Difference in Knee Joint Loading Metrics Following ACL repair versus ACL Reconstruction

By: Alexandra Ewing, MS4

Mentor: Dr. Singleton, MD

Abstract

Research question: Do individuals who undergo a primary anterior cruciate ligament (ACL) repair (ACL-r) versus standard ACL reconstruction (ACL-R) have differences in knee joint loading metrics?

Background, significance, and rational for the question: ACL injuries are one of the most common knee injuries in athletes and the general population. At this time, ACL injuries are most often treated with ACL reconstruction and even with the great advances made in technology and physician expertise, the outcomes of ACL reconstruction on joint health is bleak. Those that undergo ACL-R may result in or expedite the arthritic process and lead to articular cartilage lesions. This is hypothesized to take place due to a variety of factors, including prolonged underloading of the knee joint following surgery. Recent studies have shown that ACL-r may provide some type to the cartilage and possibly slow the effects of joint degeneration. This is said to be due to decreased surgical trauma associated with preservation of the native ACL ligament. ACL-r has been shown to benefit lower extremity and knee biomechanics and proprioception. This data is based off of older ACL-r methods and there is limited data on newer ACL-r techniques and the effect on knee joint loading. Therefore, this study is being conducted to assess the difference in knee joint loading metrics between individuals who have undergone primary ACL-r and those following standard ACL-R with a patella bone-tendon-bone autograft.

Materials and methods:

A total of 30 participants were enrolled in this study. The ACL-r group [n: 15, age(yrs): 38.8±13.9, Ht(cm): 173.4±10.0, Wt(kg): 77.9±17.5] sustained a proximal ACL disruption

(Sherman Classification Type 1 or 2) that was amendable to repair, while the ACL-R group [n: 15, age(yrs): 25.60±1.7, Ht(cm): 173.5±10.3, Wt(kg): 75.4±15.6] underwent primary reconstruction with a patella bone-tendon-bone autograft. At 12 weeks post-operation, participants in both groups completed the International Knee Documentation Committee (IKDC) questionnaire and underwent biomechanical testing. Total knee joint power measured as eccentric loading (contraction) during the descent phase of the squat and bilateral peak knee extension were calculated using the average of the middle three of five repetitions of testing on both the surgical and non-surgical limb. Three months after surgery, participants also completed a quadriceps strength test on both limbs on an isokinetic dynamometer 60 °/sec. The average peak torque of five repetitions was used to calculate the limb symmetry index (LSI). To examine differences between groups, separate ANOVAS were performed for each biomechanical variable.

Results:

The ACL-r had a significantly greater peak knee extension moment (ACL-r: 78.46±5.79%; ACL-R: 56.86±5.79%; p=0.019, ηp2=.186) , as well as total knee joint power (ACL-r: 72.47±7.39%; ACL-R: 39.70±7.39%, p=0.006, ηp2=.245) than the ACL-R group. The ACL-r group also had a significantly greater quadriceps LSI than the ACL-R group (ACL-r: 66.318±4.61%, ACL-R: 48.03±4.61%, p=0.013, ηp2=.206).

Conclusions:

Individuals who underwent ACL-r demonstrated increased knee joint loading symmetry during a single leg squat test, as well as greater quadriceps strength symmetry at 12 weeks post-operation as compared to those who underwent ACL-R.

The work presented in this thesis has been published by me and my coauthors in the following publication:

Singleton S, Scofield H, Davis B, Waller A, Garrison C, Goto S, and Hannon J. Altered Knee Loading Following Primary ACL Repair versus ACL Reconstruction. Int J Sports Phys Ther. 2023;V18(3):596-605. doi:10.26603/001c.77362

Research Question:

Do individuals who undergo Anterior cruciate ligament (ACL) reconstruction have greater severity of knee cartilage changes than individuals who undergo ACL repair at 3 months and at time of return to sports/ activities following surgery? Further, is there a relationship between knee joint loading, strength of lower limb, and knee cartilage changes seen in patients who have received ACL reconstruction or ACL repair at each measured timepoint?

We hypothesize that patients who undergo ACL repair versus those who undergo ACL reconstruction will have favorable knee joint loading metrics due to maintaining the patients' native tissue and helping prevent long-term joint degeneration.

Introduction and Significance:

ACL injuries are very common, especially in young athletes. There are approximately 250,000 ACL ruptures each year in the United States [1]. Treatment options consist of ACL repair and ACL reconstruction, where ACL repair involves repairing the injured tissue, while ACL reconstruction involves utilizing a graft, most often an autograft, to reconstruct the ligament. Whether surgical repair involves ACL repair or reconstruction, the goal is to preserve the knee's functionality and allow patients to return to sports and normal daily activities[1]. ACL-R is the currently the most recommended as it is thought that ACL-R improves knee rotational stability and help restore proper joint kinematics, both of which help decrease post-operative pain and increased patient function[2-4]. Recent studies that look at both short-and long-term outcomes following ACL-R are now showing that the outcomes may not be as favorable as originally thought.

When patients are asked about their expectations following ACL-R, 91% state they expect to return to the same level of activity they had preinjury, but return to sports data suggests that only 81% of people return any sport, 65% are able to return to the same level they were at prior to the injury, and 55% are able to return to a competitive level of activity [5,6]. Over the next 5-15 years post-injury, approximately 50% of patients who suffer an ACL injury will go on to develop knee joint osteoarthritis (OA). Studies have shown that overtime articular cartilage lesions are to be expected, and often times articular cartilage degeneration progresses to osteoarthritis [7,8]. Load and stress placed on the knee during the rehabilitation process, including overloading and underloading, are thought to play a role in the cartilage degeneration process. It used to be

thought that overloading the knee was destructive to the healing process, but recent studies show that underloading may be a contributory factor to osteoarthritis [9,10].

Knee OA and decreased likelihood of returning to the same level of activity is linked to weakness of the quadriceps muscles following ACL-R [4,11-13]. This diminished quadriceps strength following ACL-R is likely related to several factors, including graft site morbidity, post-operative swelling and pain, quadriceps atrophy, decreased knee extension range of motion, and neural changes in the sensory and motor pathways [14-21]. This decreased quadriceps strength following ACL-R can still be present long after the expected return to sport time. One study showed that when comparing average side to side quadriceps strength, the ACL-R side had a 23% and 14% strength deficits at 6 and 12 weeks, respectively [22].

With studies showing these downsides to ACL-R, there is a renewed interest in the ACL-r procedure, which is thought to potentially be more joint friendly due to the decreased surgical trauma, as well as preservation of the native ACL. ACL-r was once a more common procedure, but was abandoned in 1976 when a study by Feagin et al. demonstrated poor mid-term outcomes with nearly a 50% re-tear rate [23]. There are several limitations in these older studies, such as older techniques and cast immobilization for up to 6 weeks post-surgery, which could play a role in these poor outcomes [23-25].

New studies on early and midterm data on ACL-r shows that the re-tear rates may actually be similar to those who undergo ACL-R in specific patients and tear types [26]. Those with proximal

tears (Sherman type 1 and 2) appear to have better outcomes from ACL-r, while those with midsubstance and distal tears (Sherman type 3 and 4) are better with ACL-R [27,28].

This study was done in order to assess the differences in knee joint loading metrics during single limb squat task between individuals following ACL-r and those who underwent ACL-R with a patella bone-tendon-bone autograft. The single limb squat task was picked due to the ease of implementation during the rehabilitation process. The single limb squat is used as both an exercise in order to improve lower extremity strength and neuromuscular control, as well as a screening tool [14]. As a screening tool the single limb squat helps assess readiness for return to normal activity [29-31]. It is hypothesized that there will be improved surgical knee loading in ACL-r when compared with surgical knee loading after ACL-R at three months post-operation.

Research Materials and Methods:

Participants

Subjects were identified by coming to Texas Health Sports Medicine for an ACL injury and a total of 30 patients who met the inclusion criteria were enrolled in the study. Eligibility criterion included patients between the ages of twelve and sixty who sustained a primary ACL injury and elected to undergo either ACL-r or ACL-R. These patients were active for at least 50 hours per year and were attempting to return to their activity after surgery. Participants that had previously injured their ACL, had a simultaneous ACL tear, had full thickness chondral injuries, had a grade II or III injury of the medial collateral ligament (MCL), posterior collateral ligament (PCL) injury, or lateral collateral ligament injury were excluded from the study.

All participants underwent pre-rehabilitation education and surgical treatment with the same treating surgeon and were then tested three months following surgery. Participants in ACL-r group sustained a proximal ACL disruption (Sherman Classification Type 1 or 2) that was amendable to repair and underwent suture fixation[14,32]. Participants that were in the ACL-R group underwent a primary ACL-R with patella bone-tendon-bone autograft [14]. All participants post-operatively enrolled in and completed formal physical therapy, which was guided by the rehabilitation protocol of the treating surgeon.

ACL-r Surgical Technique

As described in Singleton et al, ACL-r was performed under arthroscopic visualization with two or three standard portals in a technique similar to that described by DiFelice et al [24], but modified

by the senior author to include only one 4.75mm SwiveLock (Arthrex, Naples, FL) secured in the anterior aspect of the native footprint on the medial wall of the lateral femoral condyle. Indications for repair were similar to that described by DiFelice et al [14,24].

ACL-R Surgical Technique

As described in Singleton et al, participants in the ACL-R group underwent a primary ACL-R with patella bone-tendon-bone autograft. The autograft bone blocks were crimped to 9mm and then two 10mm femoral and tibial tunnels created for the graft. An independent tunnel technique, utilizing the medial portal for creation of the femoral socket within the native ACL femoral attachment site, was performed in all ACL-R patients [14].

Rehabilitation protocol

All participants completed formal physical therapy, which was guided by the rehabilitation protocol of the treating surgeon and further described in Bousquet et al [33]. The protocol was divided into four phases: 1) protection, mobility, and activation (weeks 0-4), 2) stability and neuromuscular control (weeks 4-8), 3) strengthening (weeks 8-12), 4) return to sport (week 12-16). Each participant completed each phase and met specific criteria prior to progressing to the next one.

IKDC Questionnaire

A subjective patient-completed questionnaire to identify symptoms and function after knee injury. This is a subjective test where the lower scores are associated with the lowest level of function or highest level of symptoms. It involves three domains, symptoms, such as pain, swelling, locking/catching, daily activities, and current knee function [34]. All participants were given this questionnaire 12 weeks post-surgery.

Biomechanical Instrumentation

For biomechanical testing a 10-camera Motion Capture System (Qualisys AB, Göteborg, Sweden) was utilized with a sampling rate of 120 Hz. It captured joint motion in all three planes during the single limb squat. Thirty-three reflective markers were placed with double-sided tap on each participant's skin or clothing. Retroreflective markers were attached to the spinous process of the seventh cervical vertebra, twelfth thoracic vertebra, between the fourth and fifth lumbar vertebrae, sternum, bilateral acromion process, anterior superior iliac spine, posterior superior iliac spine, greater trochanter, anterior thigh, medial epicondyles of femur, lateral epicondyles of femur, anterior shank, medial malleolus, lateral malleolus, calcaneus, first metatarsal head, and fifth metatarsal head. There were an additional three retroreflective markers placed on the sacrum as a cluster. Two Advanced Medical Technology Inc. (AMTI) multi-axis force plates capturing at 1200 Hz collected the ground reaction force data, which was used to calculate the joint kinetics. These were also synchronized to the camera , which allowed for accurate time sequencing during data collection and processing.

Isokinetic Quadriceps Strength Testing

To test concentric extensor peak torque the Biodex Multi-Joint Testing and Rehabilitation System (Biodex Medical Systems, NY) was used. Extensor peak torque throughout this study will be referred to as quadriceps strength.. The femoral condyle of the limb being tested was lined up with the Biodex axis of rotation. Quadriceps strength was measured at 60 degrees per second on each limb and was consisted of five consecutive concentric contractions. For analysis, the average of the five tests was used. Tests were discarded if it resulted in a coefficient of variance greater than 15% [35,36]. Testing was performed on non-surgical limb followed by the surgical limb.

Single Limb Squat

To look at frontal, sagittal, and transverse plane kinematics, the single limb squat task was chosen due to its use throughout literature in both healthy and injured groups in order to assess quality of movement [37,38]. The single limb squat task is a foundational movement pattern during rehabilitation after ACL injury. Performance during a single limb squat is used as a proxy to asses lower extremity strength, as well as readiness to return to sport [29,39,40]. Participants from all groups were given time to warm up until they felt ready for the task. Participants were instructed to stand on one foot with their toes facing straight forward, contralateral hip and knee flexed to 90 degrees, and their hands on their waist.. They then performed five consecutive single limb squats. To ensure consistent pace across all participants being tested, a metronome set at 60 bpm was used as they completed the five single limb squats. They were told to squat to their best possible depth without losing balance. If a participant did lose their balance, the capture period was not counted and they continued with the task until five consecutive single limb squats were

completed. For data analysis, the mean of the middle three squats were utilized. All participants completed the task first on their non-surgical limb then on their surgical limb.

Data Processing and Reduction

For data processing, the peak quadriceps strength (Nm) was the average of five trials and were then normalized to body mass (Nm Kg^{-1}). The trajectories of the reflective markers were used to estimate the three-dimensional joint coordinates. All force and kinematic data was exported into Visual3D software (C-Motion, Inc. Germantown, MD) for processing, as well as reduction. The markers and force data were filtered via a fourth-order low-pass Butterworth filter with a zero-phase lag at 12 Hz. The peak knee extension moment (Nm $BW*HT^{-1}$) was calculated using an inverse dynamic approach during the descent phase of the single limb squat. The knee energy absorption (J $BW*HT^{-1}$) was calculated as an integration of the negative area of the knee joint power curve as a measure of eccentric loading (contraction) during the descent phase of the single limb squat. This may be able to shower larger differences in knee loading between groups as compared to concentric contraction. These variables were collected during the middle three trials of the five squats for the non-surgical and surgical limb and were then normalized to the participants height and body weight. For all dependent variables, a limb symmetry index (LSI) (surgical/non-surgical X 100) was calculated for all the dependent variables[14].

Statistical analysis

To compare between demographics differences between the groups independent t-tests were utilized. Those variables that showed significant differences were used as covariate for analyses. For the three variables being studied an analysis of covariance (ANOVA) with a p-value set at

$p<0.05$ was used for analysis. The Bonferroni adjustment was included for adjustment of multiple comparisons. Partial Eta squared effect sizes were calculated with standard thresholds to decipher strength of the effect.

Results

As described in Singleton et al. The results showed no difference in the mass (p=0.996), height (p=0.996), IKDC score (p=0.886) or the time between injury and surgery dates (p=0.912) between groups. There was a significant difference in age between the groups (ACL-r: 38.87 ±13.9, ACL-R: 25.60±11.78; p=0.009), with the ACL-r group being significantly older compared to the ACL-R group (Table 1).

Table 1. Participants Demographics (N=30)

	ACL-r (15)	ACL-R (15)	P-Value
Age (years)	38.87 ±13.9	25.60±11.78	0.009*
Height (cm)	173.4±10.0	173.5±10.3	0.996
Mass (Kg)	77.9±17.5	75.4±15.6	0.996
Sex (M/F)	5/10	8/7	0.269
IKDC	67.82	68.52	0.886
Injury to Surgery (Days)	55.33±47.6	57.43±53.7	0.912

*Indicates significance difference between groups; IKDC: International Knee Documentation Committee Short Form

There was a significant difference between groups in all the variables being studied while controlling for age (Table 2). The ACL-r group had a significantly greater peak knee extension moment LSI (ACL-r: 78.46±5.79%; ACL-R: 56.86±5.79%; p=0.019, η_p^2=.186) and net knee joint power LSI (ACL-r: 72.47±7.39%; ACL-R: 39.70±7.39%; p=0.006, η_p^2=.245) during the

single limb squat test when compared to the ACL-R group. The ACL-r group also showed significantly greater quadriceps LSI as compared to the ACL-R group (ACL-r: 66.318±4.61%, ACL-R: 48.03±4.61%; p=0.013, η_p^2=.206). There were no participants that experienced any major complications, such as DVT, infection, or hospitalization, at the final post-surgery follow up[14].

Table 2. Limb Strength Index Results

	ACL-r	**ACL-R**	**p**	**n_p^2**	**95% CI**
Peak knee extension moment LSI (%)	78.46±5.79	56.86±5.79	0.019*	0.186	[3.79, 39.42]
Net Knee Joint power LSI (%)	72.47±7.39	39.70±7.39	0.006*	0.245	[10.04, 55.50]
Quadriceps LSI (%)	66.318±4.61	48.03±4.61	0.013*	0.206	[4.11,32.47]

*Indicates significant differences at a .05 evaluation; η_p^2= partial eta squared effect size

Discussion:

The results of this study demonstrate that individuals who underwent ACL-r have different loading strategies during a single leg squat, as well as greater quadriceps strength symmetry in isokinetic testing when compared to those who underwent ACL-R at 3 months after surgery. Compared to participants in the ACL-R group, those who underwent ACL-r showed greater limb symmetry in peak knee extension moment, knee energy absorption, and quadriceps strength during the single limb squat task. These measurements contribute to changes in both the peak joint loading (knee extension moment) and loading over the entire movement (energy absorption), which are likely important for overall joint function and health.

Those who show quadriceps deficits at three months following ACL-R have been associated with a continued quadriceps deficit at the time of return to normal activity, as well as altered biomechanics, increased risk for second injury, and poor self-report outcomes [36,41,42]. The degree of difference in joint loading between ACL-r and ACL-R groups was large with knee joint power LSI of 72% vs 39% and quadriceps strength LSI of 66% vs 48% in the ACL-r vs ACL-R group respectively [14]. Based on previous studies conducted on long-term quadriceps strength deficits following ACL-R, it is expected that this gap would persist, but likely diminish between groups overtime [22]. Other studies, such as van der List et al. demonstrate that patients that underwent ACL-r had a faster return to normal knee range of motion [28]. Other factors that should be further investigated include those that are potentially different between the ACL-r and ACL-R procedures, such as differences in afferent signaling from knee joint due to leaving native ACL in place during ACL-r.

The strength symmetry results for the ACL-r group shows significantly greater than previous work following AC:-R at three months post-surgery in which the LSI reached 55%, which was directly related to the ability to load the surgical knee [35]. The increased strength could be due to the less traumatic nature of the ACL-r procedure, which results in less post-operative swelling and no graft site morbidity. In the ACL-R group, graft site morbidity is likely not the only factor that contributing the problem as previous studies have shown that decreased quadriceps strength was seen following ACL-R with hamstring autograft and allograft [22,43].

One study done by Lee et al. compared those who underwent ACL-R with remnant tibial stump preservation vs those who understand standard ACL-R without remnant preservation. The results of this study showed that at approximately 2 years post-operation those in the remnant preservation group performed significantly better on tests of proprioception when compared to the standard group [43]. If these findings of remnant preservation are extrapolated to leaving the native ACL in place with ACL-r, it is plausible that the results of proprioception data would be similarly improved in the ACL-r compared to the ACL-R.

Changes to afferent signaling from the knee joint as well as surrounding tissue contributes to arthrogenic muscle inhibition. The mechanisms by which this takes place include changes in discharge of articular sensory receptors, altered spinal reflex excitability, alterations in muscle resting motor thresholds, and abnormal cortical activity [16]. With ACL-r, there is less trauma to the knee joint and therefore these individuals may potentially be able to better restore joint homeostasis, leading to better afferent and efferent signaling within the joint.

Prior studies have shown that greater peak joint loading is related to decreased collagen turnover in individuals that undergo ACL-R. One study by Pietrosimone et al. in 2016 showed that at three years following ACL-R individuals with greater peak vertical ground-reaction force (vGRF) during gait was associated with decreased type II collagen breakdown [42]. Another study by Wellstandt et al. in 2016 that looked at the frontal plane joint kinetics of people with and without OA five years after ACL-R found that decreased surgical limb knee joint loading during walking was associated with early OA [44]. These two studies help support the idea that decreased knee joint loading after ACL-R is associated with OA.

Limitations of this study include the small sample size as well as the short-term follow up with participants. Another limitation is the age difference between the two groups, which could skew the results.

Future Directions

Future directions for this study would include increasing the sample size and following patients for a longer time period to see if these loading differences persist. It would also be useful to look at bioenhanced ACL-r techniques and compare that to standard ACL-r and ACL-R to see if there are potentially even better outcomes and decreased rates of OA.

Conclusions:

The results of this study demonstrate that individuals after ACL-r show increased knee joint symmetry during the single leg squat task as well as greater quadriceps strength symmetry at twelve weeks after surgery when compared to individuals who underwent ACL-R. This shows that ACL-r may potentially result in improved early knee joint loading and proprioception when compared with those who undergo ACL-R [14].

Compliance:

An IRB has been approved for this study at the UT Southwestern IRB. All confidentiality was maintained.

References

1. Chahla J, Nelson T, Dallo I, et al. Anterior cruciate ligament repair versus reconstruction: A kinematic analysis. *Knee*. Mar 2020;27(2):334-340. doi:10.1016/j.knee.2019.10.020
2. Carbone A, Rodeo S. Review of current understanding of post-traumatic osteoarthritis resulting from sports injuries. *J Orthop Res*. Mar 2017;35(3):397-405. doi:10.1002/jor.23341
3. Lieberthal J, Sambamurthy N, Scanzello CR. Inflammation in joint injury and post-traumatic osteoarthritis. *Osteoarthritis Cartilage*. Nov 2015;23(11):1825-34. doi:10.1016/j.joca.2015.08.015
4. Wang L-J, Zeng N, Yan Z-P, Li J-T, Ni G-X. Post-traumatic osteoarthritis following ACL injury. *Arthritis Research & Therapy*. 2020/03/24 2020;22(1):57. doi:10.1186/s13075-020-02156-5
5. Feucht MJ, Cotic M, Saier T, et al. Patient expectations of primary and revision anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. Jan 2016;24(1):201-7. doi:10.1007/s00167-014-3364-z
6. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. *Br J Sports Med*. Jun 2011;45(7):596-606. doi:10.1136/bjsm.2010.076364
7. Costa-Paz M, Garcia-Mansilla I, Marciano S, Ayerza MA, Muscolo DL. Knee-related quality of life, functional results and osteoarthritis at a minimum of 20 years' follow-up after anterior cruciate ligament reconstruction. *Knee*. Jun 2019;26(3):666-672. doi:10.1016/j.knee.2019.04.010
8. Sugiu K, Furumatsu T, Kodama Y, et al. Post-traumatic Articular Cartilage Lesions Increase at Second-look Arthroscopy Following Primary Anterior Cruciate Ligament Reconstruction. *Acta Med Okayama*. Jun 2019;73(3):223-228. doi:10.18926/AMO/56864
9. Pfeiffer S, Harkey MS, Stanley LE, et al. Associations Between Slower Walking Speed and T1rho Magnetic Resonance Imaging of Femoral Cartilage Following Anterior Cruciate Ligament Reconstruction. *Arthritis Care Res (Hoboken)*. Aug 2018;70(8):1132-1140. doi:10.1002/acr.23477
10. Pietrosimone B, Loeser RF, Blackburn JT, et al. Biochemical markers of cartilage metabolism are associated with walking biomechanics 6-months following anterior cruciate ligament reconstruction. *J Orthop Res*. Oct 2017;35(10):2288-2297. doi:10.1002/jor.23534
11. Kessler MA, Behrend H, Henz S, Stutz G, Rukavina A, Kuster MS. Function, osteoarthritis and activity after ACL-rupture: 11 years follow-up results of conservative versus reconstructive treatment. *Knee Surg Sports Traumatol Arthrosc*. May 2008;16(5):442-8. doi:10.1007/s00167-008-0498-x
12. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. *Br J Sports Med*. Jul 2016;50(13):804-8. doi:10.1136/bjsports-2016-096031
13. Schmitt LC, Paterno MV, Hewett TE. The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. Sep 2012;42(9):750-9. doi:10.2519/jospt.2012.4194
14. Singleton S, Scofield H, Davis B, et al. Altered Knee Loading Following Primary ACL Repair versus ACL Reconstruction. *Int J Sports Phys Ther*. 2023;V18(3):596-605. doi:10.26603/001c.77362

15. Harkey MS, Gribble PA, Pietrosimone BG. Disinhibitory Interventions and Voluntary Quadriceps Activation: A Systematic Review. *Journal of Athletic Training*. 2014;49(3):411-421. doi:10.4085/1062-6050-49.1.04
16. Sonnery-Cottet B, Saithna A, Quelard B, et al. Arthrogenic muscle inhibition after ACL reconstruction: a scoping review of the efficacy of interventions. *Br J Sports Med*. Mar 2019;53(5):289-298. doi:10.1136/bjsports-2017-098401
17. Lindström M, Strandberg S, Wredmark T, Felländer-Tsai L, Henriksson M. Functional and muscle morphometric effects of ACL reconstruction. A prospective CT study with 1 year follow-up. *Scand J Med Sci Sports*. Aug 2013;23(4):431-42. doi:10.1111/j.1600-0838.2011.01417.x
18. Pinto FG, Thaunat M, Daggett M, et al. Hamstring Contracture After ACL Reconstruction Is Associated With an Increased Risk of Cyclops Syndrome. *Orthop J Sports Med*. Jan 2017;5(1):2325967116684121. doi:10.1177/2325967116684121
19. Baumeister J, Reinecke K, Schubert M, Weiss M. Altered electrocortical brain activity after ACL reconstruction during force control. *J Orthop Res*. Sep 2011;29(9):1383-9. doi:10.1002/jor.21380
20. Baumeister J, Reinecke K, Weiss M. Changed cortical activity after anterior cruciate ligament reconstruction in a joint position paradigm: an EEG study. *Scand J Med Sci Sports*. Aug 2008;18(4):473-84. doi:10.1111/j.1600-0838.2007.00702.x
21. Rice DA, McNair PJ. Quadriceps arthrogenic muscle inhibition: neural mechanisms and treatment perspectives. *Semin Arthritis Rheum*. Dec 2010;40(3):250-66. doi:10.1016/j.semarthrit.2009.10.001
22. Lepley LK. Deficits in Quadriceps Strength and Patient-Oriented Outcomes at Return to Activity After ACL Reconstruction: A Review of the Current Literature. *Sports Health*. May 2015;7(3):231-8. doi:10.1177/1941738115578112
23. Feagin JA, Jr., Curl WW. Isolated tear of the anterior cruciate ligament: 5-year follow-up study. *Am J Sports Med*. May-Jun 1976;4(3):95-100. doi:10.1177/036354657600400301
24. DiFelice GS, van der List JP. Arthroscopic Primary Repair of Proximal Anterior Cruciate Ligament Tears. *Arthroscopy Techniques*. 2016;5(5):e1057-e1061. doi:10.1016/j.eats.2016.05.009
25. Odensten M, Lysholm J, Gillquist J. Suture of fresh ruptures of the anterior cruciate ligament. A 5-year follow-up. *Acta Orthop Scand*. Jun 1984;55(3):270-2. doi:10.3109/17453678408992354
26. DiFelice GS, van der List JP. Clinical Outcomes of Arthroscopic Primary Repair of Proximal Anterior Cruciate Ligament Tears Are Maintained at Mid-term Follow-up. *Arthroscopy*. Apr 2018;34(4):1085-1093. doi:10.1016/j.arthro.2017.10.028
27. Sherman MF, Lieber L, Bonamo JR, Podesta L, Reiter I. The long-term followup of primary anterior cruciate ligament repair. Defining a rationale for augmentation. *Am J Sports Med*. May-Jun 1991;19(3):243-55. doi:10.1177/036354659101900307
28. van der List JP, Mintz DN, DiFelice GS. The Location of Anterior Cruciate Ligament Tears: A Prevalence Study Using Magnetic Resonance Imaging. *Orthop J Sports Med*. Jun 2017;5(6):2325967117709966. doi:10.1177/2325967117709966
29. Batty LM, Feller JA, Hartwig T, Devitt BM, Webster KE. Single-Leg Squat Performance and Its Relationship to Extensor Mechanism Strength After Anterior Cruciate Ligament Reconstruction. *Am J Sports Med*. Dec 2019;47(14):3423-3428. doi:10.1177/0363546519878432

30. Hall MP, Paik RS, Ware AJ, Mohr KJ, Limpisvasti O. Neuromuscular Evaluation With Single-Leg Squat Test at 6 Months After Anterior Cruciate Ligament Reconstruction. *Orthop J Sports Med*. Mar 2015;3(3):2325967115575900. doi:10.1177/2325967115575900
31. Schmitz RJ, Harrison D, Wang H-M, Shultz SJ. Sagittal-Plane Knee Moment During Gait and Knee Cartilage Thickness. *Journal of Athletic Training*. 2017;52(6):560-566. doi:10.4085/1062-2050-52.4.05
32. Sherman MF, Bonamo JR. Primary repair of the anterior cruciate ligament. *Clin Sports Med*. Oct 1988;7(4):739-50.
33. Bousquet BA, O'Brien L, Singleton S, Beggs M. Post-Operative Criterion Based Rehabilitation of Acl Repairs: A Clinical Commentary. *Int J Sports Phys Ther*. Apr 2018;13(2):293-305.
34. Collins NJ, Misra D, Felson DT, Crossley KM, Roos EM. Measures of knee function: International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form, Knee Injury and Osteoarthritis Outcome Score (KOOS), Knee Injury and Osteoarthritis Outcome Score Physical Function Short Form (KOOS-PS), Knee Outcome Survey Activities of Daily Living Scale (KOS-ADL), Lysholm Knee Scoring Scale, Oxford Knee Score (OKS), Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), Activity Rating Scale (ARS), and Tegner Activity Score (TAS). *Arthritis Care Res (Hoboken)*. Nov 2011;63 Suppl 11(0 11):S208-28. doi:10.1002/acr.20632
35. Garrison JC, Hannon J, Goto S, Giesler L, Bush C, Bothwell JM. Participants at three months post-operative anterior cruciate ligament reconstruction (ACL-R) demonstrate differences in lower extremity energy absorption contribution and quadriceps strength compared to healthy controls. *Knee*. Oct 2018;25(5):782-789. doi:10.1016/j.knee.2018.06.014
36. Hannon JP, Wang-Price S, Goto S, et al. Twelve-Week Quadriceps Strength as A Predictor of Quadriceps Strength At Time Of Return To Sport Testing Following Bone-Patellar Tendon-Bone Autograft Anterior Cruciate Ligament Reconstruction. *Int J Sports Phys Ther*. Jun 2 2021;16(3):681-688. doi:10.26603/001c.23421
37. Hannon J, Wang-Price S, Swank C, et al. The validity and reliability of the Vail Sport Test™ as a measure of performance following anterior cruciate ligament reconstruction. *Phys Ther Sport*. Jul 2019;38:162-169. doi:10.1016/j.ptsp.2019.05.001
38. McGovern RP, Martin RL, Christoforetti JJ, Kivlan BR. Evidence-Based Procedures for Performing the Single Leg Squat and Step-down Tests in Evaluation of Non-Arthritic Hip Pain: A Literature Review. *Int J Sports Phys Ther*. Jun 2018;13(3):526-536.
39. Garrison JC, Bothwell JM, Wolf G, Aryal S, Thigpen CA. Y Balance Test Anterior Reach Symmetry at Three Months Is Related to Single Leg Functional Performance at Time of Return to Sports Following Anterior Cruciate Ligament Reconstruction. *Int J Sports Phys Ther*. Oct 2015;10(5):602-11.
40. Rambaud AJM, Ardern CL, Thoreux P, Regnaux JP, Edouard P. Criteria for return to running after anterior cruciate ligament reconstruction: a scoping review. *Br J Sports Med*. Nov 2018;52(22):1437-1444. doi:10.1136/bjsports-2017-098602
41. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med*. Oct 2010;38(10):1968-78. doi:10.1177/0363546510376053
42. Pietrosimone B, Blackburn JT, Harkey MS, et al. Greater Mechanical Loading During Walking Is Associated With Less Collagen Turnover in Individuals With Anterior Cruciate

Ligament Reconstruction. *Am J Sports Med*. Feb 2016;44(2):425-32. doi:10.1177/0363546515618380
43. Lee B-I, Kim CH, Jang BW, Hong YC, Kwon S-W. Preservation of the Tibial Remnant in Anterior Cruciate Ligament Reconstruction May Improve Postoperative Proprioceptive Function. *Orthopedics*. 2020;43(4):e231-e236. doi:doi:10.3928/01477447-20200404-04
44. Wellsandt E, Gardinier ES, Manal K, Axe MJ, Buchanan TS, Snyder-Mackler L. Decreased Knee Joint Loading Associated With Early Knee Osteoarthritis After Anterior Cruciate Ligament Injury. *Am J Sports Med*. Jan 2016;44(1):143-51. doi:10.1177/0363546515608475