ACL Risk of Reinjury: When Is It Safe to Return (Time or Criteria)

51

Stefano Della Villa, Francesco Della Villa, Margherita Ricci, Mahmut Nedim Doral, Gregory Gasbarro, and Volker Musahl

Contents

S.D. Villa • F. Della Villa • M. Ricci
Isokinetic Medical Group, FIFA Medical Centre of Excellence, Bologna, Italy

M.N. Doral
Sports Medicine Center, Hacettepe University, Ankara, Turkey

G. Gasbarro • V. Musahl (✉)
Department of Orthopaedic Surgery, University of Pittsburgh Medical Center, Pittsburgh, PA, USA
e-mail: musahlv@upmc.edu

51.1 Introduction

Anterior cruciate ligament reconstruction (ACLR) if done successfully improves stability, reduces laxity, and decreases the risk of future knee joint pathology and surgery [1, 2]. Significant advancements in surgical procedures and rehabilitation have led to improved functional outcomes and high expectations in return to sport (RTS) [3]. Despite the relatively high rate of successful outcomes following ACLR, graft failure during rehabilitation can occur [4]. In many cases, this limits an athlete's ability to return to their pre-injury level of activity with reported rates that vary from 37% to 75% [2, 4, 5]. In a recent systematic review, Ardern et al. evaluated 69 studies and 7556 participants after ACLR. On average, 81% of patients returned to some kind of sport, 65% returned to their pre-injury level of sport, and only 55% returned to competitive level sport [6]. Even though recent studies show a great difference between expectations and RTS, as RTS rates are generally reported as ranging from 60 to 80% [7–9].

One of the greatest concerns with RTS is the risk of reinjury. It is well known that the risk of sustaining a new anterior cruciate ligament (ACL) injury is 5.8% for the ipsilateral and 11.8% for the contralateral limb at a minimum of 5 years of follow-up [10]. Women have a higher incidence of ACL injury to the contralateral knee than men after reconstruction. Younger and higher-level

J. Espregueira-Mendes et al. (eds.), *Injuries and Health Problems in Football*,
DOI 10.1007/978-3-662-53924-8_51

athletes seem to be at higher risk of reinjury [11]. Graft failure may also occur as a result of errors in technique, fixation failure, or lack of biological graft incorporation into the bone tunnel [12]. Technical error has been shown to the most common etiologic factor leading to graft attrition and recurrent pathology [13]. These errors may be subdivided into the following: improper intra-articular placement of the graft, impingement of a graft in the intercondylar notch due to insufficient notchplasty or an anterior tibial tunnel, improper tensioning of the graft, or inadequate fixation [13]. A recent review found that most failures occurred 6–9 months after surgery [14].

So when is it safe to allow footballers back on the pitch? A great deal of basic science research over the last 15 years has provided insight into factors that directly influence time course and quality of graft tunnel healing [15–17]. Many of these findings however have yet to be translated to the bedside, and knowledge of the healing process in humans is limited. Strategies to enhance healing have also been explored due to great interest for earlier return to activity among competitive athletes with aggressive postoperative rehabilitation. These include the use of growth factors, periosteal augmentation, and mesenchymal stem cells [18–20].

Consistent with increasing pressures to return athletes to the field of play, methods for quantitative clinical assessment of ACL function following reconstruction have evolved. Magnetic resonance imaging (MRI) has emerged as a tool in the postoperative athlete in predicting graft health with parameters such as volume and signal intensity [21, 22]. MRI has also been used to elucidate differences in bone morphology between genders and critically evaluate postoperative patients for technical errors such as nonanatomic graft placement and graft impingement within the notch [23–25]. Similarly, electromagnetic testing and other noninvasive devices such as the KT-1000 arthrometer have recently been validated to assess ACL stability as an objective outcome measure for clinical follow-up [26–29]. Given that current parameters for return to play are largely dictated by surgeon preference and patient-reported outcomes, these quantitative measures of ACL function may help to establish a safe threshold for footballers in the immediate postoperative phase and rehabilitation process.

51.2 Clinical Strategy

51.2.1 Rehabilitation Principles

The main goal of rehabilitation following ACLR is to return the athlete to the previous level of function as quickly and as safely as possible, minimizing the risk of reinjury and degenerative changes in the joint. Recurrence after ACLR is one of the most devastating outcomes after rehabilitation and RTS. In order to reduce this phenomenon, we suggest adopting the right clinical strategy in a strong organizational context. For right clinical strategy, we mean follow a criteria-based, functional-oriented rehabilitation protocol. For strong organizational context, we mean having a proper team (including a sport medicine physician, a physical therapist, and a reconditioning specialist), a proper facility (consisting of medical offices, rehabilitation gyms, rehabilitation pool, and rehabilitation field), and a proper method (clinical strategy shared by the team).

51.2.2 Clinical Strategy

Nowadays, the most appropriate approach after ACLR is applying a criteria-based rehabilitation protocol, rather than predefined times [30–33]. Certain clinical and functional criteria must be met in order to progress throughout rehabilitation and to finally be allowed to RTS. Therefore, the time for RTS is a secondary goal, the first must be to fulfill the necessary criteria [31]. Even if criteria usually regards ROM, strength, neuromuscular control, proprioception, and endurance, validation of subjective and objective criteria for RTS is still lacking [34].

The protocol we apply in the daily clinical activity with knee patients consists of four functional steps, the so-called traffic lights, and various well-defined criteria, to be met before we proceed from one step to another:

First traffic light: walking without crutches

- Surgeon’s approval
- Absence/minimal pain and swelling
- Full knee extension
- Recovery of the correct gait cycle

Second traffic light: running on a treadmill

- No pain during walking
- Knee flexion more than 120°
- Walk on a treadmill for at least 10 min without pain or swelling
- Adequate muscle tone of the trunk, thigh, and limb

Third traffic light: starting on-field rehabilitation

- Less than a 20% deficit between the two quadriceps and hamstrings at the isokinetic test
- Run on a treadmill for at least 10 min at 8 km/h without pain or swelling

Fourth traffic light: return to the team

- Surgeon's approval
- Complete ROM
- Complete recovery of muscular strength deficit at the isokinetic test
- Complete metabolic recovery (aerobic and anaerobic threshold test)
- Complete on-field rehabilitation
- Movement patterns restoration (>90 pts. at the movement analysis test)

51.2.3 Organizational Context

Regarding the organization, we suggest having a proper facility, a proper team, and a proper method in order to control the recovery process after an ACL injury. The proper facility consists of rehabilitation gyms, rehabilitation pools, and sport fields. The use of these three areas at well-defined moments is crucial for the best recovery. The rehab gym is still considered the main area with an average of 60% of the total number of sessions. During each session specific exercises are performed, together with manual and physical therapies if needed (Fig. 51.1). After the suture removal, the patient can begin rehabilitation in the pool that will cover about 20% of the total sessions. The aquatic environment offers many advantages, such as offering the opportunity of working in the absence of gravity, controlling weight-bearing progression, and introducing

Fig. 51.1 Specific exercises performed in the gym

sport-specific movement patterns such as kicking or heading the ball. The sport field is the main facility of the last phase allowing patients to RTS.

The sport medicine team, tasked to follow the patient from the injury to RTS, consists of at least a sport medicine physician, a physiotherapist, and a reconditioning specialist. According to our method, the doctor acts as the "case manager" being in charge of the whole process. He/she plans the customized rehabilitation protocol, coordinates the team around the patient, and communicates regularly with the orthopedic surgeon. This multidisciplinary approach represents a gold standard for the recovery process. Close communication between surgical and rehabilitation team, and in the rehab team itself, is essential for successful recovery and RTS. Communication is crucial to explain the patient the goals of rehabilitation, to monitor his/her progression, and to be aware of complications.

51.2.4 Return to Sport Strategy

According to what is previously described (fourth traffic light), we allow the athlete to RTS only if certain criteria are completely satisfied. These criteria represent our RTS criteria, and we follow a potential strategy in order to accomplish each of them.

1. Recovery of muscular strength is certainly a milestone in rehabilitation, both in the literature and in our experience. Quadriceps femoris weakness is very common after ACLR and persists at long follow-up [35, 36]. We also know that strength weakness alters knee joint biomechanics and may lead to early osteoarthritis [37, 38]. It is indeed mandatory to reach the symmetry between the two limbs (100% both for extensor and flexor strength) evaluated with the isokinetic test (Fig. 51.2). In case of strength deficit, the test must be repeated until the complete recovery.

2. Metabolic recovery also plays a crucial role and has to be considered because fatigue leads to a potential risk of reinjury by altering the neuromuscular control [39]. We suggest checking aerobic and anaerobic lactate thresholds through specific tests (Fig. 51.3). Customized threshold training is subsequently proposed to guarantee a proper metabolic reconditioning. Before RTS the player has to reach the right values of aerobic and anaerobic threshold depending on the type of sport.

Fig. 51.2 The isokinetic test

Fig. 51.3 The threshold test

Fig. 51.4 The on-field rehabilitation

3. The on-field rehabilitation (OFR) is the most critical and important part of the recovery process. Sport-specific movements and drills are progressively reintroduced, and aerobic/anaerobic reconditioning is completed. Della Villa et al. demonstrated that a program of OFR allows earlier RTS without jeopardizing functional outcome at 5-year follow-up [40]. We also know that OFR may safely lead to complete functional recovery and return to sport [41]. The strategy we propose is to perform sport-specific supervised exercises both indoor (synthetic field) and outdoor (natural field) (Fig. 51.4). The protocol is progressive in terms of loading, complexity of

Fig. 51.5 Movement patterns evaluation

the proposed exercises, and velocity of the agility drills. Regarding the duration of the OFR, it mainly depends on the clinical issue.

4. Movement patterns restoration also needs to be pursued. We know that specific movement patterns are frequently associated with a certain type of injury. For example, a dynamic knee valgus may predict primary ACL injury, and altered neuromuscular control may predict second ACL injury after ACLR [42, 43]. These dangerous patterns have to be avoided in order to reduce the reinjury rate. Patients presenting with some kind of movement impairments need to be pro-habilitated to a more correct movement strategy. This is the main reason why we suggest performing a sport-specific movement analysis test (MAT) and correct the neuromuscular impairments (Fig. 51.5).

Apart from these well-established criteria, we know that prevention and psychological aspects are other "key points" in the modern rehabilitation landscape. The prevention concept should be early introduced in the recovery process: from the first specific intervention in the pool to the more specific neuromuscular programs to be performed on the field. The programs may be really effective in primary prevention, with a reduction up to 30% of injuries, in case of maximal compliance to the program [44]. Plus, educating the patient to a neuromuscular prevention program (to be performed at least three times a week) can be very effective in reducing the risk of reinjury. Psychological factors have been already studied; it seems that both fear (fear of reinjury and kinesiophobia) and innate personality traits play a role in the return to sport decision [45].

51.3 Quantitative Assessment

There have been numerous studies that focus more specifically on clinical measures to assess functional performance following ACL reconstruction. A recent systematic literature review found that concentric or isometric strength and the single-hop leg test for distance were most commonly used [46]. Myer et al. provided a more recent analysis on an athlete's single-limb performance using the single-limb symmetry index [47]. In their Level 3 case control study, single-limb vertical jump height and maximum vertical ground reaction force were measured on a portable force plate, but deficits were independent of time after reconstruction [47]. These measures can be difficult to extrapolate from the clinic to the playing field given the complexity of knee kinematics during athletic competition and considerations in regard to patient effort during clinical examination. Lentz et al. recently compared physical impairment and functional and psychosocial measures 6 months and 1 year following ACL reconstruction [48]. They found that elevated pain-related fear of movement and reinjury, quadriceps weakness, and reduced IKDC scores at 6 months post-op placing patients at risk for failure to return to sports at 1 year [48].

Reports in the early 1900s showed that the ACL also plays a role as a restraint to rotation of the knee [49]. Slocum and Larson first described a clinical examination that assessed rotatory knee stability [49]. Further work by Jakob and eventually Lemaire et al. on the basis of previous studies coined the term "pivot shift" to describe the anterolateral rotation laxity seen with ACL insufficiency [49]. This physical exam maneuver is characterized by abnormal anterior rotatory subluxation of the lateral tibial plateau when the medially rotated limb is under load in a few degrees of flexion. While still under load, spontaneous reduction occurs as the knee is flexed to 30° or 40°.

Despite a lack of standardization in the literature, the pivot shift is the most specific test to establish the diagnosis of ACL insufficiency before and after surgery [50–52]. On most occasions, pivot shift test grading in the clinic setting is subjective but used as an objective outcome tool to test dynamic laxity of the ACL. Standardizing the pivot shift test to improve inter-tester reliability has been the focus of recent work at our institution [53]. Several different approaches have been developed to assist in improving the pivot shift test: (1) measurement of knee laxity, (2) quantification of knee dynamics by acceleration, and (3) mechanization and instrumentation of the test [54]. A meta-analysis in 2012 found the KT-1000 arthrometer performed with maximum manual force has the highest sensitivity, specificity, accuracy, and positive predictive value for diagnosis of ACL rupture [26]. We utilize the KT-1000 arthrometer (MEDmetric Corporation) at our institution.

Improvements in measurement technology have allowed for quantification of dynamic knee motion with an electromagnetic motion tracking system. This permits characterization of the pivot shift by tibial anterior translation and/or tibial acceleration [54, 55]. The system (FASTRAK, Polhemus, Colchester, VT) at our institution uses an electromagnetic field with three receivers to measure the 6° of freedom of the knee at a high sampling rate (Fig. 51.6). To enhance repeatability, previous studies have shown that the pivot shift can be mechanized [56–58]. In the clinical setting, an examiner requires proprioceptive feedback to control the force and moment arm for each individual knee which introduces variability with regard to the examiner's unique testing maneuver. Standardized technique at our institution has been designed on the basis of the Galway and MacIntosh procedure [59]. A recent review described the most common torques used to simulate the pivot shift were 10-Nm valgus and 5-Nm internal rotation at 30 degrees of knee flexion [49]. However, great variability in technique remains, and no methodology can currently be defined as the gold standard. As such, further work is necessary before defining return to play criteria on the basis of the pivot shift maneuver.

51.3.1 Imaging Assessment

MRI has emerged as a powerful tool given its high sensitivity and specificity for diagnosis of ACL tears, graft tears, and associated injuries (Fig. 51.7). Our institutional protocol utilizes a 1.5-T magnet open-bore configuration (Magnetom Espree, Siemens Medical Solutions, Malvern, PA, USA) to image the ACL in multiple planes with different pulse sequences [60]. Clinical applications begin with preoperative

Fig. 51.6 Intraoperative pivot-shift measurements with electromagnetic motion trackers and quantification with iPad software

planning to define each athlete's unique bony morphology and ligamentous anatomy in an attempt to minimize the most common technical errors of reconstruction [60]. These errors can be critically evaluated with postoperative MRI in addition to assessment of ACL healing during the rehabilitation period [55].

Previous studies have focused on the process of graft healing and maturity or "ligamentization" and describe an early phase of increasing vascularity followed by remodeling and maturation phases [61, 62]. MRI evaluates this increase in vascularity during healing, which is represented by an increased signal in the graft and periligamentous tissues [63]. As the graft matures over time, MRI signal intensity on proton density (PD)-weighted sequences decreases [64]. Ntoulia et al. showed an increased in signal intensity at 6 months postoperative with no significant increase in signal by 12 months [64]. Contrast-enhanced studies have also been used to evaluate graft vascularity by calculating the enhancement index (ratio of signal-to-noise quotient [SNQ] before and after contrast) [65]. Autografts have been

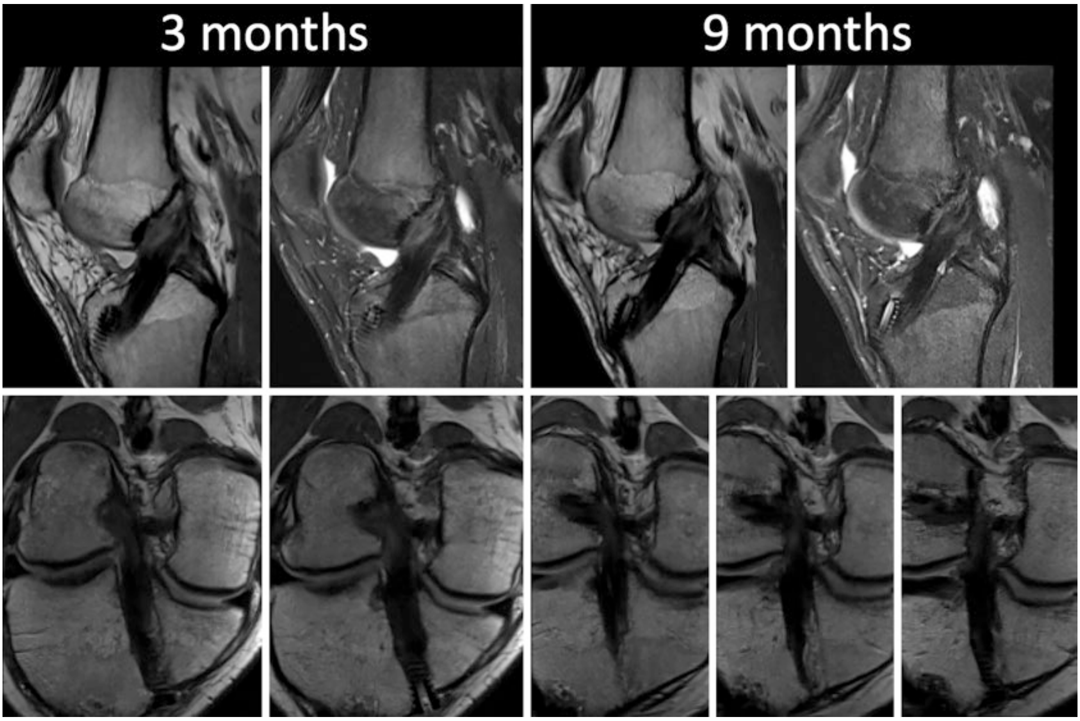

Fig. 51.7 Increased signal in ACL graft at 3 months postoperative signifies vascularity in the healing graft compared to 9 months postoperative

shown to reach peak revascularization 4–6 months after surgery, while allografts have increasing signal/noise quotient (SNQ) values 12–24 months after surgery, suggesting a slower onset and rate of revascularization [65, 66].

Variability in rates of return to play may suggest that graft healing necessary for the forces tolerated during sporting activity has not been achieved. Although signal intensity has shown promise, unrelated factors may confound interpretation such as graft impingement. One source of graft impingement is the posterior cruciate ligament, which contacts the ACL in approximately 25% of native knees [25]. Contact between the ACL graft and PCL, however, has been shown to occur in 75% of double-bundle reconstruction knees [25].

Maturation of the graft within the femoral and tibial tunnels appears to lag behind the intra-articular graft [64]. Cross-sectional imaging with MRI has been shown to be superior to plain radiographs in the assessment of tunnel healing [67]. Decreases in tunnel diameter on MRI have correlated with increased osteointegration and vascularity [67]. Sagittal oblique images, however, cannot fully visualize the boundary between the intra-femoral tunnel and intra-articular graft, and some believe coronal oblique images make evaluation of the entire course of the graft possible [68]. However, no consensus on graft visibility and prediction of graft maturation has been found, but new techniques independent of acquisition characteristics are currently being developed.

Conclusion

The current concept after ACLR is applying a criteria-based rehabilitation protocol, rather than respect prefixed times. Certain clinical and functional criteria have to be satisfied in order to progress throughout rehabilitation and to finally be allowed to RTS. The application of this kind of protocol must be emphasized to ensure optimal return to performance. Rehabilitation programs should be patient specific with respect to graft type and the biomechanical demands of an athlete's sport. In order to supplement serial examination of the postoperative athlete, new research into clinical tools and advances in imaging aim to provide objective benchmarks for safe return to play. Standardization of the pivot shift test may be a powerful tool in defining criteria for rehabilitation protocols, but further work is necessary at the current time. Correlation with serial MRI to evaluate surgical technique and graft healing may also assist with the clinical decision-making process, but no consensus in its utility has been established. The safe release of footballers to the training pitch should aim to minimize the risk of reinjury, but the scientific debate to determine the optimum time for return to sport is ongoing.

References

1. Aglietti P, Giron F, Buzzi R, Biddau F, Sasso F. Anterior cruciate ligament reconstruction: bone-patellar-bone compared with double semitendinosus and gracilis tendon graft. A prospective, randomized clinical trial. J Bone Joint Surg Am. 2004;86-A:2143–55.
2. Fithian D, Paxton E, Stone M, Luetzow WF, Csintalan RP, Phelan D, Daniel DM. Prospective trial of a treatment algorithm for the management of the anterior cruciate ligament-injured knee. Am J Sports Med. 2005;33:335–46.
3. Brukner P. Return to play – a personal perspective. Clin J Sport Med. 2005;15:459–60.
4. Yunes M, Richmond J, Engels E, Pinczewski LA. Patellar versus hamstring tendons in anterior cruciate ligament reconstruction: a meta-analysis. Arthroscopy. 2001;17:248–57.
5. Ardern C, Taylor N, Feller JA, Webster KE. Return-to-sport outcomes at 2 to 7 years after anterior cruciate ligament reconstruction surgery. Am J Sports Med. 2012;40:41–8.
6. Ardern CL, Taylor NF, Feller JA, Webster KE. Fifty-five percent 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;48:1543–52.
7. Erikson BJ, Harris JD, Cvetanovich GL, Bach BR, Bush-Joseph CA, Abrams GD, Gupta AK, McCormick FM, Cole BJ. Performance and return to sport after anterior cruciate ligament reconstruction in Male Major League Soccer players. Orthop J Sports Med. 2013;1:2325967113497189.
8. Shah VM, Andrews JR, Fleisig GS, McMichael CS, Lemak LJ. Return to play after anterior cruciate ligament reconstruction in National Football League athletes. Am J Sports Med. 2010;38:2233–9.
9. McCullough KA, Phelps KD, Spindler KP, Matava MJ, Dunn WR, Parker RD, MOON Group, Reinke EK. MOON Group: return to high school- and college-level football after anterior cruciate ligament reconstruction: a Multicenter Orthopaedic Outcomes Network (MOON) cohort study. Am J Sports Med. 2012;40:2523–9.
10. Wright RW, Magnussen RA, Dunn WR, Spindler KP. Ipsilateral graft and contralateral ACL rupture at five years or more following ACL reconstruction: a systematic review. J Bone Joint Surg Am. 2011;93(12):1159–65.
11. Shelbourne KD, Gray T, Haro HM. Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. Am J Sports Med. 2009;37:246–51.
12. Deehan D, Cawston T. The biology of integration of the anterior cruciate ligament. J Bone Joint SurgBr. 2005;87:889–95.
13. Johnson D, Swenson T, Irrgang J, Fu FH, Harner CD. Revision anterior cruciate ligament surgery: experience from Pittsburgh. Clin Orthop Relat Res. 1996;325:100–9.
14. van Eck C, Schkrohowsky J, Working Z, Irrgang JJ, Fu FH. Prospective analysis of failure rate and predictors of failure after anatomic anterior cruciate ligament reconstruction with allograft. Am J Sports Med. 2012;40:800–7.
15. Ekdahl M, Wang J, Ronga M, Fu F. Grafting healing in anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2008;16:935–47.
16. Peterson W, Laprell H. Insertion of autologous tendon grafts to the bone: a histological and immunohistochemical study of hamstring and patellar tendon grafts. Knee Surg Sports Traumatol Arthrosc. 2000;8:26–31.
17. Rodeo S, Kawamura S, Kim H, Dynybil C, Ying L. Tendon healing in a bone tunnel differs at the tunnel entrance versus the tunnel exit: an effect of graft-tunnel motion? Am J Sports Med. 2006;34:1790–800.
18. Anderson K, Seneviratne A, Izawa K, Atkinson BL, Potter HG, Rodeo SA. Augmentation of tendon healing in an intraarticular bone tunnel with use of a bone growth factor. Am J Sports Med. 2001;29:689–98.
19. Kyung H, Kim S, Oh C, Kim SJ. Tendon-to-bone tunnel healing in a rabbit model: the effect of periosteum augmentation at the tendon-to-bone interface. Knee Surg Sports Traumatol Arthrosc. 2003;11:9–15.
20. Martinek V, Latterman C, Usas A, Abramowitch S, Woo SL, Fu FH, Huard J. Enhancement of tendon-bone integration of anterior cruciate ligament graft with bone morphogenetic protein-2 gene transfer: a histological and biomechanic study. J Bone Joint Surg Am. 2002;84-A:1123–31.

21. Miyawaki M, Hensler D, Illingworth K, Irrgang JJ, Fu FH. Signal intensity on magnetic resonance imaging after allograft double-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2014;22:1002–8.
22. Biercevicz A, Akelman M, Fadale P, Hulstyn MJ, Shalvoy RM, Badger GJ, Tung GA, Oksendahl HL, Fleming BC. MRI volume and signal intensity of ACL graft predict clinical, functional, and patient-oriented outcome measures after ACL reconstruction. Am J Sports Med. 2015;43:693–9.
23. van Diek F, Wolf M, Murawski C, van Eck CF, Fu FH. Knee morphology and risk factors for developing an anterior cruciate ligament rupture: an MRI comparison between ACL-ruptured and non-injured knees. Knee Surg Sports Traumatol Arthrosc. 2014;22:987–94.
24. Vrooijjink S, Wolters F, van Eck C, et al. Measurements of knee morphometrics using MRI and arthroscopy: a comparative study between ACL-injured and non-injured subjects. Knee Surg Sports Traumatol Arthrosc. 2011;19:S12–6.
25. Kropf E, Shen W, van Eck C, et al. ACL-PCL and intercondylar notch impingement: magnetic resonance imaging of native and double-bundle ACL-reconstructed knees. Knee Surg Sports Traumatol Arthrosc. 2013;21:720–5.
26. van Eck C, Loopik M, van den Bekerom M. Methods to diagnose acute anterior cruciate ligament rupture: a meta-analysis of instrumented knee laxity tests. Knee Surg Sports Traumatol Arthrosc. 2013;21:1989–97.
27. Anderson A, Snyder R, Federspiel C, Lipscomb AB. Instrumented evaluation of knee laxity: a comparison of five arthrometers. Am J Sports Med. 1992;20:135–40.
28. Hoshino Y, Araujo P, Ahlden M, Moore CG, Kuroda R, Zaffagnini S, Karlsson J, Fu FH, Musahl V. Standardized pivot shift test improves measurement accuracy. Knee Surg Sports Traumatol Arthrosc. 2012;20:732–6.
29. Hoshino Y, Araujo P, Ahlden M, Samuelsson K, Muller B, Hofbauer M, Wolf MR, Irrgang JJ, Fu FH, Musahl V. Quantitative evaluation of the pivot shift by image analysis using the iPad. Knee Surg Sports Traumatol Arthrosc. 2013;21:975–80.
30. Adams D, Logerstedt DS, Hunter-Giordano A, Axe MJ, Snyder-Mackler L. Current concepts for anterior cruciate ligament reconstruction: a criterion-based rehabilitation progression. J Orthop Sports Phys Ther. 2012;42:601–14.
31. Kvist J. Rehabilitation following anterior cruciate ligament injury: current recommendations for sports participation. Sports Med. 2004;34:269–80.
32. Myer GD, Paterno MV, Ford KR, Quatman CE, Hewett TE. Rehabilitation after anterior cruciate ligament reconstruction: criteria-based progression through the return-to-sport phase. J Orthop Sports Phys Ther. 2006;36:385–402.
33. van Grinsven S, van Cingel RE, Holla CJ, van Loon CJ. Evidence-based rehabilitation following anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2010;18:1128–44.
34. Ellman MB, Sherman SL, Forsythe B, LaPrade RF, Cole BJ, Bach Jr BR. Return to play following anterior cruciate ligament reconstruction. J Am Acad Orthop Surg. 2015;23:283–96.
35. Palmieri-Smith RM, Thomas AC, Wojtys EM. Maximizing quadriceps strength after ACL reconstruction. Clin Sports Med. 2008;27:405–24.
36. Thomas AC, Villwock M, Wojtys EM, Palmieri-Smith RM. Lower extremity muscle strength after anterior cruciate ligament injury and reconstruction. J Athl Train. 2013;48:610–20.
37. Palmieri-Smith RM, Lepley LK. Quadriceps strength asymmetry after anterior cruciate ligament reconstruction alters knee joint biomechanics and functional performance at time of return to activity. Am J Sports Med. 2015;43:1662–9.
38. Tourville TW, Jarrell KM, Naud S. Relationship between isokinetic strength and tibiofemoral joint space width changes after anterior cruciate ligament reconstruction. Am J Sports Med. 2014;42:302–11.
39. McLean SG, Fellin RE, Suedekum N. Impact of fatigue on gender-based high-risk landing strategies. Med Sci Sports Exerc. 2007;39:502–14.
40. Della Villa S, Kon E, Filardo G, Ricci M, Vincentelli F, Delcogliano M, Marcacci M. Does intensive rehabilitation permit early return to sport without compromising the clinical outcome after arthroscopic autologous chondrocyte implantation in highly competitive athletes? Am J Sports Med. 2010;38:68–77.
41. Della Villa S, Boldrini L, Ricci M, Danelon F, Snyder-Mackler L, Nanni G, Roi GS. Clinical outcomes and return-to-sports participation of 50 soccer players after anterior cruciate ligament reconstruction through a sport-specific rehabilitation protocol. Sports Health. 2012;4:17–24.
42. Hewett TE, Myer GD, Ford KR, Heidt Jr RS, Colosimo AJ, McLean SG, 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;33:492–501.
43. Paterno MV, Schmitt LC, Ford KR, Rauh MJ, Myer GD, Huang B, 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;38:1968–78.
44. Soligard T, Myklebust G, Steffen K, Holme I, Silvers H, Bizzini M, et al. Comprehensive warm-up program to prevent injuries in young female footballers: cluster randomized controlled trial. BMJ. 2008;337:a2469.
45. Tjong V, Murnaghan M, Nyhof-Young J, Ogilvie-Harris DJ. A qualitative investigation of the decision to return to sports after anterior cruciate ligament reconstruction: to play or not to play. Am J Sports Med. 2014;42:336–42.
46. Engelen-van Melick N, van Cingel RE, Tijssen MP. Nijhuis-van der Sanden MW. Assessment of

functional performance after anterior cruciate ligament reconstruction: a systematic review of measurement procedures. Knee Surg Sports Traumatol Arthrosc. 2012;21:869–79.
47. Myer G, Martin L, Ford K, Paterno MV, Schmitt LC, Heidt Jr RS. No association of time from surgery with functional deficits in athletes after anterior cruciate ligament reconstruction: evidence for objective return-to-sport criteria. Am J Sports Med. 2012;40:2256–63.
48. Lentz T, Zeppieri G, George S, Tillman SM, Moser MW, Farmer KW. Comparison of physical impairment, functional, and psychosocial measures based on fear of reinjury/lack of confidence and return-to-sports status after ACL reconstruction. Am J Sports Med. 2015;43:345–53.
49. Arilla F, Yeung M, Bell K, Rahnemai-Azar AA, Rothraff BB, Fu FH, et al. Experiemental execution of the simulated pivot-shift test: a systematic review of techniques. Arthroscopy. 2015;31(12):2245–54.
50. Benjaminse A, Gokeler A, van der Schans C. Clinical diagnosis of an anterior cruciate ligament rupture: a meta-analysis. J Orthop Sports Phys Ther. 2006;36:267–88.
51. Kocher M, Steadman J, Briggs K, Sterett WI, Hawkins RJ. Relationships between objective assessment of ligament stability and subjective assessment of symptoms and function after anterior cruciate ligament reconstruction. Am J Sports Med. 2004;32:629–34.
52. Leitze Z, Losee R, Jokl P, Johnson TR, Feagin JA. Implications of the pivot shift in the ACL-deficient knee. Clin Orthop Relat Res. 2005;436:229–36.
53. Musahl V, Hoshino Y, Ahlden M, Araujo P, Irrgang JJ, Zaffagnini S, et al. The pivot shift: a global user guide. Knee Surg Sports Traumatol Arthrosc. 2012;20:724–31.
54. Hoshino Y, Kuroda R, Nagamune K, Yagi M, Mizuno K, Yamaguchi M, et al. In vivo measurement of the pivot-shift test in the anterior cruciate ligament-deficient knee using an electromagnetic device. Am J Sports Med. 2007;35:1098–104.
55. Labbe D, de Guise J, Mezghani N, Godbout V, Grimard G, Baillargeon D, et al. Feature selection using a principal component analysis of the kinematics of the pivot shift phenomenon. J Biomech. 2010;43:3080–4.
56. Musahl V, Bedi A, Citak M, O'Loughlin P, Choi D, Pearle AD. Effect of single-bundle and double-bundle anterior cruciate ligament reconstructions on pivot-shift kinematics in anterior cruciate ligament- and meniscus-deficient knees. Am J Sports Med. 2011;39:289–95.
57. Musahl V, Citak M, O'Loughlin P, Choi D, Bedi A, Pearle AD. The effect of medial versus lateral meniscectomy on the stability of the anterior cruciate ligament-deficient knee. Am J Sports Med. 2010;38:1591–7.
58. Musahl V, Voos J, O'Loughlin P, Stueber V, Kendoff D, Pearle AD. Mechanized pivot shift test achieves greater accuracy than manual pivot shift test. Knee Surg Sports Traumatol Arthrosc. 2009;18:1208–13.
59. Galway H, MacIntosh D. The lateral pivot shift: a symptom and sign of anterior cruciate ligament insufficiency. Clin Orthop Relat Res. 1980;147:45–50.
60. Araujo P, van Eck C, Torabi M, Fu FH. How to optimize the use of MRI in anatomic ACL reconstruction. Knee Surg Sports Traumatol Arthrosc. 2013;21:1495–501.
61. Rabuck S, Barage M, Fu F. Anterior cruciate ligament healing and advances in imaging. Clin Sports Med. 2013;32:13–20.
62. Claes S, Verdonk P, Forsyth R, Bellemans J. The "ligamentization" process in anterior cruciate ligament reconstruction: what happens to the human graft? A systemic review of the literature. Am J Sports Med. 2011;39:2476–83.
63. Choi J, Ha J, Kim Y, Shim JC, Yang SJ, Kim JG. Relationships among tendon regeneration on MRI, flexor strength, and functional performance after anterior cruciate ligament reconstruction with hamstring autograft. Am J Sports Med. 2012;40:152–62.
64. Ntoulia A, Papadopoulou F, Ristanis S, Argyropoulou M, Georgoulis AD. Revascularization process of the bone-patellar tendon-bone autograft evaluated by contrast-enhanced magnetic resonance imaging 6 and 12 months after anterior cruciate ligament reconstruction. Am J Sports Med. 2011;39:1478–86.
65. Weiler A, Peters G, Maurer J, Unterhauser FN, Südkamp NP. Biomechanical properties and vascularity of an anterior cruciate ligament graft can be predicted by contrast-enhanced magnetic resonance imaging. A two-year study in sheep. Am J Sports Med. 2001;29:751–61.
66. Muramatsu K, Hachiya Y, Izawa H. Serial evaluation of human anterior cruciate ligament grafts by contrast-enhanced magnetic resonance imaging: comparison of allografts and autografts. Arthroscopy. 2008;24:1038–44.
67. Lajtai G, Schmiedhuber G, Unger F, Aitzetmüller G, Klein M, Noszian I, et al. Bone tunnel remodeling at the site of biodegradable interference screws used for anterior cruciate ligament reconstruction: 5-year follow-up. Arthroscopy. 2001;17:597–602.
68. Ma Y, Murawski C, Rahnemai-Azar A, Maldjian C, Lynch AD, Fu FH. Graft maturity of the reconstructed anterior cruciate ligament 6 months postoperatively: a magnetic resonance imaging evaluation of quadriceps tendon with bone block and hamstrings tendon autografts. Knee Surg Sports Traumatol Arthrosc. 2015;23:661–8.