Transtibial Versus Anteromedial Portal Reaming in Anterior Cruciate Ligament Reconstruction: An Anatomic and Biomechanical Evaluation of Surgical Technique

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Purpose: The purpose of this study was to objectively evaluate the anatomic and biomechanical outcomes of anterior cruciate ligament (ACL) reconstruction with transtibial versus anteromedial portal drilling of the femoral tunnel. **Methods:** Ten human cadaveric knees (5 matched pairs) without ligament injury or pre-existing arthritis underwent ACL reconstruction by either a transtibial or anteromedial portal technique. A medial arthrotomy was created in all cases before reconstruction to determine the center of the native ACL tibial and femoral footprints. A 10-mm tibial tunnel directed toward the center of the tibial footprint was prepared in an identical fashion, starting at the anterior border of the medial collateral ligament in all cases. For transtibial femoral socket preparation (n = 5), a guidewire was placed as close to the center of the femoral footprint as possible. With anteromedial portal reconstruction (n = 5), the guidewire was positioned centrally in the femoral footprint and the tunnel drilled through the medial portal in hyperflexion. An identical graft was fixed and tensioned, and knee stability was assessed with the following standardized examinations: (1) anterior drawer, (2) Lachman, (3) maximal internal rotation at 30°, (4) manual pivot shift, and (5) instrumented pivot shift. Distance from the femoral guidewire to the center of the femoral footprint and dimensions of the tibial tunnel intra-articular aperture were measured for all specimens. Statistical analysis was completed with a repeated-measures analysis of variance and Tukey multiple comparisons test with $P \leq .05$ defined as significant. **Results:** The anteromedial portal ACL reconstruction controlled tibial translation significantly more than the transtibial reconstruction with anterior drawer, Lachman, and pivot-shift examinations of knee stability ($P \leq .05$). Anteromedial portal ACL reconstruction restored the Lachman and anterior drawer examinations to those of the intact condition and constrained translation with the manual and instrumented pivot-shift examinations more than the native ACL ($P \leq .05$). Despite optimal guidewire positioning, the transtibial technique resulted in a mean position 1.94 mm anterior and 3.26 mm superior to the center of the femoral footprint. The guidewire was positioned at the center of the femoral footprint through the anteromedial portal in all cases. The tibial tunnel intra-articular aperture was 38% larger in the anteroposterior dimension with the transtibial versus anteromedial portal technique (mean, 14.9 mm v 10.8 mm; $P \leq .05$). **Conclusions:** The anteromedial portal drilling technique allows for accurate positioning of the femoral socket in the center of the native footprint, resulting in secondary improvement in time-zero control of tibial translation with Lachman and pivot-shift testing compared with conventional transtibial ACL reconstruction. This technique respects the native ACL anatomy but cannot restore it with a single-bundle ACL reconstruction. Eccentric, posterolateral positioning of the guidewire in the tibial tunnel with the transtibial technique results in iatrogenic re-reaming of the tibial tunnel and significant intra-articular aperture expansion. **Clinical Relevance:** Anteromedial portal drilling of the femoral socket may allow for improved restoration of anatomy and stability with ACL reconstruction compared with conventional transtibial drilling techniques.

The need for anatomic anterior cruciate ligament (ACL) reconstruction to restore normal kinematics and postoperative function of the knee has been increasingly recognized.[1-5] Although translational stability can be achieved with isometric femoral positioning and a vertical graft orientation, rotational instability and a positive pivot shift may persist postoperatively.[3,6] Biomechanical studies have shown improved knee kinematics and stability with restoration of the native ligament orientation, origin, and insertion.[2,3,5-11] The surgical technique by which to prepare tibial and femoral sockets that respect the native ACL anatomy, however, remains controversial. Whereas some authors have recommended preparation of the femoral tunnel using a transtibial technique, others have advocated for independent femoral tunnel drilling through an anteromedial arthroscopic portal.

Technical modifications to the transtibial technique have been described in an effort to improve femoral tunnel obliquity and restoration of the native femoral ACL footprint. Howell et al.[12] recommended creating a tibial tunnel at a coronal angle of 65° to 70° to achieve sufficient femoral tunnel obliquity. Chhabra et al.[13] provided guidelines for using external landmarks to achieve sufficient tibial and femoral tunnel obliquity, and they reported that a tibial starting point at the midpoint between the tibial tubercle and posteromedial corner achieved a coronal angle of approximately 70°. Despite these technical modifications, however, concerns have been raised about the ability to capture the femoral ACL footprint with a transtibial technique. In a recent radiographic review, Dargel et al.[14] reported suboptimal femoral tunnel position using a transtibial technique with trajectory toward the roof of the notch and anterior to the native footprint because of constraints from the tibial tunnel orientation. Brophy et al.[1] and Pearle et al.[9] reported that the traditional arthroscopic transtibial technique predisposes patients to a "mismatch" graft position from the posterolateral tibial footprint to the anteromedial femoral footprint. Furthermore, Heming et al.[15] found that a transtibial technique could produce tunnels centered in both the tibial and femoral footprints only if a starting point prohibitively close to the joint line with a correspondingly short tibial tunnel were used.

In light of these concerns, some surgeons have advocated independent drilling of the femoral tunnel for ACL reconstruction. O'Donnell and Scerpella[16] first described a modified technique of reaming through a medial parapatellar portal, and Bottoni[17] and Harner et al.[18] have subsequently advocated use of the medial arthroscopic portal with the knee placed in hyperflexion. Preliminary radiographic and laboratory studies have reported favorable femoral tunnel placement by use of this technique. However, the potential advantages of this technique over transtibial reconstruction remain undefined.[16,19] The purpose of this study was to objectively evaluate the anatomic and biomechanical outcomes of ACL reconstruction with transtibial versus anteromedial portal drilling of the femoral tunnel. The hypothesis was that anteromedial portal reaming of the femoral socket would better restore native ligament anatomy and time-zero parameters of knee stability compared with a transtibial technique for ACL reconstruction.

METHODS

This study was approved by our institutional review board. Ten human cadaveric knees (5 matched-pair torsos transected above the pelvis; mean age, 64 years; range, 44 to 73 years) without ligament injury or pre-existing arthritis were allocated for ACL reconstruction by either a transtibial (n = 5) or anteromedial portal (n = 5) technique. The Praxim ACL Surgetics Navigation System (Praxim Medivision, La Tronche, France) was used for kinematic data acquisition. This "imageless" bone-morphing technology generates a 3-dimensional image of the patient's bony anatomy by acquiring points directly on the bone surface and then forming a statistical model to fit these points. Each knee was bench mounted in the dedicated computer navigation surgery laboratory at the study institution and positioned to allow a free flexion cycle from 0° to 130°. Steinmann pins were then placed in the distal femur and proximal tibia 10 cm from the joint line and mounted with reflective markers to provide fixed frame-of-reference points for the study. Surface landmarks were recorded, intra-articular geometry was mapped, and the 3-dimensional model was created. The knee was cycled through flexion-extension cycles, and kinematics were recorded. Pearle et al.[20] have validated this model as a reliable tool to quantify knee stability by comparison to a robotic/universal force-moment sensor (UFS) testing system. Coupled knee motions were determined by a robotic/UFS testing system and by an image-free navigation system in 6 cadaveric knees that were subjected to various tests of knee stability. The overall intraclass correlation coefficient between data from the surgical navigation system and the robotic positional sensor for all tests was 0.9976.[20]

With the native ACL intact, a navigated manual and instrumented stability examination was performed for each knee. The navigation system allowed for real-time control of the flexion angle during examination. After the level of the joint line was determined with fluoroscopy, a hook was screwed into the anterior crest of the proximal part of the tibia 8 cm distal to the joint line. The hook was used to apply an anteriorly directed force to the proximal part of the tibia by use of the technique for reproducible application of load described by Van Damme et al.[21] For the Lachman and anterior drawer examinations, the knee was flexed to 30° and 90°, respectively. A 68-N force was applied with a spring scale attached to a 6.5-mm screw in the anterior tibia for these tests. A maximum manual internal rotation force was applied to the knee flexed to 30°. A manual pivot-shift examination, as described by Noulis[22] and modified by Noyes et al.,[23] was performed for each specimen. An instrumented pivot-shift examination was performed by use of a continuous passive motion (CPM) machine that was secured to the operating room table in a 45° angle posted on a wedge (Fig 1). A custom-made foot holder was attached to allow for application of an internal rotation moment at the knee. Thigh supports were removed such that the tibia was fixed in its position in the foot holder and the femur was completely free of constraint. This allowed the femur to reproducibly subluxate posteriorly off the moving tibia (or conversely stated, the tibia subluxated anteriorly from the femur). Valgus moment was achieved by the 45° position of the CPM machine with respect to the supine position and a Velcro strap firmly secured across the proximal tibia. The motorized CPM machine then moved the knee through a range of motion, from full extension to 90° of knee flexion. The navigation system was used to record the kinematics during each of these maneuvers. Each maneuver was repeated 3 times for reproducibility and data analysis.

After testing of the intact condition, the anatomy of the ACL was defined by use of a modified approach described by Colombet et al.[24] A medial parapatellar arthrotomy was created in each knee before reconstruction to determine the center of the native ACL tibial and femoral footprints. The ACL was sectioned at its midpoint, and with traction on the ligament, the tibial and femoral footprints were carefully demarcated with electrocautery. The medial-lateral and anteroposterior dimensions of each footprint were measured and the center defined and marked with electrocautery (Fig 2). The sub-vastus arthrotomy was created such that it incorporated the anteromedial por-

FIGURE 1. (A) Schema and (B) photograph of instrumented pivot-shift device. The device allows the femur to reproducibly subluxate posteriorly off the moving tibia. A custom-made foot holder was attached to allow for application of an internal rotation moment at the knee. Thigh supports were removed such that the tibia was fixed in its position in the foot holder and the femur was completely free of constraint. Valgus moment was achieved by the 45° position of the CPM machine with respect to the supine position and a Velcro strap firmly secured across the proximal tibia. The motorized CPM machine then moved the knee through a range of motion, from full extension to 90° of knee flexion. The navigation system was used to record the kinematics during each of these maneuvers.

tal at the inferior aspect of the incision. The arthrotomy was closed in anatomic fashion after definition and marking of the ACL footprints, with care being taken to avoid imbrication or tightening of the medial retinaculum. Navigated knee stability examination of the ACL-deficient condition was then completed for all 5 maneuvers as described previously.

For the transtibial ACL reconstruction technique, a commercial tibial ACL guide (Acufex Director; Smith & Nephew, Andover, MA) was set at 55° to prepare a
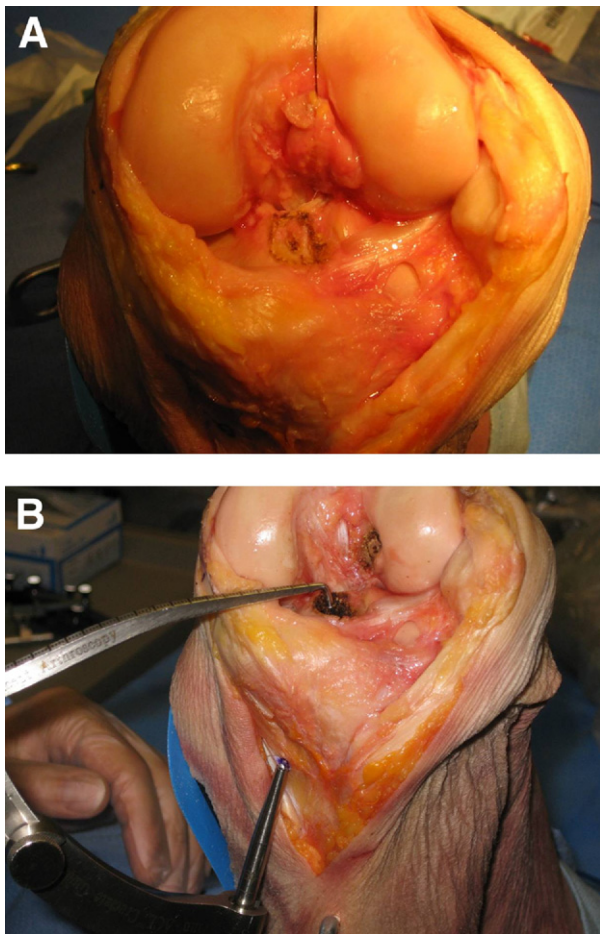
FIGURE 2. (A) Margin and center of tibial ACL footprint are demarcated by use of electrocautery by the technique defined by Colombet et al.[24] (B) Surgical technique to prepare tibial tunnel. The commercial guide was set at 55°, with the external starting point placed at the anterior fibers of the MCL and the internal target placed at the center of the tibial footprint.

10-mm tunnel as described by Rue et al.[25,26] The intra-articular exit point of the guide was placed at the center of the outlined tibial footprint (Fig 2). A 6-cm incision was then created over the medial tibial metaphysis and the pes anserinus retracted inferiorly to define the tibial insertion of the medial collateral ligament (MCL). The external starting point was placed at the anterior border of the MCL insertional fibers in all cases to allow for oblique orientation of the guide of approximately 65°, as described by Howell et al.[12] When satisfactory intra- and extra-articular starting points were confirmed, the guide pin was drilled and over-reamed with a 10-mm cannulated acorn reamer (Arthrex, Naples, FL). With the knee positioned in approximately 90° of flexion, a guidewire was passed

freehand through the tibial tunnel and placed as close to the previously marked center of the femoral footprint as possible. Knee flexion and rotation were adjusted to allow for the best possible approximation of the center of the femoral footprint with the guidewire. The distance from the guidewire tip to the center of the femoral footprint was measured in the anteroposterior and proximal-distal planes with a digital caliper device (Tresna Instruments, Columbus, OH) before reaming. Direct measurements were carefully performed directly on the specimen with a digital caliper that has been validated to be accurate within 0.1 mm. The guidewire was subsequently advanced and over-reamed with a 6-mm drill to prepare the femoral tunnel. A 10-mm tibial tunnel was used to simulate the most clinically relevant tibial tunnel size for single-bundle ACL reconstruction with a transtibial technique, as well as to simulate the typical maneuverability of the offset guide to optimize femoral position with the transtibial technique. After femoral tunnel reaming, the anteroposterior and medial-lateral dimensions of the intra-articular tibial tunnel aperture were measured with digital calipers. A 6-mm synthetic ligament device (LARS Ligament; Dijon, France) was passed and fixed with an extracortical EndoButton (Smith & Nephew) on the femoral side and with a screw-and-post construct on the tibial side. Screw-and-post tibial fixation allowed for reproducible tensioning and fixation of the graft between test conditions without risk of graft damage or iatrogenic tunnel expansion and has been shown to restore anterior laxity and construct stiffness as well as joint line fixation with an interference screw.[20] A synthetic graft was used to eliminate any confounding effect of variability in graft stiffness and strength. Although considerable concern exists regarding their biological incorporation, limiting their clinical use, autogenous tendon grafts have shown comparable biomechanical strength, stiffness, and restoration of knee stability in both time-zero and long-term biomechanical studies.[10,21,25-30] Tibial fixation was performed after 10 flexion-extension cycles, a 44-N tension was applied to each graft, and the sutures were secured by use of a screw-post construct at the proximal medial tibial metaphysis. Navigated knee stability examination of the transtibial ACL reconstruction was then completed for all 5 maneuvers, as described previously.

To confirm the absence of a time-zero biomechanical effect of an undersized graft in a 10-mm tibial tunnel, a pilot study was completed comparing biomechanical stability of knees with 6-mm versus 10-mm grafts that were placed in the same tunnels and
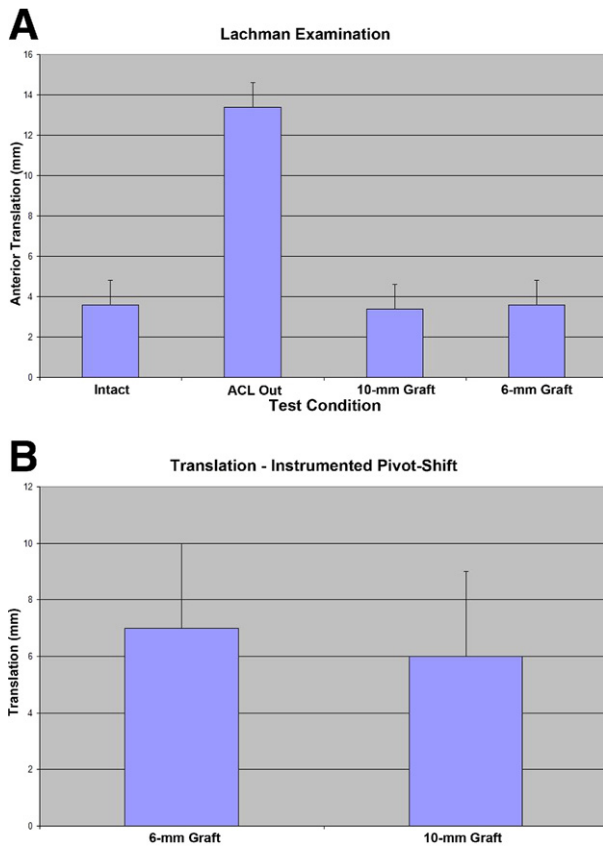
A

B

secured with identical tensioning and fixation techniques (N = 4). Results showed no statistically significant differences in the following examinations between conditions, confirming the validity of the experimental model: Lachman, anterior drawer, maximal internal rotation at 30° of flexion, and manual and instrumented pivot shift (Fig 3).

For ACL reconstruction with an anteromedial portal technique, the tibial tunnel was prepared in an identical fashion as described previously. A 1-cm anteromedial portal was created along the medial border of the patellar tendon, entering just above the anterior horn of the medial meniscus. A guidewire was placed at the marked center of the femoral footprint and over-reamed with a 6-mm drill with the knee in 110° of flexion.[17,18] The synthetic graft was fixed and tensioned in an identical fashion as described previously. Navigated knee stability examination of the anterome-

dial portal ACL reconstruction was then completed for all 5 maneuvers, as described previously.

Statistical analysis was completed with a repeated-measures analysis of variance and post hoc Tukey multiple comparisons test to compare translational and rotational differences of knee stability testing. Results from 3 repeated trials for each examination maneuver were averaged before comparison. Significance was set at $P < .05$. All statistical analyses were performed with the GraphPad Prism program (GraphPad Software, San Diego, CA). This study was powered to detect a 3-mm difference in translation during Lachman and anterior drawer examinations.

RESULTS

Lachman

The navigated Lachman examination for intact knees (n = 10) showed a mean of 6.2 ± 2.5 mm of anterior translation. Mean translation was 13.2 ± 2.9 mm for Lachman examination of the ACL-deficient condition (n = 10). Mean translation was 9.9 ± 2.3 mm and 6.3 ± 1.7 mm after transtibial (n = 5) and anteromedial portal (n = 5) ACL reconstruction, respectively (Fig 4). There was no statistically significant difference in translation between the intact ACL and anteromedial portal ACL reconstruction ($P >$
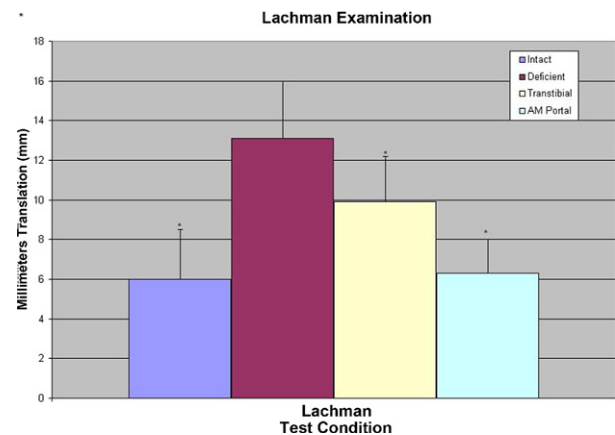
FIGURE 5. Results of navigated anterior drawer examination for intact ACL, ACL-deficient, transtibial ACL reconstruction, and anteromedial (AM) portal ACL reconstruction conditions. There was a statistically significant difference in translation between the anteromedial portal ACL reconstruction and the ACL-deficient condition ($P < .05$). However, there was no statistically significant difference between the anteromedial portal ACL reconstruction, transtibial ACL reconstruction, and intact ACL conditions ($P > .05$).

.05). There was a statistically significant difference in translation between the transtibial ACL reconstruction and the intact ACL or anteromedial portal ACL reconstruction ($P < .05$). The transtibial ACL reconstruction was not significantly different from the ACL-deficient condition ($P > .05$).
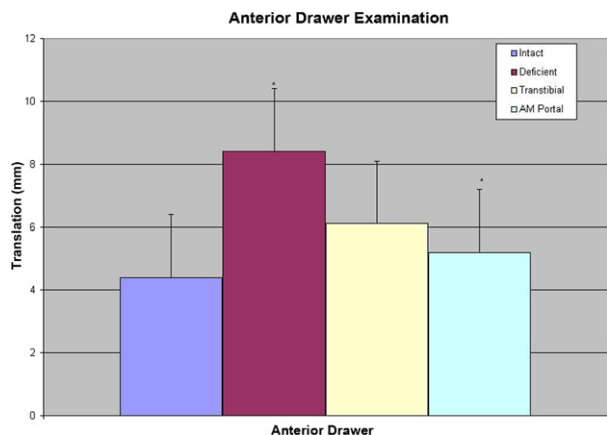
Anterior Drawer

The navigated anterior drawer examination for intact knees (n = 10) showed a mean of 4.4 ± 2.2 mm of anterior translation. Mean translation was 8.4 ± 3.9 mm for drawer examination of the ACL-deficient condition (n = 10). Mean translation was 6.1 ± 3.6 mm and 5.2 ± 2.0 mm after transtibial (n = 5) and anteromedial portal (n = 5) ACL reconstruction, respectively (Fig 5). There was a statistically significant difference in translation between the anteromedial portal ACL reconstruction and the ACL-deficient condition ($P < .05$). However, there was no statistically significant difference in anterior translation between the anteromedial portal ACL reconstruction, transtibial ACL reconstruction, and intact ACL conditions ($P > .05$).

Internal Rotation at 30°

Maximal manual internal rotation at 30° of flexion was $21.7° \pm 3.9°$ for the intact ACL condition (n = 10). Maximal internal rotation was $23.4° \pm 3.6°$ for

the ACL-deficient condition (n = 10). Maximum internal rotation was $22.3° \pm 4.5°$ and $21.3° \pm 4.4°$ after transtibial (n = 5) and anteromedial portal (n = 5) ACL reconstruction, respectively. There was no statistically significant difference between the intact ACL and the ACL-deficient, transtibial, or anteromedial portal ACL reconstructions for maximal internal rotation ($P > .05$).

Manual Pivot Shift

The manual pivot shift, as described by Noulis[22] and modified by Noyes et al.,[23] is composed of translational and rotational components of knee motion.[29] The intact knee showed 4.3 ± 1.4 mm of mean translation and $15.6° \pm 4.4°$ of mean internal rotation. The ACL-deficient knee showed 11.5 ± 2.7 mm of mean translation and $19.7° \pm 5.6°$ of mean internal rotation. After ACL reconstruction by a transtibial technique, there was 9.1 ± 2.7 mm of mean translation and $18.8° \pm 5.8°$ of mean internal rotation. There was no statistically significant difference between the ACL-deficient and transtibial ACL reconstruction conditions ($P > .05$). The knee showed significantly greater translational constraint after anteromedial portal ACL reconstruction compared with the native condition ($P < .05$), with mean translation of -5.9 ± 1.8 mm and $15.8° \pm 6.6°$ of mean internal rotation (Fig 6).
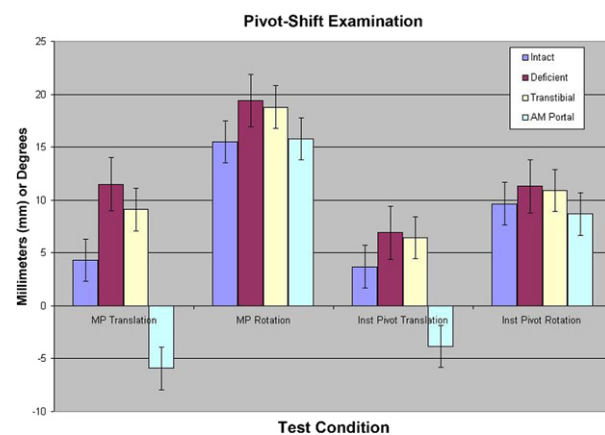
FIGURE 6. Results of navigated manual and instrumented pivot-shift examinations for intact ACL, ACL-deficient, transtibial ACL reconstruction, and anteromedial (AM) portal ACL reconstruction conditions. The knee showed significantly greater translational constraint after anteromedial portal ACL reconstruction compared with the native condition ($P < .05$). There was no statistically significant difference between the ACL-deficient and transtibial ACL reconstruction conditions ($P > .05$). (MP, manual pivot; Inst, instrumented pivot.)

Instrumented Pivot Shift

The knee kinematics during an instrumented pivot shift could also be subdivided into translational and rotational components. The intact knee showed 3.7 ± 0.6 mm of mean translation and $9.7° \pm 4.9°$ of mean internal rotation. The ACL-deficient knee showed significantly greater mean translation of 6.9 ± 1.6 mm ($P < .01$) and $11.3° \pm 2.9°$ of mean internal rotation. After ACL reconstruction by a transtibial technique, there was 7.4 ± 2.3 mm of mean translation and $10.9° \pm 1.1°$ of mean internal rotation. There was no statistically significant difference between the ACL-deficient and transtibial ACL reconstruction conditions ($P > .05$). The knee showed significantly greater translational constraint after anteromedial portal ACL reconstruction compared with the native condition ($P < .01$), with a mean translation of $3.8 \pm 0.7$ mm and $8.7° \pm 2.5°$ of mean internal rotation (Fig 6). No significant differences in mean internal rotation were detected between the intact, ACL-deficient, and both ACL reconstruction conditions ($P > .05$).

Tibial Aperture Dimensions

The mean medial-lateral and anteroposterior dimensions of the tibial intra-articular aperture after tunnel preparation measured 10.6 ± 0.3 mm and 14.9 ± 0.8 mm, respectively. By use of an anteromedial portal technique for femoral tunnel drilling, these dimensions measured 10.4 ± 0.2 mm and 10.8 ± 0.4 mm, respectively. This 38% difference in anteroposterior dimension of the tibial aperture between reconstruction techniques was statistically significant ($P < .01$) (Fig 7).

Capture of Femoral ACL Footprint

By use of a transtibial technique, the femoral tunnel guidewire was positioned as close to the center of the marked femoral footprint as possible. Despite eccentric posterolateral positioning within the tibial tunnel, the guidewire was a mean of 1.9 ± 0.5 mm anterior and 3.3 ± 1.6 mm superior to the center of the femoral footprint and primarily directed toward the anteromedial bundle (Fig 8). In contrast, the guidewire could be placed at the exact femoral footprint center in all cases when positioned and over-reamed through the anteromedial portal ($P < .05$).

DISCUSSION

In this study ACL reconstruction with anteromedial portal reaming of the femoral socket better restored
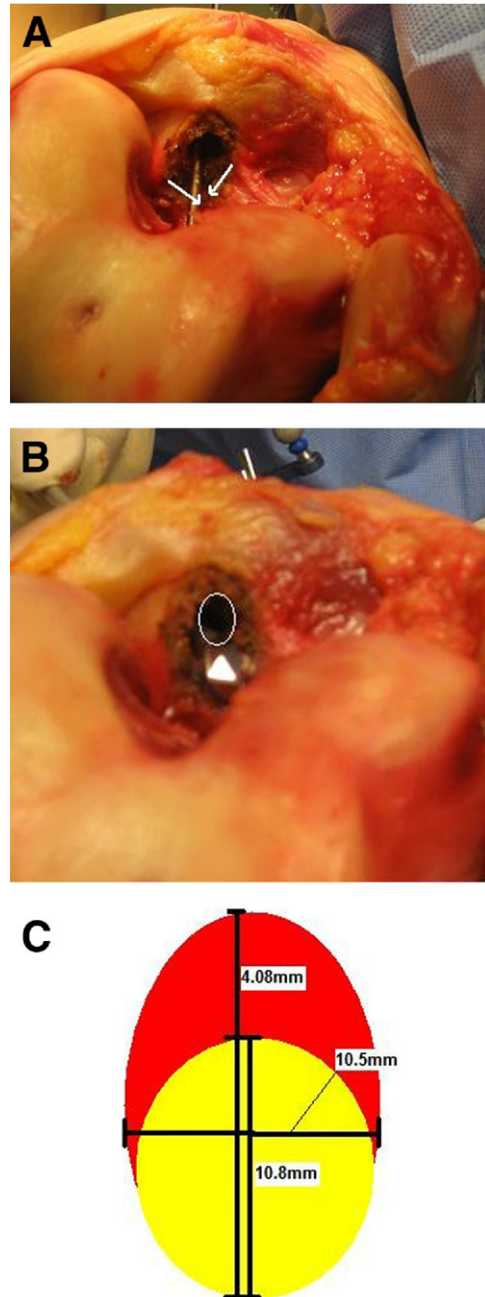
FIGURE 7. (A) The transtibial guidewire is positioned eccentrically posterior and lateral in the tibial tunnel to achieve a position near the ACL femoral footprint. The arrows show the relative posterior and lateral eccentric positioning of the guidewire in the tibial tunnel to improve positioning within the femoral footprint. (B) Because the guidewire is over-drilled, the eccentric position results in iatrogenic re-reaming of the tibial metaphyseal bone with significant secondary tunnel expansion. The circle demonstrates the eccentric reaming and iatrogenic, posterolateral expansion of the tibial aperture. (C) The tibial aperture was 38% greater in the anteroposterior dimension in the transtibial versus anteromedial portal ACL reconstruction groups ($P < .05$).

FIGURE 8. Despite optimal positioning, the transtibial guidewire could not achieve an anatomic position at the center of the femoral footprint and was more eccentrically biased toward an isolated anteromedial (AM) bundle reconstruction.
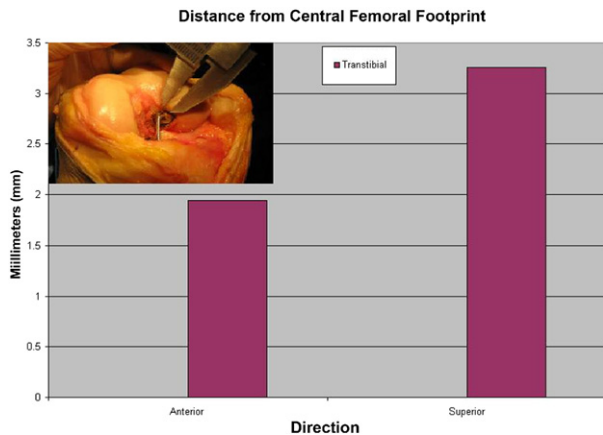
native ligament anatomy and time-zero measures of knee stability compared with a transtibial technique. The center of the native femoral ACL footprint could not be captured by use of a transtibial technique in which the tibial tunnel was anatomically restricted to capture the center of the ACL footprint.[15,31] Despite maximal eccentric positioning posteriorly and laterally in the tibial tunnel, the guidewire was always anterior and superior to the center of the femoral footprint and directed more toward the anteromedial bundle. In contrast, the anteromedial portal technique allowed guidewire positioning at the center of the femoral footprint in all cases. Whereas the magnitude of distance between the guidewire and footprint center was small (approximately 2 to 3 mm), this difference was sufficient to result in significantly inferior time-zero control of tibial translation with Lachman and pivot-shift testing compared with the anteromedial portal technique.

The biomechanical superiority of anatomic femoral tunnel positioning has been well-established in both laboratory and clinical studies.[5,6,9-11,20,21,29,30,32] Improving surgical techniques to recapitulate the anatomic footprints of the native ACL and restore normal knee kinematics has therefore become a significant focus in ACL reconstructive surgery. No consensus exists, however, on which surgical technique is optimal to reliably achieve these goals. Whereas some authors have recommended preparation of the femoral tunnel using a modified transtibial technique, others have advocated for independent femoral tunnel drilling through an anteromedial arthroscopic portal.

Modifications of the conventional transtibial technique have been described in an effort to improve femoral tunnel obliquity and restore the native femoral ACL footprint.[12,13] Despite these technical modifications, however, significant concerns exist regarding the ability to restore ACL anatomy through a transtibial technique. Dargel et al.[14] recently reported suboptimal femoral tunnel radiographic position using a transtibial technique with tunnels located in an anterior and vertical position relative to the native footprint. Giron et al.[31] reported on the technical impossibility of restoring both the anatomic tibial and femoral origins of the ACL using a transtibial technique despite any modifications. Prior work in our laboratory[1,20] and by Purnell et al.[27] has shown the traditional arthroscopic transtibial technique to predispose patients to a mismatch graft position from the posterolateral tibial footprint to the anteromedial femoral footprint. Furthermore, Heming et al.[15] recently reported that a transtibial technique could capture the native tibial and femoral footprints only if a tibial starting point prohibitively close to the joint line were used. In light of these concerns, some surgeons have advocated independent drilling of the femoral tunnel through the medial arthroscopic portal, with the knee placed in hyperflexion.[17,18] Preliminary radiographic and laboratory studies have reported favorable femoral tunnel position using this technique.[14,33]

This study presents several important differences in the time-zero anatomic and biomechanical outcomes of ACL reconstruction by use of a transtibial versus anteromedial portal technique. In concordance with Heming et al.[15] and other authors,[31] we have shown an inability to capture the center of the native femoral ACL footprint using a transtibial technique in which the tibial tunnel was anatomically restricted to capture the center of the ACL tibial footprint. Although the magnitude of distance between the guidewire and footprint center was small (approximately 2 to 3 mm), this difference was sufficient to result in significantly inferior biomechanical outcomes with standardized time-zero Lachman and pivot-shift testing compared with the anteromedial portal technique. Multiple biomechanical studies have corroborated these findings, showing that subtle differences in femoral socket position can significantly alter graft isometry and knee stability postoperatively.[1,4,6-8,34-38] Our results also support the contention that surgeons who achieve an anatomic tunnel position on the femoral side using a transtibial technique compromise the location of the tibial tunnel more posteriorly in the ACL footprint.[1,9,27] This change results in a mismatch graft

position that confers inferior stability to the knee compared with an anatomic reconstruction.

Analysis of the tibial tunnel intra-articular aperture shows additional important considerations. A 38% greater anteroposterior dimension of the tibial aperture was seen in the transtibial versus anteromedial portal group ($P < .05$). We attribute this difference to the eccentric posterior and lateral positioning of the guidewire within the tibial tunnel that is required to optimize its trajectory toward the femoral footprint. As this guidewire is over-drilled, the eccentric position results in iatrogenic re-reaming of the tibial metaphyseal bone with significant secondary tunnel expansion (Fig 7). It should be noted that our study used only a 6-mm drill for the femoral tunnel because of limitations in available sizes of the synthetic graft. A 10-mm reamer or larger is typically used for ACL reconstruction and would result in considerably greater tunnel expansion. Furthermore, the 10-mm tibial tunnel prepared in this study provided substantial ability to maneuver and optimally position an offset guide and/or femoral guide pin with a transtibial technique. A smaller tibial tunnel would further constrain the pin and likely exaggerate the nonanatomic femoral position as well as iatrogenic re-reaming of the tibial tunnel observed in this study. We believe that this time-zero technical issue is a contributing cause for the delayed tunnel expansion that has been vastly reported after transtibial ACL reconstruction.[30,39] Our findings are further corroborated by recent work by Miller et al.,[40] who reported significantly increased tibial aperture size and shape after transtibial femoral drilling with a medial tibial starting point based on computed tomography analysis. Kopf et al.[41] further confirmed these findings, reporting that drill-bit diameter, sagittal drill angle, and transverse drill angle could all affect tibial aperture size and orientation in potentially adverse ways during ACL reconstruction.

The biomechanical outcomes after ACL reconstruction with an anteromedial portal technique were superior to the transtibial ACL reconstruction. The anteromedial portal ACL reconstruction restored the Lachman examination to that of the native ACL condition, whereas the transtibial reconstruction could not be distinguished from the ACL-deficient condition. Furthermore, the translational restraint conferred by the anteromedial portal ACL reconstruction during manual and instrumented pivot-shift examination was significantly greater than both the native ACL and transtibial ACL reconstruction conditions. The implications of this "overconstraint" conferred by the anteromedial

portal ACL reconstruction in this study have yet to be defined. In a recent study evaluating the stability of single- and double-bundle ACL reconstruction, Markolf et al.[35] concluded that overconstraint of the knee may be detrimental by precipitating abnormal knee kinematics and graft forces in terminal extension that could lead to premature failure. On the other hand, overconstraint may confer some protection to the knee during the vulnerable healing and rehabilitation phases after ACL reconstruction.

Interestingly, the manual rotational examination of knee stability and the rotational component of the pivot shift did not show any significant differences between the transtibial and anteromedial ACL reconstructions. This finding is somewhat surprising in light of prior biomechanical studies that have implicated a vertical graft position resulting from a transtibial technique to confer anteroposterior but insufficient rotational stability to the knee.[3,6,10,25,26] However, Diermann et al.[42] evaluated internal tibial rotation with a simulated pivot-shift test on a robotic testing system in 7 cadaveric knees, and they found no increase in internal tibial rotation in the setting of ACL deficiency. They concluded that measures of anterior tibial translation should be evaluated rather than internal tibial rotation when using instrumented knee laxity devices under pivot-shift mechanisms. We acknowledge that our manual test for maximal internal rotation at 30° of knee flexion may lack the sensitivity to detect physiologically relevant differences. However, it should be noted that "rotational instability" from graft malpositioning has most frequently been documented as an abnormal pivot-shift examination postoperatively in the literature. Our findings suggest that it may actually be the translational and not the rotational component of the pivot-shift examination that is responsible for these detectable differences in what has been reported as "rotational instability."

Our study is not without limitations. Constraint of the intra-articular position of the tibial guide to the center of the tibial footprint was critical to our experimental design. However, the guide was also set to an angle of 55° and positioned with an external starting point at the anterior fibers of the MCL. We recognize that an alteration in the guide angle or coronal obliquity can alter the tibial tunnel trajectory and secondarily affect the ability to position the femoral guidewire. However, these parameters were selected based on guidelines in the existing literature to optimize tunnel length and obliquity using a transtibial technique.[12,25,26] In addition, our model is clinically relevant, using a common guide angle that avoids com-

plications related to graft-tunnel length mismatch or prohibitively short tunnels with an insufficient tendon-bone interface for healing. Furthermore, an external starting point at the anterior fibers of the MCL only improves the coronal obliquity for transtibial guide-wire positioning and the ability to capture the femoral footprint. We also recognize that although significant anatomic and biomechanical differences between transtibial and anteromedial portal ACL reconstructions are evident, the clinical significance of these findings is unclear. It is certainly possible that these differences may not translate into improved patient satisfaction or better functional outcomes. There is no question that successful outcomes after transtibial ACL reconstruction have been well established in the literature.[8,32] Buchner et al.[32] have reported 85% nearly normal or normal International Knee Documentation Committee scores at a mean of 6 years' follow-up after transtibial ACL reconstruction in 85 patients, with 75% showing a difference of less than 3 mm in KT-1000 measurements (MEDmetric, San Diego, CA) between knees. Maletis et al.[8] similarly reported excellent subjective and objective outcomes as well as restoration of knee stability as assessed by KT-1000 arthrometer in 96 patients with transtibial ACL reconstruction at 24 months' follow-up. Randomized, prospective studies with validated functional outcome tools are necessary to further define the clinical relevance of our findings.

CONCLUSIONS

The anteromedial portal drilling technique allows for accurate positioning of the femoral socket in the center of the native footprint, resulting in secondary improvement in time-zero control of tibial translation with Lachman and pivot-shift testing compared with conventional transtibial ACL reconstruction. This technique respects the native ACL anatomy but cannot restore it with a single-bundle ACL reconstruction. Eccentric, posterolateral positioning of the guidewire in the tibial tunnel with the transtibial technique results in iatrogenic re-reaming of the tibial tunnel and significant intra-articular aperture expansion.

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