Knee Surg Sports Traumatol Arthrosc
DOI 10.1007/s00167-011-1744-1

KNEE

Evaluation of a simulated pivot shift test: a biomechanical study

Lars Engebretsen · Coen A. Wijdicks · Colin J. Anderson · Benjamin Westerhaus · Robert F. LaPrade

Received: 24 August 2011 / Accepted: 21 October 2011

Abstract
Purpose Double-bundle anterior cruciate reconstructions have led to an increased interest in quantifying anterolateral rotatory stability. The application of combined internal rotation and valgus torques to the knee can more nearly recreate the anterolateral subluxation that occurs in the pivot shift test in vitro compared to coupled internal rotation torque and anterior tibial loads.
Methods Twelve non-paired cadaveric knees were biomechanically tested with the ACL intact and sectioned. For each test state, six-degree-of-freedom positional data were collected for two simulated pivot shift loads consisting of a 5-Nm internal rotation torque coupled with either a 10-Nm valgus torque or an 88 N anterior tibial load at 0°, 20°, 30°, 60°, and 90° of knee flexion.
Results The coupled internal rotation and valgus torques produced a significant increase in anterolateral subluxation between the ACL intact and sectioned states at all tested angles except 90° (5.9 ± 0.4 mm at 0°, 4.3 ± 0.6 mm at 20°, 3.5 ± 0.6 mm at 30°, 2.1 ± 0.6 mm at 60°). The coupled internal rotation and an anterior tibial load produced significant increases between the ACL intact and sectioned states at all tested angles except 30° (5.4 ± 0.5 mm at 0°, 3.7 ± 0.5 mm at 20°, 2.1 ± 0.8 mm at 60°, 1.4 ± 0.3 mm at 90°).
Conclusions We found that the coupled internal rotation and valgus torques best recreated the anterolateral subluxation that occurs in the pivot shift in vitro. This study describes an anterolateral subluxation test for ACL integrity in the laboratory setting.

Keywords Anterior cruciate ligament · Pivot shift test · Anterior tibial translation · Coupled loads · Anterolateral subluxation

L. Engebretsen (✉)
Department of Orthopaedic Surgery, Oslo University Hospital and Faculty of Medicine, Kirkeveien 166, 0407 Oslo, Norway
e-mail: lars.engebretsen@medisin.uio.no

C. A. Wijdicks · R. F. LaPrade
Steadman Philippon Research Institute, Vail, CO, USA

C. J. Anderson · B. Westerhaus
Department of Orthopaedic Surgery, University of Minnesota, Minneapolis, MN, USA

Introduction

The heightened interest in comparing single- and double-bundle anterior cruciate ligament (ACL) reconstructions has propagated a substantial amount of research on the biomechanics of the ACL [7, 15, 23, 26–28, 30]. The reported appeal of double-bundle ACL reconstruction is the potential to increase rotational stability when compared to single-bundle ACL reconstruction [15, 23, 26, 28]. The pivot shift test is a reliable test for determining rotational stability of a potential ACL deficient knee in vivo and can be used to distinguish early outcomes between single- and double-bundle ACL reconstructions [3, 14, 17, 21]. While the pivot shift test is the primary clinical test to measure anterolateral rotation of the knee, it is user-dependent, subjective, and can be difficult to reproduce. There also remains disagreement over how to properly recreate the pivot shift test within the laboratory [4, 13, 15, 16, 20, 26, 30]. The most commonly reported method for simulating the pivot shift in vitro is combining an internal rotation torque with a valgus torque [8, 11, 19, 23, 26, 28]. An alternative test for rotatory instability has been proposed that applies internal rotation combined with an anterior tibial load, based on previous clinical studies [9].

Published online: 05 November 2011

The purpose for this study was to compare different simulated pivot shift testing methods of an intact and sectioned ACL to determine how well clinical tests are represented in vitro. We hypothesized that the anterolateral subluxation created in the pivot shift test would be best recreated in the laboratory by applying a coupled valgus and internal rotation torque to the knee.

Materials and methods

Twelve non-paired, fresh-frozen, human cadaveric knees with no evidence of previous injury, abnormality, or disease were used in this study. The mean age of the specimens was 50.9 years (range 29–66). These specimens were concurrently used for another study examining double-bundle ACL fixation angles, and this study reports on a separate analysis of this previously reported data [2]. The knees were stored in at −20°C and thawed overnight prior to testing. The femur was sectioned 20 cm proximal, and the tibia was sectioned 13 cm distal to the joint line. The femur was placed in a cylindrical mold filled with polymethylmethacrylate (PMMA) (Dentsply, York, PA, USA) to secure the specimen for mounting in a previously described knee testing apparatus [2, 10, 26]. A threaded fiberglass rod was fixed into the intramedullary canal of the tibia to allow for the application of valgus and internal rotation loads. Anterior tibial loads were applied with an eye-screw placed into the tibial tubercle (Fig. 1). The specimens were kept moist with a 0.9% saline solution throughout the experimentation.

Data collection

The Polhemus Liberty system (Polhemus Inc, Colchester, VT) quantified the displacement of the tibia relative to the femur. The MotionMonitor (v. 8, Innovative Sports Training, Chicago, IL) software package was used with the Polhemus system to gather six-degree-of-freedom positional data from one femoral and two tibial sensors relative to a low-frequency magnetic field produced by a electromagnetic transmitter device (Fig. 1). The accuracy of this system in our laboratory was previously reported to be between 0.56° and 0.92° [10]. The distance between the electromagnetic transmitter and sensors was maintained within the previously recorded optimal range of 22.5–64.0 cm to minimize positional error [1, 22]. Data reduction was performed by a custom-written algorithm using MATLAB (v. R2007a, The MathWorks, Natick, MA). Tibial anterolateral subluxation during biomechanical testing was calculated between vectors representing the neutral position and the position of the knee during load application. The vectors were created from anatomical

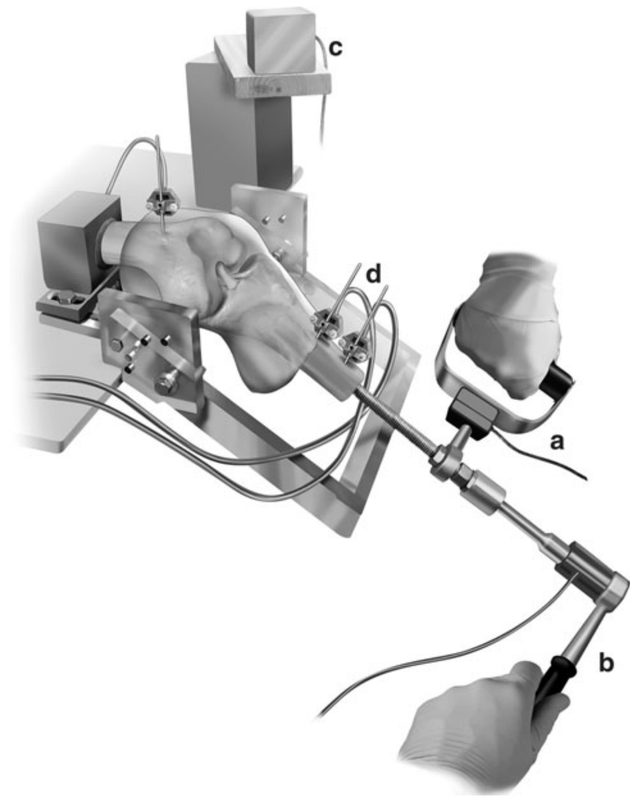

Fig. 1 Illustration of a *left* knee in the biomechanical testing apparatus during application of a simulated pivot shift. During applied valgus (**a**) with internal rotation (**b**), the electromagnetic transmitter (**c**), positioned above the knee, generated electromagnetic pulses that the sensors (**d**) received to determine three-dimensional positioning

reference points designated using a calibrated stylus that the MotionMonitor software tracked during testing. The vectors originated at the midpoint of the medial and lateral femoral epicondyles and terminated at a point immediately lateral to the patellar tendon on the anterior aspect of the lateral tibial plateau.

Biomechanical testing

The specimens were secured and placed in neutral position within a previously described testing apparatus that secured the femur in the horizontal plane and allowed free movement of the tibia on an adjustable support bar that set the knee flexion angle (Fig. 1) [5, 6, 10, 26]. The knees were tested in the intact and sectioned testing states at 0°, 20°, 30°, 60°, and 90° of knee flexion. For each knee flexion angle in each testing state, the two combined loads were applied to simulate the anterolateral subluxation of the pivot shift test consisting of a 5-Nm internal rotation torque coupled with either a 10-Nm valgus torque [26] or an 88 N anterior tibial load. The anterior tibial loads and valgus torques were applied with a 100 N force model SM S-type load cell (Interface, Scottsdale, AZ), with a manufacturer reported non-repeatability error of ±0.01%. Internal rotation torques were applied with a 15-Nm capacity shaft-style reaction torque transducer, model TS12 (Interface), with a manufacturer reported non-repeatability error of ±0.02%. The loads used were based on previous studies [26].

Statistical analysis

Two-way analysis of variance was performed comparing the intact and sectioned states, with Tukey's honest significant difference test used for *post hoc* comparisons. For all analyses, statistical significance was assumed for $P < 0.05$.

Results

Displacement data are summarized in Table 1. Results are reported as the mean ± standard error of the mean.

Anterolateral subluxation with internal rotation and valgus torques

In the intact state, mean tibial anterolateral subluxation resulting from the coupled internal rotation and valgus torques was 7.2 ± 0.9, 11.8 ± 0.9, 12.2 ± 0.8, 9.5 ± 0.9, and 8.6 ± 0.7 mm at 0°, 20°, 30°, 60, and 90° of knee flexion, respectively (Fig. 2). In the sectioned state, mean tibial anterolateral subluxation for the coupled internal rotation and valgus torques was 13.1 ± 1.3, 16.1 ± 1.5, 15.7 ± 1.4, 11.6 ± 1.5, and 9.8 ± 1.2 mm at 0°, 20°, 30°, 60°, and 90° of knee flexion, respectively. The increase in anterolateral subluxation between the intact and sectioned states for this coupled load was 5.8 ± 1.6 mm at 0°, 4.3 ± 1.7 mm at 20°, 3.5 ± 1.7 mm at 30°, 2.2 ± 1.8 mm at 60°, and 1.2 ± 1.4 mm at 90°. Tibial anterolateral subluxation significantly increased compared to the intact state at 0° ($P < 0.01$), 20° ($P < 0.01$), 30° ($P < 0.01$), and 60° ($P < 0.01$) of knee flexion.

Anterolateral subluxation with internal rotation torque and anterior tibial load

In the intact state, mean tibial anterolateral subluxation resulting from the coupled internal rotation and anterior tibial load was 9.1 ± 1.1, 12.2 ± 1.0, 12.5 ± 0.9, 8.0 ± 1.0, and 6.5 ± 0.8 mm at 0°, 20°, 30°, 60, and 90° of knee flexion, respectively (Fig. 3). In the sectioned state, mean tibial anterolateral subluxation for the coupled internal rotation and anterior tibial load was 14.5 ± 1.6, 15.9 ± 1.5, 15.0 ± 1.5, 10.1 ± 1.8, and 7.9 ± 1.1 mm at 0°, 20°, 30°, 60, and 90° of knee flexion, respectively. The increase in anterolateral subluxation between the intact and sectioned states for this coupled load was 5.5 ± 1.9 at 0°, 3.7 ± 1.8 mm at 20°, 2.5 ± 1.8 mm at 30°, 2.1 ± 2.0 mm at 60°, and 1.5 ± 1.4 mm at 90°. Tibial anterolateral subluxation significantly increased in the sectioned state compared to the intact state at 0° ($P < 0.01$), 20° ($P < 0.01$), 60° ($P < 0.05$), and 90° ($P < 0.01$).There was significantly more anterolateral subluxation from the intact to the sectioned states during the coupled internal rotation and valgus torques compared to the combined internal rotation torque and anterior tibial load at 0° ($P < 0.05$) and at 30° ($P < 0.01$).

Discussion

The most important finding of the present study was that the combination of the internal rotation, and valgus torques had a significant increase in anterolateral subluxation at 30° between the intact and sectioned ACL states (Fig. 2, Table 1). This was consistent with the range of knee flexion where the pivot shift has been reported to occur clinically. The combined

Table 1 Mean displacement with respect to the applied load (mean ± standard error of the mean)

Applied load and state	Knee flexion angle				
	0° Anterolateral subluxation (mm)	20°	30°	60°	90°
Internal rotation with valgus torque					
Intact	**7.2 ± 0.9**	**11.8 ± 0.9**	**12.2 ± 0.8**	**9.5 ± 0.9**	8.6 ± 0.7
Sectioned	**13.1 ± 1.3**	**16.1 ± 1.5**	**15.7 ± 1.4**	**11.6 ± 1.5**	9.8 ± 1.2
Difference	5.8 ± 1.6	4.3 ± 1.7	3.5 ± 1.7	2.2 ± 1.8	1.2 ± 1.4
Internal rotation with anterior tibial load					
Intact	**9.1 ± 1.1**	**12.2 ± 1.0**	12.5 ± 0.9	**8.0 ± 1.0**	**6.5 ± 0.8**
Sectioned	**14.5 ± 1.6**	**15.9 ± 1.5**	15.0 ± 1.5	**10.1 ± 1.8**	**7.9 ± 1.1**
Difference	5.5 ± 1.9	3.7 ± 1.8	2.5 ± 1.8	2.1 ± 2.0	1.5 ± 1.4

Values in bold indicate significant difference between the intact and sectioned states ($P < 0.05$)

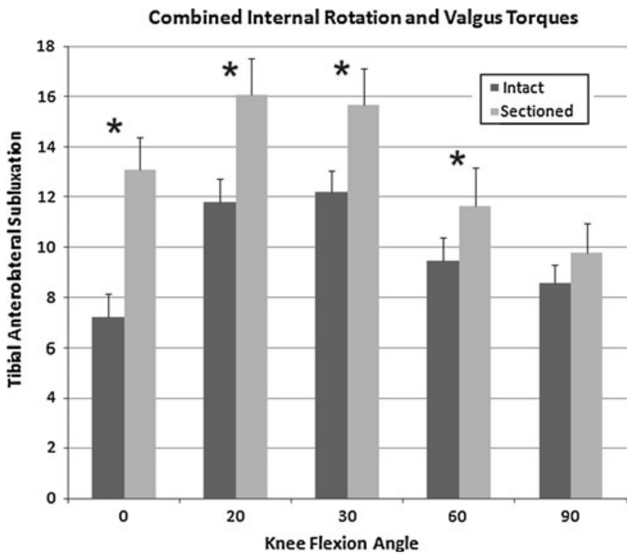

Fig. 2 Anterior tibial translation with the application of simulated pivot shift combining internal rotation and valgus torque. Values with *asterisk* indicate significant difference between sectioned and intact state ($P < 0.05$)

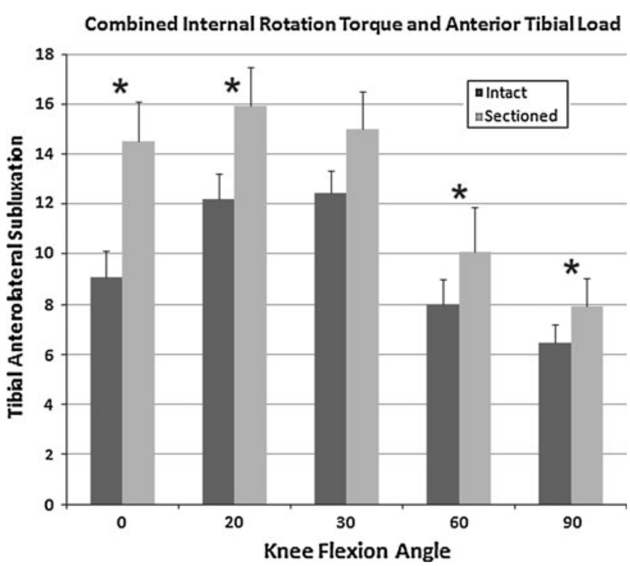

Fig. 3 Anterior tibial translation with the application of the simulated pivot shift combining internal rotation and anterior tibial load. Values with *asterisk* indicate significant difference between sectioned and intact state ($P < 0.05$)

internal rotation torque and anterior tibial load did not exhibit a significant difference in anterolateral subluxation at 30° of knee flexion between the intact and sectioned ACL states. The combined internal rotation torque and anterior tibial load did not reliably result in an increase in anterolateral subluxation of the tibia at the clinically relevant knee flexion angle for the pivot shift test in the ACL deficient knee.

In this study, we tested ACL intact and ACL sectioned knees at several clinically relevant angles of knee flexion by applying two coupled anterolateral subluxations—one that combined internal rotation and valgus torques and another that combined an internal rotation torque and an anterior tibial load to attempt to biomechanically simulate the pivot shift test. The results validated our hypothesis that the coupled anterolateral subluxation indicative of a positive pivot shift test can be most nearly replicated in vitro by combining internal rotation and valgus torques, when compared to combining an internal rotation torque and an anterior tibial load.

There remains a large variability in performing anterolateral rotational test consistently [9, 11, 12, 18, 24]. However, certain concepts are well understood about how to properly create the pivot shift in vivo. The ACL deficient knee will initially experience a subluxation of the anterolateral compartment of the knee as it approaches full extension followed by a reduction in the displaced lateral tibial plateau as the knee passes through approximately 30° of flexion due to the iliotibial band passing over the lateral femoral epicondyle and becoming a flexor [9]. This reduction causes a sudden shift of the lateral compartment, thereby producing the pivot shift phenomenon. There have been other methods proposed to identify the coupled rotatory instability indicative of ACL deficiency. Slocum et al. suggested that a similar test for rotatory instability could be produced when an anterior tibial load is applied with the knee in 90° flexion and the tibia in 15 degrees external rotation [24, 25]. Slocum et al. originally designed this method to test the integrity of the medial capsular and superficial MCL [24, 25]. Slocum et al. also stated that his rotational instability test was performed by applying an anterior load to the knee placed in 90° flexion and 15° external rotation. Galway et al. described the pivot shift as a dynamic test that involved the application of valgus and some internal rotation of the tibia [9].

There were limitations to this study. The study did not address the tension on the iliotibial band, which is an important part of causing the dynamic pivot shift [29]. This should be considered in future studies. Furthermore, the dynamic nature of the pivot shift test was not completely reproduced, because we were unable to move the knee through a full range of flexion while applying the coupled loads, given our experimental protocol. We recommend that future studies address these issues by maintaining internal rotation, valgus torque, and iliotibial band tension, while concurrently moving the knee through its range of motion to produce the pivot shift.

Conclusions

The clinical significance of this study reflects the ability of a simulated pivot shift test for ACL integrity to be recreated in the laboratory. Specifically, this study confirmed that combining internal rotation and valgus torques produced a result that more accurately tested for rotatory instability in vitro when compared to combining an internal rotation torque and anterior tibial load because it created an increased amount of anterolateral subluxation, indicative of the clinical pivot shift test, and we recommend its use in vitro to simulate the clinical pivot shift test.

Acknowledgments Funding for this study was provided by the Health South-East of Norway Grant #2009064. We would also like to thank Conrad Lindquist, and Steinar Johansen MD for their contributions.

References

1. An KN, Jacobsen MC, Berglund LJ, Chao EY (1988) Application of a magnetic tracking device to kinesiologic studies. J Biomech 21:613–620
2. Anderson CJ, Westerhaus BD, Pietrini SD, Ziegler CG, Wijdicks CA, Johansen S, Engebretsen L, Laprade RF (2010) Kinematic impact of anteromedial and posterolateral bundle graft fixation angles on double-bundle anterior cruciate ligament reconstructions. Am J Sports Med 38:1575–1583
3. Bach BR Jr, Warren RF, Wickiewicz TL (1988) The pivot shift phenomenon: results and description of a modified clinical test for anterior cruciate ligament insufficiency. Am J Sports Med 16:571–576
4. Bull AM, Andersen HN, Basso O, Targett J, Amis AA (1999) Incidence and mechanism of the pivot shift. An in vitro study. Clin Orthop Relat Res 363:219–231
5. Coobs BR, LaPrade RF, Griffith CJ, Nelson BJ (2007) Biomechanical analysis of an isolated fibular (lateral) collateral ligament reconstruction using an autogenous semitendinosus graft. Am J Sports Med 35:1521–1527
6. Coobs BR, Wijdicks CA, Armitage BM, Spiridonov SI, Westerhaus BD, Johansen S, Engebretsen L, Laprade RF (2010) An in vitro analysis of an anatomical medial knee reconstruction. Am J Sports Med 38:339–347
7. Debandi A, Maeyama A, Lu S, Hume C, Asai S, Goto B, Hoshino Y, Smolinski P, Fu FH (2011) Biomechanical comparison of three anatomic acl reconstructions in a porcine model. Knee Surg Sports Traumatol Arthrosc 19:728–735
8. Diermann N, Schumacher T, Schanz S, Raschke MJ, Petersen W, Zantop T (2009) Rotational instability of the knee: internal tibial rotation under a simulated pivot shift test. Arch Orthopaedic Trauma Surg 129:353–358
9. Galway HR, MacIntosh DL (1980) The lateral pivot shift: a symptom and sign of anterior cruciate ligament insufficiency. Clin Orthop Relat Res 147:45–50
10. Griffith CJ, LaPrade RF, Johansen S, Armitage B, Wijdicks C, Engebretsen L (2009) Medial knee injury: Part 1, static function of the individual components of the main medial knee structures. Am J Sports Med 37:1762–1770
11. Hassler H, Jakob RP (1981) on the cause of the anterolateral instability of the knee joint. A study on 20 cadaver knee joints with special regard to the tractus iliotibialis (author's transl). Arch Orthop Trauma Surg 98:45–50
12. Hughston JC, Andrews JR, Cross MJ, Moschi A (1976) Classification of knee ligament instabilities. Part I. The medial compartment and cruciate ligaments. J Bone Jt Surg Am 58:159–172
13. Kanamori A, Zeminski J, Rudy TW, Li G, Fu FH, Woo SL (2002) The effect of axial tibial torque on the function of the anterior cruciate ligament: a biomechanical study of a simulated pivot shift test. Arthroscopy 18:394–398
14. Kocher MS, Steadman JR, Briggs KK, Sterett WI, Hawkins RJ (2004) Relationships between objective assessment of ligament stability and subjective assessment of symptoms and function after anterior cruciate ligament reconstruction. Am J Sports Med 32:629–634
15. Kondo E, Merican AM, Yasuda K, Amis AA (2010) Biomechanical comparisons of knee stability after anterior cruciate ligament reconstruction between 2 clinically available transtibial procedures: anatomic double bundle versus single bundle. Am J Sports Med 38:1349–1358
16. Lie DT, Bull AM, Amis AA (2007) Persistence of the mini pivot shift after anatomically placed anterior cruciate ligament reconstruction. Clin Orthop Relat Res 457:203–209
17. Liu SH, Osti L, Henry M, Bocchi L (1995) The diagnosis of acute complete tears of the anterior cruciate ligament. Comparison of mri, arthrometry and clinical examination. J Bone Jt Surg Br 77:586–588
18. Losee RE, Johnson TR, Southwick WO (1978) Anterior subluxation of the lateral tibial plateau. A diagnostic test and operative repair. J Bone Jt Surg Am 60:1015–1030
19. Maeyama A, Hoshino Y, Debandi A, Kato Y, Saeki K, Asai S, Goto B, Smolinski P, Fu FH (2011) Evaluation of rotational instability in the anterior cruciate ligament deficient knee using triaxial accelerometer: a biomechanical model in porcine knees. Knee Surg Sports Traumatol Arthrosc 19:1233–1238
20. Markolf KL, Jackson SR, McAllister DR (2010) A comparison of 11 o'clock versus oblique femoral tunnels in the anterior cruciate ligament-reconstructed knee: knee kinematics during a simulated pivot test. Am J Sports Med 38:912–917
21. Markolf KL, Jackson SR, McAllister DR (2010) Relationship between the pivot shift and lachman tests: a cadaver study. J Bone Jt Surg Am 92:2067–2075
22. Milne AD, Chess DG, Johnson JA, King GJ (1996) Accuracy of an electromagnetic tracking device: a study of the optimal range and metal interference. J Biomech 29:791–793
23. Petersen W, Tretow H, Weimann A, Herbort M, Fu FH, Raschke M, Zantop T (2007) Biomechanical evaluation of two techniques for double-bundle anterior cruciate ligament reconstruction: one tibial tunnel versus two tibial tunnels. Am J Sports Med 35:228–234
24. Slocum DB, James SL, Larson RL, Singer KM (1976) Clinical test for anterolateral rotary instability of the knee. Clin Orthop Relat Res 118:63–69
25. Slocum DB, Larson RL (1968) Rotatory instability of the knee. Its pathogenesis and a clinical test to demonstrate its presence. J Bone Jt Surg Am 50:211–225
26. Tsai AG, Wijdicks CA, Walsh MP, Laprade RF (2010) Comparative kinematic evaluation of all-inside single-bundle and double-bundle anterior cruciate ligament reconstruction: a biomechanical study. Am J Sports Med 38:263–272
27. Xu Y, Liu J, Kramer S, Martins C, Kato Y, Linde-Rosen M, Smolinski P, Fu FH (2011) Comparison of in situ forces and knee kinematics in anteromedial and high anteromedial bundle augmentation for partially ruptured anterior cruciate ligament. Am J Sports Med 39:272–278
28. Yagi M, Wong EK, Kanamori A, Debski RE, Fu FH, Woo SL (2002) Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction. Am J Sports Med 30:660–666
29. Yamamoto Y, Hsu WH, Fisk JA, Van Scyoc AH, Miura K, Woo SL (2006) Effect of the iliotibial band on knee biomechanics during a simulated pivot shift test. J Orthop Res 24:967–973
30. Zantop T, Schumacher T, Schanz S, Raschke MJ, Petersen W (2010) Double-bundle reconstruction cannot restore intact knee kinematics in the acl/lcl-deficient knee. Arch Orthop Trauma Surg 130:1019–1026