Clin Orthop Relat Res (2016) 474:1679–1689
DOI 10.1007/s11999-016-4847-7

Clinical Orthopaedics and Related Research®
A Publication of The Association of Bone and Joint Surgeons®

CLINICAL RESEARCH

Does Anteromedial Portal Drilling Improve Footprint Placement in Anterior Cruciate Ligament Reconstruction?

Sally Arno PhD, Christopher P. Bell MSc, Michael J. Alaia MD, Brian C. Singh BS, Laith M. Jazrawi MD, Peter S. Walker PhD, Ankit Bansal MD, Garret Garofolo BS, Orrin H. Sherman MD

Received: 23 July 2015 / Accepted: 13 April 2016 / Published online: 22 April 2016

Abstract

Background Considerable debate remains over which anterior cruciate ligament (ACL) reconstruction technique can best restore knee stability. Traditionally, femoral tunnel drilling has been done through a previously drilled tibial tunnel; however, potential nonanatomic tunnel placement can produce a vertical graft, which although it would restore sagittal stability, it would not control rotational stability. To address this, some suggest that the femoral tunnel be created independently of the tibial tunnel through the use of an anteromedial (AM) portal, but whether this results in a more anatomic footprint or in stability comparable to that of the intact contralateral knee still remains controversial.

Questions/purposes (1) Does the AM technique achieve footprints closer to anatomic than the transtibial (TT) technique? (2) Does the AM technique result in stability equivalent to that of the intact contralateral knee? (3) Are there differences in patient-reported outcomes between the two techniques?

Methods Twenty male patients who underwent a bone-patellar tendon-bone autograft were recruited for this study, 10 in the TT group and 10 in the AM group. Patients in each group were randomly selected from four surgeons at our institution with both groups demonstrating similar demographics. The type of procedure chosen for each patient was based on the preferred technique of the surgeon. Some surgeons exclusively used the TT technique, whereas other surgeons specifically used the AM technique. Surgeons had no input on which patients were chosen to participate in this study. Mean postoperative time was 13 ± 2.8 and 15 ± 3.2 months for the TT and AM groups, respectively. Patients were identified retrospectively as having either the TT or AM Technique from our institutional database. At followup, clinical outcome scores were gathered as well as the footprint placement and knee stability assessed. To assess the footprint placement and knee stability, three-dimensional surface models of the femur, tibia, and ACL were created from MRI scans. The femoral and tibial footprints of the ACL reconstruction as compared with the intact contralateral ACL were determined. In addition, the AP displacement and rotational displacement of the femur were determined. Lastly, as a secondary measurement of stability, KT-1000 measurements were obtained at the followup visit. An a priori

This study was funded by a philanthropic grant from Lawrence D. Glaubinger, LLD.
All ICMJE Conflict of Interest Forms for authors and *Clinical Orthopaedics and Related Research*® editors and board members are on file with the publication and can be viewed on request.
Clinical Orthopaedics and Related Research® neither advocates nor endorses the use of any treatment, drug, or device. Readers are encouraged to always seek additional information, including FDA-approval status, of any drug or device prior to clinical use.
Each author certifies that his or her institution approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.
This work was performed at New York University Hospital for Joint Diseases, New York, NY, USA.

S. Arno, C. P. Bell, M. J. Alaia, B. C. Singh, L. M. Jazrawi, P. S. Walker, G. Garofolo, O. H. Sherman
Department of Orthopaedic Surgery, New York University Hospital for Joint Diseases, New York, NY, USA

A. Bansal
Department of Orthopaedic Surgery, Virginia Commonwealth University, Richmond, VA, USA

M. J. Alaia (✉), L. M. Jazrawi, O. H. Sherman
Division of Sports Medicine, NYU Langone Hospital for Joint Diseases, 301 E 17th Street, New York, NY 10003, USA
e-mail: michael.alaia@nyumc.org

sample size calculation indicated that with 2n = 20 patients, we could detect a difference of 1 mm with 80% power at $p < 0.05$. A Welch two-sample t-test ($p < 0.05$) was performed to determine differences in the footprint measurements, AP displacement, rotational displacement, and KT-1000 measurements between the TT and AM groups. We further used the confidence interval approach with 90% confidence intervals on the pairwise mean group differences using a Games-Howell post hoc test to assess equivalence between the TT and AM groups for the previously mentioned measures.

Results The AM and TT techniques were the same in terms of footprint except in the distal-proximal location of the femur. The TT for the femoral footprint (DP%D) was 9% ± 6%, whereas the AM was −1% ± 13% (p = 0.04). The TT technique resulted in a more proximal footprint and therefore a more vertical graft compared with intact ACL. The AP displacement and rotation between groups were the same and clinical outcomes did not demonstrate a difference.

Conclusions Although the AM portal drilling may place the femoral footprint in a more anatomic position, clinical stability and outcomes may be similar as long as attempts are made at creating an anatomic position of the graft.

Level of Evidence Level III, therapeutic study.

Introduction

Anterior cruciate ligament (ACL) reconstruction is one of the most commonly performed outpatient orthopaedic surgeries in the United States and is typically performed in the setting of sports injuries [18, 24, 26, 30, 31]. Because many patients who undergo these procedures are young and active, surgical stabilization of the knee is an attractive option [1, 18, 25, 41]. However, which technique and graft to use to best restore knee stability are matters of debate.

Autologous bone-patellar tendon-bone (BPTB) is a commonly used graft choice in ACL reconstruction [3–5, 20, 35, 43]. Anatomic placement is considered optimal to provide maximum stability. Traditionally, femoral tunnel drilling has been done through a previously drilled tibial tunnel [1, 11, 23, 26]; however, the results of this approach have sometimes been disappointing because a more vertical graft could limit rotational stability [37, 45]. Some have therefore suggested that the femoral tunnel be created independently of the tibial tunnel through the use of an anteromedial drilling portal [8, 13, 20]. Most studies report that the anatomic tibial and femoral footprints are more frequently restored using this anteromedial (AM) technique when compared with the transtibial (TT) technique [1, 26, 44, 46].

However, it is not clear if the footprints reproduced with the AM technique equate to improved knee stability as compared with the stability of the intact contralateral knee when compared with the TT technique. We therefore asked the following: (1) Does the AM technique achieve footprints closer to anatomic than the TT technique? (2) Does the AM technique result in stability equivalent to that of the intact contralateral knee? (3) Are there differences in patient-reported outcomes between the two techniques?

Patients and Methods

Patient Selection

In accordance with institutional review board approval and the Health Insurance Portability and Accountability Act (HIPAA) regulations, 20 male patients qualifying for this study were randomly selected from a retrospective database (between December 2009 and June 2011) from the cohort of four surgeons with approximately 50 years of combined experience (LMJ, ES, DP, OHS) at our teaching hospital, who predominantly performed either the TT technique or the AM technique. The indication for surgery in all cases was a symptomatic ACL tear with feelings of giving way. Choice of technique was based on which technique the surgeon performed. Some surgeons exclusively used the TT technique, whereas the other surgeons specifically used the AM technique. To be included in this study, patients needed to be male between the ages of 18 and 40 years who had undergone a unilateral ACL reconstruction with a single-bundle BTB autograft and with an intact contralateral knee and be at least 6 months postoperative, having fully completed their rehabilitation protocol and with quadriceps strength in the reconstructed leg of at least 80% that in the intact contralateral leg. Furthermore, if a meniscal defect was noted, it needed to compose less than one-third of the meniscus. Any patient undergoing a meniscal repair was excluded. Women were also excluded from the study because of possible differences in kinematics between males and females [16, 22, 39]. Of the patients who met these criteria, 20 were randomly selected by a blinded member of our research staff, 10 patients were in the TT group with a mean age of 26 ± 7 years, mean body mass index (BMI) of 25 ± 2 kg/m^2, and a mean time postoperative time of 15 ± 3 months (range, 11–20 months). The 10 patients in the AM group had a mean age of 27 ± 6 years, mean BMI of 26 ± 3 kg/m^2, and a mean time postoperatively of 13 ± 3 months (range, 8–16 months) (Table 1). The Welch two-sample t-test was used to confirm that there were no differences in age, BMI, or time postoperatively between groups (p = 0.92, p = 0.43, and p = 0.13, respectively).

Table 1. Demographics of the cohorts

Demographics	Age (years) Mean ± SD	Body mass index (kg/m^2) Mean ± SD	Postoperative followup (months) Mean ± SD
TT group (n = 10)	26.2 ± 7.1	25.4 ± 2.2	14.6 ± 3.2
AM group (n = 10)	26.5 ± 5.7	26.6 ± 2.9	13.0 ± 2.8
p value	0.92	0.42	0.13

TT = transtibial; AM = anteromedial.

Patients from both groups returned for a 6-month follow-up appointment at which time the surgeon performed a pivot shift examination, as described by Noulis and modified by Noyes et al. [32, 33].

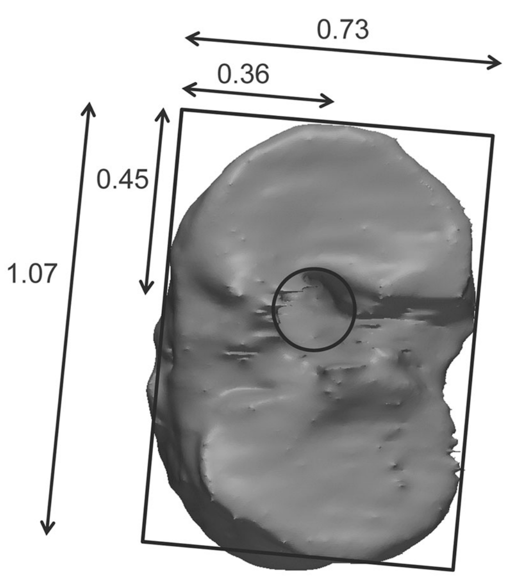
Assessment of Footprint and Stability

Assessment of the footprint for this study involved the use of MRI to assess the ACL footprint locations as well as AP displacement and rotation under applied load. The methodology used was similar to the protocol of Arno et al. [6]. Subjects were placed supine in a plastic rig with the nonsurgical knee at 15° of flexion. The subject's foot was securely placed in a surgical boot attached to a back plate. The back plate was positioned on two rails so that the distance from the receiving coil to the footrest could be adjusted based on the subject's height. A shoulder brace was also present to prevent movement of the subject once the loads were applied. On the left and right panels of the back plate, a rope was secured and pulled through an opening in the shoulder brace, where hooks were placed for the application of weights. A total compressive force of 222 N was applied along the tibial long axis and the first MRI scan completed. A Siemens MAGNETOM Verio 3-Tesla MRI machine (Siemens, Malvern, PA, USA) and Transmit/Receive 15 Channel Knee Coil with a 3D-Proton Density-non-Fat Suppressed-SPACE (Sampling Perfection with Application optimized Contrasts using different flip angle Evolutions) sequence (1000/46 [TR/TE]: flip angle, 120°; repetition time, 1000 msec; echo time, 46 msec; bandwidth, 97.3 Hz/pixel; matrix size, 320 × 300 pixels; voxel size, 0.5 × 0.5 × 0.5 mm^3) was used. On completion of this scan, an internal tibial torque of 5 Nm was applied at the surgical boot in addition to the compression, and a second scan was taken. During the second scan, the resolution was increased to 1.0 × 1.0 × 1.0 mm to reduce acquisition time from 11 minutes to 5 minutes. This was then repeated for the knee that underwent the ACL reconstruction. The loads used were chosen to mimic anatomic loading conditions, although the compression was reduced by a factor of 3 because it was not practical for patients to sustain such loads for the duration of the MRI scan [6, 15, 21].

After testing, the scans were analyzed in 3DDoctor (Able Software Corp, Lexington, MA, USA) and the femur, tibia, and ACL were manually segmented on each slice in the sagittal plane. These outlines were then combined in the software to create three-dimensional (3-D) surface models. The surface models from the compression-only and the compression-and-torque scans were exported into Rapidform XOV (Inus Technology, Seoul, Korea) for analysis. The tibia from the compression-only and the compression-and-torque scans were superimposed using a least-squares algorithm to act as a reference. The femur and ACL from the compression-and-torque scan were then transformed using the matrix from the tibia superposition. With the models properly aligned, the displacement of the femur after the application of the torque was determined in Rapidform XOV and represented by a color map. The average medial anterior and lateral posterior femoral displacement was determined using the color map histogram. The difference in displacement between the ACL-reconstructed knee and the intact contralateral knee was used for analysis such that the intact contralateral knee served as a control for each patient (MAD = medial anterior difference; LPD = lateral posterior difference) (Refer to Appendix 1 for a description of the key terms.). A difference within ± 1.0 mm was considered similar. Furthermore, the Welch two-sample t-test or the Wilcoxon rank-sum test ($p < 0.5$) combined with equivalence testing was performed to determine if the MAD and LPD measures were equivalent in the TT and AM groups. It is important to note that the displacements reported from the MRI were the result of the presence of torque and are therefore a measure of rotational stability as opposed to the KT-1000 displacements, which are a result of shear and therefore a measure of AP stability. The rotational stability was the primary stability measure in this study, which was used to test the hypothesis.

In addition to the femoral displacements resulting from the applied internal tibial torque, we also determined the amount of femoral rotation that occurred. To do this, best-fit circles were created in the sagittal section on the medial and lateral femoral condyles. The line joining these circles was a vector defined as the circular axis. The angle between the circular axis from the compression-only state and that from the compression-and-torque state was then measured in Rapidform XOR. Similar to the displacement measurements, the difference in rotation (RD) between the ACL-reconstructed knee and the intact contralateral knee was used for analysis. A difference within ± 3° was considered similar. The Welch two-sample t-test ($p < 0.5$) combined with equivalence testing was performed to determine if the rotation of the knee was equivalent in the TT and AM groups.

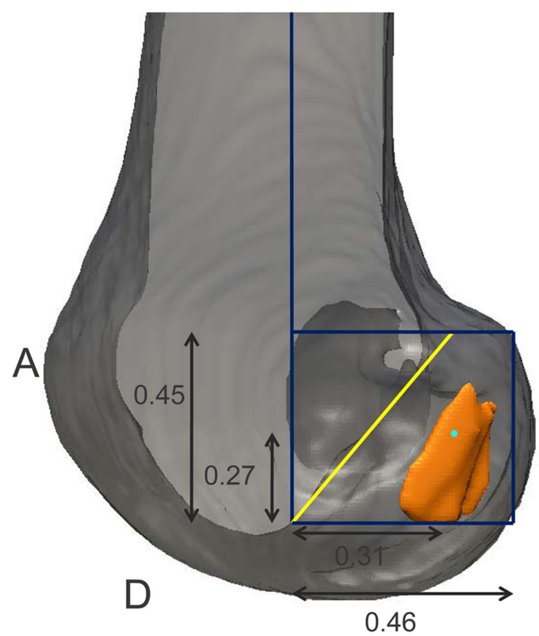
To measure the femoral and tibial footprint position, images of the compression-only 3-D model in the sagittal and axial plane were obtained from Rapidform XOV and opened in Google SketchUp (Google Inc, Mountain View, CA, USA), similar to the methodology of Tsukada et al. [45] To determine the tibial footprint position, a box was drawn around the tibia in the axial plane and the AP and mediolateral (ML) distance was measured (Fig. 1). The distance from the center of the tibial footprint to the anterior line of the box was measured and divided by the AP distance of the box to get the TAP%. This was repeated in the ML direction to determine the ML%. On the femur, a box was drawn in the sagittal plane bounding the area from the femoral axis to the most posterior aspect of the femoral condyle and the most proximal and distal aspects of Blumensaat's line (Fig. 2). The AP and distal-proximal (DP) measurements of this box were then measured. The distance from the centroid of the femoral footprint to the anterior line of the box was measured and divided by the AP distance to get the FAP%. Likewise, the distance from the centroid of the femoral footprint to the distal aspect of the box was determined and divided by the DP distance to obtain the DP%. Each of these measures of the ACL footprint was taken five times and the average value reported. In addition, all measurements were completed for the ACL reconstruction as well as the intact contralateral ACL and the difference between the two measurements calculated (ML% D; TAP% D; DP% D; FAP% D). A difference within 10% was considered similar. In addition to the footprint position, ImageJ (National Institutes of Health, Bethesda, MD, USA) was used to measure the percentage of the intact contralateral ACL femoral footprint, which was overlapped by the ACL reconstruction footprint. To obtain this measurement, Rapidform XOV was used to mirror and align the left femur and ACL to



$$\mathbf{ML\%} = \frac{Center\text{–}to\text{–}Medial}{ML} = \frac{0.45}{1.07} = 42\%$$

$$\mathbf{AP\%} = \frac{Center\text{–}to\text{–}Anterior}{AP} = \frac{0.36}{0.73} = 49\%$$

Fig. 1 A box bounding the most AP and ML aspects of the tibial plateau was used to determine the relative position of the ACL footprint.



$$\mathbf{AP\%} = \frac{Centroid\text{–}to\text{–}Axis}{AP} = \frac{0.31}{0.46} = 67\%$$

$$\mathbf{DP\%} = \frac{Centroid\text{–}to\text{–}Distal}{DP} = \frac{0.27}{0.45} = 60\%$$

Fig. 2 A box bounding the area from the femoral axis to the most posterior aspect of the femoral condyle and the most proximal and distal aspects of Blumensaat's line (yellow line) was used to determine the relative position of the ACL footprint. A = anterior; D = distal.

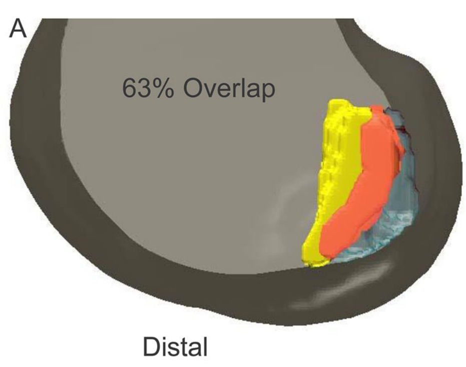
match the right femur. A sagittal image was imported into ImageJ and the portion of the intact contralateral ACL footprint, which was overlapped by the ACL reconstruction footprint, was determined (Fig. 3). This was then divided by the total area of the intact contralateral ACL footprint to define the %Overlap. A %Overlap equal to or greater than 70% was considered similar.

Secondary Assessment of Stability

Patients underwent testing of AP stability using the KT-1000 arthrometer (MEDmetric Corporation, San Diego, CA, USA). The patients were asked to lie supine and the knee flexed to 30° with the aid of a thigh support. Knee flexion was confirmed with a goniometer that was also used to determine the ROM in both limbs. The arthrometer was securely fastened to the anterior tibia and measurements obtained at 67 N, 89 N, and 133 N. Four measurements were taken at each force and the mean used for analysis. The difference in measurement between the reconstructed and intact contralateral knee was then calculated (KT-1000 D).

Patient-reported Outcomes

At the time of final follow-up for this study, patients filled out the following questionnaires: Tegner activity scale, Lysholm knee scoring scale, and the Knee Injury and Osteoarthritis Outcome Score (KOOS). These data were used to compare the two groups and were not used to determine the efficacy of either technique.



$$\%\text{Overlap} = \frac{\text{Area of Intact ACL Footprint Overlapped by the ACL Reconstruction (Orange)}}{\text{Area of Intact ACL Footprint (Blue+Orange)}}$$

Fig. 3 %Overlap was used as a secondary measure of the femoral footprint placement with respect to the intact ACL. ACL reconstruction footprint = yellow; intact ACL footprint = blue; portion of intact ACL footprint overlapped by the ACL reconstruction footprint = orange. A = anterior.

Statistical Methods

The Welch two-sample t-test ($p < 0.05$) combined with equivalence testing was performed to determine if the footprint location differences between knees (ie, ML%D) were equivalent in the TT and AM groups and to determine if the %Overlap was equivalent in the TT and AM groups. This statistical test was also used to determine if the KT-1000 measurements differed between the TT and AM groups and if the patient outcome scores were different for the TT and AM groups. To determine if all values were similar, we further performed the confidence interval approach because of its popularity as an equivalency testing method and its ease of use and interpretation [36]. We calculated the 90% confidence intervals on the pairwise mean group differences using a Games-Howell post hoc test. It is these 90% confidence intervals, taken from the post hoc comparisons, which were used to test whether the mean group differences were within the equivalence intervals. If the confidence intervals were within the equivalence intervals, equivalency was concluded. To assess equivalence for the primary hypothesis, an equivalence interval of ± 10% was used. To assess equivalence for the secondary hypothesis, an equivalence interval of ± 1 mm was used.

An a priori sample size calculation, based on the data of Bowers et al. [11], indicated that with 2n = 20 patients, we could detect a difference of 1 mm with 80% power at $p < 0.05$.

Results

Analysis of Graft Footprints and Stability

Overall, the footprint analysis revealed that the tibial and femoral footprint difference measures were equivalent between the TT and AM groups for all but the DP% D (Table 2). ML%D for the tibial footprint in the TT group was −3% ± 3%, whereas for the AM group, it was −2% ± 4% resulting in a p value of 0.65, although the TAP%D for the tibial footprint was 5% ± 9% for the TT group and 3% ± 6% for the AM group (p = 0.56). On the other hand, the DP%D for the femoral footprint was 9% ± 6% for the TT group and −1% ± 13% for the AM group (p = 0.04). The FAP%D for the TT group was −9% ± 8% and −7% ± 8% for the AM group (p = 0.64). In the TT group, the ACL femoral footprint was more proximal than the intact ACL, resulting in a more vertical graft. The tibial footprint of the ACL reconstruction of all but three patients in the TT group and four patients in the AM group was placed further posterior and medial than the intact contralateral ACL tibial footprint.

Table 2. Mean ± SD footprint difference measures (difference = ACL reconstructed knee placement—intact contralateral knee displacement) in the TT (n = 10) and AM (n = 10) groups*

Group	Tibial footprint		Femoral footprint	
	ML% D	TAP% D	DP% D	FAP% D
TT group	−3% ± 3%	5% ± 9%	9% ± 6%	−9% ± 8%
AM group	−2% ± 4%	3% ± 6%	−1% ± 13%	−7% ± 8%
p value	0.65	0.56	0.04	0.64
Equivalent?	Yes	Yes	No	Yes

* Only the DP% D was found to be statistically different between groups; ML% D = mediolateral % difference; TAP% D = tibial AP% difference; DP% D = distal-proximal % difference; FAP% D = femoral AP % difference; TT = transtibial; AM = anteromedial.

Table 3. Mean ± SD displacement and rotation differences (difference = ACL reconstructed knee – intact contralateral knee) in the TT (n = 10) and AM (n = 10) groups*

Group	KT-1000 D			MRI displacement		MRI rotation
	67 N	89 N	133 N	MAD	LPD	RD
TT group	0.5 ± 1.3	0.6 ± 1.7	1.2 ± 2.1	0.06 ± 0.42	0.16 ± 0.93	1.33° ± 1.05°
AM group	−0.2 ± 1.3	0.0 ± 1.3	0.1 ± 1.6	0.08 ± 0.50	0.25 ± 1.17	1.46° ± 1.26°
p value	0.26	0.36	0.21	0.52	0.62	0.81
Equivalent?	Yes	Yes	Yes	Yes	Yes	Yes

* All measures were found to be statistically equivalent between groups; all displacements are in mm and rotation is in degrees; KT-1000 is a measure of AP stability and all MRI parameters are a measure of rotational stability; KT-1000 D = KT-1000 arthrometer measurement difference; MAD = medial anterior displacement difference; LPD = lateral posterior displacement difference; RD = rotation difference; TT = transtibial; AM = anteromedial.

With the numbers available, the %Overlap of the femoral footprint was found to be no greater in the AM group (61%) than in the TT group (55%; p = 0.63).

Of interest, only three patients in the cohort of 20 had all femoral and tibial footprint measures within the acceptable values for similarity and yet all three patients exhibited discrepancies in the rotational stability measures between knees. All other patients had at least one tibial or femoral footprint measure outside of the acceptable values for similarity. The greatest discrepancy was seen for a patient (TT group) whose femoral footprint was shifted proximal and posterior compared with the intact footprint (DP% D of 22%, FAP% D of 12%, and a %Overlap of 19%) resulting in a more vertical graft, yet this patient exhibited the smallest between knee difference in stability of the 20-patient cohort (MAD of 0.07 mm, a LPD of 0.46 mm, and a RD of 0.18°).

Secondary Stability

The KT-1000D measures for both the TT and AM groups at all forces were found to be similar (Table 3). The KT-1000D measured at 67 N, 89 N, and 133 N. For the TT group, the measurements were found to be 0.5 ± 1.3, 0.6 ± 1.7, and 1.2 ± 2.1, respectively, whereas the AM group demonstrated −0.2 ± 1.3, 0.0 ± 1.3, and 0.1 ± 1.6, respectively (p = 0.26, p = 0.36, p = 0.21). This was consistent with the clinical pivot shift examination, which was negative for all patients. Overall, the ROM between limbs was similar with an average of 139° ± 3° in the intact contralateral limb and an average of 135° ± 11° in the ACL-reconstructed limb.

MRI measures indicated that the MAD, LPD, and RD measures, indicating rotational stability, were equivalent among the TT and AM groups (Table 3). These findings were similar to those obtained with arthrometry. In the intact contralateral knee, the femur underwent an external rotation relative to the tibia with a small anterior displacement of the medial condyle (overall average = 0.94 mm) and a larger posterior displacement of the lateral condyle (overall average = 1.49 mm). In the ACL-reconstructed knee, a similar external rotation was seen (Fig. 4). There were eight patients in the TT group and seven in the AM group who had similar rotational stability measures between knees (MAD and LPD within ± 1.0 mm; RD within ± 3°) as the result of the application of an internal torque during the MRI. Of the five patients who did have a discrepancy between knees, one patient (AM group) also had a limited ROM of 100°. There was otherwise no

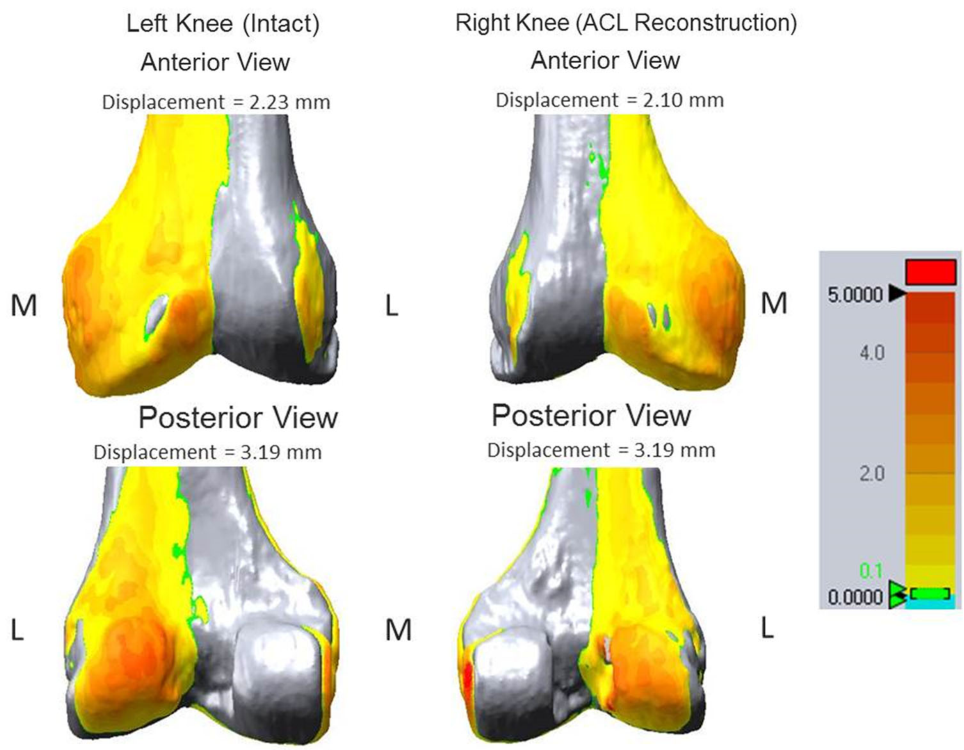


Fig. 4 In the intact contralateral knee (left column), relative to the tibia, the femur underwent an external rotation such that medial anterior and lateral posterior displacement occurred. In the ACL-reconstructed knee (right column), a similar external femoral rotation was seen. The example shown is for a patient from the TT group and was representative of a typical case. The footprint measures for this patient were as follows, indicating a posterior medial tibial footprint and proximal anterior femoral footprint and thus a vertical graft: ML% D = −6%, TAP% D = 21%, DP% D = 8%, FAP% D = −16%, and %Overlap = 48%. M = medial; L = lateral.

Table 4. Mean ± SD patient-reported outcomes in the TT (n = 10) and AM (n = 10) groups*

Group	Lysholm	KOOS					Tegner	
		Symptoms	Pain	Daily living	Sports and recreation	Quality of life	Preoperative	Postoperative
TT group	90 ± 8	86 ± 12	92 ± 8	98 ± 5	78 ± 21	70 ± 24	8 ± 1	7 ± 2
AM group	91 ± 9	86 ± 16	88 ± 14	94 ± 11	73 ± 24	62 ± 28	8 ± 1	6 ± 2
p value	0.71	0.95	0.85	0.43	0.63	0.51	0.26	0.51

* The performed statistical analysis indicated no difference for all measures between groups; TT = transtibial; AM = anteromedial; KOOS = Knee Injury and Osteoarthritis Outcome Score.

association between the rotational stability measures and the questionnaire scores or ROM.

Clinical Outcome Scores

There were no differences between the TT and AM groups with the numbers available in any of the questionnaire scores. The Lysholm score for the TT group was 90 ± 8, whereas the AM group had a score of 91 ± 9 (p = 0.71). The Tegner preoperative mean score for the TT group was 8 ± 1 and 8 ± 1 for the AM group (p = 0.26). The postoperative mean score also showed no different with the TT group presenting with 7 ± 2, whereas the AM group was 6 ± 2 (p = 0.51). All five measures on the KOOS (symptoms, pain, daily living, sports and recreation, and quality of life) showed no difference between the TT and AM groups (Table 4).

Discussion

ACL reconstruction is one of the most commonly performed outpatient orthopaedic surgeries in the United States and is typically performed in the setting of sports injuries Although there is general agreement that axial and rotational stability is important to provide in the course of surgical reconstruction, the optimal method of doing so remains controversial. Autologous BPTB is a commonly used graft choice in ACL reconstruction, and anatomic placement of the graft is generally sought. Two possible methods of doing so are transtibial placement of the femoral tunnel and creation of the femoral tunnel through a separate anteromedial incision. However, it is not clear if the graft footprints reproduced with the AM technique equate to improved knee stability as compared with the stability of the intact contralateral knee when compared with the TT technique. We therefore asked the following: (1) Does the AM technique achieve footprints closer to anatomic than the TT technique? (2) Does the AM technique result in stability equivalent to that of the intact contralateral knee? (3) Are there differences in patient-reported outcomes between the two techniques?

There are several limitations to this study. The cohort of this study was primarily composed of young active men. Women were excluded from the study given the possible differences in kinematics between males and females [16, 22, 39]. It is, therefore, important to consider that our results may only represent the young active male population. Although patients were instructed at the time of MRI testing to relax their leg and not resist the applied loads; some muscle activation was likely to occur to maintain that position for the full scan time affecting stability measurement. Because quadriceps strength and ROM are considered factors that affect knee stability, the excellent ROM and quadriceps strength in our cohort may have contributed to the lack of statistical significance in the stability measures [29, 37]. In addition, 11 patients had meniscal pathology, composing less than one-third of the meniscus, at the time of their ACL reconstruction. Because the meniscus is considered to be an important secondary stabilizer in the knee, such pathology may play a role in the patient's postoperative stability [2, 19, 28, 47]. The size and type of meniscal defect may have attributed to discrepancies in stability between knees as much as the ACL reconstruction drilling technique [7, 14, 17, 48]. Another factor that may play a role in postoperative stability is graft tension [12, 18]. Although graft tension was not measured in this study, it was confirmed for all patients using a standard tension protocol. In addition, the use of a BTB autograft in this study may have played a critical role in the consistent displacement results seen because the reliable bone healing may make these grafts more resilient to minor deviations in anatomic positioning compared with hamstrings or allografts [42, 49]. Selection bias, although a limitation, was limited because a research associate selected the patients for this study not knowing the clinical outcome of the patient and were selected randomly on the technique that was done for their surgery and if they met the qualifications for the study. In addition, we believe that the combined experience of the surgeons involved also minimized bias based on experience.

Achieving an anatomic footprint is considered critical to achieving tibiofemoral stability after an ACL reconstruction [1, 3, 10, 11, 30, 38, 43], yet there is currently little agreement on the ideal footprint placement of a single-bundle ACL reconstruction. McConkey et al. [30] showed that when 12 surgeons reviewed the femoral and tibial tunnels in 72 cadaveric knees, there was poor agreement (< 5%) on what was considered the ideal tunnel placement, although 88% of the femoral tunnels and 78% of the tibial tunnels were created within the study criteria [4]. An anatomic femoral footprint with the TT technique can be achieved if the tibial tunnel is placed further posterior and medial [11, 34]. In our study, the tibial footprint created with both the AM and TT techniques was further posterior and medial of the intact contralateral footprint. Similar to Bowers et al. [11], we found that the posterior placement of the tibial tunnel resulted in an anterior placement of the femoral tunnel in the TT group. However, in contrast to their findings [11], our results suggest that in the TT group, the ACL reconstruction was shifted proximal of the intact ACL footprint for all 10 patients, thereby resulting in more vertical grafts. In stark contrast, six of 10 patients in the AM group had ACL footprints, which were located distal to the intact ACL footprint location. This is consistent with others who have indicated that the AM technique more accurately restores the native ACL footprint [1, 11, 44]. This is a clinically relevant finding, because vertical grafts may be more subjected to rotational instability. However, the differences in the footprint position, although statistically significant, were small and our study was underpowered in terms of assessing clinical stability.

It should be noted that the results seen in this study were restricted to 15° for the MRI analysis and 30° for the arthrometer measurements. However, in yet-unpublished work, gait analysis was also performed on these patients, which indicated that the stability seen at these two flexion angles was maintained throughout the full ROM. Future study would benefit from larger cohorts, longer followup, and gait and landing analysis to further study the clinical differences, if any, between TT and AM techniques.

The measures of AP stability (KT-1000D) and rotational stability (MAD, LPD, and RD), in this study, were found to be equivalent between groups. These results are consistent with Schairer et al. [38] and Sim et al. [40] who found no difference in AP translation compared with the intact knee with either the TT or AM technique. This is in contrast to Bedi et al. [9, 10] who found the AM technique to result in more accurate positioning of the ACL footprint compared with the TT technique, which corresponded with less tibial translation according to the Lachman and pivot shift test as tested on five matched cadaveric knee pairs. In regard to rotational stability, Schairer et al. noted more total tibial rotation in the TT group compared with the AM group [38]. In addition, Sim et al. found that when torque was applied, the modified TT technique, which placed the tibial tunnel in the posterolateral quadrant of the intact footprint, failed to restore intact anterior tibial translation at both 0° and 30° compared with the AM technique, which only failed to do so at 30°. However, similar to our study, Sim et al. [40] went on to conclude that both techniques were similar in their ability to restore rotational stability of the knee. The similar results in our patient cohorts could be attributed to the fact that the surgeons erred for a more anatomic position, especially for the femoral socket. Similarities in the tunnel positions likely led to similarities in graft obliquity and stabilized the knee equally in both groups.

In addition, in this small, selected group, we found no differences between the techniques in terms of activity scores, validated knee scores, or the KOOS score. This agrees with some of the findings by Alentorn-Geli et al. [4], who demonstrated no differences in Lysholm or Tegner scores; however, they did find improved International Knee Documentation Committee scores in those undergoing an AM portal-based reconstruction. Koutras et al. [27] demonstrated no differences in Lysholm scores at 6 months in patients undergoing hamstring autograft when comparing TT versus AM groups using hamstring autograft. Although are results are in agreement with some of the findings in these studies, our study was not powered to detect significant differences in this regard.

In conclusion, although the AM portal drilling may place the femoral footprint in a more anatomic position, clinical stability is similar as long as attempts are made at creating an anatomic position of the graft. Therefore, surgeons who feel more comfortable creating the femoral tunnel through the tibia may expect similar outcomes assuming the tunnels approach the anatomic locations.

Acknowledgments We thank Samir Nayyar MD, Eric Strauss MD, and David Pereira MD, for their aid in patient recruitment. In addition, we thank KellyAnne McGorty, Kashif Khokhar, and Luis Beltran MD, for their assistance in obtaining and reviewing the MRI scans. We also thank Cheongeun Oh PhD, for her assistance with the statistical analysis.

Appendix 1

Summary of key terms

Key term	Description
KT-1000D	The difference in KT-1000 measurements between the ACL-reconstructed knee and the intact contralateral knee
MAD	The difference in medial anterior displacement, of the femur with respect to the tibia, between the ACL-reconstructed knee and the intact contralateral knee
LPD	The difference in lateral posterior displacement, of the femur with respect to the tibia, between the ACL-reconstructed knee and the intact contralateral knee
RD	The difference in femoral rotation between the ACL-reconstructed knee and the intact contralateral knee
ML%D	The difference in the mediolateral % position of the tibial footprint between the ACL-reconstructed knee and the intact contralateral knee; a positive value indicates the ACL reconstruction footprint is shifted lateral of the intact ACL footprint
TAP%D	The difference in the AP % position of the tibial footprint between the ACL-reconstructed knee and the intact contralateral knee; a positive value indicates the ACL reconstruction footprint is shifted posterior of the intact ACL footprint
DP%D	The difference in the distal-proximal % position of the femoral footprint between the ACL-reconstructed knee and the intact contralateral knee; a positive value indicates the ACL reconstruction footprint is shifted proximal of the intact ACL footprint
FAP%D	The difference in the AP % position of the femoral footprint between the ACL-reconstructed knee and the intact contralateral knee; a positive value indicates the ACL reconstruction footprint is shifted posterior of the intact ACL footprint

ACL = anterior cruciate ligament.

References

1. Abebe ES, Moorman CT 3rd, Dziedzic TS, Spritzer CE, Cothran RL, Taylor DC, Garrett WE Jr, DeFrate LE. Femoral tunnel placement during anterior cruciate ligament reconstruction: an in vivo imaging analysis comparing transtibial and 2-incision tibial tunnel-independent techniques. *Am J Sports Med.* 2009;37:1904–1911.
2. Ahmed AM, Burke DL, Yu A. In-vitro measurement of static pressure distribution in synovial joints–Part II: Retropatellar surface. *J Biomech Eng.* 1983;105:226–236.
3. Ahn JH, Lee SH, Yoo JC, Ha HC. Measurement of the graft angles for the anterior cruciate ligament reconstruction with transtibial technique using postoperative magnetic resonance imaging in comparative study. *Knee Surg Sports Traumatol Arthrosc.* 2007;15:1293–1300.
4. 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 Surgery Sports Traumatol Arthrosc.* 2010;18:1013–1037.
5. 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.
6. Arno S, Chaudhary M, Walker PS, Forman R, Glassner P, Regatte R, Oh C. Anterior-posterior stability of the knee by an MR image subtraction method. *Knee.* 2012;19:445–449.
7. Arno S, Hadley S, Campbell KA, Bell CP, Hall M, Beltran LS, Recht MP, Sherman OH, Walker PS. The effect of arthroscopic partial medial meniscectomy on tibiofemoral stability. *Am J Sports Med.* 2013;41:73–79.

8. Basdekis G, Abisafi C, Christel P. Influence of knee flexion angle on femoral tunnel characteristics when drilled through the anteromedial portal during anterior cruciate ligament reconstruction. *Arthroscopy.* 2008;24:459–464.
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.
10. Bedi A, Raphael B, Maderazo A, Pavlov H, Williams RJ 3rd. Transtibial versus anteromedial portal drilling for anterior cruciate ligament reconstruction: a cadaveric study of femoral tunnel length and obliquity. *Arthroscopy.* 2010;26:342–350.
11. Bowers AL, Bedi A, Lipman JD, Potter HG, Rodeo SA, Pearle AD, Warren RF, Altchek DW. 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.
12. 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.
13. Cain EL Jr, Clancy WG Jr. Anatomic endoscopic anterior cruciate ligament reconstruction with patella tendon autograft. *Orthop Clin North Am.* 2002;33:717–725.
14. Costa CR, Morrison WB, Carrino JA. Medial meniscus extrusion on knee MRI: is extent associated with severity of degeneration or type of tear? *AJR Am J Roentgenol.* 2004;183:17–23.
15. D'Lima DD, Patil S, Steklov N, Chien S, Colwell CW Jr. In vivo knee moments and shear after total knee arthroplasty. *J Biomech.* 2007;40(Suppl 1):S11–17.
16. Deie M, Sakamaki Y, Sumen Y, Urabe Y, Ikuta Y. Anterior knee laxity in young women varies with their menstrual cycle. *Int Orthop.* 2002;26:154–156.
17. Englund M, Roos EM, Lohmander LS. Impact of type of meniscal tear on radiographic and symptomatic knee osteoarthritis: a sixteen-year followup of meniscectomy with matched controls. *Arthritis Rheum.* 2003;48:2178–2187.
18. Fleming BC, Fadale PD, Hulstyn MJ, Shalvoy RM, Oksendahl HL, Badger GJ, Tung GA. The effect of initial graft tension after anterior cruciate ligament reconstruction: a randomized clinical trial with 36-month follow-up. *Am J Sports Med.* 2013;41:25–34.
19. Ghosh P, Taylor TK. The knee joint meniscus. A fibrocartilage of some distinction. *Clin Orthop Relat Res.* 1987;224:52–63.
20. Harner CD, Honkamp NJ, Ranawat AS. Anteromedial portal technique for creating the anterior cruciate ligament femoral tunnel. *Arthroscopy.* 2008;24:113–115.
21. Heinlein B, Kutzner I, Graichen F, Bender A, Rohlmann A, Halder AM, Beier A, Bergmann G. ESB Clinical Biomechanics Award 2008: Complete data of total knee replacement loading for level walking and stair climbing measured in vivo with a follow-up of 6–10 months. *Clin Biomech (Bristol, Avon).* 2009;24:315–326.
22. Heitz NA, Eisenman PA, Beck CL, Walker JA. Hormonal changes throughout the menstrual cycle and increased anterior cruciate ligament laxity in females. *J Athl Train.* 1999;34:144–149.
23. Heming JF, Rand J, Steiner ME. Anatomical limitations of transtibial drilling in anterior cruciate ligament reconstruction. *Am J Sports Med.* 2007;35:1708–1715.
24. Hewett TE, Di Stasi SL, Myer GD. Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. *Am J Sports Med.* 2013;41:216–224.
25. Janssen KW, Orchard JW, Driscoll TR, van Mechelen W. High incidence and costs for anterior cruciate ligament reconstructions performed in Australia from 2003–2004 to 2007–2008: time for an anterior cruciate ligament register by Scandinavian model? *Scand J Med Sci Sports.* 2012;22:495–501.
26. Kopf S, Pombo MW, Shen W, Irrgang JJ, Fu FH. The ability of 3 different approaches to restore the anatomic anteromedial bundle femoral insertion site during anatomic anterior cruciate ligament reconstruction. *Arthroscopy.* 2011;27:200–206.
27. Koutras G, Papadopoulos P, Terzidis IP, Gigis I, Pappas E. Short-term functional and clinical outcomes after ACL reconstruction with hamstrings autograft: transtibial versus anteromedial portal technique. *Knee Surg Sports Traumatol Arthrosc.* 2013;21:1904–1909.
28. Kurosawa H, Fukubayashi T, Nakajima H. Load-bearing mode of the knee joint: physical behavior of the knee joint with or without menisci. *Clin Orthop Relat Res.* 1980;149:283–290.
29. Lewek M, Rudolph K, Axe M, Snyder-Mackler L. The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. *Clin Biomech (Bristol, Avon).* 2002;17:56–63.
30. McConkey MO, Amendola A, Ramme AJ, Dunn WR, Flanigan DC, Britton CL, Group MK, Wolf BR, Spindler KP, Carey JL, Cox CL, Kaeding CC, Wright RW, Matava MJ, Brophy RH, Smith MV, McCarty EC, Vida AF, Wolcott M, Marx RG, Parker RD, Andrish JF, Jones MH. Arthroscopic agreement among surgeons on anterior cruciate ligament tunnel placement. *Am J Sports Med.* 2012;40:2737–2746.
31. Miller MD, Gerdeman AC, Miller CD, Hart JM, Gaskin CM, Golish SR, Clancy WG Jr. The effects of extra-articular starting point and transtibial femoral drilling on the intra-articular aperture of the tibial tunnel in ACL reconstruction. *Am J Sports Med.* 2010;38:707–712.
32. Noulis GC. Sprains of the knee. 1875. *Clin Orthop Relat Res.* 1997;341:5–6.
33. Noyes FR, Grood ES, Cummings JF, Wroble RR. An analysis of the pivot shift phenomenon. The knee motions and subluxations induced by different examiners. *Am J Sports Med.* 1991;19:148–155.
34. Piasecki DP, Bach BR Jr, Espinoza Orias AA, Verma NN. Anterior cruciate ligament reconstruction: can anatomic femoral placement be achieved with a transtibial technique? *Am J Sports Med.* 2011;39:1306–1315.
35. Poulsen MR, Johnson DL. Graft selection in anterior cruciate ligament surgery. *Orthopedics.* 2010;33:832.
36. Rogers JL, Howard KI, Vessey JT. Using significance tests to evaluate equivalence between two experimental groups. *Psychol Bull.* 1993;113:553–565.
37. Rudolph KS, Axe MJ, Buchanan TS, Scholz JP, Snyder-Mackler L. Dynamic stability in the anterior cruciate ligament deficient knee. *Knee Surg Sports Traumatol Arthrosc.* 2001;9:62–71.
38. 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.
39. Shultz SJ, Gansneder BM, Sander TC, Kirk SE, Perrin DH. Absolute serum hormone levels predict the magnitude of change in anterior knee laxity across the menstrual cycle. *J Orthop Res.* 2006;24:124–131.
40. 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.
41. Snyder-Mackler L, Fitzgerald GK, Bartolozzi AR, 3rd, Ciccotti MG. The relationship between passive joint laxity and functional outcome after anterior cruciate ligament injury. *Am J Sports Med.* 1997;25:191–195.

42. Spindler KP, Kuhn JE, Freedman KB, Matthews CE, Dittus RS, Harrell FE Jr. Anterior cruciate ligament reconstruction autograft choice: bone-tendon-bone versus hamstring: does it really matter? A systematic review. *Am J Sports Med.* 2004;32: 1986–1995.
43. Strauss EJ, Barker JU, McGill K, Cole BJ, Bach BR Jr, Verma NN. Can anatomic femoral tunnel placement be achieved using a transtibial technique for hamstring anterior cruciate ligament reconstruction? *Am J Sports Med.* 2011;39:1263–1269.
44. Tompkins M, Milewski MD, Brockmeier SF, Gaskin CM, Hart JM, Miller MD. Anatomic femoral tunnel drilling in anterior cruciate ligament reconstruction: use of an accessory medial portal versus traditional transtibial drilling. *Am J Sports Med.* 2012;40:1313–1321.
45. Tsukada H, Ishibashi Y, Tsuda E, Fukuda A, Toh S. Anatomical analysis of the anterior cruciate ligament femoral and tibial footprints. *J Orthop Sci.* 2008;13:122–129.
46. Tudisco C, Bisicchia S. Drilling the femoral tunnel during ACL reconstruction: transtibial versus anteromedial portal techniques. *Orthopedics.* 2012;35:e1166–1172.
47. Walker PS, Erkman MJ. The role of the menisci in force transmission across the knee. *Clin Orthop Relat Res.* 1975;109:184–192.
48. Watanabe Y, Scyoc AV, Tsuda E, Debski RE, Woo SL. Biomechanical function of the posterior horn of the medial meniscus: a human cadaveric study. *J Orthop Sci.* 2004;9:280–284.
49. Yunes M, Richmond JC, Engels EA, Pinczewski LA. Patellar versus hamstring tendons in anterior cruciate ligament reconstruction: a meta-analysis. *Arthroscopy.* 2001;17:248–257.