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A Comparison of Single Leg Squat and Side Step Cut Kinematics in Healthy and ACL Reconstructed Populations

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A Comparison of Single Leg Squat and Side Step Cut Kinematics in Healthy and ACL Reconstructed Populations

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B.S., Bridgewater State University, 2009

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Masters of Science Thesis

A Comparison of Single Leg Squat and Side Step Cut Kinematics in Healthy and ACL Reconstructed Populations

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ABSTRACT

A Comparison of Single Leg Squat and Side Step Cut Kinematics in Healthy and ACL Reconstructed Populations

Jarrett JE Sorge, University of Connecticut

STUDY DESIGN: Case Control Study

OBJECTIVE: To compare single leg squat (SLS) kinematics to side step cut (SSC) kinematics and vertical ground reaction force in individuals with a history of ACL reconstruction and healthy controls.

BACKGROUND: There are currently no objective criteria to progress athletes into cutting activities during rehabilitation. The single leg squat possesses similar three-planar neuromuscular control as a cutting task. Assessing movement dysfunction during the single leg squat could limit injury risk during cutting activities.

METHODS: 44 individuals active in cutting, jumping, or landing activities participated in this study. 22 athletes had a history of ACL reconstruction (14 male, 8 female) Age, 21.7 ± 3.8 years; Height, 174.5 ± 7.2 cm; Mass, 76.2 ± 9.9 kg). 22 healthy athletes (14 male, 8 female) with no history of ACL reconstruction or any other lower extremity surgery (Age: 21.6 ± 3.6 years; height: 173.8 ± 9.2 cm; mass: 75.0 ± 10.5) served as a matched control group based on sex, height, mass, age, and activity level. Kinematic data was collected during both tasks; participants completed five single leg squats and two side step cutting tasks on each leg. The means across were determined and correlated between tasks. Independent sample t-tests were used to determine any significance between groups.

RESULTS: Individuals with a history of ACL reconstruction squatted and cut with significantly less sagittal plane motion compared to healthy controls. Healthy controls also cut with more trunk rotation towards the direction of travel and higher VGRF compared to individuals with a history of ACLR. Numerous correlations were seen between tasks.

CONCLUSION: Sagittal, frontal, and transverse plane motion during the SLS were predictive of motion during the SSC. Lack of frontal and transverse plane trunk, hip, and knee control during the SLS resulted in positions of increased lateral trunk flexion, hip adduction, and medial knee displacement during a cutting task. The SLS can be used as a clinical predictor of SSC in athletes during injury prevention or return to play rehabilitation.

Key Words: single leg squat, cutting, side step cut, anterior cruciate ligament, injury prevention

Review of the Literature

Anterior cruciate ligament (ACL) injuries are one of the most debilitating musculoskeletal injuries suffered in sport. The ACL is a primary stabilizer of the knee; therefore, rupture can lead to functional instability. An estimated 75,000-250,000 ACL injuries occur annually in the United States; this estimate has risen through the years due to the dramatic increase in sport participation from a pediatric age through adult life.¹⁻³ Since the passing of Title IX in 1972, male athletic participation has increased 3% while female participation has increased more than 9-fold (0.3 million to 2.8 million).⁴ ACL injuries have been reported at a frequency 2-9 times greater in females compared to males in the same cutting and jumping sports.^{5,6} Although the United States has no national injury tracking system, Marshall et al.³ reported through survey that 1 in 90 hospital or emergency room visits involved a cruciate ligament injury. These injuries require long-term health care, treatment, and rehabilitation. The root of ACL injury prevention involves undertaking a comprehensive understanding of the etiology of ACL injury, identifying and modifying risk factors that predispose athletes to ACL injury, and following evidence based return to play guidelines that minimize the risk of re-injury.

Cost Association

ACL-Reconstruction (ACLR) is the standard treatment for ACL rupture, designed to limit long-term intra-articular damage and restore stability and function.⁷ Not all ACL deficient patients require surgical reconstruction; the decision is based on their ability to maintain adequate knee function.⁵ An estimated two-thirds of patients opt for reconstruction, which rapidly becomes costly with surgery and rehabilitation estimated at \$17,000-25,000 per incidence.^{2,8} However, long term cost analysis shows that ACL reconstruction is not

significantly more expensive than conservative treatment due to the associated meniscal injuries and early development of osteoarthritis in those who elect not to have reconstructive surgery.⁹

Return to Play and Quality of Life

ACL injuries are not only costly, but can also have dramatic effects on a patient's return to participation, activity level, and long term quality of life. ACL injuries can result in the loss of entire seasons of participation or the loss of scholarship for the high school athlete.¹⁰ In a study concerning return to play and future ACL risk, Brophy et al.¹¹ determined that 72% of soccer athletes returned to their sport at an average of 12-14 months after surgery, with 85% of those returning to soccer at the same or higher level of play. At a long term follow up of 7-8 years post ACLR, only 35% were still playing their sport. Of those still playing, only 46% were still playing at the same or higher level of play as before their injury.¹¹ Similarly, Ardern et al.¹² surveyed 314 ACLR individuals 2-7 years after reconstruction. The investigators found that only 41% of their participants had attempted competitive sport at follow-up, and only 29% were actively participating at their pre-injury competitive level.¹² More than one-half of the studied individuals who did not return to their pre-injury level of competition cited function of their knee as their reasoning.¹²

Lohmander et al.¹³ found that radiographic patellofemoral or tibiofemoral osteoarthritis was present in 51% of the ACL injured female soccer athletes studied 12 years after injury. Of the 84 women who answered the questionnaires, 75% reported having symptoms affecting their knee related quality of life (Figure 1).

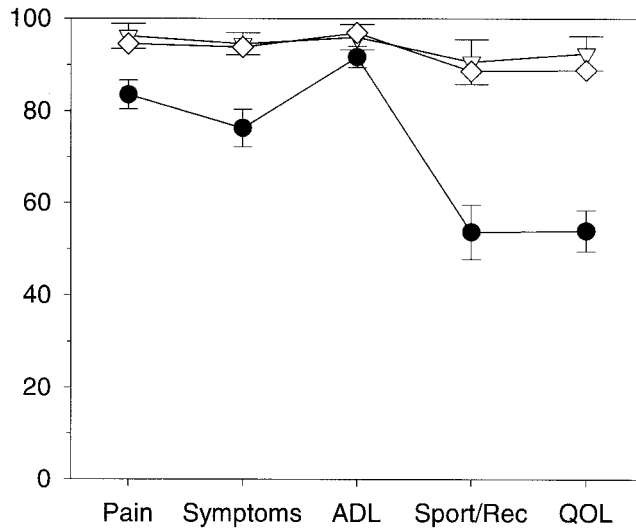


Figure 1. *Knee Injury and Osteoarthritis Score (KOOS) results reported by Lohmander et al¹³*
The ACL injured female soccer players (mean age 31) are represented by solid circles, the
reference group with no symptoms of knee OA (mean age 55) are represented by triangles, and
the reference group of uninjured female soccer players (mean age 20) are represented by
diamonds

Ahlden et al.¹⁴ conducted the largest known study reporting results in over 16,000 patients with a history of ACL reconstruction through the Swedish National ACL Register. The study

collected results KOOS scores from registry respondents at 1, 2, and 5 years postoperatively.

Ahlden found that patients who underwent a second surgery had significantly poorer knee related quality of life compared to those who had had their first reconstruction. Participants with an additional ACL reconstruction also displayed no significant improvement in symptoms, pain, and activities of daily living at 5 years post surgery compared with their preoperative values.¹⁵

ACL Injury Mechanism

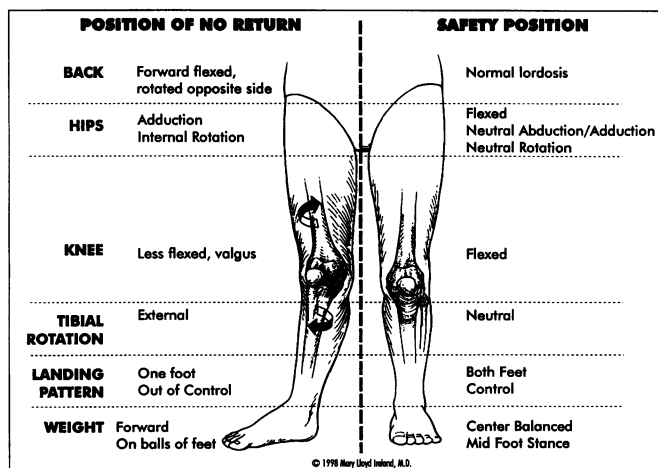
ACL injuries are characterized by a contact or non-contact mechanism. A non-contact mechanism involves no contact with an opposing player, equipment, or ground at the time of injury. Mechanisms of non-contact ACL injury normally involve multi-planar knee loading events.^{1,16} The most common mechanism reported by the athlete is planting and pivoting.⁶ An

ACL injury normally involves a change of direction or cut, combined with deceleration, the knee near full extension, and the foot fixed on the playing surface.^{1,16,17} In one of the first studies to retrospectively analyze mechanisms of ACL injury, Boden et al.¹⁶ surveyed 132 patients (143 knees) after sustaining an ACL injury. The study found that a noncontact mechanism was the cause of 72% sustained injuries.¹⁶ Additionally, the National Collegiate Athletic Association (NCAA) studied ACL injuries prospectively in men's and women's basketball and men's and women's soccer. Each sport had high incidences of non-contact ACL injury, men's and women's basketball athletes experiencing the highest incidence rate at 80% each. The non-contact rate in men's and women's soccer was slightly lower; women's soccer suffered a 63% rate and men's soccer a 48% rate of non-contact ACL injury.⁶ In an even higher estimate, Myklebust et al.¹⁸ followed 212 teams in the three upper level men's and women's Norwegian handball divisions through two full seasons (estimated 3392 players) and found that 95% of ACL injuries occurred without contact from another player.

Ireland described the “position of no return” (Figure 2) as the reported vulnerable cause of noncontact ACL injury. The position of no return is described as including a forward flexed back, adducted and internally rotated hips, the knee in a less flexed and valgus position, tibia rotated, and landing on one foot with the weight forward.¹⁹ Hewett et al.⁸ described four positions that seemed to occur during many ACL injuries, especially in women: as the athlete lands, the knee buckles inward, the knee is relatively straight, most of the athlete's weight is on the single limb, and the trunk tends to be flexed laterally, causing the athlete's center of mass to be shifted outside the base of support. These events also occur in men, but seem to be more exaggerated in women.⁸ The results from observational studies generally agree that valgus motion, often accompanied with transverse plane knee rotation motions, were contributing

factors to the ACL injury mechanism.^{1,4,16,17} Hewett et al.²⁰ also demonstrated that ACL injuries demonstrated both lateral trunk motion and knee abduction.²⁰ Boden et al.¹⁶ added, through the use of video analysis, the position of the leg after a non-contact injury was near foot-strike with the knee close to full extension.

Figure 2. The “Position of No Return” for ACL Injury compared with the “Safe Position” as described by Ireland et al.¹⁹



Risk Factors of Non-Contact ACL Injury

Identification of risk factors that predispose athletes to non-contact ACL rupture has become a crucial aspect of injury prevention. There have many studies that have looked at identifying non-modifiable and modifiable risk factors and explaining their roles in ACL injury. Many of the risk factors aim to explain the greater risk of ACL injury in female athletes incident compared to men participating in the same activities.

Non-Modifiable Risk Factors

There are several anatomical risk factors that have been proposed to explain the risk of ACL injury, especially in female athletes. Joint laxity, narrow intercondylar notch width,

posterior tibial plateau slope, and static alignment, have all been extensively researched.^{10,17,21,22} Ligamentous laxity at the ACL can be objectively reported by measuring the anterior translation of the tibia, mostly commonly using a KT-1000 ligament arthrometer.²² Several studies have reported that a combination of risk factors increases the risk of ACL injury. Uhorchak et al.²³ reported that the combination of body weight, BMI, intercondylar notch width, as well as joint laxity were all significant risk factors for ACL injuries. Evans et al,²⁴ concluded that an elevated BMI as well as a narrow notch width may predispose young military athletes to ACL injury.

Gender differences have been extensively researched in terms of ACL injury risk. Long-term NCAA injury data investigations have proven to show that there is a much higher ACL injury incident in women when compared to men participating in the same sports.^{6,25} Hormonal influences have been a proposed reasoning for the higher rate of ACL injury in females.^{26,27} Females may have increased anterior-posterior knee laxity during the preovulatory phase of their menstrual cycle, subsequently causing greater ACL injury risk. Another gender specific risk factor associated with ACL injury is quadriceps angle (Q-Angle). Q-Angle is the angle drawn from the ASIS to the midpoint in the patella and then from the midpoint of the patella to the tibial tuberosity. A high Q-Angle is reported to possibly alter biomechanics at the lower limb and place the knee in positions of valgus stress. However, Myer et al.²⁸ reported that increases in static Q-Angle measurements were not predictive of ACL injury risk during dynamic movement. Q-Angle has also been shown to not be a significant factor in peak knee valgus during a single leg squat task.²⁹

Modifiable Risk Factors

Modifiable risk factors have also been extensively studied in relation to ACL injury prevention. Lack of active neuromuscular control may destabilize the knee and increase the ACL injury risk in athletes. The term “neuromuscular control” refers to the unconscious dynamic stabilization at a particular joint in response to sensory stimuli.³⁰ Dynamic stabilization at the knee is extremely important for the prevention of ACL injury; without proper dynamic stabilizers, the ACL would fail with forces sustained during everyday activities.²² Co-activation of the hamstrings, quadriceps, and gastrocnemius muscles at the knee are all important in the dynamic stabilization at the knee.^{10,22} ACL injury occurs during moments of high load at the knee when muscular control is not adequate enough to prevent translation at the knee.

Considering the gender bias seen with noncontact ACL injury, several studies have looked at comparing movement patterns between men and women. Women have also been shown to move, land, and absorb forces differently from men. In a systematic review, Dai et al.²¹ summarized that females tend to restrict sagittal plane motion and increase motion in the frontal and transverse planes when performing athletic tasks. This combination of motion results in increased loading at the knee and specifically the ACL. Hewett et al.⁴ screened 205 female athletes who were participants in high-risk sports and followed them to determine risk factors of ACL injury in female athletes. Of the 205 athletes screened, 9 had a confirmed ACL rupture. All 9 displayed eight degrees greater knee abduction angle, a 2.5 times greater knee abduction moment, and 20% higher ground reaction force when compared with the 196 uninjured. They concluded that knee abduction moments and angles during landing tasks were predictors of ACL risk in female athletes.⁴

Myer et al.³¹ prospectively studied the hamstring and quadriceps strength and ratio of male and female athletes prior to injury. Female athletes who subsequently suffered ACL injury

had less hamstring strength but not quadriceps strength. Conversely, female athletes who did not suffer ACL injury had less quadriceps strength without decreased hamstring strength compared to males.³¹ Griffin et al.³⁰ reported on the consensus statement made at the Hunt Valley Consensus Conference that neuromuscular factors are significant contributors to ACL injury rate in females. Several studies have reported that during cutting tasks, females exhibit much greater peak valgus moments and frontal plane motion compared to males given the same tasks.^{32,33} Although evidence is becoming increasingly abundant, further research needs to be conducted to prove that risk factors vary between males and females.

Incidence of ACL Re-Injury

The most significant risk factor for ACL injury is a previous history of ACL rupture.^{34,35} Risk of a second ACL injury is greatest with the return to cutting and pivoting sport-specific activities, especially in the first 12 months following ACL reconstruction.^{35,36} Paterno et al.³⁶ reported that within the first 12 months of activity after return to sport, subjects with ACLR were 15 times more likely to sustain an ACL injury compared with subjects with no history of ACLR. Rate of injury to the graft as well as the contralateral knee during return to play has been studied extensively. In a large cohort study, Shelbourne et al.³⁷ prospectively followed 1415 people for five years who underwent ACL reconstruction. Of the 1415 people, 136 (9.6%) suffered a subsequent injury to either knee at follow up. 45% of subsequent tears were on the ACLR side, and 55% of tears were on the contralateral side.³⁷ No significant difference between men and women for subsequent ACL tear in the ACL reconstructed knee was reported; however, women had a significantly higher incidence of ACL injury to the contralateral knee.³⁷

Two other studies reported similar results with respect to rate of contralateral knee injury. Salmon et al.³⁵ followed up with 612 ACLR patients five years after reconstruction, and 71 had suffered an additional ACL injury. ACL graft rupture occurred in 39 patients (6%) and contralateral ACL rupture occurred in 35 patients (6%). 3 patients suffered both a graft rupture and a contralateral ACL injury.³⁵ Wright et al.³⁴ prospectively followed 235 patients after reconstruction and reported 14 (6%) subsequent ACL ruptures. Seven ruptures were graft ruptures and 7 ruptures were of the contralateral knee. In a smaller prospective study that only includes ACLR individuals who suffered a non-contact mechanism of injury, Paterno et al.³⁶ found a much higher incidence of re-injury. Of the 63 subjects that met the inclusion criteria, 16 suffered a subsequent noncontact ACL injury, 12 to the contralateral knee. ACL injury rates (reinjury or contralateral injury) after ACL reconstruction range from 1 in 4 (25%) to 1 in 17 (6%) after return to sport participation.³⁴⁻³⁶ Identification of biomechanical risk factors is necessary to effectively reduce the high rate of re-injury.

Return to Play Timetable

In addition to limiting intra-articular damage, restoring function and stability, the goal of ACL reconstruction is to return the patient to his or her previous level of activity as quickly and safely as possible. Failure to restore adequate range of motion, strength, and normal gait during rehabilitation often results in long-term deficits and a poorer quality of life. ACLR patients have been shown to seek treatment for symptoms of osteoarthritis 15-20 years before patients without a history of ACL reconstruction.⁵ Benyonn et al.³⁸ and Shelbourne et al.³⁹ have both demonstrated that accelerated ACLR rehabilitation (19 weeks) produces the same effects (knee laxity, clinical outcome, patient satisfaction, patient function, and proprioception) compared with a group of non-accelerated (32 weeks) rehabilitation.

Rehabilitation Phases

Preoperative Phase

There is no consensus on the correct or ideal timing of ACL reconstruction.⁵ Many patients have difficulty regaining range of motion prior to surgery; therefore, many surgeons suggest preoperative rehabilitation prior to surgery that will accelerate postoperative rehabilitation. The main goals of the preoperative phase are to reduce swelling, pain, restore full range of motion, regain neuromuscular control, and normalize gait prior to surgery.^{5,7,40,41} Another critical aspect of the preoperative phase is patient education. Informing athletes on surgeon selection, the surgical procedure, as well as the rehabilitative process are all necessary components of the preoperative phase.

Early Postoperative Phase: Day 1 – Week 4

The early postoperative phase begins during the first hours after surgery and extends to 2-4 weeks after surgery. The two main goals of early rehabilitation are achievement of full extension and regaining neuromuscular control.⁴⁰ One of the most common complications after ACL reconstruction is loss of range of motion. Restoration of motion, especially terminal knee extension is the primary goal during the first days of rehabilitation after ACL reconstruction.⁴¹ Rehabilitation that incorporates early joint motion has been found to be beneficial for reducing pain and decreasing scar tissue formation.⁴² Failure to extend the knee fully results in abnormal joint arthrokinematics and quadriceps inhibition.⁴¹ Rehabilitation and restoration of motion begin immediately after surgery with the use of a continuous passive motion machine, designed to minimize the effects of immobilization⁴³ and continues with active range of motion protocols.

In addition, an aggressive approach to controlling pain and inflammation prevents quadriceps inhibition, maintains knee extension, and allows for a quicker return to weight bearing.⁷

The trend in ACL rehabilitation is toward earlier weight bearing. Investigations have shown that immediate weight bearing does not compromise the ACL graft and may be beneficial at reducing the incidence of anterior knee pain.⁴² Patients are partial weight bearing immediately after surgery, aided by crutches and are gradually progressed to full weight bearing between days 4-14 post-operation, as leg strength improves, gait normalizes, and the patient gains confidence.^{7,40,41} Patellar mobilization as well as a combination of safe isometric and isotonic closed and open kinetic chain strengthening exercises are initiated during the first two weeks after surgery.^{7,41} Strengthening is often assisted by electrical neuromuscular stimulation to facilitate quadriceps contraction, to minimize atrophy, and to reeducate the muscle.⁴³

Criteria used to progress patients to the second phase of rehabilitation include: quadriceps control, full passive knee extension, passive range of motion 0° to 90°, normal patellar mobility compared contralaterally, minimal joint effusion, and independent ambulation, with or without crutches.^{7,40,41}

Intermediate Postoperative Phase: Week 4-12

The intermediate postoperative phase begins once patients have sufficiently completed the goals defined during the early rehabilitative phase. The primary goals during the intermediate phase are to regain full flexion and hyperextension, increase strength and neuromuscular control, improve proprioception, and achieve normal gait.⁴⁰ The intermediate postoperative phase is a critical time period because the processes of graft healing and tunnel formation are at their most vulnerable stages.^{7,40,42} Rehabilitation exercises during this phase

should be prescribed with maximal graft protection in mind.⁴³ Rehabilitation is continued from stage one, with progressions in open and closed kinetic chain exercises, as well as incorporating active motion and cardiovascular endurance through the stationary bicycle and aquatic therapy.^{39,41} Cryotherapy should be continued to address pain control and joint effusion.⁷ Flexion can be gradually increased while normal extension and patellar mobility should be maintained.⁷ Incorporation of proprioceptive drills as well as neuromuscular control exercises attempt to facilitate joint stiffness and co-contraction of the quadriceps, hamstrings, and gastroc-soleus complex at the knee. Muscular co-contraction at the knee protects the graft from anterior translation forces that could disrupt the maturation and incorporation of the graft.⁴⁰ Gait training on a treadmill to identify and correct any gait pattern impairments is essential once the patient begins full weight bearing ambulation.⁷ Deficits present in the early stages of rehabilitation will most likely persist through the late stages if not addressed.

Criteria to progress athletes to the late stage of postoperative rehabilitation include: minimal joint line or patellofemoral pain, minimal joint effusion, full extension, at least 125° of flexion, normal gait pattern, and quadriceps and hamstring strength 60% compared to contralateral side.^{7,41}

Late Postoperative Phase: Week 12 – Return to Play

Early stage ACL rehabilitation often follows strict criteria based guidelines for range of motion and exercise selection and progression. In contrast, late stage rehabilitation is typically broader with generalized categories of exercise selection and limited objective progressions.⁴⁴ During late stage rehabilitation, running and sport specific drills are initiated and functional strength and proprioception is normalized.⁴⁰ Graft fixation and maturation continues to be a

primary concern; controlled loading enhances ligament healing, while excessive loading can potentially damage the graft.⁴⁴ Shelbourne et al.³⁹ reported positive objective and subjective results in one of the first accelerated (6 month) rehabilitation and return to play studies after ACL reconstruction. Since then, the majority of ACL studies show a return to sport using an accelerated rehabilitation at 6 to 12 months.⁴⁰

Functional training and sport specific drills incorporate exercises that are relevant the athlete's sport into the rehabilitation program.⁴⁰ Neuromuscular training becomes the main focus of rehabilitation, with emphasis placed on static and dynamic stability. Patients must be trained to allow them to possess sufficient functional stability to prevent the knee from positions that are risk factors of subsequent tears or graft elongation.^{7,44} Plyometric exercises are also emphasized during late stage rehabilitation, designed to recruit the neuromuscular system and elastic properties of the muscles and joints surrounding the knee.⁴⁰ Straight line running is normally incorporated by three to four months, with duration and speed minimized to allow for neuromuscular adaptation.^{7,40} Speed and duration are increased gradually over the course of the late stage, with patient education and compliance to ensure the patient does not do too much too soon.⁴⁰ Once straight ahead running is performed successfully and without setback, variations in running, cutting, and agility activities are introduced as well as dynamic movements in the frontal and transverse planes.^{7,40}

Return to Play Criteria

There has been no specific measurable outcome criterion shown to correlate with successful return to sports in the ACL reconstructed athlete. Most clinicians use a combination of functional, clinical, and subjective testing.⁴⁰ In a systematic review, Barber-Westin et al.⁴⁵

found that 60% of studies reported time postoperatively as criteria for return to play following ACL reconstruction. Myer et al.⁴⁶ studied the deficits in strength, control, and performance of limbs in athletes cleared for return to play following ACLR. The study found that there was significant asymmetry between limbs of the ACLR group with respect to force generation (vertical jump height) and force absorption (VGRF) when compared to a control group. These results indicate that up to 11 months after surgery and after release to sport, there are still significant deficits between the reconstructed limb and the non-injured limb that are independent of time after surgery.⁴⁶ Time from surgery is a counterintuitive criterion that does not address the neuromuscular and biomechanical deficiencies that an athlete might possess.⁴⁶ There is a need for individualized objective and subjective guidelines to safely progress the ACLR athlete into their return to sport participation.

Myer et al.⁴⁴ created a 5-phase rehabilitation protocol with individual goals and criteria for progression through each phase. This criteria for return to sport included: (1) drop vertical jump landing force bilateral symmetry (within 15%), (2) T-test time (within 10%), (3) single limb average peak power test for 10 seconds (bilateral symmetry within 15%), (4) reassessment of tuck jump (20 percentage points of improvement from initial test score or perfect 80 point score).⁴⁴ Van Grinsven⁷ listed a similar 4 phase rehabilitation progression with criteria to progress to each phase. Return to sport criteria included: (1) (VAS score), no pain or swelling (2) full flexion and extension, (3) quadriceps and hamstring strength >85% compared to contralateral side, (4) Hop tests (one-legged timed hop test, single leg hop for distance, triple hop for distance) >85% compared to the contralateral side.⁷ The general consensus is that once a patient has gained full range of motion, his or her hop tests are over 85% compared to the

healthy side, his or her strength ratio of the quadriceps and hamstrings are over 85% compared to the healthy side, and the physician has cleared the athlete, they can now return to sport.^{7,40,44,47}

Although isokinetic testing and single leg hop tests are more objective measurements compared to time postoperatively, they fail to address the multi-planar motion that is characterized in a cutting task. Cutting involves frontal, sagittal, and transverse plane motion at the trunk, hip, knee, and ankle; whereas, isokinetic tests and single leg hop tests generally only assess sagittal plane motions. Initiating cutting is a very important phase of rehabilitation; however, there fails to be objective criteria that address the multi-planar movement involved in cutting in the literature. The single leg squat has been used as a valid and reliable assessment tool for the analysis of faulty movement patterns especially in regard to preventing injury at the trunk, hip, and knee.⁴⁸⁻⁵⁰ Previous research has shown kinematic and biomechanical landing differences between genders and ACLR history during cutting tasks.^{32,51-55} These differences, especially increased frontal and transverse plane motion and limited sagittal plane motion, have been shown to occur in both single leg squat and cutting tasks in these populations.^{52,54-59} Determining a correlation between the movements would help clinicians make rehabilitation progression decisions that limit injury risk.

Movement Components of the Side Step Cut

The initiation of cutting is an important part of rehabilitation and must be done safely and with objective criteria for the progression to cutting. Cutting has been one of the proposed causes of noncontact injury to the ACL.^{1,16,17} Allowing an ACLR athlete to initiate cutting prematurely can increase the risk of re-injury. Cutting in the ACLR athlete has been extensively studied. Many studies have reported that the side step cutting maneuver places a much greater

strain on the knee because of the higher moments of frontal plane motion, especially in women.^{20,33,52,54}

Sagittal Plane Motion

Malinzak et al.⁵² conducted one of the initial studies that compared knee motion during various athletic tasks between men and women. The investigators found that female subjects were demonstrated less knee flexion during cutting tasks. Females also displayed greater normalized quadriceps activation and less hamstring activation.⁵² Blackburn et al.⁶⁰ found that active trunk flexion during landing promoted more knee and hip flexion compared to a more erect trunk posture. Others have reported that during deceleration, female athletes exhibit less hip flexion.⁵⁴ Miranda et al.⁵³ compared side step cutting kinematics between males and females with ACLR to a control group. They reported that females with no history of ACL reconstruction appeared to perform the jump cut maneuver with greater landing stiffness than males with or without a history of ACLR and females with a history of ACLR.⁵³ Males and females with a history of ACLR performed the jump-cut maneuver with less energy than the control group, resulting in lower peak vertical GRF.⁵³ Coats-Thomas compared ACL intact males and females to ACL reconstructed males and females during a side step cutting task. They reported that there was a delayed peak activation of the quadriceps, hamstring, and gastrocnemius muscles after landing in ACL reconstructed men and women compared to the healthy control group. ACL reconstructed men and women also had a higher quadriceps activation compared to hamstring activation during the load phase when compared to healthy controls.⁶¹ Hanson et al.⁶² also studied muscle activation during a cutting task, comparing Division I male and female soccer players. They found that females displayed significantly greater vastus lateralis activation compared to males during the preparatory and load phase of a

cutting task, reaffirming that females cut with great quadriceps activation than males.⁶² Without co-activation of the hamstrings during cutting tasks, increased quadriceps activation puts greater load on the ACL.

Frontal Plane Motion

Several studies have reported that women have had a much greater tendency to cut with high knee abduction moments compared to men during a side step cutting task.^{32,52,55} Kristianslund et al.⁶³ compared the differences between a drop jump and a side step cut in 184 handball players. Knee abduction moments were shown to be 6 times higher in a side step cutting task compared to a drop vertical jump task. They also reported that athletes had lower knee flexion angles and higher knee valgus and internal rotation angles both at initial contact and at maximum flexion.⁶³ Jamison et al.⁶⁴ found a positive association between knee abduction moment and lateral trunk deviation during a side step cut. As the torso moves away from the cutting direction, the knee abduction moment increases. Imwalle et al.⁵¹ found that the most significant predictor of knee abduction was hip adduction during a 45° and 90° cutting task in healthy female soccer players. Females have been shown to have greater hip adductor moments during deceleration and have exhibited decreased hip extensor moments compared with male athletes, possibly attributing to their higher incidence of ACL injury.⁵⁴ Hewett et al.²⁰ found that ACLR female subjects showed greater lateral trunk and knee abduction moments at landing compared with uninjured control groups. This lack of neuromuscular trunk control and trunk stability has been reported as leading to uncontrolled knee abduction and ACL strain.

Transverse Plane Motion

Pollard et al.⁵⁴ found that when compared with male athletes, female athletes demonstrated significantly greater hip internal rotation during the early phase of the side step cutting maneuver. McLean et al.³⁰ also reported that peak knee valgus loading was directly associated with higher initial hip flexion and hip internal rotation positions. Frank et al.⁶⁵ found that internal trunk rotation displacement was the greatest predictor for knee varus moment during a cutting task in healthy athletes. Less trunk rotation displacement toward the direction of cutting and hip adduction moment were associated with greater in knee varus moment during cutting.⁶⁵

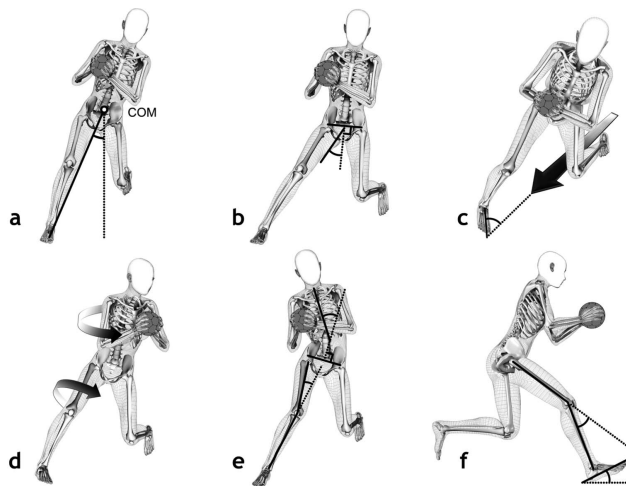


Figure 3. *Technique Factors at Initial Contact of a Cutting Task described by Kristianslund et al.*⁶⁶

Movement Components of the Single Leg Squat

The single leg squat is a closed kinetic chain exercise that can be initiated during the early stages of ACL rehabilitation. Myer et al.⁴⁴ listed the single leg squat as an exercise to improve single leg weight bearing strength and knee flexion angles during phase 1 of their return to play protocol. Wilk et al.⁴¹ also incorporated single leg stance and single leg balance during the early weeks of their rehabilitation protocol. There have been numerous studies that have

focused on the differences between men and women and various kinematic chain recruitment strategies for single leg squat completion. The single leg squat has been previously used as a screening tool for injury risk.^{50,58} Single leg stance exercises have been used as strengthening exercises for the hip, especially in regards to gluteus medius activation. The gluteus medius is the primary hip stabilizer in both the frontal and transverse planes. Inactivation or weakness of the gluteus medius results in femoral adduction and internal rotation, and an increase in medial knee displacement; risk factors for ACL injury.¹⁹ Single leg squat exercises have been shown to produce higher peak gluteus maximus and medius activation when compared to double limb stance exercises.^{67,68} Utilizing single leg squat as an assessment for functional dynamic position in athletes is important because of the ability to incorporate it into the earlier stages of ACLR rehabilitation.

Single Leg Squat as an Injury Assessment

Biomechanical analysis utilizing validated and reliable clinical screening assessment have been utilized to determine modifiable injury risk in athletes and to attempt to screen athletes for potential injury. Several studies have attempted to validate the single leg squat as an observational movement dysfunction screening assessment tool. Chmielewski et al.⁶⁹ estimated the intra and interrater reliability of the single leg squat as a movement assessment. Graders rating the movement using an ordinal grading system (poor, fair, good) resulted in good reliability between graders. However, when asked to specifically rate the movement using different body segments, reliability decreased.⁶⁹ These findings were determined to be better than chance but not high enough reliability to be used clinically. Poulsen et al.⁷⁰ also used an ordinal scale to grade single leg squat motion. Poulsen had intrarater reliability ranging from (0.38 – 0.94) and the generalized weighted kappa score for interrater reliability (0.68). Like

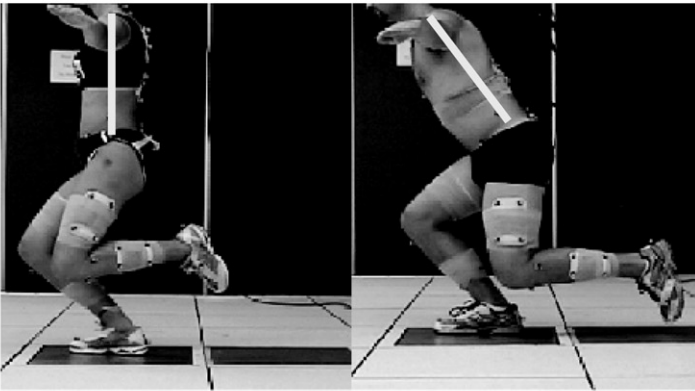
Chmielewski, Poulsen et al.'s results did not create enough reliability to exceed a minimal clinical standard. Both studies attributed their lack of reliability due to the subjective nature of the scoring and the lack of education given to the graders before evaluation. Crossley et al.⁴⁹ also used an ordinal scale to grade single leg squat performance, but had a much more developed determination of criterion to determine a good, fair, or poor squat. Using this method of assessment, Crossley et al.⁴⁹ had acceptable reliability for clinical use. Intrarater reliability ranged from ($k=0.61 - 0.80$) and interrater reliability ranged from ($k= 0.60 - 0.80$). Stensrud et al.⁵⁰ evaluated subjective assessment of subjective single leg squat and compared it to re-assessment through 2-d video analysis. Receiver operating characteristic (ROC) showed strong reliability ($AUC = 0.88 - 0.89$). Weeks et al.⁴⁸ compared 2 dimensional SLS analysis to 3 dimensional motion analysis to determine reliability between experienced clinicians and students. Intra-class correlation coefficients were calculated to estimate the reliability between the groups. Interrater reliability was good for experienced clinicians ($ICC = 0.71$) and students ($ICC = 0.60$). Intrarater reliability was excellent for experienced clinicians ($ICC = 0.81$) and good for students ($ICC = 0.71$).⁴⁸ These previous studies show that the single leg squat can be used as clinical screening tool, but there is a need for more standardized and reliable criterion for clinicians to use during grading and assessment.

Sagittal Plane Motion

Compared to males, females use significantly less trunk flexion during the descent phase of the single leg squat (Figure 3).⁵⁷ Increased trunk flexion during the single leg squat has been shown to reduce strain on the ACL by increasing hamstring force output by 35% during the single leg squat.⁷¹ Females have also shown to demonstrate more ankle dorsiflexion and hip

flexion compared to men during a single leg squat.⁵⁹ Limited dorsiflexion range of motion during the single leg squat has been shown to produce positions of medial knee displacement.⁷²

Figure 4. *Observed gender differences during the decent phase of a single leg squat task in the sagittal plane.*⁵⁷

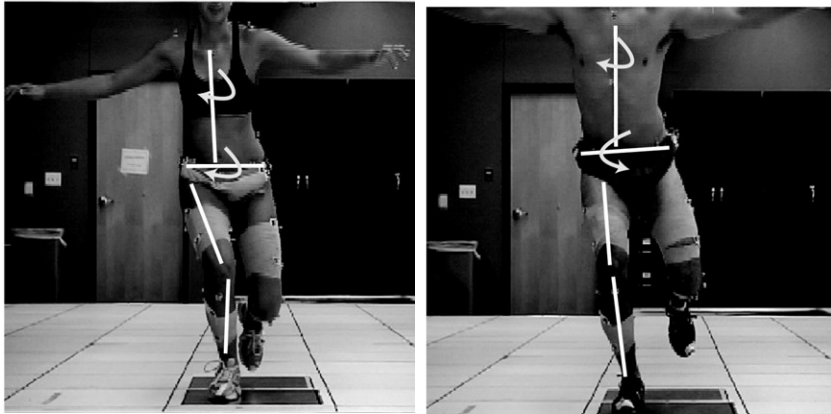


Frontal Plane Motion During the Single Leg Squat

Crossley et al.⁴⁹ were the first researchers to study that functional performance of the single leg squat could indicate hip muscle function. They found that people who had poor performance in the single leg squat task (balance, trunk, pelvis, hip, and knee positioning) were shown to have delay in hip abductor activation. This was an important finding because of the tendency for the hip to move into adduction with decreased activity of the gluteus medius, a component of the “position of no return” as described by Ireland.¹⁹ Graci et al.⁵⁷ found that females experience greater hip adduction and knee abduction at both 45° and peak knee flexion of a single leg squat task (Figure 4). Zeller et al.⁵⁹ also found that females started in a more knee valgus position and remained in a valgus position throughout the single leg squat in comparison to men. Conversely, Pantano et al.²⁹ reported that static knee valgus, especially in relation to an increased Q-Angle, did not relate to the amount of knee valgus seen during a single leg squat,

and should not be used to predict knee valgus during the task. Mauntel et al.⁷² indicated that during a single leg squat, healthy subjects who displayed medial knee displacement had a higher reliance on their hip adductors rather than an inadequate activation of the hip abductors.

Figure 5. *Observed gender differences during the decent phase of a single leg squat task in the frontal plane.*⁵⁷



Transverse Plane Motion

Limited research into transverse plane motion during the single leg squat has been reported. Graci et al.⁵⁷ reported that females rotated their trunk toward the weight-bearing limb less than males. Women have also shown significantly more ankle pronation and hip external rotation during the single leg squat.⁵⁹

Recognition of Risk Factors

The gold standard for recognizing ACL injury risk factors is in a laboratory setting using 3D motion analysis software and forceplate data. However, this method is very expensive, costing thousands of dollars to acquire all necessary equipment, and requires specialty training for clinicians. Although the gold standard, motion analysis in a laboratory lacks the feasible

practical application that clinicians are looking for when attempting to evaluate athletes with injury risk factors. There is a need for an evaluation tool that can be reliable, easily used, and practical in a real time setting.

Video analysis has become a more efficient evaluative tool popularly used in sport medicine settings to evaluate movement dysfunction and injury risk. Video analysis requires less expensive equipment is much more feasible for transportation. Padua et al.^{73,74} published the Landing Error Scoring System (LESS), which has been shown to be a valid and reliable assessment tool for recognizing ACL risk factors in athletes performing a jump-landing task during video analysis as well as real time assessment. Several other studies have also shown good inter and intra-rater reliability during single leg squat video analysis.⁴⁸⁻⁵⁰ Video analysis provides clinicians the ability to view a dynamic task in a more controlled environment and allows clinicians the ability to slow down movement and find peak positions of various joint segments when looking for injury risk that they may not see during a real time assessment.

Conclusion

Objective return to play criteria has been demonstrated as an extremely important component of ACL rehabilitation. There is very little research to determine objective requirements to initiate cutting during the rehabilitation program. Cutting involves movement in the sagittal, frontal and transverse planes that can cause much higher loads to the ACL than straight ahead running. It has also been shown that females experience these loads more than men, possibly a contributing factor to the dramatic increase in ACL injury incidence in women. The single leg squat has similar multi-plane movement components as the side step cut. Single leg squat assessment has been shown to be consistent with video analysis in analyzing frontal

plane knee motion deficits during single leg squat performance, providing a time and cost effective screening tool.^{48,50} Attempting to screen athletes through a cost and time effective screening tool assessment could help reduce risk of re-injury during return to sport.

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Introduction

Anterior cruciate ligament (ACL) injuries are one of the most debilitating injuries suffered in sport. An estimated 200,000 ACL injuries occur annually in the United States¹, a number that is likely to rise due to an increase in sport participation at young ages.^{2,3} ACL-Reconstruction (ACLR) has become the standard treatment for ACL rupture. Two-thirds of patients opt for reconstruction after ACL rupture, which rapidly becomes costly with surgery and rehabilitation estimates between \$17,000-25,000 per incidence.^{3,4} Following ACLR, athletes who are able to return to sport participation are at a high risk for ACL re-injury to both the ipsilateral and contralateral knee.⁵⁻⁹ More over, 12-year follow-up shows that the majority of ACLR patients present with early symptoms of osteoarthritis, pain, and decreased knee-related quality of life;¹⁰ reinjury increases these risks further.¹¹ Return-to-play criteria guidelines must address the reinjury risk.

The high rate of ACL re-injury, especially following return to cutting and pivoting activities, and the poor long-term health outcomes after ACLR, require better understanding of prevention strategies. Previous investigators have reported that ACL rupture is most commonly a result of a non-contact mechanism (70% of the time); other studies have reported it as high as 95%.¹²⁻¹⁴ Joint kinematics contribute to ACL injury incidence. Video analysis has described key trunk, hip, and knee moments that increase risk of ACL injury.¹⁵⁻¹⁷ In addition, frontal plane knee loading and high peak vertical ground reaction forces during landing tasks have been shown to be predictors of ACL injury, especially in female athletes.¹⁵⁻¹⁷ Landing with high peak ground reaction force, as well as lateral trunk flexion, excessive frontal plane motion, and limited lower extremity flexion increases excessive frontal plane motion and injury risk.¹⁸⁻²⁰ These modifiable risk factors have been shown to predict subsequent ACL injuries in athletes with previous

ACLR; thus, athletes may not have corrected the risk factors that put them at risk for the original injury.⁹ Therefore, it is critical to find ways to screen athletes for these specific movement characteristics that may influence injury risk.

Post-operative rehabilitation plays a critical role in returning ACLR patients to their athletic or occupational activities as soon as possible. However, to our knowledge, there is no consensus on a specific rehabilitation protocol advancing athletes back to play. Although the early phase of ACLR rehabilitation has specific and criteria-based guidelines for range of motion, exercise selection progressions and guidelines for the later stages of rehabilitation become more vague.²¹ Late stage rehabilitation movements, such as running, cutting, and jumping, expose ACLR patients to higher loads and motions that pose the greatest risk of re-injury. There is limited evidence to appropriately progress through these late stages of rehabilitation while also limiting injury risk. There have been several proposed subjective and objective return to play and rehabilitative criteria-based progression assessments.²¹⁻²³ The introduction of cutting is an important phase of the rehabilitation progression and should be initiated carefully. Both clinician and athlete should feel comfortable and confident with the strength and neuromuscular control needed to safely perform the motion in all three planes. The single leg squat has been used as a valid and reliable assessment tool for the analysis of faulty movement patterns at the trunk, hip, and knee.²⁴⁻²⁶ Kinematic and biomechanical differences in landing exist between genders and athletes with a history of ACLR history.^{16-18,27-29} These differences, especially greater frontal and transverse plane motion and limited sagittal plane motion, have been shown to occur in both single leg squat and cutting tasks in these populations.^{16,18,28,30-33} However, currently there is no valid clinical assessment tool for cutting tasks.

Therefore, the purpose of this study was to determine if there is a correlation between single leg

squat kinematics and side step cut kinematics in both healthy adults and adults with a history of ACL reconstruction.

Methods

Participants

Forty-four individuals active in cutting, jumping, or landing activities participated in this study. Twenty-two athletes had a history of ACL reconstruction (14 male, 8 female) Age, 21.7 ± 3.8 years; Height, 174.5 ± 7.2 cm; Mass, 76.2 ± 9.9 kg). 22 healthy athletes (14 male, 8 female) with no history of ACL reconstruction or any other lower extremity surgery (Age: 21.6 ± 3.6 years; height: 173.8 ± 9.2 cm; mass: 75.0 ± 10.5) served as a matched control group (TABLE 1). Participants were included if they met the following criteria: 1) had a history of ACL reconstruction (TABLE 2), 2) active in jumping, cutting, and/or landing activities, 3) and were between the ages of 13-40 years old. Twenty-two healthy participants, with no history of ACL reconstruction or any other lower extremity surgery were then recruited and matched based on their age, sex, height, mass, and activity level to the ACLR group. Participants in the HC group were excluded based on asymmetrical knee laxity, measured by the study physician using a KT-2000 during a pretesting knee assessment. Participants were recruited by verbal invitation, the UCONN LISTSERV, flyers posted on bulletin boards, and flyers distributed by email. Prior to testing sessions, informational meetings were held with all participants in which they provided informed consent to participate in the study. Forms were approved by the University of Connecticut Institutional Review Board.

The study began in October 2013 and was completed in February 2014. Participants attended a single test session, lasting 90-120 minutes in the Human Performance Laboratory at the University of Connecticut. Prior to the testing session, participants were asked to complete eight questionnaires to determine injury history, activity level, and subjective knee function ratings. Questionnaires included: 1) baseline questionnaire, 2) the International Knee

Documentation Committee (IKDC) Participant Knee form, 3) the Knee Injury and Osteoarthritis Outcome Score (KOOS) form, 4) Tegner Activity Scale, 5) Lysholm Activity Scale, and 6) Marx Activity Rating scale, 7) Tampa Scale of Kinesiophobia (TSK), and 8) the International Physical Activity Questionnaire (IPAQ).

TABLE 1

Participant Demographics		
	<i>ACLR</i>	<i>Controls</i>
Males	14	14
Females	8	8
Age, (y)	21.7±3.8	21.6±3.6
Mass (kg)	76.2±9.9	75.0±10.5
Height (cm)	174.5±7.2	173.8±9.2

TABLE 2

	Mean ± SD	Median	Range
Time Since ACLR (months)	55.7 ± 37.4	42	16 - 168

Procedures

Participants wore a t-shirt, shorts, and athletic shoes to the testing session. The participants' height, weight, and dominant leg were recorded at the beginning of the testing session. A physician that was a member of the research team evaluated and cleared participants prior to completing the study. The physician measured all participants' knee laxity using a KT-2000 prior to clearance for participation. Participants were allowed to perform a standard warm-up consisting of jogging and self-selected stretching. Participants received instructions prior to

each task and were allowed as many practice trials as necessary to feel comfortable with the task and perform it correctly. During the testing session, participants completed two separate tasks: 1) a single leg squat, and 2) a side step cut. Tasks were performed in random order.

Single Leg Squat

Participants began the single leg squat on the force plate, standing on one leg, with their hands on their hips, and their knee in full extension. Participants were instructed to squat as if they were sitting in a chair and then return to the starting position. Participants were instructed to do this task for five consecutive repetitions. Participants completed the single leg squat task on both legs.

Side Step Cut

Participants began the side step cut task on a 30 cm high box. Participants were asked to jump off of the box a distance of half their body height, land with their foot in a target area, and perform a sixty degree cut towards their contralateral side. This distance provided a small challenge to the participant but was not so challenging as to be difficult to perform. Cone markers were placed to indicate the desired 60⁰ cut angles. Participants were asked to perform this task two consecutive times on each leg.

Two standard digital cameras on tripods were stationed 48 inches about the ground approximately 12 feet from the jump box to capture frontal and sagittal plane motion of both tasks. Two digital cameras videotaped all movement and clinical balance tests, one in the front of the participant and one to the left of the participant in order to capture both frontal and sagittal plane images. The tasks were graded at a later date from the videotapes. Some of the items were assessed at the moment of initial contact with the ground, while others were assessments of

motion in the few seconds following initial ground contact. These included: 1) trunk, hip, and knee flexion sagittal plane motion (peak angle and displacement) 2) trunk, hip, and knee frontal plane motion (peak angle and displacement) 3) trunk, hip, knee, and foot transverse plane motion (peak angle and displacement) and overall impression of squat and cutting “quality.” All of these items can be reasonably expected to be associated with an increased force on the ACL.

Instrumentation

An electromagnetic motion analysis system Trackstar; Ascension Technologies, Inc., Burlington, VT) synchronized with a non-conductive force plate (model 4060-NC; Bertec Corporation, Columbus, OH) collected three-dimensional lower extremity kinematics and kinetics at sampling frequencies of 144 Hz and 1440 Hz, respectively, during the movement tests. Six electromagnetic sensors were placed and secured with double-sided tape bilaterally on the anteromedial tibia, lateral thigh, and on the sacrum and thorax. Eight bony landmarks were digitized to determine joint centers¹ using a stylus with a seventh sensor attached: medial and lateral malleoli, medial and lateral femoral epicondyles, bilateral anterior superior iliac spines, T12/L1 spinous process, and C7 spinous process. Three-dimensional coordinates of the lower extremity and trunk were estimated using MotionMonitor software (Innovative Sports Technology, Chicago, IL). Euler angles calculated joint angles of the knee, hip and trunk. All kinematic data was filtered with a fourth-order low-pass Butterworth filter at 14.5 Hz. Kinematic and kinetic data were reduced using a customized software program to determine joint angles at initial contact, peak and minimum joint angles, and peak and minimum joint kinetics.

Data Reduction and Analyses

The averages across the trials were calculated for peak, minimum, and displacement for kinematic and kinetic variables associated with the movement tests. Three dimensional peak trunk, hip, and knee angles were determined during the stance phase of the sidestep cutting task. The stance phase was defined as the time period between initial contact with the force plate until takeoff for the rebound jump. Initial contact was defined as when vertical ground reaction force exceeds 10 N. Takeoff was identified as the time when vertical ground reaction force drops below 10 N. Peak vertical ground reaction force and joint moments for trunk flexion-extension, trunk lateral flexion, trunk rotation, hip flexion-extension, hip abduction-adduction, hip internal-external rotation, knee flexion-extension, knee valgus-varus, and knee internal-external rotation, and medial knee displacement were also determined during the stance phase. The peak vertical ground reaction force was normalized to body weight (N) for each participant's (% body weight).

The limb with the most recent ACL reconstruction was used as the testing limb in the ACLR group. Healthy control limbs were then determined based on the limb dominance of the ACLR limb. Limb dominance was determined by what foot the participant felt they could kick a ball farthest with. The association between tasks was analyzed using Pearson correlation coefficients. P level was set at a priori of < 0.05 for all variables. Independent sample T-tests were then used to evaluate any significance between groups. All data were analyzed using SPSS (version 21.0, SPSS Inc, Chicago, Illinois).

1. Bell AL, Pedersen DR, Brand RA. A comparison of the accuracy of several hip center location prediction methods. *J Biomech*. 1990;23(6):617–621.

RESULTS

We observed numerous correlations for dependent variables during the single leg squat and cutting task ($P<0.05$) (TABLE 10-11). We also observed several significant differences between the healthy and ACLR groups during both tasks (TABLE 3-8). During the single leg squat, the ACLR group displayed less sagittal plane motion, specifically: peak hip flexion ($P=0.02$), hip flexion displacement ($P=0.04$), knee flexion displacement ($P=0.01$), and trunk flexion displacement ($P=0.03$). During the cutting task, participants in the ACLR group possessed lower VGRF ($P<0.001$), less knee ($P=0.03$) and hip ($P=0.04$) flexion at initial contact, as well as less peak hip ($P=0.03$) and trunk ($P=0.04$) flexion (FIGURE 6-8).

DISCUSSION

The findings of this study indicate that single leg squat (SLS) kinematics are highly correlated with movements during side step cutting (SSC) in both healthy individuals and individuals with a history of ACLR, which support our hypotheses (TABLE 9). Evaluating movement patterns during a SLS may enable clinicians to predict movement pattern dysfunctions during more dynamic, sport-specific movements. Utilizing the SLS as a clinical assessment tool to evaluate injury risk may enhance injury prevention and rehabilitation efforts.

Medial motion of the knee joint, as measured by two-dimensional medial knee displacement (MKD) and three-dimensional knee valgus are often implicated during lower extremity injury mechanisms^{7,34,35} and, consequently, are a focus of clinical evaluations. Knee valgus motion and torque also predict future ACL injury risk.³⁶ This motion may be a movement compensation that leads to abnormal loading throughout the hip and knee joints as it likely results from a combination of hip adduction, hip internal rotation, tibial abduction, tibial internal rotation, and ankle eversion.³⁵ Our findings demonstrate that participants who perform a cutting task with excessive MKD, or knee valgus, also demonstrate these motions during a single leg squat. This combination of uncontrolled movement at the hip, knee, and ankle may increase future injury risk.^{7,12} Mauntel et al.³⁷ found that participants who had MKD during a SLS utilized the hip adductor muscles to a greater extent and possessed limited passive ankle dorsiflexion compared to those who did not display MKD.³⁷ Padua et al.³⁴ reported similar findings during a double leg squat. Inactivation or weakness of the gluteus medius results in adduction and internal rotation at the hip and increased MKD.²⁶ Addressing the gluteus/adductor activation ratio through gluteal strengthening and adductor inactivation as well as increasing dorsiflexion range of motion should be emphasized during rehabilitation and injury prevention.

Focusing on these issues may allow for reduced MKD during SLS, which may translate to biomechanics during dynamic cutting tasks and reduce injury risk.³⁷

In addition to MKD, other movements during the SLS (ie. hip adduction, lateral trunk flexion, and trunk, hip, and knee rotation displacement) also predicted MKD during the cutting task. These variables were also correlated between the SLS and SSC. Poor hip and trunk neuromuscular control may result in excessive knee joint loading. Hip adduction may be an important clinical variable to evaluate during a SLS as it has been shown during a jump landing to predict future ACL injury risk.³⁸ Trunk rotation away from the direction of the cut, hip internal rotation, and knee internal rotation have also been shown to be predictors of ACL loading in previous research.^{18,20,27,29,39} Trunk control has recently been more extensively studied on its role in ACL injury.^{20,40,41} Limiting rotation at the trunk may inhibit the “turn-key” mechanism described by Frank et al.⁴⁰ that exaggerates knee transverse plane motion seen during higher intensity movements. Limiting trunk rotation and lateral flexion, as well as emphasizing moderate trunk flexion during the squat may be a critical aspect of ACL injury prevention. This movement pattern should then be conveyed into more dynamic movement cutting progressions with an emphasis placed on teaching athletes to cut with their trunk facing their new direction of travel.

Hip and knee sagittal plane motion during the SLS was only moderately correlated with motion during the cutting task in the ACLR group, but not in the HC group. These findings were in contrast to our hypotheses, and we believe may be a result of the generally limited amount of sagittal plane motion utilized in a cutting task compared to the SLS. On average, our participants performed the SSC task with approximately 50-60 degrees less knee flexion and 20-30 degrees less hip flexion compared to the SLS. We may have only observed the moderate correlation for

the ACLR group because these participants completed the SLS with significantly less hip and knee flexion compared to the healthy group with relatively more variability. This inherent variability within the ACLR group may positively influence the ability to see the relationship between flexion utilized between the two tasks. We believe evaluating sagittal plane motion during a SLS may still be clinically important for both healthy and ACLR populations since it may represent limitations in other neuromuscular factors, such as quadriceps strength and ankle dorsiflexion motion^{37,42}, but this motion appears unrelated to motion that occurs during a cutting task. In contrast, to our knowledge, no research has implicated sagittal plane motion or forces during a cutting task with injury risk. Instead of absorbing force through flexion, individuals may rely on frontal and transverse plane motion to change direction during cutting tasks and future research should further evaluate the role of sagittal plane motion during sidestep cutting on injury risk.

Our ACLR population was very diverse; participants ranging from 16 months to 14 years since their reconstruction. Though our ACLR group had all been cleared and were active in sports requiring landing and change of direction, we observed significant group difference between the ACLR and HC groups in each task. These group differences may be influential factors that contribute to the high rate of ACL reinjury.⁶ The ACLR group displayed significantly less peak sagittal plane motion and sagittal plane displacement in both tasks and at initial contact during the cutting task. Previous research has shown that increased landing stiffness, characterized by limited trunk, hip, and knee flexion place individuals at risk for ACL injury.^{12,43-45} Lack of sagittal plane motion in the ACLR group shows that the ACLR participants were not absorbing force during their cutting task. However, we found that the ACLR group had less normalized VGRF during the cut compared to the HC group. This is especially alarming

because the ACLR group chose to cut with less effort and still were unable absorb this reduced force using sagittal plane motion compared to the healthy controls. Our VGRF results are similar to those published by Miranda et al.¹⁷ and Paterno et al.⁴⁶ Miranda et al. reported reduced VGRFs during a cutting task in their ACLR group compared to healthy controls and Paterno et al. reported reduced VGRFs in an ACLR participants' injured limb compared to their uninjured limb. History of ACLR seems to be continuously showing that athletes, regardless of time from surgery, are unable to cut and absorb forces through sagittal plane motion on their injured limb. ACLR athletes may be choosing to absorb force in other planes of motion, which we saw in our results. Quadriceps strength impairment is a consequence after ACL injury,^{47,48} most likely due to arthrogenic muscular inhibition seen after ACLR.⁴⁹ Clinicians need to assess side-to-side asymmetrical force production and absorption differences in their athletes before making return to play decisions. We also observed trunk rotational differences between groups. Participants with a history of ACLR rotated their trunk away from the direction of the cut compared to the healthy controls. Trunk rotation away from the direction of the cut has been shown to further increase frontal plane knee loading, which may increase ACL injury risk.⁴⁰ These group differences reiterate previous research showing that individuals with ACLR history continue to possess modifiable differences regardless of time from surgery.⁵⁰

Currently, there are few objective criteria to determine when ACLR patients can safely advance to cutting and pivoting progressions during rehabilitation and return to play.²³ Examples of objective measures used are: circumferential thigh girth measurement, goniometry, functional performance hop tests, and isokinetic tests. There has also been a push in sports medicine for patient oriented outcomes to capture their health-related quality of life after injury. The Visual Analog Scale (VAS) and the International Knee Documentation Committee Subjective Form

(IKDC) have been used to determine subjective outcomes after knee injury.²¹⁻²³ The consensus is a patient can return to sport once they have gained full knee range of motion, their hop tests are over 85% compared to the healthy side, their strength ratio of the quadriceps and hamstrings are over 85% compared to the healthy side, and the athlete has been cleared by their physician.²¹⁻²³

The aforementioned assessments address knee pain, function, force generation, and sagittal plane strength; however, they fail to address the multi-planar motion involved in cutting, one of the proposed mechanisms of ACL (re)injury.^{2,12,51} Allowing patients to progress to late stage rehabilitative movements based on a time criteria and not neuromuscular strength and postural control, fails to take into account the individuality of ACL rehabilitation. Each patient rehabilitates and gains functional control at a different rate; therefore patients need an individualized strength and control assessment during their return to play progression. Our findings have determined that there is no longer a need for a cutting screening assessment. Clinicians can use real time or two-dimensional video analysis of a SLS and can accurately predict movement biomechanics during a cut.

Understanding that athletes who perform a SLS with increased MKD, lateral trunk flexion, hip adduction/abduction, and trunk/hip rotation are at risk for increased ACL loading can allow clinicians to screen athletes who do not possess the neuromuscular control to correctly perform a cutting task, reducing the high rate of ACL reinjury.^{6,7} Reducing injury risk during rehabilitation of ACL reconstruction or correcting neuromuscular deficiencies through injury prevention is a goal that all clinicians, coaches, and athletes share. The SLS should be utilized as an assessment as well as a strengthening, balance, and control exercise during injury prevention, especially in athletes rehabilitating from ACLR. Several studies have found that neuromuscular

and strength training have improved performance as well as landing biomechanics.^{45,52,53} The three planar control that the SLS requires properly prepares athletes for a cutting return to sport progression.

Our study simply shows that the way an individual, with or without a history of lower extremity surgery, controls their movement during a single leg squat indicates their control during a cutting task. Our study does not indicate whether improvement in single leg squat control would result in improvements in cutting mechanics. Further research should therefore evaluate if improvement in dynamic control and range of motion during the single leg squat also improves control and motion during cutting tasks in both a healthy and ACLR population. This study's implications to sport participation are also limited because we used an anticipated cutting task, which allowed us to see how our participants' chose to move and allowed us to better standardize the task. Houck et al. found that frontal plane knee moments were significantly higher during an unanticipated cutting task when compared to an anticipated task.⁵⁴ The loads placed on our participants were therefore most likely less than the loads required during an unanticipated or spontaneous cut that they face during normal sport participation because they were able to plan their movement. There is also limited research comparing movement strategies between individuals with a history of ACLR and matched controls during a single leg squat. Further studies need to continue exploring differences in SLS, cutting, and landing strategies between healthy and ACLR groups.

Conclusion

Readiness to return to cutting during return to sport participation is a clinical decision that needs to be made with objective criteria. Currently, there are insufficient guidelines for screening

whether ACLR patients have the proper neuromuscular control needed to safely return to cutting progressions. Increased dynamic movement such as cutting and pivoting puts athletes at a higher risk for injury or reinjury⁶; evaluating and predicting movement can enable clinicians to limit injury risk. Our results suggest that lack of frontal and transverse plane trunk, hip, and knee control during the SLS resulted in positions of increased lateral trunk flexion, hip adduction, and MKD during a cutting task; which have all been shown to be significant predictors of ACL loading during dynamic cutting tasks.^{19,20,36,54} Utilizing the SLS as a screening tool for injury risk can help clinicians make rehabilitative progression decisions based on objective criteria.

APPENDIX

TABLE 3. Means \pm SD *Indicates Significant Difference

Task	Sagittal Plane	ACLR	HC
SLS	Trunk Flexion	23.95 \pm 16.11	25.51 \pm 14.28
SLS	Trunk Flexion Displacement*	-11.78 \pm 6.31	-17.33 \pm 8.30
SLS	Hip Flexion*	-55.90 \pm 21.57	-72.33 \pm 18.79
SLS	Hip Flexion Displacement*	-49.63 \pm 16.30	-60.40 \pm 13.90
SLS	Knee Flexion	64.42 \pm 16.33	72.33 \pm 9.89
SLS	Knee Flexion Displacement*	-60.69 \pm 12.57	-69.86 \pm 10.25

TABLE 4. Means \pm SD *Indicates Significant Difference

Task	Frontal Plane	ACLR	HC
SLS	Lateral Trunk Flex Away Stance Leg	4.10 \pm 6.14	4.33 \pm 4.76
SLS	Lateral Trunk Flex Toward Stance Leg	4.85 \pm 7.69	5.52 \pm 4.80
SLS	Lateral Trunk Flexion Displacement	0.70 \pm 5.69	1.15 \pm 6.73
SLS	Hip Adduction	7.52 \pm 8.97	9.19 \pm 9.06
SLS	Hip Abduction	13.42 \pm 12.54	
SLS	Hip Adduction Displacement	5.89 \pm 17.96	
SLS	MKD	0.124 \pm .093	.099 \pm .104
SLS	Knee Valgus	1.46 \pm 8.08	4.74 \pm 10.57
SLS	Knee Varus	5.23 \pm 10.42	3.66 \pm 6.52
SLS	Knee Valgus Displacement	3.68 \pm 11.28	-1.09 \pm 13.60

TABLE 5. Means \pm SD *Indicates Significant Difference

Task	Transverse Plane	ACLR	HC
SLS	Trunk Rotation Toward Stance Leg	2.80 \pm 13.47	-.531 \pm 7.15
SLS	Trunk Rotation Away Stance Leg	4.29 \pm 11.17	-.674 \pm 6.95
SLS	Trunk Rotation Displacement	1.49 \pm 6.19	-.057 \pm 8.58
SLS	Hip IR	6.92 \pm 10.27	6.64 \pm 10.05
SLS	Hip ER	9.90 \pm 11.24	7.30 \pm 7.97
SLS	Hip Rotation Displacement	2.98 \pm 10.42	.699 \pm 11.25
SLS	Knee IR	-1.19 \pm 9.33	.988 \pm 8.44
SLS	Knee ER	0.69 \pm 10.03	.067 \pm 9.28
SLS	Knee Rotation Displacement	3.52 \pm 9.00	-.921 \pm 12.14

TABLE 6. Means \pm SD *Indicates Significant Difference

Task	Sagittal Plane	ACLR	HC
Cut	VGRF*	2.23 \pm .34	2.88 \pm 0.54
Cut	Trunk Flexion	23.27 \pm 7.50	25.97 \pm 12.73
Cut	Trunk Flexion Disp	11.71 \pm 5.00	11.82 \pm 5.67
Cut	Trunk Flexion IC	12.73 \pm 7.77	15.96 \pm 10.02
Cut	HipFlexion IC*	-24.96 \pm 13.23	-32.61 \pm 10.22
Cut	Hip Flexion Disp	10.20 \pm 4.70	12.92 \pm 6.23
Cut	Hip Flexion*	-29.38 \pm 16.39	-39.30 \pm 11.58
Cut	Knee Flexion IC*	11.45 \pm 11.52	17.70 \pm 8.70
Cut	Knee Flexion	43.64 \pm 14.55	47.78 \pm 11.61
Cut	Knee Flexion Disp	32.95 \pm 8.78	33.07 \pm 11.18

TABLE 7. Means \pm SD *Indicates Significant Difference

Task	Frontal Plane	ACLR	HC
Cut	Lateral Trunk Flex Away Stance Leg	3.85 \pm 7.20	5.09 \pm 8.10
Cut	Lateral Trunk Flexion Displacement	9.02 \pm 5.83	11.37 \pm 4.86
Cut	Lateral Trunk Flex Toward Stance Leg	6.88 \pm 8.71	5.59 \pm 9.68
Cut	Lateral Trunk Flexion IC	1.09 \pm 7.24	.484 \pm 6.79
Cut	Hip Adduction IC	-5.81 \pm 7.57	-9.71 \pm 7.82
Cut	Hip Adduction	-.2.91 \pm 8.70	-8.69 \pm 8.60
Cut	Hip Adduction Displacement	11.87 \pm 4.65	10.59 \pm 6.08
Cut	Hip Abduction	0.10 \pm 11.03	-6.05 \pm 9.78
Cut	MKD	.122 \pm .117	.100 \pm .109
Cut	Knee Valgus IC	-2.30 \pm 5.93	-1.32 \pm 5.10
Cut	Knee Valgus	-1.44 \pm 8.30	-1.44 \pm 7.38
Cut	Knee Valgus Displacement	6.75 \pm 5.35	7.06 \pm 3.21
Cut	Knee Varus	-1.64 \pm 7.74	-1.34 \pm 7.26

TABLE 8. Means \pm SD *Indicates Significant Difference

Task	Sagittal Plane	ACLR	HC
Cut	VGRF*	2.23 \pm .34	2.88 \pm 0.54
Cut	Trunk Flexion	23.27 \pm 7.50	25.97 \pm 12.73
Cut	Trunk Flexion Disp	11.71 \pm 5.00	11.82 \pm 5.67
Cut	Trunk Flexion IC	12.73 \pm 7.77	15.96 \pm 10.02
Cut	HipFlexion IC*	-24.96 \pm 13.23	-32.61 \pm 10.22
Cut	Hip Flexion Disp	10.20 \pm 4.70	12.92 \pm 6.23
Cut	Hip Flexion*	-29.38 \pm 16.39	-39.30 \pm 11.58
Cut	Knee Flexion IC*	11.45 \pm 11.52	17.70 \pm 8.70
Cut	Knee Flexion	43.64 \pm 14.55	47.78 \pm 11.61
Cut	Knee Flexion Disp	32.95 \pm 8.78	33.07 \pm 11.18

FIGURE 6. Sagittal plane group differences in SLS kinematics

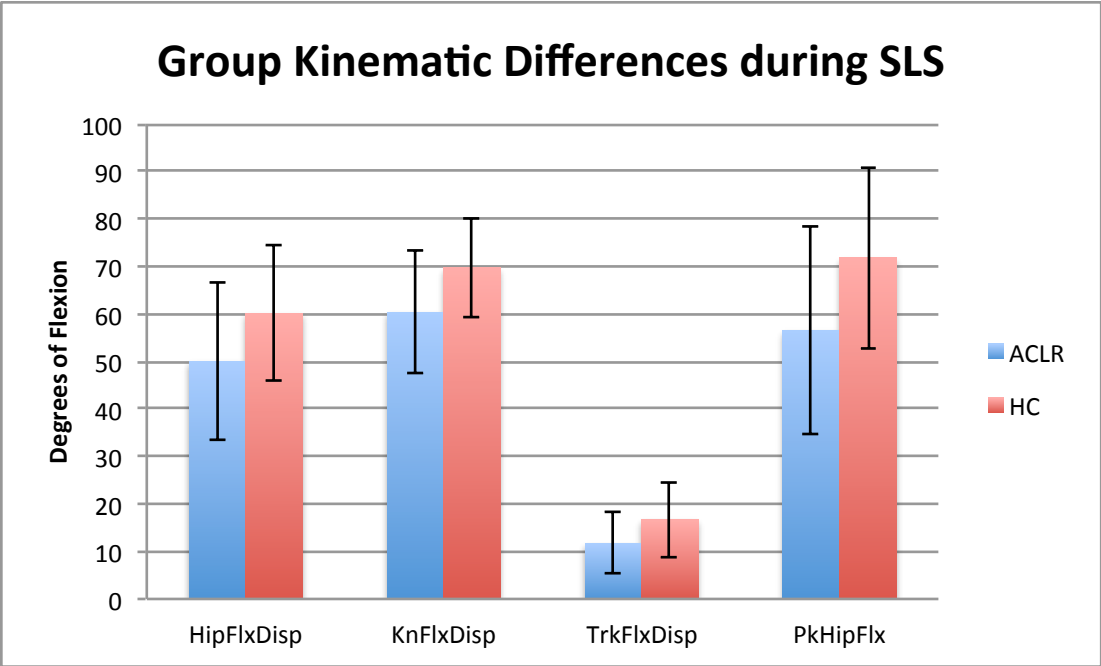


FIGURE 7. Sagittal and transverse plane group differences in SSC kinematics

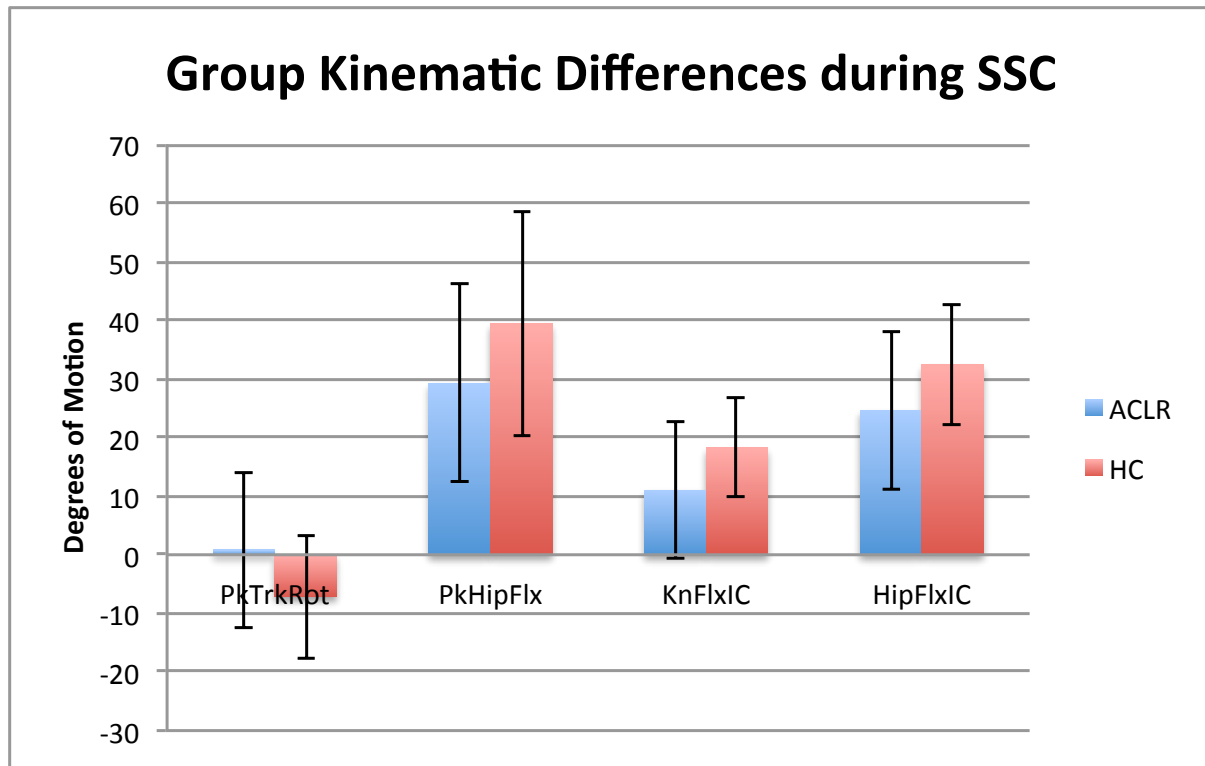


FIGURE 8. VGRF group differences during the SSC

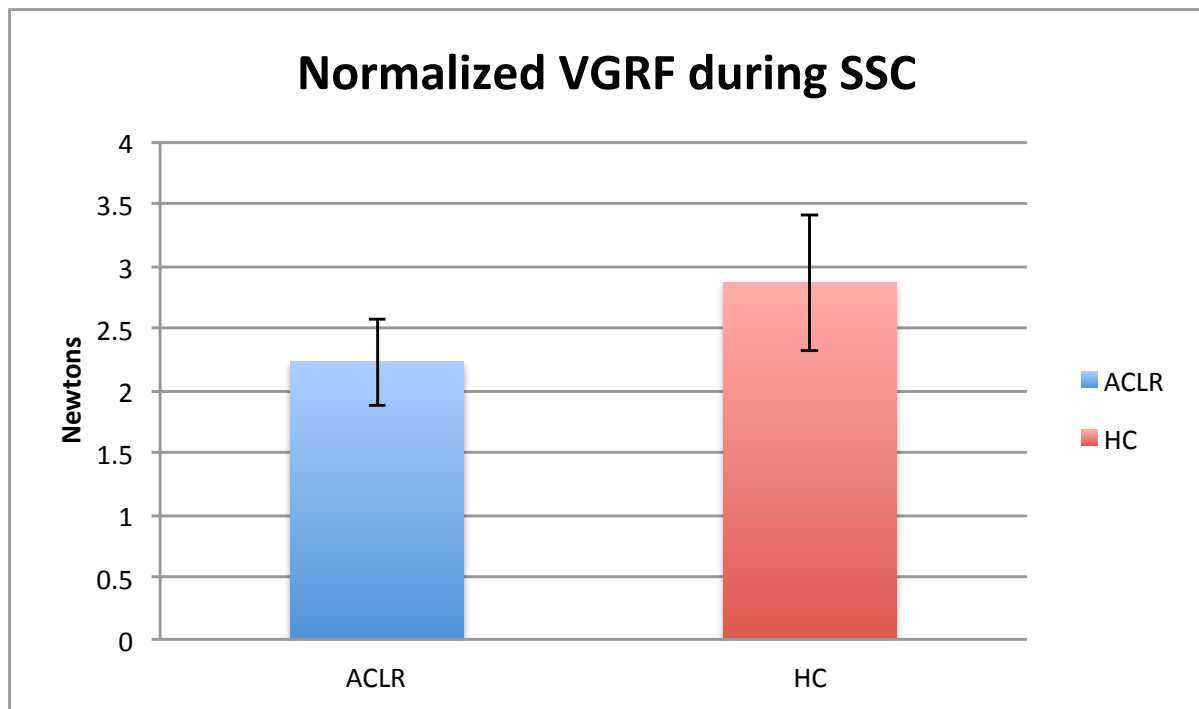


TABLE 9. Significant research question correlations between tasks

Research Question	ACLR				Research Question	Healthy Controls			
	Cut Variable	SLS Variable	R-value	P-value		Cut Variable	SLS Variable	R-value	P-value
Strong Correlations									
2g	MKD	MKD	0.89	<.001	1g	MKD	MKD	0.89	<.001
2i	Hip ER	Hip ER	0.80	<.001	1j	Knee ER	Knee ER	0.79	<.001
2i	Hip IR	Hip IR	0.71	<.001	1j	Knee IR	Knee IR	0.75	<.001
Moderate Correlations									
2d	Knee Flexion	Knee Flexion	0.63	0.002	1i	Hip IR	Hip IR	0.61	0.002
2h	Trunk Rot Away Stance Leg	Trunk Rot Away Stance Leg	0.60	0.005	1h	Trunk Rot Away Stance Leg	Trunk Rot Away Stance Leg	0.58	0.004
2b	Trunk Flexion	Trunk Flexion	0.60	0.007	1h	Trunk Rot Toward Stance Leg	Trunk Rot Toward Stance Leg	0.51	0.014
2j	Knee ER	Knee ER	0.59	0.006	1f	Hip Adduction	Hip Adduction	0.59	0.003
2f	Hip Adduction	Hip Adduction	0.56	0.01	1i	Hip ER	Hip ER	0.53	0.011
2j	Knee IR	Knee IR	0.52	0.02	1g	Knee Valgus	Knee Valgus	0.66	0.001
2c	Hip Flexion	Hip Flexion	0.52	0.02					
Weak Correlations									
2a	VGRF	Knee Flexion	0.44	0.04	1e	Lat Trunk Flex Away Stance Leg	Lat Trunk Flex Away Stance Leg	0.46	0.027

TABLE 10.

<i>Strong Correlations of SLS to SSC Kinematics in Healthy Controls</i>			
SLS	Cut	R Value	P Value
<i>Strong Transverse Plane Correlations</i>			
Hip Rotation Disp	Trunk Rot Toward Stance Leg	0.795	<.001
Knee ER	Knee ER	0.79	<.001
Knee Rotation Disp	Trunk Rot Toward Stance Leg	0.766	<.001
Knee IR	Knee IR	0.745	<.001
Hip IR	Knee ER	-0.739	<.001
<i>Strong Frontal Plane Correlations</i>			
MKD	MKD	0.89	<.001
Knee Valgus Disp	MKD	0.877	<.001
Hip Adduction Disp	MKD	0.875	<.001
Trunk Lateral Flexion Disp	MKD	0.856	<.001
Hip Abduction	MKD	0.816	<.001
Knee Valgus	MKD	-0.717	<.001
<i>Strong Multiplanar Correlations</i>			
Hip Rotation Disp	MKD	0.918	<.001
Knee Rotation Disp	MKD	0.882	<.001
Trunk Rotation Disp	Trunk Rot Toward Stance Leg Disp	0.831	<.001
Trunk Rotation Disp	MKD	0.823	<.001
Hip Adduction Disp	Trunk Rot Toward Stance Leg	0.82	<.001
MKD	Trunk Rot Toward Stance Leg	0.804	<.001
Trunk Lateral Flexion Disp	Trunk Rot Toward Stance Leg	0.787	<.001
Knee Valgus Disp	Trunk Rot Toward Stance Leg	0.774	<.001
Hip Abduction	Trunk Rot Toward Stance Leg	0.759	<.001
Hip IR	Knee Valgus	0.702	<.001
Hip Rotation Disp	Hip Adduction	-0.716	<.001

TABLE 11.

<i>Strong Correlations of SLS to SSC Kinematics in Individuals with a History of ACLR</i>			
SLS	Cut	R Value	P Value
<i>Strong Transverse Plane Correlations</i>			
Hip ER	Hip ER	0.8	<.001
Trunk Rot Toward Stance Leg	Trunk Rotation IC	0.77	<.001
Hip IR	Hip IR	0.71	<.001
Hip Rotation Disp	Trunk Rot Away Stance Leg	-0.72	0.001
Trunk Rotation Disp	Trunk Rot Away Stance Leg	-0.79	<.001
<i>Strong Frontal Plane Correlations</i>			
MKD	MKD	0.894	<.001
Hip Abduction	Hip Abduction	0.72	<.001
Knee Varus	Knee Varus	0.71	<.001
MKD	Hip Abduction	0.7	0.001
Lateral Trunk Flex Toward Stance Leg	Lateral Trunk Flex Toward Stance Leg	0.7	<.001
Hip Adduction	Lateral Trunk Flex Toward Stance Leg	-0.702	0.001
<i>Strong Multiplanar Correlations</i>			
Hip Abduction	Trunk Rot Away Stance Leg	-0.747	<.001
Hip Adduction Disp	Trunk Rot Away Stance Leg	-0.766	<.001
MKD	Trunk Rot Away Stance Leg	-0.794	<.001

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