Passive Anterior Tibial Subluxation in Anterior Cruciate Ligament–Deficient Knees

Miho J. Tanaka,*† MD, Kristofer J. Jones,‡ MD, Andrew M. Gargiulo,§ MD, Demetris Delos,‡ MD, Thomas L. Wickiewicz,‡ MD, Hollis G. Potter,‡ MD, and Andrew D. Pearle,‡ MD

Investigation performed at Hospital for Special Surgery, New York, New York

Background: Abnormal anterior-posterior and rotational motion secondary to anterior cruciate ligament (ACL) insufficiency is typically described in terms of dynamic laxity. An original description of the abnormal tibiofemoral relationship in the setting of ACL insufficiency has highlighted the presence of a fixed anterior tibial subluxation in this population of failed ACL reconstruction (ACLR); however, no study has quantified the degree of tibial subluxation in both the medial and lateral compartments.

Purpose: To measure and compare the amount of anterior tibial subluxation among various states of ACL competency, including (1) intact ACL, (2) acute ACL disruption, and (3) failed ACLR (ie, patients requiring revision ACLR). We hypothesized that anterior tibial displacement would be greater in the lateral compartment and in cases of failed ACLR compared with intact and acute ACL injured states.

Study Design: Cross-sectional study; Level of evidence, 3.

Methods: Using sagittal magnetic resonance imaging (MRI) and a standardized measurement technique, we determined the amount of anterior tibial subluxation relative to a constant posterior condylar reference point. Measurements were performed in both the medial and the lateral compartments and were compared with 1-way analysis of variance. The presence of meniscal tears along with meniscal volume loss and chondral damage was correlated with the amount of subluxation in each group.

Results: Compared with the intact ACL state, the medial tibial plateau was positioned more anteriorly relative to the femur in both acute ACL injured knees (mean 1.0 mm) and those that failed ACLR (mean 1.8 mm) (P = .072). In the lateral compartment, there was 0.8 mm of mean anterior tibial displacement after acute ACL injury and 3.9 mm of mean anterior subluxation in patients who failed ACLR ($P < .001$). Mean anterior displacement of the lateral plateau in patients who failed ACLR was almost 5 times greater than the amount observed in patients with acute ACL injuries. There was no correlation between meniscal/chondral injury and the amount of subluxation.

Conclusion: Patients who require revision ACLR have an abnormal tibiofemoral relationship noted on MRI that is most pronounced in the lateral compartment and should be taken into account during revision surgery. These observations may explain the suboptimal clinical results seen in some patients who undergo revision ACLR.

Keywords: ACL tear; tibial subluxation; revision ACL reconstruction; anatomic ACL reconstruction

Anterior cruciate ligament (ACL) insufficiency can result in knee laxity and dysfunction, because the ACL plays a pivotal role in the maintenance of anterior-posterior translation and rotation of the tibia relative to the femur.[5,9] Anterior cruciate ligament reconstruction (ACLR) is a widely accepted treatment for active patients who demonstrate symptomatic instability, and there is recent evidence that graft placement aligned with native footprint sites can accurately restore knee kinematics and improve functional outcomes.[7,12,17,19] While clinical outcomes after primary ACLR have been predictable, results after revision ACLR often demonstrate inferior functional scores and lower patient-reported outcomes.[23,24] Additionally, failure rates after revision ACLR have been estimated to be 3 to 4 times higher than those associated with primary ACLR.[23] While the reasons for poor clinical outcomes are often multifactorial in the revision setting, technical error—including improper tunnel placement, inadequate graft tissue, insufficient graft tensioning, and failure to recognize and treat concomitant injuries—is often cited as the underlying cause for operative failure.[16]

Commonly, ACL insufficiency is described in terms of dynamic laxity, because the abnormal anterior-posterior and rotational motion between the tibia and femur is clinically tested by use of specific examination maneuvers (eg, Lachman test, pivot shift).[18] Studies have demonstrated

*Address correspondence to Miho J. Tanaka, MD, Regeneration Orthopedics, 6 McBride & Son Center Drive, Suite 204, St Louis, MO 63005 (e-mail: mjtanaka@gmail.com).

†Regeneration Orthopedics, St Louis, Missouri.

‡Hospital for Special Surgery, New York, New York.

§Department of Radiology, Northwestern University, Chicago, Illinois.

The authors declared that they have no conflicts of interest in the authorship and publication of this contribution.

The American Journal of Sports Medicine, Vol. 41, No. 10
DOI: 10.1177/0363546513498995

that objective laxity of the knee can be quantified by use of commercially available devices, such as the KT-1000 arthrometer (MEDmetric, San Diego, California) to determine side-to-side differences in tibial translation.[10,11] Dynamic stress radiographs and electromagnetic measurement systems also have been used to assess ACL competency with success.[6] Despite the utility of dynamic testing, only a few studies have investigated the static relationship between the tibia and femur in patients with ACL insufficiency. Almekinders et al[2,4] provided an original description using lateral radiographs of irreducible tibial subluxation in patients who underwent ACLR. This study attempts to accurately quantify the abnormal tibiofemoral relationship in patients with ACL insufficiency using magnetic resonance imaging (MRI). The purpose of this study was to measure and compare the amount of anterior tibial subluxation among various states of ACL competency, including (1) intact ACL, (2) acute ACL disruption, and (3) failed ACLR (ie, patients requiring revision ACLR). We hypothesized the following: (1) the amount of anterior tibial subluxation would vary by the tibial compartment measured (medial vs lateral) and the type of ACL injury (acute vs failed prior ACLR); (2) anterior tibial subluxation would be significantly greater in the lateral compartment and in cases of failed ACLRs compared with intact and acutely ACL injured states; and (3) the presence of concomitant meniscal or chondral injury would positively correlate with the amount of passive anterior tibial subluxation in patients who failed prior ACLR.

MATERIALS AND METHODS

After gaining approval from our institutional review board, we performed a computerized search of our institutional imaging database to identify all knee MRIs that were obtained by the senior authors (T.L.W., A.D.P) between January 1, 2007, and March 31, 2012. All identified studies were subsequently classified into 1 of 3 experimental groups according to the status of the ACL. Any patient with an intact ACL, acute ACL tear, or failed ACLR was eligible for inclusion. Those who had concurrent injuries to other ligaments or had undergone previous procedures besides ACLR were excluded from the study. The intact ACL group was composed of patients who underwent bilateral knee MRI evaluation after acute, unilateral ACL injury during a previous investigation.[8] An acute ACL disruption was defined as complete disruption of ligament fibers with a translational bone bruise in the lateral compartment on MRI examination after a history of traumatic injury. A patient was assigned to the failed ACLR group if there was complete discontinuity of ACL fibers on MRI examination and a history of ACLR.

Technique for MRI Measurement of Tibial Subluxation

A standard institutional MRI examination with a 1.5-T superconducting magnet (Horizon LX; GE Medical Systems, Milwaukee, Wisconsin) was performed in each case. Each patient was examined in the supine position with a pillow under the knee to support it in a relaxed position of mild extension and slight external rotation. This extremity position was kept constant among patients to control for measurement error with the use of sponges in a tight-fitting extremity coil (8-channel knee coil, MedRad, Warrendale, Pennsylvania). Electronic measurements were performed by 1 of 2 authors (M.J.T., A.M.G.) based on a technique described and validated by Iwaki et al,[14] using the flexion facet. Sagittal proton density images were used to draw a best fit circle over the subchondral line of the posterior condyle. A line perpendicular to the tibial plateau was then drawn along the posterior margin of this circle. A second line, also perpendicular to the tibial plateau, was drawn through the posterior aspect of the tibia. The distance between these 2 lines was then measured along the perpendicular axis to determine the amount of anterior tibial subluxation (Figure 1).

Measurements were performed separately in both the medial and lateral compartments for each knee. To ensure consistency and reliability between compartment measurements, a standard MRI was used for each compartment. For medial compartment measurements, we identified the MRI that showed the insertion of the medial gastrocnemius tendon on the femur. For lateral compartment measurements, the MRI illustrating the most medial cut of the fibula at the tibiofibular joint was identified. We calculated interobserver correlation before performing the study using 10 sample knees.

Each MRI was evaluated for the presence of medial or lateral meniscal tears. The precise location of these tears was documented along with the presence of volume loss from prior meniscectomy. The presence of osteoarthritic changes in the medial or lateral compartment was also noted and recorded at this time by use of a modified Outerbridge scoring system previously assessed for accuracy.[21]

Statistical analysis was performed with 1-way analysis of variance (ANOVA) to detect any significant differences between each group. A linear regression model was created to identify any correlation between passive anterior tibial subluxation and the presence of medial or lateral meniscal tears, or the presence of osteoarthritis, which was defined as diffuse grade 4 chondral changes and osteophyte formation.

RESULTS

We identified 215 knee MRI examinations that were obtained by the senior authors during the aforementioned time period. Overall, 113 met our inclusion criteria (27 intact ACL, 63 acute ACL tears, and 16 failed ACLRs). The mean radius of the medial condyle was 18.8 $\pm$ 2.2 mm, and the mean radius of the lateral condyle was 19.1 $\pm$ 2.4 mm. The interobserver correlation coefficient was 0.72 for the medial compartment and 0.96 for lateral compartment measurements.

Medial Compartment

The results of our measurements from the medial compartment are summarized in Table 1. In the ACL intact group, the average position of the tibia was 0.4 $\pm$ 2.6 mm

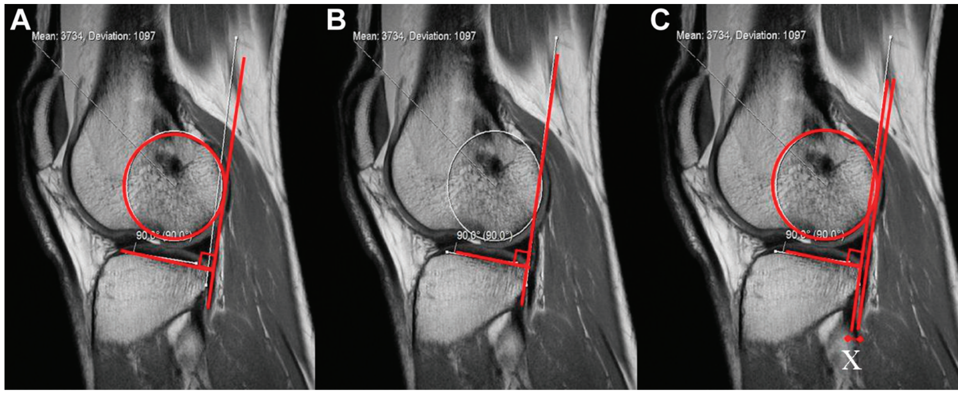

Figure 1. Measurement technique (described by Iwaki et al[14]). (A) A best-fit circle was drawn over the subchondral line of the posterior condyle, and a line perpendicular to the tibial plateau was then drawn along the posterior margin of this circle. (B) A second line, also perpendicular to the tibial plateau, was drawn through the posterior aspect of the tibia. (C) The distance between these 2 lines was then measured along the perpendicular axis to determine the amount of anterior tibial subluxation (displayed as measurement X).

TABLE 1
Results of Measurements From the Medial Compartment[a]

	Distance From Posterior Condylar Line			Relative Anterior Translation vs Normal Knee
	Mean ± SD	Range	95% CI	
Normal knee (n = 27)	–0.4 ± 2.6	–5.0 to 7.0	–1.4 to 0.6	
Acute ACL tear (n = 63)	0.6 ± 2.8	–6.1 to 6.9	–0.1 to 1.3	1.0
Failed ACLR (n = 16)	1.4 ± 2.8	–5.2 to 6.0	0.1 to 2.6	1.8

[a]All values given in millimeters. $P = .072$ for all results. ACL, anterior cruciate ligament; ACLR, ACL reconstruction; CI, confidence interval; SD, standard deviation.

TABLE 2
Results of Measurements From the Lateral Compartment[a]

	Distance From Posterior Condylar Line			Relative Anterior Translation vs Normal Knee
	Mean ± SD	Range	95% CI	
Normal knee (n = 27)	1.8 ± 2.3	–3.0 to 6.9	0.9 to 2.7	
Acute ACL tear (n = 63)	2.6 ± 3.3	–2.6 to 10.0	1.8 to 3.5	0.8
Failed ACLR (n = 16)	5.7 ± 5.3	–2.2 to 20.4	3.4 to 8.1	3.9

[a]All values given in millimeters. $P < .001$ for all results. ACL, anterior cruciate ligament; ACLR, ACL reconstruction; CI, confidence interval; SD, standard deviation.

posterior to the posterior condylar line. Compared with this position in the intact knees, the tibia was anteriorly translated an average of 1.0 ± 2.8 mm in the ACL-deficient knees and 1.8 ± 2.8 mm in those knees that failed prior ACLR. These measurements of the tibial position relative to the femur were not significantly different between the groups ($P = .072$). Figure 2 shows the distribution of tibial positions for each group within the medial compartment. However, ACL insufficient knees, both acutely injured and those with failed ligament reconstructions, were 4 times more likely to demonstrate at least 2 mm of anterior tibial subluxation in the medial compartment compared with ACL intact knees (odds ratio [OR] 4.059; 95% confidence interval [CI], 1.293-12.740, $P = .017$).

Lateral Compartment

The results of our measurements from the lateral compartment are summarized in Table 2. On average, we found 0.8 ± 3.3 mm of mean anterior tibial subluxation in acutely injured ACL-deficient knees relative to the intact state ($P < .001$). In the setting of failed ACLRs, the lateral tibial position was anteriorly subluxated a mean of 3.9 ± 5.3 mm compared with ACL intact knees ($P < .001$). Overall, anterior

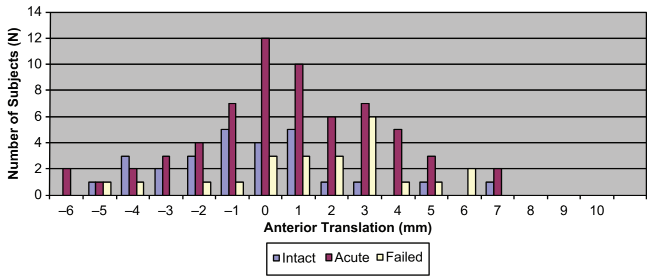

Figure 2. Distribution of the tibial position relative to the femur in the medial compartment for each group.

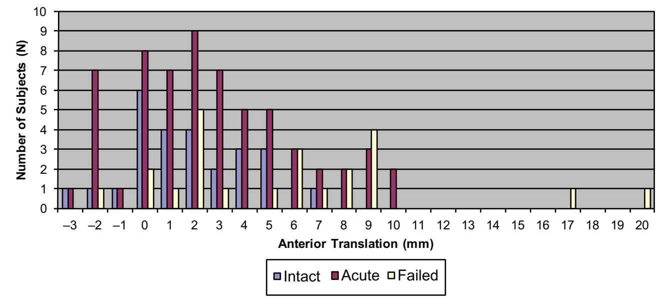

Figure 3. Distribution of the tibial position relative to the femur in the lateral compartment for each group.

TABLE 3
Linear Regression Model for Anterior Tibial Subluxation in the Medial Compartment[a]

Model	Unstandardized Coefficients B	Unstandardized Coefficients SE	*P* Value	95% CI for B Lower Bound	95% CI for B Upper Bound
1 (Constant)	–0.38	0.55	.489	–1.48	0.71
Acute ACL	1.08	0.72	.135	–0.34	2.50
Failed ACLR	1.35	0.95	.156	–0.53	3.23
Medial meniscus	–0.01	0.60	.992	–1.19	1.18
Lateral meniscus	–0.19	0.59	.752	–1.35	0.98
Osteoarthritis	1.83	1.15	.116	–0.46	4.11

[a]Dependent variable: medial distance $R^2 = 0.090$. ACL, anterior cruciate ligament; ACLR, ACL reconstruction; CI, confidence interval; SE, standard error.

TABLE 4
Linear Regression Model for Anterior Tibial Subluxation in the Lateral Compartment[a]

Model	Unstandardized Coefficients B	Unstandardized Coefficients SE	*P* Value	95% CI for B Lower Bound	95% CI for B Upper Bound
1 (Constant)	1.99	0.68	.004	0.65	3.33
Acute ACL	1.00	0.88	.259	–0.75	2.75
Failed ACLR	3.49	1.16	.003	1.19	5.80
Medial meniscus	–0.12	0.73	.866	–1.58	1.33
Lateral meniscus	–1.36	0.72	.062	–2.79	0.07
Osteoarthritis	1.90	1.42	.182	–0.91	4.71

[a]Dependent variable: lateral distance: $R^2 = 0.273$. ACL, anterior cruciate ligament; ACLR, ACL reconstruction; CI, confidence interval; SE, standard error.

subluxation of the lateral tibia in patients with failed ACLRs was almost 5 times greater than the amount of displacement observed in patients with acute ACL injuries. Figure 3 demonstrates the distribution of measurements performed in the lateral compartment. Patients with failed ACLRs were twice as likely to have 5 mm or more of anterior tibial subluxation in the lateral compartment compared with ACL intact knees (OR, 2.06; 95% CI, 0.624-6.916; $P = .352$). In the failed reconstruction group, 2 subjects (12.5%) had greater than 15 mm of passive anterior tibial subluxation (17 and 20 mm) in the lateral compartment.

Linear regression models of the medial and lateral compartments are shown in Tables 3 and 4, respectively. As noted, the presence of failed ACLR was positively correlated with anterior subluxation of the lateral compartment. No correlation was found between the presence of medial or lateral meniscal tears or volume loss with the degree of anterior tibial displacement in either compartment. We were not able to detect an association between tibial subluxation and the presence of more severe significant chondral injury (diffuse grade IV chondral changes) in either compartment.

DISCUSSION

This study provides a descriptive quantification of passive anterior subluxation of each tibial compartment relative to the femur in ACL-deficient knees. Using standardized MRI measurements of the knee in an unloaded examination, we found an average of 3.9 mm of anterior tibial subluxation in the lateral compartment in patients with failed ACLRs. This amount of subluxation was significantly more than measurements obtained in patients with an acute ACL injury (0.8 mm).

In an early study by Almekinders et al,[2] the authors compared the lateral radiographs of patients with ACL graft failure and those who underwent successful ACLRs. A standardized measurement technique demonstrated that the tibial position was approximately 6% more anterior in the ACL graft failure group. The authors found that lateral radiographs with significant subluxation gave the impression of roof impingement in the graft failure group. However, critical analysis of tibial tunnel placement was found to be satisfactory, and Almekinders et al concluded that graft failure secondarily allowed tibial subluxation, thus giving the radiographic impression of impingement. Our study supports Alkeminders' findings that anteriorization of the tibia is evident in knees with failed ACLRs. We further quantified these findings between medial and lateral anterior translation of 1.8 mm and 3.9 mm, respectively.

A subsequent study by Almekinders et al[3] compared the tibiofemoral relationship between 2 experimental groups composed of patients who underwent successful ACLR (n = 15) and an age-matched control group with normal knees (n = 14). Using lateral radiographs in full extension, the authors measured the maximal posterior tibial position relative to a femoral reference point under a standardized posterior directed force and found that control knees translated an average of 4.0 mm. In comparison, patients who underwent successful ACLR could not be reduced to the same maximal position. The authors concluded that the ACLR group was unable to achieve a reduced position secondary to a fixed anterior subluxation; however, the clinical and anatomic explanation for this irreducible subluxation was not specifically addressed. The limitations of lateral radiographs were evident in this study, as the authors were unable to comment on the degree of subluxation in each tibial compartment.

In 2004, Almekinders et al[4] attempted to determine whether the abnormal tibiofemoral relationship was directly associated with ACLR or was merely a process that occurred as a part of the natural history of ACL injury. Interestingly, the authors found that patients with untreated ACL ruptures and no radiographic evidence of osteoarthritis demonstrated a maximum posterior tibial position that was similar to that of normal knees (−2.3 mm vs −3.9 mm). When considering this result in conjunction with the fact that irreducible anterior subluxation was observed in patients who underwent ACLR, the authors concluded that surgical intervention may play a role in the development of the fixed tibial displacement. They proposed that violation of the posterior cruciate ligament synovial sheath with subsequent fibrosis and contracture could account for this phenomenon.

Biomechanical studies have highlighted the importance of the medial meniscus as a secondary stabilizer to anteroposterior translation in the ACL-deficient knee.[1,22] Using a goat model, Jackson et al[15] demonstrated significant adaptive changes to the meniscus in the ACL-deficient knee, including an increase in cross-sectional area and volume of the menisci that was particularly evident in the posterior horn of the medial meniscus. Additionally, hypertrophy of the posterior capsule was evident on histological examination. While similar adaptive changes have not been documented in human studies, these observations could provide a plausible explanation for the irreducible tibial subluxation observed in clinical studies. Similar to our study, the study by Almekinders et al[4] did not find a correlation between meniscal or chondral injury and the degree of tibial subluxation.

Overall, our study adds further elements to the original concept described by Almekinders et al[3,4] through detailed MRI measurement of the medial and lateral tibial compartments in the setting of ACL deficiency. While our measurements confirm previous observations of anterior tibial subluxation in other studies, our results also suggest that there may be a component of internal rotation of the tibia in full extension. This is demonstrated by pronounced subluxation of the lateral compartment in the setting of failed ACLR and has been suggested by recent studies evaluating rotational laxity in ACL-deficient knees.[13,20]

In light of the recent trend toward anatomic ACLR, these observations raise potential concerns regarding our ability to reestablish a normal tibiofemoral relationship. Excessive anterior tibial subluxation may make it difficult to find the appropriate tunnel positions during ligament reconstruction, and this abnormal position of the tibia raises concerns regarding notch impingement if bone tunnels are placed in the anatomic footprints. When comparing the position of the tibia in acute ACL injuries and the failed ACLR group, we found that the anterior position of the tibia in the setting of revision surgery was more pronounced. While this observation suggests that chronicity may play a role in this developmental process, we were not able to identify any correlation between tibial subluxation and the presence of meniscal injury or osteoarthritic changes.

We acknowledge that our study has several weaknesses. The retrospective design has obvious limitations. While the MRI protocol for knee examinations is well standardized at our institution with coil fixation, there may have been slight variability in knee flexion angles at the time of the examination secondary to patient positioning or knee flexion contracture. The validated MRI measurement technique described by Iwaki et al[14] was chosen for this reason, as it accounts for variability in the flexion angle of the knee at the time of examination. However, we have noted that this method depends somewhat on the shape of the tibial slope, which we did not account for in this study. Variability in femoral condylar size may also account for some minor differences in the measurements that were obtained. Finally, the presence of measurement error could play a role in our study. While our interobserver correlation coefficient was calculated to be nearly perfect in this study, it was slightly lower in the medial compartment, possibly attributable to greater variability in the landmarks used to determine the image used for measurement in this compartment.

Overall, our study demonstrates an average of 3.9 mm of anterior tibial subluxation within the lateral compartment in patients who require revision ACLR. In 12.5% of cases requiring revision surgery, anterior displacement was greater than 15 mm. This association between anterior tibial subluxation and revision ACLR may provide a mechanistic explanation for the suboptimal clinical results of ACL revision reconstruction. Extreme tibial subluxation of up to 10 to 15 mm in the lateral compartment was demonstrated in some cases of failed ACLR; these knees in particular may be poor candidates for attempted ACL revision reconstruction. It is unclear from this study whether the subluxation demonstrated in the failed ACLR group is reducible with standard ACLR techniques, and further studies are needed to evaluate this. We were not able to find a significant correlation between anterior subluxation and the presence of meniscal injury or osteoarthritic changes. Larger prospective, longitudinal studies will be necessary to determine the natural evolution of this process and the effect on clinical outcome in the revision setting. More sophisticated MRI studies may be necessary to propose optimal tunnel placement in the setting of tibial subluxation as there is a theoretical concern for graft impingement in patients with significant anterior tibial displacement.

ACKNOWLEDGMENT

The authors gratefully acknowledge the contribution of Joseph T. Nguyen, MPH, for the statistical analysis performed in this study.

REFERENCES

1. Allen CR, Wong EK, Livesay GA, Sakane M, Fu FH, Woo SLY. Importance of the medial meniscus in the anterior cruciate ligament-deficient knee. *J Orthop Res*. 2000;8(1):109-115.
2. Almekinders LC, Chiavetta JB, Clarke JP. Radiographic evaluation of anterior cruciate ligament graft failure with special reference to tibial tunnel placement. *Arthroscopy*. 1998;14(2):206-211.
3. Almekinders LC, de Castro D. Fixed tibial subluxation after successful anterior cruciate ligament reconstruction. *Am J Sports Med*. 2001;29(3):280-283.
4. Almekinders LC, Pandarinath R, Rahusen FT. Knee stability following anterior cruciate ligament rupture and surgery: the contribution of irreducible tibial subluxation. *J Bone Joint Surg Am*. 2004;86(5):983-987.
5. Amis AA, Dawkins GP. Functional anatomy of the anterior cruciate ligament: fibre bundle actions related to ligament replacements and injuries. *J Bone Joint Surg Br*. 1991;73:260-267.
6. Araki D, Kuroda R, Kubo S, et al. The use of an electromagnetic measurement system for anterior tibial displacement during the Lachman test. *Arthroscopy*. 2011;27(6):792-802.
7. Bedi A, Maak T, Musahl V, et al. Effect of tunnel position and graft size in single-bundle anterior cruciate ligament reconstruction: an evaluation of time-zero knee stability. *Arthroscopy*. 2011;27:1543-1551.
8. Bowers AL, Bedi A, Lipman JD, et al. Comparison of anterior cruciate ligament tunnel position and graft obliquity with transtibial and anteromedial portal femoral tunnel reaming techniques using high-resolution magnetic resonance imaging. *Arthroscopy*. 2011;27(11):1511-1522.
9. Butler DL, Noyes FR, Grood ES. Ligamentous restraints to anterior-posterior drawer in the human knee: a biomechanical study. *J Bone Joint Surg Am*. 1980;62:259-270.
10. Daniel DM, Malcolm LL, Losse G, Stone ML, Sachs R, Burks R. Instrumented measurement of anterior laxity of the knee. *J Bone Joint Surg Am*. 1985;67(5):720-726.
11. Daniel DM, Stone ML, Sachs R, Malcolm L. Instrumented measurement of anterior knee laxity in patient with acute anterior cruciate ligament disruption. *Am J Sports Med*. 1985;13(6):401-407.
12. Fernandes TL, Fregni F, Weaver K, Pedrinelli A, Camanho GL, Hernandez AJ. The influence of femoral tunnel position in single-bundle ACL reconstruction on functional outcomes and return to sports [published online November 7, 2012]. *Knee Surg Traumatol Arthrosc*. doi:10.1007/s00167-012-2288-8.
13. Haughom BD, Souza R, Schairer WW, Li X, Ma CB. Evaluating rotational kinematics of the knee in ACL-ruptured and healthy patients using 3.0 Tesla magnetic resonance imaging. *Knee Surg Sports Traumatol Arthrosc*. 2012;20(4):663-670.
14. Iwaki H, Pinskerova V, Freeman MA. Tibiofemoral movement 1: the shapes and relative movements of the femur and tibia in the unloaded cadaver knee. *J Bone Joint Surg Br*. 2000;82(8):1189-1195.
15. Jackson DW, Schreck P, Jacobson S, Simon TM. Reduced anterior tibial translation associated with adaptive changes in the anterior cruciate ligament-deficient joint: goat model. *J Orthop Res*. 1999;17(6):810-816.
16. Kamath GV, Redfern JC, Greis PE, Burks RT. Revision anterior cruciate ligament reconstruction. *Am J Sports Med*. 2011;39(1):199-217.
17. Karlsson J, Irrgang JJ, van Eck CF, Samuelsson K, Mejia HA, Fu FH. Anatomic single- and double-bundle anterior cruciate ligament reconstruction, part 2: clinical application of surgical technique. *Am J Sports Med*. 2011;39:2016-2026.
18. Logan MC, Williams A, Lavelle J, Gedroyc W, Freeman M. What really happens during the Lachman test? A dynamic MRI analysis of tibiofemoral motion. *Am J Sports Med*. 2004;32(2):369-375.
19. Musahl V, Plakseychuk A, VanScyoc A, et al. Varying femoral tunnels between the anatomical footprint and isometric positions: effect on kinematics of the anterior cruciate ligament-reconstructed knee. *Am J Sports Med*. 2005;33:712-718.
20. Okazaki K, Tashiro Y, Izawa T, Matsuda S, Iwamoto Y. Rotatory laxity evaluation of the knee using modified Slocum's test in open magnetic resonance imaging. *Knee Surg Sports Traumatol Arthrosc*. 2012;20(4):679-685.
21. Potter HG, Linklater JM, Allen AA, Hannafin JA, Haas SB. Magnetic resonance imaging of articular cartilage in the knee: an evaluation with use of fast-spin-echo imaging. *J Bone Joint Surg Am*. 1998;80(9):1276-1284.
22. Shoemaker SC, Markolf KL. The role of the meniscus in the anterior-posterior stability of the loaded anterior cruciate-deficient knee. *J Bone Joint Surg Am*. 1986;68:71-79.
23. Wright RW, Gill CS, Chen L, et al. Outcome of revision anterior cruciate ligament reconstruction: a systematic review. *J Bone Joint Surg Am*. 2012;94(6):531-536.
24. Wright RW, Spindler K, Huston L, et al. Revision ACL reconstruction outcomes: MOON cohort. *J Knee Surg*. 2011;24(4):289-294.