,261] The mechanoreceptors that innervate the native ACL are damaged when the ACL tears, compromising afferent signals to the spinal cord and CNS.[181,240] Most of the mechanoreceptors are located near the foot of the ACL, which is removed during reconstruction to create a tunnel through which the graft will be placed.[181,182] Mechanoreceptors do not reinnervate the graft after ACLR and therefore the afferent communication between the ACL graft and the rest of the nervous system is diminished. Increased activation of the lingual gyrus occurs as a result of diminished afferent neural conduction, additionally the rehabilitation process after ACLR increases awareness of the injured limb that results in a visual-motor link.[184] Splitting attention between external stimuli and stabilizing the knee creates conflict in choosing a motor goal.[184,262–264] As reported in studies on jump[73] and COD performance,[72] drawing attention away from the task by means of external stimulus such as dribbling a soccer ball[265] or performing a subsequent task[266] exacerbates high risk biomechanics that can lead to an ACL injury. Increased activation of the lingual gyrus and of the primary motor cortex suggest that brain is relying on visual-spatial afferent information regarding knee joint position and top-down control of the quadriceps to generate the force needed to execute the selected motor plan.[1,184] The neuroplastic adaptions that occur in the brain after ACLR may affect reaction time and the individual’s ability to respond to external stimuli while simultaneously stabilizing the knee.

The time from presentation of a stimulus to the initiation of a movement is termed reaction time (RT). It can be further categorized as simple RT in which the individual responds each time a stimulus is presented or choice RT in which the individual must decide how to respond to a stimulus. RT is influenced by the number of options presented during the decision-making process,[267] subjective value of each option,[268] and congruency between stimulus and appropriate response.[264] In order to respond to a stimulus, like making an agile movement in response to an approaching opponent, several decisions need to be made in a relatively short amount of time. Wong et al.[262] present a model that illustrates the process of selecting and executing a motor plan after the presentation of a stimulus (Figure 2.3).[262] The model is divided into two portions, the ‘What’ and the ‘How’. The objective of the ‘What’ portion of the model is to select a motor goal in response to the object, a stimulus, and requires the individual’s attention to identify the object and its location within the environment.[262] This portion of the model takes the most time and therefore makes up the majority of RT. Identifying the object generates a priority map to describe the object within the environment which aides in selecting a motor goal.[262] In context of COD, an individual identifies an opponent or obstacle, the object, within the field of play, the environment, noting the object’s orientation to the individual, the object’s speed, and the object's trajectory. The individual then decides to engage or evade the object, selects a motor plan, and applies rules for the task (COD). Rules in this context do not refer to the rules of the sport, but rather to rules for executing a motor plan to achieve the desired goal. Task constraints such as rules in sports can effect movement execution and have been described using Newell's Constraint Theory,[269] but are not included explicitly in the model presented by Wong et al.[262]

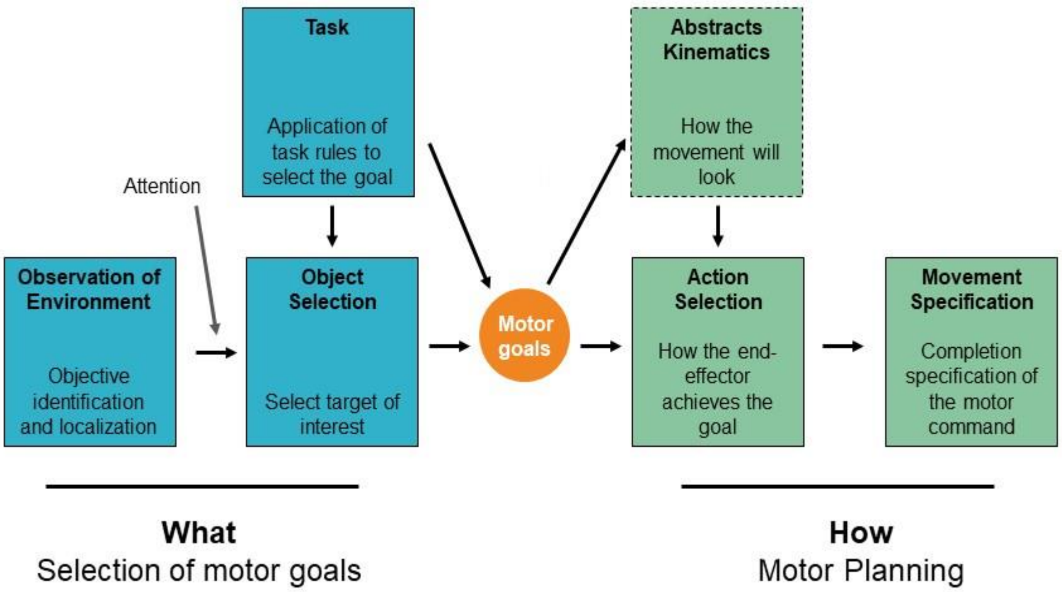

Figure 2.3: Perception to Movement Pathway Adapted from Wong et al. 2015[262]

Once a motor goal is selected a motor plan can be conceived as the individual proceeds to the 'How' portion of the model. In this portion, there are two steps, (1) action selection and (2) movement specification with an optional third step, abstract kinematics. Developing a motor plan is a faster process than selecting a motor goal. Point-to-point movements can be generated in as little as 160 ms by selecting a preplanned control policy which are stored in the prefrontal cortex; the area of the brain responsible for decision-making.[270] A control policy determines movement trajectory based on the joint position, motor goal, and cost of distance between effector and the endpoint.[271] The individual must choose an action and describe the motion of the end-effector (i.e. body or body part), then determine the complete motor command and postural adjustments to perform the motor command.[262] The third step in the 'How' portion of the model is 'Abstract Kinematics'. This section is considered optional, but may be necessary under circumstances in which alternative motor-planning is required to perform the motor command.[262] Under such circumstances, the motor goal can be achieved through multiple avenues, because it does not have execution-specific parameters. This is referred to as motor equivalence.[262] Abstract kinematics may be important in executing agile maneuvers when environmental and task constraints can affect the motor command. For example, a running back in American football carrying the ball could select and execute a motor goal in which he runs from the line of scrimmage to the endzone in a straight line. However, this motor goal does not account for opposing players, field conditions, or boundary lines which will inevitably lead to a premature end of the play. Rather, abstract kinematics are needed to account for these variables. The position of the opposing players in relation to the running back will constantly change as the play progresses; the running back will have to continuously assess and adapt to the field of play. Abstract kinematics are cognitively demanding and increase reaction time, should a scenario arise in which the running back must decide quickly to avoid an opponent, abstract kinematics may cause hesitation increasing ground contact time leading to injury.

Research on RT in individuals with ACLR has focused on three areas (1) response to postural perturbations, (2) muscle contraction latency measured via EMG, and (3) performance on neurocognitive assessments. Surprisingly, no longitudinal studies have documented the clinical progression of RT after ACLR, nor is there any research on RT during functional assessments like those used in RTS criteria. One study found that fear-avoidance and visuomotor RT (VMRT), a measure of the individual's ability to respond to central and peripheral visual stimuli during task, were moderately correlated in individuals with ACLR (time since surgery =7.15±4.43 years) between.[272] RT has also been assessed using neurocognitive assessments like the ImPACT which is used to evaluate baseline and post-concussion brain function.[233] One study found that those who sustained an ACL injury within 3 years of neurocognitive baseline testing (ImPACT) had a significantly slower RT (0.57±0.07 s, $F_{1,158}$=9.66; p=0.002; d=0.46; 95%CI[0.55 to 0.59]), compared to those individuals that did not sustain an ACL injury during the same period of time (RT non-injured=0.53±0.10 s).[233] An additional study examined COD performance in collegiate club soccer players found that visual memory composite score on the ImPACT is a stronger predictor of peak knee valgus angle (R^2=0.52) when making a sidestep cut and dribbling a soccer ball than RT, and therefore may contribute to neuromuscular control to a greater extent than RT.[265]

It should be noted that visual memory is processed in the lingual gyrus which undergoes functional neuroplastic changes after ACLR that will affect both visual memory and RT.[184] One study compared RT on a computer based card-flipping task in which participants pressed a key when a card was flipped up to show the face value. No differences were found between the ACLR group and the healthy controls for RT; however, the authors did note that the ACLR group performed better on visuomotor scanning tasks than the healthy controls. Again these findings reflect those fMRI studies[184] that have shown increase activation in the lingual gyrus.[273] A cross-sectional study found that individuals with ACLR (8.91±5.97 years post-surgery) do not have significantly slower RT on a simple reaction test using the hand or the foot, but they are significantly slower on a postural stability test that requires stepping forward with the foot that corresponded to a light stimulus.[274] This finding is of interest as it may imply that individuals with ACLR perform worse under increased cognitive demands. In healthy individuals, additional cognitive demand during a drop vertical jump has been shown to result in greater vGRF and lesser peak knee flexion angles[73] and decreased hop distance during single leg hop assessments,[49] which may be risk factors for ACL injury.

To maintain joint stability during voluntary movement, compensatory postural adjustments are made in response to unpredicted perturbation while anticipatory postural adjustments are made in response to predicted perturbation.[275–277] The latency period from initiation of the perturbation to onset of contraction can be used to assess ability to stabilize the joint after ACLR.[277,278] A single longitudinal study examined the progression of compensatory and anticipatory latencies in males with ACLR compared to healthy controls.[278] Assessments were performed prior to surgery, two months and 6 months post-surgery. Quadriceps compensatory and anticipatory latencies were measured using EMG during a perturbation task in which the participant was positioned in a reclined position and the researcher held the heel of the ACLR limb in his/her palm to maintain the knee at the starting joint angle.[278] The participant was asked to completely relax the muscles of the ACLR limb. The researcher would then unexpectedly drop the heel and the participant would return the knee to the starting joint angle as quickly as possible. Individuals with ACLR had longer latency of compensatory responses than the healthy controls in the vastus lateralis and vastus medialis at all three time points.[278] During a the same task repeated under predictable conditions in which the participant dropped their own heel, the vastus lateralis of individuals with ACLR responded faster than the healthy participants as well as when compared to the pre-operative assessment and the assessment completed two months post-surgery; however, there were no differences between groups 6 months post-surgery.[278] This study provides evidence that RT maybe slower after ACLR under unpredictable conditions and shows progression of the quadriceps ability to contract in response to perturbation; however, these findings may not be reflective of RT during functional tasks or during athletic performance. Stated differently, the assessment utilized in this study, while allowing for exceptional experimental control, lacks ecological validity as it is performed in a non-weight bearing position in a controlled environment which is not indicative of the environment in which ACL injury occurs. Another longitudinal study measured muscle RT using EMG during a single leg landing from a 25 cm box in individuals with ACLR. Pre-surgical, the vastus medialis showed the slowest RT compared to the ipsilateral vastus lateralis, rectus femoris, biceps femoris and semitendinosus.[279] However, 6 months after surgery, vastus medialis RT in the ACLR limb was equivalent to that of the contralateral limb.[279] The same decline in RT from pre-surgery to 6 months post-surgical occurred in the ACLR limb vastus lateralis, rectus femoris, biceps femoris, and semitendinosus, at which time there were no differences in RT between limbs.[279] This study did successfully find delayed muscle contraction onset during a dynamic task, however, RT from presentation of stimulus to initiation of movement was not measured. Rather, the authors reported muscle latency from initial contact with a force plate to peak amplitude EMG activity as RT. Within the context of functional assessments, this study did not record RT, but their findings may suggest that RT is negatively affected after ACLR. It should also be noted that both studies showed that muscle latency normalized 6 months after ACLR, the same time frame in which the H-reflex also normalizes in this population. Based on the nature of both tasks, it is possible these assessments are a better measure of reflex pathway restoration, not RT during functional tasks.

Functional Adaptations During Running Gait

Changes in gait, which have been linked to the development of osteoarthritis after ACLR[280,281], have been reported as early as 4 weeks post-ACLR[282] and remain as long as 2 years after surgery.[283] At 4 and 12 weeks post-surgery, the ACLR limb experiences a smaller knee extension moment impulse during gait (-0.15 SE=0.006 Nm*s/kg; d=1.3) than does the contralateral limb.[282] At 17 weeks post-surgery, while running the ACLR limb exhibits a smaller knee extensor moment impulse compared to the contralateral limb (-0.1, SE=0.03 Nm*s/kg; p=0.004; d=1.82).[282] Across all time points, during walking gait the ACLR limb exhibits less knee flexion (-4.4° SE=0.63°; p=0.042; d=1.89) than the contralateral limb.[282] One study found that individuals with ACLR approximately 2 years after surgery exhibit greater divergence in flexion-extension moment while walking compared to healthy controls ($F_{2,15}$=5.43, p=0.016).[284] Physically active females with ACLR, 5 years (average time since surgery=5.2±3.2 years) post-surgery run and walk with greater impact force normalized to body weight and with a higher average loading rate compared to healthy controls matched for age, sex, height, and weight.[285] Females with ACLR walk with significantly greater hip extension moment (-0.3±0.4 $Nm*kg^{-1*}m^{-1}$) than healthy controls(-0.1±0.4 $Nm*kg^{-1*}m^{-1}$); however this difference was not found when the participants were running.[285] Similar results were found for knee extensor moment; females with ACLR walked with smaller knee extension moment (0.04±0.2 $Nm*kg^{-1*}m^{-1}$) compared to healthy controls (0.23±0.1 $Nm*kg^{-1*}m^{-1}$).[285] Those with ACLR walk with a 21% greater knee abduction moment that may contribute to progression of osteoarthritis.[280] Linear speed during sprinting after ACLR has not been reported in the literature; however linear speed has a strong positive relationship to hamstring and quadriceps strength, which are persistently weak in individuals with ACLR and therefore it is hypothesized linear speed during sprinting is slower after ACLR.[286,287]

Functional Adaptations During Jump Landing and Hopping

The vastii muscles are one of the main contributors to center of mass (COM) acceleration during a countermovement jump (CMJ).[288] Persistent quadriceps weakness after ACLR[289] inhibits the individual from generating force to jump or hop. A cross-sectional study examined CMJ performance in professional soccer players grouped by time since surgery.[290] Group 1 was less than 6 months post-ACLR; Group 2 was 6-9 months post-ACLR; Group 3 was more than 9 months post-ACLR; and Group 4 were healthy controls. Regardless of time since surgery, the ACLR groups did not jump as high as the healthy controls and individuals 6-months post-ACLR performed the worst out of the 4 groups.[290] In the same study, there was a significant between limb difference for eccentric RTD and peak landing vGRF and were less symmetrical than the control group for both variables in individuals with ACLR regardless of group membership.[290] RTD is a predictor of vertical jump height in this population and therefore maybe a good clinical indicator of quadriceps strength recovery.[226] The differences in CMJ performance between individuals 6 months or more after ACLR compared to healthy controls is clinically relevant. Though these individuals may be ready to begin training to integrate back into to training for their sport and they have reached the recommend time after surgery to RTS,[12] they are not performing at an equal level to healthy controls which could indicate persistent dysfunction resulting in elevated risk of second injury. At 9 months after ACLR, there were no differences in jump height or single leg hop distance between those with ACLR and healthy controls. However, the ACLR group exhibited greater biomechanical asymmetries in jumping and hopping than did the healthy controls. This finding implies that individuals with ACLR adopt compensatory movement patterns to mask neuromuscular deficits. It also highlights a key issue in clinical and field-based assessments used to determine RTS after ACLR.

Change of Direction and Anterior Cruciate Ligament Injury

Evidence suggests that the current approach to identifying individuals at an increased risk of a secondary ACL injury via single leg hop distance performance and symmetry is not adequate. In part, this is because of the limited relationship between single leg hop performance and lower extremity biomechanics and sport related movements.[22,46,60,291,292] COD and agility maneuvers are common evasive strategies in sport and they have been identified as a leading cause of ACL injury.[27,28,34,63] In handball athletes, more than 50% of ACL injuries occurred during COD.[28] The authors observed that these injuries occurred when the athlete’s attention was directed at an opposing player or when reacting to ball movement.[28] COD performed under increased cognitive demand has been shown to increase knee valgus angle that stresses the ACL and can cause injury.[72,290] Despite the known risk of injury during COD and agility maneuvers, they are not assessed as part of RTS criteria after ACLR. Furthermore, clinical progression of COD performance after ACLR has not been documented. It is a logical step to examine the functional progression COD performance after ACLR to better understand functional deficits these individuals face when attempting to RTS.

Nine months after ACLR, male athletes (age=24.8±4.8 years) that participate in multidirectional field sports did not exhibit between limb differences in completion time or ground contact time when performing a 5 m sprint followed by a 90° COD under anticipated and unanticipated conditions.[30] However, there were significant differences between the anticipated and unanticipated conditions for completion time (ACLR anticipated=1.44±0.13 s; ACLR unanticipated=153±0.12 s; $p<0.001$; $d=0.73$), ground contact time (ACLR anticipated=0.33±0.05 s; ACLR unanticipated=0.35±0.05 s; $p<0.001$; $d=0.35$), and velocity at initial contact (ACLR anticipated=2.63±0.32 m/s; ACLR unanticipated=2.54±0.12 m/s $p<0.001$; $d=0.34$).[30] The more concerning finding in this study was the biomechanical differences between limbs and between conditions. COD performed on the ACLR limb was completed with a significantly lesser peak knee valgus moment during mid-stance.[30] During the stance phase, the ACLR performed COD with a smaller knee flexion angle, a smaller knee external rotation moment and lesser knee extension moment.[30] During the unanticipated COD, the pelvis rotated less toward the new direction when using the ACLR limb,[30] which has been shown to increase knee valgus moment in healthy individuals.[99] Similarly individuals with ACLR displayed less symmetrical anticipated and unanticipated COD completion times and they were more asymmetrical in ground reaction forces, hip abduction angle (anticipated condition only), and knee flexion angle (unanticipated condition only) when compared to individuals without ACLR.[29] Slower completion times compared to healthy and high risk biomechanics during COD 9 months after ACLR are indicators that full integration into sport at this time point may not be prudent. Incomplete recovery resulting in inability to adequately perform COD tasks in a safe and effective manner may increase the risk of a second ACL injury. These studies support the hypothesis that COD performance under anticipated and unanticipated conditions is necessary to safely integrate back into sport after ACLR.

Following ACLR, quadriceps strength and single leg hop performance are often used as RTS criteria;[12] however evidence is accumulating that there is a disconnect between meeting criteria and reduced risk of a second ACL injury.[22,60,291] Female basketball players 12-60 months post-ACLR divided into groups based on meeting quadriceps strength and single leg hop RTS criteria (time since surgery RTS pass=36.1±12.6 months; time since surgery RTS fail=34.0±14.7 months) and were compared to healthy controls on a single leg jump cutting task before and after a fatiguing exercise protocol.[293] No significant group by exercise interaction or exercise main effect for any landing biomechanics during the jump cutting task, but there was a significant group main effect for peak anterior tibial shear force (ATSF) symmetry ($F_{2,27}=3.494$, $p=0.04$, $\eta^2=0.206$). The RTS pass ($p=0.01$) and the RTS fail ($p=0.009$) exhibited greater peak ATSF asymmetry compared to the healthy controls.[293] The ACL's primary role is to prevent anterior translation of the tibia on the femur. Increased ATSF places greater strain on the ACL and can cause injury. The findings of this study are evidence that individuals with ACLR continue to experience functional deficits years after surgery and that meeting RTS criteria is not an indication of full recovery in this population. These findings were corroborated by another study that found that athletes that returned to sport 7 months after ACLR and did not meet return to sports criteria were at 4 times greater risk of sustaining a second ACL injury within 6 months of returning to sport.[294] This study included the T-test, a field based COD assessment, as part of RTS criteria and found no difference in completion time between individuals who sustained a second ACL injury and those that did not.

Longitudinal data describing the progression of COD performance after ACLR has not been published. Multiple cross sectional studies have been published on COD performance later than 1 year after ACLR.[133,134,258,293,295–298] However there are methodological concerns that should be taken into consideration when evaluating the quality of data collected in these studies. One study examined differences between healthy controls and females with ACLR in knee displacement, velocity, and time to peak vGRF with and without visual disruption when side stepping at a 45° angle.[295] Despite significant differences between groups, the task used in this study may not be representative of COD performance.[295] While standing still, participants initiated a trial by catching a ball and stepping in the direction indicating by a tone heard through a set of headphones. The task lacks ecological validity and does not adequately replicate COD because there was no deceleration phase leading to a directional change. The eccentric loading and rotation of the trunk toward the new trajectory that occur during deceleration, load the limb that is to propel the individual in the new direction. Removing deceleration from the task unloads the push-off limb and reduces the forces that contribute to ACL injury. Another study examined COD at 90° and found no difference in peak knee valgus angle between limbs. This study used a heterogenous and small sample (n= 10; 8 females/2 males; range of time since surgery 12-65 months) and only one maximal effort trial was collected per leg.[296] A study comparing functional outcomes between those that return to sport and those that did not 2-year post-ACLR did not find a significant differences between groups in completion time on the shuttle run test (three 180° directional changes separated by 20 foot sprints), but did find significant differences between groups on the carioca test and the co-contraction test.[299] None of the assessments were conducted under unanticipated conditions, which reduces the neurocognitive demand and ecological validity. The carioca test and the co-contraction test may not be representative of COD performance. In the carioca test, the participant repeatedly crosses one leg over and then behind the other for 40 feet then returns to the starting line. While there is a directional change, a majority of the assessment is spent performing the carioca and therefore linear speed may explain results rather than ability to COD. In the co-contraction test, the participant shuffles around a 180° semi-circle five times while attached to a large rubber band that prevents the participant from deviating from the semi-circle's perimeter. There is no reactionary component to the assessment and restricting free motion with the rubber band prevents accurate assessment of the participant's ability to perform the task. To note, there is a large, negative correlation between completion time and self-reported knee function on the co-contraction test ($r=-0.569$, $p=0.001$), the shuttle run test ($r=-0.512$; $p=0.004$), and a moderate, negative correlation the carioca test ($r=-0.453$, $p=0.012$) in individuals with ACLR.[298] This maybe an indication these assessments may also need to be incorporated into RTS criteria after ACLR in addition to anticipated and unanticipated COD assessments.

RETURN TO SPORT CRITERIA

The need to mitigate ACL injuries has continued to grow over the last two decades as the rate of primary[9,59] and secondary[17] ACL injuries continues to rise. Based on the adaptations the individual undergoes after ACLR, it has become clear a single assessment is not a comprehensive approach to determine who is ready to participate in sports and who is at an increased risk of an ACL injury. Therefore, test batteries comprised of functional assessments, strength measurements, and patient-reported outcomes have been adopted within the literature and as part of clinical practice to mitigate the risk of ACL injury.[12,39,43,74] Contemporary RTS criteria are based on symmetrical performance on single leg hop assessments and symmetrical quadriceps strength in addition to time since surgery.[12,39] A widely cited study showed that individuals with ACLR reduced the risk of a second ACL injury by 50% for each month they delayed returning to sport until 9 months after surgery.[12] The same study also found that for every 1% increase in quadriceps strength symmetry results in a 3% reduction in reinjury rate and individuals with single leg hop distance symmetry greater than 90% limb symmetry index (LSI) had lower risk of reinjury within 2 years of returning to sport.[12] More recent literature has identified weak points in the many of the assessments used as RTS criteria.[60,291,292] In general, assessments used in current RTS criteria use single plane movements performed in a controlled environment. The assessments are poor at identifying individuals at an increased risk of a second ACL injury nor do they mimic the demands of sport. More comprehensive assessments are needed to measure knee function after ACLR and determine RTS status.

LIMITATIONS IN RETURN TO SPORT CRITIERIA

RTS criteria like hop assessments and quadriceps strength symmetry are based on assumptions that limit identification of individuals at an increased risk of a second ACL injury. For instance, it is assumed that the contralateral limb's strength and hop performance can be used as a barometer for recovery. However this approach is short sited as contralateral limb strength is also weaker after ACLR.[300,301] Additionally, LSI overestimates knee function after ACLR.[45,291] In individuals 14-55 years old (average age=26.6±10.0 years), only 57.1% achieved greater than 90% LSI on both strength and 4 single leg hop assessments (single leg, crossover, triple hop for distance, 6-meter timed hop) six months after ACLR[291] Of those individuals, 20% sustained a second ACL injury within 2 years of ACLR.[291] Furthermore, asymmetrical hop performance in healthy male collegiate athletes does not affect COD speed, which may indicate that performance on either task is mutually exclusive and must therefore be assessed independently.[302] Quadriceps strength and hop distance symmetry are indicators of performance solely in the sagittal plane under controlled conditions. Performance on such assessments cannot be extrapolated to assume performance in when moving through other planes of motion or under greater neurocognitive demand.

Another assumption regarding single leg hop performance is that the knee will experience lower risk kinematics and kinetics as a function of hopping further and more symmetrically. This is not the case in young individuals (21.5±2.3 years old) with ACLR who exhibited limited agreement between knee flexion angle (κ=0.033, p=0.387) and triple hop distance symmetry, and between peak internal knee extension moment (κ=0.022, p=0.475) and triple hop distance symmetry.[46] Despite no significant between group differences in hop distance symmetry, nine months post-surgery, individuals with ACLR exhibit significantly greater knee valgus moment (9.8±0.7 Nm/kg, 95%CI[8.7-10.9], d=0.52) during a single leg hop for distance compared to healthy controls (6.4±1.0 Nm/kg, 95%CI[6.19-6.68]).[29] Regardless of single leg hop distance symmetry, individuals less than a year removed from ACLR land with lesser knee flexion moment and energy absorption at the knee on the ACLR limb compared to healthy controls and the contralateral limb.[292] Individuals with asymmetrical and symmetrical single leg hop distances also had lesser knee adduction moment compared to controls.[292] Despite the relationship between single leg hop distance and quadriceps strength,[303] it does not appear that hop assessments adequately account for or identify individuals with high risk biomechanics. High risk biomechanics during single leg hop assessments are alarming as hop assessments are deemed to be safer than other activities like COD or agile maneuvers. In ability to stabilize the knee during hop assessments is an indication the individual is not prepared multiplanar motion.

It is also assumed that knee kinematics and kinetics are consistent across movement patterns and simple, uniplanar movements are predictive of more complex movements. This assumption is not supported by the literature as evidenced by the poor correlation in knee abduction moment (ρ=0.135) between a drop vertical jump (uniplanar motion) and a sidestep cut, a change of direction task. In addition, knee valgus angle during drop vertical jump and knee abduction moment in sidestep cutting (ρ=0.238) are also poorly correlated.[117] Perhaps of the greatest concern, is that the knee abduction moment during sidestep cutting is 6 times greater (sidestep cut=1.58±0.60 Nm/kg) than that which occurs during drop vertical jump (0.25±0.16 Nm/kg).[117] Landing with a knee abduction moment greater than 25 Nm, is associated with a greater risk of ACL injury.[97] Based on these findings, while performing COD, a 90.9 kg (200 lbs) individual will experience a knee abduction moment of 143.6 Nm, a force 5.7 times greater than the threshold indicating increased risk of ACL injury. Differences in lower extremity biomechanics become exaggerated when neurocognitive demands are increased such as performing the tasks under unanticipated conditions or adding a subsequent movement.[72,73,266] In healthy female athletes, knee abduction angle at initial contact is greater during an unplanned sidestep cut (8.2±4.9°) than during a planned single leg drop landing (2.34±2.4°, p<0.001) and a single leg countermovement jump (2.1±2.1°, p<0.001).[304] COD and agility movements can result in high risk biomechanics associated with ACL injury. Such movements are ubiquitous in sport and the findings discussed above are further evidence that multiplanar motions need to be assessed prior to RTS after ACLR.

Current RTS criteria does not include open-skill tasks, despite that they have been found to be different skill sets from closed-skill tasks,[35,305] and it is recommend that open-skill tasks be included in RTS assessments.[43] Closed-skill tasks, like hop assessments, are pre-planned movements with a predictable outcome. They do not require situational processing or reaction to a stimulus. Open-skill tasks are unpredictable and reactionary. The additional cognitive demand during open-skill tasks like making an unanticipated sidestep cut increases ACL loading,[52] and increases knee flexion, valgus and internal rotation angle, and results in greater knee flexion and valgus moments.[129] Most sports do require a reactionary component, given the impact making unanticipated movements can have on lower extremity biomechanics, open-skill tasks should be included when making a RTS decision after ACLR.

ASSESSING ACTIVITY SPECIFIC DEMANDS

Change of Direction and Agility

Change of direction (COD) and agility are common tactical maneuvers in sports used to evade or engage an opponent or obstacle. Though similar, these terms are not interchangeable and are considered different skill sets.[35,305] COD is the execution of a preplanned movement to change the body’s trajectory, whereas agility is an unplanned, reactive COD made in response to a stimulus. COD is a closed skill with predictable temporal and spatial constraints, whereas agility is an open skill that requires a cognitive response to stimulus.[305] These skills are often assessed during side-step cutting, crossover step, and a jump landing to a cut. A side-step cut involves running forward with a single COD typically at an angle between 45° and 180° from the original trajectory. The crossover step is a lateral movement like shuffling. Jump landing to a cut can be performed on a single leg or both legs. The individual jumps from a box to landing target and either steps or hops in a desired direction. COD and agility need to be assessed using multiple maneuvers as different joint angles and moments vary between tasks.[125,126,306] Biomechanical demands of COD are angle and velocity dependent which means kinetic and kinematics will differ when attempting COD at different angles and will be influenced by approach velocity.[119] At angles less than 45°, minimal deceleration is needed to COD; however as the angle increases, or becomes sharper, the individual must decelerate more which reduces entry and exit speeds and slows down time to completion. Breaking forces need to be applied over several steps to decelerate the body before COD which requires eccentric loading of the quadriceps and hamstrings.[26,307] Female soccer players that were categorized as having high eccentric strength were faster to complete COD tasks and had faster entry speeds during the last two steps prior to COD.[307] Greater braking force during the penultimate step reduces knee abduction moment when COD angle is greater than 60°.

When changing direction, the body must be decelerated over several steps. To decelerate, the hamstrings must eccentrically contract to slow the body's center of mass (COM) and stabilize the knee.[121,307] In the event the individual does not decelerate adequately to COD, the COM will continue in the original trajectory limiting the trunk rotation toward the desired direction and increasing the internal knee varus moment.[99] In attempt to compensate for inadequate deceleration, individuals may also increase trunk flexion at the expense of increasing internal knee external rotation moment and knee abduction moment. Either scenario is of concern for individuals with ACLR as increased internal knee varus moment and internal knee external rotation moment increase stress on the ACL and can lead to injury. The penultimate (second to last) and the final step are particularly important in this process and subsequently the steps during which injury will most likely occur. The penultimate step is responsible for generating the horizontal breaking force (HBF) needed to slow the body's COM to reduce loading on the final step. Symmetrical eccentric quadriceps and hamstring strength is necessary to stabilize the knee while decelerating, to offload the final step before COD. Insufficient eccentric results in greater loads placed on the final step and jeopardizes the integrity of the ACL. Additional strength. sufficient hip and knee flexion must occur while decelerating. A smaller ratio results in greater knee abduction that can put undue stress on the ACL that can lead to an injury.

High-risk biomechanics experienced during evasive maneuvers are exacerbated under unanticipated conditions. Therefore, it is important to assess COD as an open skill (agility) from a performance standpoint, but also to mitigate the risk of a second injury. During an unanticipated 45° angle cut, knee abduction angle, knee abduction moment and anterior tibial shear force significantly increase at initial contact in comparison to an unanticipated deceleration. This is an important distinction for individuals with ACLR that may have adequate eccentric hamstring strength to decelerate but may not be able to stabilize the knee when transverse or sagittal plane motions are introduced. Side-cutting performed under unanticipated conditions increases knee flexion, but also results in a significant increase in knee valgus angle (*side-cutting:* anticipated =0.7±6.8°, unanticipated = -0.7±9.6° valgus, p=0.011), but the same conditions do not increase knee valgus angle during cross-cutting (*cross-cutting:* anticipated=0.6±7.7°, unanticipated=2.6±8.6°, p=0.930). During both tasks under unanticipated conditions, knee flexion moment significantly increases (*side-cutting*: anticipated=2.41±2.54 Nm/kg, unanticipated=5.33±2.81 Nm/kg, p<0.001; *cross-cutting:* anticipated=2.10±1.33 Nm/kg, unanticipated=2.42±1.87 Nm/kg, p<0.001) as does knee valgus moment (*side-cutting:* anticipated=-0.10±1.00 Nm/kg, unanticipated=-1.44±1.16 Nm/kg, p<0.001; *cross-cutting:* anticipated=0.36±0.49 Nm/kg, unanticipated=0.24±0.59 Nm/kg, p<0.001). During a single leg land-and-cut task, individuals landed with less knee flexion angle at initial contact and greater vertical ground reaction forces (vGRF). Unanticipated side-cutting has also been shown to increase ACL loading.

Many of these studies have focused on healthy individuals as the hypothesized effects of anticipation during COD and agility would increase the risk of ACL. However, it is important to assess these tasks when preparing to release an individual with ACLR for unrestricted sports participation. Nine months after ACLR, when performing an unanticipated side cutting maneuver, individuals have greater ipsilateral pelvic rotation which increases knee valgus moment, and the COM was closer to the stance leg. Positioning the COM over the stance leg during COD, fixes the foot to the ground and causes the knee to abduct and increase the strain on the ACL. It should be noted that completion time on common field-based COD and agility assessments such as the T-test, has not consistently shown differences between healthy individuals and those with ACLR. It is unlikely COD and agility performance is equivalent between healthy individuals and individuals with ACLR based on the functional limitations in strength, biomechanics differences in COD tasks and in jump landing and hopping tasks after ACLR. Therefore, questions remain as to whether field-based assessments are sensitive enough to detect performance differences in these groups or are individuals with ACLR adopting compensatory strategies to mask physical deficits. To date there has not been any research done on the progression of COD and agility performance after ACLR to answer these questions.

The Reactive Strength Index and the Reactive Strength Index Modified

Many athletic movements utilize the stretch-shortening cycle (SSC) to improve efficiency and increase force production. The SSC performance can be improved through plyometric training, a mode of exercise that utilizes rapid eccentric loading of a muscle to stimulate the muscle spindle and increase the force of the proceeding concentric contraction. COD and agility maneuvers use the SSC do decelerate the body using eccentric loading of the lower extremity musculature, then concentrically contracting to propel the individual in the chosen direction. To date, there has been no research done directly comparing COD and agility performance to plyometric performance. However, many of the biomechanical determinants of COD and agility performance are analogous to the in plyometric performance.

The Reactive Strength Index (RSI) is a ratio of jump height to ground contact time during a DVJ. The Reactive Strength Index modified (RSIm), is a ratio of jump height to time to take off during a CMJ. Both are reliable means to quantify plyometric performance. The RSI is a predictor of single leg hop performance in individuals with ACLR,[149] and those with lower pre-injury RSI are more likely to sustain an ACL injury (OR=0.33, 95%CI=0.13-6.21, *p*=0.017). To improve RSI, jump height must increase and ground contact time must decrease. The biomechanical determinants to improve RSI, also protect the knee. Increased hamstring stiffness decreases ground contact time by increasing braking force and utilizing SSC to propel the individual. The hamstrings reduce the amount of tibial shear force on the knee, and they are 64% more active during the braking phase of a DVJ than during the concentric or eccentric phase of a CMJ. Individuals with a stiffer hamstring demonstrate greater knee flexion at peak tibial shear force and internal knee extension and knee varus moments during a DVJ. Shorter ground contact also improves time to completion on COD tasks and increases jump height during the DVJ.

FIELD BASED AGILITY AND CHANGE OF DIRECTION ASSESSMENTS

Motion capture systems and force plates are gold standard means of measurement in human biomechanics, but they are cost prohibitive, and most clinicians do not have access to such technology. Field-based assessments can give valid and reliable measurements of performance variables on COD and agility tasks such as reaction time and completion time.[308–311] Precautions should be taken when selecting COD assessments as linear speed,[118,312] test distance,[313] and the number of COD[313,314] during the assessment can bias the results and mask COD performance. There is a strong correlation (r=0.87, *p*=0.01) between completion time and the time to travel 1 m after a directional change in 5-0-5 agility test.[313] However measuring time to travel 1 m after a directional change can be challenging when using timing gates as there needs to be a greater distance between them to work properly.[313] Some controversy exists regarding the correlation between the number of directional changes and peak linear speed,[35,118,313] however strong correlations have been found between acceleration speed and completion time on COD tasks.[313,314] This evidence suggest that in addition to measuring completion time, the time between directional changes must also be recorded to describe COD performance. Additionally, COD assessments should be evaluated under planned and unanticipated conditions. Closed-skill COD in which individual is aware of the route and when to make directional changes is a different skill set from open-skill COD, also called agility, in which the individual must make a directional change in response to stimulus.[35,305,315]

The Pro-Agility Test

The pro-agility test, or 5-10-5, (Figure 2.4) is a reliable (ICC=0.90, 95%CI[0.84-0.94]) field-based COD assessment.[311] The assessments requires two 180° directional changes, the first after a 5 yard sprint and the second after a 10 yard sprint. There are three acceleration phases in the assessment, the first occurs when starting the assessment and the other two acceleration phases occur after each directional change. The pro-agility is not equipment intensive and can be administered using cones or other markers positioned 5 yards apart in a straight line. Completion time can be measured using an electronic timing system or stop-watch, however an electronic system is preferred as stop-watch times tend to faster and less accurate.[316] The pro-agility is a good choice to include in RTS criteria because the short distance between directional changes limit the individuals ability to reach peak linear speed and there are multiple directional changes which may further limit the bias toward linear speed. It is also a relatively short assessment requiring maximal effort for less than 6 seconds,[311] which is beneficial in individuals with ACLR who have been deconditioned while recovering from surgery. The pro-agility can be conducted under anticipated and unanticipated conditions. Under anticipated conditions, the participant begins at the middle cone and has a preplanned route to run either to the left or right cone first, change directions and run 10 yards to the opposite cone, change directions again and run back to the middle cone. Unanticipated conditions should also be included to assess agility and can be accomplished in multiple ways. When performing the pro-agility, it is important to standardize starting position and the number of directional changes per trial to allow for comparison between trials and participants. To date, there is not a standardized method for administering the pro-agility under unanticipated conditions.

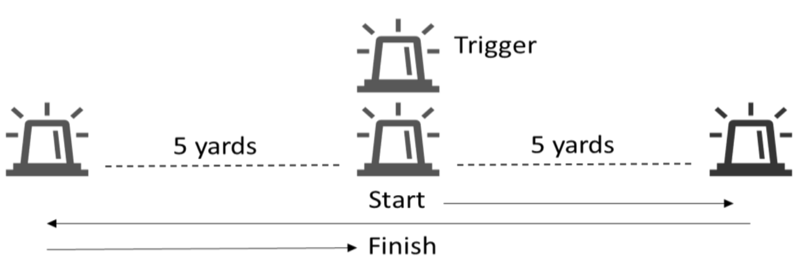

Figure 2.4: Pro-Agility

The T-Test

The T-test (Figure 2.5) is a field-based COD assessment like the pro-agility, except the T-test incorporates forward and backward running and 90° angle directional changes. The T-test has high interrater reliability (ICC=0.98, 95%CI[0.97-0.99]) and acceptable test-retest reliability (ICC=0.83; 95%CI[0.75-0.88]) in active duty service members,[308] and it has good between-session reliability for recreationally active females ($ICC_{3,1}$=0.96, 95%CI[12.84-13.19]) and males ($ICC_{3,1}$=0.82, 95%CI[10.64-10.835]).[310] The T-test has four directional changes, two at 90° and two 180°. Multiple directional changes at varying degrees and five acceleration phases aid in reducing linear speed bias in the T-test. It is a short test, ~12 seconds,[308] which makes it a good option for individuals with ACLR who are deconditioned. Like the pro-agility, the T-test can be administered under anticipated and unanticipated conditions. Again, it is important to standardize starting position and the number of directional changes during the unanticipated trials to allow for comparison between trials and participants.

The T-test is a reliable assessment of COD performance,[317] but completion time may not be sensitive enough to functional deficits in this population. It may be more suitable to assess the time between each directional change under anticipated and unanticipated conditions rather than completion time when assessing between limb differences. Individuals with ACLR have been shown to have slower completion times than healthy controls (ACLR=12.69±1.84 s; healthy control=11.76±1.36 s; p=0.05; d=0.93, 95%CI[0.33 to 1.53]),[133] which may indicate completion time is better suited to compare ACLR and healthy individuals when making RTS decisions.

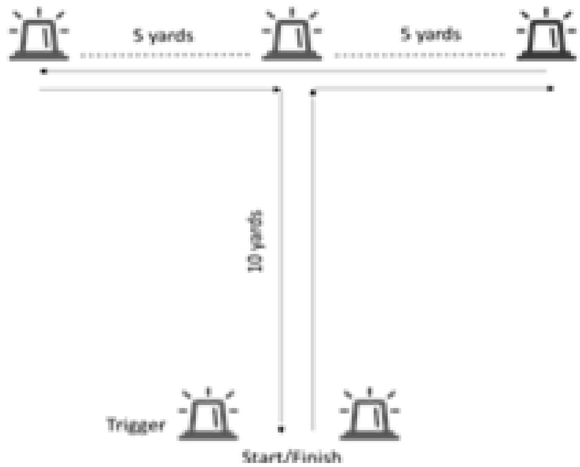

Figure 2.5: T-Test

CONCLUSION

Individuals integrating into sports after ACLR face an outsized risk of sustaining a second injury. Current RTS criteria does not adequately identify individuals at an increased risk for a second ACL injury due to a disconnect with sport related movements and they overestimate knee function after ACLR. COD is a leading cause of ACL injury, yet it is not evaluated as part of RTS criteria following ACLR. In part, the omission of COD from RTS criteria is due to a lack of research on the progression of COD performance after ACLR. Therefore, the purpose of the following studies is to assess lower extremity biomechanics and COD performance in young individuals with a history of ACLR.

ABSTRACT

Context: Individuals with anterior cruciate ligament (ACL) reconstruction (ACLR) do not return to pre-injury level of sport at the same rate when compared to those undergoing other knee surgeries. Those that do successfully integrate into sport face a 6 times greater risk of a second ACL injury than those without a history of ACLR. Demographic information, surgical characteristics, functional outcomes, and patient-reported function have been identified as obstacles to return to sport and risk factors for second ACL injury. However, these risk factors have not be assessed as part of the same predictive model. Therefore, the purpose of this study was to determine the association between demographic information, surgical characteristics, patient-reported function, and objective strength and hopping outcomes collected within 1-year post-ACLR with the incidence of re-injury and return to sport assessed 2-years after ACLR.

Methods: Ninety-one individuals (50 female/41 male; age=21.3±7.1 years) were enrolled within 1-year of ACLR (months since surgery=7.2±2.5) and completed a 2-year follow-up interview regarding return to sport status and history of second ACL injury. At the initial assessment demographic information and surgical characteristics were collected and participants completed an isokinetic quadriceps and hamstring strength at 60°/s assessment, three single leg hop assessments, the Tegner Activity Scale (TAS) and the Tampa Scale for Kinesiophobia (TSK-11). Separate logistic regression models with odds ratio and 95% confidence intervals were used to analyze the association between return to sport and second ACL injury with their respective predictor variables. The α-priori alpha level was 0.05. Model quality was compared between models using the Akaike Information Criterion (AIC), higher AIC values indicate poor model quality. Model fit was assessed using deviance from a saturated model, higher deviance indicated worse model fit.

Results: All models generated to predict return to sport status were significant; however, the Participant Characteristic Model (age, sex, and meniscal procedure at the time of ACLR) had the lowest AIC (61.2) and was therefore the model of the highest quality. The Participant Characteristic Model, the Patient-Reported Outcome Model, and the Functional Model were not significant and unable to predict second ACL injury. The models for return to sport and second ACL injury were not enhanced with the addition of patient-reported outcomes or functional data.

Conclusion: Demographic information and surgical characteristics were predictive of return to sport status after ACLR; however, these results should be interpreted carefully as the included models were of low quality (high AIC) and did not fit the data well (high deviance).

INTRODUCTION

Sixty-five percent of individuals return to pre-injury level of sport participation, and only 55% return to competitive sport following anterior cruciate ligament reconstruction (ACLR).[10] This aforementioned rate of return to sport after ACLR is considerably lower compared to meniscal repair (81% to 89%) [318] or collateral ligament injuries (95%).[319] Among individuals who do successfully return to sport after ACLR, approximately 30% will sustain a second ACL injury within two years of returning to sport.[11] Demographic factors have been one of the most commonly reported predictors of second injury risk in this population.[17,18,91,320] The risk of ACL re-injury among individuals younger than 21 years old is nearly 8 times greater than older individuals with ACLR[90] in part due to the fact that younger individuals are more likely to integrate back into sports, and are exposed to scenarios in which ACL injury may occur.[17,91] Further complicating this issue, young women are 2-8 times greater risk of ACL injury and 5 times greater risk of a second ACL injury[71,80] compared to their male counterparts. The outsized risk of ACL injury in female athletes has been attributed to differences in lower extremity biomechmanics,[103,104] fluctuations of hormonal levels throughout the menstrual cycle,[84] and anatomical differences in the structure of the knee.[85] While age and sex are risk factors for ACL injury, they are non-modifiable and as a result, it is important that we identify modifiable risk factors early in the recovery process that can be addressed during rehabilitation to mitigate risk of a second ACL injury.

Most individuals with ACLR complete 4-6 months of structured outpatient rehabilitation after which they are cleared by their surgeon for a graduated return to unrestricted physical activity or sport participation.[21] A recent study found that supervised rehabilitation is terminated 5 months or less in 56% of cases and 6-8 months in only 32% of cases.[21] Unfortunately, due to health insurance restrictions rehabilitative care ends regardless of whether the individual has fully recovered physically or mentally.[15,42,61,92,204] At this time few individuals with ACLR have not met clinical recommendations for quadriceps strength and single leg hop symmetry,[13–15] and still exhibit a negative psychological response to injury.[321–323] As a result, both psychological and physical factors have been shown to contribute to unsuccessful return to sport and risk of re-injury independent of the previously mentioned risk factors. Individuals with ACLR experience a myriad of functional limitations, including quadriceps and hamstrings weakness,[227,289,324] and diminished performance on functional tasks such as single leg hopping,[15,60,292] that persist well beyond the completion of rehabilitation. Six months after ACLR, only 30% of individuals exhibit symmetrical quadriceps strength and symmetrical hop performance, asymmetry in these assessments has been highlighted as potential risk factors for a second ACL injury.[291] For example, Grindem et al.,[12] determined that there is a 3% reduction in reinjury risk or every 1% increase in quadriceps strength symmetry.[12] When used in conjunction with single leg hop symmetry and delayed return to sport until 9 months after ACLR , the risk of reinjury declines 84%.[12] It is important to understand how these modifiable clinical indicators in conjunction with nonmodifiable risk factors like sex and age affect return to pre-injury level of sport and the risk of a second ACL injury.

Psychological wellbeing influences readiness for return to sport and the risk of future ACL injury among individuals with recent ACLR, but its influence on knee function and lower extremity biomechanics is not well understood. The Stress and Injury model presents framework to suggest cognitive demand, such as the presence of kinesiophobia, can cause a negative physiological response during competition thereby elevating the risk of injury.[31] Individuals with ACLR that report greater kinesiophobia at the time of return to sports are 13 times more likely to sustain a second ACL within 12 months of their return to sport,[92] and are 17% less likely to return to pre-injury level of sport after ACLR.[325] Functional deficits in lower extremity biomechanics have also been reported in individuals with ACLR and high kinesiophobia including bilateral decreased knee flexion,[326] increased vGRF in the contralateral limb during jump landing,[327] and slower lower extremity reaction time.[272] Exacerbation of aberrant lower extremity biomechanics due to psychological response to injury is of concern as it may increase the likelihood of a second ACL injury. Psychological factors have been assessed as predictors of reinjury, but functional outcomes have not been included in predictive models. The combination of psychological and functional outcomes may be a better approach to identifying risk of reinjury after ACLR.

Identifying modifiable and non-modifiable risk factors earlier in the recovery process can help clinicians to mitigate the risk of a second injury and facilitate a safe and timely return to sport for individuals with ACLR. Therefore, the purpose of this study was to determine the association between age, sex, surgical characteristics, patient-reported function, and objective strength and hopping outcomes collected within 1-year post-ACLR with the incidence of re-injury and return to sport assessed 2-years after ACLR. We hypothesize that male sex, younger age (<21 years old), greater involved limb quadriceps strength, and positive psychological response to injury assessed at the end of formalized rehabilitative care will be associated with return to sport 2-years after ACLR. Our secondary hypothesis is that female sex, older age (>21 years old), lesser involved limb quadriceps strength, and negative psychological response to injury will predict second ACL injury 2-years after ACLR.

METHODS

This was a longitudinal cohort study design with data collected at the end of formalized rehabilitative care after ACLR and again 2 years after ACLR. This study was part of a prospective study to assess recovery over the first 2 years after ACLR. Participants are evaluated at 4 months, 5-6 months, 9 months, 12 months, and 24 months post-surgical. The assessment at 4 months does not include all strength and single leg hop assessments, therefore the assessment included in this study was the earliest assessment within the first year of recovery which included all strength and single leg hop assessments. All participants completed the informed consent or assent process prior to engaging in any study related activities. The Michigan State University Institutional Review Board approved this study.

Participants

One hundred seventy-three (173) participants were recruited during their post-operative follow-up assessment. To be included in the study participants had to be 13-40 years old and enroll in the study within 1 year of ACLR. Participants were excluded if they had any neurological or cardiovascular conditions that would prevent participation in study activities or were taking or prescribed medication that would affect participation in study activities at the time of enrollment.

Procedures

During the initial laboratory visit, participants completed a knee injury health history form and a series of patient-reported outcomes questionnaires to evaluate psychological response to injury and physical activity level. Functional assessments included 3 single leg hop tests and an isokinetic strength assessment.

Knee Injury History

Knee health history was collected during review of participant medical records at Michigan State University Sports Medicine. Knee health history included surgical details including complete diagnosis, graft source, concomitant surgical procedures, and time from surgery to date of testing. Participants were asked to describe their knee injury as either contact or non-contact. A contact injury was defined as contact between the participant's upper or lower body with another person leading to ACL injury. A non-contact injury was characterized by contact with the playing surface not with another person.

Patient Reported Outcome Measures

All patient reported outcome measures were captured during the initial, in-person study visit via an online survey platform (Qualtrics). The Tampa Scale for Kinesiophobia-11 (TSK-11) was used to assess pain-related fear of movement and reinjury. This measure has good test-retest reliability (ICC=0.81, SEM=2.54) and good internal consistency (Cronbach alpha=0.79).[328] The scale ranges from 11-44 with higher scores indicating greater kinesiophobia. The Tegner Activity Scale (TAS) was used to measure physical activity. Individuals are asked to rate their physical activity on scale of 0-10 before their injury and for the present day. Higher scores indicate higher levels of physical activity. The TAS has demonstrated acceptable test-rest reliability (ICC=0.80; 95%CI=0.66-0.89; SEM=0.64).[329]

Isokinetic Strength Assessment

Quadriceps peak torque was assessed using an isokinetic dynamometer (Biodex multimode dynamometer, Shirley, NY, USA) with adjustable straps at the chest, waist, thigh, and lower leg. The participant was seated with the hips flexed to 85° and arms crossed over the chest. During the isokinetic assessment, participants were instructed to kick out (knee extension) and pull back on the dynamometer attachment as quickly and forcefully as possible. Participants completed one set of 5 consecutive knee extension. and knee flexion movements at 60°/s. Verbal encouragement was provided during the assessment. Data were collected bilaterally, and the uninvolved limb was tested first. Limb symmetry index (LSI) was calculated by dividing the quadriceps strength of ACLR limb by that of the contralateral limb.

Single Leg Hop Assessment

During the single leg hop, participants were asked to hop from the starting line as far as possible. Participants could practice each task until they were comfortable performing it and could rest between trials. On each task participants were asked to hop on single leg for maximal distance and to stick the landing. Distance (cm) was measured from the starting line to the back of the heel. A trial was considered unsuccessful if the participant could not stick the landing. Three trials were collected bilaterally for each task. The uninvolved limb was always tested first. An average hop distance was calculated across all three trials and normalized to leg length for each hop assessment. Limb symmetry index (LSI) was calculated by dividing the average hop distance of ACLR limb by that of the contralateral limb.

Two-year Follow-up

Participants were contacted by three members of the research team (TB, MM, CK) via phone or email to complete the 2-year follow-up assessment. Participants were asked about subsequent knee injuries since the initial ACLR (e.g., meniscal injury, ACL injury, cyclops lesion etc), their current physical activity level, and whether they returned to their pre-injury level of sport. Injuries and complete diagnosis were confirmed through chart review of their medical records at the referring surgeons' clinic. Updated contact information was obtained through chart review for participants that had changed phone numbers or email addresses. Those that did not respond to follow-up emails or phone calls were contacted monthly.

Statistical Analysis

Means and standard deviations were calculated for continuous demographic data and functional data. Medians and ranges or frequencies were presented for categorical or nominal data, respectively. Separate logistic regression models were used to analyze the association between return to sport and second ACL injury and their respective predictor variables. Odds ratios with 95% confidence intervals (95% CI) were also calculated. In a logistic regression, an odds ratio >1 indicates the outcome variable is more likely to occur. For the odds ratio to be significant, the 95% CI cannot include 1. Models were built in blocks. The first block included age, sex, and meniscal procedure. The second block included the TSK-11 and TAS. The third block included strength and single leg hop assessments. Models were built by sequentially adding each block to the model while retaining the blocks from the previous model. This approach was taken to create three models for each outcome variable (return to sport status and second ACL injury). The first model, the Participant Characteristic Model, included the predictor variables in block 1. The second model, the Patient-Reported Outcome Model (PRO), included predictor variables in block 1 and 2. The third model, the Functional Model, included predictor variables from block 1, 2, and 3. Collinearity was assessed using the variance inflation factor (VIF). Predictors with a VIF of greater than 5 were removed from the final model. Maximum likelihood was assessed using McFadden's R^2, values closer to 1 indicate the outcome is more likely to occur based on the included predictors. The Akaike information criterion (AIC) was used to assess between model quality. The AIC is a measure of model fit and generalizability, lower AIC values indicate the model is better fit to the data relative to the other models generated. Deviance was used to assess deviance of the fitted model from a perfect model. Models are assigned a probability from 0 to 1, higher values indicating greater deviance from the perfect model. Statistical analysis was conducted using Jamovi (Jamovi Project. *Jamovi* Version 1.6). The α-priori alpha level was set at 0.05.

RESULTS

Of the 173 individuals contacted for follow-up, 93 individuals (50 female/43 female) responded (54%) to the two year follow phone calls or emails. Demographic information, surgery characteristics, and patient reported outcome measure data for individuals who were successfully contacted for 2-year follow-up can be found in Table 3.1.

Table 3.1: Demographic Information at Initial Assessment

	N=91
Months Since Surgery to 2-year Follow-up	27.8±5.5
Sex (Female/Male)	50/41
Months since surgery at the initial assessment	7.2±2.5
Height (cm)	176.0±8.9
Weight (kg)	76.6±15.5
BMI	24.5±3.9
Age (years)	21.3±7.1
Graft source (HT/BPTB/QT/AG)	61/19/1/10
Meniscal Procedure	42
TAS (median score)	6 [2,10]
TSK-11	18.8±4.4

BMI=body mass index; HT=hamstring tendon; BPTB=bone patellar tendon bone; QT=quadriceps tendon; AG=allograft; TAS=Tegner Activity Scale; TSK-11= Tampa Scale for Kinesiophobia

Table 3.2: Functional Data at Initial Assessment

	ACLR Mean±SD	Contralateral Mean±SD	LSI Mean±SD
Isokinetic Knee Extension Strength (Nm/kg)	1.76±0.64	2.47±0.67	72.0%±21.0%
Isokinetic Knee Flexion Strength (Nm/kg)	1.06±0.35	1.29±0.39	83.8%±20.3%
Single Hop (x leg length)	1.39±0.40	1.51±0.37	91.6%±13.1%
Triple Hop (x leg length)	4.63±1.17	4.91±1.10	94.0%±9.3%
Crossover hop (x leg length)	4.10±1.19	4.19±1.17	98.3%±6.8%

Nm/kg=newton meters per kilogram; LSI=limb symmetry index

Table 3.3: Demographic Information of Non-Responders to Follow-up

	N=120
Sex (Female/Male)	67/53
Months since surgery	6.52±1.73
Height (cm)	172±10.7
Weight (kg)	75.9±20.6
BMI	25.2±5.57
Age (years)	22.0±8.56
Graft source (HT/BPTB/QT/AG) (n=118)	65/27/1/25
Meniscal Procedure (n=119)	67
TAS (median score) (n=115)	5 [1, 10]
TSK-11 (n=114)	20±4.58

BMI=body mass index; HT=hamstring tendon; BPTB=bone patellar tendon bone; QT=quadriceps tendon; AG=allograft; TAS=Tegner Activity Scale; TSK-11= Tampa Scale for Kinesiophobia

Table 3.4: Functional Data of Non-Responders to Follow-up

	ACLR Mean±SD	Contralateral Mean±SD	LSI Mean±SD
Isokinetic Knee Extension Strength (Nm/kg)	1.64±0.59	2.27±0.66	73.2%±22.2%
Isokinetic Knee Flexion Strength (Nm/kg)	0.90±0.27	1.12±0.30	81.8%±17.6%
Single Hop (x leg length)	1.28±0.44	1.43±0.38	88.2%±155%
Triple Hop (x leg length)	4.36±1.32	4.64±1.16	93.0%±11.5%
Crossover hop (x leg length)	3.82±1.31	3.92±1.25	96.4%±5.9%

Nm/kg=newton meters per kilogram; LSI=limb symmetry index; all hop distances were normalized to leg length

Two-Year Follow-up

Quadriceps and hamstring strength and single leg hop assessment data for individuals who were successfully contacted for 2-year follow-up can be found in Table 3.2. Demographic information for individuals who were contacted but did respond to phone calls or emails at the 2-year follow-up can be found in Table 3.3 and their functional data can be found in Table 3.4. Following chart review, record of a meniscal procedure was not documented for one participant who did not respond to the 2-year follow-up; therefore, data was reported for 119 participants.

Five individuals that did not respond at the 2-year follow-up did not complete the TAS (n=115) and 6 individuals did not complete the TSK-11 (n=114).

Demographic information for individuals that sustained a second ACL injury can be found in Table 3.5 and their functional data at their initial assessment can be found in Table 3.6. Of the 91 participants included in this study, 81 returned to pre-injury sport (89%). Five women and 2 men (n=7, 7.6%) sustained a second ACL injury. Five of these injuries occurred in participant's contralateral limb (4 female, 1 male) and 2 occurred to the ipsilateral limb (1 female, 1 male).

Table 3.5: Demographic Information for Individuals with a Second ACL Injury

	N=7
Months Since Surgery to 2-year Follow-up	25.6±4.0
Sex (Female/Male)	5/2
Months since surgery at initial assessment	6.5±0.98
Height (cm)	174±7.2
Weight (kg)	71.0±9.3
BMI	23.3±2.1
Age (years)	19.4±6.3
Graft source (HT/BPTB/QT/AG)	5/1/0/1
Meniscal Procedure	5
TAS (median score)	7 [4, 10]
TSK-11	19.3±3.8
Returned to Sport	4

BMI=body mass index; HT=hamstring tendon; BPTB=bone patellar tendon bone; QT=quadriceps tendon; AG=allograft; TAS=Tegner Activity Scale; TSK-11= Tampa Scale for Kinesiophobia

Table 3.6: Functional Data for Individuals with a Second ACL Injury

	ACLR Mean±SD	Contralateral Mean±SD	LSI Mean±SD
Isokinetic Knee Extension Strength (Nm/kg)	1.7±0.85	2.6±0.89	64.9%±16.4%
Isokinetic Knee Flexion Strength (Nm/kg)	1.0±0.42	1.2±0.42	85.0%±9.8%
Single Hop (x leg length)	1.4±0.48	1.54±0.43	89.6%±8.5%
Triple Hop (x leg length)	4.7±1.2	5.1±1.2	92.4%±6.6%
Crossover hop (x leg length)	4.2±1.2	4.4±1.2	96.7%±3.7%

Nm/kg=newton meters per kilogram; LSI=limb symmetry index all hop distances were normalized to leg length

Logistic Regression

The logistic regression models for second ACL injury can be found in Table 3.7. None of the models generated to predict second ACL injury were statistically significant. Additionally, high deviance and high AIC of each model indicates the models were of low quality and did not fit the data well. The logistic regression models for return to sport after ACLR can be found in Table 3.8. All models were statistically significant, but the participant characteristic model had the lowest AIC (61.2) indicating the addition of patient-reported outcomes measures and functional data did not enhance model fit or quality beyond demographic and surgical factors. While all models were significant, high deviance and AIC of each model indicated a poorly fit, low quality model.

Table 3.7: Logistic Regression Models for Second ACL Injury

							Model Fit Measures			Overall Model Test		
Predictor	Est.	SE	Z	*P*	Odds Ratio	95% CI	Deviance	AIC	R^2	X^2	Df	*P*
Participant Characteristic Model												
Intercept	0.35	1.60	0.22	0.83	1.42	0.06, 32.60	43.6	53.6	0.11	5.43	4	0.25
Age	0.09	0.08	1.10	0.27	1.09	0.93, 1.28						
Return to Sport	-1.17	0.87	-1.34	0.18	0.31	0.06, 1.71						
Sex	0.51	0.91	0.57	0.57	1.67	0.28, 9.86						
Meniscus Procedure	1.26	0.91	1.39	0.16	3.53	0.60, 20.8						
PRO Model												
Intercept	3.18	4.57	0.70	0.49	24.0	0.003, 1.8^{5}	39.2	61.2	0.20	9.83	6	0.40
Age	0.08	0.08	0.98	0.33	1.08	0.93, 1.26						
Return to Sport	-1.34	0.89	-1.50	0.13	0.26	0.05, 1.51						
Sex	0.73	0.96	0.76	0.45	2.07	0.32, 13.49						
Meniscus Procedure	1.31	0.92	1.43	0.15	3.71	0.62, 22.30						
Pre-injury TAS	-0.29	0.42	-0.70	0.49	0.75	0.33, 1.70						
TSK-11	-0.01	0.10	-0.05	0.96	0.99	0.83, 1.20						
Functional Model												
Intercept	4.40	7.83	0.56	0.57	81.22	1.75^{-5}, 3.76^{8}	40.2	60.2	0.18	8.79	9	0.46
Age	0.12	0.10	1.20	0.23	1.13	0.93, 1.38						
Return to Sport	-2.13	1.23	-1.69	0.09	0.12	0.01, 1.41						
Sex	0.44	1.02	0.43	0.66	1.56	0.21, 11.51						
Meniscus Procedure	1.74	1.10	1.57	0.12	5.72	0.65, 50.14						
Pre-injury TAS	-0.40	0.45	-0.89	0.37	0.67	0.28, 1.62						
TSK-11	0.05	0.11	0.49	0.62	1.06	0.85, 1.32						
Single Hop LSI	0.03	6.06	0.004	1.00	1.03	7.11^{-6}, 1.07^{4}						
Quadriceps Strength LSI	2.81	3.77	0.75	0.46	16.69	0.01, 2.70^{4}						
Hamstring Strength LSI	-4.85	3.22	-1.50	0.13	0.01	1.44^{-5}, 4.28						

TSK-11=Tampa Scale for Kinesiophobia; TAS=Tegner Activity Score; LSI=limb symmetry index

Table 3.8: Logistic Regression Models for Return to Sport

							Model Fit Measures			Overall Model Test		
Predictor	Est.	SE	Z	*P*	Odds Ratio	95% CI	Deviance	AIC	R^2	χ^2	Df	*P*
Participant Characteristic Model												
Intercept	-3.31	1.13	-2.92	0.004	0.04	0.004, 0.34	53.2	61.2	0.15	9.35	3	0.03
Age	0.08	0.04	1.88	0.06	1.08	1.00, 1.17						
Sex	0.32	0.72	0.45	0.65	1.38	0.34, 5.61						
Meniscus Procedure	-1.70	0.84	-2.03	0.04	0.18	0.03, 0.94						
PRO Model												
Intercept	-2.75	3.46	-0.80	0.43	0.06	7.25^{-5}, 56.34	51.0	63.0	0.18	11.51	5	0.04
Age	0.07	0.04	1.68	0.09	1.07	0.99, 1.16						
Sex	0.52	0.76	0.69	0.49	1.68	0.38, 7.40						
Meniscus Procedure	-1.82	0.88	-2.08	0.04	0.16	0.03, 0.90						
TSK-11	0.10	0.09	1.08	0.28	1.10	0.92, 1.32						
Pre-injury TAS	-0.28	0.31	-0.90	0.37	0.76	0.42, 1.39						
Functional Model												
Intercept	1.18	4.15	0.29	0.78	3.27	9.60^{-4}, 1.1^{5}	47.9	63.9	0.24	14.70	8	0.04
Age	0.05	0.05	1.12	0.26	1.05	0.96, 1.15						
Sex	0.39	0.79	0.49	0.63	1.47	0.31, 6.96						
Meniscus Procedure	-1.45	0.92	-1.58	0.11	0.24	0.04, 1.41						
TSK-11	0.07	0.10	0.72	0.47	1.07	0.89, 1.30						
Pre-injury TAS	-0.31	0.33	-0.96	0.34	0.73	0.38, 1.39						
Quadriceps Strength LSI	-2.66	2.41	-1.11	0.27	0.07	6.21^{-4}, 7.83						
Hamstring Strength LSI	-1.24	2.49	-0.50	0.62	0.29	0.002, 37.99						

TSK-11=Tampa Scale for Kinesiophobia; TAS=Tegner Activity Score; LSI=limb symmetry index

DISCUSSION

Individuals that successfully return to sport after ACLR face a 6 times greater risk of a future ACL injury than those who have not had primary ACLR.[11] Rehabilitative care is often terminated before individuals with ACLR are fully recovered, which contributes to the outsized risk of subsequent injury in this population.[20,21] Therefore, to mitigate such risk it is important to identify modifiable and non-modifiable risk factors that may prevent return to sport or increase the risk of reinjury. The purpose of this study was to determine the association between demographic information, surgical characteristics, patient-reported function, and objective lower extremity function collected within 1-year post-ACLR with the incidence of second ACL injury and return to pre-injury level of sport assessed at least 2-years after primary ACLR. In this study only 7.7% of individuals with whom we were able to establish contact 2-years after ACLR had sustained a second ACL injury and our models were unable to predict second ACL injury. Conversely, 89% of individuals made a return to pre-injury level of sport. The Participant Characteristic Model for return to sport status was significant and had the lowest AIC compared to the Patient-Reported Outcome Model and the Functional Model. Our models were not enhanced when patient-reported outcomes measures or functional data from the initial assessment after ACLR were included in the model. The results of this study should be interpreted carefully, as the participant characteristic model for return to sport status did have a high AIC indicating the model poorly fit the data.

Age and sex,[18,322,331] quadriceps strength and single leg hop distance,[332–334] and patient-reported outcome measures[334,335] are associated with return to sport status after ACLR. In this study, the Participant Characteristic Model included participant age, sex, and meniscal procedure at the time of ACLR and was predictive of return to pre-injury sport after ACLR. Patient age was the strongest predictor in our model, but contrary to previous studies that have reported younger individuals are more likely to return to sport after ACLR,[18,322,336] older individuals were modestly more likely to return to sport in the current study. To note, the average age of our sample (21.3 years) was younger than other studies that have assessed age a predictor of return to sport status.[18,322] In our sample, 80% were younger than 25 years of age and among the 10 participants (11%) who reported not returning to sport, 5 were 16 to 20 years old and 5 were 30 to 38 years old. We expected sex to be a predictor of return to sport status as female athletes are less likely to return to sports after ACLR and face a 2-8 times greater risk of ACL injury compared to their male counterparts.[18,71,79] Males recover from ACLR faster than females[337] and have better psychological readiness to return to sport.[338,339] In the current study, males were 1.8 times more likely to return to sport than females. Although this finding is consistent with the literature,[18,322] the odds ratio for in this study was not significant. Of the 81 participants that returned to sport, 45 were female. The discrepancy between men and women in return to sport status may not have been large enough to predict return to sport status based on sex. Additionally, an equal number of males and females (n=5) did not return to sport, which also may have contributed to the outcome of this study. Concomitant meniscal procedure and ACLR negatively affect return to sport status,[340,341] The odds ratio for meniscal procedure in this study was less than one (OR=0.18, p=0.04) indicating individuals with a meniscal procedure at the time of ACLR were less likely to return to sport. Age and sex are risk factors for unsuccessful return to sport after ACLR; however, they are non-modifiable. The models in this study were not enhanced after including patient-reported outcome measures and functional data, additional research is needed to identify outcomes early in recovery after ACLR that limit return to sport.

Our models were not able to predict occurrence of a second ACL injury. The Patient Characteristic Model was the strongest model (ACI=53.6); however, it was not statistically significant. Only 7% of our sample sustained a second ACL injury, which is surprising as 80% of the sample was younger than 25 years old, 89% reported returning to sport, and the sample was predominately female.[17,18,322,342] The functional outcomes at the initial assessment, also suggest participants in this study were at an increased risk of a second ACL injury. Of the 91 participants included in this study, only 1 participant met clinical recommendations for all single leg hop assessments and quadriceps strength (Table 10). Concerns have been raised regarding quadriceps strength and single leg hop assessments in both pediatric and young adult populations. The use of LSI to determine restoration of function during these assessments consistently overestimates knee function and preparedness to return to sport after ACLR.[45,47,291,292] Clinical recommendations established for adults are often applied in pediatric population, despite lack of validation in this population.[14] More concerning is that a low proportion of pediatric and young adults are meeting those clinical recommendations at the time of return to sport.[13,14,343] While only 7% of individuals included in this study sustained a second ACL injury, this should not negate concerns regarding the low number of individuals meeting clinical recommendations before returning to sport. The rate of second ACL injury in young females with asymmetrical single leg hop distance is 20%;[42] and those with asymmetrical quadriceps strength and asymmetrical single leg hop distance are more likely to sustain a second ACL injury (HR=4.1, 95% confidence interval-1.9 to 9.2, $p \leq 0.001$).[294] Context around the study period may have played an important role in the relatively small number of second ACL injuries. Most participants in this study (n=73) were in their second year of recovery after ACLR in 2020 when sport participation was heavily restricted in response to the COVID-19 pandemic. While 81 participants reported returning to sport, actual participation was limited during the study period and therefore exposure to scenarios that can lead to an ACL injury was reduced. Our findings show that despite clinical recommendations, individuals with ACLR are returning to sport before they are physically prepared to do so. Continued efforts are needed to assess age- and population-specific functional outcome measures that can more readily identify individuals with ACLR that are prepared to return to sport.

Table 3.9: Frequency of Individuals Meeting Clinical Recommendations

Clinical Recommendation	
Quadriceps Strength Symmetry ≥ 90% LSI	13 (14.3%)
Single Hop Symmetry ≥ 90% LSI	66 (72.5%)
Triple Hop Symmetry ≥ 90% LSI	72 (79.1%)
Crossover Hop Symmetry ≥ 90% LSI	85 (93.4%)
Met All Single Leg Hop Criteria	63 (69.2%)
Met Quadriceps Strength and Single Leg Hop Criteria	2 (2.2%)
TSK-11 <17	32 (35.2%)
Met 4 criteria	1 (1.1%)

The discrepancy in the literature regarding young individuals meeting evidence-based clinical recommendations is part of a larger question regarding the validity of functional assessments to adequately identify individuals at increased risk of ACL injury. Several clinical indicators of reduced risk of second ACL injury have been proposed in the literature. Quadriceps strength symmetry and single leg hop symmetry greater than 90% after ACLR is associated with reduced risk of second ACL injury after return to sport.[12] Those with high kinesiophobia (TSK-11 score ≥17) have a 13 times greater risk of a second ACL injury.[92] Despite evidence-based clinical recommendations, rehabilitative care is terminated before individuals with ACLR are mentally or physically prepared to integrate into sport. In the current study, none of the participants met all clinical recommendations for quadriceps strength symmetry, single leg hop symmetry, and TSK-11(Table 3.9). Our results are consistent with previously published data that has shown that the majority of individuals with ACLR fail to meet return to sport criteria within the first year after surgery.[15] Furthermore, limb symmetry during single leg hop assessments has been shown to overestimate knee function after ACLR,[291] which is reflected in our results as only 14.3%of participants had adequate quadriceps strength symmetry while 69.2% of participants achieved adequate symmetry on all 3 single leg hop assessments. This study shows that few individuals with ACLR are meeting minimum evidence-based criteria to integrate into sport and continued rehabilitative care is needed beyond the first year of recovery in this population.

This study was not without limitation. It is possible the predictor variables included in this study are not adequate predictors of either return to sport status or second ACL injury. Decreased risk of ACL injury is associated with functional outcomes such as quadriceps strength and single leg hopping.[12,39,74,294,303,344] However, single leg hop distance symmetry overestimates knee function after ACLR[291] and is not indicative safe lower extremity biomechanics that would protect the ACL during athletic movement.[46,292] Similar results have been reported in such drop jumps and change of direction. While no differences in strength measures, jump height, or time to completion were found, the ACLR limb demonstrated high-risk biomechanics that place additional stress on the ACL.[29,30] Recently functional assessments used to make return to sport decisions after ACLR have been called into question for inadequately identifying individuals at an increased risk of a second injury and for omitting sport-specific tasks.[22,60] These assessments are conducted in a controlled environment under pre-planned conditions that is not representative of the demands of sport. Increased cognitive demand such as reacting to a stimulus negatively affects lower extremity biomechanics and increases the risk of a second ACL injury.[48,49,72,73] Without a reactionary component, it is difficult to adequately determine preparedness to meet the demands of sport after ACLR. Our results support these criticisms as we were unable to predict return to sport status or second ACL injury based on commonly used return to sport criteria.

CONCLUSION

Sex, age, and surgical characteristics were predictive of return to sport after ACLR; however, these results should be interpreted carefully as the included models were of low quality. Results of this study found a limited number of individuals are meeting recommended clinical guidelines for quadriceps strength symmetry, and kinesiophobia within the first year after ACLR, despite achieving symmetrical hop distance. Our results indicate that extended rehabilitative care is warranted beyond one year after ACLR.

ABSTRACT

Context: Individuals with anterior cruciate ligament reconstruction (ACLR) exhibit aberrant lower extremity biomechanics during change of direction (COD), yet it is not assessed as part of return to sport (RTS) criteria. Therefore, there is a need to assess the differences between commonly used RTS criteria such as the drop vertical jump and COD to identify unique demands that may imply COD needs to be considered prior to integration into sports after ACLR. The purpose of this study was to compare between limb differences in biomechanical (i.e. ground contact time (GCT), reactive strength index (RSI), and peak vertical ground reaction force (vGRF)) outcomes during a traditional single leg drop jump (SLV) and a single leg crossover hop (SLC) involving COD among individuals with a history of unilateral ACLR. The secondary purpose of this study was to assess the relationship between the SLV and the SLC among individuals with a history of unilateral ACLR.

Methods: Forty-eight individuals with a unilateral history of ACLR (33 female/15male; age=22.6±5.1 years; months since surgery=37.3±22.7) participated in this cross-sectional study. A biomechanical analysis using 3D motion capture was conducted while the participants completed a SLV and SLC. Each land was divided into the deceleration phase, amortization phase, and acceleration phase based on position of center of mass (COM). Peak vertical ground reaction force (vGRF) was identified during each phase and during ground contact time (GCT). Vertical impulse force (VIF) was equal to the peak vGRF during deceleration. Vertical Propulsion Force (VPF) was equal to the peak vGRF during acceleration. Reactive strength index (RSI) was calculated by dividing jump height by GCT during the SLV. RSI was calculated by diving hop distance by GCT during the SLC. Separate Spearman’s rho correlations for the SLV and SLC were used to assess the relationship between GCT, RSI, VIF, VPF and vGRF in the ACLR and the contralateral limb. Kruskal-Wallis tests and Eta Squared effect sizes were

used to identify biomechanical differences and the magnitude of differences between tasks and between limbs. The α-priori alpha level was set at 0.05.

Results: No between limb differences were found during either task. Moderate to strong relationships were found between the SLC and SLV for all lower extremity biomechanical variables of interest. The strongest relationships for the ACLR limb were between peak vGRF (ρ=0.75, p<0.001); VPF (ρ=0.75, p<0.001); RSI (ρ=0.60, p<0.001); and GCT (ρ=0.61, p<0.001).

Conclusions: There were no between limb differences during the SLC and SLV. Deceleration and amortization phases were longer during the SLC, suggesting more time was needed to stabilize the knee and rotate the trunk toward the new trajectory during the change of direction task. Correlations between tasks were weakest during the amortization and acceleration phases. Change of direction did impose unique demands in comparison to the SLV and may need to be assessed prior to integration into sport after ACLR.

INTRODUCTION

Only 65% of individuals will return to their preinjury level of sport and 55% of individuals will return to competitive level of sport after anterior cruciate ligament reconstruction (ACLR).[10] Among those that do return to sports, 30% will sustain a second ACL injury within 2 years, a six times greater risk of injury than those without an ACL injury.[11] The outsized risk of a second ACL injury in this population is a multifactorial issue including morphological changes in the quadriceps[7,192,194] and persistent neurological inhibition[1,4,243,247] to the muscle. Following ACLR, the quadriceps atrophy, become increasingly fibrotic[6], and the presence of intramuscular fat increases.[7,192,194] These morphological changes reduce the cross-sectional area of the available contractile tissue and contribute to persistent quadriceps weakness in this population.[7,192,194] Peripheral deafferentation after ACLR alters afferent neural input from the joint to the gamma motor neuron feedback loop, which in turn sends altered efferent neural output back to the quadriceps.[1,4,243,247] These changes affect the quadriceps' ability to generate force[289] and reactively stabilize the knee.[295,345] Persistent quadriceps weakness reduces the ability to decelerate the center of mass (COM) adequately resulting in longer ground contact time, high vertical ground reaction force (vGRF),[151] and limits trunk rotation toward the new trajectory during athletic movements like change of direction (COD).[99] In concert, these factors increase external knee valgus which can compromise the integrity of the ACL and lead to injury.[99]

High velocity COD is an important skill in multidirectional sports.[118,305,346] COD is a combination of braking and propulsive forces that decelerate the COM and reaccelerate in the new trajectory.[26,125,151,307] It is important to note that COD does not encompass reaction to a stimulus and is a pre-planned movement.[118,347] The velocity at which COD can be performed is inversely related to the sharpness of the angle needed to change direction.[118,119] At angles less than 45°, minimal deceleration is needed; however, angles larger than 45° require the COM to decelerate or even stop before the COD can be performed.[119] Deceleration eccentrically loads the thigh musculature activating the stretch shortening cycle (SSC) which stores energy in the muscle and tendons needed to increase force production and propel the COM in its new trajectory.[348–351] The SSC contributes to increased force production during high velocity athletic movements like sprinting, jumping, and COD. However, the SSC maybe negatively affected after ACLR due to the loss of the mechanoreceptors in the native ACL[182,240] and changes in the quadriceps morphology.[7,192–194,225]Due to the high risk of ACL injury during COD,[28,34,63] it is a logical step to investigate SSC performance during COD after ACLR.

The reactive strength index (RSI) is a ratio of jump height to ground contact time used to measure SSC performance[40,352] during a single leg drop vertical jump (SLV).[353] Like performing a COD, RSI improves with decreased ground contact time and is therefore influenced by lower extremity strength.[150,354] Evidence shows that individuals with ACLR and ACL deficiency exhibit gamma-loop[4] and stretch reflex dysfunction[5] that negatively effects the SSC, therefore the RSI may be lower in the reconstructed limb compared to that of the contralateral limb indicating worse SSC performance that can negatively affect athletic performance and the ability to reactively stabilize the knee.[5] Field-based COD assessments, such as the shuttle test and t-test, inconsistently measure performance deficits after ACLR,[29,30,133,299] nor are they able to measure differences in ground contact time or SSC performance. Evidence suggests a relationship does exist between RSI and single leg hop performance after ACLR,[149] and between RSI and risk of ACL injury in young, active individuals.[148] It is possible the RSI could explain reduced performance and functional impact of persistent quadriceps weakness. However, the RSI's utility in this capacity has not been established and warrants further investigation.

Persistent quadriceps weakness and peripheral deafferentation after ACLR negatively affects COD performance and may have deleterious effects on the SSC. Due to the risk of ACL injury during COD, it is a logical step to investigate SSC performance during COD after ACLR. Therefore, the purpose of this study was to compare biomechanical (i.e. ground contact time, RSI, and peak vGRF) outcomes during a traditional SLV and a SLC involving COD among individuals with a history of unilateral ACLR. Both tasks were included in this study to examine potential deficits in SSC performance and its effects on common athletic movements that can lead to ACL injury. The secondary purpose is to assess the relationship between biomechanical outcome measures (i.e. ground contact time, RSI, vGRF, acceleration time, and deceleration) between the SLV and SLC. We hypothesize there will be a strong correlation between biomechanical outcomes (peak vGRF, vertical impact force, and deceleration time) during deceleration and weak to moderate correlations in biomechanical outcomes (vertical propulsion force, amortization time, and acceleration time) during the amortization and acceleration phase between tasks.

METHODS

This cross-sectional descriptive laboratory design included a single data collection session during which participants completed two drop jump tasks, the SLV and the SLC as part of a 3D biomechanical analysis. The study was approved by the Michigan State University Institutional Review Board and all participants provided written informed consent prior to participation.

Participants

A general health history and knee specific health history were used to determine eligibility to participate in the study. Participants were between 18 and 40 years old, had undergone ACLR, and were cleared by a medical professional for unrestricted physical activity. Individuals were excluded from this study if they had a history of bilateral ACLR or had sustained an injury to the lower extremity within 6 weeks of testing. Participants were also excluded if they had been diagnosed with a cardiovascular or neurological disorder or if they were prescribed or taking medication that would limit ability to participate in study activities. Those with medial collateral ligament injuries (n=5) or underwent a concomitant meniscal surgery (n=28) at the time of their ACLR were included Participant demographics and surgical characteristics can be found in Table 4.1. One participant withdrew from the study due to fear of performing the hopping tasks and their data was not included in final data set.

Table 4.1: Demographic and Surgical Data

	N=48
Sex (female/male)	33/15
Age (years)	22.6±5.1
Height (cm)	173±10.3
Body mass (kg)	72.5±11.2
Months since surgery	37.3±22.7
Primary Graft Source (HT/BPTB/QT/AG)	23/19/2/4
Secondary Graft Source (HT/BPTB/QT/AG)	0/4/1/3
Primary Meniscectomy (N)	9
Secondary Meniscectomy (N)	3
Primary Meniscal Repair (N)	21
Secondary Meniscal Repair (N)	3

HT=hamstring autograft; BPTB= bone patellar tendon bone autograft; QT=quadriceps tendon autograft; AG=allograft

Procedures

After determining eligibility, height (cm) and body mass (kg) were collected. A 3D motion capture system was used to conduct a biomechanical analysis while the participants performed a SLV and SLC.

Lower Extremity Biomechanics

Kinematic data were collected during a SLV and a SLC using a ten-camera Motion Analysis System (Bonita 10, Vicon Motion Systems, Inc., Lake Forest, CA, USA). Kinematic data were collected at 240 Hz. Kinetic data were collected during both tasks using an embedded force plate (Advanced Mechanical Technology, Inc., Watertown, MA, USA). Kinetic data were collected at 1,200 Hz.

Prior to data collection, participants were outfitted with 8 clusters each comprised of 4 passive reflective markers for a total of 32 markers. Clusters were placed over the thoracic and lumbar spines, bilaterally on the lateral thighs, lateral lower legs, and the dorsal aspects of the feet. A stylus with 4 reflective markers was used to identify the spinous process at C7, T12, and L5 and the medial and lateral joint line of the tibiofemoral joint, the distal end of the medial and lateral malleoli, and the distal end of the second toe to digitize the segments and estimate the joint centers using a centroid method.[355] The Bell method was used to calculate hip-joint center.[356]

Following setup, participants were instructed to stand on a 30-cm box positioned 40 cm away from the middle of the force plate. When performing the SLV, participants jumped from the box to the force plate then immediately jumped vertically as high as possible. During the SLC, participants followed the same procedure but were instructed to hop off the force plate at a 45° angle in the direction opposite of the working leg. Participants were instructed to hop off the force plate as quickly as possible and to hop as far as possible. The distance hopped was then measured with a tape measure from the middle of the force plate to the back of the participant's heel. Participants could practice until they felt confident performing each task. For both tasks, a trial was successful if the participant was able to complete the task without loss of balance or contacting the floor with the opposite foot. Three successful trials were collected bilaterally for each task and the contralateral limb was always tested first.

Data were captured and processed using The Motion Monitor (Innovative Sports Training, Inc, Chicago, IL, USA) software. Kinematic data were filtered using a fourth-order Butterworth filter with a cutoff frequency of 12 Hz and kinetic data were filtered using fourth-order Butterworth filter with a cutoff frequency of 100 Hz. Jump height during the SLV was calculated from the COM's lowest point using the acceleration of the COM divided by twice the force of gravity, Equation 1.

Equation 1. $Jump\ Height = (COM\ velocity)^2/(9.81\ x\ 2)$

During both SLV and SLC, ground contact time was measured from initial contact (vGRF>10 N) to takeoff (vGRF<10 N). Calculations for all variables of interest can be found in Table 4.2. An average across three successful trials was used for analysis.

The SLC and SLV were divided into three phases for analysis (Figure 4.1). The downward phase was during deceleration, defined as the time of initial contact to the time the COM reached its lowest point. The second phase was the amortization phase, which occurred from the time the COM reached its lowest point (amortization start time) to the time when COM position increased 0.01 m (amortization end time). The third phase was occurred during acceleration and was defined as the time from the end of the amortization phase to takeoff. Peak vGRF (Figure. 4.2)

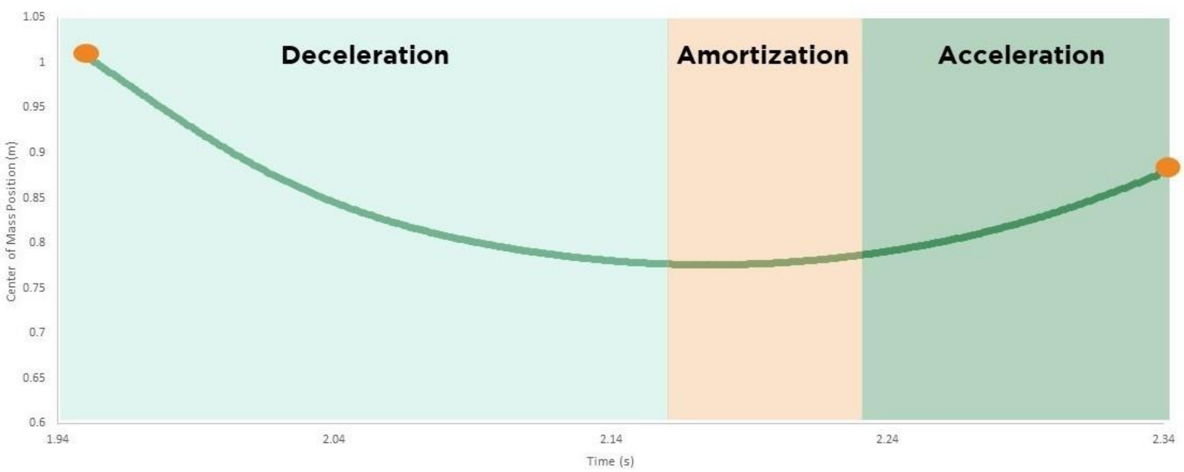

Figure 4.1: Landing Phases Based on Position of the Center of Mass The orange dots indicated initial contact during the deceleration phase and takeoff during the acceleration phase.

during each phase was recorded ($vGRF_{decel}$, $vGRF_{amort}$, $vGRF_{accel}$). Time of initial contact to time of peak vGRF was used to determine which phase of landing peak vGRF occurred. Time of initial contact to time of peak vGRF were compared between limbs for both tasks. Vertical impact force and vertical propulsion force were measured to assess peak vGRF during deceleration and acceleration, respectively.

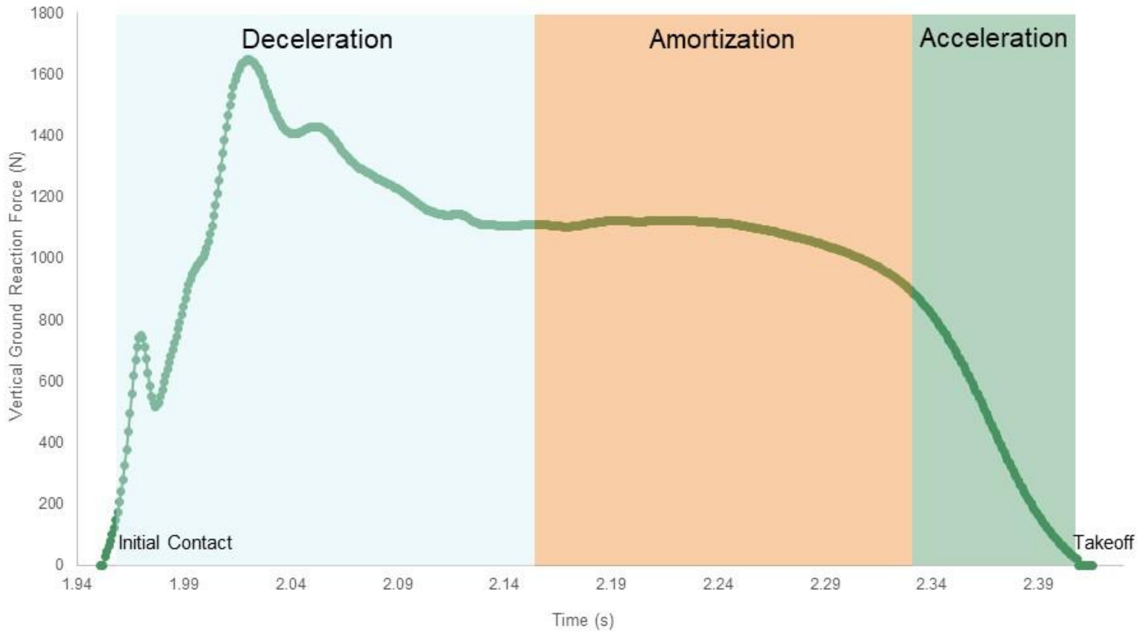

Figure 4.2: Vertical Ground Reaction Force During Each Landing Phase

Table 4.2: Lower Extremity Biomechanics Equations

Variable	Equation
peak vGRF	Peak vGRF/body mass in newtons
Ground Contact Time	Takeoff time – initial contact time
Deceleration Time	Time of COM lowest position – initial contact time
Amortization Time	Time of COM exceeds 0.01 – Time of COM lowest position
Acceleration Time	Takeoff time - Time of COM lowest position +0.01
Vertical Impact Force	$vGRF_{decel}$ / body mass in newtons
Peak vGRF during Amortization	$vGRF_{amort}$/body mass in newtons
Vertical Propulsion Force	$vGRF_{accel}$ / body mass in newtons
Reactive Strength Index during the SLC	Hop distance / ground contact time
Reactive Strength Index during the SLV	Jump height / ground contact time

Sample Size Estimation

This study was part of a larger study that assessed the relationship between quadriceps strength characteristics and lower extremity loading during a single leg step down task and single leg crossover hop task in individuals with a history of ACLR. Based on the relationship between the ACLR limb and the contralateral limb vGRF during the SLC (r=0.73) and the magnitude of difference in vGRF (f=0.19) between limbs and tasks, the minimum sample size was estimated to be 34 participants assuming α-priori alpha level of 0.05 and acceptable 1-β of 0.80 (G*Power, Heinrich-Heine-Universität Düsseldorf).[357,358]

Statistical Analysis

Mean values and standard deviations were calculated for all continuous demographic and surgical variables. Medians and ranges or frequencies were presented for non-continuous data. Shapiro-Wilk tests were used to assess the normality of biomechanics variables. Average RSI and jump height in both limbs during the SLV and for peak vGRF, contact time, deceleration time, and acceleration time in the contralateral limb and deceleration time in both limbs during the SLC were found to be non-normally distributed and an appropriate Kruskal-Wallis tests and Eta squared effect sizes were used to compare differences between limbs and between tasks. Effect sizes were categorized as small (η^2=0.01-0.05), medium (η^2=0.06-0.13), or large ($\eta^2 \geq 0.14$).[359,360] Separate Spearman Rho Correlation coefficients assessed the relationship between biomechanical outcomes and task performance (i.e., jump height and hop distance) in the ACLR and the contralateral limb during the SLV and SLC. Correlations were categorized as weak ($r<0.39$); moderate (r=0.4-0.69); or strong ($r \geq 0.70$).[361] The α-priori alpha level was set at 0.05. Outliers were identified using box plots. Outliers were defined as a data point that was more than 3 standard deviations from the mean. Those values were then matched to their corresponding participant for each variable. Any participants that were identified as outliers in two or more variables on either limb and influenced the ρ value by greater than 10% were removed prior to the final analysis.[362]

RESULTS

Four participants (2 female/2 male) were removed from the dataset prior to analysis due to outliers in several variables that were not representative of the sample. Demographic data for the outliers removed from prior to analysis can be found in Table 4.3.

Table 4.3: Outlier Demographic and Surgical Data

	N=4
Sex (female/male)	2/2
Age (years)	24.3±3.8
Height (cm)	177±4.1
Body mass (kg)	85±11
Months since surgery	48.5±38.2
Primary Graft Source (HT/BPTB/QT/AG)	3/1/0/0
Secondary Graft Source (HT/BPTB/QT/AG)	0/1/0/0
Primary Meniscectomy (N)	1
Secondary Meniscectomy (N)	0
Primary Meniscal Repair (N)	1
Secondary Meniscal Repair (N)	1

HT=hamstring autograft; BPTB= bone patellar tendon bone autograft; QT=quadriceps tendon autograft; AG=allograft

Limb Comparison

Between limb comparisons for the SLC and the SLV can be found in Table 4.4 and 4.5, respectively. There were no significant between limb differences in lower extremity biomechanics assessed during the SLV or SLC tasks.

Table 4.4: Medians and Range for Biomechanical Outcome Measures on the SLC

	ACL Median [Range]	Contralateral Median [Range]	χ^2	df	*p*-value	Eta^2
peak vGRF ($N \bullet kg^{-1}$)	3.39 [2.50,4.29]	3.49 [2.49, 4.59]	1.84	1	0.18	0.02
VIF ($N \bullet kg^{-1}$)	3.39 [2.50, 4.29]	3.49 [2.49, 4.59]	1.84	1	0.18	0.02
$vGRF_{amort}$ ($N \bullet kg^{-1}$)	1.76 [1.16, 2.55]	1.88 [1.14, 2.71]	0.91	1	0.34	0.01
VPF ($N \bullet kg^{-1}$)	1.82 [1.49, 2.41]	1.85 [1.54, 2.41]	0.99	1	0.32	0.01
GCT (ms)	580 [320, 1060]	550 [360, 1150]	0.60	1	0.44	0.01
Deceleration Time (ms)	270 [160, 730]	205 [140, 790]	0.46	1	0.50	0.00
Amortization Time (ms)	70 [40, 150]	60 [30, 130]	1.57	1	0.21	0.02
Acceleration Time (ms)	210 [120, 390]	210 [30, 430]	0.55	1	0.46	0.01
IC to peak vGRF (ms)	60 [40, 2730]	60 [40, 2330]	0.04	1	0.84	$4.28e^{-1}$
RSI (m/s)	2.18 [1.20, 6.51]	2.25 [1.27, 5.33]	0.76	1	0.38	0.01
Hop distance (m)	1.20 [0.70, 2.01]	1.24 [0.67, 1.99]	0.13	1	0.72	0.00

SLC=single leg crossover hop; vGRF=vertical ground reaction force; VIF=vertical impact force; VPF=vertical propulsion force; RSI=reactive strength index; IC=initial contact *=significant finding

Table 4.5: Medians and Range for Biomechanical Outcome Measures on the SLV

	ACL Median [Range]	Contralateral Median [Range]	χ^2	df	*p*-value	Eta^2
peak vGRF ($N \bullet kg^{-1}$)	3.39 [2.40, 4.46]	3.34 [2.31, 5.12]	0.00	1	0.96	0.00
VIF ($N \bullet kg^{-1}$)	3.39 [2.40, 4.46]	3.34 [2.31, 5.12]	0.00	1	0.96	0.00
$vGRF_{amort}$ ($N \bullet kg^{-1}$)	1.90 [1.36, 2.74]	1.97 [1.34, 2.90]	1.61	1	0.21	0.02
VPF ($N \bullet kg^{-1}$)	1.95 [1.63, 2.63]	2.01 [1.63, 2.69]	0.65	1	0.42	0.01
GCT (ms)	520 [340, 680]	490 [330, 680]	1.03	1	0.31	0.01
Deceleration Time (ms)	220 [140, 300]	210 [130, 280]	1.23	1	0.27	0.01
Amortization Time (ms)	60 [40,120]	60 [40, 150]	1.85	1	0.17	0.02
Acceleration Time (ms)	230 [130, 340]	220 [150, 330]	0.09	1	0.76	0.00
IC to peak vGRF (ms)	60 [40, 100]	60 [40, 110]	0.12	1	0.73	0.00
RSI (m/s)	0.24 [0.08, 0.64]	0.24 [0.08, 0.72]	0.00	1	0.97	0.00
Jump Height (m)	0.12 [0.04, 0.29]	0.12 [0.04, 0.28]	0.00	1	0.98	0.00

SLV=single leg vertical jump; vGRF=vertical ground reaction force; VIF=vertical impact force; VPF=vertical propulsion force; RSI=reactive strength index; IC=initial contact *=significant finding

Correlations Between SLV and SLC

Correlations between the SLV and SLC can be found in Table 4.6. For the ACLR limb there were significant moderate to strong correlations between tasks for all biomechanical outcome measures of interest. The strongest correlations were found for peak vGRF ($\rho=0.75$, $p<0.001$) and VIF ($\rho=0.75$, $p<0.001$). For the contralateral limb there were significant moderate correlations between tasks for all biomechanical variables of interest. The strongest correlations were found for GCT (ρ=0.69, p<0.001) and for VPF (ρ=0.70, p<0.001).

Table 4.6: Correlation Coefficients Between the SLC and SLV

	ACL		Contralateral	
	Rho	*P*	Rho	*P*
peak vGRF ($N \cdot kg^{-1}$)	0.75*	<0.001	0.58*	<0.001
VIF ($N \cdot kg^{-1}$)	0.75*	<0.001	0.58*	<0.001
$vGRF_{amort}$ ($N \cdot kg^{-1}$)	0.60*	<0.001	0.61*	<0.001
VPF ($N \cdot kg^{-1}$)	0.67*	<0.001	0.70*	<0.001
GCT (s)	0.61*	<0.001	0.69*	<0.001
Deceleration Time (s)	0.55*	<0.001	0.68*	<0.001
Amortization Time (s)	0.42*	0.003	0.43*	0.002
Acceleration Time (s)	0.45*	0.001	0.50*	<0.001
RSI (m/s)	0.60*	<0.001	0.67*	<0.001
Hop Distance/ Jump height (m)	0.57*	<0.001	0.59*	<0.001

vGRF=vertical ground reaction force; VIF= vertical impact force; VPF=vertical propulsion force; RSI=reactive strength index; *=significant finding

Time from Initial Contact to Peak vGRF During Ground Contact

Time from initial contact to peak vGRF can be found in Table 3.4 and Table 3.5 for the SLC and the SLV, respectively. The median time from initial contact to peak vGRF was 60ms [40ms, 2730ms] on the ACLR limb and 60ms [40ms, 2330ms] on the contralateral limb during the SLC. The median time from initial contact to peak vGRF was 60ms [40ms, 100ms] on the ACLR limb and 60ms [40ms, 110ms] on the contralateral limb during the SLV. There were no significant differences between limbs for either task. For both limbs during both tasks, peak vGRF occurred during the deceleration phase.

DISCUSSION

Persistent quadriceps weakness after ACLR is a result of morphological changes in the quadriceps tissue[7,192,194] and joint deafferentation[1,5,243,247] which negatively affects the SSC and limits reactive stability of the knee increasing risk of ACL injury during COD.[4,5] Individuals with ACLR can perform COD tasks with completion times equivalent to healthy individuals; however, these individuals adopt high-risk pattern of trunk flexion, external knee valgus angle, and GCT which exposes them to elevated risk of second knee injury as compare to healthy controls.[29,30] Contrary to previous literature[100,105,116,363–365] and to our hypothesis, the results of this study indicate no between limb differences during either task. Other studies have found that the ACLR limb exhibits high risk biomechanics during drop jumps[102,366,367] and COD tasks[29,30,368,369] when compared to the contralateral limb. We found significant moderate to strong correlations in biomechanical variables of interest between the SLC and SLV. Of note, the strongest relationships were found during deceleration when the two tasks were identical while weaker relationships were found during amortization and the acceleration phase. In part, the weaker relationships during the last two phases of each task maybe attributed to task complexity. The SLC requires rotation of the trunk toward a new trajectory and motion through the transverse plane, whereas the SLV is sagittal plane movement that does not require trunk rotation.

Significant moderate to strong relationships were found between tasks for all lower extremity biomechanical outcome measures of interest on both limbs. Adequate deceleration is needed to slow the momentum of the COM in preparation to change directions. Elongating the deceleration time is a compensatory strategy employed when quadriceps eccentric strength is not adequate to slow the momentum of the COM. The weakest correlations between tasks were between deceleration time, the amortization time and acceleration time. Deceleration time was longer during the SLC, which may be attributed to decreased eccentric quadriceps strength and decreased trunk stability reported in other studies.[99,307,370,371] Task complexity following the initial jump landing may explain the difference between tasks. The strongest relationships were between deceleration time and VIF. Logically, this is makes sense, as the demands of each task are similar until the acceleration phase. Weaker relationships between tasks during the amortization phase and acceleration time highlights differences between tasks. The amortization phase was also longer during the SLC, which may be an indication of inadequate knee stability to facilitate propulsion. Interestingly, acceleration time was shorter and VPF was lower in the SLC but resulted in greater hop distance compared to jump height during the SLV. The difference in propulsion can be attributed to increased power production at the hip and ankle during the drop horizontal hop compared to that of the drop vertical jump.[372] It should also be noted this same study reported significantly higher work contribution at the knee during landing, which corroborates the findings of the current study in which deceleration time was elongated during the SLC.

The RSI is a ratio of jump height to ground contact time. The RSI is a strong predictor of triple hop distance after ACLR[149] and associated with risk of ACL injury.[148] The results of this study did not reveal a significant difference between the ACLR limb and the contralateral limb during either task. Healthy individuals exhibit higher RSI values during a single leg jump,[353] than those reported in the current study indicating both limbs are affected after ACLR. While no differences were found between limbs on either task, symmetrical hop performance in individuals with ACLR is not synonymous with safe landing biomechanics[292] and over estimates knee function in this population.[291] It should not be assumed that symmetrical RSI is indicative of recovered SSC performance after ACLR. A similar study examined RSI during a drop horizontal hop in healthy individuals which reported greater hop distance and lower GCT than the current study.[373] This is further evidence, that the SSC is negatively affected after ACLR. The RSI during the SLC was substantially higher for both limbs compared to that of the SLV, which was driven by hop distance in the SLC, despite longer GCT during this task. The magnitude of difference between tasks is supported by the correlation analysis that revealed a moderate correlation between GCT, jump height and hop distance, and the RSI. Differences between tasks may be attributed to task complexity after deceleration. Both tasks are performed identically until the COM reaches its lowest point which is the start of the amortization phase. At this point, we found the weakest associations between tasks in amortization time and acceleration time. Based on the substantial difference in hop distance during the SLC compared to jump height on the SLV, it may not be appropriate to compare RSI values between horizontal hops and vertical jumps.

In the current study, deceleration time, amortization time, and GCT were not significantly different between limbs during the SLC. Individuals with ACLR demonstrate greater asymmetry in lower extremity biomechanics during drop jumps and COD tasks compared to healthy individuals.[29] As previously mentioned, the participants in this study exhibited lower RSI during the SLC compared to healthy individuals, which appears to be driven by longer GCT.[373] Longer deceleration time is an indication of inadequate eccentric quadriceps strength to meet the demands of the task.[124,307] Extended amortization phase may indicate a delay in muscle spindle activation resulting from joint deafferentation and disruption of the gamma-motor feedback loop.[1,4,5,231] Greater eccentric quadriceps strength is significantly correlated with GCT and faster COD completion times[307] as it is needed to decelerate the COM and stabilize the knee to facilitate trunk rotation toward the new trajectory during COD. In concert with previously published research, this is of significance as increased GCT is a risk factor for ACL injury,[132] and limited trunk rotation toward the new COM trajectory prior to acceleration during COD is associated with increased external knee valgus,[99] both of which increase the risk a ACL injury. Future intervention studies are needed to assess the influence of eccentric quadriceps strengthening and progressive decelerating training on COD performance.

The contradiction between our results and previously published literature based on the magnitude of difference between measures spurred additional questions regarding the timing of each variable included in the current study. Based on our findings, we divided each task into the deceleration phase, amortization phase, and acceleration phase and assessed peak vGRF which corresponds to peak ACL loading during the landing.[111,369] In both tasks and on both limbs, peak vGRF occurred during the deceleration phase which indicates that ACL is under the greatest strain and is at the greatest risk of injury early in the process of landing. The median time from initial contact to peak vGRF was 60ms during both tasks, approximately the same timeframe in which ACL injuries occur during jump landing and COD movements.[132] Shorter time to peak vGRF is associated with high-risk lower extremity biomechanics as young, healthy females exhibit shorter amount of time between knee valgus moment and peak vGRF during COD than their male counterparts.[374] High knee valgus angle and moment are predictive of ACL injury (r^2=0.88)[96] as they increase joint loading during landing.[375] Reaching peak vGRF and knee valgus moment concurrently in addition to high force magnitude during athletic movements, particularly in young females, may increase the risk of ACL injury. While it may not be possible to reduce GCT to less than 60ms through rehabilitation, improvements in lower extremity biomechanics and quadriceps strength can be achieved to stabilize the knee. Plyometric training improves preparatory and reactive muscle activation,[376] and reduces knee valgus angle during jumping tasks.[377,378] While plyometric training does improve COD performance variables such as completion time, the effectiveness of plyometric training to improve lower extremity biomechanics during COD individuals with ACLR has not been investigated.

There are several limitations that should be considered when evaluating the findings of this study. The sample used in this study had a heterogenous time since surgery spanning 5 to 90 months. We also included 8 participants who had undergone two ipsilateral ACLR. Individuals with ACLR revision exhibit worse outcomes[91,379,380] than those with primary ACLR, which also have affected our results. Additionally, the cross-sectional design of this study limits our ability to extrapolate the findings to individuals with ACLR at a specific time in their recovery. Prospective research to assess lower extremity biomechanics during COD individuals with

ACLR at the time of return to sport is warranted. The SLC was performed under planned conditions in which the participant was aware of which direction to go after contacting the force plate. The task was not representative cognitive demands encounter during sport and may not be an accurate representation of COD performance under unplanned conditions in which the individual must respond to stimulus when changing direction. Previous research has shown that increased cognitive demand negatively affects lower extremity kinetic and kinematics during COD, increasing the risk of ACL injury.[72,73] Despite this short coming, increased ground contact time and reduced RSI during the SLC in comparison to values reported in healthy individuals does indicate individuals with ACLR demonstrate movement patterns that may place them at increased risk of ACL injury during COD.

CONCLUSION

The results of this study found no between limb differences during the SLC and SLV. Deceleration and amortization phases were longer during the SLC, suggesting more time was needed to stabilize the knee and rotate the trunk toward the new trajectory during the change of direction task. Correlations between tasks were weakest during the amortization and acceleration phases. Change of direction did impose unique demands in comparison to the SLV and may need to be assessed prior to integration into sport after ACLR.

ABSTRACT

Context: Change of direction (COD) is a leading cause of anterior cruciate ligament (ACL) injury and is a fear-evoking task in individuals with ACL reconstruction (ACLR). Psychological response to injury may negatively affect lower extremity biomechanics during fear-evoking tasks like COD, increasing the risk of a second ACL injury. The purpose of this study was to assess the relationship between lower extremity biomechanics during a single leg crossover hop (SLC), with 3 measures of psychological response to injury in individuals with ACLR.

Methods: Forty-six individuals (32 female/14male; age=22.9±5.1 years; months since surgery=39±24) participated in this cross-sectional study. A kinematic and kinetic analysis using 3D motion capture was conducted during the SLC. Three successful trials were collected from each leg. Averages were calculated across three successful trials. To assess psychological response to injury, participants completed the Tampa Scale for Kinesiophobia (TSK-11), the ACL Return to Sport after Injury (ACL-RSI) scale and the Athlete Fear-avoidance Questionnaire (AFAQ). Spearman's rho correlations were used to assess the relationship between biomechanical variables of interest and psychological response to injury measures. The α-priori alpha level was set at 0.05.

Results: ACL-RSI had a weak, positive correlation with knee flexion excursion in the ACLR limb (ρ=0.30, p=0.04). No significant relationships were identified between frontal plane joint moments and excursion and psychological response to injury outcome measures. There was a positive, weak correlation between reactive strength index and the ACL-RSI (ρ=0.31, p=0.03) and a positive, moderate correlation between hop distance and the ACL-RSI (ρ=0.42, p=0.01) on the ACLR limb. TSK-11 and AFAQ were not related to any biomechanical variables of interest.

Conclusion: Greater psychological readiness to return to sport was weakly related to greater knee flexion excursion and higher reactive strength index when COD was performed on the

ACLR limb. Though the relationships were weak, our findings indicate greater psychological readiness is related to safer lower extremity biomechanics and improved stretch-shortening cycle performance during COD.

INTRODUCTION

Anterior cruciate ligament reconstruction (ACLR) and rehabilitation is meant to restore knee function and facilitate return to pre-injury levels of physical activity. However, 30% of individuals with ACLR will sustain a second ACL injury after returning to sport.[11] Persistent strength quadriceps weakness[289], asymmetrical single-leg hop distance[12], and negative psychological response to injury[323,381–385] have been identified as risk factors for a second ACL injury. Specifically, fear of movement, fear of re-injury, and fear-avoidance beliefss[383,386] have been linked to reduced likelihood of returning to sport and increased risk of ACL re-injury.[381] A recent study by Paterno et al.[92] reported that the risk of a second ACL injury in individuals who report a negative psychological response to injury after ACLR is 13 times greater than in individuals who report a positive psychological response to injury within 2 years of surgery. Despite the alarming evidence linking psychological response to injury to risk of re-injury after ACLR, our understanding of how psychological outcomes influence modifiable physical risk factors for re-injury remains limited.

Individuals with ACLR that exhibit a negative psychological response to injury are less likely to return to sport and are at greater risk of reinjury.[92,321,323,384,385] The Stress and Injury model (Figure 5.1) describes how the stress response to athletic situations may potentially elevate the risk of injury. The psychological response to injury can act as a stressor and lead to future injury in individuals who have experienced ACL injury and ACLR. The Stress Response portion of the model is comprised of (1) Cognitive Appraisal of demands, resources, and consequences and (2) Physiological and Attentional Aspects including increased muscle tension, narrowing of the visual field, and increased distractibility. When encountering a stressful situation, such as engaging an opponent during competition, the individual undergoes a cognitive appraisal of their ability to meet the demands of the situation. Should they conclude they are unable to meet those demands a negative physiological response occurs (e.g., increased muscle tension and decreased attention).[31] Muscle tension increases in stressful situations[387] and anticipation and divided attention alter biomechanics during cutting and jumping tasks in a manner consistent with non-contact knee injuries.[72,73,388] However, our understanding of the relationship between psychological response to injury and lower extremity biomechanics during activities that commonly lead to ACL injury is limited.

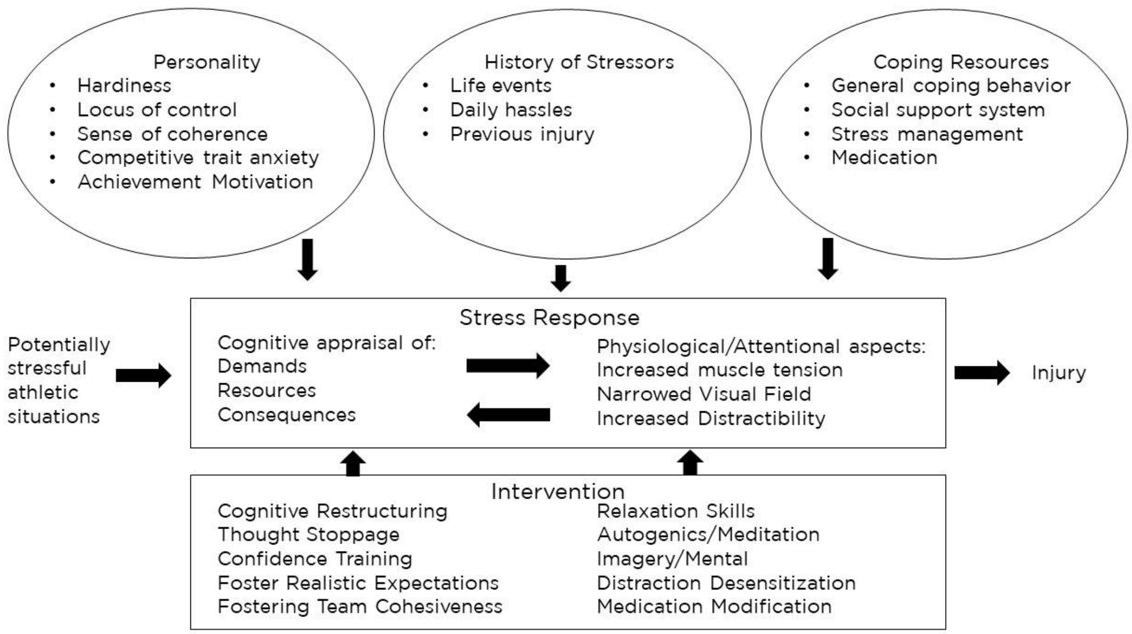

Figure 5.1: Stress and Injury Model Adapted from Andersen and Williams 1986[31]

The psychological response to ACL injury has been assessed using multiple patient-reported outcomes that encompass multiple psychological constructs (Table 5.1). However, these constructs are often considered synonymous, despite important distinctions in their clinical presentation and impact on clinically meaningful outcome measures among this patient population. The most commonly used patient-reported outcomes used to evaluate the psychological effects of ACL injury and ACLR are the TSK-11,[32,92,326,327,389,390] the ACL-

RSI,[321,323,383,385,391,392] and the AFAQ.[339,393,394] Among studies that have attempted to assess the association between psychological outcomes and biomechanical outcomes that have been linked to ACL re-injury the results have been highly variable depending on the patient-reported outcome utilized, the functional task included, and the biomechanical variable of interest. For example, an inverse relationship has been found between peak vertical ground reaction force measured during a double leg landing and kinesiophobia,[327] while high risk frontal plane kinematics have been linked to greater psychological readiness to return to sport.[391] Though similar in presentation, kinesiophobia, psychological readiness to return to sport, and fear-avoidance belief may have unique effects on athletic performance, particularly in high fear-evoking tasks such as change of direction (COD) or jump landing.[32]

Table 5.1: Psychological Response to Injury Constructs and Descriptions

Outcome Measure	Construct	Description
Tampa Scale of Kinesiophobia (TSK-11)	Kinesiophobia	Excessive, irrational, and debilitating fear to perform physical movements because the individual feels vulnerable to injury.[395,396]
Anterior Cruciate Ligament Return to Sport after Injury (ACL-RSI)	Psychological readiness	Emotional response Confidence in performance Risk appraisal related to sport participation[397]
Athlete Fear-Avoidance Questionnaire (AFAQ)	Fear-avoidance beliefs	Individual's response to pain. Individuals with avoidance behavior are motivated by fear and to avoid pain experience and painful activities.[398]

The Stress and Injury model as it applies to individuals with ACLR has been supported by biomechanical research that has shown performing athletic movements like a drop vertical jump[73] or cutting task[72] under cognitive demand, such as reacting to a ball or other stimulus, leads to increased knee valgus angle and ACL loading when compared to performing the same task without additional cognitive demand. The psychological response to an ACL injury is an example of cognitive demand and may impose similar negative effects on lower extremity biomechanics. Per the framework of the Stress and Injury model, cognitive appraisal of a stressful situation and perceived knee function to meet those demands of the stressful situation can negatively influence the stress response and may negatively alter lower extremity biomechanics.[389,390,399,400] This hypothesis is supported by the relationship between psychological response to injury and performance on functional tasks,[399,401] and rate of return to sport after ACLR.[92,321] Among individuals with ACLR, a negative psychological response to injury has been associated with decreased hip, knee, and trunk flexion[326] during single leg landing which can contribute to an ACL injury.[96,107] However, there has been no research to assess the relationship between psychological response to injury COD, a leading cause of ACL injury[28,34,63] and commonly reported fear-evoking task in individuals with ACLR.[32] Therefore, we propose that psychological response to injury may negatively affect performance on fear-evoking tasks after ACLR and contribute to the outsized risk of a second injury in this population.[402] Understanding the relationship between psychological response to injury and jump landing and COD performance may aid in identifying modifiable risk factors that can be addressed during rehabilitation and mitigate the risk of a second injury. Therefore, the purpose of this study is to assess the association between measures of psychological response to injury and lower extremity biomechanics during a single leg crossover hop (SLC), amongst individuals with a history of ACLR. We hypothesize that high TSK-11 and AFAQ score and low ACL-RSI score will be associated with stiffer jump landing (low knee and hip sagittal plane excursion), greater knee abduction angle, and longer ground contact time during the SLC.

METHODS

This cross-sectional descriptive laboratory study was approved by the Michigan State University Institutional Review Board and all participants provided written, informed consent.

Participants

Participants (N=46) were included in this study if they were 18-40 years old, had undergone unilateral ACLR, and were cleared by a medical professional for unrestricted physical activity (Table 5.2). Individuals with concomitant medial collateral ligament injuries (n=5) or had concomitant meniscal surgery (n=28) at the time of ACLR were included. Exclusion criteria included history of bilateral ACLR, cardiovascular or neurological disorders or prescribed or taking medication that would limit ability to participate in study activities. Eight participants did have a history of multiple ACLR on the same limb and were included in the final analysis.

Table 5.2: Demographic Information

	N=46
Sex (female/male)	32/14
Age (years)	22.9±5.1
Height (cm)	1.7±0.10
Body mass (kg)	73.5±11
Months since surgery	39±24
Primary Graft Source (HT/BPTB/QT/AG)	22/19/2/3
Secondary Graft Source (HT/BPTB/QT/AG)	0/3/0/3
Primary Meniscectomy (N)	9
Secondary Meniscectomy (N)	3
Primary Meniscal Repair (N)	20
Secondary Meniscal Repair (N)	3
ACL-RSI(median score [range])	56.70 [4.14, 100]
TSK-11 (median score [range])	20.50 [11.00, 28.00]
AFAQ (median score [range])	19.00 [10.00, 36.00]

HT=hamstring autograft; BPTB= bone patellar tendon bone autograft; QT=quadriceps tendon autograft; AG=allograft; ACL-REACTIVE STRENGTH INDEX=ACL Return to Sport after Injury; TSK-11=Tampa Scale for Kinesiophobia-11; AFAQ=Athlete Fear-Avoidance Questionnaire

Procedures

Participants completed a general health history form and a knee specific health history form, which were used to determine eligibility to participate in the study. Once eligibility was established, we collected their height (cm) and body mass (kg). Participants then completed a biomechanical analysis using a 3D motion capture system during a single leg crossover jump (SLC).[224] After the motion analysis assessment, participants completed the Tampa Scale for Kinesiophobia-11 (TSK-11), the ACL Return to Sport After Injury Scale (ACL-RSI), and the Athlete Fear-Avoidance Belief Questionnaire (AFAQ) via an online platform.

Kinesiophobia

Kinesiophobia was measured using the TSK-11[328] The 11 items on the TSK-11 are scored on a scale of 1 (strongly disagree) to 4 (strongly agree).[403] Scores range from 11 to 44, higher scores indicate greater fear of pain, movement, and injury.[403] The TSK-11 demonstrates good internal consistency (Cronbach α=0.79) and test-retest reliability (ICC=0.81, SEM=2.54).[328] Individuals with a score of ≥17 are considered to have greater fear after ACLR.[92,390] The TSK-11 questionnaire can be found in Appendix A.

Psychological Readiness to Return to Sport

The ACL-RSI scale was used to assess psychological readiness to return to sport. This 12-item scale measures psychological readiness in three areas: emotion, confidence in performance, and risk appraisal.[404] Items that examine emotion are related to nervousness about participating in sport, the individual's frustration with their knee in respect to their sport, and fear of reinjury while playing sport. Confidence items assess the individual's confidence in playing their sport without concern for their knee and ability to perform at previous level of sport participation. Risk appraisal items assess the individual's appraisal of how likely they feel they are to reinjury themselves while playing sports. An ACL-RSI score of less than 56 is strongly correlated with failure to return to previous level sport within 2 years after ACLR.[397,405] The ACL-RSI has acceptable reliability (Cronbach's alpha=0.92) and there is a significant difference in ACL-RSI score between individuals with ACLR that have returned to sport and those that have not.[406] The ACL-RSI questionnaire can be found in Appendix B.

Fear-Avoidance Beliefs

The AFAQ was used to assess fear-avoidance behavior.[407] The AFAQ is a 10-item scale each scored on a 1 (Not at all) to 5 (Completely agree) scale. Scores range from 10-50, with higher scores indicating greater fear-avoidance beliefs. The AFAQ demonstrates high internal consistency (Cronbach's alpha=0.81).[407] The AFAQ questionnaire can be found in Appendix C.

Lower Extremity Biomechanics

Kinematic and kinetic data were captured during a SLC using a ten-camera Vicon Bonita 10 Motion Analysis System (Vicon Motion Systems, Inc., Lake Forest, CA, USA) and an embedded force plate (Advanced Mechanical Technology, Inc., Watertown, MA, USA), respectively. Kinematic data were collected at 240 Hz and kinetic data were collected at 1,200 Hz. Eight clusters of 4 reflective markers were attached to the participant at the thigh, shank, foot, and upper and lower back. A stylus with 4 reflective markers was used to identify the spinous process at C7, T12, and L5 and the medial and lateral joint line of the tibiofemoral joint, the distal end of the medial and lateral malleoli, and the distal end of the second toe to digitize the segments and estimate the joint centers using a centroid method.[355] The Bell method was used to calculate hip-joint center.[356]

To perform the SLC, participants stood on a single leg on top of a 30-cm box positioned 40 cm away from the middle of the force plate. They were instructed to jump off the box to the tape target on the force plate then hop a 45° angle in the direction opposite of the working leg. Tape was fixed to the floor to designate the 45° angle. Hop distance was then measured with a tape measure from the middle of the force plate to the back of the participant's heel. Practice trials were allotted until the participant felt confident performing each task. A trial was successful if the participant was able to complete the task without loss of balance or contacting the floor with the opposite foot or with the hands. Three successful trials were collected bilaterally, the contralateral limb was always tested first. We did not standardize shoe selection, but all participants did wear athletic shoes during data collection.

Kinematic and kinetic data was processed using the Motion Monitor (Innovative Sports Training, Inc, Chicago, IL, USA) software. Kinetic and kinematic data were filtered using a fourth-order Butterworth filter with a cutoff frequency of 12 Hz for kinematic data and 100 Hz for kinetic data. Initial contact was made when vGRF exceeded 10 N. Ground contact time was measured from initial contact to takeoff (vGRF<10 N). An average across three successful trials was used for analysis.

Sample Size Estimation

This study was part of a larger study that assessed the relationship between quadriceps strength characteristics (quadriceps peak torque and rate of torque development) and lower extremity biomechanics during a single leg step down task and single leg crossover hop task in individuals with a history of ACLR.[224] Our sample size estimation was calculated using the reactive strength index and ACL-RSI and data from this prior publication. The sample size estimate was made using α-priori level of 0.05, an acceptable 1-β of 0.80, and moderate correlation (r=0.40) between the reactive strength index and ACL-RSI. We estimated that an acceptable minimum sample size would be 47 participants. The sample size estimate was calculated using an online sample size calculator.[408]

Statistical Analysis

For all continuous demographic dependent variables, means and standard deviations were calculated. For categorical and nominal data, medians and ranges or frequencies were presented, respectively. Based on the results of the Shapiro-Wilk test, the data were not normally distributed and therefore non-parametric analyses were used. Spearman's Rank correlation was used to assess the relationship between biomechanical variables of interest and psychological response to injury measures on the SLC. Correlations were categorized as weak (ρ=0.10-0.39); moderate (ρ =0.40-0.69); or strong (ρ ≥0.70).[361,409]The α-priori alpha level was set at 0.05.

RESULTS

Means and standard deviations for demographic and surgical characteristics can be found in Table 5.2. Medians and interquartile range for frontal and sagittal plane joint moments and excursions can be found in Table 5.3. Five participants were removed from the dataset prior to analysis due to outliers in several variables that were not representative of the sample. Outliers were identified using box plots then matched with the corresponding participant. Any outliers that affected the ρ-value by more than 10%, positively or negatively, were removed prior to analysis.

Table 5.3: Medians and Interquartile Range for the ACLR and Contralateral Limb

	ACLR Median [IQR]	Contralateral Median [IQR]
Peak Knee Extension Moment (N)	0.37 [0.56]	0.10 [0.38]
Peak Hip Flexion Moment (N)	-0.53 [2.54]	-0.21 [3.38]
Knee Flexion Excursion (°)	43.10 [12.8]	49.70 [10.00]
Hip Flexion Excursion (°)	26.20 [12.5]	25.90 [16.8]
Peak Knee Abduction (°)	2.80 [4.88]	3.50 [4.42]
Peak Hip Abduction (°)	-2.20 [8.48]	-1.35 [10.29]
Peak Knee Abduction Moment (N)	0.46 [0.87]	0.15 [0.75]
Peak Hip Abduction Moment (N)	-0.34 [0.50]	0.03 [0.66]
Peak vGRF (N)	2465 [733]	2491 [512]
RSI (m/s)	2.10 [1.36]	2.25 [1.00]
Hop Distance (cm)	1.19 [0.38]	1.24 [0.32]

For frontal plane motion at the hip, positive values indicate adduction, negative values indicate abduction. For frontal plane motion at the knee, positive values indicate abduction, negative values indicate. For sagittal plane motion at the knee and hip, positive values indicate flexion, negative values indicate extension. RSI=reactive strength index

Biomechanics and Psychological Response to Injury

Correlation coefficients for sagittal plane biomechanics and frontal plane biomechanics can be found in Table 5.4 and 5.5, respectively. A weak, positive correlation was identified between the ACL-RSI and sagittal plane joint excursion at the knee in the ACLR limb during the SLC (ρ=0.30, *p*=0.04). No significant relationships were identified between frontal plane joint moments and excursion and psychological response to injury outcome measures. There was a positive, weak correlation between reactive strength index and the ACL-RSI (ρ=0.31, *p*=0.03) and a positive, moderate correlation between hop distance and the ACL-RSI (ρ=0.42, *p*=0.01) on the ACLR limb.

Table 5.4: Sagittal Plane Biomechanics and Psychological Response to Injury

		Knee		Hip	
		ACLR	Contralateral	ACLR	Contralateral
ACL-RSI	ρ	0.30*	0.14	0.19	0.23
	P-value	0.04	0.37	0.21	0.13
TSK-11	ρ	0.14	0.25	0.02	-0.02
	P-value	0.35	0.10	0.90	0.87
AFAQ	ρ	0.05	0.18	0.08	0.05
	P-value	0.76	0.24	0.58	0.75

ACL-RSI= ACL Return to Sport Injury; TSK-11=Tampa Scale of Kinesiophobia; AFAQ=Athlete Fear-avoidance Questionnaire; *=significant finding

Table 5.5: Frontal Plane Biomechanics and Psychological Response to Injury

		Knee Abduction				Hip Abduction				Hop Performance					
		Moment		Excursion		Moment		Excursion		vGRF		RSI		Hop Distance	
		ACLR	Con	ACLR	Con	ACLR	Con	ACLR	Con	ACLR	Con	ACLR	Con	ACLR	Con
ACL-RSI	ρ	0.07	0.09	-0.01	-0.12	0.04	0.09	0.11	0.02	0.13	0.001	0.31*	0.23	0.42*	0.39*
	P	0.63	0.53	0.94	0.43	0.82	0.54	0.48	0.91	0.39	0.99	0.03	0.13	0.01	0.01
TSK-11	ρ	0.03	0.06	0.17	0.13	-0.02	-0.14	-0.01	0.07	-0.21	-0.19	0.01	0.03	0.10	0.15
	P	0.82	0.71	0.26	0.40	0.88	0.34	0.94	0.64	0.16	0.21	0.94	0.85	0.53	0.33
AFAQ	ρ	-0.25	0.02	0.06	-0.01	-0.03	-0.05	-0.01	0.03	-0.16	-0.11	-0.26	-0.15	-0.16	-0.09
	P	0.09	0.89	0.71	0.92	0.83	0.72	0.97	0.84	0.28	0.48	0.08	0.33	0.30	0.55

ACLR=ACL reconstruction; Con=contralateral; ACL-RSI= ACL Return to Sport Injury; TSK-11=Tampa Scale of Kinesiophobia; AFAQ=Athlete Fear-avoidance Questionnaire; vGRF=vertical ground reaction force; RSI=reactive strength index; *=significant finding

DISCUSSION

Despite the relationship between psychological response to injury and re-injury after ACLR, little is known about the relationship between psychological response to injury and modifiable risk factors for ACL injury such as lower extremity biomechanics. The purpose of this study was to assess the relationship between commonly used psychological response to injury outcome measures and lower extremity biomechanics during the SLC which is a sport-related COD task. The most notable findings of this study were the positive relationships between knee flexion excursion and the ACL-RSI and between ACL-RSI score and reactive strength index in the ACLR limb. Despite bilateral aberrant lower extremity biomechanics[327,363] and deficits in quadriceps strength[300,410,411] after ACLR, psychological response to injury was not related to lower extremity biomechanics and only weakly related to hop performance on the contralateral limb in this study. Previous studies have reported a relationship between the TSK-11 and knee flexion[412] and vGRF in the ACLR limb during double leg landing.[327] The AFAQ is associated with health related quality of life,[393] and self-reported knee function[394] in individuals with ACLR. In this study the TSK-11 and AFAQ were not significantly related to our variables of interest during the SLC task. Based on these findings, it appears that the relationship between psychological response to injury and biomechanics is construct dependent.

Greater knee flexion during landing[108,365,413,414] and high ACL-RSI score[323,385] are associated with reduced risk of ACL injury. In this study, individuals with higher ACL-RSI scores displayed greater knee flexion excursion during the SLC. A study by Trigsted et al.[326] involving individuals with unilateral ACLR found a similar relationship between TSK-11 scores and peak knee flexion during a double leg drop jump.[326] Despite similar findings in both studies, it is interesting that different psychological response to injury constructs were found to be related to knee flexion which raises an interesting question regarding kinesiophobia and self-efficacy as assessed by the ACL-RSI. In the framework posed by the Stress and Injury model, kinesiophobia and self-efficacy are possibly the factors that influence lower extremity biomechanics after ACLR. High self-efficacy to meet the demands of the task may mitigate the negative physiological effects of kinesiophobia that negatively affect lower extremity biomechanics. Individuals with chronic low back pain and high self-efficacy experience less disability and less pain than those with low self-efficacy.[415] We propose that adequate self-efficacy in the presence of kinesiophobia may facilitate safer lower extremity biomechanics in individuals with ACLR. However, there are two caveats to consider regarding our conclusions. First, Trigsted et al. did not report ACL-RSI scores, so we cannot make a direct comparison based on psychological readiness to return to sport. We based our conclusions on equivalent TSK-11 scores in both studies, and high ACL-RSI scores in the current study. Second, the correlations in this study are weak and therefore their immediate clinical adoption is not warranted. Longitudinal data examining the association between lower extremity biomechanics and psychological response to injury during the transition from formalize rehabilitative care to unrestricted physical activity is needed to assess their influence on risk of second ACL injury.

Previous research has shown frontal plane motion at the knee is associated with ACL injury,[96,126,416,417]however, limited research has been conducted to examine the relationship between psychological readiness to return to sport and lower extremity biomechanics after ACLR. Nagelli et al.,[391] reported greater frontal plane knee and hip range of motion predicted ACL-RSI scores during a single leg landing but found no relationship between ACL-RSI score and sagittal plane motion at the knee or hip.[391] While the relationship between ACL-RSI and frontal plane knee motion reported by Nagelli et al.,[391] is counter intuitive, other studies have shown patient-reported outcomes such as self-reported knee function improve in light of aberrant lower extremity biomechanics[413,418,419] and deficits in quadriceps strength.[420–422] In the present study, we did not find a relationship between frontal plane motion at the knee or hip with any of the psychological response to injury outcomes. It is possible the tasks included in our study and that of Nagelli et al., were not challenging enough to elicit a negative psychological response and bolstered ACL-RSI scores. Future research should include tasks with reactionary components or competition-like scenarios that are more representative of sport. This may change the participant's cognitive appraisal of their ability to meet the demands of the task and provide a more accurate display of lower extremity biomechanics during sport.

This is the first study to assess the relationship between psychological response to injury outcome measures and reactive strength index. The reactive strength index is associated with risk of ACL injury[148] and is associated with better performance of sport related tasks in individuals with ACLR.[149,423,424] The results of this study showed those with higher reactive strength index had better psychological readiness to return to sport. More importantly, this relationship was found during COD, a commonly reported fear-evoking task in individuals with ACLR. Based on the results of this study, ACL-RSI scores maybe related to stretch-shortening cycle performance (reactive strength index) and maybe an indicator of preparedness to perform sport related movements. While this relationship was significant, it was weak and participants in this study exhibited lower reactive strength index than healthy individuals during a drop horizontal hop.[373] Participants in this study exhibited an ACL-RSI score greater than 56 which is associated with successful return to sport after ACLR; however the low reactive strength in comparison to healthy individuals indicates psychological response to injury outpaces physical recovery. This may tempt those with ACLR to participate in activities they are not physically ready to perform and contribute to the outsized risk of second ACL injury in this population. Further investigation into the relationship between these variables and their influence on second ACL injury is warranted.

This study is not without limitation. The cross-sectional design of the study, homogenous time since surgery, and non-normally distributed data limit extrapolation of the results. It is possible that participant's confidence was improved through the practice trials and lead to better performance on the SLC and improved scores on the psychological response to injury outcome measures. In part, this may explain the weaker relationships identified in this study compared to previously published research. Despite validation of the psychological response to injury outcome measures used in this study and their common use in ACLR literature, there is question as to whether these outcome measures adequately assess psychological readiness to return to sport, kinesiophobia, and fear-avoidance belief or their underlying constructs. It is possible, these outcome measures are not sensitive enough to assess psychological response to injury independently. Despite a median score of greater than 17 on the TSK-11, which has been proposed as the cutoff score for high kinesiophobia, only one participant withdrew from the study out of fear of performing the SLC. This is further evidence to support our hypothesis that self-efficacy to meet the demands of a task in the presence of kinesiophobia may influence lower extremity biomechanics after ACLR and may influence participation in more demanding sport and physical activity. Furthermore, none of the psychological response to injury outcome measures included in this study include questions pertaining to specific tasks, sport-related scenarios, or provide space for the participant to provide context around their answers to each question. It is our recommendation that clinical use of these outcome measures be coupled with a follow up interview to draw specific conclusions regarding the psychological well-being of the individual with ACLR.

CONCLUSION

During COD, knee flexion excursion and reactive strength index were related to high psychological readiness to return to sport in individuals with ACLR. Our results indicate those with high psychological readiness maybe better prepared to integrate into sport participation. Caution in clinical adoption should be taken as the relationships found in this study were weak. Research in this area has yielded inconsistent results and therefore further exploration of the relationship between lower extremity biomechanics and psychological response to injury is warranted.

APPENDICIES

APPENDIX A. Tampa Scale for Kinesiophobia

Tampa Scale for Kinesiophobia (TSK-11)
1. I'm afraid that I might injure myself if I exercise
2. If I were to try to overcome it, my pain would increase
3. My body is telling me I have something dangerously wrong
4. People aren't taking my medical condition serious enough
5. My accident has put my body at risk for the rest of my life
6. Pain always means I have injured my body
7. Simply being careful that I do not make any unnecessary movements is the safest thing I can do to prevent my pain from worsening.
8. I wouldn't have this much pain if there weren't something potentially dangerous going on in my body
9. Pain lets me know when to stop exercising so that I don't injure myself
10. I can't do all of the things normal people do because it's too easy for me to get injured
11. No one should have to exercise when he/she is in pain

Each item is graded on a 4-point scale from 'Strong disagree' to 'Strongly agree'

APPENDIX B. Anterior Cruciate Ligament Return to Sport after Injury

Anterior Cruciate Ligament Return to Sport after Injury (ACL-RSI)
1. Are you confident that you can perform at your previous level of sport participation?
2. Do you think you are likely to re-injure your knee by participating in sport?
3. Are you confident that your knee will not give away by playing your sport?
4. Are you confident that you could play your sport without concern for your knee?
5. Do you find it frustrating to have to consider you knee with respect to your sport?
6. Are you fearful of re-injuring your knee by playing your sport?
7. Are you confident about your knee holding up under pressure?
8. Are you afraid of accidently injuring your knee by playing your sport?
9. Do thoughts of having to go through surgery and rehabilitation prevent you from playing your sport?
10. Are you confident about your ability to perform well at your sport?
11. Do you feel relaxed about playing your sport?

Each item is evaluated on a 0 to 10 scale, 0= Not at all relaxed, 10=fully relaxed. Scores are summed and multiplied by 10

APPENDIX C. Athlete Fear Avoidance Questionnaire

Athlete Fear Avoidance Questionnaire (AFABQ)
1. I will never be able to play as I did before my injury
2. I am worried about my role with the team changing
3. I am worried about what other people will think of me if I don't perform at the same level
4. I am not sure what my injury is.
5. I believe that my current injury has jeopardized my future athletic abilities
6. I am not comfortable going back to play until I am 100%
7. People don't understand how serious my injury is
8. I don't know if I am ready to play
9. I worry if I go back to play too soon I will make my knee worse
10. When my pain is intense, I worry that my injury is a very serious one.

Each item is evaluated on a 5-point scale, 1=not at all, 5=Completely agree

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