Doctor of Physical Therapy Program Case Reports

2017

University of Wisconsin-Madison ACL Return to Sport Protocol – Modifying Clinical Interventions Based on Objective Measures: A Case Report

Sarah Jentink
University of Iowa

University of Wisconsin-Madison ACL Return to Sport Protocol – Modifying Clinical Interventions Based on Objective Measures: A Case Report

Sarah Jentink

DPT Class of 2017
Department of Physical Therapy & Rehabilitation Science
The University of Iowa

Abstract

Background: Predictive factors for reinjury, following an anterior cruciate ligament reconstruction (ACLR), have been clearly stated in literature. However, objective measures to prevent reinjury have not been implicated in a standardized form for clinical use. **Purpose:** The purpose of this case report is to present the clinical significance of using an ACLR progressive testing protocol to influence an individual's plan of care, preparing them for return to sport. **Case Description:** The patient was a 26-year-old athlete who competed nationally in ultimate frisbee and underwent rehabilitation following her second ACLR with a medial meniscus repair. Interventions were based off of the UW-Madison return to sport testing protocol. Testing included the following: KT1000, leg-press, Y-balance, Biodex, vertical jump, vertical hop, 4 vertical hop, horizontal hop and 4 cross-over hop test, and was designed around literature cited for decreasing risk of reinjury following an ACLR. **Outcomes:** At 10.1 weeks following ACLR surgery, the KT1000, leg-press and Y-balance assessments were performed. Outcome measures demonstrated a limb symmetry index of 92% on the single-leg press test and 100% on the Y-balance test. Biodex isokinetic strength assessment was held secondary to tissue healing times. The patient's plan of care was then progressed to prepare the patient for follow-up testing in 1.5 months. **Discussion:** This case report describes the clinical application of integrating both professional judgement and progressive testing within an individual's plan of care, in order to optimize their return to sport and decrease their risk of reinjury.

Introduction

The anterior cruciate ligament (ACL) is composed of an anterior-medial and posterior-lateral bundle of collagen that work to prevent anterior translation of the tibia as well as hyperextension of the knee. Secondary functions include prevention of tibial rotation and varus-valgus restraint, making the ACL critical to functional knee stability.[1] Over 200,000 individuals are estimated to suffer from an ACL injury every year in the United States,[1] making it one of the most commonly observed knee injuries in sports.[2] Of these athletes, 81% return to sport and 55% return to sport competitively.[3] Studies have shown that individuals who return to sport with an ACL-deficient knee run an increased risk for further injury, including meniscal tears, osteochondral injuries and arthrosis secondary to the instability.[1,4,5] For this reason, approximately 100,000 reconstructions are performed each year[1] in order to increase knee stability for return to sport. Increased stability does not, however, mean risk-free.

The highest risk for re-injury following ACL reconstruction is within the first 7-12 months following clearance to compete[6,7] and is said to be 15 times greater than those who have not suffered from an ACL tear. [1,4,8,9] After one year, however, the risk is not absent. A long-term study completed by Salmon et al.[6] demonstrated that 12% of individuals ruptured a second ACL within five years, while a 15 year follow-up study performed by Ley et al. [10] reported 18.8% of participants suffered from re-injury In both studies, the contralateral and ipsilateral leg were included in the results. With such a high incidence for re-injury, numerous studies have been funded to isolate predictive factors in ACL ruptures.

Predictive factors include environmental demands of the sport such as cutting, jumping and pivoting [8,9,13] being female, strength asymmetries and biomechanical movement faults. [4,8,9] A systematic review done by Ardern et al.[13] found symmetrical knee function to be one of many predictors for a successful return to sport. Additional factors include fear of reinjury and activity limitations following rehabilitation. [13] Symmetrical knee function relates to both strength and movement quality. A quadriceps force (QF) difference of 15% or greater has been shown to increase an individual's risk for reinjury significantly.[7,11] Jumping and landing techniques have also been shown to affect risk for reinjury.[11,12] Identified risk factors include single leg postural stability, increased frontal plane valgus, increased internal knee extensor moment at initial contact, asymmetrical vertical ground reaction force and rate of limb loading during jump assessments.[11,12] Each factor contributes to individuals' abilities to control their lower extremity through movement and stabilize their knee.

While many predictive factors have been noted with objective criteria aimed around prevention of reinjury, little research has been done on the clinical application of these measures throughout a plan of care. An analysis done by Barber-Westin and Noyes [14] reported that only 13% of studies use objective measures in determining readiness for return to sport and only 32% of studies looked at post-operative time frames in determining return to sport. Thus while researches have relied on objective measures to determine readiness for return to sport, clinically these objective measures are not routinely used. As follows, the purpose of this case was to demonstrate the clinical integration of both objective measures and clinical judgement within a rehabilitation treatment plan during the return to sport of a high-level athlete.

Case Description

A 26-year-old female was referred to physical therapy following a left knee ACL rupture. The patient was a high level ultimate frisbee athlete, who competes at a national level. The mechanism of injury included another player running into the patient's knee after landing a jump on defense. The patient's knee was forced into internal rotation and an audible "pop" was heard. Following MR imaging, the patient was found to have a left ACL rupture, bony contusions of the lateral femoral condyle and lateral tibial plateau and medial meniscal tear of the posterior horn. The patient had suffered a non-contact ACL injury on the contralateral limb four years earlier. Prior to surgical intervention for the current ACL rupture, the patient underwent rehabilitation at an outpatient facility, which included balance and strength work. The patient underwent a left knee ACL reconstruction using a hamstring autograft with triple semitendinosus and double gracilis graft as well as a meniscal repair. The surgery was performed two months following the initial onset of injury. Due to the meniscal repair, the patient wore a brace locked in extension for four weeks following surgery, and was limited to 90 degrees of passive flexion during this time frame.

Intervention

The patient was seen for 11 treatment sessions prior to progressive testing. Early treatment sessions had an emphasis on full knee extension and flexion, restoring quadriceps function, controlling pain, joint effusion, restoring a proper gait pattern and slowly discontinuing the need for an assistive device. Following this, treatment sessions worked on progressing into athletic stance for basic loading, strengthening and proprioceptive work. Testing was completed after 2.5 months of rehabilitation. Progressive testing is a series of clinical measures which allow a clinician to objectify a patient's progress throughout the rehabilitation process. The objective measures used have been identified as having an impact on successful return to sport following an ACLR. Testing includes joint laxity assessment, strength, jumping/landing mechanics, performance testing and psychological testing. Progression of the assessments are based on limb symmetry as well as the therapist's assessment of movement quality and clinical judgment.[15] As a general rule, testing is scheduled at 2,3,4 and 6 months following ACL reconstruction with continued testing occurring roughly every 1-2 months until clearance for return to sport is obtained.[15] Tissue healing times are taken into account when progressing a patient through testing. For instance, the patient in this case report underwent a meniscal repair in addition to her ACLR. The extended time spent in a locked brace to allow for improved tissue healing capacity of the meniscus delayed the patient in her rehab progression and therefore was held from testing until 2.5 months. In the same manner, a patient would not be allowed to progress to jump testing until the new ligament was strong enough to handle impact based on time, strength and movement quality. Treatment sessions following progressive testing are then designed to address deficits found in the objective measures and observed impairments in movement quality, as well as prepare the patient for follow-up testing.

Outcome Measures

Approximately 2.5 months following surgery, the patient underwent her first round of progressive testing. Due to ACL grafts being most vulnerable at 6-8 weeks post-operation, no testing was performed until two months after surgery.[4,16] Leading up to initial testing, the patient had been working on single leg balance, gait training, and quadriceps and hip strengthening. On this date the patient was assessed using the KT1000, Horizontal leg-press and Y-balance.

KT1000

The KT1000 is an instrument used to assess the anterior and posterior laxity of the tibia on the femur.[17] Compared to alternative assessments such as the Stryker knee laxity system and Genucom knee analysis system, the KT1000 has the greatest sensitivity (0.93), specificity (0.93), accuracy (0.93) and positive predictive value (6.9) for a maximal manual pull. [18] The patient scored a 1 millimeter side-to-side difference on the maximal manual pull, indicating that the graft was holding well. A 0-3 millimeter difference in laxity between knees has been found in 95% of uninjured knees, and is used as a baseline expectation following surgery.[1] A difference of 5 millimeter or more suggests that the graft has been torn or stretched. Values of increased laxity are often indicative of increased effusion secondary to overload, suggesting that the treatment plan may be too aggressive.

Table 1: Patient's KT-1000 test results

KT-1000 Testing

	Anterior				Posterior		Comments:
	15#	*20#*	*30#*	*Max*	*15#*	*20#*	0
Uninvolved	3	6	9	10	1.5	2.5	
Involved	2	4	6	9	2.5	3.5	
		Difference	**-3**	**-1**	← Good limb symmetry		

Leg Press

The horizontal leg press is a functional measure used to detect strength asymmetries in the lower extremities. A study completed by Schmitt et al. showed that weaker quadriceps function is predictive of impaired landing mechanics when analyzing the drop vertical jump, which has been directly correlated with increased risk for a second ACL rupture.[7,11] The study demonstrated that participants with symmetrical strength of 90% or greater following an ACLR had jumping mechanics that resembled uninjured participants. Symmetry less than 85% was predictive of deficits in peak external knee flexion moment, peak vertical ground reaction force and peak loading rates for the uninvolved limb as well as asymmetries on the vertical hop test at the time of return to sport.[7] Poor joint loading patterns and landing mechanics have been shown to increase risk of reinjury.[11] Specifically, knee abduction and extension moments as well as hip rotation during early landing predicted ACL injury with high sensitivity and specificity (0.73 and 0.78, 0.92 and 0.88, 0.77 and 0.81).[11,19] These factors, along with single limb stability can increase risk of ACL reinjury 2-8 times. The correlation between symmetrical leg strength and landing mechanics are very clear.

Maximal load on the lower extremities occurs most often during the first 30-100 milliseconds of landing [20,21] thus recruitment of the quadriceps and hamstrings is critical to stability and force absorption.[11] During low flexion, the quadriceps and hamstrings provide 80% of the resistance to frontal plane movement. Unequal recruitment can quickly lead to increased valgus, vertical ground reaction force and loading rate of the uninvolved leg, and ultimately ACL rupture of either the same or contralateral leg.[11]

The criterion for the leg strength symmetry cut-off of >90%, used for the leg press test, was determined based on an isometric Biodex dynamometer study.[7] According to Jones et al.[22] the leg press is a functional measure that can effectively be used to determine leg strength asymmetries. While the leg press cannot be directly compared to the Biodex results, it allowed for general deficits in the leg strength to be noted earlier in the rehab process through maximal effort, closed-chain assessments of leg strength through an increased ROM. Later in the rehabilitation process, the patient will undergo isokinetic testing on the Biodex to check progression of leg strength symmetry and look more specifically at hamstring to quadriceps ratio and peak force development. Secondary to tissue healing times, the Biodex is not utilized until a minimum of three months following surgery, as the open-chain maximal strength assessment increases stress on the reconstructed ACL. [23]

The patient received a 92% limb symmetry index (LSI) on the leg press assessment. Prior to testing, the patient completed 10 leg presses at 100% bodyweight (BW) and five single leg presses at an RPE of 5/10. The patient's knees were positioned at 90 degrees. Starting with the uninvolved leg, the patient was then asked to perform the single leg press until failure. The weight used is estimated for a 2-6 repetition maximum. The patient was allowed to begin with two feet to push into knee extension, but was required to use only one leg for the remainder of the test. Once the patient took greater than 2 seconds to initiate leg extension, the trial was terminated. The test was then performed on the surgical leg. The patient performed 2 reps at 160 pounds on the uninvolved leg and 7 repetitions at 130 pounds on the involved leg, which was calculated at 134% and 124% of BW. Strength as a percent of body weight was then used to calculate the LSI of 92%. Since the patient had an LSI >90%, she was allowed to progress to the Y-balance for functional testing.

Table 2: Patient's Single-leg Press test results

Single-leg Press Test

Uninvolved				Involved				LSI
Reps	Weight	Est. Max	STR:BW	Reps	Weight	Est. Max	STR:BW	92%
2	160	170	134%	7	130	157	124%	

Y-Balance

The patient scored a 100% LSI on the Y-balance test. The Y-balance is a single-limb lower extremity test that predicts risk of reinjury through a composite distance score in the directions of anterior, posterior-medial and posterior-lateral single leg reaching. It requires the same movement patterns as the singe leg squat test. Crossley et al.[24] showed that individuals who perform a single leg squat with good mechanics have earlier activation of anterior gluteus medius. Additionally, Ayotte et al.[25] demonstrated that the single leg squat requires increased activation of gluteus maximus, vastus medialis oblique and biceps femoris, as well as gluteus medius. Increased gluteal and quadriceps activation have been shown to decrease both hip internal rotation and knee valgus during functional activities, decreasing risk for reinjury following ACLR.[11] Early detection of single leg control deficits is used to help guide our rehabilitation plan of care. Garrison et al.[26] showed that there is a strong relationship between Y-balance anterior reach symmetry at 12 weeks and functional single leg performance at return to sport, stating that a difference greater than 4 centimeters between involved and uninvolved limbs predicted less than 90% limb symmetry on both the single hop and triple hop distance at time of discharge with a sensitivity of 0.96 and 0.92. Hop tests are commonly used as clinical measurements for performance prior to return to sport.[27,28]

During the Y-balance test, the patient was given 3 practice trials in each direction, beginning with the uninvolved leg. Three more trials were then performed with the greatest of three recorded for the anterior, posterior-lateral and posterior-medial directions. The patient is required to have < 4-centimeter side-to-side difference with each reach, to be objectively cleared from this test. Qualitative clearance requires minimal re-trials, proper hip, trunk and knee alignment, as observed by the clinician, throughout testing. However, because the patient was only 2.5 months post-op, with delayed strengthening secondary to 4-weeks of braced extension, a clinical judgement was made to hold testing until her follow-up in 1.5 months.

Table 3: Patient's Y-Balance test results

Y-Balance Test

	Anterior	Post-Med	Post-Lat	Composite	LSI	Comments:
Uninvolved	55.5	95	91	88.8	100%	Good limb control B, especially for only being 2 mo
Involved	55	93	93	88.6		
Difference	-0.5	-2	2	-0.2	←	Good limb symmetry
Attempts	100%	100%	100%	100%		

Plan of Care

Based on the test results, we can confidently say that the patient is progressed well through rehabilitation. With a LSI of 100% at 2.5 months, the Y-balance suggests that the patient will have promising outcome measures at the time for return to sport assessment. Y Balance outcomes are directly correlated with hop test results.[3] No qualitative red flags throughout the movement such as repeated trials, increased trunk rotation, increased knee valgus or decreased frontal plane hip control were present. Minimal to no hip adduction or lateral shift was noted and the patient was able to maintain balance throughout the single leg task. However, the speed of the movement was decreased. This indicated that the patient had good quadriceps and gluteal strength as well as early neuromuscular activation of these muscles for progression into functional tasks. However, based on our observation, continued hip strengthening, eccentric control and movement in and out of position at varying speeds will be a focus of future treatment sessions. If the patient had demonstrated additional qualitative or quantitative faults in either the objective measure or observed movement patterns, our treatment plans would then be targeted at improving those deficits.

The patient demonstrated a 92% symmetry between lower extremities for single leg strength. Although these results do not transfer directly to the Biodex, the horizontal leg press is supported for use in detecting limb strength asymmetries.[22] No qualitative red flags were noted such as increased time for quadriceps activation, inability to eccentrically control the load or compensatory hip rotation during testing. It was noted that the number of repetitions varied from surgical to nonsurgical leg upon testing, suggesting that the LSI may be slightly higher or lower. With 92% symmetry, unilateral strengthening will continue to be progressed and focused on during future treatment sessions, specifically gluteals, quadriceps and hamstring strengthening.

The patient was cleared to start light agility work and dynamic warm-ups secondary to great outcome measures. Additionally, the patient was cleared to participate in SPECTRUM phase 1, an ACL return to sport class that meets two times per week and focuses on movement control, strength and proprioception. At follow-up testing in 1.5 months, the patient will be tested on the Biodex as well as a series of jump tests if isokinetic strength results demonstrate that impact assessment is appropriate. Future treatment sessions will also be focused around improved eccentric and concentric muscle control, improving the hamstring to quadriceps strength ratio and readying for impact in order to prepare for testing.

Treatment session #12

Treatment session 1, following testing, was designed to continue with strengthening and progress single leg control. At this point, the patient had participated in four spectrum classes. The treatment began with a dynamic warm-up: knee to chest, marching, shuffling in an athletic stance, forward and lateral skips, forward T-hamstring stretch, carioca and glute cross-over stretch. Therapeutic exercise worked on progressing athletic stance and squat from double leg to single leg, and moving in and out of position faster while controlling load. The home exercise program (HEP) prescribed included moving from an athletic stance to squat with a medicine ball (MB) toss, moving from a squat position into triple extension, performing medicine ball wall throws while in an athletic stance and catching a medicine ball bounce with deceleration into a single leg squat.

Treatment session #13

Treatment session 2 was designed to progress strengthening, begin preparation for impact and increase hamstring strengthening. The patient reported that she had begun to perform small single leg step downs at spectrum. A dynamic warm-up was performed at the beginning of the treatment session. Single leg stance was progressed to include single leg squat with a palloff press and medicine ball toss. Quick movements from squat to triple extension were progressed into single leg squat with extension and a medicine ball drop, with faster movements in and out of position, working on both stability and strength. In preparation for impact, the patient performed rapid double leg jump rope with a quick drop into a squat. Bridging, with toes up, was progressed to include lower extremity walk-outs with upper extremity perturbations for increased hamstring activation and postural control. At the end of the treatment session, the patient noted mild hamstring irritation and pull near the ischial tuberosity insertion, with single leg loading, stating that she may have strained it prior to her injury. Additionally, the patient stated that she had been performing russian twists regularly for core strengthening. It was hypothesized that the increase in hip flexor activation could be biasing the pelvis into an anterior pelvic tilt, putting the hamstrings into a lengthened position during single leg loading and stressing an already injured tissue. The patient was started on a transverse abdominus strengthening program in order to increase core and pelvic control. Exercise progression included belly button to spine in a hook-lying position into bent knee single leg lifts with manual resistance at the knee.

Treatment session #14

Treatment session 3 was focused on beginning impact, increasing hamstring strength and progressing from static to dynamic strengthening. A dynamic warm-up was performed at the beginning of the treatment session which included forward and backward skips, forward and lateral lunges, shuffling and carioca with high knee cross-over. The patient performed double leg low amplitude jumps with a quick drop into a squat for eccentric loading, a squat into triple extension with a 10-pound medicine ball, an unweighted squat into full extension with a jump for submaximal height, a double leg jump with a medicine ball toss and slow deceleration into a double leg squat, and double leg jumps onto a small box with a step down and single leg lower. Hamstring strengthening was progressed to include a single leg RDL with a 30-pound free-weight, unweighted prone hamstring curls with quick contractions and bridging on a BOSU ball with a single-leg lift. Transverse abdominus strengthening was also progressed through the Sarhmann series to include straight leg and upper extremity work. HEP modifications included the single leg dead lift, adding a small amplitude jump with triple extension out of a squat position and progression of Sarhmann series.

Discussion

The purpose of this case report was to describe the clinical application of integrating both professional judgement and progressive testing within an individual's plan of care, in order to optimize their return to sport and decrease their risk of reinjury following an ACLR. Treatment sessions were designed to address observed movement quality impairments as well as strength and balance deficits as demonstrated by the functional progressive testing. Specifically, single leg control was analyzed bilaterally via the Y-balance and the horizontal leg press. Results of the Y-balance and leg strength symmetry have been shown to predict individual success rate upon return to sport. These tests were used to modify and shape proceeding treatment sessions and prepare the athlete appropriately.

The patient demonstrated 92% LSI for leg symmetry strength during the horizontal leg press and 100% LSI during the Y-balance test 2.5 months following her ACLR as well as a 1 millimeter difference on the KT1000. Subjective criterion for the Y-balance included ability to maintain balance and stability, depth and speed of squat, trunk and pelvic rotations/shifts, as well as frontal and transverse movements of the knee and hip. Subjective criterion for the leg press included eccentric control of the limb, hip rotation resulting in knee valgus and compensatory use of the trunk, upper extremities or non-testing lower extremity during the assessment. No red flags were noted and the patient was observed to have good movement quality with minimal compensatory movements. Collectively, these measures indicate that our patient was progressed with an appropriate intensity, demonstrated appropriate strength and movement control for her stage in recovery, and was ready to progress to more dynamic strengthening, preparing her for functional movements and impact. Follow-up testing sessions were and will continue to be utilized to help guide the treatment plan and appropriately prepare our patient for sport demands. The patient underwent three treatment sessions following the first round of progressive testing, which focused on double and single leg stability, eccentric control of the quadriceps while moving in and out of position faster, core and hamstring strengthening as well as preparation for impact. The patient will have one additional treatment session prior to her upcoming testing, in which progression of hamstring strengthening and single leg stability will be focused on.

A prospective study done by Toole et al.[29] looked at 117 athletes one year following return to sport, to determine if meeting the recommended cutoffs for strength assessments and hop tests correlated with return to sport. The study found that only 13.9% of participants met the 90% LSI for quadriceps and hamstrings strength as well as 90% LSI for the single leg hop test. More specifically, 70-80% of individuals tested met the criteria for the single-leg hop test, while only 43.5% met the criteria for quadriceps strength LSI. After analysis, the study concluded that individuals who met the criteria for both strength and hop assessments participated at a higher level of sports one year following clearance to play (81.3%) as compared to those who did not meet both criteria (60.2%).

It is clear that there is validity behind the recommended cutoffs for return to sport. In order to provide patients with the most optimal return, physical therapists can individualize their treatments through observed movement quality, tissue healing times as well as progressive testing. Progressive testing allows for continual modification and guidance of treatment, in order to increase the likelihood that the patient will meet recommended cutoffs for strength, balance and neuromuscular control prior to discharge.

Limitations

Anticipated barriers to incorporating the recommended measures into clearance for return to sport include: time, cost and availability of testing equipment, and insurance reimbursement. Alternative measuring techniques should be utilized whenever possible. Although secondary methods may not have been verified by research, they will at the very least provide feedback to clinicians and help to identify red flags and deficits within a plan of care, for that individual. For instance, a jump pad is a more cost-effective way to look at ground reaction force if force plates are not available. Floor markings can easily be utilized in place of a Y-balance set up. Additionally, leg strength symmetry for both quadriceps and hamstrings could be assessed with the use of a hand-held dynamometer if a Biodex is not feasible. A video camera could be used for observed movement quality/LESS testing and tape measures on the floor could be utilized for hop testing.

Conclusion

This case report provides insight on the clinical application of utilizing objective measures in addition to clinical judgement when generating a plan of care, prior to return to sport. Strength, balance and postural control deficits were monitored throughout the rehabilitation process in order to influence the treatment plan following an ACLR. Results highlighted deficits, provided objective measures to monitor progress as well as treatment goals for follow-up assessments. It is important to note that while objective testing was utilized to help guide the treatment plan, clinical judgment of movement quality and readiness for progression were fully utilized. The combination of clinical judgement and progressive testing can be utilized in order to optimize an individual's return to sport following ACLR.

References

1. Azar FM, Beaty JH, Canale ST. Campbells Operative Orthopaedics: 13th edition. Philadelphia: Elsevier; 2017. Chapter 45, 2121-2297.e16
2. Michaelidis M, Koumantakis GA. Effects of knee injury primary prevention programs on anterior cruciate ligament injury rates in female athletes in different sports: a systematic review. Phys Ther Sport. 2014;15(3):200-10.
3. Ardern CL, Taylor NF, Feller JA, Webster KE. Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. Br J Sports Med. 2014;48(21):1543-52.
4. Joreitz R, Lynch A, Rabuck S, Lynch B, Davin S, Irrgang J. PATIENT-SPECIFIC AND SURGERY-SPECIFIC FACTORS THAT AFFECT RETURN TO SPORT AFTER ACL RECONSTRUCTION. Clinical Commentary. J Orthop Sports Phys Ther. 2016;11(2):264-278.
5. Kim HJ, Lee JH, Ahn SE, Park MJ, Lee DH. Influence of Anterior Cruciate Ligament Tear on Thigh Muscle Strength and Hamstring-to-Quadriceps Ratio: A Meta-Analysis. PLoS ONE. 2016;11(1):e0146234.
6. Salmon L, Russell V, Musgrove T, Pinczewski L, Refshauge K. Incidence and risk factors for graft rupture and contralateral rupture after anterior cruciate ligament reconstruction. Arthroscopy. 2005;21(8):948-57.
7. Schmitt LC, Paterno MV, Ford KR, Gregory DM, Hewett TE. Strength Asymmetry and Landing Mechanics at Return to Sport after Anterior Cruciate Ligament Reconstruction. Med Sci Sports Exerc. 2015;47(7):1426-34.
8. Paterno MV, Rauh MJ, Schitt LC, Ford KR, Hewett TE. Incidence of Contralateral and Ipsilateral Anterior Cruciate Ligament (ACL) Injury After Primary ACL Reconstruction and Return to Sport. Clin J Sport Med. 2012; 22(2):116-121
9. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of Second ACL Injuries 2 Years After Primary ACL Reconstruction and Return to Sport. Am J Sports Med. 2014;42(7):1567-73.
10. Leys T, Salmon L, Waller A, Linklater J, Pinczewski L. Clinical results and risk factors for reinjury 15 years after anterior cruciate ligament reconstruction: a prospective study of hamstring and patellar tendon grafts. Am J Sports Med. 2012;40(3):595-605.
11. 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. 2010;38(10):1968-78.
12. Paterno MV, Ford KR, Myer GD, Heyl R, Hewett TE. Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. Clin J Sport Med. 2007;17(4):258-62.
13. 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. 2011;45(7):596-606.
14. Barber-westin SD, Noyes FR. Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. Arthroscopy. 2011;27(12):1697-705.
15. UW-Health: University of Wisconsin Sports Medicine. Rehabilitation Guide: *Anterior Ligament Reconstruction*. UW Health Sports Medicine. UWsportsmedicine.org. Updated 2017.
16. Janssen RP, Scheffler SU. Intra-articular remodelling of hamstring tendon grafts after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2014;22(9):2102-8.
17. Monaco E, Labianca L, Maestri B, De carli A, Conteduca F, Ferretti A. Instrumented measurements of knee laxity: KT-1000 versus navigation. Knee Surg Sports Traumatol Arthrosc. 2009;17(6):617-21.

18. Van eck CF, Loopik M, Van den bekerom MP, Fu FH, Kerkhoffs GM. Methods to diagnose acute anterior cruciate ligament rupture: a meta-analysis of instrumented knee laxity tests. Knee Surg Sports Traumatol Arthrosc. 2013;21(9):1989-97.
19. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. Am J Sports Med. 2005;33(4):492-501.
20. Krosshaug T, Slauterbeck JR, Engebretsen L, Bahr R. Biomechanical analysis of anterior cruciate ligament injury mechanisms: three-dimensional motion reconstruction from video sequences. Scand J Med Sci Sports. 2007;17(5):508-19.
21. Boden BP, Sheehan FT, Torg JS, Hewett TE. Noncontact anterior cruciate ligament injuries: mechanisms and risk factors. J Am Acad Orthop Surg. 2010;18(9):520-7.
22. Jones PA, Bampouras TM. A comparison of isokinetic and functional methods of assessing bilateral strength imbalance. J Strength Cond Res. 2010;24(6):1553-8.
23. Jenkins WL, Munns SW, Jayaraman G, Wertzberger KL, Neely K. A measurement of anterior tibial displacement in the closed and open kinetic chain. J Orthop Sports Phys Ther. 1997;25(1):49-56.
24. Crossley KM, Zhang WJ, Schache AG, Bryant A, Cowan SM. Performance on the single-leg squat task indicates hip abductor muscle function. Am J Sports Med. 2011;39(4):866-73.
25. Ayotte NW, Stetts DM, Keenan G, Greenway EH. Electromyographical analysis of selected lower extremity muscles during 5 unilateral weight-bearing exercises. J Orthop Sports Phys Ther. 2007;37(2):48-55.
26. 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. 2015;10(5):602-11.
27. Pua YH, Mentiplay BF, Clark RA, Ho JY. Associations Among Quadriceps Strength and Rate of Torque Development 6 Weeks Post Anterior Cruciate Ligament Reconstruction and Future Hop and Vertical Jump Performance: A Prospective Cohort Study. J Orthop Sports Phys Ther. 2017;47(11):845-852.
28. Hopper DM, Strauss GR, Boyle JJ, Bell J. Functional recovery after anterior cruciate ligament reconstruction: a longitudinal perspective. Arch Phys Med Rehabil. 2008;89(8):1535-41.
29. Toole AR, Ithurburn MP, Rauh MJ, Hewett TE, Paterno MV, Schmitt LC. Young Athletes Cleared for Sports Participation After Anterior Cruciate Ligament Reconstruction: How Many Actually Meet Recommended Return-to-Sport Criterion Cutoffs?. J Orthop Sports Phys Ther. 2017;47(11):825-833