Systematic Review

Anteromedial Versus Transtibial Tunnel Drilling in Anterior Cruciate Ligament Reconstructions: A Systematic Review

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Purpose: Failure to anatomically reconstruct the femoral footprint can lead to rotational instability and clinical failure. Thus we sought to compare femoral tunnel drilling techniques, specifically anteromedial (AM) and transtibial (TT) methods, with respect to rotational stability. **Methods:** In this study we evaluated available scientific support for the ability of both techniques to achieve rotational stability of the knee through a systematic review of the literature for directly comparative biomechanical and clinical studies. **Results:** We identified 9 studies (5 clinical Level II or III studies and 4 cadaveric studies) that directly compared AM and TT techniques. Three cadaveric and 2 clinical studies showed superior rotational stability with the AM technique as compared with the TT technique, whereas 2 cadaveric studies and 1 clinical study were unable to show any similar differences. Two studies showed superior clinical outcomes with the AM technique, whereas 3 studies were unable to show any difference. **Conclusions:** In this systematic review of clinical and biomechanical studies directly comparing AM and TT techniques for anterior cruciate ligament reconstruction (ACLR) in the literature, there are mixed results, with some studies finding superior rotational stability and clinical outcomes with the AM technique and some finding no difference. No studies showed significantly better results with the TT technique. This study shows that the AM portal technique for ACLR may be more likely to produce improved clinical and biomechanical outcomes but that the TT technique is capable of producing similar outcomes. **Level of Evidence:** Level III, systematic review of Level II and III studies plus cadaver studies.

Technical errors are often cited as the leading cause of anterior cruciate ligament reconstruction (ACLR) failure.[1,2] The most common technical error is nonanatomic tunnel placement with failure to reconstitute rotational stability.[1,2] Historical techniques placed the femoral tunnel high and medial within the intercondylar notch.[2,3] This reconstruction resulted in stability of the knee in the sagittal plane and reduction of laxity on Lachman testing.[2,3] However, recent anatomic studies have shown that femoral tunnels placed in this location (11-o'clock position in a right knee) are nonanatomic and may not reconstitute rotational stability.[4] Failure to eliminate the pivot-shift phenomenon results in continued clinical instability and may also increase the risk of graft failure. Clinical instability with pivot-shift testing has been shown to be the best predictor of postoperative patient dissatisfaction.[3,5]

Several authors have argued that nonanatomic tunnel placement arises from errors in surgical technique.[2,6-8] Anatomic tunnel placement is believed to result in improved outcomes[9] and should be the goal of ACLR regardless of surgical technique. The most common method for drilling the femoral tunnel is through the tibial tunnel using the transtibial (TT) technique, which is the method of choice of 70% to 85% of the members of the American Orthopaedic Society for Sports Medicine, according to a recent survey.[10] Concerns that this method may be contributing to clinical failure through nonanatomic reconstruction led to the development of the anteromedial (AM) technique, in which the femoral tunnel is drilled through an accessory arthroscopic portal with the knee hyperflexed.[1-3] Proponents of the TT technique argue that anatomic tunnel placement can be achieved with appropriate surgical technique and avoids complications that can occur with AM portal drilling.[11,12] Proponents of the AM technique argue that it avoids the constraint of the tibial tunnel and therefore allows a more anatomic femoral and tibial footprint placement and better elimination of the pivot-shift phenomenon.[1-3]

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The purposes of this study were (1) to conduct a systematic review of clinical and biomechanical evidence directly comparing AM and TT femoral drilling techniques in ACLR, (2) to provide treatment recommendations based on the best currently available evidence, and (3) to highlight gaps in the literature that require future research. The hypothesis of this study was that both techniques, if performed properly, would be able to achieve translational and rotational stability.

Methods

A systematic review of the literature was performed of the PubMed, Cochrane Database of Systematic Reviews, BMJ Clinical Evidence, and Embase databases. The search query terms used were as follows: (anteromedial OR medial OR free-hand OR accessory) AND (transtibial OR trans-tibial) AND (cruciate OR ACL). The search was performed on December 9, 2012. The search was limited to articles written in English. Search terms were broad so as to encompass all possibilities for applicable studies. All reviewed articles were then manually cross-referenced to make certain no relevant studies were missed.

The abstracts that resulted from these searches were reviewed by the lead author. Inclusion criteria were direct comparison of AM and TT femoral drilling techniques for single-bundle ACLR. Both clinical and cadaveric studies were included. Studies pertaining to a single technique (i.e., without cohorts for both AM and TT techniques) were excluded because a previous systematic review has been performed on non-comparative trials.[10] The following exclusion criteria were used: studies with fewer than 5 samples per group and studies without clinical or biomechanical stability outcomes. We excluded those studies with data only pertaining to the anatomic or radiographic position of the graft. Our rationale for the exclusion of such studies was that they provide only indirect data on the effect of tunnel drilling technique on rotational stability. Therefore interpretation of these studies requires the use of several assumptions about the effect of tunnel position on rotational stability. Given that these assumptions are examined by other studies included in this analysis, studies without clinical or biomechanical outcomes were excluded. We then obtained full articles for those studies that directly compared AM and TT techniques either in vivo or in vitro. The references of each of these citations were manually screened to ensure that no studies were missed. In addition, we manually searched the tables of contents of the following journals for the last 2 years for any additional studies comparing these drilling techniques: *Journal of Bone and Joint Surgery; American Journal of Sports Medicine; Clinical Orthopaedics and Related Research; Arthroscopy;* and *Knee Surgery, Sports Traumatology, and Arthroscopy*. A Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram shows our study selection algorithm (Fig 1).

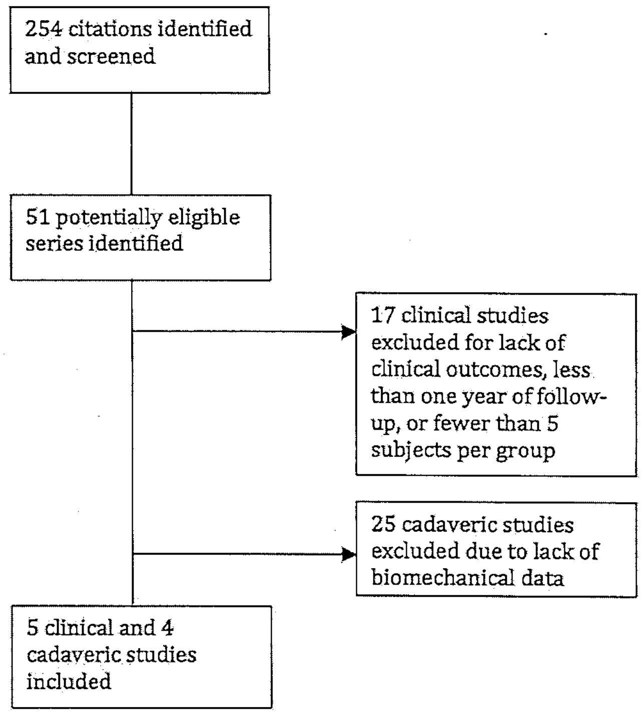

Fig 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart showing effect of exclusion criteria on number of included studies. Initial literature searches showed 254 citations; 9 ultimately were included.

From the remaining studies, the following data were extracted: author, journal of publication, year of publication, sample size, method of tunnel placement, results of any biomechanical testing, results of physical examination testing, and standardized outcome results. Biomechanical outcomes collected included anterior tibial translation to an anterior tibial force (i.e., Lachman) and anterior tibial translation to a combined valgus and internal rotation force (i.e., pivot shift). Physical examination findings collected included the distribution of Lachman grades, distribution of pivot-shift grades, and results of KT-1000 arthrometer (MEDmetric, San Diego, CA) testing. Standardized outcomes collected included International Knee Documentation Committee (IKDC) scores,[13] Lysholm scores,[14] Tegner scores,[15] and rates and time to return to play. Study quality was judged based on the selection criteria, study design, completeness of follow-up, clarity of description of the intervention, clarity of description of the outcome measure, and completeness of the data provided.

Given the heterogeneity in study design, meta-analysis was believed to be inappropriate, and thus no attempt to statistically compare studies was made. Instead, a description of these studies and interpretation of their findings in combination is provided. All

Table 1. Summary of Results of Trials Comparing AM and TT Techniques for Drilling Femoral Tunnel in ACLR: Cadaveric Studies

Author	Year	No. of Samples	Tunnel Technique	Anterior Force (N)	Anterior Translation (mm) at 30° of Flexion With Anterior Force	Anterior Translation (mm) at 60° of Flexion With Anterior Force	Rotational Force	Anterior Translation (mm) at 15° of Flexion With Combined Force	Anterior Translation (mm) at 30° of Flexion With Combined Force
Bedi et al.[37]	2011	5	AM	68	6.3 ± 1.7*	NA	Unmeasured	3.8 ± 0.7	NA
		5	TT	68	9.9 ± 2.3*	NA	Unmeasured	7.4 ± 2.3	NA
Sim et al.[29]	2011	8	AM	134	NA	2.7 ± 1.7	134-N anterior, 10-Nm valgus, and 5-Nm internal rotation loads	NA	1.7 ± 0.5
		8	TT	134	NA	3.1 ± 2.1		NA	3.0 ± 1.6
Steiner et al.[30]	2009	10	AM	156	5.0 ± 3.3*	NA	156-N anterior and 10-Nm internal rotation loads	NA	7.2 ± 3.3*
		10	TT	156	8.9 ± 3.6*	NA		NA	9.2 ± 3.2*
Tudisco and Bisicchia[31]	2012	6	AM	134	3.0 ± 1.0	NA	Unmeasured	100% "normal" on manual pivot-shift tests*	
		6	TT	134	4.0 ± 1.0	NA	Unmeasured	100% "glide" on manual pivot-shift tests*	

NA, not applicable.
*Statistically significant differences ($P < .05$).

analyses were performed with Excel X (Microsoft, Redmond, WA).

Results

Literature Review

Two hundred fifty-four citations were returned by the initial search. After application of the inclusion criteria, 51 studies comparing the AM and TT drilling techniques remained. Of the 23 clinical studies, 17 were excluded because they did not contain any clinical follow-up data or had fewer than 5 patients per group. The vast majority of excluded studies reported solely on radiographic measurement of osseous tunnel or articular aperture position or size and intraoperative measurement of osseous tunnel or articular aperture position or size.[7,8,16-23] Nine studies met our inclusion criteria (Tables 1 and 2). Of the 29 cadaveric studies, 25 did not contain any biomechanical data examining knee stability and reported solely on the length, orientation, or position of the osseous tunnels or size or position of the apertures of these tunnels.[12,17,24-28] Only 4 studies reported on the biomechanical stability of their cadaveric reconstructions (Table 1).[12,29-31]

Clinical Studies

Of the 5 clinical studies that provided direct comparative outcomes between AM and TT techniques, 4 were retrospective trials (Level of Evidence III) and 1 was a lower-quality randomized clinical trial (Level of Evidence II). The clinical studies included a total of 425 patients, 188 of whom underwent ACLR by the AM technique and 237 of whom underwent ACLR by the TT technique. For all but 1 study,[32] the minimum follow-up was 12 months. Three studies used autograft hamstring tendons,[33-35] and 2 studies used bone—patellar tendon—bone allografts and autografts.[32,36] Of the authors using a TT technique, none described using any specific modifications of the TT technique to attempt to reach the anatomic footprint of the anterior cruciate ligament (ACL), although 1 study did describe aiming for the 10- to 11-o'clock position.[35] One study described aiming for the 11-o'clock position,[33] 1 specifically described using an unmodified technique,[32] and 2 did not describe their technique in sufficient detail to determine whether a modified or unmodified technique was used.[34,36]

Several of these studies reported physical examination findings in patients postoperatively. Four of 5 studies reported findings of the Lachman test.[32-34,36] Three of these studies showed no difference in the number of patients with restoration of a normal Lachman test.[33,34,36] Alentorn-Geli et al.[32] found that significantly more patients in their AM cohort than in their TT cohort had a normal Lachman test at final follow-up. Three of 5 studies examined their patients with the pivot-shift test at final follow-up.[32,34,36] One study reported no difference in the number of patients

Table 2. Summary of Results of Trials Comparing AM and TT Techniques for Drilling Femoral Tunnel in ACLR: Clinical Studies

Author	Year	Minimum Length of Follow-up (mo)	No. of Patients	Tunnel Technique	KT-1000 Average Maximum Manual Displacement (mm)	No. of Patients With Negative Lachman Test	No. of Patients With Negative Pivot-Shift Test	Lysholm Score	Tegner Score	IKDC Grade/Score	Time From Surgery to Return to Play (mo)
Alentorn-Geli et al.[32]	2010	24	26	AM	0.2 ± 1.6*	21*	19*	99.3 ± 2.3	7.8 ± 1.6	26 A/B*	7*
			21	TT	1.9 ± 1.8*	11*	7*	97 ± 7.2	7.1 ± 1.3	19 A/B*	8*
Kim et al.[36]	2011	12	33	AM	2.8	28	30*	88.3 ± 13.1	NR	32 A/B	NR
			33	TT	3.1	27	26	77.2 ± 19.3	NR	31 A/B	NR
Mardani-Kivi[33]	2012	12	64	AM	NR	47	NR	96.1 ± 3.0*	NR	94.8 ± 3.9*	NR
			60	TT	NR	38	NR	92.2 ± 3.1*	NR	89.2 ± 4.1*	NR
Xu et al.[34]	2011	12	19	AM	1.57 ± 2.14,	Values NR,	Values NR,	NR	NR	87.5 ± 13.3,	NR
			53	TT	no differences	no differences	no differences	NR	NR	no differences	NR
Zhang et al.[35]	2012	12	19	AM	1.96 ± 1.02	NR	NR	95.1 ± 1.0	NR	NR	NR
			53	TT	2.14 ± 0.91	NR	NR	94.5 ± 1.1	NR	NR	NR

NR, results of test for subgroup were not reported.
*Statistically significant differences ($P < .05$).

with a normal pivot-shift test at final follow-up, although the specific number of patients was not reported.[34] Two showed significantly more patients with a normal pivot-shift test in their AM cohorts than in their TT cohorts.[32,36] Four of 5 studies examined their patients with an instrumented Lachman test at final follow-up, 3 of which showed no difference[34-36] and 1 of which showed significantly lower mean KT-1000 average maximum manual displacement (in millimeters) in their AM cohort than in their TT cohort.[32]

Several studies reported on the clinical outcomes of their patients. Only a single study reported outcomes using the Tegner score, showing no difference between the AM and TT cohorts.[32] Only a single study reported the mean time from surgery to return to play, finding a significantly quicker return for the AM cohort.[32] Four of 5 studies reported outcomes using the IKDC system: 2 reported their results as "grades" (A, normal; B, nearly normal; C, abnormal; and D, severely abnormal)[32,36] and 2 reported their results as subjective scores.[33,34] Two of these studies reported significantly more patients with higher IKDC grades and significantly higher mean IKDC scores in the AM cohort than the TT cohort,[32,33] and 2 of these studies reported no differences in the distribution of IKDC grades or in mean IKDC scores.[34,36] Four of 5 studies reported outcomes using the Lysholm score: 3 found no difference in mean Lysholm scores between the AM and TT cohorts,[32,35,36] and 1 found significantly higher mean Lysholm scores in their AM cohort than in their TT cohort.[33]

Qualitative evaluation of study quality showed significant weaknesses in all studies, including lack of a sufficient description of overall study design (inclusion/exclusion criteria and so on)[34]; lack of an adequate description of surgical technique (i.e., techniques used in tunnel placement)[34,36]; lack of adequate description of study methodology (i.e., method of treatment allocation)[35]; lack of adequate reporting of results[34]; lack of randomization[32-34,36]; lack of blinding of examiners[32-36]; lack of power analyses to differentiate nonsignificant results from type II error[33-36]; and lack of inclusion of all patients, leading to concern for possible selection bias.[32]

Cadaveric Studies

The 4 included cadaveric comparative biomechanical studies analyzed a total of 58 knees, 29 of which underwent reconstruction with the AM technique and 29 of which underwent reconstruction with the TT technique. These studies biomechanically compared knees using 2 methods that are analogous to the Lachman and pivot-shift tests. In the Lachman analog, anterior tibial translation (in millimeters) was measured in response to varying degrees of anterior tibial force at varying degrees of knee flexion. In the pivot-shift analog, anterior tibial translation (in millimeters) was measured in response to a combined anterior tibial load, valgus torque, and internal or external rotation torque, again at varying degrees of knee flexion.

All 4 cadaveric studies measured anterior tibial translation in response to an anterior tibial load, which varied from 68 to 156 N. Three studies measured translation at 30° of knee flexion,[30,31,37] and 1 study measured translation at 60° of knee flexion.[29] Two studies found significantly less anterior tibial translation in those cadaveric knees reconstructed with the AM technique than the TT technique using 68- and 156-N loads at 30° of flexion.[30,37] Two studies found no differences in anterior tibial translation with 134-N loads at 30° and 60° of flexion.[29,31] Of note, these studies also described dissections to analyze tunnel position after testing, with 1 study achieving anatomic femoral tunnel position with the TT technique by the authors' own criteria[29] and 3 studies failing to achieve anatomic femoral tunnel position with the TT technique by the authors' own criteria.[30,31,37]

All 4 cadaveric studies reported anterior tibial translation in response to a combined anterior load, valgus torque, and rotational torque. The force used for these loads and torques varied between studies and was unmeasured in 2 studies, which limits comparison among studies. One study performed testing at 15° of flexion,[37] and 2 studies performed testing at 30° of flexion.[29,30] Whereas 1 study did report a significant difference in mean anterior translation between cadaveric knees reconstructed with the AM and TT techniques,[30] 2 other studies were unable to show any significant difference.[29,37] One study performed manual pivot-shift testing on their cadaveric legs, which consisted of the mid thigh to distal calf and did not have attached feet or hips.[31] This study found all cadavers reconstructed with the AM technique to have "normal" pivot-shift tests and all cadavers reconstructed with the TT technique to have a "glide" on pivot-shift testing.[31]

Qualitative evaluation of study quality showed significant weaknesses in all studies, including lack of a significant difference between the intact ACL and an ACL-deficient knee, indicating a high likelihood of type II error[37]; lack of a power analysis for nonsignificant results[37]; lack of use of new cadavers for each test and instead filling prior drill holes with cement[29]; lack of examiner blinding[31]; and lack of measurement of applied forces.[31,37]

Discussion

In this systematic review of clinical and biomechanical studies directly comparing AM and TT techniques for ACLR in the literature, 9 studies were identified with conflicting results. Whereas 2 clinical studies[32,36] and 2 cadaveric studies[30,31] showed a significant difference in the degree of rotational stability reconstructed, 1 clinical study[34] and 2 cadaveric studies[29,37] showed no difference. Clinical outcomes were similarly mixed: Some studies showed a significantly quicker return to play,[32] better IKDC scores,[32,33] and better Lysholm scores[33] with the AM technique, whereas other studies showed no difference in Tegner scores,[32] IKDC scores,[34,36] or Lysholm scores.[32,35,36] No studies showed significantly better results with the TT technique. This study shows that the AM portal technique for ACLR may be more likely to produce improved clinical and biomechanical outcomes but that the TT technique is capable of producing similar outcomes.

The results of ACLR are likely more dependent on reproducing the normal ACL anatomy than the technique used to achieve this location. Although several authors have argued that the centroid of the femoral footprint of the ACL[2,38,39] cannot be reached through a TT approach,[6] others have shown that with appropriate modifications of the surgical technique, the TT technique can achieve an anatomic reconstruction.[4,38,40] These modifications include use of an accessory transpatellar tendon portal for placement of the tibial aiming device, use of a tibial tunnel starting point at the junction of the pes anserinus and medial collateral ligament fibers, adequate rotation of the 7-mm offset femoral wire aimer to improve lateralization, and adjustment of the tibial aiming device so as to achieve 55° to 60° of angulation of the tibial tunnel in the coronal plane.[29,41] With these technical modifications, the TT technique can provide excellent long-term outcomes with very low failure rates.[42] In a large clinical study, Howell et al.[4] retrospectively reviewed 119 patients who underwent ACLR using the TT technique and showed that the TT technique can lead to nonanatomic vertical graft placement and failure to restore physiologic rotational laxity. However, the vast majority of cases with vertical grafts and residual laxity were associated with 2 of their 5 surgeons, suggesting that variations in surgical technique may allow nonanatomic graft placement with the TT method without necessitating vertical graft placement.

The AM technique may be more technically complex and can involve a steep learning curve. The technique was originally described using a difficult-to-maintain hyperflexed position while the reamer is advanced over a Beath pin that can impinge on and damage the medial femoral condyle or anterior horn of the medial meniscus. The hyperflexed position can limit visualization, which can be further obscured when the fat pad is displaced as the reamer is introduced.[43] In addition, the AM technique can lead to shorter femoral tunnels.[25] Shorter tunnels have been shown in an animal model to have a decreased load to failure.[44] Other theoretical concerns with the AM technique include a potentially higher frequency of graft-tunnel mismatch and the possibility that it may be more difficult to ensure that an interference screw is introduced collinear to the femoral tunnel.

Thus the AM technique may predispose patients to fixation complications or failure, and although clinical evidence of these potential complications is thus far lacking, surgeons using this technique must be familiar with multiple methods of fixation for ACLR. An additional concern with the AM technique is the tendency to "over-constrain" the knee, as shown by Bedi et al.[37] Over time, excess graft tension can lead to graft breakdown and failure, subluxation of the tibia, and increased articular contact pressures.[45,46] Finally, although the increased freedom afforded by the AM technique can be used to place the femoral tunnel in the anatomic footprint, the technique does not guarantee appropriate tunnel placement, and thus vertical tunnels can be created just as in TT techniques without proper knowledge of the anatomy of the footprint. Given the questionable benefit offered by the AM technique in conflicting comparative trials,[29,30,32,37] surgeons may be hesitant to switch to the AM technique. With 80% of orthopaedists performing fewer than 10 ACLRs per year,[6] transitioning to this technique may be difficult because most practicing orthopaedic surgeons have not been trained on the technique.

Much of the literature comparing methods of ACLR has been focused on the location of the femoral tunnel; however, recently, more attention has been paid to the location of the tibial tunnel. Modification of the TT technique to improve femoral tunnel location may do so by sacrificing anatomic tibial tunnel location. Specifically, efforts to lateralize the femoral tunnel may require medialization of the tibial tunnel into a nonanatomic position.[47] The increased obliquity may also shorten the tibial tunnel,[26] which may weaken tibial fixation[44] and predispose patients toward graft-construct mismatch. The increased obliquity may also widen the aperture of the tibial tunnel[37] and place the extra-articular exit point close to the joint line[17] and through the medial collateral ligament.[30] Other authors have been concerned that the TT approach may lead to posteriorization of the tibial tunnel, resulting in a vertical graft construct in the sagittal plane[48] or possibly increased risk of graft rupture.[9] In a cadaveric study, Bedi et al.[49] found that the more anterior the tibial tunnel, the better the restraint against the anterior translation of the lateral compartment. In a clinical study evaluating the obliquity of ACL grafts in participants in the National Football League, Mall et al.[50] found that tibial tunnels less than 37% posterior to the anterior tibia had significantly improved anterior-to-posterior stability as noted on Lachman examination.

Limitations

This systematic review has a number of limitations. First, the quality of our conclusions is limited by biases within the available literature. The included studies have a number of important flaws, including a large number of excluded patients, lack of randomization, lack of blinding, lack of a power analysis, and heterogeneity in results depending on the outcome measure selected. A further limitation is that the outcome measures used may be insufficiently sensitive to diagnose clinically significant subtle rotational instability experienced by patients. These issues limit the recommendations that can be made. No definite conclusions can be drawn from the literature at this time. The lack of high-level clinical evidence in the literature calls for the need for more research in this area. No Level I studies have been conducted. Until such data are available, any recommendation for 1 method of femoral tunnel creation over another will be weakly supported.

Conclusions

In this systematic review of clinical and cadaveric studies directly comparing AM and TT techniques for ACLR in the literature, there are mixed results, with some studies finding superior rotational stability and clinical outcomes with the AM technique and some finding no difference. No studies showed significantly better results with the TT technique. This study shows that the AM portal technique for ACLR may be more likely to produce improved clinical and biomechanical outcomes but that the TT technique is capable of producing similar outcomes.

References

1. Marchant BG, Noyes FR, Barber-Westin SD, Fleckenstein C. Prevalence of nonanatomical graft placement in a series of failed anterior cruciate ligament reconstructions. *Am J Sports Med* 2010;38:1987-1996.
2. Scopp JM, Jasper LE, Belkoff SM, Moorman CT III. The effect of oblique femoral tunnel placement on rotational constraint of the knee reconstructed using patellar tendon autografts. *Arthroscopy* 2004;20:294-299.
3. Lee MC, Seong SC, Lee S, et al. Vertical femoral tunnel placement results in rotational knee laxity after anterior cruciate ligament reconstruction. *Arthroscopy* 2007;23: 771-778.
4. Howell SM, Gittins ME, Gottlieb JE, Traina SM, Zoellner TM. The relationship between the angle of the tibial tunnel in the coronal plane and loss of flexion and anterior laxity after anterior cruciate ligament reconstruction. *Am J Sports Med* 2001;29:567-574.
5. 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;32:629-634.
6. Arnold MP, Kooloos J, van Kampen A. Single-incision technique misses the anatomical femoral anterior cruciate ligament insertion: A cadaver study. *Knee Surg Sports Traumatol Arthrosc* 2001;9:194-199.
7. Chhabra A, Kline AJ, Nilles KM, Harner CD. Tunnel expansion after anterior cruciate ligament reconstruction with autogenous hamstrings: A comparison of the medial

portal and transtibial techniques. *Arthroscopy* 2006;22: 1107-1112.
8. Hantes ME, Zachos VC, Liantsis A, Venouziou A, Karantanas AH, Malizos KN. Differences in graft orientation using the transtibial and anteromedial portal technique in anterior cruciate ligament reconstruction: A magnetic resonance imaging study. *Knee Surg Sports Traumatol Arthrosc* 2009;17:880-886.
9. Pinczewski LA, Lyman J, Salmon LJ, Russell VJ, Roe J, Linklater JA. 10-year comparison of anterior cruciate ligament reconstructions with hamstring tendon and patellar tendon autograft: A controlled, prospective trial. *Am J Sports Med* 2007;35:564-574.
10. Alentorn-Geli E, Lajara F, Samitier G, Cugat R. The transtibial versus the anteromedial portal technique in the arthroscopic bone-patellar tendon-bone anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2010;18:1013-1037.
11. Nakamura M, Deie M, Shibuya H, et al. Potential risks of femoral tunnel drilling through the far anteromedial portal: A cadaveric study. *Arthroscopy* 2009;25:481-487.
12. Bedi A, Raphael B, Maderazo A, Pavlov H, Williams RJ III. Transtibial versus anteromedial portal drilling for anterior cruciate ligament reconstruction: A cadaveric study of femoral tunnel length and obliquity. *Arthroscopy* 2010;26: 342-350.
13. Hefti F, Muller W, Jakob RP, Staubli HU. Evaluation of knee ligament injuries with the IKDC form. *Knee Surg Sports Traumatol Arthrosc* 1993;1:226-234.
14. Lysholm J, Gillquist J. Evaluation of knee ligament surgery results with special emphasis on use of a scoring scale. *Am J Sports Med* 1982;10:150-154.
15. Tegner Y, Lysholm J. Rating systems in the evaluation of knee ligament injuries. *Clin Orthop Relat Res* 1985;(198):43-49.
16. 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;27:1511-1522.
17. Chang CB, Yoo JH, Chung BJ, Seong SC, Kim TK. Oblique femoral tunnel placement can increase risks of short femoral tunnel and cross-pin protrusion in anterior cruciate ligament reconstruction. *Am J Sports Med* 2010;38: 1237-1245.
18. Dargel J, Schmidt-Wiethoff R, Fischer S, Mader K, Koebke J, Schneider T. Femoral bone tunnel placement using the transtibial tunnel or the anteromedial portal in ACL reconstruction: A radiographic evaluation. *Knee Surg Sports Traumatol Arthrosc* 2009;17:220-227.
19. Ilahi OA, Ventura NJ, Qadeer AA. Femoral tunnel length: Accessory anteromedial portal drilling versus transtibial drilling. *Arthroscopy* 2012;28:486-491.
20. Lee JK, Lee MC, Lee S, et al. Paper # 187: Position of the femoral tunnel in single bundle ACL reconstruction with modified transtibial technique. *Arthroscopy* 2011;27:e194-e195 (abstr).
21. Schairer WW, Haughom BD, Morse LJ, Li X, Ma CB. Magnetic resonance imaging evaluation of knee kinematics after anterior cruciate ligament reconstruction with anteromedial and transtibial femoral tunnel drilling techniques. *Arthroscopy* 2011;27:1663-1670.
22. Silva A, Sampaio R, Pinto E. ACL reconstruction: Comparison between transtibial and anteromedial portal techniques. *Knee Surg Sports Traumatol Arthrosc* 2012;20:896-903.
23. Wang JH, Kim JG, Lee DK, Lim HC, Ahn JH. Comparison of femoral graft bending angle and tunnel length between transtibial technique and transportal technique in anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2012;20:1584-1593.
24. Gadikota HR, Sim JA, Hosseini A, Gill TJ, Li G. The relationship between femoral tunnels created by the transtibial, anteromedial portal, and outside-in techniques and the anterior cruciate ligament footprint. *Am J Sports Med* 2012;40:882-888.
25. Golish SR, Baumfeld JA, Schoderbek RJ, Miller MD. The effect of femoral tunnel starting position on tunnel length in anterior cruciate ligament reconstruction: A cadaveric study. *Arthroscopy* 2007;23:1187-1192.
26. Hamilton SC, Jackson ER II, Karas SG. Anterior cruciate ligament femoral tunnel drilling through anteromedial portal: Axial plane drill angle affects tunnel length. *Arthroscopy* 2011;27:522-525.
27. Lubowitz JH, Konicek J. Anterior cruciate ligament femoral tunnel length: Cadaveric analysis comparing anteromedial portal versus outside-in technique. *Arthroscopy* 2010;26:1357-1362.
28. Steiner M. Flexible instruments outperform rigid instruments to place anatomic anterior cruciate ligament femoral tunnels without hyperflexion. *Arthroscopy* 2012;28:835-843.
29. Sim JA, Gadikota HR, Li JS, Li G, Gill TJ. Biomechanical evaluation of knee joint laxities and graft forces after anterior cruciate ligament reconstruction by anteromedial portal, outside-in, and transtibial techniques. *Am J Sports Med* 2011;39:2604-2610.
30. Steiner ME, Battaglia TC, Heming JF, Rand JD, Festa A, Baria M. Independent drilling outperforms conventional transtibial drilling in anterior cruciate ligament reconstruction. *Am J Sports Med* 2009;37:1912-1919.
31. Tudisco C, Bisicchia S. Drilling the femoral tunnel during ACL reconstruction: Transtibial versus anteromedial portal techniques. *Orthopedics* 2012;35:e1166-e1172.
32. Alentorn-Geli E, Samitier G, Alvarez P, Steinbacher G, Cugat R. Anteromedial portal versus transtibial drilling techniques in ACL reconstruction: A blinded cross-sectional study at two- to five-year follow-up. *Int Orthop* 2010;34:747-754.
33. Mardani-Kivi M, Madadi F, Keyhani S, Karimi-Mobarake M, Hashemi-Motlagh K, Saheb-Ekhtiari K. Antero-medial portal vs. transtibial techniques for drilling femoral tunnel in ACL reconstruction using 4-strand hamstring tendon: A cross-sectional study with 1-year follow-up. *Med Sci Monit* 2012;18:CR674-CR679.
34. Xu Y, Ao Y, Wang J, Yu J, Cui G. Relation of tunnel enlargement and tunnel placement after single-bundle anterior cruciate ligament reconstruction. *Arthroscopy* 2011;27:923-932.
35. Zhang Q, Zhang S, Li R, Liu Y, Cao X. Comparison of two methods of femoral tunnel preparation in single-bundle anterior cruciate ligament reconstruction: A prospective randomized study. *Acta Cir Bras* 2012;27:572-576.
36. Kim M-K, Lee B-C, Park J-H. Anatomic single bundle anterior cruciate ligament reconstruction by the two

anteromedial portal method: The comparison of transportal and transtibial techniques. *Knee Surg Relat Res* 2011;23:213-219.
37. Bedi A, Musahl V, Steuber V, et al. Transtibial versus anteromedial portal reaming in anterior cruciate ligament reconstruction: An anatomic and biomechanical evaluation of surgical technique. *Arthroscopy* 2011;27:380-390.
38. Rue JP, Ghodadra N, Bach BR Jr. Femoral tunnel placement in single-bundle anterior cruciate ligament reconstruction: A cadaveric study relating transtibial lateralized femoral tunnel position to the anteromedial and posterolateral bundle femoral origins of the anterior cruciate ligament. *Am J Sports Med* 2008;36:73-79.
39. Shino K, Nakata K, Nakamura N, Toritsuka Y, Nakagawa S, Horibe S. Anatomically oriented anterior cruciate ligament reconstruction with a bone-patellar tendon-bone graft via rectangular socket and tunnel: A snug-fit and impingement-free grafting technique. *Arthroscopy* 2005;21:1402.
40. Rue JP, Ghodadra N, Lewis PB, Bach BR Jr. Femoral and tibial tunnel position using a transtibial drilled anterior cruciate ligament reconstruction technique. *J Knee Surg* 2008;21:246-249.
41. Grumet R, Bach BR. Arthroscopically assisted ACL reconstruction using bone-tendon-bone autograft. In: Bach Jr BR, Provencher MT, eds. *ACL surgery: How to get it right the first time and what to do if it fails*. Thorofare, NJ: SLACK Incorporated, 2010;87-98.
42. Bach BR Jr, Tradonsky S, Bojchuk J, Levy ME, Bush-Joseph CA, Khan NH. Arthroscopically assisted anterior cruciate ligament reconstruction using patellar tendon autograft. Five- to nine-year follow-up evaluation. *Am J Sports Med* 1998;26:20-29.
43. Lubowitz JH. Anteromedial portal technique for the anterior cruciate ligament femoral socket: Pitfalls and solutions. *Arthroscopy* 2009;25:95-101.
44. Greis PE, Burks RT, Bachus K, Luker MG. The influence of tendon length and fit on the strength of a tendon-bone tunnel complex. A biomechanical and histologic study in the dog. *Am J Sports Med* 2001;29:493-497.
45. Brady MF, Bradley MP, Fleming BC, Fadale PD, Hulstyn MJ, Banerjee R. Effects of initial graft tension on the tibiofemoral compressive forces and joint position after anterior cruciate ligament reconstruction. *Am J Sports Med* 2007;35:395-403.
46. Hoshino Y, Kuroda R, Nagamune K, et al. The effect of graft tensioning in anatomic 2-bundle ACL reconstruction on knee joint kinematics. *Knee Surg Sports Traumatol Arthrosc* 2007;15:508-514.
47. Kopf S, Forsythe B, Wong AK, et al. Nonanatomic tunnel position in traditional transtibial single-bundle anterior cruciate ligament reconstruction evaluated by three-dimensional computed tomography. *J Bone Joint Surg Am* 2010;92:1427-1431.
48. Silva A, Sampaio R, Pinto E. Placement of femoral tunnel between the AM and PL bundles using a transtibial technique in single-bundle ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2010;18:1245-1251.
49. Bedi A, Maak T, Musahl V, et al. Effect of tibial tunnel position on stability of the knee after anterior cruciate ligament reconstruction: Is the tibial tunnel position most important? *Am J Sports Med* 2011;39:366-373.
50. Mall NA, Matava MJ, Wright RW, Brophy RH. Relation between anterior cruciate ligament graft obliquity and knee laxity in elite athletes at the National Football League combine. *Arthroscopy* 2012;28:1104-1113.