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# Evaluation of the Single-Incision Arthroscopic Technique for Anterior Cruciate Ligament Replacement

## A Study of Tibial Tunnel Placement, Intraoperative Graft Tension, and Stability

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## ABSTRACT

The tension in an anterior cruciate ligament graft may not be normal when the femoral tunnel is placed using the single-incision arthroscopic technique because the femoral tunnel is drilled through the tibial tunnel. We hypothesized that the in vivo tensile behavior of the double-looped semitendinosus and gracilis tendon graft can be normal or abnormal compared with the native anterior cruciate ligament, that the placement and angle of the tibial tunnel can predict the tensile behavior of the graft, that the graft with abnormal tensile behavior is associated with a nonanatomically placed tibial tunnel, and that the tensile behavior of the graft determines the stability of the reconstructed knee at 1 year. Total tension in the graft and knee flexion angle were measured in 14 subjects as the knee was flexed from 0° to 90°. A graft force greater than 40 N at 80° of flexion was considered abnormal. One year after surgery, the angle and position of the tibial tunnel were determined from roentgenograms, and knee stability was measured with a KT-1000 arthrometer. The criteria for anatomic tibial tunnel placement in the sagittal and coronal planes were derived from magnetic resonance images of uninjured knees. The tensile graft behavior was either normal (4 of 14) or abnormal (10 of 14) with the single-incision arthrosopic technique. The angle of the tibial tunnel in the coronal plane was predictive of abnormal tensile behavior. Abnormal tensile behavior occurred in anatomically placed tibial tunnels and was compatible with a stable and functional reconstructed knee at 1 year.

The single-incision arthroscopic technique for reconstructing a torn ACL has gained popularity over the two-incision technique because of improved cosmesis, shorter operative time, and similar clinical outcome.[5,10,22] However, a potential disadvantage of the single-incision arthroscopic technique is that the femoral tunnel cannot be freely placed inside the intercondylar notch (Fig. 1).

Free placement may be clinically important because the placement of the femoral tunnel determines the forces in the graft.[4,15,16,18,20] A femoral tunnel positioned too anterior or distal causes abnormal increases in graft tension with flexion[15,17,19] that may result in graft failure, loss of fixation, or limited motion.

The outcome of ACL reconstructions may be improved if the femoral tunnel is placed so that the tension in the graft replicates the normal tensile behavior or strain of the ACL.[26] The force in the ACL follows a consistent pattern during passive knee motion from full extension to 90° of flexion. The highest force occurs in full extension and the lowest between 10° to 90° of flexion. In the graft, abnormal tensile behavior exists when elevated forces occur between 30° and 90° of flexion, with the highest force at 80° of flexion.[17] The first objective in this study was to measure the in vivo forces in a double-looped semitendi-

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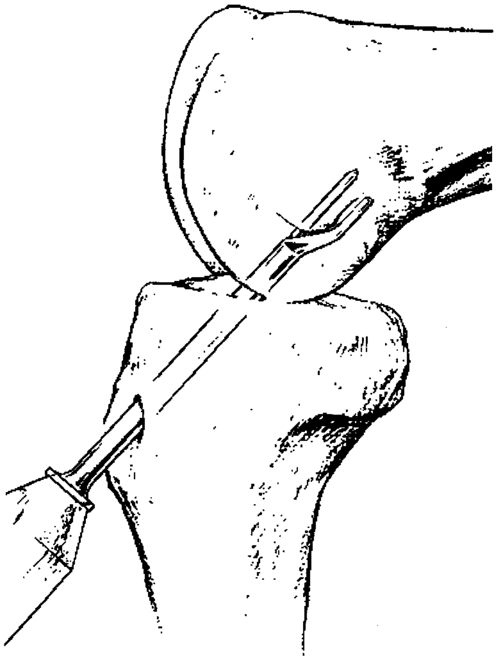

**Figure 1.** In the single-incision arthroscopic technique for ACL reconstruction, the femoral tunnel cannot be freely placed inside the intercondylar notch because the femoral guide is passed through the tibial tunnel. The similar diameters of the femoral aimer and tibial tunnel prevent independent placement of the femoral tunnel in both the sagittal (shown here) and coronal planes. Thus, the angle and position of the tibial tunnel may influence the placement of the femoral tunnel, and because femoral tunnel placement determines the tensile behavior of the graft, the stability of the knee may be determined by tibial tunnel placement.

nosus and gracilis tendon graft during passive motion when the femoral tunnel was placed using the single-incision arthroscopic technique and to determine whether this technique provided a pattern of graft tension that was similar to that of the normal ACL.

Free placement of the femoral tunnel cannot be achieved with the single-incision arthroscopic technique because the femoral drill guide and reamer are inserted through the tibial tunnel.[6,10–12] The maneuverability of these two instruments is limited because the tibial tunnel is relatively long (40 to 55 mm) and the diameter of the instruments is similar to that of the tibial tunnel (8 to 10 mm). It follows that the placement of the tibial tunnel may influence the placement of the femoral tunnel. Therefore, the second objective was to determine if the placement of the tibial tunnel (that is, angle and position in the sagittal and coronal planes) is predictive of the tensile behavior of the graft.

Assuming that the placement of the tibial tunnel was predictive of graft force, then a more anatomic placement of the tibial tunnel might restore normal tensile behavior to the graft. To determine if the tibial tunnel was properly placed in grafts with either normal or abnormal tensile behavior, a criterion for an anatomically placed tibial tunnel had to be established. In the sagittal plane, the criterion for anatomic tibial tunnel placement has been derived from MRI studies of knees with intact ACLs,[9,25] but no criterion has been established for the coronal plane. Therefore, the third objective of this study was to first determine the criterion for anatomic placement of the tibial tunnel in the coronal plane using MRI and then to determine whether the tibial tunnels were placed anatomically in knees where the grafts demonstrated normal or abnormal behavior.

Although it has been suggested that the outcome of ACL reconstructions may be improved if the tension in the graft replicates the normal tensile behavior of the ACL,[17] this has not been proven. The fourth and final objective of this study was to determine if the tensile behavior of the graft was predictive of the stability of the reconstructed knee at 1 year.

## MATERIALS AND METHODS

Graft tension was measured intraoperatively on 13 men and 1 woman requiring reconstruction for torn ACLs between December 1994 to March 1995. The mean patient age at the time of the operation was 26 years (range, 15 to 34). All patients had been athletically active before the injury; 10 had been injured during a noncontact, deceleration maneuver on a planted foot (71%), and 4 had been injured in collisions (29%). At the time of operation, 4 of the 14 subjects had had a previous knee operation. Two subjects each had had an arthroscopic partial medial meniscectomy, one had had an arthroscopic partial medial and lateral meniscectomy, and one had had an open ACL repair with a partial medial meniscectomy. Five reconstructions were performed within 6 months of injury, and nine were performed later (mean, 41 months; range, 1 to 153). Both acute and chronic knee injuries were included in this study because there is no significant difference in the stability of the reconstructed knees between these two groups at 2 years.[13] All subjects agreed to participate in the study and signed consent forms approved by the Human Subjects Review Board at Methodist and Mercy Hospitals, Sacramento, California, and University of California, Davis, California.

### Operative Technique and Acquisition of Intraoperative Data

The semitendinosus and gracilis tendons were harvested and a suture (No. 5 Ti-Cron, Davis and Geck, Danbury, Connecticut) was sewn to each end of each tendon. The midpoint of each tendon was looped over a suture to form a four-bundle graft. The graft was sized by drawing it through a series of cylinders (Arthrotek, Inc., Warsaw, Indiana). The diameter of the smallest cylinder that freely passed over the four-bundle graft was used as the basis to select the reamer for drilling the tibial and femoral tunnels.

Before drilling the tibial and femoral tunnels, the menisci were inspected arthroscopically and tears were either repaired or partially excised. A previously described technique was used to reconstruct the knee.[11] Briefly, the placement of the tibial tunnel in the sagittal plane was customized for variability in knee extension and roof angle and a roofplasty was performed to avoid roof impingement. The femoral tunnel was placed by inserting a femoral guide through the tibial tunnel (Size-Specific Femoral Guide, Arthrotek, Inc.). The femoral guide had a tongue-like extension that was hooked posterior to the intercondylar roof in the over-the-top position. This extension centered the femoral tunnel 5 to 7 mm distal to the proximal edge of the intercondylar roof at approximately the 11-o'clock position for the right knee and at approximately the 1-o'clock position for the left knee. A 25-mm-long, closed-end femoral tunnel was drilled. The thickness of the posterior wall of the femoral tunnel was inspected with a probe and measured.

A fixation device (Bone Mulch Screw, Arthrotek, Inc.) was inserted through the lateral femoral condyle until the tip of the device crossed the femoral tunnel (Fig. 2). The midpoint of each tendon was looped over the beam with the free ends of each bundle exiting the tibial tunnel.[6,11,12,28]

A frame supporting four load cells (Precision Measurements, Ann Arbor, Michigan) was fixed to the tibia to measure graft tension (Fig. 3). Each load cell measured tension from 0 to 150 N. Each bundle was attached to a load cell by passing the suture through the end of the load cell and out its side and clamping it with a hose clamp. The connection resisted slippage up to 120 N. The accuracy and error analysis of this system has been previously reported and the error of the graft tension measurement was less than 10%.[27,28]

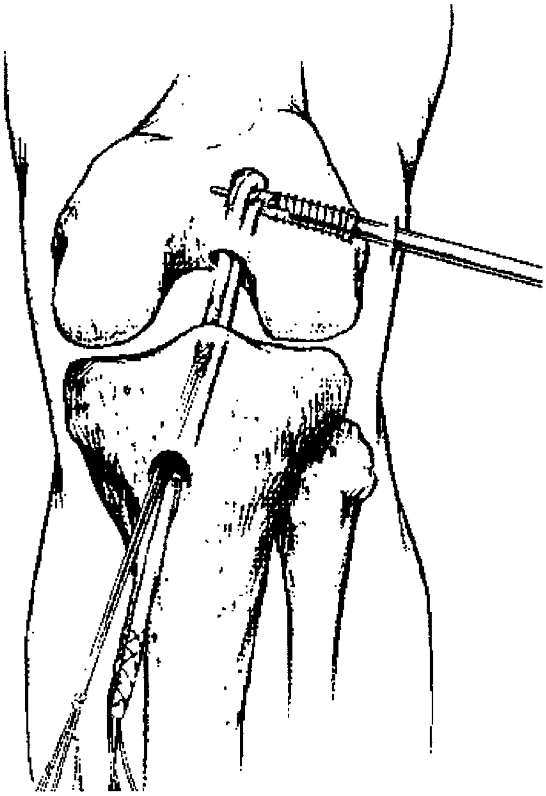

**Figure 2.** The tip of the fixation device spanned the femoral tunnel. Gracilis and semitendinosus tendons were passed around the tip of the device to form a four-bundle graft. Sutures attached to the ends of each tendon extended outside the tibial tunnel and were used to attach the tendons to the load cells (Fig. 3).

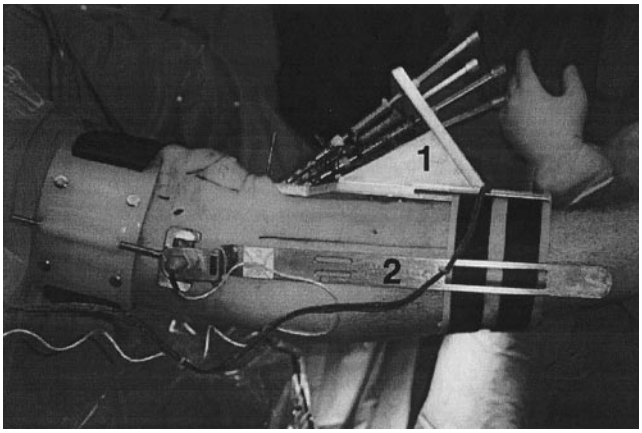

**Figure 3.** In the experimental setup for measuring graft tension and knee flexion angle intraoperatively, the frame (1), containing four load cells connected to manual adjustment screws, was fixed directly to the tibia with two pins. The suture, attached to a graft bundle, was clamped to a load cell and the screw was used to adjust manually the tension in the bundle. The output from the load cells and the electrogoniometer (2) were connected to a computer, allowing simultaneous measurement of the graft tension and flexion angle.

The method for passively moving the knee was standardized. The surgeon supported the posterior tibia just proximal to the ankle and extended the knee until resistance was felt (that is, until full extension). Gravity was then used to flex the knee to 90° while the posterior tibia was supported. An electrogoniometer (made in our laboratory) measured the flexion angle. The knee was neither manually compressed, distracted, rotated, nor angulated during passive flexion.

The flexion angle for pretensioning the graft was chosen so that each bundle retained tension during passive motion of the knee from 0° to 90°. Each bundle was pretensioned to 20 N at 30° of flexion. The motion arc where the tension in the graft was lowest was determined. The flexion angle closest to full extension within this motion arc was used as the flexion angle to set the graft tension (range, 25° to 40°). The knee was positioned at this selected flexion angle and each bundle was tensioned to 5 N. The knee was cycled 10 times to precondition the graft. The tension in each bundle was restored to 5 N and the tension and flexion angle were simultaneously recorded by a personal computer while the knee was cycled eight more times.

After removal of the load cells, the graft bundles were secured to the tibia under a 20-mm-diameter soft tissue washer. Two of the four bundles were wrapped 180° clockwise and the other two counterclockwise around a 4.5-mm cortical screw. Two assistants applied an unmeasured tension to each of the four bundles with the knee in maximum extension while the surgeon tightened the screw to compress the washer. Bone was compacted into the femoral tunnel through a bore in the femoral fixation device to fill voids between the tendon and wall of the femoral tunnel.[6,11,12,28]

### Rehabilitation Program

The knee was rehabilitated without either immobilization or bracing.[10,12,13] Patients were instructed to bear weight as tolerated, to begin unrestricted closed and open kinetic chain knee extension exercises at week 4, to resume straight-line running at week 8 to 10, and to return to unrestricted activities and sports 4 months after surgery. All patients discarded their crutches within 4 weeks of surgery. A physical therapist supervised the rehabilitation of six patients. Eight patients performed the rehabilitation without supervision. Patients were released to unrestricted activities 4 months after surgery.

### Stability and Clinical Outcome

One of the coauthors (MLD) assessed the clinical outcome 1 year after the procedure without knowing either the placement of the tibial tunnel or the graft tension. Stability was measured at 1 year because it was assumed to be predictive of long-term stability. This assumption was based on previous studies that have shown that the stability at 2 years is predicted by laxity measurements at 3,[24] 4,[10,13] and 6 months[21] after surgery. A continuous measurement of stability was required to statistically compare tibial tunnel placement with stability. The treated knee was defined as unstable when it had a 3-mm or greater increase in anterior displacement compared with the contralateral knee, measured by a KT-1000 arthrometer (MEDmetric, San Diego, California) during a manual maximum anterior drawer test applied to the tibia with the knee in 20° to 30° of flexion. The manufacturer of the arthrometer uses this difference to determine whether an injured knee has a torn ACL.[2,3] The interobserver reliability of laxity testing using this instrument in our clinical setting has been previously reported.[13]

The level of activity to which the patient returned, the distance attained in the single-legged hop test, the results recorded on the International Knee Documentation Committee (IKDC) form, and differences in thigh girth, extension, and flexion were determined as described previously.[13]

### Roentgenographic Assessment

Another coauthor (SMH) measured the placement (angle and position) of the tibial tunnel from a lateral roentgenogram of the fully extended knee and an AP roentgenogram of the intercondylar notch obtained 1 year after surgery. The interobserver reliability of these measurements in the sagittal plane has previously been described.[7] The plane of the articular surface of the tibia was defined by a line between the most superior points of the anterior and posterior margins and one between the medial and lateral margins of the proximal end of the tibia.

In the sagittal plane, the position of the axis of the tibial tunnel was calculated by extending the center axis of the tibial tunnel to its intersection with the anteroposterior line of the tibial plateau; the distance from this intersection to the anterior end of the line was then measured (Fig. 4). This distance was divided by the length of the anteroposterior line of the tibial plateau, and the result expressed as a percentage. Impingement of the graft by the intercondylar roof was considered to have been avoided when the anterior border of the tibial tunnel was either in line with, or 1 to 2 mm posterior to, the point of intersection of the line of the slope of the intercondylar roof with the plane of the articular surface of the tibial plateau.[7,13,14] The angle of the tibial tunnel was measured as the angle subtended by the axis of the tibial tunnel and its intersection with the anteroposterior line of the tibial plateau.

From the anteroposterior view of the intercondylar notch, the position of the center axis of the tibial tunnel in the coronal plane was calculated by extending the center axis of the tibial tunnel to its intersection with the mediolateral line of the tibial plateau; the distance from this intersection to the medial end of the line was then meas-

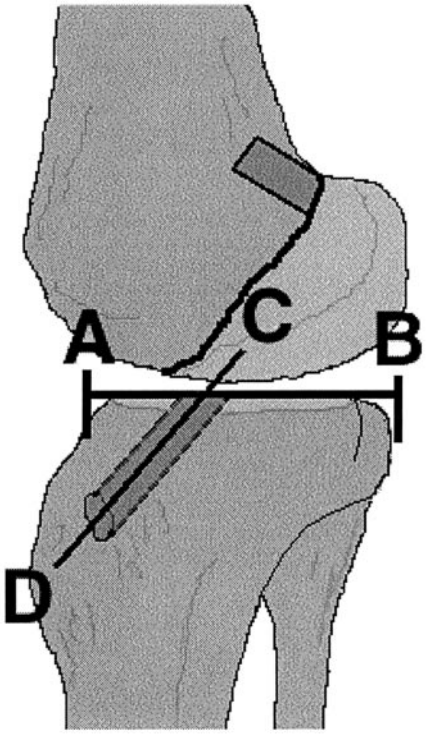

**Figure 4.** The position of the center of the tibial tunnel in the sagittal plane was determined by dividing the distance from the anterior edge of the tibia to the center of the tibial tunnel (AC) by the depth of the articular surface of the tibial plateau (AB), and multiplying by 100. The angle formed by ACD was defined as the angle of the tibial tunnel in the sagittal plane.

ured (Fig. 5). This distance was divided by the width of the mediolateral line of the tibial plateau, and the result expressed as a percentage. The position of the edges of the tibial tunnel with respect to the medial and lateral tibial spines was categorized as being medial to the medial spine, contained between the two spines, or lateral to the lateral spine. The angle of the axis of the tibial tunnel was measured as the angle subtended by the axis of the tibial tunnel and its intersection with the medial end of the mediolateral line of the tibial plateau.

### Angle and Position of the Native ACL in the Coronal Plane

The angle and position of the native ACL in the coronal plane were determined from control subjects using MRI (Fig. 6). Nine men and five women with an average age of 35 years (range, 17 to 64) who had no joint space narrowing, ligament injuries, or osteophytes underwent an MRI. Imaging was performed using a Signa scanner (General Electric Co., Milwaukee, Wisconsin) employing a 1.5-T magnet and a dedicated knee coil (Quadrature extremity coil, Medrad, Inc., Indianola, Pennsylvania). A previously described technique was used to obtain an oblique, sagittal image to localize the ACL from origin to insertion.[8] Next, an oblique coronal view of the ACL was obtained using a spin-echo technique with a repetition time of 450 ms and an echo time of 17 ms. Five, 3-mm-thick slices with a 1-mm gap were acquired using two signal acquisitions, a 16-cm field of view, and a 192 × 256 pixel matrix. The angle and position of the center of the ACL were determined using the previously described technique for determining the orientation of the tibial tunnel from the AP roentgenogram (Fig. 4).

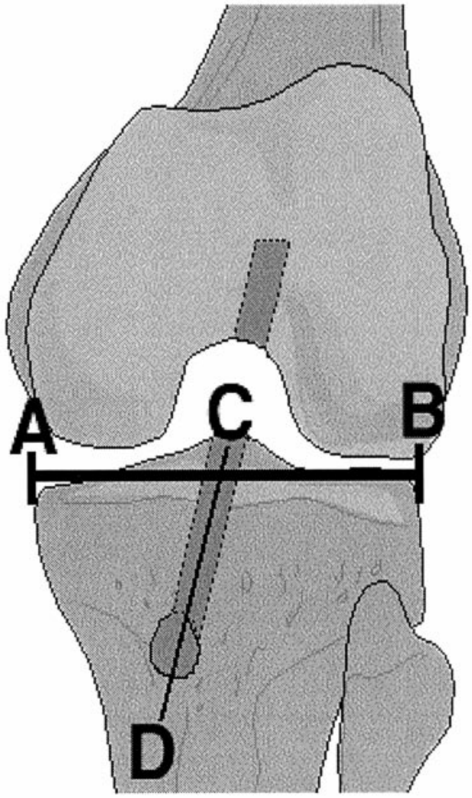

**Figure 5.** The position of the center of the tibial tunnel in the coronal plane was determined by dividing the distance from the medial edge of the tibia to the center of the tibial tunnel (AC) by the width of the articular surface of the tibial plateau (AB), and multiplying by 100. The angle formed by ACD was defined as the tibial tunnel angle.

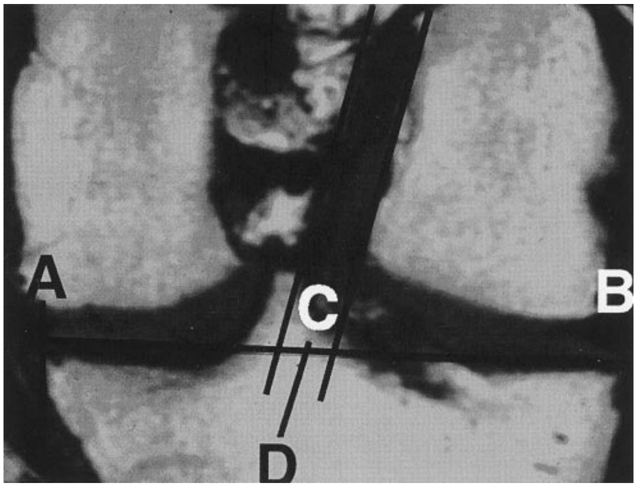

**Figure 6.** The position of the center of the native ACL in the coronal plane was determined by dividing the distance from the medial edge of the tibia to the center of the ACL (AC) by the width of the articular surface of the tibial plateau (AB), and multiplying by 100 (left knee). The angle formed by ACD was defined as the angle the normal ACL formed with the tibial plateau.

### Statistical Analysis

The total graft tension was computed for each subject by summing the tension in the four bundles at 10° increments from 0° to 80° of flexion for each cycle. At each of the nine flexion angles the total graft tension was averaged for the eight cycles to produce an average tension-flexion curve for the subject (Fig. 7).[28] Knees with a graft force greater than 40 N at 80° of flexion were considered to have abnormal tensile behavior. For all of the statistical analyses, the graft force at 80° of flexion was used as an indicator of the tensile behavior of the graft because when the forces in the graft are minimal at this flexion angle, tensile behavior is normal, and when the forces in the graft are greater than 40 N at this flexion angle, the tensile behavior is abnormal.[17]

To determine if any combination of the four tibial tunnel variables (that is, angle and position in the sagittal and coronal planes) was predictive of the tension in the graft at each flexion angle, three-dimensional surface plots were constructed to compare all pairs of tunnel variables to graft tension. Because no dependence was evident for any combination, simple regression was used to determine which of the four tunnel variables predicted graft tension

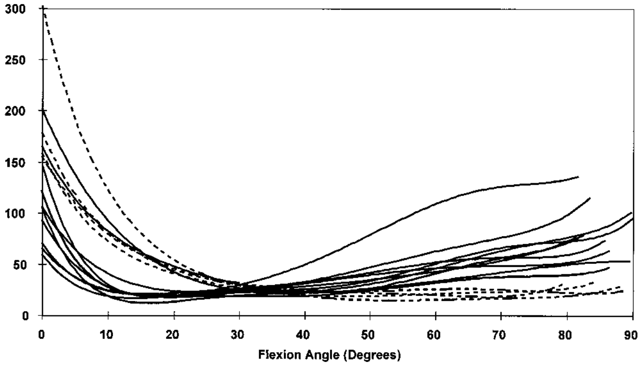

**Figure 7.** Comparison of the graft tensile behavior in 14 subjects. The tensile behavior was abnormal in 10 knees because the graft force increased with passive knee flexion (solid lines). The tensile behavior was normal in four knees because the graft force remained unchanged with knee flexion, that is, similar to that of the native ACL (dotted lines).

at 0° and 80° of flexion, where the greatest differences in graft tension were observed between the reconstructed knees. The threshold for statistical significance was set at $P \leq 0.05$.

To determine if the tibial tunnel was anatomically placed, the subjects were separated into two groups distinguished by whether the graft had normal or abnormal tensile behavior. For each group, unpaired Student's *t*-tests were used to compare the position of the tibial tunnel in the sagittal plane with the anatomic position of the ACL previously reported[9] and to compare both the angle and position of the tibial tunnel in the coronal plane with the angle and position of the native ACL determined from MRI. The threshold for statistical significance was set at $P \leq 0.05$.

To determine if the tensile behavior of the graft was predictive of the stability of the knee at 1 year, a regression analysis was used to relate the graft tension at 80° of flexion to the difference in anterior displacement between the operated and contralateral knee at a manual maximum force. The threshold for statistical significance was set at $P \leq 0.05$.

## RESULTS

### Operative Findings

Two subjects had isolated injuries to the ACL. Two subjects each had an intact medial meniscus with a lateral meniscal tear that was left alone in one subject and partially excised in one subject. Five subjects each had an intact lateral meniscus with a medial meniscal tear that had been partially excised previously in two subjects, repaired in one subject, left alone in one subject, and partially excised in the other subject. Five subjects had injuries to both the medial and lateral menisci; in one subject both menisci had previously been partially excised, in two subjects both menisci were partially excised at the time of reconstruction, in one subject the medial meniscus had previously been partially excised and the tear in the lateral meniscus was left alone, and in one subject both menisci were torn but left alone (Table 1). The medial and lateral collateral ligaments were intact in all knees.

The sagittal position of the femoral tunnel was characterized during arthroscopic examination by inspecting and measuring with a probe the thickness of the posterior wall of the femoral tunnel. The thickness ranged from 1 to 2 mm, indicating that the femoral tunnel was positioned as far posteriorly as possible without drilling through the back wall of the tunnel. The coronal position of the center of the femoral tunnel was controlled by inserting the guide pin into the roof of the notch at the 11-o'clock position for the right knee and the 1-o'clock position for the left knee.

TABLE 1
Characteristics, Intraoperative Findings, Stability, Outcome, and Graft Tension of 14 Subjects

| Age | Sex | Status of meniscus |  | Increase in anterior displacement, treated vs. untreated knee (mm) | IKDC grade[a] | Graft tensile behavior | Tibial tunnel placement[b] |  |  |  | Tension (N) |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Medial | Lateral |  |  |  | Sagittal angle (deg) | Sagittal position (%) | Coronal angle (deg) | Coronal position (%) | At 0° of flexion | At 80° of flexion |
| 24 | M | Excised | Normal | 3.5 | B | Abnormal | 73 | 46 | 87 | 47 | 61 | 130 |
| 29 | M | Stable | Normal | 0.5 | B | Normal | 77 | 44 | 75 | 46 | 151 | 30 |
| 31 | M | Normal | Normal | 1.5 | B | Abnormal | 75 | 43 | 70 | 43 | 74 | 68 |
| 24 | M | Repaired | Normal | 0.0 | B | Abnormal | 75 | 47 | 79 | 49 | 131 | 89 |
| 24 | W | Normal | Normal | 2.0 | B | Normal | 77 | 47 | 80 | 47 | 175 | 20 |
| 26 | M | Excised | Excised | 1.0 | A | Abnormal | 80 | 41 | 77 | 48 | 165 | 41 |
| 33 | M | Normal | Stable | 0.5 | B | Abnormal | 72 | 41 | 73 | 43 | 199 | 50 |
| 34 | M | Excised | Excised | 2.0 | B | Abnormal | 73 | 44 | 72 | 43 | 87 | 78 |
| 33 | M | Excised | Normal | 1.0 | A | Abnormal | 77 | 44 | 72 | 45 | 129 | 70 |
| 18 | M | Normal | Excised | 1.0 | B | Abnormal | 78 | 42 | 73 | 43 | 103 | 51 |
| 30 | M | Excised | Normal | 1.0 | B | Normal | 77 | 48 | 75 | 48 | 297 | 17 |
| 21 | M | Excised | Stable | 4.5 | B | Abnormal | 70 | 50 | 78 | 48 | 70 | 63 |
| 15 | M | Stable | Stable | 1.0 | A | Abnormal | 75 | 43 | 77 | 47 | 62 | 75 |
| 25 | M | Excised | Excised | 2.0 | B | Normal | 68 | 45 | 68 | 42 | 143 | 22 |

[a] International Knee Documentation Committee; A, normal; B, nearly normal.
[b] See text at "Roentgenographic Assessment" for method by which position was determined.

### Clinical Outcome

All 14 subjects had a firm endpoint on Lachman testing and no pivot shift. Arthrometric testing with the KT-1000 arthrometer indicated that 12 subjects had less than a 3-mm increase in anterior displacement of the treated knee compared with the contralateral knee during application of a manual maximum force. These knees were considered stable. Two subjects had an anterior displacement greater than 3 mm (3.5 and 4.5 mm, respectively) and, although designated as unstable knees on the basis of the arthrometric measurement, they lacked a pivot shift and were considered stable by the subjects. Although two knees in our study were unstable by arthrometric criteria, they were stable, functional knees according to outcome measures used in other studies.[21] Both "unstable" knees had abnormal graft tensile behavior with tensions of 68 and 130 N, respectively, at 80° of flexion.

Before injuring their knees, 13 subjects had participated in strenuous sports such as football, soccer, and basketball that required jumping, pivoting, and hard cutting maneuvers. Ten subjects returned to this level of function after the reconstruction. Three subjects returned to moderate activities such as heavy manual work, skiing, tennis, baseball, and volleyball. One subject participated in moderate activities both before the ACL injury and after reconstruction.

The treated leg had a reduction in thigh circumference compared with the contralateral thigh that averaged 1.6 cm (range, 3.5 cm less to 1 cm more than the contralateral thigh), a limitation of extension that averaged less than 1° (range, 0° to 3°), and a limitation of flexion that averaged 2.4° (range, 0° to 10°). On their treated legs, 12 subjects could jump more than 90% of the distance jumped on their contralateral legs. Based on the IKDC evaluation form, 3 knees were classified as normal and 11 knees as nearly normal.

### Either Normal or Abnormal Tensile Behavior Produced

The single-incision arthroscopic technique produced either normal or abnormal tensile behavior of the graft. The graft force increased similarly in all 14 subjects with passive extension. However, in 4 knees, the force in the graft did not increase with passive flexion, while in 10 knees the graft force did increase with passive flexion. The greatest variability in graft force occurred at 80° of flexion (Fig. 7). In four subjects, the tensile behavior of the graft was normal because the graft force at 80° of flexion was less than 40 N. In 10 subjects, the tensile behavior of the graft was abnormal because the graft force at 80° of flexion was greater than 40 N. The average graft force was 142 ± 59 N (range, 78 to 296) at 0° and 60 ± 30 N (range, 17 to 130) at 80° of flexion.

### Tibial Tunnel Placement Predictive of Tensile Behavior

Only the angle of the tibial tunnel in the coronal plane predicted the force in the graft at 80° of flexion ($r^2 = 0.438$, $P = 0.014$). High graft forces, indicative of abnormal graft tensile behavior, were associated with a tibial tunnel that was angled close to perpendicular to the tibial plateau. Lower graft forces, indicative of normal graft tensile behavior, were associated with a tibial tunnel that was angled more oblique to the tibial plateau. The tibial tunnel position in the coronal plane and the angle and position in the sagittal plane were not predictive of graft tension at 80° of flexion. None of the four tunnel placement variables predicted graft tension at 0° of flexion.

### Anatomic Tibial Tunnel Placement

In the sagittal plane, the tibial tunnel was placed anatomically and without roof impingement in all 14 knees. The center of the tibial tunnel (average, 45% ± 3%; range, 41% to 50%) was the same as the position recommended for centering the tibial tunnel (44% ± 2%)[9,25] based on MRI scans of the native ACL ($P = 0.259$). The angle of the tibial tunnel averaged 75° ± 3.3° (range, 68° to 80°). The anterior edge of the tibial tunnel was either in line or 1 to 2 mm posterior to the intersection of the slope of the intercondylar roof with the tibial plateau in every knee, verifying that the graft had been placed without roof impingement.[7–9,14,25]

In the coronal plane, the tibial tunnel was positioned anatomically in all 14 knees. There was no significant difference between the position of the tibial tunnel in knees with normal tensile behavior (average, 46% ± 3%; range, 42% to 48%) ($P = 0.439$) and knees with abnormal tensile behavior (average, 46% ± 3%; range, 43% to 49%) ($P = 0.337$) compared with the native ACL (average, 47% ± 2%; range, 43% to 51%). Both the width of the tibial tunnel and the width of the insertion of the ACL were always between the tibial spines. The angle of the tibial tunnel in the coronal plane was within normal anatomic limits in 13 of 14 knees. There was no significant difference between the angle of the tibial tunnel in knees with normal tensile behavior (average, 75° ± 5°; range 68° to 80°) ($P = 0.618$) and knees with abnormal tensile behavior (average, 75° ± 5°; range, 70° to 87°) ($P = 0.546$) compared with the native ACL (average, 76° ± 3°; range, 71° to 81°). The one knee with nonanatomic placement had an angle of the tibial tunnel in the coronal plane of 87°, abnormal tensile behavior, the highest tension at 80° of flexion (130 N), and a 3.5-mm increase in anterior laxity compared with the normal knee.

### Graft Force Not Predictive of Later Knee Stability

There was no significant relationship between the force in the graft at 80° of flexion and stability in the reconstructed knee at 1 year ($r^2 = 0.119$, $P = 0.249$). The stability was the same for knees with normal (1.4 ± 0.7 mm) and abnormal (1.6 ± 1.4 mm) tensile behavior of the graft ($P = 0.768$).

## DISCUSSION

The objectives of this study were to determine if the double-looped semitendinosus and gracilis tendon grafts inserted using the single-incision arthroscopic technique had normal or abnormal tensile behavior, whether the placement of the tibial tunnel predicted the tensile behavior of the graft, whether the tibial tunnel was placed nonanatomically in knees with abnormal tensile behavior, and whether the tensile behavior determined the stability of the reconstructed knee at 1 year. Before discussing the findings from this study, a critical examination of the experimental techniques is warranted to determine how the methodology may have affected the interpretation of the results.

## Methodologic Issues

Although there was considerable variability in the maximum force of the graft with the knee in full passive extension, this variability was expected based on the tensile behavior of the native ACL. After subtracting the 20 N of pretension, the force in the graft with the knee in passive full extension ranged from 58 to 276 N (average, 122 ± 62 N; $N = 14$). The force in the native ACL in passive full extension ranged from 50 to 240 N (average, 118 ± 30 N; $N = 17$)[18] and was not significantly different from that in the graft ($P = 0.816$). Therefore, the variability in tension in the double-looped semitendinosus and gracilis tendon graft and that of the native ACL in full extension was nearly identical. The cause of this variability is unknown but may be related to differences in kinematics among knees.

Our inability to measure the tension in the graft after fixation did not change the conclusion that the tensile behavior of the graft did not predict the stability of the reconstructed knee at 1 year. Although increasing the pretension increased the forces in the graft at each flexion angle,[17, 29] the shape of the tension-flexion curve was unaffected by the pretension applied to the graft. Therefore, the tensile behavior of the graft could not be changed either from a normal to an abnormal pattern or from an abnormal to a normal pattern by changing the pretension in the graft.

It is unlikely that the tensile behavior of the graft was affected by whether a meniscus was intact or partially excised. If the tensile behavior of the graft was determined by the condition of the meniscus, then the knees in which the graft had normal tensile behavior should have had a normal medial meniscus. Of the four knees in this study with normal tensile behavior of the graft, the medial meniscus was partially excised in two, and a stable tear was left alone in one. Therefore, an intact medial meniscus was not required for normal tensile behavior. Furthermore, Markolf et al.[17] observed grafts with normal tensile behavior and grafts with abnormal tensile behavior in ACL-reconstructed cadaveric knees with intact menisci. Therefore, the condition of the menisci does not seem to determine the tensile behavior of the graft.

Although it was of interest to test the hypothesis of Markolf et al. that the tension rise in flexion was related to placement of the femoral tunnel, this was impractical because of difficulties in accurately determining femoral tunnel placement. The thickness of the posterior wall and the orientation in the coronal plane of the femoral tunnel were recorded during arthroscopic surgery, but the placement of the femoral tunnel could not be confirmed postoperatively. Consistent with the experience of others, neither the angle nor the position of the femoral tunnel could be reliably measured from roentgenograms.[23] The problem was further complicated by the indistinct outline of the femoral tunnel, which may have been affected by the compaction of cancellous bone into the femoral tunnel through the femoral fixation device. Furthermore, the placement of the femoral tunnel could not be defined in a pilot study using computerized tomography and MRI because image artifacts from the femoral fixation device obscured the margins of the tunnel.

## Interpretation of Results

This study demonstrated that the in vivo force of a double-looped semitendinosus and gracilis graft has either normal or abnormal tensile behavior when the graft is implanted using the single-incision arthroscopic technique. Positioning and drilling the femoral tunnel through a tibial tunnel resulted in abnormal tensile behavior in 10 of 14 grafts because the force in the graft was greater than 40 N at 80° of flexion. The increase in graft force with knee flexion was considered abnormal because these forces were higher at 80° of flexion than the forces in the ACL.[17]

Since the single-incision arthroscopic technique resulted in two different patterns of graft tension, the next step was to determine if the placement of the tibial tunnel (that is, position and angle) predicted the tensile behavior of the graft. The tension in the graft at 80° of flexion was predicted by the angle of the tibial tunnel in the coronal plane. Therefore, the angle of the tibial tunnel in the coronal plane can be used to predict whether the graft will have either normal or abnormal tensile behavior. However, since the cause of the abnormal increase in graft force in 80° of flexion was not determined, it would be incorrect to assume that the tensile behavior of the graft can be controlled by adjusting the angle of the tibial tunnel in the coronal plane. Furthermore, because the tibial tunnel was placed anatomically (as indicated by MRI) in the coronal plane in 9 of the 10 reconstructed knees that exhibited elevated tensions with flexion and in the sagittal plane in all of the reconstructed knees that exhibited elevated tensions, the tension rise with flexion was not related to nonanatomic placement.

Although a correlation was demonstrated between the angle of the tibial tunnel in the coronal plane and graft tension at 80° of flexion, the cause of the abnormal tensile behavior remains unknown. The type of graft and whether the tunnels were placed using a single-incision arthroscopic or two-incision technique do not appear to be causative factors. Both normal and abnormal tensile behavior have been observed with a bone-patellar tendon-bone graft implanted using a two-incision technique in vitro. Markolf et al.[17] hypothesized that the increase in graft tension with flexion was caused by anterior placement of the femoral tunnel. It was suggested that the premature tension increase with flexion could be prevented with more accurate femoral tunnel placement.

Although the placement of the femoral tunnel could not be quantified using imaging techniques, two reasons can be offered to explain why neither inconsistent placement nor anterior positioning of the femoral tunnel was a likely cause of the tension increase in the graft with flexion in our study. First, the placement of the femoral tunnel was verified arthroscopically and was the same for each case in both the sagittal and coronal planes. In the sagittal plane, the thickness of the posterior wall of the femoral tunnel was 2 mm or less, indicating that the tunnel was positioned as far posteriorly as possible. In the coronal plane, the guide wire entered the intercondylar roof at the 11-o'clock position for the right knee and at the 1-o'clock position for the left knee. Second, the tensile behaviors of the anterior and posterior bundles, which were measured in the same subjects and reported in another study, were observed to replicate the reciprocal behavior of the anteromedial and posterolateral bands of the native ACL.[28] For reciprocal tensile behavior to occur, the femoral tunnel had to be positioned consistently. A posterior position would have caused the tension in all four bundles to increase in extension but not in flexion. An anterior position would have caused the tension in all four bundles to increase in flexion but not in extension. For the anterior bundles to tighten in flexion and the posterior bundles to tighten in extension, the femoral tunnel had to be positioned partially anterior and posterior to the isometric point on the femur.[28] Therefore, anterior positioning of the femoral tunnel and reciprocal tensile behavior of the graft cannot coexist. The cause of the abnormal tensile behavior of the graft in our study could not have been anterior positioning of the femoral tunnel.

Assuming that there is a preventable cause for the abnormal tensile behavior of the graft, it remains to be determined whether it is necessary to avoid this tension pattern when implanting the graft. The findings of Tohyama et al.[26] in a study of elongation of a bone-patellar tendon-bone graft in the canine knee suggest that abnormal tensile behavior should be avoided. These authors demonstrated significantly more anterior laxity and less stiffness in canine knees with grafts that had greater graft elongation with flexion than the native ACL. They believe that the graft elongation behavior at the time of reconstruction is a critical factor that influences the long-term success of ACL reconstruction.

While we agree that replicating the tensile behavior of the native ACL is ideal, it must be understood that the stability and clinical success of our patients at 1 year was not predicted by the tensile behavior of the graft. However, stability may have been affected either by the intraarticular tension in the graft immediately after final fixation or by an interaction between the intraarticular tension and the placement of the tibial tunnel. Unfortunately, these two factors could not be evaluated because the intraarticular tension in the double-looped semitendinosus and gracilis tendon graft could not be measured after graft fixation was completed. Nevertheless, the application of an unmeasured pretension to the graft with the knee in full extension has been shown to be effective in restoring stability in 90% (37 of 41)[13] and 91% (61 of 67)[10] of reconstructed knees using this graft. Any inconsistency in intraarticular graft tension between knees does not alter the conclusion that the graft tension at 80° of flexion does not predict the stability of the reconstructed knee at 1 year.

The tension in the grafts with abnormal tensile behavior at 80° to 90° of flexion is likely an underestimation of the tension in the graft with the knee in full flexion. The maximum tension in the native ACL[30] and in an ACL graft[1] past 10° to 20° of flexion occurs with the knee in full flexion, not between 50° and 90°. Furthermore, the change in length or tension of a graft may be proportionally greater from 90° to 140° than from 0° to 90°.[1]

Neither our study that used a double-looped semitendinosus and gracilis tendon graft and a single-incision arthroscopic technique nor the study of Markolf et al.[17] that used a bone-patellar tendon-bone graft and a two-incision technique identified the cause of the abnormal tensile behavior of the graft. Proving that the cause is the angle of the tibial tunnel in the coronal plane will require an in vitro study in which the tibial tunnel is placed anatomically in the sagittal plane without roof impingement, the position of the tibial tunnel in the coronal plane is anatomically placed, a common femoral tunnel is used, and the angle of the tibial tunnel in the coronal plane is varied, showing that the tension rise in flexion is directly related to the angle of the tibial tunnel. If customizing the angle of the tibial tunnel in the coronal plane is shown to prevent the abnormal tensile behavior of the graft, then predicting the angle required for establishing normal tensile behavior for a given knee and accurately orienting the desired angle intraoperatively will be technically challenging.

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