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Instability Following ACL Rupture: What Do We Need to Restore During Reconstruction

Instabilität nach einer Vorderen Kreuzbandruptur: Was müssen wir operativ rekonstruieren?

REVIEW

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Summary

› **ACL injury** involves sagittal plane and rotatory instability; with its reconstruction aimed at restoring this instability. There remains room for improvement in long-term clinical outcomes and preventing recurrent instability. Therefore, it is important to understand the biomechanical parameters that require attention during reconstruction to optimize patient outcomes.
› **In the setting of ACL injury,** the armamentarium of the orthopaedic surgeon includes multiple physical examination maneuvers, quantitative measures of knee instability, and advanced imaging to determine the pattern of instability and inform surgical planning. The pivot shift phenomenon, as a measure of rotatory instability, is one of the key biomechanical parameters which must be restored after reconstruction and which is not fully restored by non-anatomic ACL reconstruction.
› **Anatomic ACL reconstruction** represents the "gold-standard", as it has demonstrated enhanced ability to restore rotatory instability, reduce anterior tibial translation, and improve patient reported outcomes compared to non-anatomic techniques. Repair of concurrent ligamentous and meniscal injuries, as well as possible extra-articular procedures, may enhance the restoration of rotatory stability. Lateral extra-articular tenodesis may be indicated in patients with high pivot shift, who play sports with aggressive rotatory motion, or who have generalized laxity.
› **This article** details the approach to knee instability following ACL rupture and the optimal techniques to restore the rotatory stability post-reconstruction.

Zusammenfassung

› **Verletzungen des vorderen Kreuzbandes (VKB)** führen zur Instabilität in der sagittalen Ebene und zur Rotationsinstabilität. Ziel der VKB-Rekonstruktion ist es deshalb, eben diese Instabilitäten zu beheben. Hierbei gilt es, die langfristigen Ergebnisse zu verbessern und erneute Instabilitäten zu verhindern. Um die Rekonstruktionen diesbezüglich zu optimieren, ist es wichtig, die entscheidenden biomechanischen Parameter zu kennen.
› **Auf der Grundlage verschiedener klinischer Tests,** der quantitativ bestimmten Instabilität und der verbesserten Bildgebung trifft der Chirurg die Entscheidung bezüglich des operativen Procederes. Das Pivot-Shift-Phänomen ist dabei ein Maß für die Rotationsinstabilität und ist einer der wichtigsten biomechanischen Parameter, die nach der Rekonstruktion wiederhergestellt werden müssen. Durch nicht-anatomische Rekonstruktionstechniken wird die dies jedoch nicht vollständig wiederhergestellt.
› **Aus diesem Grund** stellt die anatomische VKB-Rekonstruktion den Goldstandard dar. Damit wird im Vergleich zu nicht-anatomischen Techniken die Rotationsinstabilität besser behoben, die anteriore tibiale Translation (aTT) verringert und verbesserte subjektive klinische Ergebnisse erzielt. Im Falle von zusätzlichen ligamentären Verletzungen oder Meniskusrissen sollten diese ebenfalls adressiert werden und auch die Möglichkeit einer extraartikulären Stabilisierung sollte in Betracht gezogen werden, um die Rotationsstabilität zu verbessern. Dabei kann eine laterale extraartikuläre Tenodese bei Patienten mit hoher Pivot-Shift-Bewegung, aggressivem Rotationssport oder genereller Gelenklaxität angezeigt sein.
› **Dieser Artikel** befasst sich mit der Knieinstabilität nach VKB-Ruptur und den optimalen Versorgungstechniken, um die Rotationsstabilität wiederherzustellen.

KEY WORDS:
ACL Reconstruction, ACL Instability, Knee Instability, Multi-Ligament Knee Injury, Lateral Extra-Articular Tenodesis

SCHLÜSSELWÖRTER:
ACL-Rekonstruktion, ACL-Instabilität, Knie-Instabilität, Mehrbändige Knieverletzung, laterale extraartikuläre Tenodese

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Introduction

Anterior cruciate ligament (ACL) reconstruction is a common and quite successful operation; though close analyses of outcomes leaves much opportunity for improvement. Understanding the factors which can optimize patient outcomes by improving function and restoring knee stability is paramount, as the ACL functions as a major stabilizer to anterior translation of the tibia and rotatory forces (4, 11). ACL rupture, therefore, results in complex rotatory instability, which must be addressed at the time of reconstruction surgery to improve patient outcomes, minimize recurrences, and optimize return to pre-injury levels of play.

Diagnosis and management of ACL injury hinges on many factors, not the least of which include injury mechanism, chronicity, age, and associated ›

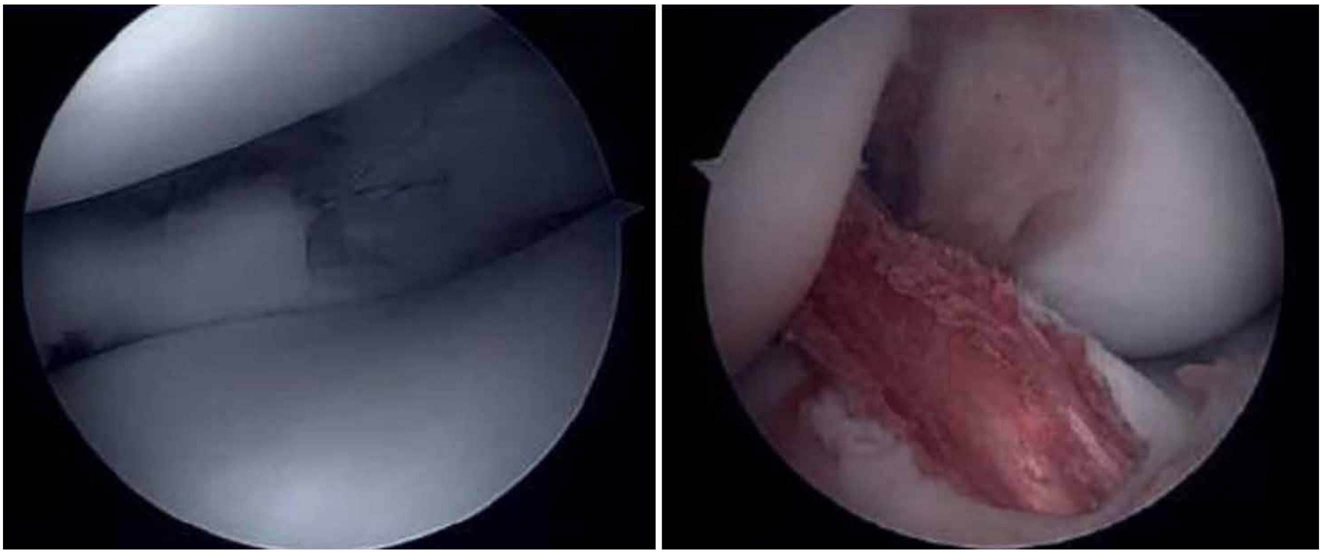

Figure 1
Intra-operative images of lateral meniscus repair and ACL reconstruction with quadriceps tendon autograft.

meniscal, collateral/cruciate ligament and/or chondral injuries. Both physical exam and imaging remain invaluable tools for determining the appropriate treatment approach. There exist a subset of patients, who have persistent rotatory knee instability, despite successful ACL reconstruction, which is not without consequence, given that residual rotatory knee instability is associated with worse postoperative outcomes (12). Though "failure" of a primary ACL reconstruction has been defined in multiple ways, with no universal definition in current practice, approximately 18% to 40% of patients experience recurrent subjective instability or inability to return to previous level of sports participation (5,6). In fact, ACL reconstruction failure within the first year has been seen with graft failure and recurrent instability due to technical error or unrecognized associated ligamentous injuries (51).

This article reviews the patient evaluation of instability after ACL rupture and the surgical techniques to restore stability with ACL reconstruction.

Physical Exam

ACL insufficiency is associated with rotatory instability, and frequently presents with concurrent injury. Several physical exam maneuvers have been described in the diagnosis of ACL tear (24). The anterior drawer and Lachman tests have high sensitivity (94.4% and 93.5%, respectively) (38) for ACL rupture, but only evaluate sagittal plane laxity. Alternatively, the pivot shift test can be used to assess rotatory laxity. Examination of the medial and lateral collateral ligaments, posterolateral corner, posterior cruciate ligament, and menisci are equally important to determine concurrent injuries which may be contributing to rotatory instability.

Pivot Shift Examination

Initially described in 1972, the pivot shift test was developed to examine lateral compartment rotatory laxity with ACL insufficiency (17), and is graded on a subjective scale: grade I (glide), grade II (clunk), and grade III (gross) (27). The pivot shift maneuver reproduces the subluxation event that occurs at the time of ACL rupture. A positive test is seen with a rapid reduction of an anteriorly subluxated lateral tibial plateau as the knee is brought from extension into flexion with an internal rotation and valgus stress (7). The pivot shift test has the highest specificity for ACL rupture (97%-99%), as compared to the anterior drawer and Lachman tests, and the highest positive predictive value (44).

There can be variability in the pivot shift test depending on examiner technique and familiarity. Additionally, significant differences in objective pivot shifts have been reported between conscious and anesthetized patients (37). Quantitative pivot shift testing is increasingly used to provide objective data for defining rotatory laxity (2, 8, 25, 32, 40, 54, 55). When clinical pivot shift was divided into high grade (grade II or grade III) and low grade (grade 0 and grade I), quantitative pivot shift shows significant differences in lateral compartment translation and acceleration ($p<0.05$) (40). In fact, there is also a correlation between generalized joint laxity and quantitative pivot shift values in the contralateral healthy knee of ACL-injured patients (Rho 0.235, $p<0.05$) (48). Therefore, non-invasive quantitative pivot shift measurements can be useful preoperatively to quantify the degree of rotatory laxity, intraoperatively to assess the success of restoration of rotatory stability, and postoperatively to track graft healing and stability during recovery.

Imaging

Advanced imaging is the mainstay for evaluation of rotatory knee instability and associated injuries. Magnetic resonance imaging (MRI) has become the "gold-standard" for diagnosis of ACL injury, with both high sensitivity (90-95%) and specificity (95-100%) (29). A diagnosis of ACL rupture is based upon common findings of ACL change in morphology (i.e. disrupted, attenuated, edematous), anterior tibial translation, and typical bone bruising pattern on the lateral femoral condyle and lateral tibial plateau. MRI must be carefully assessed for associated injuries including the collateral ligaments (22.5%) (33), posterolateral corner (11%) (33), and the menisci (48-62%) (19). Clinical correlation with the patient's symptoms, objective physical examination findings, and intraoperative assessment is essential in determining the appropriate surgical reconstruction plan.

Anatomic Reconstruction

Anatomic repair or reconstruction is a guiding principle of orthopaedic surgery and has been shown to lead to improved patient reported outcomes, decreased anterior tibial translation, and increased rate of negative pivot shift in ACL reconstruction compared with non-anatomic reconstruction (26). Biomechanical studies have shown that an anatomically reconstructed ACL has similar rotatory stability to the native ACL, but non-anatomic ACL reconstruction does not restore the rotatory instability (52). Non-anatomic ACL reconstruction also shows increased anterior laxity with internal rotation at 30 degrees of flexion (35). Furthermore, double-bundle anatomic reconstruction was shown to restore 97%±9% of the in situ forces, while single-bundle reconstruction only restored 60%±40% of the in situ forces seen in the native ACL (26). In a prospective randomized controlled trial comparing conventional single-bundle reconstruction, anatomic single-bundle reconstruction, and anatomic double-bundle reconstruction, the double-bundle reconstruction provided the best stability at 5-year follow-up (26). Non-anatomic reconstruction had increased side-to-side KT-1000 anterior translation and a higher percentage of patients with persistent rotatory instability compared to anatomic double-bundle reconstruction at 5-year follow-up. Side-to-side KT-1000 differences were 1.2mm, 1.6mm, and 2.0mm in the anatomic double-bundle, anatomic single-bundle, and non-anatomic single-bundle groups, respectively. The pivot shift test was negative at 5-year follow-up in 93.1% versus 66.7% versus 41.3% in the anatomic double-bundle, anatomic single-bundle, and non-anatomic reconstruction, respectively (26).

Clinical outcome differences have not been as clear as the biomechanical data. A large meta-analysis investigating transtibial versus independent drilling techniques for ACL reconstruction reiterated the biomechanical advantage of anatomic reconstruction, but failed to show a difference in International Knee Documentation Committee (IKDC) or Tegner scores (46). This growing body of research supports anatomic single- and double-bundle ACL reconstruction to restore rotatory knee stability associated with ACL injury, but further studies are needed to show the long-term clinical benefit.

There has been a resurgence of interest in primary ACL repair to restore anatomic orientation of the ACL and maintain proprioception, but systematic reviews, and randomized trails comparing ACL repair with and without internal bracing to ACL reconstruction have shown increased rates of failure, decreased patient function, and increased rotatory instability in patient undergoing primary repair (15, 20). At this time, there is no proven role for primary repair in ACL reconstruction to restore rotatory stability.

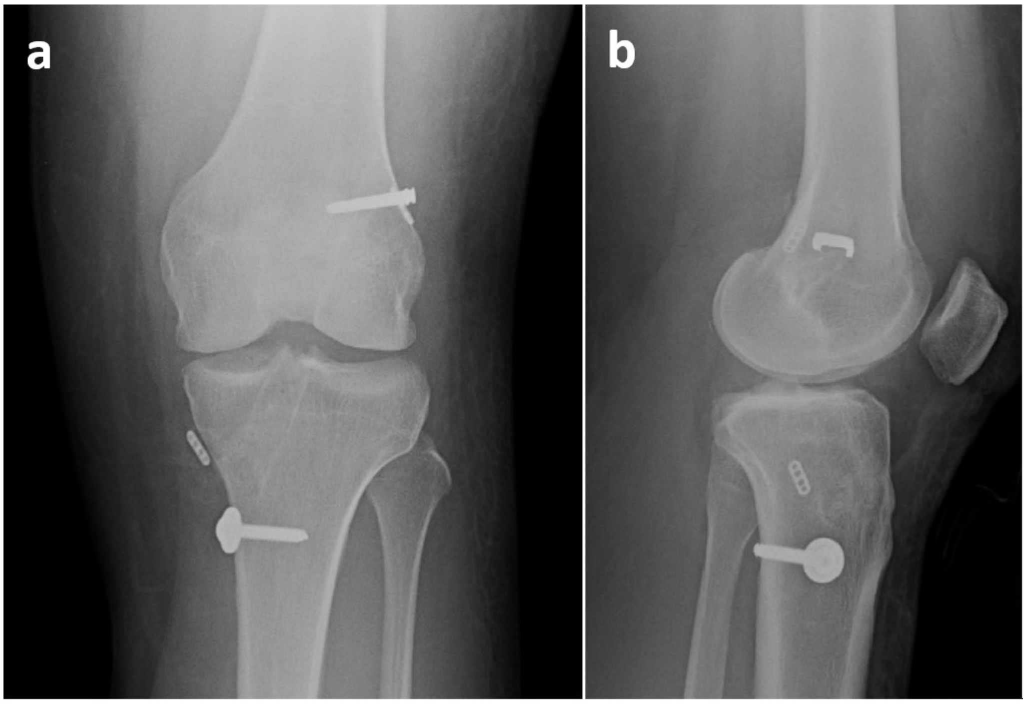

Figure 2
(a) AP and (b) lateral radiographs of ACL reconstruction, meniscus repair, and LET with bone staple fixation.

Operative Considerations

Examination Under Anesthesia

Assessment of sagittal plane and rotatory knee instability is performed after induction of anesthesia. Patients under general anesthesia show significantly increased pivot shift grading and anterior tibial translation (3.0±2.1mm versus 2.2±1.7mm in awake patients, $p<0.01$) as compared to awake patients (37). Preoperative exam under anesthesia can confirm diagnosis and depict the degree of laxity. Subsequent intraoperative exam under anesthesia offers objective feedback on the success of the restoration of stability. Persistent rotatory or sagittal plane laxity seen intraoperatively should be addressed through the repair of additional injured structures or potentially augmentation with an extra-articular procedure, such as a lateral extra-articular tenodesis (21).

Tunnel Position

Femoral tunnel malposition has been cited as the most frequent cause of ACL reconstruction failure and persistent instability (13). The location and orientation of the femoral tunnel are of critical importance during ACL reconstruction. Common issues are anterior placement of the femoral tunnel relative to the native ACL insertion and a more vertical orientation of the tunnel and graft. Anteriorly placed femoral tunnels produce grafts tight in flexion and may lead to loss of knee flexion (28). Posteriorly malpositioned tibial tunnels can have the same affect with loss of flexion. The non-anatomic anterior and high femoral tunnel also creates a more vertical graft orientation. Vertical orientation of the graft restores sagittal plane stability, but does not restore rotatory stability as compared to an anatomic reconstruction (1, 34).

Transtibial femoral tunnel creation has been shown to result in more vertical femoral tunnels, predisposing patients to recurrent rotatory instability and increasing the risk of revision surgery (9, 14). The use of an accessory medial portal for drilling the femoral tunnel in the anatomic femoral footprint and at a more horizontal orientation improves the overall graft biomechanics (46, 50).

Surgical Repair of Associated Injuries

It is crucial to recognize associated injuries when determining the treatment plan for ACL injuries. Associated injuries commonly seen with ACL rupture include medial or lateral meniscus, including posterior roots, collateral ligaments, posterolateral corner structures, and the anterolateral complex (ALC) (16, 30, 41, 42, 49). Greater objective rotatory laxity can be observed in patients with lateral meniscus lesions, anterolateral capsular injury, increased posterior tibial slope, and participation in pivoting sports at the time of injury (43, 47). In addition, MRI evidence of a concomitant injury to the anterolateral capsule, medial meniscus, or lateral meniscus has been shown to be associated with increased quantitative, standardized pivot shift test in patients with an ACL injury (43). High-grade rotatory instability is more frequently seen with medial and lateral meniscal tears, while concurrent MCL or posterolateral corner injuries may only lead to low-grade rotatory instability (41). Anterolateral capsular injury is present in 50% of acute ACL tears, but there is increasing evidence that the inconsistently present thickening of the anterolateral capsule of the knee is neither biomechanically nor clinically important (10, 22, 39).

The general principal of the surgery after ACL rupture is to restore the native anatomy to maximize restoration of rotatory stability. Given the previously described increased quantitative laxity with associated lesions, repair or reconstruction of those concomitantly injured structure should be performed at the time of ACL reconstruction. This includes repairing medial and lateral menisci and repairing or reconstructing collaterals or the posterolateral corner in order to optimally restore knee stability and prevent increased strain on the ACL graft. "Ramp lesions", involving the posterior horn of the medial meniscus, are seen in 16% of injuries and represent a destabilizing injury which should be corrected at the time of ACL reconstruction (36). Medial meniscus repair has been shown to reduce tibial translation in a cadaveric model (3). The goal is to formulate an individualized approach to the ACL reconstruction and associated injuries.

Lateral Extra-Articular Tenodesis

The specific evidence-based indications for lateral extra-articular tenodesis (LET) have yet to be defined, but has been recommended for use in revision ACL reconstruction, severe rotatory instability, participation in pivoting/high risk sports, and generalized ligamentous laxity (18). LET has been proposed as a technique to improve rotatory laxity of the knee in the setting of ACL reconstruction (21). In the setting of single-bundle ACL reconstruction, LET reduces varus/valgus laxity, as well as internal/external rotation in full flexion, but did not restore pivot shift, as compared to anatomic double-bundle reconstruction (53). In a cadaveric model of ACL rupture and anterolateral capsule injury, ACL reconstruction together with LET reduced anterior translation of the lateral tibia during pivot shift as compared to isolated ACL reconstruction (23). In addition, LET was a necessary augmentation to ACL reconstruction to restore rotatory stability in response to an internal tibial torque in the anterolateral capsule deficient knee (21). Improved rotatory stability with LET may help to prevent graft elongation (45). However, it has also been shown that LET augmentation in the setting of isolated ACL rupture does not improve stability beyond typical intra-articular ACL reconstruction (4, 23). Furthermore, combined ACL reconstruction and LET can over-constrain internal rotation of the knee when the anterolateral capsule is intact (23). The authors consider LET in ACL rupture patients with high grade quantitative pivot shift, including greater than 6-8mm lateral translation and 10m/s^2 acceleration, revision ACL reconstruction with a persistent high-grade pivot shift after managing associated injuries, and ACL reconstruction in the setting of generalized hyperlaxity. LET is avoided with isolated ACL rupture and low quantitative pivot shift test.

Case Example

A 14-year-old male presented to the clinic with a right knee injury, two weeks after sustaining a non-contact pivoting injury to the right knee while playing football. He was diagnosed with a complete femoral-sided ACL tear and a posterior horn lateral meniscus tear. After discussion with the patient and his parents, they elected for surgical intervention. Examination under anesthesia findings included grade 2 pivot shift, 2B Lachman, 3.2mm translation on quantitative pivot shift (1.7 mm side-to-side difference), and 9.2m/sec^2 (1.6m/sec^2 side-to-side difference) acceleration on accelerometer testing. Diagnostic arthroscopy revealed a complex, radial tear posterior horn lateral meniscus and complete femoral-sided ACL tear. He underwent ACL reconstruction with quadriceps tendon autograft and lateral meniscus repair (Fig. 1). Given his high degree of quantitative preoperative rotatory instability, a modified Lemaire's lateral extra-articular tenodesis was also performed routing a 5cm long by 5mm wide strip of IT band deep to the lateral collateral ligament and fixed to Lemaire's point (31) in 60 degrees flexion with an extra small staple (Fig. 2).

Conclusion

Restoration of rotatory stability after ACL rupture requires careful preoperative assessment and surgical planning. Anatomic ACL reconstruction and repair of associated meniscal and ligamentous injuries is the mainstay of treatment. Lateral extra-articular tenodesis can be used to augment ACL reconstruction in the setting of associated anterolateral capsular injury with high grade pivot shift, revision ACL reconstruction and persistent instability after addressing concomitant injuries, and possibly generalized ligamentous laxity.

Conflict of Interest

The authors have no conflict of interest.

References

(1) **ABEBE ES, UTTURKAR GM, TAYLOR DC, SPRITZER CE, KIM JP, MOORMAN CT 3RD, GARRETT WE, DEFRATE LE.** The effects of femoral graft placement on in vivo knee kinematics after anterior cruciate ligament reconstruction. J Biomech. 2011; 44: 924-929. doi:10.1016/j.jbiomech.2010.11.028

(2) **AHLDÉN M, ARAUJO P, HOSHINO Y, SAMUELSSON K, MIDDLETON KK, NAGAMUNE K, KARLSSON J, MUSAHL V.** Clinical grading of the pivot shift test correlates best with tibial acceleration. Knee Surg Sports Traumatol Arthrosc. 2012; 20: 708-712. doi:10.1007/s00167-011-1863-8

(3) **AHN JH, BAE TS, KANG K-S, KANG SY, LEE SH.** Longitudinal tear of the medial meniscus posterior horn in the anterior cruciate ligament-deficient knee significantly influences anterior stability. Am J Sports Med. 2011; 39: 2187-2193. doi:10.1177/0363546511416597

(4) **AMIS AA, SCAMMELL BE.** Extra-Articular Anterior Intra-Articular Reconstruction Ligament and of the. J Bone Jt Surg. 1993; 75–B: 812-817. doi:10.1302/0301-620X.75B5.8376447

(5) **ANDERSON AF, SNYDER RB, LIPSCOMB AB.** Anterior cruciate ligament reconstruction. A prospective randomized study of three surgical methods. Am J Sports Med. 2001. doi:10.1177/036354650 10290030201

(6) **ARDERN CL, TAYLOR NF, 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: 41-48. doi:10.1177/0363546511422999

(7) **ARILLA FV, YEUNG M, BELL K, RAHNEMAI-AZAR AA, ROTHRAUFF BB, FU FH, DEBSKI RE, AYENI OR, MUSAHL V.** Experimental execution of the simulated pivot-shift test: A systematic review of techniques. Arthroscopy. 2015; 31: 2445-2454. doi:10.1016/j.arthro.2015.06.027

(8) **BEDI A, MUSAHL V, LANE C, CITAK M, WARREN RF, PEARLE AD.** Lateral compartment translation predicts the grade of pivot shift: A cadaveric and clinical analysis. Knee Surg Sports Traumatol Arthrosc. 2010; 18: 1269-1276. doi:10.1007/s00167-010-1160-y

(9) **BEDI A, MUSAHL V, STEUBER V, KENDOFF D, CHOI D, ALLEN AA, PEARLE AD, ALTCHEK DW.** Transtibial versus anteromedial portal reaming in anterior cruciate ligament reconstruction: An anatomic and biomechanical evaluation of surgical technique. Arthroscopy. 2011; 27: 380-390. doi:10.1016/j.arthro.2010.07.018

(10) **BELL KM, RAHNEMAI-AZAR AA, IRARRAZAVAL S, GUENTHER D, FU FH, MUSAHL V, DEBSKI RE.** In situ force in the anterior cruciate ligament, the lateral collateral ligament, and the anterolateral capsule complex during a simulated pivot shift test. J Orthop Res. 2018; 36: 847-853. doi:10.1002/jor.23676

(11) **BUTLER D, NOYES F, GROOD E.** Ligamentous restraints to anterior-posterior drawer in the human knee: A biomechanical study. J Bone Joint Surg Am. 1980; 62: 259-270. doi:10.2106/00004623-198062020-00013

(12) **CHAMBAT P, GUIER C, SONNERY-COTTET B, FAYARD JM, THAUNAT M.** The evolution of ACL reconstruction over the last fifty years. Int Orthop. 2013; 37: 181-186. doi:10.1007/s00264-012-1759-3

(13) **CHEN JL, ALLEN CR, STEPHENS TE, HAAS AK, HUSTON LJ, WRIGHT RW, FEELEY BT; MULTICENTER ACL REVISION STUDY (MARS) GROUP.** Differences in mechanisms of failure, intraoperative findings, and surgical characteristics between single- and multiple-revision ACL reconstructions: A MARS cohort study. Am J Sports Med. 2013; 41: 1571-1578. doi:10.1177/0363546513487980

(14) **DESAI N, ANDERNORD D, SUNDEMO D, ALENTORN-GELI E, MUSAHL V, FU F, FORSSBLAD M, SAMUELSSON K.** Revision surgery in anterior cruciate ligament reconstruction: a cohort study of 17,682 patients from the Swedish National Knee Ligament Register. Knee Surg Sports Traumatol Arthrosc. 2017; 25: 1542-1554. doi:10.1007/s00167-016-4399-0

(15) **VAN ECK CF, LIMPISVASTI O, ELATTRACHE NS.** Is There a Role for Internal Bracing and Repair of the Anterior Cruciate Ligament? A Systematic Literature Review. Am J Sports Med. 2018; 46: 2291-2298. doi:10.1177/0363546517717956

(16) **FETTO JF, MARSHALL JL.** Injury to the anterior cruciate ligament producing the pivot-shift sign. An experimental study on cadaver specimens. J Bone Joint Surg Am. 1979; 61: 710-714.

(17) **GALWAY R, BEAUPRE A, MACINTOSH DL.** Pivot shift: a clinical sign of symptomatic anterior cruciate insufficiency. J Bone Jt. Surg Br. 1972; 54: 763-764.

(18) **GETGOOD A, LITCHFIELD R, HEWISON C, BRYANT DM, MCCORMACK RG, HEARD M, MACDONALD PB, SPALDING T, VERDONK P, PETERSON D, BARDANA D, REZANSOFF A.** Anterior Cruciate Ligament Reconstruction With or Without a Lateral Extra-Articular Tenodesis – Assessment of Failure at One Year from the ISAKOS Sponsored Stability Study. Arthroscopy. 2017; 33: e120. doi:10.1016/j.arthro.2017.08.139

(19) **GRANAN L-P, INACIO MCS, MALETIS GB, FUNAHASHI TT, ENGEBRETSEN L.** Intraoperative findings and procedures in culturally and geographically different patient and surgeon populations: an anterior cruciate ligament reconstruction registry comparison between Norway and the USA. Acta Orthop. 2012; 83: 577-582. doi:10.3109/17453674.2012.741451

(20) **GRØNTVEDT T, ENGEBRETSEN L, BENUM P, FASTING O, MOLSTER A, STRAN T.** A prospective, randomized study of three operations for acute rupture of the anterior cruciate ligament. Five-year follow-up of one hundred and thirty-one patients. J Bone Joint Surg Am. 1996; 78: 159-168. doi:10.2106/00004623-199602000-00001

(21) **GUENTHER D, IRARRÁZAVAL S, BELL KM, RAHNEMAI-AZAR AA, FU FH, DEBSKI RE, MUSAHL V.** The Role of Extra-Articular Tenodesis in Combined ACL and Anterolateral Capsular Injury. J Bone Jt Surg. 2017; 99: 1654-1660. doi:10.2106/JBJS.16.01462

(22) **GUENTHER D, RAHNEMAI-AZAR AA, BELL KM, IRARRÁZAVAL S, FU FH, MUSAHL V, DEBSKI RE.** The Anterolateral Capsule of the Knee Behaves Like a Sheet of Fibrous Tissue. Am J Sports Med. 2017; 45: 849-855. doi:10.1177/0363546516674477

(23) **HERBST E, ARILLA FV, GUENTHER D, YACUZZI C, RAHNEMAI-AZAR AA, FU FH, DEBSKI RE, MUSAHL V.** Lateral Extra-articular Tenodesis Has No Effect in Knees With Isolated Anterior Cruciate Ligament Injury. Arthroscopy. 2018; 34: 251-260. doi:10.1016/j.arthro.2017.08.258

(24) **HOPPE DJ, TRUNTZER JN, SHAPIRO LM, ABRAMS GD, SAFRAN MR.** Diagnostic Accuracy of 3 Physical Examination Tests in the Assessment of Hip Microinstability. Orthop J Sports Med. 2017; 5: 2325967117740121. doi:10.1177/2325967117740121

(25) **HOSHINO Y, ARAUJO P, AHLDÉN 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: 975-980. doi:10.1007/s00167-013-2396-0

(26) **HUSSEIN M, VAN ECK CF, CRETNIK A, DINEVSKI D, FU FH.** Prospective randomized clinical evaluation of conventional single-bundle, anatomic single-bundle, and anatomic double-bundle anterior cruciate ligament reconstruction: 281 cases with 3- to 5-year follow-up. Am J Sports Med. 2012; 40: 512-520. doi:10.1177/0363546511426416

(27) **JAKOB RP, STÄUBLI HU, DELAND JT.** Grading the pivot shift. Objective tests with implications for treatment. J Bone Jt Surg. 1987; 69: 294-299. doi:10.1302/0301-620X.69B2.3818763

(28) **KAMATH GV, REDFERN JC, GREIS PE, BURKS RT.** Revision anterior cruciate ligament reconstruction. Am J Sports Med. 2011; 39: 199-217. doi:10.1177/0363546510370929

(29) **KLASS D, TOMS AP, GREENWOOD R, HOPGOOD P.** MR imaging of acute anterior cruciate ligament injuries. Knee. 2007; 14: 339-347. doi:10.1016/j.knee.2007.04.008

(30) **KOCHER MS, STEADMAN JR, BRIGGS KK, 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. doi:10.1177/0363546503261722

(31) **KRACKOW KA, BROOKS RL.** Optimization of knee ligament position for lateral extraarticular reconstruction. Am J Sports Med. 1983; 11: 293-302. doi:10.1177/036354658301100503

(32) **KUBO S, MURATSU H, YOSHIYA S, MIZUNO K, KUROSAKA M.** Reliability and usefulness of a new in vivo measurement system of the pivot shift. Clin Orthop Relat Res. 2007; 54-58. doi:10.1097/BLO.0b013e31802b4a38

(33) **LAPRADE RF, WENTORF FA, FRITTS H, GUNDRY C, HIGHTOWER CD.** A prospective magnetic resonance imaging study of the incidence of posterolateral and multiple ligament injuries in acute knee injuries presenting with a hemarthrosis. Arthroscopy. 2007; 23: 1341-1347. doi:10.1016/j.arthro.2007.07.024

(34) **LEE MC, SEONG SC, LEE S, CHANG CB, PARK YK, JO H, KIM CH.** Vertical Femoral Tunnel Placement Results in Rotational Knee Laxity After Anterior Cruciate Ligament Reconstruction. Arthroscopy. 2007; 23: 771-778. doi:10.1016/j.arthro.2007.04.016

(35) **LIM HC, YOON YC, WANG JH, BAE JH.** Anatomical versus non-anatomical single bundle anterior cruciate ligament reconstruction: A cadaveric study of comparison of knee stability. Clin Orthop Surg. 2012; 4: 249-255. doi:10.4055/cios.2012.4.4.249

(36) **LIU X, ZHANG H, HONG L, WANG XS, ZHANG J.** Arthroscopic prevalence of ramp lesion in 868 patients with anterior cruciate ligament injury. Am J Sports Med. 2011; 39: 832-837. doi:10.1177/0363546510388933

(37) **LOPOMO N, SIGNORELLI C, RAHNEMAI-AZAR AA, RAGGI F, HOSHINO Y, SAMUELSSON K, MUSAHL V, KARLSSON J, KURODA R, ZAFFAGNINI S; PIVOT STUDY GROUP.** Analysis of the influence of anaesthesia on the clinical and quantitative assessment of the pivot shift: a multicenter international study. Knee Surg Sports Traumatol Arthrosc. 2017; 25: 3004-3011. doi:10.1007/s00167-016-4130-1

(38) **MAKHMALBAF H, MORADI A, GANJI S, OMIDI-KASHANI F.** Accuracy of lachman and anterior drawer tests for anterior cruciate ligament injuries. Arch Bone Jt Surg. 2013; 1: 94-97.

(39) **MIYAJI N, HOSHINO Y, TANAKA T, NISHIDA K, NISHIZAWA Y, ARAKI D, KANZAKI N, MATSUSHITA T, KURODA R.** Anterolateral Capsule Injury Did Not Aggravate Rotational Laxity of the Anterior Cruciate Ligament Injured Knees Measured by Quantitative Pivot-shift Evaluation. Orthop J Sports Med. 2017; 5: 2325967117S00354. doi:10.1177/2325967117S00354

(40) **MUSAHL V, GRIFFITH C, IRRGANG JJ, HOSHINO Y, KURODA R, LOPOMO N, ZAFFAGNINI S, SAMUELSSON K, KARLSSON J; PIVOT STUDY GROUP.** Validation of Quantitative Measures of Rotatory Knee Laxity. Am J Sports Med. 2016; 44: 2393-2398. doi:10.1177/0363546516650667

(41) **MUSAHL V, BURNHAM J, LIAN J, POPCHAK A, SVANTESSON E, KURODA R, ZAFFAGNINI S, SAMUELSSON K; PIVOT STUDY GROUP.** High-grade rotatory knee laxity may be predictable in ACL injuries. Knee Surg Sports Traumatol Arthrosc. 2018 [Epub ahead of print]. doi:10.1007/s00167-018-5019-y

(42) **MUSAHL V, AYENI OR, CITAK M, IRRGANG JJ, PEARLE AD, WICKIEWICZ TL.** The influence of bony morphology on the magnitude of the pivot shift. Knee Surg Sports Traumatol Arthrosc. 2010; 18: 1232-1238. doi:10.1007/s00167-010-1129-x

(43) **MUSAHL V, COSTELLO J, ARNER JW, FU FH, HOSHINO Y, LOPOMO N, SAMUELSSON K, IRRGANG JJ.** The Influence of Meniscal and Anterolateral Capsular Injury on Knee Laxity in Patients with Anterior Cruciate Ligament Injuries. Am J Sports Med. 2016. doi:10.1177/0363546516659649

(44) **OSTROWSKI JA.** Accuracy of 3 diagnostic tests for anterior cruciate ligament tears. J Athl Train. 2006; 41: 120-121.

(45) **PERNIN J, VERDONK P, SI SELMI TA, MASSIN P, NEYRET P.** Long-term follow-up of 24.5 years after intra-articular anterior cruciate ligament reconstruction with lateral extra-articular augmentation. Am J Sports Med. 2010; 38: 1094-1102. doi:10.1177/0363546509361018

(46) **RIBOH JC, HASSELBLAD V, GODIN JA, MATHER RC.** Transtibial versus independent drilling techniques for anterior cruciate ligament reconstruction: A systematic review, meta-analysis, and meta-regression. Am J Sports Med. 2013; 41: 2693-2702. doi:10.1177/0363546513506979

(47) **SONG GY, ZHANG H, WANG QQ, ZHANG J, LI Y, FENG H.** Risk Factors Associated with Grade 3 Pivot Shift after Acute Anterior Cruciate Ligament Injuries. Am J Sports Med. 2016; 44: 362-369. doi:10.1177/0363546515613069

(48) **SUNDEMO D, BLOM A, HOSHINO Y, KURODA R, LOPOMO NF, ZAFFAGNINI S, MUSAHL V, IRRGANG JJ, KARLSSON J, SAMUELSSON K; PIVOT STUDY GROUP.** Correlation between quantitative pivot shift and generalized joint laxity: a prospective multicenter study of ACL ruptures. Knee Surg Sports Traumatol Arthrosc. 2018; 26: 2362-2370. doi:10.1007/s00167-017-4785-2

(49) **TANAKA M, VYAS D, MOLONEY G, BEDI A, PEARLE AD, MUSAHL V.** What does it take to have a high-grade pivot shift? Knee Surg Sports Traumatol Arthrosc. 2012; 20: 737-742. doi:10.1007/s00167-011-1866-5

(50) **VENOSA M, DELCOGLIANO M, PADUA R, ALVITI F, DELCOGLIANO A.** Femoral tunnel positioning in anterior cruciate ligament reconstruction: Anteromedial portal versus transtibial technique—a randomized clinical trial. Joints. 2017; 5: 34-38. doi:10.1055/s-0037-1601413

(51) **WILDE J, BEDI A, ALTCHEK DW.** Revision Anterior Cruciate Ligament Reconstruction. Sports Health. 2014; 6: 504-518. doi:10.1177/1941738113500910

(52) **YAGI M, WONG EK, KANAMORI A, DEBSKI RE, FU FH, WOO SLY.** Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction. Am J Sports Med. 2002; 30: 660-666. doi:10.1177/03635465020300050501

(53) **ZAFFAGNINI S, SIGNORELLI C, LOPOMO N, BONANZINGA T, MARCHEGGIANI MUCCIOLI GM, BIGNOZZI S, VISANI A, MARCACCI M.** Anatomic double-bundle and over-the-top single-bundle with additional extra-articular tenodesis: An in vivo quantitative assessment of knee laxity in two different ACL reconstructions. Knee Surg Sports Traumatol Arthrosc. 2012; 20: 153-159. doi:10.1007/s00167-011-1589-7

(54) **ZAFFAGNINI S, LOPOMO N, SIGNORELLI C, MARCHEGGIANI MUCCIOLI GM, BONANZINGA T, GRASSI A, VISANI A, MARCACCI M.** Innovative Technology for Knee Laxity Evaluation: Clinical Applicability and Reliability of Inertial Sensors for Quantitative Analysis of the Pivot-Shift Test. Clin Sports Med. 2013; 32: 61-70. doi:10.1016/j.csm.2012.08.007

(55) **ZAFFAGNINI S, LOPOMO N, SIGNORELLI C, MARCHEGGIANI MUCCIOLI GM, BONANZINGA T, GRASSI A, RAGGI F, VISANI A, MARCACCI M.** Inertial sensors to quantify the pivot shift test in the treatment of anterior cruciate ligament injury. Joints. 2014; 02: 124-129. doi:10.11138/jts/2014.2.3.124