

EFFECT OF THE ANGLE OF THE FEMORAL AND TIBIAL TUNNELS IN THE CORONAL PLANE AND INCREMENTAL EXCISION OF THE POSTERIOR CRUCIATE LIGAMENT ON TENSION OF AN ANTERIOR CRUCIATE LIGAMENT GRAFT: AN IN VITRO STUDY

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Background: High tension in an anterior cruciate ligament graft adversely affects both the graft and the knee; however, it is unknown why high graft tension in flexion occurs in association with a posterior femoral tunnel. The purpose of the present study was to determine the effect of the angle of the femoral and tibial tunnels in the coronal plane and incremental excision of the posterior cruciate ligament on the tension of an anterior cruciate ligament graft during passive flexion.

Methods: Eight cadaveric knees were tested. The angle of the tibial tunnel was varied to 60°, 70°, and 80° in the coronal plane with use of three interchangeable, low-friction bushings. The femoral tunnel, with a 1-mm-thick posterior wall, was drilled through the tibial tunnel bushing with use of the transtibial technique. After the graft had been tested in all three tibial bushings with one femoral tunnel, the femoral tunnel was filled with bone cement and the tunnel combinations were tested. Lastly, the graft was replaced in the 80° femoral and tibial tunnels, and the tests were repeated with excision of the lateral edge of the posterior cruciate ligament in 2-mm increments. Graft tension, the flexion angle, and anteroposterior laxity were recorded in a six-degrees-of-freedom load-application system that passively moved the knee from 0° to 120° of flexion.

Results: The graft tension at 120° of flexion was affected by the angle of the femoral tunnel and by incremental excision of the posterior cruciate ligament. The highest graft tension at 120° of flexion was 169 ± 9 N, which was detected with the graft in the 80° femoral and 80° tibial tunnels. The lowest graft tension at 120° of flexion was 76 ± 8 N, which was detected with the graft in the 60° femoral and 60° tibial tunnels. The graft tension of 76 N at 120° of flexion with the graft in the 60° femoral and 60° tibial tunnels was closer to the tension in the intact anterior cruciate ligament. Excision of the lateral edge of the posterior cruciate ligament in 2 and 4-mm increments significantly lowered the graft tension at 120° of flexion without changing the anteroposterior position of the tibia.

Conclusions: Placing the femoral tunnel at 60° in the coronal plane lowers graft tension in flexion. Our results suggest that high graft tension in flexion is caused by impingement of the graft against the posterior cruciate ligament, which results from placing the femoral tunnel medially at the apex of the notch in the coronal plane.

Clinical Relevance: For the surgeon who prefers the transtibial technique, the present study shows that controlling the angle of the tibial tunnel controls the angle of the femoral tunnel and the graft tension in flexion.

The outcome of anterior cruciate ligament reconstruction might be improved if the femoral and tibial tunnels are placed so that the graft tension replicates the tensile behavior of the intact anterior cruciate ligament^{1,2}.

Graft tension that is higher than that in the intact anterior cruciate ligament has consequences³, including excessive graft wear at the femoral tunnel⁴, poor vascularity, myxoid degeneration, inferior mechanical properties of the graft^{5,6}, posterior

subluxation of the tibia⁷⁻¹⁰, and inhibited knee extension⁷.

High graft tension in flexion has been observed in knees that have been reconstructed with a bone-patellar tendon-bone graft and in those that have been reconstructed with a double-looped semitendinosus and gracilis graft. Placing the femoral tunnel posteriorly and placing the tibial and femoral tunnels with use of an isometer do not prevent high graft tension in flexion^{3,11-13}. Although high graft tension in flexion is commonly observed in association with a posterior femoral tunnel, we found no studies that determined its cause¹¹.

Chance observations of several failed anterior cruciate ligament grafts during arthroscopy suggested that the grafts might have stretched as a result of impingement against the lateral edge of the posterior cruciate ligament during flexion. These observations suggested that medial placement of the femoral tunnel, which had resulted from drilling the femoral tunnel through a vertical tibial tunnel in the coronal plane, might have caused impingement of the graft against the posterior cruciate ligament, resulting in high graft tension in flexion. This theory led to the current study.

The purposes of the present study were to evaluate the transtibial technique and to determine the effects of the angles, of the femoral and tibial tunnels in the coronal plane and incremental excision of the posterior cruciate ligament on the tension of an anterior cruciate ligament graft during passive flexion. We tested the hypothesis that the angle of the femoral tunnel (60°, 70°, or 80°) and the angle of the tibial tunnel (60°, 70°, or 80°) in the coronal plane determine graft tension in flexion. We also tested the hypothesis that impingement of the graft on the posterior cruciate ligament is the cause of the increase in graft tension in flexion.

Materials and Methods

Specimen Selection

Eleven fresh-frozen cadaveric knees were evaluated radiographically, and three were excluded because they had evidence of degenerative arthritis or chondrocalcinosis. The eight remaining knees were used in the present study. These knees had been obtained from individuals who had been an average of sixty-three years old (range, forty-three to seventy-six years old) at the time of death. Inspection at the time of anterior cruciate ligament reconstruction revealed no evidence of moderate or severe degenerative arthritis or torn menisci.

Measurement of Extension and Limits of Motion of the Intact Knee

A six-degrees-of-freedom load-application system was used to determine reference positions of the tibia relative to the femur for each intact knee^{14,15}.

Each specimen was aligned with use of the functional axes method^{14,16}, in which the natural axes of joint motion are aligned with those of the load-application system. Accordingly, as the knee is moved in flexion-extension, coupled anterior-posterior and compression-distraction translations are virtually eliminated¹⁴.

A load cycle was applied at 0°, 30°, 60°, 90°, and 120° of

flexion to precondition the intact knee. Each load cycle consisted of the application of an anterior force from 0 to 250 N, removal of the anterior force, the application of a posterior force from 0 to 250 N, and removal of the posterior force. Each force was applied and removed in 50-N increments of load. This preconditioning protocol produces a repeatable load-displacement cycle¹⁴. Following preconditioning, a 2.5-Nm extension moment was applied to define 0° of knee extension¹⁷.

After preconditioning, each specimen was subjected to an anterior-posterior-anterior load cycle to determine two limits of motion at 30° of flexion¹⁸. A 45-N anterior force was applied to the tibia and then was removed in 15-N increments. A 45-N posterior force was then applied to the tibia and was removed in 15-N increments. The position of the tibia on the femur after removal of the 45-N posterior force defined the 0-N posterior limit, which was the reference position of the tibia relative to the femur without any load. Next, a 225-N anterior force was applied to the tibia. The position of the tibia on the femur at 225-N of anterior force defined the 225-N anterior limit, which was the reference position of the tibia relative to the femur under 225 N of anterior load.

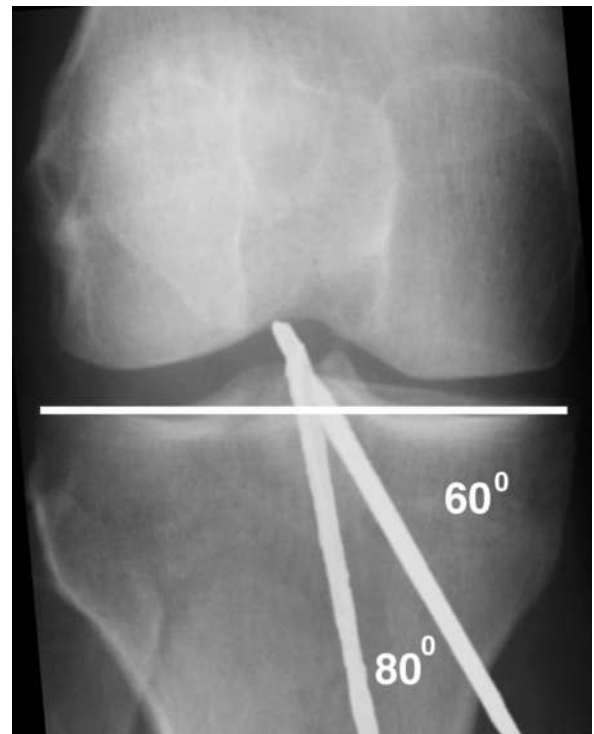


Fig. 1

Anteroposterior radiograph of a right knee, showing two guide-wires entering the knee between the medial and lateral tibial spines. One guide-wire formed an angle of 60° with the medial joint line, and the other formed an angle of 80°. Drilling over these two guide-wires with a 12-mm-diameter cannulated reamer created the wedge defect. Three interchangeable tibial bushings were inserted into the wedge defect to vary the angle of the tibial tunnel to 60°, 70°, and 80° in the coronal plane.

Graft Preparation

A double-loop tendon graft constructed from bovine extensor tendons was used to reconstruct the anterior cruciate ligament¹⁹. The graft was prepared by removing muscle and trimming the tendons until two tendons, folded in half side-by-side, fit snugly inside a 9-mm-diameter cylinder (Sizing Sleeves; Arthrotek, Warsaw, Indiana). The free ends of each tendon were sewn with 1-0 braided suture with use of a criss-crossing stitch to facilitate passage of the graft in the knee^{11,12}.

Technique for Placing and Changing the Angles of the Femoral and Tibial Tunnels

The knee was removed from the load-application system. Medial and lateral parapatellar incisions were made, and the patella and the patellar tendon were reflected distally. The joint was inspected, and the anterior cruciate ligament was excised. A wedge defect was created in the tibia to allow insertion of

three interchangeable tibial bushings that were used to vary the angle of the tibial tunnel in the coronal plane. The placement of two 2.4-mm-diameter guide-wires in the sagittal and coronal planes with use of a tibial drill-guide (Howell Tibial Guide; Arthrotek) determined the position of the wedge defect (Fig. 1).

In the sagittal plane, the tibial drill-guide was positioned against the intercondylar roof with the knee in full extension. The offset of the tip of the guide places the guide-wire 4 to 5 mm posterior and parallel to the slope of the intercondylar roof, which customizes the placement of the guide-wires in the sagittal plane for variability in knee extension and variability in the angle of the intercondylar roof and avoids roof impingement of the graft²⁰⁻²³. In the coronal plane, the tibial drill-guide was inclined to place one guide-wire at 60° and the other at 80° relative to the medial joint line of the tibia.

The placement of the guide-wires was assessed with use

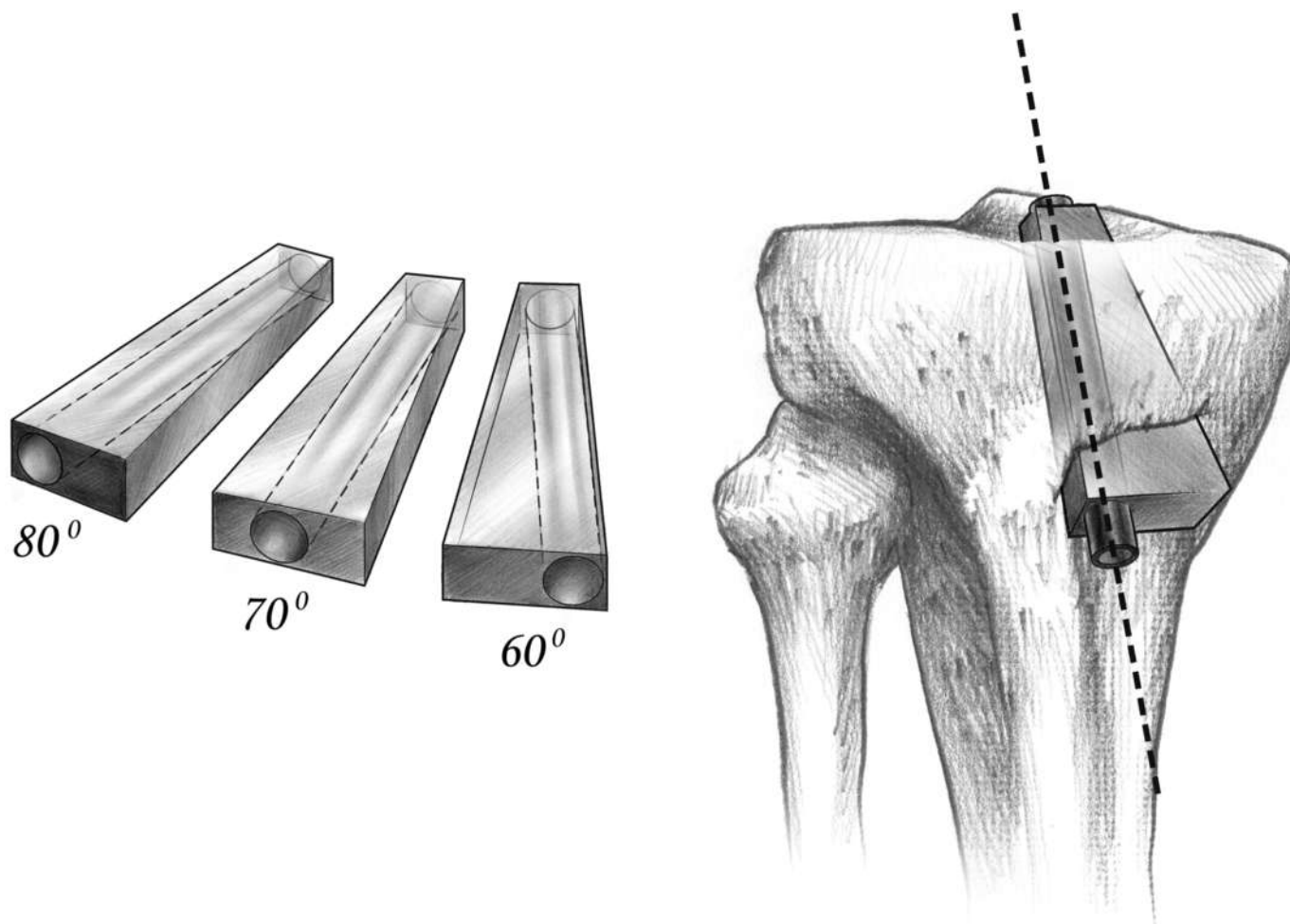


Fig. 2

A wedge defect was created in the tibia to allow insertion of three interchangeable tibial bushings that were used to vary the angle of the tibial tunnel to 60°, 70°, and 80° in the coronal plane. The illustration on the right shows the tibia with the 80° tibial bushing, which positions the graft more vertically in the coronal plane and results in more impingement against the posterior cruciate ligament during flexion than is the case when the 60° and 70° bushings are used. The cylinder inside the bushing (the axis of which is indicated by the dotted line) centered the femoral aimer in the tibial tunnel and was removed from the bushing before placement of the graft.

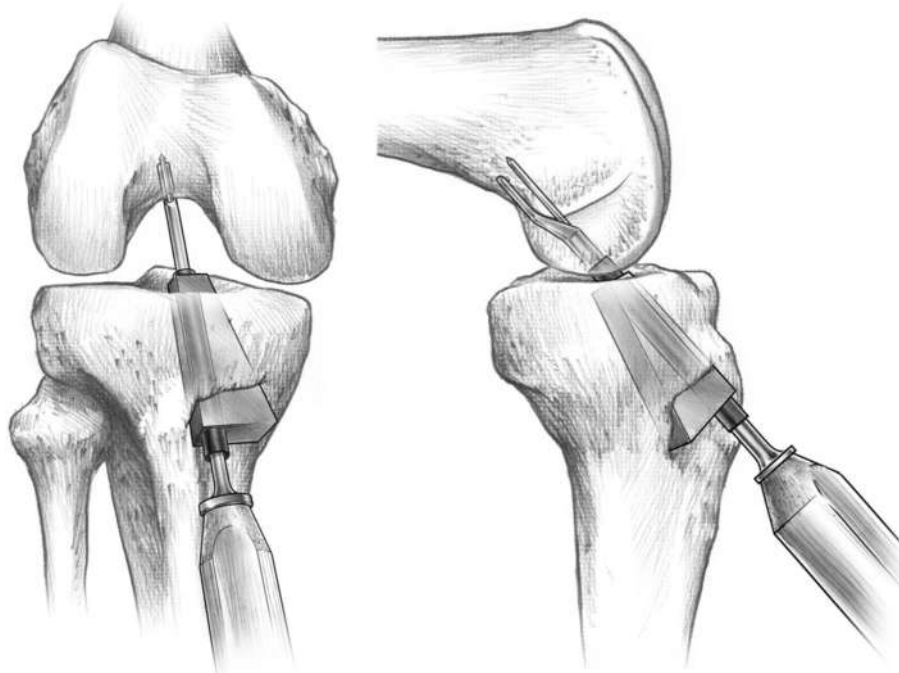


Fig. 3

The femoral tunnel was positioned by inserting a femoral aimer through the tibial tunnel in the tibial bushing. A hollow cylinder was placed around the shaft to center the femoral aimer in the tibial tunnel. The hook of the aimer was positioned in the over-the-top position, and a 2.4-mm guide-wire was drilled into the femur. The offset of the hook was 5.5 mm, which created a 1-mm posterior wall when the femoral tunnel was drilled with a 9-mm reamer.

of anteroposterior and lateral radiographs made with the knee in maximum extension. In the coronal plane, the three radiographic criteria for proper guide-wire placement were that (1) each guide-wire entered the intercondylar notch midway between the medial and lateral tibial spines, (2) one guide-wire formed an angle of 60° with the medial joint line of the tibia, and (3) one guide-wire formed an angle of 80° with the medial joint line of the tibia. In the sagittal plane, the radiographic criterion for proper guide-wire placement was that each of the guide-wires coursed 4 to 5 mm posterior and parallel to the slope of the intercondylar roof²³. The average angle (and standard deviation) between the guide-wire and the anterior joint line of the tibia was $58^\circ \pm 3.6^\circ$ in the sagittal plane.

Drilling over the two guide-wires with a 12-mm-diameter cannulated reamer created the wedge defect in the tibia. The bone bridging the two tunnels was removed. An aluminum wedge was impacted into the tibia. The walls of the wedge defect were reinforced with bone cement.

Three low-friction tibial bushings were machined from polytetrafluoroethylene (Teflon; Dupont, Wilmington, Delaware) to fit the wedge defect (Fig. 2). In each bushing, a 9-mm-diameter tibial tunnel was drilled at an angle of 60° , 70° , or 80° in the coronal plane. These three tibial tunnel angles represent the tunnel angles that have been reported in clinical studies^{11,24}. Changing the tibial bushing varied the angle of the tibial tunnel in the coronal plane. Shims were used to secure the tibial bushing in the wedge defect with use of a previously described technique²⁵.

We used the transtibial technique and drilled the femoral tunnel through the tibial tunnel. The angle of the femoral tunnel in the coronal plane was defined by the angle of the tibial bushing through which the femoral tunnel was drilled. Because we

were unable to devise a technique to vary the angle of the femoral tunnel with use of an interchangeable bushing, the graft tension was measured for the 60° , 70° , and 80° tibial tunnels at each femoral tunnel angle before the femoral tunnel was filled with bone cement and the subsequent femoral tunnel was drilled. The order of testing of the tibial tunnel angles at each femoral tunnel angle and the order of testing of the femoral tunnel angles were selected with use of randomization protocols.

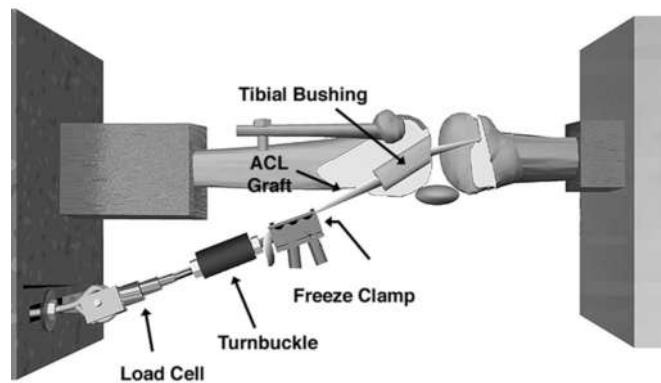


Fig. 4

Diagram of the reconstructed knee, which is placed prone for testing in the load-application system (not shown). The anterior cruciate ligament graft was looped over a 4-mm-diameter steel fixation post that bisected the cross section of the femoral tunnel (not shown). The graft was passed through an interchangeable tibial tunnel bushing made of low-friction Teflon. The free end of the graft was gripped in a freeze-clamp that was attached with a turnbuckle to a tension load-cell. Turning the turnbuckle changed graft tension and adjusted the anterior laxity of the knee at 30° of flexion.

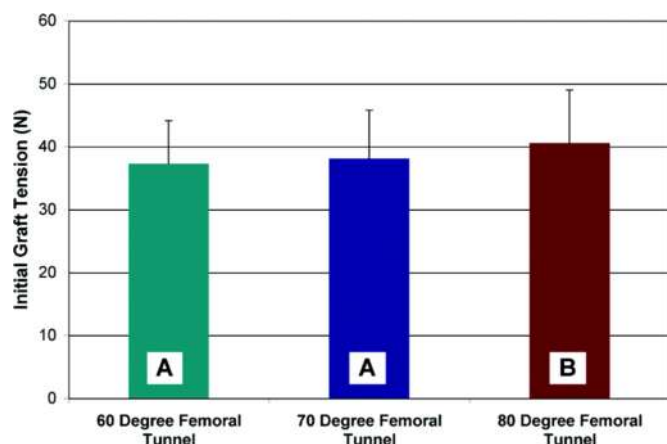


Fig. 5

The angle of the femoral tunnel ($p = 0.0007$), but not the angle of the tibial tunnel ($p = 0.09$), affected the initial graft tension used to restore anterior laxity at 30° of flexion at 225 N of anterior force. The initial graft tension associated with an 80° femoral tunnel (41 N) was 3 N greater than the initial graft tension associated with a 70° femoral tunnel (38 N) ($p = 0.031$) and 4 N greater than the initial graft tension associated with a 60° femoral tunnel (37 N) ($p = 0.021$); however, there was no difference in the initial graft tensions associated with reconstructions that involved 70° and 60° femoral tunnels ($p = 0.4327$). The error bars indicate one standard deviation. (The columns with different letters [i.e., A or B] are significantly different.)

The placement of the femoral tunnel was determined by inserting a femoral aimer through the tibial tunnel (Fig. 3). The femoral aimer was centered in the tibial tunnel by placing a hollow cylinder with an 8.5-mm outside diameter around the 6-mm-diameter shaft of the femoral aimer. The size of the offset of the femoral aimer was specific for the diameter of the

femoral tunnel so that the posterior wall was no more than 1 mm thick. We used a 9-mm femoral aimer that had a 5.5-mm offset (Size-Specific Femoral Aimer; Arthrotek). The tongue-like extension of the femoral aimer was hooked posterior to the intercondylar roof in line with the axis of the tibial tunnel. Gravity flexed the knee until the femoral aimer locked into position. The flexion angle at which the femoral aimer locked into position varied between knees (range, 65° to 90°) and was determined by the orientation of the tibial tunnel and the geometry of the knee. A 2.4-mm guide-wire was drilled into the femur in line with the axis of the tibial tunnel. A 35-mm-long closed-end femoral tunnel was drilled with a 9-mm cannulated reamer. The walls of the femoral tunnel were reinforced with bone cement.

The double-looped tendon graft was fixed inside the femoral tunnel by looping both tendons around a 4-mm-diameter steel rod that spanned the metaphysis of the femur. The steel rod was positioned in a 10-mm-diameter transverse tunnel that was drilled inside the femoral tunnel with use of a guide (U-Shaped Drill Guide; Arthrotek). The steel rod was centered in a column of bone cement that filled the transverse tunnel with use of a previously described technique²⁶.

Measurement of Graft Tension and Flexion Angle for Nine Femoral and Tibial Tunnel Angle Combinations

After the first femoral tunnel had been prepared, the tibial bushing was removed and a randomly selected tibial bushing was fixed in the wedge defect with shims. The double-loop tendon graft was passed through the femoral and tibial tunnels and was looped around the 4-mm-diameter steel rod. The reconstructed knee was replaced in the load-application system, and the free ends of each tendon exiting the tibial tunnel were tensioned equally and were gripped with a liquid nitro-

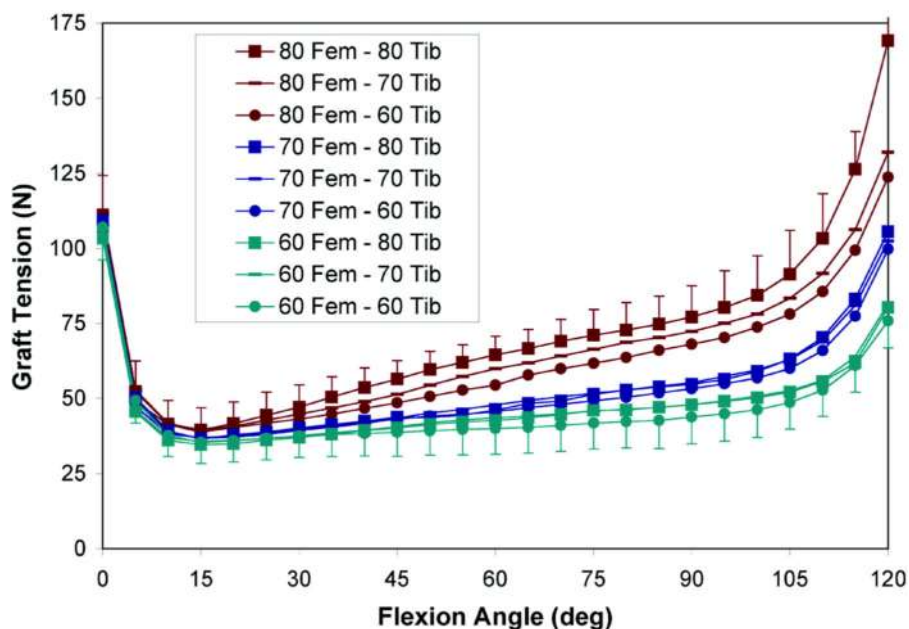


Fig. 6

The tension in the anterior cruciate ligament graft from 0° to 120° of flexion is displayed for each femoral and tibial tunnel angle combination. Graft tension at 120° of flexion was different among the 60° , 70° , and 80° femoral tunnels ($p < 0.0001$). The lowest graft tension at 120° of flexion was associated with the 60° femoral tunnel.

gen freeze-clamp (Fig. 4). The freeze-clamp was attached to a turnbuckle, which was attached to a tension load-cell (model L1650; Futek, Irvine, California), which was connected to a steel plate. The load-cell had a maximum rating of 445 N and an imprecision of ± 0.5 N. Turning the turnbuckle applied the initial graft tension.

For each tunnel angle combination, the reconstructed knee was preconditioned, with use of the same protocol that had been used for the intact knee, after the application of a 150-N load to the graft with the knee in full extension. After preconditioning, the initial tension of the reconstructed knee was adjusted until the 225-N anterior limit matched that of the intact knee at 30° of flexion. The load-application system passively moved the knee from full extension to 120° of flexion while graft tension, the flexion angle, and the anteroposterior position of the tibia relative to the femur were recorded in 0.1-N, 1°, and 0.1-mm increments, respectively. After testing of all three tibial tunnels with one of the femoral tunnels, the femoral tunnel and the transverse tunnel containing the steel rod were filled with bone cement. The reconstruction and the tests described above were repeated for the other two femoral tunnel angles, which were selected at random.

Measurement of Graft Tension, Flexion Angle, and Anteroposterior Position of the Tibia After Incremental Excision of the Posterior Cruciate Ligament

To determine the effect of incremental excision of the posterior cruciate ligament on graft tension, the knee was reconstructed with use of the 80° femoral and 80° tibial tunnels. This tunnel angle combination was chosen because it was associated with the greatest graft tension at 120° as well as with the greatest visible impingement of the graft against the posterior cruciate ligament. The knee was preconditioned, the laxity was matched to that of the intact knee at 30° of flexion, and the graft tension, the flexion angle, and the anteroposterior position of the tibia on the femur were recorded from 0° to 120° of flexion. The knee

was removed from the load-application system and was placed in 90° of flexion, which tensioned the posterior cruciate ligament. With use of a ruler, marks were placed at 2-mm and 4-mm increments parallel to the lateral edge of the posterior cruciate ligament. The tests were repeated after excision of 2 mm of the lateral edge of the posterior cruciate ligament and were repeated one final time after excision of 4 mm of the lateral edge of the posterior cruciate ligament.

Statistical Analysis

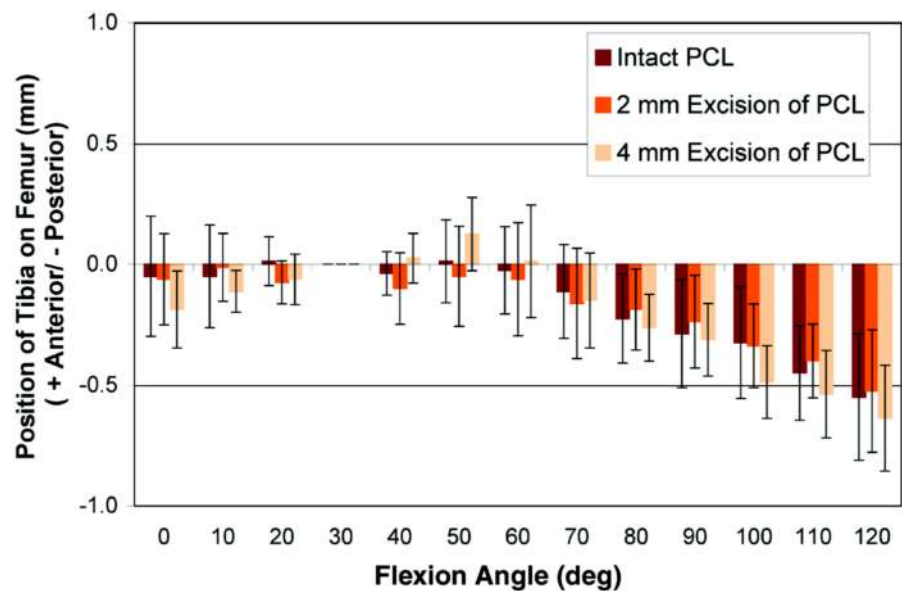
The data concerning the effect of the angle of the femoral tunnel and the angle of the tibial tunnel in the coronal plane on the initial graft tension were modeled with use of a two-factor repeated-measures analysis of variance, with each tunnel having three levels (60°, 70°, and 80°). The interaction between the angle of the femoral tunnel and the angle of the tibial tunnel was not significant ($p = 0.5165$); therefore, significant main effects were further analyzed with Tukey's test to determine which femoral tunnel angle and which tibial tunnel angle resulted in a different initial graft tension.

The data concerning the effect of the angle of the femoral tunnel and the angle of the tibial tunnel in the coronal plane on graft tension at 120° of flexion were modeled with use of a two-factor repeated measures analysis of variance, with each tunnel having three levels (60°, 70°, and 80°). Because there was an interaction between the angle of the femoral tunnel and the angle of the tibial tunnel ($p < 0.0001$), the data concerning the effect of the femoral and tibial tunnel angle combination on graft tension at 120° of flexion were evaluated with a cell means model²⁷, with the femoral and tibial tunnel angle combination having nine levels (60°-60°, 60°-70°, 60°-80°, 70°-60°, 70°-70°, 70°-80°, 80°-60°, 80°-70°, and 80°-80°). Significant main effects were further analyzed with Tukey's test to determine which femoral and tibial tunnel angle combination resulted in a different graft tension at 120° of flexion.

The data concerning the effect of the condition of the

Fig. 7

Excision of 2 and 4 mm of the posterior cruciate ligament (PCL) did not affect the anteroposterior position of the tibia on the femur compared with that of the knee with the intact posterior cruciate ligament at any of the thirteen flexion angles ($p = 0.4275$). Therefore, the decrease in graft tension at 120° of flexion resulting from incremental excision of the posterior cruciate ligament cannot be caused by a change in the anteroposterior position of the tibia on the femur. The error bars indicate one standard deviation.



posterior cruciate ligament on the anteroposterior position of the tibia were modeled with use of a two-factor repeated-measures analysis of variance, with the condition of the posterior cruciate ligament having three levels (intact, 2 mm excised, and 4 mm excised) and the flexion angle having thirteen levels (0°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, 90°, 100°, 110°, and 120°) with the graft in the 80° femoral tunnel-80° tibial tunnel combination. The interaction between the condition of the posterior cruciate ligament and the flexion angle was not significant ($p = 0.9685$); therefore, significant main effects were further analyzed with Tukey's test to determine which condition of the posterior cruciate ligament and which flexion angle resulted in a different anteroposterior position of the tibia.

The data concerning the effect of incremental excision of the posterior cruciate ligament on the initial graft tension and the graft tension at 120° of flexion were modeled with a one-factor repeated-measures analysis of variance with the condition of the posterior cruciate ligament having three levels (intact, 2 mm excised, and 4 mm excised). Significant main effects were further analyzed with Tukey's test to determine which conditions of the posterior cruciate ligament affected the initial graft tension and the graft tension at 120° of flexion.

The level of significance was set at $p < 0.05$. Statistical analyses were performed with the use of SAS software (version 8.0; SAS Institute, Cary, North Carolina).

Results

The angle of the femoral tunnel ($p = 0.0007$), but not the angle of the tibial tunnel ($p = 0.09$), significantly affected the initial graft tension used to restore anterior laxity at 30° of flexion at 225 N of anterior force (Fig. 5). There was no difference in the initial graft tension used for the femoral and tibial tunnel angle combinations involving a 60° or 70° femoral tunnel; however, there was a small difference in the initial graft

tension between combinations involving 60° and 80° femoral tunnels and between those involving 70° and 80° femoral tunnels ($p < 0.05$). The tibial tunnel angle did not affect initial graft tension. The initial graft tension associated with the femoral and tibial tunnel angle combinations involving an 80° femoral tunnel (41 ± 8.4 N) was 3 N greater than the initial graft tension associated with the 70° femoral tunnel (38 ± 7.7 N) ($p < 0.05$) and 4 N greater than the initial graft tension associated with the 60° femoral tunnel (37 ± 6.8 N) ($p < 0.05$).

Both the angle of the femoral tunnel and the angle of the tibial tunnel in the coronal plane affected graft tension at 120° of flexion ($p < 0.0001$), but because of the interaction ($p < 0.0001$) the effect of the tibial tunnel depended on the angle of the femoral tunnel. Graft tension at 120° of flexion increased as the angle of the femoral tunnel and the angle of the tibial tunnel increased (Fig. 6). The 80° femoral tunnel-80° tibial tunnel combination was associated with the greatest graft tension (169 ± 9 N), and the 60° femoral tunnel-60° tibial tunnel combination was associated with the lowest graft tension (76 ± 8 N). The effect of the femoral tunnel angle predominated so that for each angle of the tibial tunnel, increasing the angle of the femoral tunnel caused a significant increase in graft tension at 120° of flexion ($p = 0.0007$). The angle of the tibial tunnel in the coronal plane did not affect graft tension at 120° of flexion when the graft was placed in either a 60° or 70° femoral tunnel ($p = 0.9412$). The angle of the tibial tunnel only affected graft tension at 120° of flexion when the angle of the femoral tunnel was 80°. The graft tension at 120° of flexion was significantly different between femoral and tibial tunnel angle combinations in which the femoral tunnel angle was different ($p < 0.05$).

Incremental excision of 2 mm and 4 mm of the posterior cruciate ligament did not affect either the anteroposterior position of the tibia on the femur at any of the thirteen flexion an-

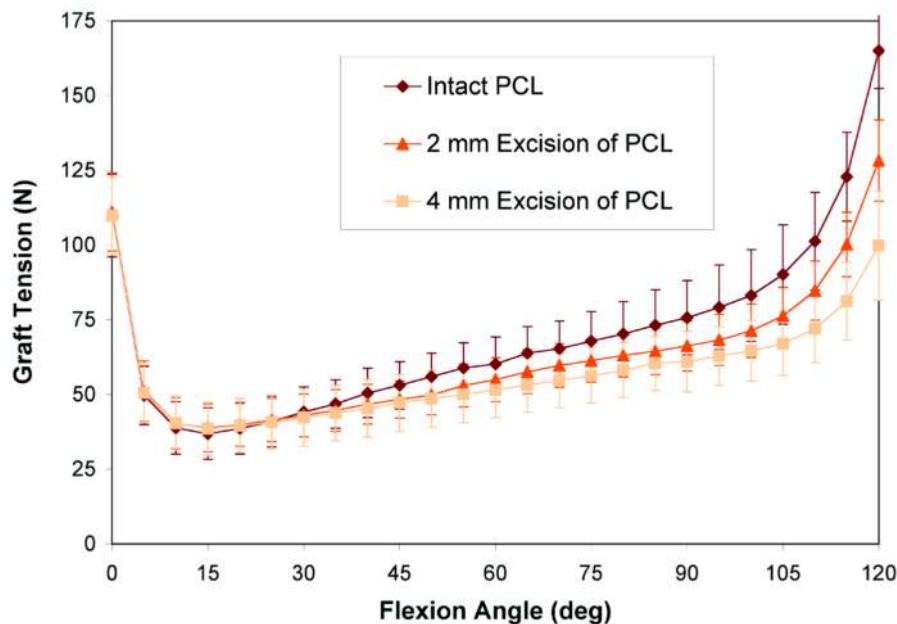


Fig. 8

Graph of the tension in the anterior cruciate ligament graft from 0° to 120° of flexion with the posterior cruciate ligament (PCL) intact and after the excision of 2 and 4 mm of the lateral edge of the ligament. Graft tension at 120° of flexion decreased from 165 N with the posterior cruciate ligament intact to 100 N after excision of 4 mm of the ligament ($p < 0.05$).

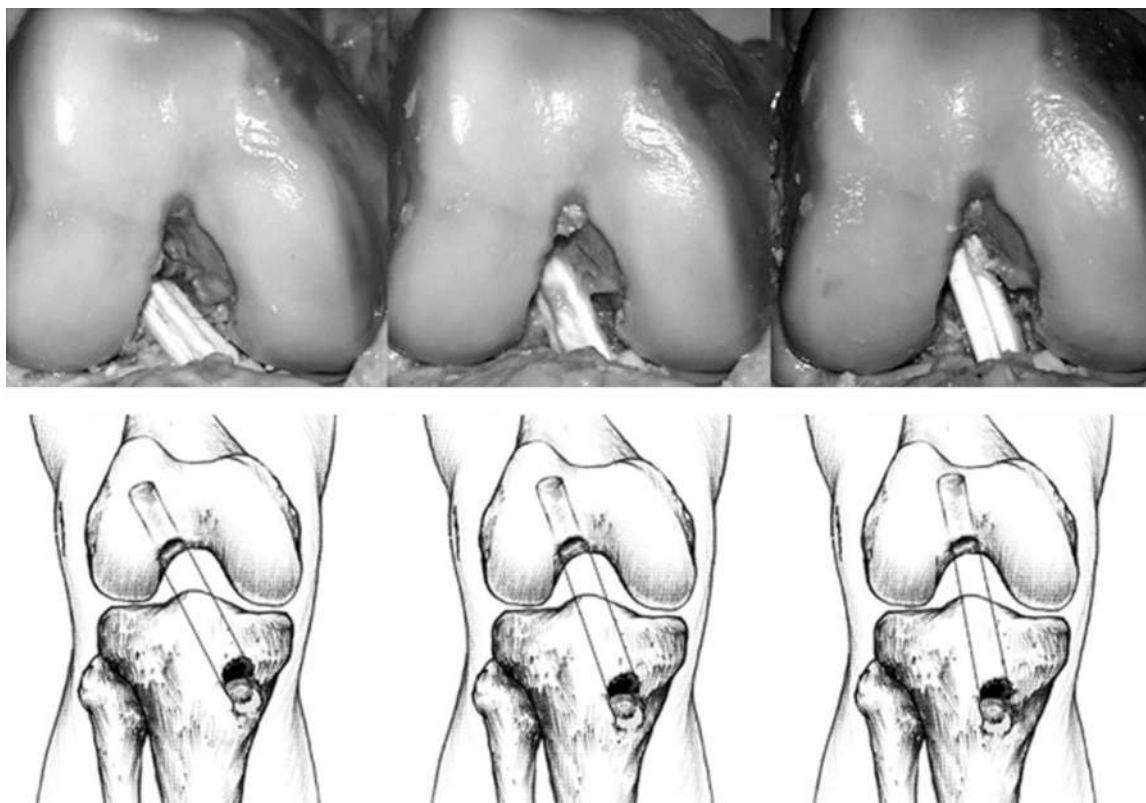


Fig. 9

Composite illustration consisting of notch-view photographs of the reconstructed knee and drawings of the femoral and tibial tunnel angles in the coronal plane (left pair, 60° femoral tunnel-60° tibial tunnel; center pair, 70° femoral tunnel-70° tibial tunnel; right pair, 80° femoral tunnel-80° tibial tunnel). The more oblique orientation of the graft in the 60° femoral tunnel-60° tibial tunnel combination is associated with less impingement against the posterior cruciate ligament, and the more vertical orientation of the 80° femoral tunnel-80° tibial tunnel combination is associated with more impingement against the posterior cruciate ligament.

gles ($p = 0.4275$) or the initial graft tension ($p = 0.3348$). At a particular flexion angle, the anteroposterior position of the tibia on the femur never differed by >0.1 mm between the specimens with an intact posterior cruciate ligament, those with a 2-mm excision, and those with a 4-mm excision (Fig. 7). The initial graft tension used to restore anterior laxity at 30° of flexion at 225 N of anterior force was always 42 or 43 N.

Incremental excision of the posterior cruciate ligament affected graft tension at 120° of flexion ($p < 0.0001$). Graft tension at 120° of flexion decreased as excision of the lateral edge of the posterior cruciate ligament increased and was significantly different among all three conditions of the posterior cruciate ligament ($p < 0.05$) (Fig. 8). Graft tension at 120° of flexion was 37 N less after 2 mm of excision and 65 N less after 4 mm of excision compared with that measured when the posterior cruciate ligament was intact ($p < 0.05$).

The repeatability of the surgical technique and preconditioning was determined by comparing plots of graft tension as a function of the flexion angle after each knee had been reconstructed twice with use of the 80° femoral-80° tibial tunnel combination. Each knee was reconstructed with the 80°

femoral-80° tibial tunnel combination once during measurement of graft tension for the nine femoral and tibial tunnel angle combinations and once during measurement of graft tension prior to incremental excision of the posterior cruciate ligament. A comparison of the plots from these two reconstructions that used the same tunnels showed that the graft tension was repeatable.

Discussion

The most important findings of the present study were that placing the femoral and tibial tunnels at 60° in the coronal plane lowers graft tension at 120° of flexion and that minimizing impingement of the graft against the lateral edge of the posterior cruciate ligament during flexion is the mechanism responsible for lowering graft tension in flexion. Before discussing the clinical implications of these observations, several methods issues and limitations of the study should be reviewed.

Methods Issues and Limitations

One methods issue was whether the high graft tension at 120° of flexion was caused by anterior placement of the femoral

tunnel^{3,28} rather than by the angle of the femoral tunnel in the coronal plane. We avoided anterior placement of the femoral tunnel by using an over-the-top femoral aimer that limits the thickness of the posterior wall of the tunnel to 1 mm (Fig. 3)¹³.

A second methods issue was whether the high graft tension at 120° of flexion was caused by the small difference in initial tension between femoral and tibial tunnel angle combinations rather than by the angle of the femoral tunnel in the coronal plane. The effect of the difference in initial tension can be analyzed by correcting the tension at 0° of extension and at 120° of flexion by subtracting the difference in initial tension. The average initial tension was 37, 38, and 41 N for the three femoral and tibial tunnel angle combinations associated with the 60°, 70°, and 80° femoral tunnels, respectively. The corrected tension at 0° of extension was similar (106, 107, and 106 N) and the corrected tension at 120° of flexion was different (79, 102, and 138 N) for each of the three tunnel combinations with the 60°, 70°, and 80° femoral tunnels. Therefore, the small difference in initial tension (4 N) cannot explain the large difference in graft tension at 120° of flexion (59 N).

A third methods issue was whether the reduction in graft tension at 120° of flexion after incremental excision of the posterior cruciate ligament was caused by posterior subluxation of the tibia on the femur. The position of the tibia at 120° of flexion was similar when the specimens were tested with the posterior cruciate ligament intact (-0.6 ± 0.4 mm), after a 2-mm excision (-0.5 ± 0.4 mm), and after a 4-mm excision (-0.6 ± 0.3 mm). Excision of 4 mm of the posterior cruciate ligament, which represents a cross-sectional area of approximately 12 mm², decreased the relatively large cross-sectional area of the posterior cruciate ligament (reported¹⁴ to be 41 mm²) by only 29%. Apparently, the remaining portion of the posterior cruciate ligament was sufficient to maintain the anteroposterior position of the tibia on the femur during passive flexion of the knee.

A fourth methods issue was whether the high graft tension at 120° of flexion was affected by differences in graft motion at the intra-articular opening of the tibial tunnel. Graft motion probably differed in the medial-lateral direction because the diameter of the opening was affected by the obliquity of the 60°, 70°, and 80° tibial tunnels. The medial-lateral diameter of the opening was 10.4 mm for the 60° tunnel, 9.6 mm for the 70° tunnel, and 9.2 mm for the 80° tunnel. The anterior-posterior diameter of the opening was the same for each tunnel (10.6 mm). In the medial-lateral direction, the graft could move 0.4 mm more in a 70° tunnel than in an 80° tunnel, 0.8 mm more in a 60° tunnel than in a 70° tunnel, and 1.2 mm more in a 60° tunnel than in an 80° tunnel. However, our results showed that the angle of the tibial tunnel did not affect graft tension at 120° of flexion with the graft in either a 60° or 70° femoral tunnel and had a small effect with the graft in the 80° femoral tunnel. Therefore, graft motion in the medial-lateral direction had little effect on graft tension at 120° of flexion.

One limitation of our study was that we did not determine whether moving the intra-articular opening of the tibial

tunnel medially affects graft tension in flexion. Our results suggest that moving the tibial tunnel medially might increase impingement of the graft against the posterior cruciate ligament, which would increase graft tension. An increase in graft tension in flexion might limit flexion or increase anterior laxity. Romano et al., in a clinical study of medial placement of the tibial tunnel in knees reconstructed with use of the two-incision technique, noted a loss of flexion when the intra-articular opening of the tibial tunnel was at least partially medial to the medial tibial spine²⁹. Our results agree with the observation by Romano et al. that placement of the tibial tunnel medial to the medial tibial spine should be avoided²⁹ and suggest that impingement of the graft against the posterior cruciate ligament causes the loss of flexion.

A second limitation of our study was that we did not determine whether the effects of the femoral and tibial tunnels and the posterior cruciate ligament on graft tension are different for different types of grafts, such as a patellar tendon graft that does not fill the tunnel.

A third limitation of our study was that we did not translate the radiographic technique that we used for determining the orientation of the femoral tunnel in the coronal plane into an arthroscopic technique. Determination of the orientation of the femoral tunnel with an arthroscope depends on standardization of the arthroscopic projection of the notch. Our attempts to standardize the arthroscopic projection have been unsuccessful because of four variables that are difficult to control. We have observed that the arthroscopic projection of the notch is substantially affected by the choice of portal (i.e., anteromedial, transpatellar, or anterolateral), slight variations in the placement of the portal, rotation of the camera, and rotation of the 30° arthroscope. Determining whether the arthroscope can be used to relate the orientation of a tibial or femoral guide-wire to the time on a clock-face depends on the development of a method that standardizes the arthroscopic projection of the notch. Without further study, we cannot recommend the use of an arthroscopic technique to determine the orientation of the femoral tunnel in the coronal plane.

A fourth limitation of our study was that we performed multiple tests on a cadaveric knee specimen with use of the same graft. Multiple tests raise the possibility that the knee tissues and the graft could degrade or stretch during the experiment. The repeatability analysis suggested that stretching or degradation did not occur. Furthermore, the randomization of the testing sequence of the nine femoral and tibial tunnel angle combinations avoided any systematic carry-over effects from multiple tests performed on a cadaveric knee specimen with use of the same graft.

A fifth limitation of our study was that we did not measure, and therefore could not compare, the anterior laxity at 120° of flexion with the graft in each femoral and tibial tunnel angle combination. There is a possibility that lowering graft tension at 120° of flexion with the use of a 60° or 70° femoral tunnel might increase anterior laxity at high flexion angles. However, this concern was not supported by

the results of a clinical study that showed less anterior laxity at 30° of flexion in knees in which the femoral tunnel had a lower angle (65° to 74°) than in those in which it had a higher angle (75° to 85°)²⁵. Therefore, an angle of the femoral tunnel (i.e., 60° or 70°) that lowers graft tension at 120° of flexion is associated with better anterior laxity at 30° of flexion than an angle of the femoral tunnel (i.e., 80°) that raises graft tension at 120° of flexion.

Interpretation and Significance of Results

Our study demonstrated that impingement of the graft against the posterior cruciate ligament was a cause of high graft tension in flexion. Impingement of the graft against the posterior cruciate ligament was observed as the femoral tunnel was placed more vertically (at angles of 70° and 80°) (Fig. 9). Incremental excision of 2 and 4 mm of the lateral edge of the posterior cruciate ligament reduced impingement between the graft and the posterior cruciate ligament, lowering graft tension in flexion. Therefore, a strategy for lowering graft tension in flexion is to obliquely orient the graft in the notch so that there is little contact between the graft and the posterior cruciate ligament in flexion.

The change in graft tension between 0° of extension and 120° of flexion with the 60° femoral tunnel-60° tibial tunnel combination was more similar to the change in tension of the intact anterior cruciate ligament than the change in tension with the 80° femoral tunnel-80° tibial tunnel combination was. Therefore, the tension in a graft in a 60° femoral tunnel-60° tibial tunnel combination most closely replicates the tension in the intact anterior cruciate ligament.

In the present study, the location of the center of the tibial tunnel in the sagittal plane from the anterior joint line of the tibia (46% ± 4%; range, 42% to 50%) was similar to the location of the center of the tibial tunnel as reported in two clinical studies that involved the same type of tibial guide that references the intercondylar roof (47% ± 4% [range, 40% to 55%]¹¹ and 45% ± 3% [range, 41% to 50%]³¹). Centering the tibial tunnel 46% from the anterior joint line placed the center of the tunnel 4.8 mm posterior to the center of the insertion of the intact anterior cruciate ligament (normalized to an average-sized 60-mm tibial plateau)²². This tunnel location placed the graft fibers anatomically; that is, all of the graft fibers were within the pathway of the intact anterior cruciate ligament and roof impingement was avoided without the performance of a roofplasty²².

For the surgeon who prefers the transtibial technique, our study showed that controlling the angle of the tibial tunnel controls the angle of the femoral tunnel. The degree of angulation of a 6-mm-diameter femoral aimer inside the tibial tunnel decreased as the tunnel diameter decreased and the length increased. For a 40-mm-long tibial tunnel, the angulation of a femoral aimer was 3°, 4°, 6°, 7°, and 9° inside a tibial tunnel with a diameter of 8, 9, 10, 11, and 12 mm, respectively. The degree of angulation was limited to ≤4° in 8 and 9-mm-diameter tibial tunnels, which are the most common tunnel diameters used in association with a double-looped semiten-

dinosus and gracilis graft³⁰. Therefore, neither an 8 nor a 9-mm-diameter tibial tunnel placed at 70° or 80° in the coronal plane allows enough angulation of the femoral aimer to place the femoral tunnel at 60°.

Our technique for controlling the placement of the femoral tunnel in the coronal plane is to drill the tibial tunnel at an angle of 65° in the coronal plane. We drill the tibial tunnel at an angle of 65° instead of 60° to reduce the chance of placing the femoral tunnel at an angle of <60° or >70° and because the starting point of a 60° tibial tunnel is close to the posteromedial edge of the tibia, which interferes with fixation. Striving for a 65° tibial tunnel places the angle between 59° and 71° in the coronal plane 95% of the time because the accuracy of the tibial guide without radiographic verification is ±3° (standard deviation)²⁴. The femoral tunnel is placed at 61° or 62° in a 65° tibial tunnel by angulating the tip of the femoral aimer laterally. Lateral angulation of the tip of the femoral aimer in an 8 or 9-mm-diameter tibial tunnel decreases the angle of the femoral tunnel by 3° or 4°. Decreasing the angle of the femoral tunnel by angulating the aimer laterally shifts the graft away from the posterior cruciate ligament and minimizes impingement of the graft against the posterior cruciate ligament.

One advantage of the transtibial technique is that once the tibial tunnel has been placed correctly in the sagittal and coronal planes, correct placement of the femoral tunnel is automatic. Radiographic verification that the tibial guide-wire is 4 to 5 mm posterior and parallel to the intercondylar roof in the extended knee and at an angle of 60° in the coronal plane guarantees that, when the femoral tunnel is placed by centering the femoral aimer in the tibial tunnel, the tension in the graft will be similar to that in the intact anterior cruciate ligament. Therefore, the most important tunnel in the transtibial technique is the tibial tunnel.

The present study of the transtibial technique showed that measuring the angle of the tibial guide-wire with respect to the medial joint line of the tibia on an anteroposterior radiograph predicted graft tension in flexion. This prediction was confirmed by the results of a clinical study that showed that the angle of the tibial tunnel in the coronal plane, as measured on an anteroposterior radiograph made one year postoperatively, predicted the in vivo graft tension at the time of implantation³¹. These observations suggest that high graft tension in flexion can be avoided by checking the angle of the tibial guide-wire on an intraoperative anteroposterior radiograph and adjusting the angle of the tibial tunnel before drilling the femoral tunnel.

Checking the angle of the tibial guide-wire on an intraoperative radiograph might improve the accuracy of drilling the angle of the tibial tunnel in the coronal plane. A multicenter clinical study in which intraoperative radiographs were not used showed that surgeons drilled the angle of the tibial tunnel in the coronal plane inaccurately²⁴. The use of an alignment rod placed transversely in the handle of the tibial guide and drilling through the superficial fibers of the medial collateral ligament improved the accuracy of

drilling the angle of the tibial tunnel by reducing the variability in half²⁴.

The results of the present study provide a biomechanical explanation for the clinical observation that loss of flexion and anterior laxity are greater when the tibial tunnel is drilled at an angle of $\geq 75^\circ$ in the coronal plane with use of the transtibial technique¹⁹. The present study indicates that drilling the femoral tunnel through a $\geq 75^\circ$ tibial tunnel causes graft impingement against the posterior cruciate ligament, increasing graft tension in flexion. The higher graft tension might explain the limitation in flexion that was observed in the clinical study¹⁹. Impingement of the graft against the posterior cruciate ligament, which stretches the graft, might explain the greater anterior laxity.

In summary, placing the femoral tunnel at 60° in the coronal plane minimizes impingement of the graft against the posterior cruciate ligament and decreases graft tension in flexion. Decreasing impingement against the posterior cruciate ligament and decreasing graft tension in flexion might improve flexion and anterior laxity²⁴. The technique for minimizing graft tension in flexion with the transtibial technique is to place the tibial tunnel at 60° in the coronal plane because the

angle of the femoral tunnel and tension in the graft are controlled by the angle of the tibial tunnel. ■

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