EFFECT OF QUADRICEP STRENGTH SYMMETRY ON KNEE JOINT SYMMETRY DURING SLS IN ACLR AND HEALTHY INDIVIDUALS

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A tear of the anterior cruciate ligament (ACL) is one of the most common and costly injuries for active adults and athletes. This injury causes short- and long-term problems economically through increased health care costs and physically through delayed playing time and early-onset knee osteoarthritis (OA). Athletes returning to high level sports after ACL reconstruction are over four times more likely to reinjure the reconstructed ACL(ACLR) than athletes at lower levels. Risk factors for reinjury are an area of interest for researchers in order to minimize this short-term burden. The high rates of a second ACL tear suggest current inadequate return-to-play (RTP) criteria which focuses on establishing symmetry between the injured and uninjured limb mainly through clinical hop tests and self-reported function surveys such as the KOOS and IKDC. However, to date, the only significant risk factors for a second ACL injury are time after an ACLR and quadricep strength symmetry. Quadricep strength symmetry is most commonly assessed using a dynamometer. However, these devices are not typically found in clinical settings. Thus, a clinically applicable movement that could ultimately be added to the RTP criteria to assess quadricep strength asymmetry is the single leg squat (SLS). **PURPOSE:** The purpose of this study was to determine the effect of quadriceps strength LSI on knee joint biomechanics LSI during a single leg squat in ACLR and healthy individuals. **METHODS:** A two cohort (ACLR and healthy) within-groups study design was used to assess the purpose of this study. ACLR individuals (n=10) filled out the KOOS self-report survey. Both healthy (n=10) and ACLR underwent the single leg hop for distance, triple leg hop for distance, and 6m timed hop on both limbs. All participants were then strength assessed on the quadriceps for both limbs using a dynamometer; isometrically at 60 degrees. Lastly, using a 10-camera motion capture system, participants completed 5 SLS per limb as well as a landing task from 75% their maximal hop distance. **RESULTS:** ACLR participants were split into two groups: those with >90% quadricep strength symmetry and those with <90% quadricep strength symmetry. All groups achieved an average hop distance LSI of greater than 90%. There was no effect within group or between group for any of the biomechanical measurements (peak knee flexion angle, peak knee extensor torque, total knee mechanical work) during the SLS. There were not any strong correlations between quadricep strength LSI and peak knee extensor torque or total mechanical work during the SLS. **CONCLUSION:** The SLS functional task was not sensitive enough to detect isometric quadricep strength deficiencies. Individuals in all groups appeared to move similarly through the SLS, both through the biomechanical LSIs but also joint contributions of the hip, knee, and ankle. The only distinction that the <90% ACLR group had from the other two groups was their peak knee extensor torques normalized to body mass during the isometric contractions. They displayed a 2.0 Nm/kg normalized torque for both limbs, while both the >90% ACLR and healthy controls displayed a 3.0 Nm/kg normalized torque for both limbs. This overall suggested that future studies should look at both limbs reaching functionality and strength before RTP, with functionality being defined by absolute values, not the contralateral limb in comparison to the ipsilateral limb.

Effect of Quadricep Strength Symmetry on Knee Joint Symmetry during SLS in ACLR and Healthy Individuals

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Table of Contents

List of Tables

List of Figures

Chapter 1- Introduction

A tear of the anterior cruciate ligament (ACL) is one of the most common and costly injuries for active adults and athletes. It is estimated around 200,000 individuals in the United States suffer an ACL tear annually. (Mather et al., 2013). This injury causes short- and long-term problems economically through increased health care costs and physically through delayed playing time and early-onset knee osteoarthritis (OA). (Mather et al., 2013) A main long-term burden for ACL injured individuals would be the higher prevalence of knee OA later in life. As high as 50-90% of those with ACL injuries are diagnosed with post-traumatic knee osteoarthritis (OA). (Wang et al., 2020) A major short-term burden of the initial injury is the risk for a second ACL injury. Athletes returning to high level sports after ACL reconstruction are over four times more likely to reinjure the reconstructed ACL than athletes at lower levels. Risk factors for reinjury are an area of interest for researchers in order to minimize this short-term burden. (Grindem et al.,2016) The primary treatment to restore knee joint stability and return the player back to sport is an ACL reconstruction. However, after reconstruction and returning to sport, the risk for a second ACL injury is a staggering 15 times higher than an individual who has never sustained an ACL injury. (Paterno et al., 2012)

The high rates of a second ACL tear suggest current inadequate return-to-play (RTP) criteria. Much of the RTP criteria focuses on establishing symmetry between the operated limb and non-operated limb. (Grindem et al., 2016) Limb symmetries are established through functional hop test batteries as well as quadriceps and hamstring strength. Self-reported subjective measures of symptoms, function, and quality of life also comprise the RTP criteria. (Grindem et al., 2016) Despite significantly lower single leg hop distance symmetry of

90.01±9.46% at 9 months after ACLR than 96.30 ± 6.46% for 24 months post ACLR, patients are still typically medically cleared to RTP at 6 to 9 months. (Curran et al.,2020) This suggests an inadequate clearing of patients to return to activity. However, to date, the only significant risk factors for a second ACL injury are time after an ACLR and quadricep strength symmetry but not functional hop test symmetry. (Grindem et al.,2016)

It has never been shown in the literature that functional hop test symmetries were significant on their own in predicting a risk for a second ACL injury. The main factor assessed in the functional hop tests is symmetry of >90% for the involved vs non-involved limb. This symmetry assessment may not be appropriate in fulfilling RTP criteria because 37% of ACLR patients and 38% of healthy controls demonstrate symmetry <90% in the single leg hop functional tests. (Wren et al., 2018) This indicates that healthy controls and ACLR patients have similar rates of asymmetry likelihood. This could be due to ACLR patients naturally relying on joint contributions from other joints to complete the hopping tasks. In addition, despite symmetrical single leg hop distances, compensatory movement patterns are evident through a decreased range of motion of the knee and increased ROM at the hip and ankle on the reconstructed limb when compared to the non-reconstructed limb. (Orishimo et al., 2010) This shows that some individuals adjust how they move to accomplish functional tasks and achieve bilateral symmetry in order to compensate for their reconstruction and recovering limb.

While functional hop assessments are used to measure hop distance symmetry between limbs, the risk factors for a second ACL injury include quadricep strength asymmetry and time since reconstruction. (Grindem et al., 2016) It was found that for every one percentage point increase in strength symmetry of the quadriceps, the reinjury rate was reduced by 3%. (Grindem et al.,2016) A potential reason why functional tests are not showing to be predictive of a second

ACL injury is that they are not adequately assessing quadricep strength symmetries, a known risk factor. Quadricep strength symmetry is most commonly assessed using a dynamometer. However, these devices are not typically found in clinical settings. It was shown that in healthy individuals, a single leg squat is a quadriceps dominated task. (Khuu et al., 2019) Thus, a clinically applicable movement that could ultimately be added to the RTP criteria to assess quadricep strength asymmetry is the single leg squat (SLS).

Purpose

The purpose of this study was to determine the effect of quadriceps strength LSI on knee joint biomechanics LSI during a single leg squat in ACLR and healthy individuals.

Hypothesis

During a single-leg squat, individuals (ACLR or healthy controls) with quadriceps strength symmetry < 90% will exhibit knee joint biomechanical symmetry <90% whereas individuals with quadriceps strength symmetry > 90% will achieve knee joint biomechanical symmetry > 90%.

Delimitations

The main delimitation of this study was that younger, athletic populations that were still recreationally active, as measured by the Tegnar scale, were recruited. The time gap after a reconstruction ranged from about 7 months up to 5 years post-reconstruction, but all ACLR individuals self-reported they were medically cleared to return to activity prior to enrollment in the study.

Limitations

A limitation was that since this study mainly recruited college-aged individuals, the results could not be extrapolated to elite athletic populations or younger adolescent (< 18yrs old) populations. Since we also recruited active participants, results of this study cannot be generalized to individuals who are not recreationally active, i.e. ACLR who did not return to sports.

Operational Definitions

Limb Symmetry Index (LSI): In the ACLR participants, LSI was determined as the ratio of the reconstructed limb over the non-reconstructed limb x 100. In healthy participants, LSI was determined as the ratio of the reconstructed-matched limb over the non-reconstructed matched limb. LSI was calculated for any test (functional hop test, quadriceps strength) where measurements were performed on each limb.

Quadricep deficiency: a clinically determined construct where the reconstructed limb possesses <90% strength in comparison to the non-reconstructed limb.

Significance

By determining if individuals with poor quadricep strength symmetry (assessed on a dynamometer) also exhibit poor knee joint biomechanical symmetries during the SLS, the results of this thesis will provide a first look at whether the SLS could potentially become a surrogate for assessing quadriceps strength symmetry. In the long-term, if it can be determined that visual inspection of the SLS shows easy to detect movement (kinematic) compensations that are associated with quadriceps strength deficits, this would give clinicians a valuable examination tool that can be utilized without the use of expensive equipment that they may not possess (such as motion capture systems or dynamometers), allowing for a more functional assessment of quadricep strength symmetry, a known risk factor for a second ACL injury.

Chapter 2- Review of Literature

Impact of an ACL Injury

One of the most common injuries amongst active individuals in the United States is an anterior cruciate ligament (ACL) tear, with an annual incidence of 200,000. (Mather et al.,2013) This causes both long and short-term burdens for society and the affected individual. Long-term burdens associated with an ACL tear include outcomes such as post-traumatic knee osteoarthritis (OA) and economic burdens on society. As high as 50-90% of those with ACL injuries get diagnosed later on in life with post-traumatic knee osteoarthritis (OA). (Wang et al., 2020) Twelve years after an ACL rupture, 42% of female soccer players had symptomatic knee OA. (Lohmander et al., 2004) The mean age of these females at the follow-up was 31 years. (Lohmander et al., 2004) This shows that at the mean age of 31, after ACL injury and reconstruction, people are experiencing symptomatic OA, significantly decreasing their quality of life at a young age. According to Mather et al., even after ACL reconstruction, the annual cost due to the development of OA in these individuals is $2.78 billion. For an ACL reconstruction (ACLR) the long-term cost beyond 6 years was 27% of the total costs to society due to ACLR, with the mean lifetime cost of each patient being $38,121. (Mather et al.,2013) The total long-term burden of ACL tears and the ensuing reconstruction is estimated to be $7.6 billion annually, just in the United States alone. (Mather et al., 2013) The prevention of ACL injuries are crucial for the improvement of long-term burdens of United States society as well improvement of quality of life for active individuals.

Short-term burdens of an ACL injury include outcomes such as a second-ACL injury, time lost due to rehabilitation, or not returning to play (RTP) with the same levels of ability (strength and functional) as before the injury. Second-ACL injury risk is 15 times higher than an individual who has not had an original injury. (Paterno et al., 2012) Individuals are on average, medically cleared to RTP 6 to 7 months after a reconstruction. (Curran et al., 2020) This equates to 6 to 7 months of playing time lost to the individual, potentially affecting an athletes' career. It was also found that 82% of patients returned to some kind of sport after a reconstruction, meaning that about 18% do not even return to an activity. (Webster et al., 2019) In addition, only 44% were found to return to their pre-injury competitive sport. (Webster et al.,2019) The other 56% did not return back to their pre-injury sport. This means that less than half of individuals who sustain an ACL injury are actually returning to their athletic careers. In terms of an individual's ability to RTP at a level comparable to pre-injury, a 2015 review showed that only about 53% of individuals return to pre-injury level. (Webster et al.,2019) This clearly shows the prevalence of ACL short term burdens and the close attention that it requires. In addition, these short-term burdens added up have the potential to turn into long-term burdens not only for the individual, but for society as well.

Once the ACL is torn, the most common means of treatment is a reconstruction of the ACL (ACLR). (King et al., 2020) A reconstruction restores stability to the knee by preventing anterior translation of the tibia relative to the femur. Two of the most common reconstructions performed in the United States is the bone-patellar tendon-bone graft and hamstring tendon graft. (Heijne et al., 2009) Hamstring tendon grafts involve harvesting of the semitendinosus tendon to become the reconstructed ACL while the bone-patellar tendon-bone graft involves harvesting the central third of the patellar tendon along with bone plugs from the patella and tibia. The hamstring tendon graft has become more common amongst the athletic population because it has been shown to have a more rapid recovery rate as well as an easier ability to partake in accelerated activities sooner than the bone-patellar tendon-bone graft. (Goldblatt et al.,2005) Although hamstring tendon grafts have become more common recently, it was found that a hamstring grafts resulted in a significantly lower quadriceps strength symmetry in comparison to the patellar tendon grafts. (Heijne et al., 2009) This could potentially lead to a second ACL injury if quadriceps strength is not restored to within 90% of the non-operated limb. The main goal of the post-reconstruction rehabilitation is to become as functional as possible in the shortest, but safest time frame. Once people appear recovered, they go through a series of examinations in order to test their overall functionality and strength of the knee's surrounding muscles to determine whether or not they are ready to return to play.

Second Injury Rates High Suggesting Inadequate Return to Play (RTP) Criteria

With roughly 200,000 individuals being affected annually by an ACL tear, the risk for a second ACL tear after a reconstruction is 15 times higher than in an individual who has not experienced the initial injury. (Mather et al., 2014; Paterno et al., 2012) This high rate of a second ACL injury after returning to play suggests that the RTP criteria is not adequately mitigating the risk for a second injury. The current RTP criteria traditionally consists of assessment of quadricep strength symmetry, four functional hop tests (single-leg hop for distance, crossover hop for distance, triple hop for distance, 6m timed hop), and patient-oriented objective surveys (KOOS, global rating scale(GRS), IKDC). (Grindem et al.,2016; Culvenor et al., 2016)

Quadricep strength symmetry of >90% between the reconstructed and non-reconstructed limbs is usually assessed using a dynamometer. (Grindem et al.,2016) The symmetry of >90% is what classifies an individual to pass the strength criteria. When an individual tears their ACL and has it reconstructed, regaining quadriceps strength is important due to a strength deficit. One reason for this strength deficit resides in whether the patient had a femoral nerve block at the time of reconstruction. Everhart et al. 2020 found that 7.7% of individuals who had a femoral nerve block experienced an ACL graft rupture within two years post-reconstruction compared to 2.9% of individuals who did not have a femoral nerve block sustained an ACL graft rupture within 2 years post-reconstruction. (Everhart et al 2020) In addition, the ability to achieve quadriceps strength symmetry was lower in the femoral nerve block group.

Another reason for this strength deficit is because of an arthrogenic muscle inhibition after in an injury to the ACL. Arthrogenic muscle inhibition is usually seen post-knee injury due to neural inhibition preventing quadriceps from fully activating. (Rice et al., 2009). It was shown that there was a decrease in signaling from joint afferents in the quadriceps in people with ACL injuries in comparison to those without an injury. (Konishi et al., 2002). People who had an ACL reconstruction were also shown to increase their frontal cortex activity during a maximum isometric voluntary contraction. (Baumeister et al., 2011). Baumeister et al. shows that a higher brain working memory was functioning in order to perform strength assessments for those with ACL reconstructions in comparison to those without. This suggests that the potential strength of the quadriceps could be limited post ACL injury due to a neurological inhibition. Therefore, strength testing quadriceps strength testing is important for RTP criteria.

The methods by which quadriceps strength is assessed is inconsistent. Isometric quadricep strength is tested mainly by the leg flexion at 60 degrees. (Grindem et al.,2016) However, other studies used 45-degree angles of flexion, or isokinetic strength tests at fast and slow velocities. (Mirkov et al.,2017; Everhart et al., 2019) How quadriceps strength is assessed varies across practitioners, creating an inconsistent, undefined strength condition to test for, potentially playing a role in high second ACL injury rates. Despite these inconsistencies, quadriceps strength symmetry >90% remains integral to RTP criteria regardless of how quadriceps strength is assessed.

Functional hop tests performed on each limb independently to determine symmetries between the reconstructed and non-reconstructed limb are another common component of RTP criteria. One of the most common hop tests is the single leg hop for distance. This hop test involves the subject being told to jump as far as possible for each limb individually. (Gauffin et al.,1992) A second hop test is the crossover hop for distance. It is similar to the single leg hop for distance except that there is a 15 cm medial-lateral deviation in the middle in which the individual must cross when hopping. (Davies et al.,2019) A third hop test is the triple hop for distance. This involves measuring the distance from the toe of the take-off on the first hop to the heel of the landing on the third hop. (Davies et al.,2019) The fourth hop test is the 6m hop for time. The time aspect of this particular hop test is measured routinely by the use of a stopwatch, which in turn adds a human error to the measurement of time collected. (Davies et al.,2019) In comparison to the other three tests, this test was found to have lower intraclass correlation values, suggesting lower reliability (Davies et al.,2019) and explains why this test is not consistently used across practitioners. (Davies et al.,2019) Of these four hop tests, the first three are consistently used, and are goal-oriented tasks to assess the functionality of the reconstructed limb in comparison to the non-reconstructed limb.

The last component of the RTP criteria are the patient-oriented instruments, the KOS, global rating scale (GRS), IKDC, and KOOS. The KOS is a self-reported assessment on a scale of 0 to 100 (the best) of symptoms and functions throughout activities of daily living. (Grindem et al.,2016) The GRS is a self-reported assessment on a scale of 0 to 100 (function the same as prior to injury) of current knee function. (Grindem et al.,2016) The IKDC is completed after an ACLR and is a self-reported assessment on a scale of 0 to 100 (best) of knee symptoms, functions, and sports activities. (Culvenor et al., 2016) This assessment is valid in evaluating functional status in those who have undergone ACLR specifically. Lastly, the KOOS addresses daily function and symptoms just like the other patient-reported instruments, but also has a subscale for quality of life. (Lynch et al.,2017). This addresses the patients' adaption to the ACL injury in environments that the clinicians are not exposed to, allowing for a more rounded view on how the patient is functionally performing. The functionality of ACL injured patients is a part of identifying a positive outcome of a reconstruction and the patient-oriented instruments help to give clinicians an idea of that functionality. (Lynch et al.,2017) These patient-oriented instruments play a role in deciding if a patient can RTP, therefore influencing the risk possible for a second ACL injury.

Patients are most commonly medically cleared to activity around 6 to 9 months post-ACLR. (Curran et al., 2020) This is the case despite reported significantly lower single leg hop distance symmetry of 90.01± 9.46% at 9 months after ACLR than 96.30 ± 6.46% at 24 months post ACLR. (Curran et al.,2020) In addition, only the patients who were 24 months post-reconstruction achieved functional symmetry (>90%) for all four hop tests. (Curran et al.,2020) Welling et al. found that patients score significantly better on hop tests at 9 months compared to 6 months. More specifically, 62.9% passed the hop test symmetry criteria at 6 months post-ACLR while 77.4% passed at 9 months. (Welling et al.,2018) Despite this data for the RTP criteria, the 2nd injury rates are still high, potentially due to the clearance to RTP at 6 to 9 months, while Curran et al. showed a significant increase in hop symmetry as time passed beyond 9 months.

To date, the RTP criteria that have been significantly shown to be risk factors for a second ACL injury are quadricep strength symmetry and time, not functional hop tests or patient-oriented instruments. (Grindem et al.,2016) This suggests overall inadequate RTP criteria and requires further study into known risk factors for a second ACL injury.

Why Functional Tests are Not Predictive of a Second ACL Injury

Functional hop tests are currently a main component of return-to-play (RTP) criteria after an ACL reconstruction. However, it has never been shown in the literature where the hop tests were significant on their own in predicting a risk for a second ACL injury. Grindem et al. showed a 1 in 18 reinjury rate for those who passed the all RTP criteria, with the RTP criteria including four different hop tests, quadricep strength symmetry, and a self-reported survey. It was found overall that the knee reinjury rate was four times higher in ACLR patients who RTP, suggesting that there is a good portion of individuals who are not recovering fully but are still passing the hop RTP criteria. (Grindem et al.,2016) Thus, the RTP criteria is inadequate when looking at symmetry in the single-leg hop tests.

The distance that a person hops on each limb individually must be symmetrical (>90%) in order to pass the functional RTP criteria. This symmetry assessment may not be ideal in indicating passing RTP based on 37% of ACLR patients and 38% of healthy controls showing symmetry < 90% in the single leg hop functional test. (Wren et al., 2018) With similar asymmetries, it is hard to justify using the hop functional test on its own to assess RTP readiness. In the same study, those who had undergone an ACLR were shown to offload the reconstructed knee during the landing phase of the single leg hop for distance. (Wren et al.,2018) The hip and ankle compensated for the energy absorption while knee energy absorption was lower on the reconstructed vs non-reconstructed limb, all while still landing symmetrical distances on both limbs. (Wren et al., 2018) This shows that hop test symmetry may not adequately show a player's RTP true readiness because individuals can achieve symmetry by compensating their movement patterns.

Amongst people with ACL deficiency, it has also been shown that they are able to adapt by compensation in order to achieve hop test symmetry >90%. Participants with ruptured ACLs who showed symmetrical hop length amongst the injured and non-injured limb, also showed a lower extensor torque in the knee (quadriceps effort) when landing from the single leg hop on the ACL deficient vs healthy limb. (Gauffin, 1992) This appears to be due to a higher angle of flexion for the hip joint which implies a higher demand for hip extensor muscles in the landing phase of the hop. (Gauffin, 1992) Thus, these data show that ACL deficient subjects can achieve hop distance symmetry by compensating more with the hip extensors which allow for the off-loading of knee extensors.

Asymmetries of movement patterns despite symmetrical single hop distances was further seen through a decreased knee flexion and knee extensor moments on the reconstructed limb when compared to the non-reconstructed limb of ACLR patients. (Orishimo et al., 2010) This decreased knee range of motion and lower knee extensor moment was compensated by a 38% greater peak moment and a 21% greater peak power by the hip extensors along with a 42% increase in energy dissipation at the ankle during landing. (Orishimo et al., 2010) This is evidence that the knee extensor (quadriceps) can functionally be off-loaded during single leg hop testing in ACL reconstructed individuals. Additionally, these are biomechanical measurements that cannot be assessed simply by measuring the distance an individual can hop on each limb post ACLR. Taken collectively, knee function does not appear to be adequately assessed based on single limb hop distance symmetry alone based on the abundance of compensations for the ACL reconstructed or deficient limb in comparison to the healthy limb. (Grindem et al.,2016, Orishimo et al.,2010, Gauffin,1992)

There have been other attempts at creating a functional RTP criteria in addition to the functional hop tests already in place in order to best assess the function of the knee and a patient’s ability to RTP safely. A double-leg jump landing and single-leg jump cutting test were attempted in accordance with the single-leg hop test, mainly to assess differences in knee flexion angles and extension moments for the hop landing. (Chang et al., 2018) It was found that there were not any differences in the knee extension moments in the groups that passed or failed the RTP hop test symmetry criteria in the jump landing and jump cutting tests. (Chang et al., 2018) This lack of differentiation shows that the additional functional assessments of double-leg jump landing and single-leg jump cutting do not help assess the function of the knee to RTP any further than the standard single-leg hop does. In order for functional tests to be included as part of the RTP, the functional task should be reflective of knee extensor efforts because quadricep strength symmetry has been shown to be a risk factor for a second ACL injury.

While functional assessments measure values such as distance or distance symmetry, known risk factors for a second ACL injury are quadricep strength asymmetry and time. (Grindem et al., 2016) It was found that for every one percentage point increase in strength symmetry of the quadriceps, the reinjury rate was reduced by 3%. (Grindem et al.,2016) A potential reason why these functional tests are not showing to be predictive of a second ACL injury is that they are not adequately assessing quadricep strength symmetries, a known risk factor. The movements being assessed by functional hop tests are able to be compensated for through the usage of the hip and ankle as shown above. (Orishimo et al.,2010, Gauffin,1992, Wren et al., 2018) A potential movement that might be added to the RTP criteria that could potentially assess quadricep strength asymmetry is the single leg squat (SLS). Based on the finding of Grindem et al that quadricep strength asymmetry is a risk factor for a second ACL injury, it is hypothesized that the SLS could assess quadricep strength symmetry just as well as a dynamometer; the gold standard for measuring muscle strength. If this were the case, the SLS could be used in clinical settings in order to determine quadricep strength symmetry, therefore creating a more clinically applicable test as part of the RTP criteria that is a risk factor for a second ACL injury.

Single Leg Squat Assessing Quadricep Strength Symmetry

Quadricep strength asymmetry is a known risk factor for a second ACL injury, therefore it is important to look further into a functional assessment of quadricep strength asymmetry. (Grindem et al., 2016) The current gold standard instrumentation for measuring quadricep strength symmetry is the dynamometer, however, it is not commonly found in clinical settings. A more clinically applicable measurement of quadricep strength symmetry could be the single leg squat. As shown by Khuu et al., in a single leg squat, the knee extensor moment torques at 60-degree knee flexion during the single leg squat was almost three times higher than the hip extensor and ankle plantar flexor moments. This suggests a larger activation and usage of the quadricep muscles compared to other lower extremity muscles of the hip and ankle. It was also found that there was a significant increase in hip flexion on the stance limb as the non-stance knee became more flexed. (Khuu et al., 2016) The increase in the hip flexion is showing a compensation for the lack of biomechanical movement in the knee joint in certain single-leg squat forms, once again activating the quadriceps through the single-leg squat.

The single-leg squat has the potential to be a surrogate and functional assessment of quadricep strength symmetry, something that is lacking from the current functional assessments within the RTP criteria. The functional hop tests have been shown to be inadequate in assessing RTP readiness on their own, and not aligning with the shown risk factors by Grindem of quadricep strength symmetry and time. The overall purpose of this study was to determine the effect of quadriceps strength LSI on knee joint biomechanics LSI during a single leg squat in ACLR and healthy individuals. The hypothesis is that during a single-leg squat, individuals (ACLR or healthy controls) with quadriceps strength symmetry < 90% will exhibit knee joint biomechanical symmetry's <90% whereas individuals with quadriceps strength symmetry > 90% will achieve knee joint biomechanical symmetry > 90%.

Chapter 3-Methods

The purpose of this study was to determine the effect of quadriceps strength LSI on knee joint biomechanics LSI during a single leg squat in ACLR and healthy individuals. Quadriceps strength deficits (isometric quadriceps strength LSI <90%) are commonly seen in ACL reconstructed populations, but they are not common in healthy populations. Because the main focus of this thesis was to determine the extent to which quadriceps strength LSI, a known risk factor for a second ACL injury, corresponds to knee biomechanical LSIs during a functional task in an ACL reconstructed population, this thesis determined if quadriceps strength LSI has an effect on functional knee biomechanical LSI in ACLR and healthy groups.

Design

To address the purpose of this thesis, a two cohort (ACLR and healthy cohorts) study design was used to determine whether quadriceps strength LSI corresponds to knee joint biomechanical LSIs during a single leg squat in both ACLR and healthy groups. Additionally, between subjects comparisons were made to determine if ACLR participants with low quadriceps strength LSI (<90%) also have poor knee biomechanical LSIs compared to ACLR participants with high quadriceps strength LSI (>90%) and healthy controls. Thus overall, this thesis followed a mixed model design with both within group and between group comparisons.

Participants

There were a total of 20 participants, with 10 healthy adults for the control group and 10 participants who have undergone ACLR surgery within the last five years. Four ACLR individuals achieved a strength symmetry of <90% and six achieved a strength symmetry of >90%. The sample size of the ACLR group was based on previous work in the lab showing that 50% of ACLR subjects had quadriceps strength LSI <90%. Individuals with ACLR were self-reportedly medically cleared to return to play at the time of testing. In addition, they only had undergone ACL surgery on one limb. The control group participants were recreationally active with no history of knee joint injuries or surgeries. ACLR and healthy groups were matched based on activity level and sex.

Procedures

Data for this study was collected in the Performance Optimization Lab, located in room 332 Ward Sports Medicine Building at East Carolina University. Both the healthy controls and the ACLR group underwent the same testing procedures. The participants were in body-tight attire with athletic shoes.

Upon arrival to the lab, the participants started by providing university approved (Appendix I) informed consent (Appendix II). Next, the ACLR participants completed a patient reported outcome survey, the Knee Injury and Osteoarthritis Outcome Score (KOOS) (Appendix III). The KOOS assesses the functional abilities of the individual's knee in everyday life. The participant filled the KOOS out themselves, reflecting on their own self-reported symptoms, functional ability, and quality of life. The data collector completed the Tegner Activity Scale (Tegner, 1985) which assesses the participant's activity level on a scale from 0-10. (Appendix IV). A score of a zero indicates that there is no movement or activity due to disability or sickness and a score of 10 indicates an activity level of an elite, national level athlete. Based on previous lab data and with our inclusion criteria requiring all participants to be at least recreationally active, we expected activity scores ranging from 5 to 7. This indicates an activity level of 2-5 times a week partaking in a recreational and/or competitive sport of some sort.

All participants then underwent the traditional functional hop tests associated with traditional RTP criteria: the single-leg hop for maximal distance, triple-hop for maximal distance, and the 6m timed hop. (Figure 1). The main purpose of these procedures in this study is to compare their results with the current literature including RTP criteria. It will also help to show if the SLS adds varying or different data in reference to the current RTP criteria. All participants performed practice trials until comfortable with the task followed by three test trials. The single leg hop for maximal distance was performed by taking off of one limb and hopping as far as one can, landing with the same leg that was used to take off. 75% of the maximal single-leg hop for distance was calculated and used during motion analysis. The triple-hop for distance was performed similarly to the single-leg hop for maximal distance, except three hops in a row were performed and the total distance calculated. The next hop test was the 6m timed hop which consists of the participant hopping a total distance of 6m as fast as they can on each limb individually. The 6m was measured out before the assessment took place and marked on the ground. All of these assessments had breaks in between them to minimize fatigue. The single leg hop tests were performed bilaterally, starting on the ACLR limb first.

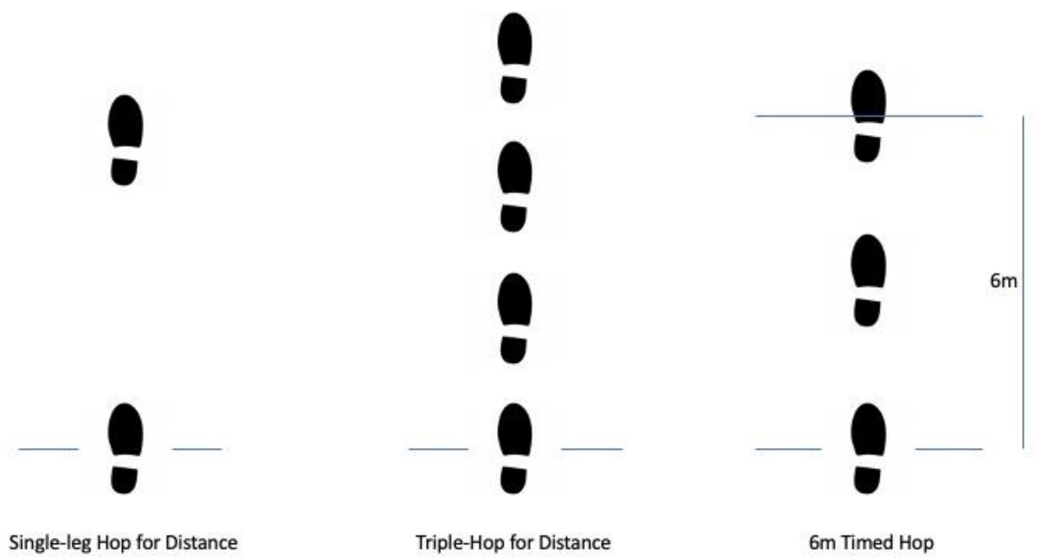


Figure 1. The varying RTP criteria hop tests. The distance was measured after a single-hop for each limb, seen in the far left figure. The middle figure shows the triple-hop for distance; where the total distance from the take-off of the first hop to the landing of the third hop was measured. The far right figure displays the 6 m timed hop where the amount of time to hop 6m was recorded.

Next, quadricep strength was assessed using an HUMAC NORM dynamometer (CSMI, model 502140, Stoughton, MA). The participants were seated with hips flexed at 90 degrees, strapped in across the chest line and thigh and with the knee joint aligned with the head of the dynamometer. Participants were given 2 test trials to get accustomed to the test and also allow the examiner to ensure that the subjects were appropriately secured in the dynamometer. Isometric quadriceps maximum strength with the knee at 60 degrees of flexion was tested bilaterally and served as a comparison to the quadriceps strength LSI literature and was the basis by which the quadriceps strength LSI was determined. (Batty et al., 2019; Pietrosimone et al., 2016). Three total test trials with rest in between trials were given.

The participants were then instructed to perform the SLS, set up with the 10-camera motion capture system (Opus 300+ Cameras, Qualisys, Goteborg, Sweden) and synchronized with force plate (AMTI, Newton, MA) data in order to assess the biomechanics associated with the SLS. A 46-marker set was used to track the lower extremities, pelvis, and trunk segments. This included four trunk markers (right and left acromion processes, cervical vertebrae 7, sternum), eight pelvis markers (right and left iliac crests, right and left greater trochanters, right and left anterior superior iliac spine, right and left posterior superior iliac spine), four markers on a rigid plastic shell were placed on each thigh and shank, two knee markers for each knee (lateral and medial epicondyles), and lastly seven foot markers (medial and lateral malleoli, metatarsal heads 1 and 5, rigid shells containing three markers on top of the foot). A representation of marker placement for the lower extremities, pelvis, and trunk is shown in Figure 2.

Once marker placement was complete, the participant was first asked to stand on the force plate, aligned with the global coordinate system, with his/ her arms extended to the sides in order to capture two static calibration trials. The global coordinate system was defined as the positive x in the anterior direction of the lab, the positive y in the left direction of the lab, and the positive z in the upward direction of the lab above the force plate. These trials were used to define each of the segments and make an eight-segment model in Visual 3D during data reduction. The 46 markers were used to track the individual segments during the dynamic motion trials.

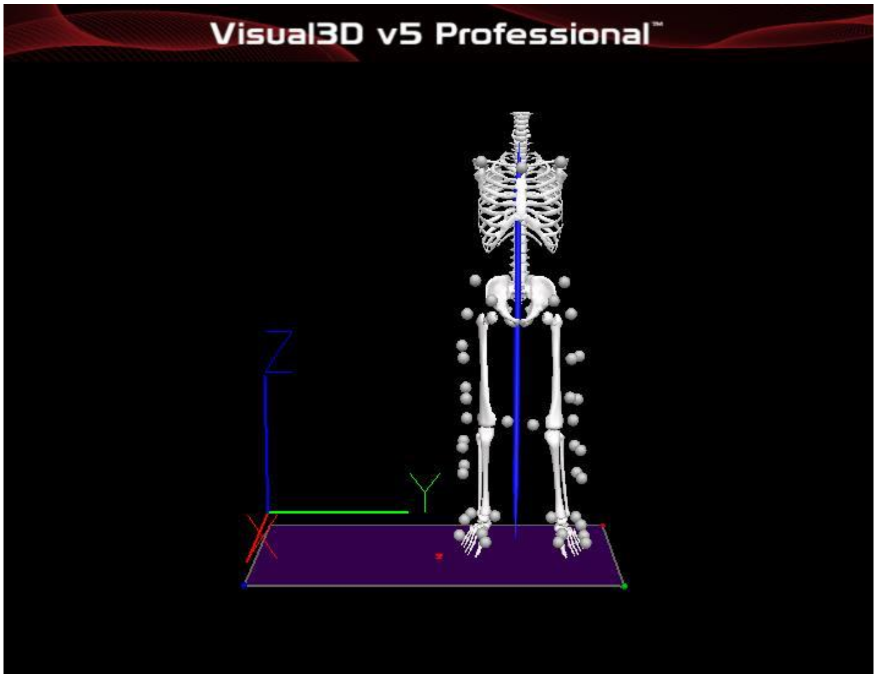


Figure 2. The eight segment model during static calibration in Visual 3D.

The participants were next given minimal general instructions on how to perform the SLS in order to allow for natural variation in performance. This instruction included the phrases "while balancing and standing upright on one limb, perform the squat with the non-stance knee parallel to the stance knee during the squat to the best of your ability" and "the squat should be performed to the best of your ability, going as deep as comfortable while maintaining balance on the stance limb and then come back up in a smooth, controlled, and coordinated manner". The participants were allowed a few practice trials in order to become comfortable performing the task. Thus, the speed of the squat was considered to be self-selected. This was followed by a set of five SLS trials for each limb, starting with the ACLR limb.

The last task using the motion capture system was performing a single leg hop onto the force plate at 75% of the maximum distance achieved during the previously collected clinical single leg hop test. The distance was measured out and for three trials on each limb, the participant was asked to hop that distance onto the force plate. This was done in order to analyze the biomechanics during landing on the individual limbs. While this task was not part of the purpose of this thesis, it helped to ascertain if any compensations, ie quadriceps off-loading due to quadriceps strength deficits, were present in both the SLS and single leg hop for distance test. In addition, since the single leg (SL) hop for distance is currently used for RTP criteria, this comparison between SLS and SL hop landing allowed for a qualitative understanding if the SLS offered unique information that the SL hop test does not in terms of which task could better identify 'functional' quadriceps LSI.

Data Reduction

The data from the dynamometer trials and hop tests were used in order to calculate participant LSIs. The isometric quadriceps strength measured from the dynamometer trials determined the quadriceps strength LSIs; calculated by dividing the reconstructed limb by the non-reconstructed limb and multiplying by 100. These isometric quadricep strength LSIs were used to divide the ACLR individuals into one of two groups: >90% ACLR and <90% ACLR. The same formula was used for the clinical hop test length LSI. LSIs for healthy subjects were calculated based on 'reconstructed' and 'non-reconstructed' matched limbs.

For the analysis of the SLS and single-leg hop while using the Qualysis system, an eight segment model (trunk, pelvis, left and right thigh, left and right shank, left and right foot) was first created in Visual 3D. The segments were created individually, and distal and proximal ends of the segments were used to define the limb and therefore, the limb lengths. This model was created from the calibration trial and then applied to the motion trials: SLS and single-leg hop trials through assigning the model to these motion files exported from QTM. A low-pass filter of 50 Hz was run for the force plate data while marker data was low pass filtered at 10Hz. Each squatting and landing trial had events created for the start and stop of each trial. The start event for the squatting trials were marked as beginning of knee flexion from the balanced extended state. The end event for the squatting trials were marked as the end of knee extension. The start event for the landing trials were marked as the first frame the limb hit the force plate. The end event for the landing trials were marked as the end of knee flexion once the participant became stable on the landing limb.

Lower extremity kinematics (hip, knee, and ankle: joint angle, joint position, joint velocity) and kinetics (hip, knee, and ankle: torque, power, work, impulse) were calculated by running a pipeline within Visual 3D for those trials. This pipeline used inverse dynamics in order to calculate the lower extremity joint torques (Appendix V).

Statistical Approach

Mixed-model 3x2 ANOVAs were conducted comparing lower extremity biomechanical variables (focusing on knee kinematics, knee extensor torques and knee mechanical work) across (between-subject factor) the three groups: ACLR participants with low quadriceps strength LSI (<90%), ACLR participants with high quadriceps strength LSI (>90%), and healthy controls and across reconstructed vs non-reconstructed limbs (within-subject factor). For the reconstructed vs non-reconstructed limbs, the healthy subjects were matched to the ACLR sample by activity score and sex. Thus, when referencing “injured” vs “non-injured” limbs in the healthy group, it is implied that these were “injured-matched” and “non-injured matched” limbs. Because the focus of this thesis compared quadricep strength LSI to functional LSI during the SLS and single-leg hopping tasks, this assumed a difference between injured and uninjured limbs. Therefore, follow-up paired samples t-test was run to compare injured versus uninjured limbs for all three groups. Cohen's *d* with Hedge's *g* correction were also computed to determine the magnitude of the difference between the two limbs.

Correlational analyses determined the association between quadricep strength LSI to knee extensor torque LSI and the association between quadriceps strength LSI to total knee mechanical work LSI during SLS and SL hop landing tasks. These correlations were run on all subjects combined as well as stratified by group.

Chapter 4- Results

The purpose of this study was to determine the effect of quadriceps strength LSI on knee joint biomechanics LSI during a single leg squat in ACLR and healthy individuals. It was hypothesized that during a single-leg squat, individuals (ACLR or healthy controls) with quadriceps strength symmetry < 90% will exhibit knee joint biomechanical symmetry's <90% whereas individuals with quadriceps strength symmetry > 90% will achieve knee joint biomechanical symmetry > 90%.

There were 20 total participants, 14 females and 6 males. The average age was 22.2 ± 1.9. Ten participants had had an ACLR within the past five years (4.2 ± 0.8) and had been cleared to return to play by a practitioner (7 females, 3 males). Ten participants were healthy controls and had no history of any lower extremity injury (7 females, 3 males). All participants were classified as either a 6 or a 7 on the Tegner activity scale. (Table 1). The ACLR and healthy controls were matched based on sex and Tegner activity score. Participants were split into one of three groups: ACLR with quadricep strength LSI <90%, ACLR with quadricep strength >90% and healthy. The ACLR quadricep strength LSI <90% included 4 participants and the LSI >90% included 6 participants. LSIs were calculated using the peak isometric quadriceps torque collected on the dynamometer at 60 degrees of knee flexion.

	ACLR <90%	ACLR >90%	Healthy	Total
N	4	6	10	20
Sex	2F, 2M	5F, 1M	7F, 3M	14F, 6M
Age	21.7 (2.36)	22.2 (2.14)	22.4 (1.96)	22.2 (1.99)
Height (cm)	166.0 (3.09)	165.5 (7.08)	168.8 (10.61)	167.3 (8.40)
Weight (kg)	74.6 (12.79)	77.8 (13.91)	68.2 (16.29)	72.4 (14.90)
Tegner	6.7 (0.50)	6.2 (0.41)	6.5 (0.53)	6.45 (0.51)

Table 1. Demographics of the participant population. Mean (SD).

KOOS forms were filled out by those in the ACLR group. The average percentages per section were: 79% ± 16.0 for symptoms, 87.3% ± 10.2 for pain, 92.5% ± 8.8 for function, 82.8% ± 17.9 for sport function, and 72.9% ± 19.3 for quality of life. Everyone completed the clinical hop tests commonly used to determine readiness for return to sport: single hop for distance, triple hop for distance, and 6m timed hop. All groups achieved on average >90% LSI for all three of the hop tests. For the single leg hop, there were two participants who achieved a LSI <90% within the <90% ACLR group, one participant who achieved a LSI <90% within the >90% ACLR group, and no participants achieved a LSI <90% within the healthy group (Table 2).

	<90% ACLR	**>90% ACLR**	**Healthy**
Single Leg Hop	93.1 (6.16)	99.9 (6.66)	103.5 (5.68)
Triple Leg Hop	90.1 (4.37)	99.2 (12.41)	100.0 (6.74)
6m Timed Hop	111.7 (9.08)	98.2 (6.65)	96.8 (6.68)

Table 3. LSIs for clinical hop tests. LSI calculated as injured/uninjured x 100. Mean (SD).

Knee Peak Flexion Angles During the SLS

Repeated measures 3 x 2 ANOVA was run for the knee peak flexion angles during the SLS within individuals' limbs and between the three groups. There was no significant difference in the peak knee flexion angle for main effect between the injured and uninjured limbs (p=0.505, d=0.28). A similar trend was seen for the main effect between group, with no significant difference between <90% ACLR, >90% ACLR, and healthy (p=0.328). There was also no significant group and limb interaction (p=0.333). Means (SD) are reported in Table 3.

Knee Peak Extensor Torques During SLS

For peak knee extensor torques during the SLS a 3 x 2 repeated measures ANOVA was run for limb and group. There was no significant main effect between the injured and uninjured limb ($p=0.143$, $d=0.36$). There was also no significant main effect between groups as well ($p=0.367$). For interactions between group and limb there was no significant differences ($p=0.863$).

Knee Total Mechanical Work During SLS

Mechanical work was totaled as the sum of the absolute value of negative mechanical work during descent plus the positive mechanical work during ascent and compared within limbs and across groups through a 3 x 2 repeated measures ANOVA. The total mechanical work during the SLS had no significant main effect between limbs ($p=0.856$, $d=0.07$). The between group main effect also showed no significance ($p=0.340$). Lastly, the interaction between limb and group showed no significance ($p=0.390$).

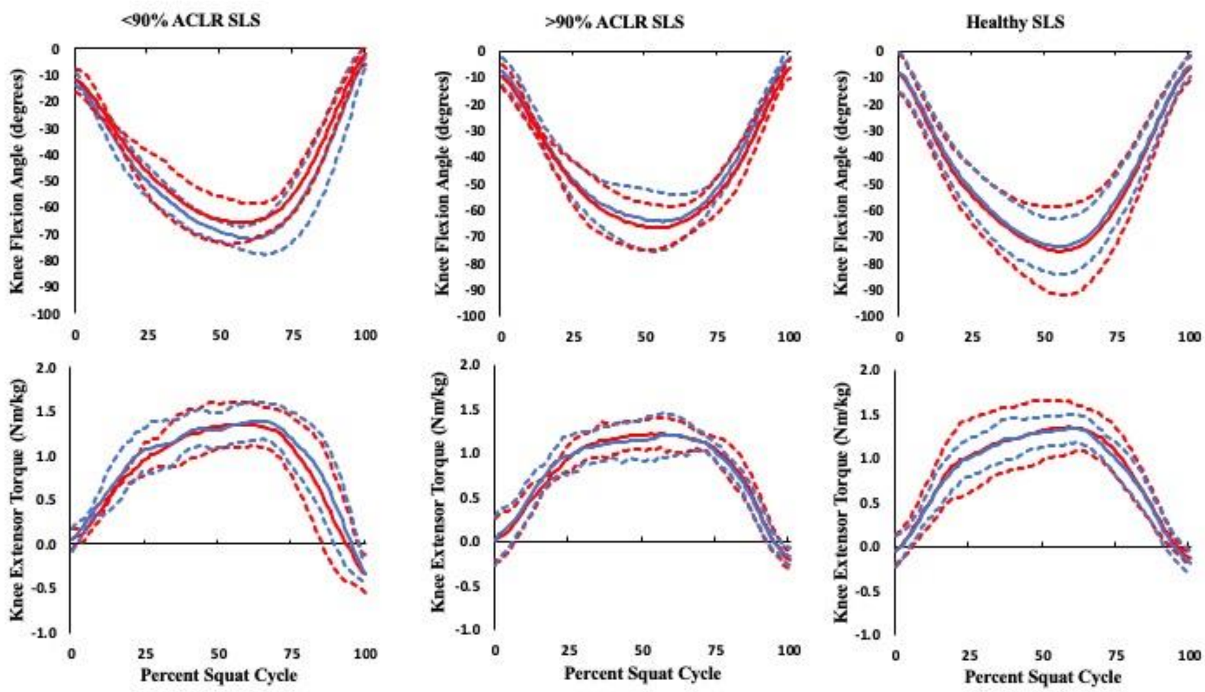


Figure 3. SLS Biomechanics. Red = Injured limb, blue = uninjured limb. Solid line = mean, dotted = +/- 1 SD. Ensemble average curves used for visualization purposes only.

	<90 % ACLR		>90% ACLR		Healthy	
	Injured	Uninjured	Injured	Uninjured	Injured	Uninjured
Peak Knee Flexion	-71.9 ± 8.63	-75.8 ± 7.15	-70.3 ± 8.89	-66.6 ± 11.84	-81.3 ± 19.9	-76 ± 12.62
Peak Knee Torque	1.7 ± 0.56	1.5 ± 0.23	1.4 ± 0.18	1.3 ± 0.19	1.6 ± 0.36	1.5 ± 0.15
Total Knee Work	1.5 ± 0.59	1.8 ± 0.56	1.4 ± 0.25	1.4 ± 0.45	1.9 ± 0.89	1.7 ± 0.39

Table 5. SLS biomechanics. Mean ± SD. Units: degrees for flexion angle, Nm/kg for peak torque and J/kg for total work.

Knee Peak Flexion Angles During Landing

Repeated measures 3 x 2 ANOVA was run for peak knee flexion angle during the landing task. Between limbs within subjects there was no significant difference in effect (p=0.869, d=0.02). There was also not a significant difference in the main effect between-group during the landing task (p=0.129). For the limb and group interaction, there was no significant interaction between the two (p=0.435).

Knee Peak Extensor Torques During Landing

A repeated measures 3 x 2 ANOVA was run for the landing task, with no significance between limbs (p=0.438, d=0.08). This was also seen with no main effect between groups (p=0.615). The limb and group interaction showed no significance (p=0.395).

Knee Total Mechanical Work During Landing

There was a significant main effect for limb (p=0.04, d=0.51). Pooled across group, the injured limb average was 0.17 J/kg lower than the uninjured limb average. However, there was not a significance in the main effect between groups (p=0.366). There was also not a significant interaction between limb and group (p=0.802).

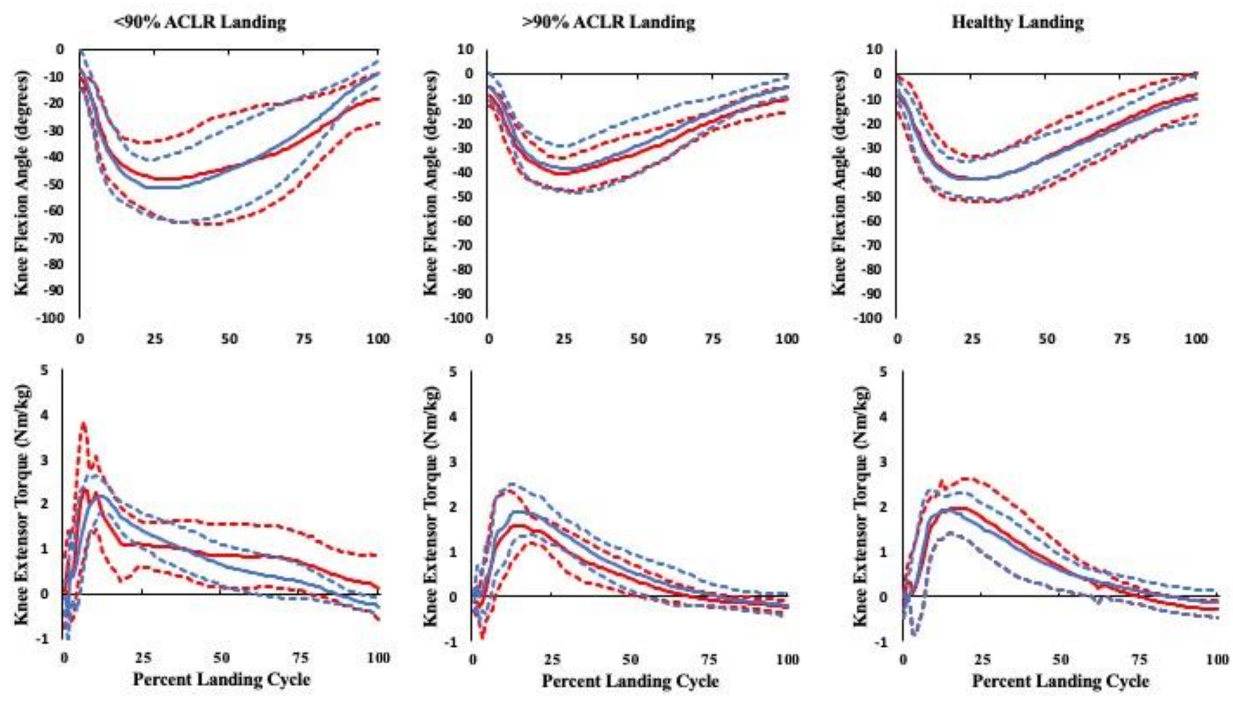


Figure 4. Landing Biomechanics. Red = Injured limb, blue = uninjured limb. Solid line = mean, dotted = +/- 1 SD. Ensemble average curves used for visualization purposes only.

						red
l						7.09
Peak Knee Torque	2.3 ± 0.89	2.6 ± 0.31	2.3 ± 0.51	2.3 ± 0.52	2.6 ± 0.53	2.5 ± 0.31
Total Knee Work	1.4 ± 1.05	1.6 ± 0.62	0.9 ± 0.45	1.2 ± 0.52	1.2 ± 0.34	1.3 ± 0.39

Table 7. Landing biomechanics. Mean ± SD. Units: degrees for flexion angle, Nm/kg for peak torque and J/kg for total work.

Within-Group, Limb-to-Limb Differences in SLS and Hop Landing

Follow-up analysis of paired samples t-tests and effect sizes (Cohen's D_{rmg}) between limb in all three groups for peak knee flexion, peak knee extensor torque, and total knee mechanical work during the SLS and single leg landing task. (Table 5). Overall, effect sizes (Cohen's D_{rmg} with Hedge's *g* correction) were low to moderate during the SLS and hop landing with no significant differences between limbs.

		Peak Knee Flexion	Peak Knee Torque	Total Knee Work
SLS	<90% ACLR	0.52 / 0.314	0.32 / 0.512	-0.45 / 0.378
	>90% ACLR	-0.37 / 0.370	-0.41 / 0.331	-0.06 / 0.889
	Healthy	-0.43 / 0.189	0.33 / 0.305	0.27 / 0.386
Landing	<90% ACLR	0.39 / 0.432	-0.43 / 0.395	-0.43 / 0.483
	>90% ACLR	-0.37 / 0.377	-0.15 / 0.703	-0.54 / 0.213
	Healthy	0.16 / 0.600	0.17 / 0.595	-0.50 / 0.131

Table 9. Cohen's D_{rmg} / p-value. Paired samples t-tests were run between limb within the three groups for both the SLS and single leg hop landing task.

Correlational Analysis

There was no significant correlation detected between quadricep strength LSI (all participants combined, n=20) to knee extensor torque LSI during SLS (r= 0.063, p=0.36). There was also no significant correlation detected between quadricep strength LSI (all subjects combined, n=20) to total knee mechanical work LSI during a SLS (r=0.29, p=0.11). There was a significant correlation detected between quadricep strength LSI and peak knee extensor torque LSI during the landing task (r=0.453, p=0.023). There was no significant correlation between quadricep strength LSI and knee total mechanical work during landing (r=0.36, p=0.06). (Appendix VI reports the scatterplots for these analyses)

The data was then split into two groups to break down the data further: <90% ACLR in one group and >90% ACLR and healthy controls in the other group. Within the <90% ACLR group for the SLS, there was not a significant correlation between quadricep strength LSI and knee peak torque LSI or knee total work LSI (p=-0.474, p=0.294 respectively). Within the >90% ACLR and healthy control correlations, there were no significant correlations between the quadricep strength LSI and knee peak torque LSI or knee total work LSI (p=0.295, p=0.149 respectively).

Lastly, the data was split into three groups: <90% ACLR, >90% ACLR, and healthy controls for the relations within the SLS (Appendix VII). For the <90% ACLR group, there was no significant correlation between quadricep strength LSI and peak knee flexion angle LSI (r = -0.147, p = 0.425), between quadricep strength LSI and peak knee torque LSI (r = -0.474, p = 0.26), or between quadricep strength LSI and total knee mechanical work LSI (r = 0.294, p = 0.35). For the >90% ACLR group, there was no significant correlation between quadricep strength LSI and peak knee flexion angle LSI (r = -0.56, p = 0.12) or between quadricep strength LSI and total knee mechanical work LSI (r = -0.556, p = 0.12). However, there was a significant correlation between quadricep strength LSI and peak knee torque LSI (r = -0.85, p = 0.015). For the healthy control group, there was no significant correlation between quadricep strength LSI and peak knee flexion angle LSI (r = -0.14, p = 0.35), between quadricep strength LSI and peak knee torque LSI (r = 0.38, p = 0.14), or between quadricep strength LSI and total knee mechanical work LSI (r = 0.207, p = 0.28).

Chapter 5- Discussion

The purpose of this study was to determine the effect of quadriceps strength LSI on knee joint biomechanics LSI during a single leg squat in ACLR and healthy individuals. It was hypothesized that during a single-leg squat, individuals with quadriceps strength symmetry < 90% will exhibit knee joint biomechanical symmetry's <90% whereas individuals with quadriceps strength symmetry > 90% will achieve knee joint biomechanical symmetry > 90%. Neither of the hypotheses were supported by the data as there were no detected significant differences in the knee LSIs (peak knee flexion, peak knee torque, total knee mechanical work) during the SLS of how the <90% ACLR group individuals moved in comparison to the contralateral limb or the other two groups, >90% ACLR and healthy. This suggests that the biomechanics of the single leg squat was overall not sensitive enough to detect maximal isometric quadricep strength deficiencies greater than 10%.

SLS In Detecting Maximal Isometric Quadricep Strength Deficiency

The results indicated that although the SLS is a primarily quadricep dominated task, it does not appear sensitive enough to detect a maximal isometric quadricep strength deficiency, a known risk factor for a second ACL injury. (Grindem et al., 2016) This can be seen through the similarity in the knee biomechanics through all three groups during the SLS (Figure 3) for both limbs- resulting in non-statistically different LSIs across groups. In addition, the knee biomechanical LSIs of the SLS did not correlate with the quadricep strength LSI (or deficiency). More specifically, there was no correlation between SLS peak knee extensor torque LSI or total knee mechanical work LSI to quadricep strength LSI (r=0.063, r=0.29 respectively). Thus, the hypothesis is not supported with the current results.

Looking closer at the biomechanical data of the SLS during the descent phase only, as seen in Table 6, there is a commonality amongst the degree of peak knee flexion and negative mechanical knee work for both limbs (injured and uninjured) across all three groups. When looking at the ranges of values within the groups, it can be seen that all groups overlap in terms of degrees of peak knee flexion and negative mechanical work. The first hypothesis was not supported by this data because the <90% ACLR group had a 95% LSI for peak knee flexion despite have a quadriceps strength LSI <90%. However, the <90% group had an 88% LSI for negative knee mechanical work, but the ranges of the injured and uninjured limbs suggest enough variability for overlap of individual subject's descending knee work. This shows that there was no visual difference in the degree to which an individual uses their quadriceps during the SLS between the injured and uninjured limb. This could be due to multiple factors.

		Peak Knee Flexion		Knee Mechanical Negative Work	
		Mean (SD)	(min, max)	Mean (SD)	(min, max)
< 90% ACLR	Injured	-71.9 (8.63)	(-62.9, -82.1)	-0.79 (0.29)	(-0.48, -1.18)
	Uninjured	-75.8 (7.15)	(-65.1, -79.5)	-0.89 (0.26)	(-0.56, -1.18)
> 90% ACLR	Injured	-70.3 (8.89)	(-57.6, -78.9)	-0.69 (0.13)	(-0.5, -0.85)
	Uninjured	-66.6 (11.84)	(-55.5, -88.0)	-0.70 (0.23)	(-0.44, -1.11)
Healthy	Injured	-81.3 (19.9)	(-59.4, -123.2)	-0.95 (0.43)	(-0.47, -1.94)
	Uninjured	-76 (12.62)	(-53.3, -99.2)	-0.86 (0.15)	(-0.54, -1.06)

Table 11. Biomechanics of the SLS including the range for each group.

Firstly, the SLS is a functional task that does not require maximal quadriceps effort. When looking at the participants' self-reported KOOS, both >90% ACLR and <90% ACLR groups reported appropriate functional levels during activities of daily living (95.3(8.02), 86.8(8.82) respectively) and slightly less functional in sport (90.8(14.97), 66.7(10.41)). This functionality was also seen within the clinical hop test LSI results, with all groups achieving an

LSI >90% on average (Table 2). The main clinical assessment- the single leg hop for distance- showed >90% LSI average for both ACLR groups (two participants achieving <90% in the <90% ACLR group and one participant achieving <90% in the >90% ACLR group) and the healthy group (none achieving <90%). Thus, with 7 of the 10 ACLR subjects achieving >90% LSI in the single-leg hop for distance, this further highlights a high level of functionality amongst all individuals who have cleared to RTP when assessing LSI.

When looking at how the SLS is achieved biomechanically in all individuals, there seems to be a commonality amongst the varying joint contributions. In analyzing energy absorption (negative mechanical work) relative percentages for the hip, knee, and ankle joints, the <90% ACLR group on average (SD) for the injured limb showed 32.7% (14.7) hip, 50.0% (9.9) knee, and 17.2% (9.5) ankle. The >90% ACLR group's injured limb on average showed 37.4% (13.0) for hip, 47.9% (7.5) for knee, and 14.7% (6.4) for ankle. The healthy control group's injured-matched limbs showed 35.5% (17.5) for hip, 49.5% (13.9) for knee, and 15.0% (6.3) for ankle. When looking at these contributions by the injured or injured-matched limbs during the SLS across all groups, it appears that individuals were performing the SLS in a similar manner supporting the common notion that the SLS is a quadriceps dominated task where the relative contributions from the quadriceps was 50% and the hip extensors and ankle plantarflexors combined for the other 50% on average. (Khuu et al., 2016)

While the SLS requires an extensor torque, the <90% ACLR group were functional enough (defined by LSI) to perform the SLS similarly between limbs and in comparison to those with a quadricep strength LSI >90%. The link between functionality and quadricep strength may simply not be through a SLS. This idea was also supported by a study looking at maximum knee flexion angle in relation to knee extensor strength by Batty et al. in 2019. This study specifically looked at 100 participants who had undergone an ACL reconstruction by collecting SLS and isokinetic data at 6 months and 12 months post-reconstruction. They found a weak linear relationship between SLS maximum knee flexion angle to knee extensor strength. This was due to SLS peak flexion angle symmetry (measured using LSI) at 6 (95% LSI) and 12 (97.6% LSI) months despite the average knee extensor strength LSI being 76.2% and 87.3% at 6 and 12 months respectively. This thesis used participants with an average post-reconstruction time of 4.2 years, but even at 6- and 12-months post-reconstruction, individuals are showing to be functional by LSI definitions even with strength deficits greater than 10% (Batty et al 2019), further supporting that the SLS is not an adequate functional task as defined by the LSI to detect maximal quadriceps strength deficits greater than 10%.

The lack of supporting evidence and data detecting functional SLS LSI differences between <90% ACLR, >90% ACLR, and healthy groups could also suggest that the SLS cannot be related to a maximal effort task assessing quadricep strength such as isometric dynamometer testing. Secondary analysis looked at peak isometric quadriceps torques normalized to body mass as well as the SLS and single leg hop landing. Within the <90% ACLR group, the peak quadriceps strength was 2.0 Nm/kg while the >90% ACLR and healthy group was 3.0 Nm/kg ($p=0.067$, Cohen's $D_g=1.04$). The quadriceps strength torques were about two times higher than the SLS peak extensor torques for >90% ACLR and healthy group. However, the SLS only produced about a 1.3-1.7 Nm/kg normalized torque regardless of group. A secondary analysis showed no significant correlation between the absolute torque produced during the isometric contractions to the absolute torque produced during the SLS for the injured ($r = -0.294$, $p = 0.21$)or the uninjured limb ($r = -0.22$, $p = 0.26$). This can also help to explain how the <90%

ACLR are able to achieve symmetrical functionality, they are achieving extensor torques necessary for functional movement that does not require maximal effort. By these values, one can conclude that the SLS does not require the amount of effort and strength that a maximum contraction trial requires (despite coming close to the threshold), limiting the SLS ability to detect a quadricep strength deficiency.

		Isometric	SLS	Land
<90% ACLR	Injured	1.9 (0.38)	1.7 (0.56)	2.3 (0.89)
	Uninjured	2.5 (0.29)	1.5 (0.23)	2.6 (0.31)
>90% ACLR	Injured	3.09 (1.07)	1.4 (0.18)	2.3 (0.51)
	Uninjured	3.1 (1.05)	1.3 (0.19)	2.3 (0.52)
Healthy	Injured	3.0 (1.22)	1.6 (0.36)	2.6 (0.53)
	Uninjured	3.2 (1.23)	1.5 (0.15)	2.5 (0.31)

Table 13. Knee extensor torques normalized to mass. Isometric= maximal quadricep contraction at 60 degrees. SLS= single leg squat. Landing= landing portion of single leg hop task. Mean (SD). Units = Nm/kg.

Another potential reason as to why the SLS did not show to be related to the isometric maximum quadriceps strength could be the SLS utilized both an eccentric and concentric contraction of the quadriceps. Depending on the speed the participant completed the SLS, the amount of potential torque that could be created differs. The faster the participant performed the descent portion of the SLS, there was a higher potential for amount of torque that could be produced since this phase of the SLS mainly consists of an eccentric contraction by the quadriceps. Since our participants completed the SLS at self-selected speeds, time was not controlled, therefore varying the potential for peak torque amongst the participants. The varying speeds at which they completed the contractions of the SLS potentially could have confounded the comparison to the isometric contractions.

Given why all participants functionally achieved the SLS similarly despite quadricep strength LSI, a main conclusion was that there was no effect of quadricep strength LSI on knee biomechanical measurement LSI. Regardless of quadricep strength LSI (group), there was no relationship to the LSI peak extensor torque (r=0.063) or total mechanical work (r=0.29). Even with an imbalance in limbs for quadricep strength for the <90% ACLR group, how the SLS was performed did not change, further supporting the SLS how we assessed it did not adequately show a strength deficit. One of the main findings of this study was that the SLS (how it was administered) was not sensitive enough to detect isometric quadricep strength deficiency through the SLS biomechanical LSIs.

< 90% ACLR Differentiation

This current study found that the functional SLS test does not highlight what differentiates the <90% ACLR group from the >90% ACLR and healthy control group. As expected, when looking at the RTP criteria, specifically the hop test LSIs, there was no clear distinction or difference between relating quadricep strength LSI to hop distance LSI (only two in the >90% ACLR and one in the >90% ACLR group did not achieve hop symmetry). Within RTP, the only risk factors found for a second ACL injury was quadricep strength asymmetry and time. (Grindem et al., 2016). Relating the quadricep strength to functionality is where the hole in the research lies. What biomechanical variables differentiates the < 90% ACLR group and makes them at risk is the question.

While the ACLR groups were specifically made by separating subjects with quadriceps strength LSI <90% and above 90%, the absolute quadriceps strength of the <90% ACLR group suggests that the absolute strength may be more important than LSI. This absolute strength average for the <90% ACLR group was 1.9 Nm/kg for the injured limb and 2.5 Nm/kg for the uninjured limb while the >90% ACLR group average was 3.09 Nm/kg for the injured limb and 3.10 Nm/kg for the uninjured limb (Table 7). This creates a question of whether the risk is within the LSI metric or within the absolute strength deficiency (in comparison to normative values) of both limbs post reconstruction. A study done by Paterno et al. in 2014 looked at incidence rates of a second ACL tear within two years post-reconstruction in athletes. It was found that contralateral ACL injuries occurred more frequently than ipsilateral ACL injuries (20.5% versus 9%). This suggests that both limbs should be carefully looked at when clearing an individual to RTP, not just the injured. A ratio like the LSI only offers focus on the injured limb matching the uninjured limb in performance when absolute strength of both limbs should be taken into consideration.

In consideration of both limbs post-reconstruction, Chung et al. in 2015 analyzed absolute isokinetic muscle strength as well as single leg hop function for both the contralateral and ipsilateral limbs up to 24 months post-reconstruction. Their main finding was that even at 24 months post-reconstruction, both the contralateral (276.6 Nm (42.8), 158.4 cm (25.3)) and the ipsilateral (242.8 Nm (55.5), 143.1 cm (30.1)) limb were not able to achieve extensor strength or hop test distance of the control group (290.9 Nm (40.1), 176.3 cm (24.7)) ($p<.05$) despite no significance in difference between limbs at 24-months. This finding helps to support the idea that an LSI measurement may not be the best or most accurate for assessing an individual's readiness to RTP.

Pietrosimone et al. in 2016 did a study looking at the relation of normalized quadricep strength or LSI as a better predictor of self-reported function using the IKDC index. Their main finding was that individuals who had a normalized quadricep strength of over 3.0 Nm/kg had the best accuracy of self-reported function in comparison to those with an LSI >90%. This matched the data found in our study because it was found that the 3.0 Nm/kg seems to be the strength value that was achieved by individuals >90% ACLR and healthy controls. This along with the results of our study show that perhaps looking at the normalized strength of each limb may be a better measurement of RTP readiness, not LSI.

Normalization of the single leg hop task as well showed varying results from the single leg hop test LSI measurement. The LSI measurement showed that there was no difference between the average of the three groups, therefore when defining functional as >90% LSI, all three groups were functional. However, when normalizing the single leg hop distance for both limbs (to participant height), those in the ACLR groups hopped less distance than healthy controls. (0.82 (0.19), (0.98 (0.18) respectively for the injured limb). This difference was not statistically significant but produced a large effect size. (p=0.078, d=3.00). This idea was also seen in a study done by Wren et al. in 2015. When looking at 46 individuals post-reconstruction in comparison to 39 healthy controls, the ACLR individuals were not able to hop as far on either limb regardless of strength asymmetry. This further supports the importance of evaluating absolute data, not just LSI.

Clinical Aspects That Affected Biomechanical Outcome

Despite all of the biomechanical factors that influenced the outcomes of this study, there were also many clinical factors that could have played a role in participant's performance as well. A few main extrinsic factors could have been graft time and quality of healthcare in general. There is varying literature on the differing graft types, potentially influencing how an individual is able to perform. A study done by Bell et al. in 2014 looked specifically at graft type to the biomechanics of a SLS and found no relation of knee biomechanics during a SLS to graft type. However, when looking at lower extremity strength, Cristiani et al. found that hamstring tendon graft individuals has significantly less hamstring strength at 12 months post-reconstruction. Also, the quality of not only the surgeon's ability, but also the quality of the rehabilitation that participants received during their recovery. This thesis did not control for surgeon, graft type, or look into the type of therapy received post-reconstruction. Because of this, these extrinsic factors could potentially be confounding factors for the movement results that were seen.

There are also intrinsic factors that could have played a role in the variation of performance and functionality as well. More specifically compliance as well as the state of healing of the reconstructed ligament. Whether a participant is compliant or not can play a role in their rehabilitation and post-reconstruction abilities and performance. A meta-analysis done by Sugimoto et al. in 2013 found that those who were considered to have a low compliance rate in neuromuscular interventions were 4.9 times more likely to have a second ACL tear than those with a high compliance rate. This is something important to note since it was not controlled for or documented within this study. The other important consideration is the healing state of the ligament that was once a tendon. A study done by Beynnon in 2005 found that it took about two years post-reconstruction for markers of knee cartilage healing to decrease back down to normal levels. Since our participants were 4-5 years post-reconstruction, their reconstructed ligament were likely at a different healing state compared to individuals who are normally 7-9 months post-reconstruction and returning to play. However, this may be something to consider for future studies looking at individuals who had not had as much time pass since reconstruction.

Strengths and Limitations

A main strength of this study included looking at the direct comparison of a functional task to absolute quadricep strength. This has not been looked at in a functional task other than hop tasks. Another strength of this study was its assessment of a fairly active population. The Tegner scores ranged between a 6 and a 7, giving an insight into how an active population moves biomechanically post-reconstruction. This study also successfully activity matched healthy controls to the ACLR participants, allowing for direct comparison of limbs between subjects when controlling for activity level.

There were a few limitations within this study. One main limitation was the sample size. There was a group with only four participants and so more may be needed to make a definitive conclusion pertaining to the overall data in comparison to previous data. However, given the effect sizes from comparing the injured limb to the uninjured limb in the <90% ACLR group during the SLS for peak knee flexion angle, peak knee extensor torque, and total knee mechanical work being low (Cohen's D_{rmg} = 0.32) to moderate (Cohen's D_{rmg} = 0.52) from Table 5, sample size estimation using G*Power revealed that we would have been required to recruit 32-79 subjects that all had more than 10% quadriceps strength deficits to be included in the <90% ACLR group, depending on which effect size is used, to achieve statistical differences between the injured and uninjured limbs during the SLS with a statistical power of 0.80. However, based on our data, the results showed on average, a difference of four degrees of knee flexion between the injured and uninjured limbs. Since four degrees of knee flexion would not be identifiable within clinics by the naked eye, we do not believe the SLS as we tested it to be clinically relevant.

Another limitation was that every ACLR participant was 4-5 years post reconstruction. To better understand movement adaptations post reconstruction, less time since reconstruction could potentially show larger functional differences such as knee extensor torque as seen in Wren et al during the landing task at 5-12 months post-reconstruction. However, for the SLS, Batty et al found similar results to our study, with their ACLR participants being 6- and 12-months post-reconstruction. Since this is the time range that is at most risk for a second ACL injury (Paterno et al., 2012; Curran et al., 2020), it is the time range that would be ideal to assess in the future to see if results varied from literature.

One last limitation would be the instructions given to participants on the performance of the SLS. The wording in this study was to "squat as low as comfortable". Perhaps other wordings such as "as low as possible" would have instructed participants to squat deeper than they showed to during this study. The wording that was used in this study could have potentially limited the extent to which an individual completed the SLS.

Future Application

Looking for a proper functional task to assess RTP readiness is essential for help in prevention of a second ACL injury. Given that one of the risk factors is quadricep strength asymmetry, individuals at clinics without a dynamometer need to be properly assessed for RTP readiness. However, given the commonalities in literature about quadricep strength data as well as what was found in this study, this functional task would need to require at least 3.0 Nm/kg normalized extensor torque for both injured and uninjured limbs in order to require the same demands as a maximum contraction. In other words, a clinical tool needed to assess quadricep strength asymmetries should be able to assess close to threshold strength during the task. The landing from the single leg hop test require 76% extensor torque of the maximum isometric torque and the SLS required 50% extensor torque of the maximum isometric torque in the >90% ACLR and healthy group and 60-89% in the <90% ACLR group, explaining why neither have been able to follow the trends of the dynamometer strength training in terms of LSI.

Both limbs will need to be in consideration given that the only differentiating factor biomechanically for the < 90% ACLR group was that both limbs only produced ~2-2.5 Nm/kg normalized isometric torque for both limbs in comparison to both other groups (>90% ACLR and healthy) who produced 3.0 Nm/kg normalized isometric torque for both limbs. Also, the LSI measurements of the single leg hop shielded the individual limbs' ability to hop as far as the healthy controls. All groups achieved an average symmetrical LSI for the single leg hop task, but when looking at the injured and uninjured limbs individually amongst groups, ACLR individuals were not able to hop as far as the healthy controls on either limb, but this difference was not significant. The RTP readiness may be more a factor of both limbs rather than the ratio between the two. Future research should focus on absolute performance of both limbs, not just the injured vs uninjured limb.

Conclusion

The SLS functional task as assessed in this study was not sensitive enough to detect isometric quadricep strength deficiencies. Individuals in all groups appeared to move similarly through the SLS, both through the biomechanical LSIs but also joint contributions of the hip, knee, and ankle. The only distinction that the <90% ACLR group had from the other two groups were their peak knee extensor torques normalized to body mass during the isometric contractions. They displayed a 2.0 Nm/kg normalized torque for both limbs, while both the >90% ACLR and healthy controls displayed a 3.0 Nm/kg normalized torque for both limbs. This overall suggested that future studies should look at both limbs reaching functionality and strength before RTP, with functionality being defined by absolute values, not the contralateral limb in comparison to the ipsilateral limb.

References

Arundale, Amelia J. H., et al. "TWO YEAR ACL REINJURY RATE OF 2.5%: OUTCOMES REPORT OF THE MEN IN A SECONDARY ACL INJURY PREVENTION PROGRAM (ACL-SPORTS)." *International Journal of Sports Physical Therapy*, vol. 13, no. 3, 2018, pp. 422–31, doi:10.26603/ijspt20180422.

Baumeister, J., Reinecke, K., Schubert, M., & Weiß, M. (2011). *Altered electrocortical brain activity after ACL reconstruction during force control*. 7.

Batty, L. M., Feller, J. A., Hartwig, T., Devitt, B. M., & Webster, K. E. (2019). Single-Leg Squat Performance and Its Relationship to Extensor Mechanism Strength After Anterior Cruciate Ligament Reconstruction. *The American Journal of Sports Medicine*, *47*(14), 3423–3428. https://doi.org/10.1177/0363546519878432

Beischer, Susanne, et al. "Young Athletes Who Return to Sport Before 9 Months After Anterior Cruciate Ligament Reconstruction Have a Rate of New Injury 7 Times That of Those Who Delay Return." *Journal of Orthopaedic & Sports Physical Therapy*, vol. 50, no. 2, 2020, pp. 83–90, doi:10.2519/jospt.2020.9071.

Bell, David R., et al. "Squatting Mechanics in People With and Without Anterior Cruciate Ligament Reconstruction: The Influence of Graft Type." *The American Journal of Sports Medicine*, vol. 42, no. 12, Dec. 2014, pp. 2979–87, doi:10.1177/0363546514552630.

Beynnon, Bruce D., and Braden C. Fleming. "Anterior Cruciate Ligament Strain In-Vivo: A Review of Previous Work." *Journal of Biomechanics*, vol. 31, no. 6, 1998, pp. 519–25, doi:10.1016/S0021-9290(98)00044-X.

Beynnon, B. D., Uh, B. S., Johnson, R. J., Abate, J. A., Nichols, C. E., Fleming, B. C., Poole, A. R., & Roos, H. (2005). Rehabilitation after Anterior Cruciate Ligament Reconstruction: A

Prospective, Randomized, Double-Blind Comparison of Programs Administered over 2 Different Time Intervals. *The American Journal of Sports Medicine*, *33*(3), 347–359. https://doi.org/10.1177/0363546504268406

Chung, K. S., Ha, J. K., Yeom, C. H., Ra, H. J., Lim, J. W., Kwon, M. S., & Kim, J. G. (2015). Are Muscle Strength and Function of the Uninjured Lower Limb Weakened After Anterior Cruciate Ligament Injury?: Two-Year Follow-up After Reconstruction. *The American Journal of Sports Medicine*, *43*(12), 3013–3021. https://doi.org/10.1177/0363546515606126

Cristiani, R., Mikkelsen, C., Wange, P., Olsson, D., Stålman, A., & Engström, B. (2021). Autograft type affects muscle strength and hop performance after ACL reconstruction. A randomised controlled trial comparing patellar tendon and hamstring tendon autografts with standard or accelerated rehabilitation. *Knee Surgery, Sports Traumatology, Arthroscopy*, *29*(9), 3025–3036. https://doi.org/10.1007/s00167-020-06334-5

Culvenor, Adam G., et al. “Dynamic Single-Leg Postural Control Is Impaired Bilaterally Following Anterior Cruciate Ligament Reconstruction: Implications for Reinjury Risk.” *Journal of Orthopaedic & Sports Physical Therapy*, vol. 46, no. 5, 2016, pp. 357–64, doi:10.2519/jospt.2016.6305.

Curran, Michael T., et al. “A Cross-Sectional Examination of Quadriceps Strength, Biomechanical Function, and Functional Performance From 9 to 24 Months After Anterior Cruciate Ligament Reconstruction.” *The American Journal of Sports Medicine*, vol. 48, no. 10, Aug. 2020, pp. 2438–46, doi:10.1177/0363546520940310.

Davies, William T., et al. “Is It Time We Better Understood the Tests We Are Using for Return to Sport Decision Making Following ACL Reconstruction? A Critical Review of the Hop Tests.”

Sports Medicine (Auckland, N.z.), vol. 50, no. 3, 2020, pp. 485–95, doi:10.1007/s40279-019-01221-7.

Everhart, Joshua S., et al. "Femoral Nerve Block at Time of ACL Reconstruction Causes Lasting Quadriceps Strength Deficits and May Increase Short-Term Risk of Re-Injury." *Knee Surgery, Sports Traumatology, Arthroscopy*, vol. 28, no. 6, June 2020, pp. 1894–900, doi:10.1007/s00167-019-05628-7.

Gauffin, Håkan, and Hans Tropp. "Altered Movement and Muscular-Activation Patterns during the One-Legged Jump in Patients with an Old Anterior Cruciate Ligament Rupture." *The American Journal of Sports Medicine*, vol. 20, no. 2, 1992, pp. 182–92, doi:10.1177/036354659202000215.

Goldblatt, John P., et al. "Reconstruction of the Anterior Cruciate Ligament: Meta-Analysis of Patellar Tendon Versus Hamstring Tendon Autograft." *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, vol. 21, no. 7, 2005, pp. 791–803, doi:10.1016/j.arthro.2005.04.107.

Grindem, Hege, et al. "Simple Decision Rules Can Reduce Reinjury Risk by 84% after ACL Reconstruction: The Delaware-Oslo ACL Cohort Study." *British Journal of Sports Medicine*, vol. 50, no. 13, 2016, pp. 804–08, doi:10.1136/bjsports-2016-096031.

Heijne, Annette, and Suzanne Werner. "A 2-Year Follow-up of Rehabilitation after ACL Reconstruction Using Patellar Tendon or Hamstring Tendon Grafts: A Prospective Randomised Outcome Study." *Knee Surgery, Sports Traumatology, Arthroscopy*, vol. 18, no. 6, 2010, pp. 805–13, doi:10.1007/s00167-009-0961-3.

Ithurburn, Matthew P., et al. "Knee Function, Strength, and Resumption of Preinjury Sports Participation in Young Athletes Following Anterior Cruciate Ligament Reconstruction." *Journal* *of Orthopaedic & Sports Physical Therapy*, vol. 49, no. 3, 2019, pp. 145–53, doi:10.2519/jospt.2019.8624.

Kaeding, Christopher C., et al. "Risk Factors and Predictors of Subsequent ACL Injury in Either Knee after ACL Reconstruction: Prospective Analysis of 2488 Primary ACL Reconstructions from the MOON Cohort." *The American Journal of Sports Medicine*, vol. 43, no. 7, July 2015, pp. 1583–90, doi:10.1177/0363546515578836.

Khuu, Anne, et al. *NOT ALL SINGLE LEG SQUATS ARE EQUAL: A BIOMECHANICAL COMPARISON OF THREE VARIATIONS*. P. 11.

King, Enda. "Factors Influencing Return to Play and Second Anterior Cruciate Ligament Injury Rates in Level 1 Athletes After Primary Anterior Cruciate Ligament Reconstruction: 2-Year Follow-up on 1432 Reconstructions at a Single Center." *The American Journal of Sports Medicine*, vol. 48, no. 4, 2020, p. 13.

Konishi, Y., Fukubayashi, T., & Takeshita, D. (2002). Possible mechanism of quadriceps femoris weakness in patients with ruptured anterior cruciate ligament: *Medicine & Science in Sports & Exercise*, *34*(9), 1414–1418. https://doi.org/10.1097/00005768-200209000-00003

Kulas, Anthony S., et al. "Trunk Position Modulates Anterior Cruciate Ligament Forces and Strains during a Single-Leg Squat." *Clinical Biomechanics*, vol. 27, no. 1, 2012, pp. 16–21, doi:10.1016/j.clinbiomech.2011.07.009.

Landing Biomechanics in Anterior Cruciate Ligament Reconstructed Females Who Pass or Fail a Functional Test Battery | Elsevier Enhanced Reader. Doi:10.1016/j.knee.2018.09.006. Accessed 2 Sept. 2020.

Lohmander, L. S. (n.d.). *High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury*. 8., 2004

Lohmander, L. Stefan, et al. "The Long-Term Consequence of Anterior Cruciate Ligament and Meniscus Injuries: Osteoarthritis." *The American Journal of Sports Medicine*, vol. 35, no. 10, 2007, pp. 1756–69, doi:10.1177/0363546507307396.

Lynch, Andrew D., et al. "Consensus Criteria for Defining 'Successful Outcome' after ACL Injury and Reconstruction: A Delaware-Oslo ACL Cohort Investigation." *British Journal of Sports Medicine*, vol. 49, no. 5, 2015, pp. 335–42, doi:10.1136/bjsports-2013-092299.

Mather, Richard C., et al. "Societal and Economic Impact of Anterior Cruciate Ligament Tears." *The Journal of Bone and Joint Surgery. American Volume*, vol. 95, no. 19, Oct. 2013, pp. 1751–59, doi:10.2106/JBJS.L.01705.

Mirkov, Dragan M., et al. "Contralateral Limb Deficit after ACL-Reconstruction: An Analysis of Early and Late Phase of Rate of Force Development." *Journal of Sports Sciences*, vol. 35, no. 5, Mar. 2017, pp. 435–40, doi:10.1080/02640414.2016.1168933.

Orishimo, Karl F., et al. "Adaptations in Single-Leg Hop Biomechanics Following Anterior Cruciate Ligament Reconstruction." *Knee Surgery, Sports Traumatology, Arthroscopy*, vol. 18, no. 11, 2010, pp. 1587–93, doi:10.1007/s00167-010-1185-2.

Paterno, Mark V., Laura C. Schmitt, et al. "Biomechanical Measures During Landing and Postural Stability Predict Second Anterior Cruciate Ligament Injury After Anterior Cruciate Ligament Reconstruction and Return to Sport." *The American Journal of Sports Medicine*, vol. 38, no. 10, Oct. 2010, pp. 1968–78, doi:10.1177/0363546510376053.

Paterno, Mark V., Mitchell J. Rauh, et al. "Incidence of Contralateral and Ipsilateral Anterior Cruciate Ligament (ACL) Injury After Primary ACL Reconstruction and Return to Sport." *Clinical Journal of Sport Medicine : Official Journal of the Canadian Academy of Sport Medicine*, vol. 22, no. 2, Mar. 2012, pp. 116–21, doi:10.1097/JSM.0b013e318246ef9e.

Paterno, M. V., Rauh, M. J., Schmitt, L. C., Ford, K. R., & Hewett, T. E. (2014). Incidence of Second ACL Injuries 2 Years After Primary ACL Reconstruction and Return to Sport. *The American Journal of Sports Medicine*, *42*(7), 1567–1573. https://doi.org/10.1177/0363546514530088

---. “Incidence of Second ACL Injuries 2 Years After Primary ACL Reconstruction and Return to Sport.” *The American Journal of Sports Medicine*, vol. 42, no. 7, 2014, pp. 1567–73, doi:10.1177/0363546514530088.

Pietrosimone, B., Lepley, A. S., Harkey, M. S., Luc-Harkey, B. A., Blackburn, J. T., Gribble, P. A., Spang, J. T., & Sohn, D. H. (2016). Quadriceps Strength Predicts Self-reported Function Post-ACL Reconstruction. *Medicine & Science in Sports & Exercise*, *48*(9), 1671–1677. https://doi.org/10.1249/MSS.0000000000000946

Rice, D. A., & McNair, P. J. (2010). Quadriceps Arthrogenic Muscle Inhibition: Neural Mechanisms and Treatment Perspectives. *Seminars in Arthritis and Rheumatism*, *40*(3), 250–266. https://doi.org/10.1016/j.semarthrit.2009.10.001

Sanders, Thomas L., et al. “Incidence of Anterior Cruciate Ligament Tears and Reconstruction: A 21-Year Population-Based Study.” *The American Journal of Sports Medicine*, vol. 44, no. 6, 2016, pp. 1502–07, doi:10.1177/0363546516629944.

Sugimoto, D., Myer, G. D., Bush, H. M., Klugman, M. F., McKeon, J. M. M., & Hewett, T. E. (2012). Compliance With Neuromuscular Training and Anterior Cruciate Ligament Injury Risk Reduction in Female Athletes: A Meta-Analysis. *Journal of Athletic Training*, *47*(6), 714–723. https://doi.org/10.4085/1062-6050-47.6.10

Tegner M, Y. (1985). *Rating Systems in the Evaluation of Knee Ligament Injuries*. *198*, 7.

Wang, Li-Juan, et al. “Post-Traumatic Osteoarthritis Following ACL Injury.” *Arthritis Research & Therapy*, vol. 22, no. 1, 2020, p. 57, doi:10.1186/s13075-020-02156-5.

Webster, Kate E., and Julian A. Feller. “A Research Update on the State of Play for Return to Sport after Anterior Cruciate Ligament Reconstruction.” *Journal of Orthopaedics and Traumatology*, vol. 20, no. 1, 2019, p. 10, doi:10.1186/s10195-018-0516-9.

Welling, Wouter, et al. “Low Rates of Patients Meeting Return to Sport Criteria 9 Months after Anterior Cruciate Ligament Reconstruction: A Prospective Longitudinal Study.” *Knee Surgery, Sports Traumatology, Arthroscopy*, vol. 26, no. 12, 2018, pp. 3636–44, doi:10.1007/s00167-018-4916-4.

Wren, Tishya A. L., et al. “Hop Distance Symmetry Does Not Indicate Normal Landing Biomechanics in Adolescent Athletes With Recent Anterior Cruciate Ligament Reconstruction.” *Journal of Orthopaedic & Sports Physical Therapy*, vol. 48, no. 8, 2018, pp. 622–29, doi:10.2519/jospt.2018.7817.

Yamazaki, J., et al. “Differences in Kinematics of Single Leg Squatting between Anterior Cruciate Ligament-Injured Patients and Healthy Controls.” *Knee Surgery, Sports Traumatology, Arthroscopy*, vol. 18, no. 1, 2010, pp. 56–63, doi:10.1007/s00167-009-0892-z.

Appendix I- IRB Approval Letter

EAST CAROLINA UNIVERSITY
University & Medical Center Institutional Review Board
4N-64 Brody Medical Sciences Building· Mail Stop 682
600 Moye Boulevard · Greenville, NC 27834
Office 252-744-2914 · Fax 252-744-2284 ·
rede.ecu.edu/umcirb/

Notification of Initial Approval: Expedited

From: Biomedical IRB
To: Anthony Kulas
CC:
Date: 3/16/2021
Re: UMCIRB 21-000438
, Effect of Strength Symmetry on Single Leg Squat and Return to Sport Criteria

I am pleased to inform you that your Expedited Application was approved. Approval of the study and any consent form(s) occurred on 3/15/2021. The research study is eligible for review under expedited category # 4,6,7. The Chairperson (or designee) deemed this study no more than minimal risk.

As the Principal Investigator you are explicitly responsible for the conduct of all aspects of this study and must adhere to all reporting requirements for the study. Your responsibilities include but are not limited to:

1. Ensuring changes to the approved research (including the UMCIRB approved consent document) are initiated only after UMCIRB review and approval except when necessary to eliminate an apparent immediate hazard to the participant. All changes (e.g. a change in procedure, number of participants, personnel, study locations, new recruitment materials, study instruments, etc.) must be prospectively reviewed and approved by the UMCIRB before they are implemented;

2. Where informed consent has not been waived by the UMCIRB, ensuring that only valid versions of the UMCIRB approved, date-stamped informed consent document(s) are used for obtaining informed consent (consent documents with the IRB approval date stamp are found under the Documents tab in the ePIRATE study workspace);

3. Promptly reporting to the UMCIRB all unanticipated problems involving risks to participants and others;

4. Submission of a final report application to the UMICRB prior to the expected end date provided in the IRB application in order to document human research activity has ended and to provide a timepoint in which to base document retention; and

5. Submission of an amendment to extend the expected end date if the study is not expected to be completed by that date. The amendment should be submitted 30 days prior to the UMCIRB approved expected end date or as soon as the Investigator is aware that the study will not be completed by that date.

The approval includes the following items:

Name	Description
Informed-Consent-Document_Revised.doc	Consent Forms
IRB Protocol_revised	Study Protocol or Grant Application
KOOS Survery	Surveys and Questionnaires
Recruitment Announcement	Recruitment Documents/Scripts
Screening Questionnaire	Recruitment Documents/Scripts
Tegner Activity Scale	Surveys and Questionnaires

For research studies where a waiver or alteration of HIPAA Authorization has been approved, the IRB states that each of the waiver criteria in 45 CFR 164.512(i)(1)(i)(A) and (2)(i) through (v) have been met. Additionally, the elements of PHI to be collected as described in items 1 and 2 of the Application for Waiver of Authorization have been determined to be the minimal necessary for the specified research.

The Chairperson (or designee) does not have a potential for conflict of interest on this study.

IRB00000705 East Carolina U IRB #1 (Biomedical) IORG0000418
IRB00003781 East Carolina U IRB #2 (Behavioral/SS) IORG0000418

Appendix II – Informed Consent

Informed Consent to Participate in Research

Information to consider before taking part in research that has no more than minimal risk.

Title of Research Study: Effect of Quadricep Strength Symmetry on Knee Joint Symmetry during SLS in ACLR and Healthy Individuals

Principal Investigator: Anthony S. Kulas (Person in Charge of this Study)
Institution, Department or Division: East Carolina University Department of Kinesiology
Address: A17 Minges Coliseum
Telephone #: 252-737-2884

Researchers at East Carolina University (ECU) study issues related to society, health problems, environmental problems, behavior problems and the human condition. To do this, we need the help of volunteers who are willing to take part in research.

Why am I being invited to take part in this research?
The purpose of this research is to determine the effect of quadricep strength symmetry on knee joint symmetry biomechanics in ACLR (anterior cruciate ligament reconstructed) and healthy controls. You are being invited to take part in this research because you: 1) are recreationally active, and 2) you have no known history of knee injuries or surgeries; or you have had anterior cruciate ligament reconstruction. The decision to take part in this research is yours to make. By doing this research, we hope to learn the effect of quadriceps strength deficits on limb performance during a single leg squat.

If you volunteer to take part in this research, you will be one of about 60 people to do so.

Are there reasons I should not take part in this research?
I understand I should not volunteer to be in this research study if I am under 18 or over 25 years of age, if I have a history of knee injuries or surgeries, or if I have had anterior cruciate ligament reconstructive surgery and not been medically cleared for unrestricted activities.

What other choices do I have if I do not take part in this research?
You can choose not to participate.

Where is the research going to take place and how long will it last?
The research will be conducted in the Biomechanics Lab, located in room 332 of the Ward Sports Medicine Building at East Carolina University. You will need to come to the Biomechanics Lab one time during the study. The total amount of time you will be asked to volunteer for this study is approximately 2 and a half hours.

What will I be asked to do?

You will be asked to do the following:

- You will be asked to complete the Knee Injury and Osteoarthritis Score (KOOS) and the Tegner Activity Scale questionnaires, perform five trials of each of the following single leg hop tests: single-leg hop for distance, single-leg triple hop for distance, and 6-meter timed single-leg hop. In addition, you will be asked to perform five trials of isometric and isokinetic dynamometer strength tests to assess knee extensor and flexor strength on each limb, and then perform a three single-leg squats and three single leg hops for distance on each limb.
- Motion capture will be used to analyze these movements and this system collects the movement of the markers. Thus, no recognizable features will be recorded. We will also take several standard anthropometric measurements i.e. height and weight. However, all tests will also be video recorded. This will record all of the movements during the hops and single-leg squat. Each of the data files for the motion capture and the video recorded trials will be named using the previously determined alphanumeric code to anonymize the data. Only study staff will have access to all recorded data. All videos will have participant's facial and other identifying features blurred using video editing software. It will be destroyed 3 years after the completion of the study. They will deleted off the data server 3 years after the completion of the study. You have the right to allow or disallow video recording.

  Participant agrees to be videotaped
  ___________YES ___________NO

What might I experience if I take part in the research?
We don't know of any risks (the chance of harm) associated with this research. Any risks that may occur with this research are no more than what you would experience in everyday life. We don't know if you will benefit from taking part in this study. There may not be any personal benefit to you but the information gained by doing this research may help others in the future.

Will I be paid for taking part in this research?
We will not be able to pay you for the time you volunteer while being in this study.

Will it cost me to take part in this research?
It will not cost you any money to be part of the research.

Who will know that I took part in this research and learn personal information about me?
ECU and the people and organizations listed below may know that you took part in this research and may see information about you that is normally kept private. With your permission, these people may use your private information to do this research:

- Any agency of the federal, state, or local government that regulates human research. This includes the Office for Human Research Protections.
- The University & Medical Center Institutional Review Board (UMCIRB) and its staff have responsibility for overseeing your welfare during this research and may need to see research records that identify you.

How will you keep the information you collect about me secure? How long will you keep it?
If you elect to enroll in this study by signing this informed consent document, you will be assigned an alphanumeric code. Only this alphanumeric code, not your name, will appear on all electronically saved measurements. All data collected from you will only have this alphanumeric code associated with it and this data will be backed up on a network server in this lab. The only person to have access to the master

list of names which link your name to your alphanumeric code will be the researchers identified here, Ms. Claire Wilhelm and Dr. Anthony S. Kulas. All paperwork and forms linking you to the study will be kept in the Pis office which remains locked except when in use. This information will be kept secure for a period of three years following the closure of the study, after which this information will be shredded or electronically deleted.

What if I decide I don't want to continue in this research?

You can stop at any time after it has already started. There will be no consequences if you stop and you will not be criticized. You will not lose any benefits that you normally receive.

Who should I contact if I have questions?

The people conducting this study will be able to answer any questions concerning this research, now or in the future. You may contact the Principal Investigator at (252) 737-2884 (days, between 8am-5pm).

If you have questions about your rights as someone taking part in research, you may call the University & Medical Center Institutional Review Board (UMCIRB) at phone number 252-744-2914 (days, 8:00 am-5:00 pm). If you would like to report a complaint or concern about this research study, you may call the Director for Human Research Protections, at 252-744-2914

Is there anything else I should know?

All movement tests, single leg squat and single leg hop for distance, will be video recorded. Your information collected as part of the research, even if identifiers are removed or fascial features blurred, will not be used or distributed for future studies.

If you are an ACLR subject, after your data has been collected, your quadriceps strength symmetry between the reconstructed and non-reconstructed limb will determine placement in one of two groups. These groups are either limb symmetry of greater than or equal to 90% or less than 90%.

I have decided I want to take part in this research. What should I do now?

The person obtaining informed consent will ask you to read the following and if you agree, you should sign this form:

- I have read (or had read to me) all of the above information.
- I have had an opportunity to ask questions about things in this research I did not understand and have received satisfactory answers.
- I know that I can stop taking part in this study at any time.
- By signing this informed consent form, I am not giving up any of my rights.
- I have been given a copy of this consent document, and it is mine to keep.

____

Participant's Name (PRINT) **Signature** **Date**

Person Obtaining Informed Consent: I have conducted the initial informed consent process. I have orally reviewed the contents of the consent document with the person who has signed above, and answered all of the person's questions about the research.

____

Person Obtaining Consent (PRINT) **Signature** **Date**

Principal Investigator (PRINT) Signature Date

Appendix III – KOOS

Knee injury and Osteoarthritis Outcome Score (KOOS), English version LK1.0

KOOS KNEE SURVEY

INSTRUCTIONS: This survey asks for your view about your knee. This information will help us keep track of how you feel about your knee and how well you are able to perform your usual activities.
Answer every question by ticking the appropriate box, only one box for each question. If you are unsure about how to answer a question, please give the best answer you can.

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

S1. Do you have swelling in your knee?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S2. Do you feel grinding, hear clicking or any other type of noise when your knee moves?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S3. Does your knee catch or hang up when moving?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S4. Can you straighten your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

S5. Can you bend your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

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

S6. How severe is your knee joint stiffness after first wakening in the morning?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

S7. How severe is your knee stiffness after sitting, lying or resting **later in the day**?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Pain

P1. How often do you experience knee pain?

Never	Monthly	Weekly	Daily	Always
☐	☐	☐	☐	☐

What amount of knee pain have you experienced the **last week** during the following activities?

P2. Twisting/pivoting on your knee

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P3. Straightening knee fully

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P4. Bending knee fully

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P5. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P6. Going up or down stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P7. At night while in bed

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P8. Sitting or lying

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P9. Standing upright

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Function, daily living

The following questions concern your physical function. By this we mean your ability to move around and to look after yourself. For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A1. Descending stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A2. Ascending stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

For each of the following activities please indicate the degree of difficulty yo have experienced in the **last week** due to your knee.

A3. Rising from sitting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A4. Standing

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A5. Bending to floor/pick up an object

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A6. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A7. Getting in/out of car

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A8. Going shopping

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A9. Putting on socks/stockings

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A10. Rising from bed

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A11. Taking off socks/stockings

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A12. Lying in bed (turning over, maintaining knee position)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A13. Getting in/out of bath

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A14. Sitting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A15. Getting on/off toilet

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A16. Heavy domestic duties (moving heavy boxes, scrubbing floors, etc)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A17. Light domestic duties (cooking, dusting, etc)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Function, sports and recreational activities

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

SP1. Squatting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP2. Running

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP3. Jumping

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP4. Twisting/pivoting on your injured knee

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP5. Kneeling

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Quality of Life

Q1. How often are you aware of your knee problem?

Never	Monthly	Weekly	Daily	Constantly
☐	☐	☐	☐	☐

Q2. Have you modified your life style to avoid potentially damaging activities to your knee?

Not at all	Mildly	Moderately	Severely	Totally
☐	☐	☐	☐	☐

Q3. How much are you troubled with lack of confidence in your knee?

Not at all	Mildly	Moderately	Severely	Extremely
☐	☐	☐	☐	☐

Q4. In general, how much difficulty do you have with your knee?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Thank you very much for completing all the questions in this questionnaire.

Appendix IV- Tegner Activity Scores

Tegner Activity Score

Please check the circle that best fits the highest level of activity you are currently performing OR if you have presently injured your ACL, please check the circle that best fits the highest level of activity prior to your injury.

◯ Competitive Sports- Soccer, football - National and International Elite

◯ Competitive Sports- Soccer, football (lower divisions), Ice Hockey, Wrestling, Gymnastics

◯ Competitive Sports- Bandy, Squash, Badminton, Field Events, Downhill Skiing

◯ Competitive Sports- Tennis, Track, Motorcross, Speedway, Handball, Basketball, Cross Country
Recreational Sports- Soccer, Bandy, Ice Hockey, Squash, Field Events, Cross Country

◯ Recreational Sports- Tennis, Badminton, Handball, Basketball, Downhill Skiing, Jogging (at least 5x a week)

◯ Work – Heavy labor (e.g. building, forestry); OR
Competitive sports – cycling, cross-country skiing; OR
Recreational Sports – jogging on uneven ground at least twice weekly.

◯ Work – Moderately heavy labor (e.g. truck driving, heavy domestic work); OR
Recreational Sports – cycling, cross-country skiing, jogging on even ground at least twice weekly.

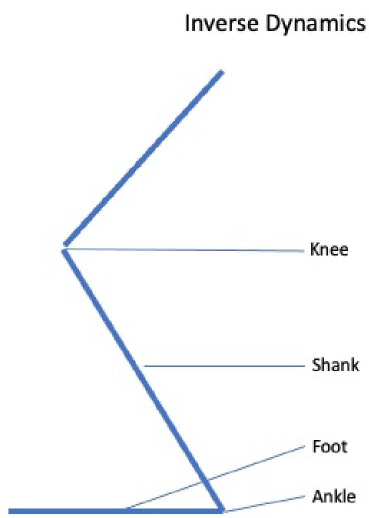
◯ Work – Light labor; Walking on uneven ground possible but impossible to walk in forest

◯ Work – Sedentary work; Walking on even ground possible

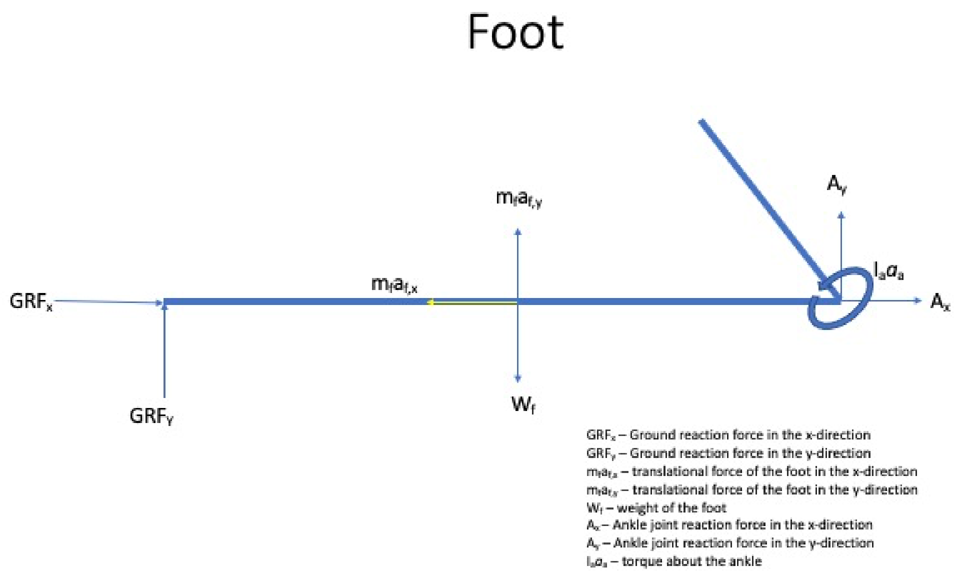
◯ Sick leave or disability pension because of knee problems

Appendix V-Inverse Dynamics

Inverse dynamics is a common way in order to calculate joint torques and is what is used in V3D when running pipeline commands. The image below shows the lower extremities in the midst of a single leg squat, displaying the stance limb. The varying lines represent the different segments from bottom to top: foot, shank, and thigh. In order to solve for the joint torques, one must start from the bottom and work up through the limbs and joints.

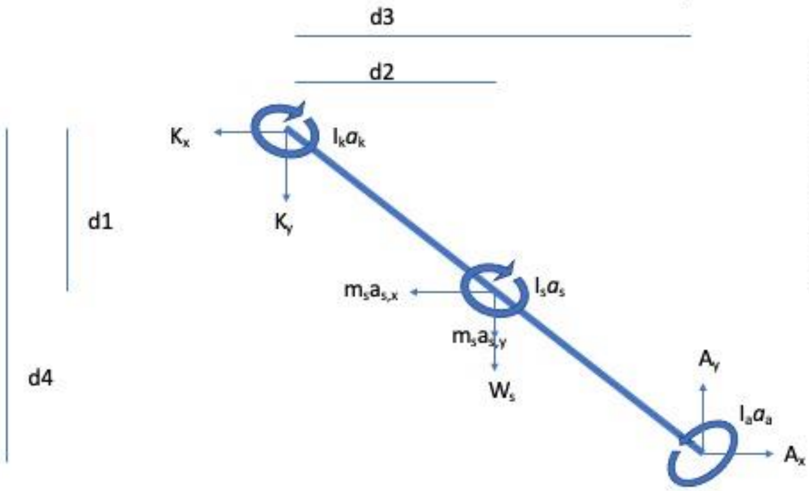


The first segment analyzed when solving through inverse dynamics is the foot. The forces that play into the calculation of the ankle joint reaction force are the ground reaction forces, the linear acceleration forces of the foot, the weight of the foot, and the sum of the torques about the ankle. In order to solve for the ankle joint reaction forces, all of the forces in the x direction are equal to the ankle joint reaction force in the x direction and all of the forces in the y direction are equal to the ankle joint reaction force in the y direction of the ankle joint force. For the 2D diagrams below, the directions are in x and y, but in visual 3d they are x and z.



In order to calculate the knee joint reaction force, one must use the summed ankle torques as a representation of the force affect the foot has on the shank, and indirectly the knee. The forces affecting the knee joint reaction force are the ankle joint reaction forces, the weight of the shank, the shank torques, the linear acceleration of the shank, and the knee torque. The knee joint reaction forces will be calculated by setting the forces moving in the clockwise direction equal to those moving in the counterclockwise direction. The distances are used in order to calculate moment arms.

Shank/Knee



A_x – Ankle joint reaction force in the x-direction
A_y – Ankle joint reaction force in the y-direction
$I_a\alpha_a$ – torque about the ankle
W_s – weight of the shank
$m_s a_{s,x}$ – translational force of the shank in the x-direction
$m_s a_{s,y}$ - translational force of the shank in the y-direction
$I_s\alpha_s$ – torque about the shank
K_x– knee joint reaction force in the x-direction
K_y – knee joint reaction force in the y-direction
$I_k\alpha_k$ – torque about the knee
d1 & d2– distance from knee to the shank center of mass
d3 & d4 – distance from knee joint center to ankle joint center

Clockwise = Counterclockwise

$$I_a\alpha_a = A_x(\Delta y) + A_y(0.5 l_{ft}) + GRF_x(\Delta y) + GRF_y(0.5 l_{ft}) + I_{ft}\alpha_{ft}$$

$$I_k\alpha_k + I_s\alpha_s + m_s a_{s,x}(d1) + m_s a_{s,y}(d2) = I_a\alpha_a + W_s(d2) + A_x(d4) + A_y(d3)$$

Joint Reaction Forces

Right = Left

$$K_x = A_x - m_s a_{s,x}$$

$$K_y = A_y - m_s a_{s,y}$$

$$A_x = -GRF_x - m_f a_{f,x}$$

$$A_y = W_f - GRF_y - m_f a_{f,y}$$

Appendix VI-Correlation Scatterplots

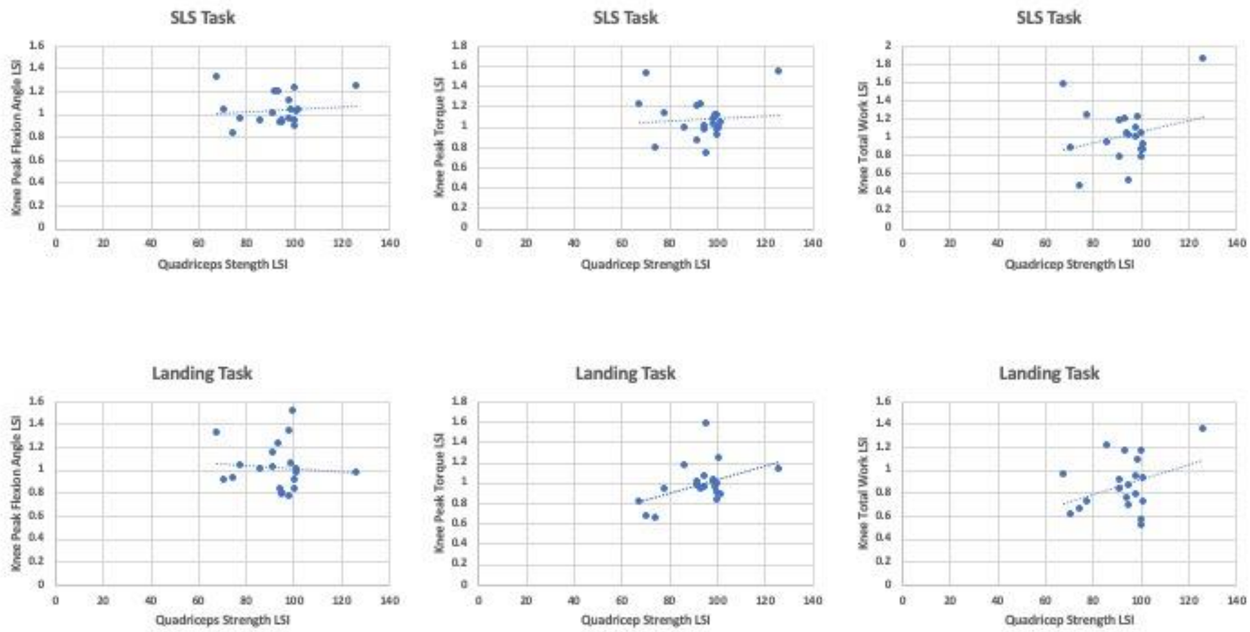


Figure 5. Correlations of quadricep strength LSI to knee peak flexion angle LSI, knee peak torque LSI, knee total work LSI.

Appendix VII-Split Correlation Scatterplots

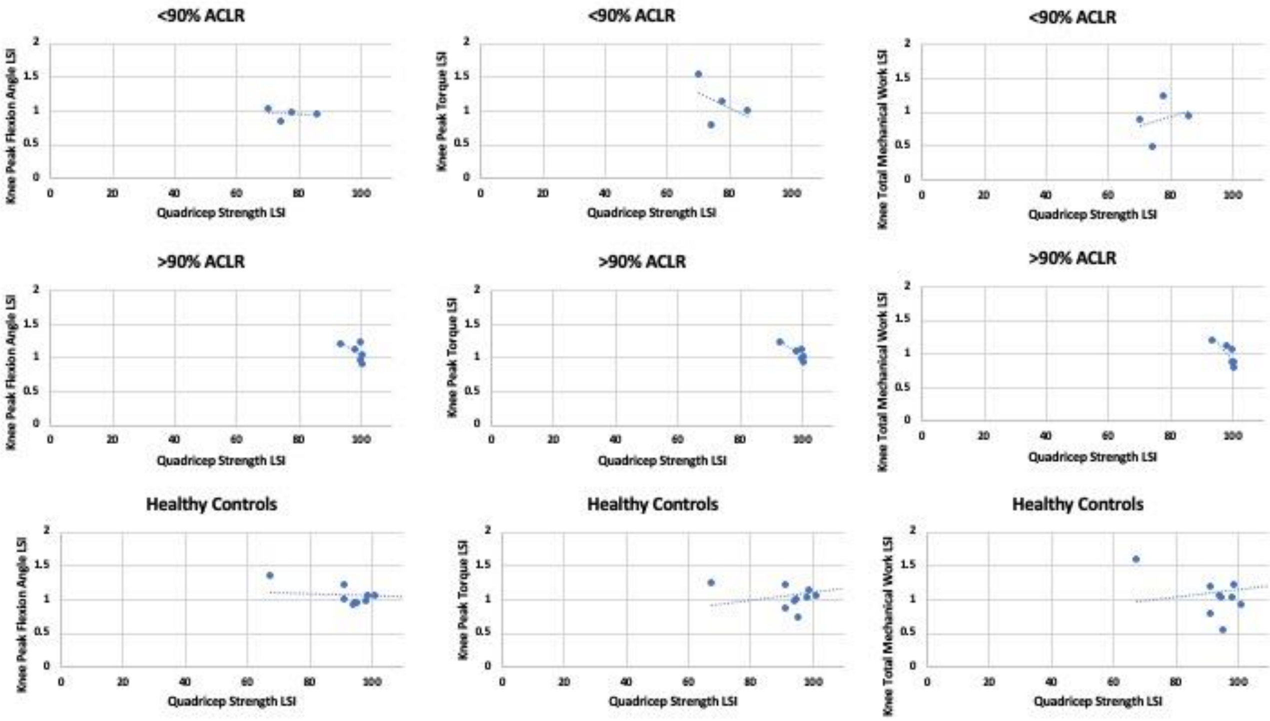


Figure 6. Correlations of quadricep strength LSI to knee peak flexion angle LSI, knee peak torque LSI, knee total work LSI for the three groups: <90% ACLR, >90% ACLR, and Healthy Controls.