Operative Techniques in
Sports Medicine

Loss of Motion Due to Graft Impingement (Roof Impingement and Posterior Cruciate Ligament Impingement)

Stephen M. Howell, MD

This article discusses how to prevent loss of extension from roof impingement and loss of flexion from posterior cruciate ligament impingement while performing an anterior cruciate ligament reconstruction. The definition, complications, and diagnosis of roof and posterior cruciate ligament impingement are discussed. The rationale and a proven technique for placing the tunnels with the transtibial technique in which the tibial tunnel is drilled first and the femoral tunnel is drilled through the tibial tunnel is presented. Clinical and biomechanical studies show that the key tunnel in the transtibial technique is the tibial tunnel. These studies also show that correct placement of the tibial tunnel in the sagittal and coronal planes, and subsequent drilling of the femoral tunnel through the tibial tunnel, avoids extension loss from roof impingement, avoids flexion loss from posterior cruciate ligament impingement, replicates the tension pattern of the intact anterior cruciate ligament, and restores anterior laxity to the reconstructed knee.
Oper Tech Sports Med 14:27-35

KEYWORDS **anterior, posterior, cruciate ligament, roof impingement, graft**

The patient complaining of inability to fully extend the knee after an anterior cruciate ligament reconstruction should be evaluated for roof impingement. Roof impingement occurs in the sagittal plane when the intercondylar roof contacts the anterior cruciate ligament graft before the knee reaches full hyperextension. The surgeon causes extension loss and roof impingement when some portion of the tibial tunnel is placed anterior to the tibial intersection of the intercondylar roof in the extended knee. When the entire tibial tunnel is placed anterior to the intercondylar roof, the impingement is more severe, resulting in abrasion and stretch-out of the graft and recurrent anterior instability.[1-4] Therefore, the prevention of extension loss and maintenance of anterior laxity requires proper placement of the tibial tunnel in the sagittal plane.

A loss of extension on clinical examination, a lateral radiograph of the knee in maximum extension, magnetic resonance imaging, and arthroscopy are helpful in diagnosing roof impingement. A lateral radiograph of the knee in maximum extension is diagnostic of roof impingement when the tibial tunnel is anterior to the intercondylar roof (Fig. 1).[4] The lateral radiograph is less helpful in the evaluation of a bone–patellar tendon–bone graft with roof impingement than a soft-tissue graft because the bone plug may obscure the wall and orientation of the tibial tunnel and because the tendon does not fill the bone tunnel. A magnetic resonance imaging scan is diagnostic of roof impingement when there is a pathognomonic regionalized signal increase in the graft confined to the distal two-thirds of the ligament within the intercondylar notch. The portion of the anterior cruciate ligament graft in the tibial and femoral tunnel, and the portion of the graft that exits the femoral tunnel retain a low signal, which is identical to the normal low signal of the posterior cruciate ligament and patellar tendon.[5-7] Arthroscopy is diagnostic of roof impingement when the anterior cruciate ligament graft is frayed, fragmented, or a fibrous nodule (ie, Cyclops lesion) is formed at the entrance of the tibial tunnel into the notch (Fig. 2).[8]

Adjunct Professor, Department of Mechanical Engineering, University of California at Davis, Sacramento, CA.

Address reprint requests to Stephen M. Howell, MD, 8100 Timberlake Way, Suite F, Sacramento, CA 95823. E-mail: sebhowell@mac.com

1060-1872/06/$-see front matter
doi:10.1053/j.otsm.2006.02.010

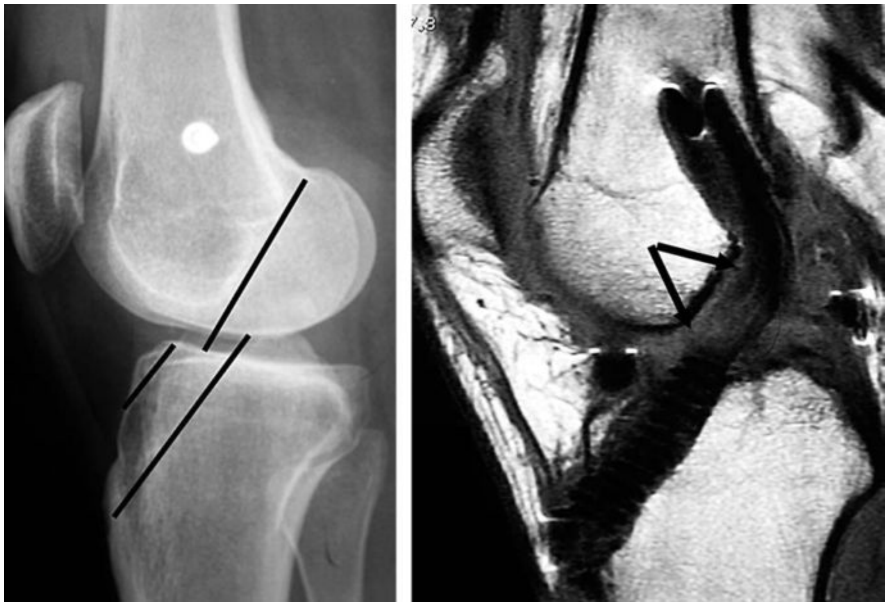

Figure 1 The patient with this lateral radiograph and sagittal magnetic resonance imaging complained of the inability to fully extend the knee. The lateral radiograph of the knee in extension was diagnostic of roof impingement because a portion of the tibial tunnel was placed anterior to the intercondylar roof. The sagittal magnetic resonance image was diagnostic of roof impingement because there was a regionalized pathognomonic signal increase confined to the distal two-thirds of the graft inside the notch (region between arrows). The center of the tibial tunnel should have been placed 5 mm posterior and parallel to the intercondylar roof to prevent roof impingement.

Definition, Complications, and Diagnosis of Flexion Loss from Posterior Cruciate Ligament Impingement

The patient complaining of inability to fully flex the knee after an anterior cruciate ligament reconstruction should be evaluated for posterior cruciate ligament impingement. Posterior cruciate ligament impingement occurs in the coronal plane when the anterior cruciate ligament graft contacts and wraps around the posterior cruciate ligament before the knee reaches terminal flexion. The surgeon causes flexion loss and posterior cruciate ligament impingement when the notch is not widened and the tibial tunnel is placed medial and vertical in the coronal plane. Medial and vertical placement of the tibial tunnel in a narrow notch places the femoral tunnel at the apex of the notch too close to the posterior cruciate ligament when the transtibial technique is used to drill the femoral tunnel through the tibial tunnel. Posterior cruciate ligament impingement causes a tension rise in flexion that either limits flexion or stretches the anterior cruciate ligament graft resulting in anterior instability.[9-11] Therefore, the prevention of extension loss and anterior laxity requires proper placement of the tibial tunnel in the coronal plane.

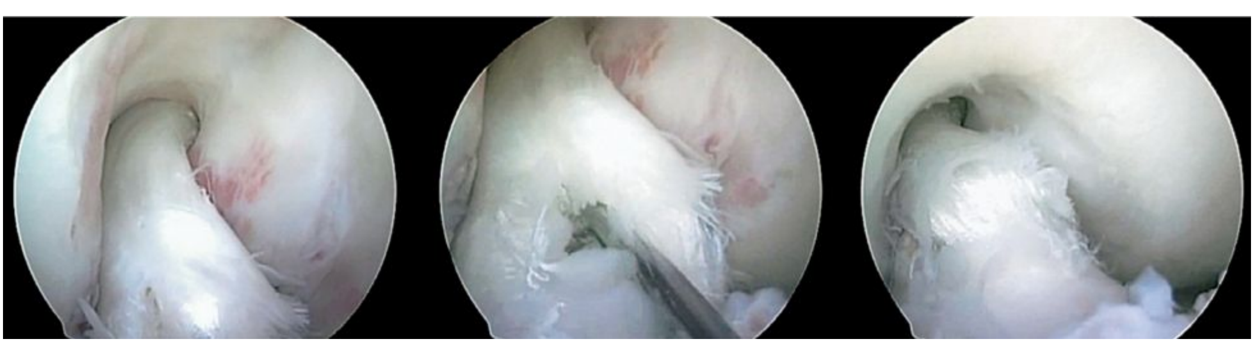

Figure 2 A view of an anterior cruciate ligament graft in a right knee subjected to both posterior cruciate ligament and roof impingement. The arthroscopic findings of posterior cruciate ligament impingement include deformation of the anterior cruciate ligament graft by the posterior cruciate ligament at the apex of the notch and no space between the posterior cruciate ligament and anterior cruciate ligament graft (left). The arthroscopic findings of roof impingement include parallel fragmentation (middle with probe), fraying of the anterior surface of the graft and guillotined fibers (right), and the fibrous nodule or Cyclops lesion (not shown). (Color version of figure is available online.)

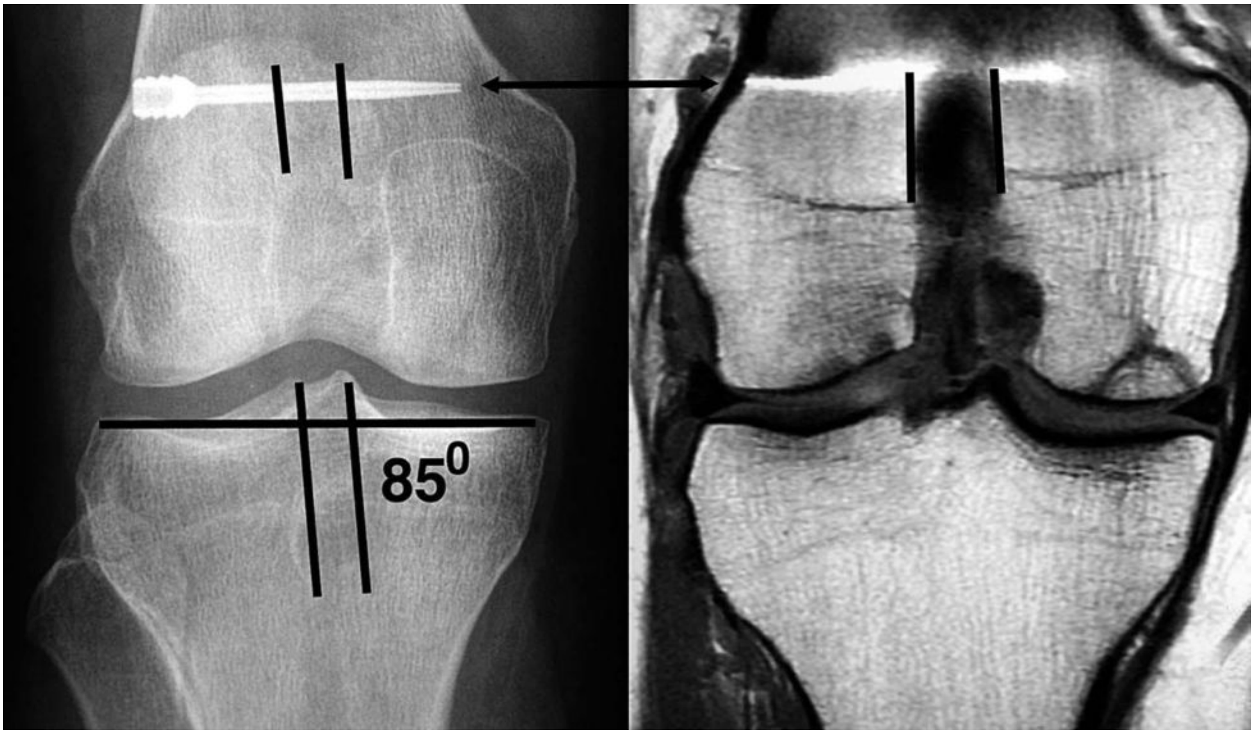

Figure 3 The patient with this anteroposterior radiograph and coronal magnetic resonance image complained of the inability to fully flex the knee. The anteroposterior radiograph was diagnostic of posterior cruciate ligament impingement because the angle of the tibial tunnel with respect to the medial joint line was greater than 70°. The coronal magnetic resonance image was diagnostic of posterior cruciate ligament impingement because the femoral tunnel was at the apex of the notch and there was no space between the posterior cruciate ligament and anterior cruciate ligament graft at the apex of the notch. The tibial tunnel should have been placed at 60 to 65° with respect to the medial joint line of the tibia to prevent posterior cruciate ligament impingement.

A loss of flexion on clinical examination, the operative note, an anteroposterior and notch radiograph, magnetic resonance imaging (magnetic resonance imaging), and arthroscopy can all be used to diagnose posterior cruciate ligament impingement. A review of the operative note will tell whether bone was removed from the lateral femoral condyle (ie, a wallplasty) until the space between the posterior cruciate ligament and lateral femoral condyle exceeds the width of the anterior cruciate ligament graft by 1 mm. If a wallplasty was not performed, then posterior cruciate ligament impingement can be suspected. An anteroposterior or notch radiograph is diagnostic of posterior cruciate ligament impingement when the tibial tunnel is at an angle greater than 70° with respect to the medial joint line or when the lateral edge of the tibial tunnel is medial to the apex of the lateral tibial spine (Fig. 3).[10] A magnetic resonance imaging scan shows the femoral tunnel at the apex of the notch, or a three-dimensional reconstruction shows no space between the anterior cruciate ligament graft and posterior cruciate ligament and the course of the anterior cruciate ligament graft is crooked because it is deformed by the posterior cruciate ligament.[9] Arthroscopy is diagnostic of posterior cruciate ligament impingement when there is no space between the anterior cruciate ligament graft and posterior cruciate ligament at the apex of the notch and the anterior cruciate ligament graft is slack and bows laterally with the knee in 30^0 of knee flexion.[11] Surgeons that avoid posterior cruciate ligament impingement will find their patients have better knee flexion and better anterior and rotatory stability.[9,10]

Rationale for Preventing Extension and Flexion Loss

The rationale for preventing extension and flexion loss from roof and posterior cruciate ligament impingement requires an understanding that there are substantial differences in the cross-sectional anatomy between the intact anterior cruciate ligament, anterior cruciate ligament graft, posterior cruciate ligament, and intercondylar notch. In the sagittal plane, the insertion of the intact anterior cruciate ligament is broad (19-23 mm), indistinct, irregular in shape, and more than twice the sagittal width of the proximal portion of the ligament (10 mm). Grafts are more uniform in sagittal width from origin to insertion (8-10 mm), and cannot replicate the broad insertion of the intact ACL.[3,12] Therefore, placing the tibial tunnel anteromedially in the broad insertion of the intact ACL places the graft too anterior and causes roof impingement[1-4,13]

There is wide variability in roof angle and knee extension between patients that can be accounted for by customizing the placement of the tibial tunnel in the sagittal plane. Roof

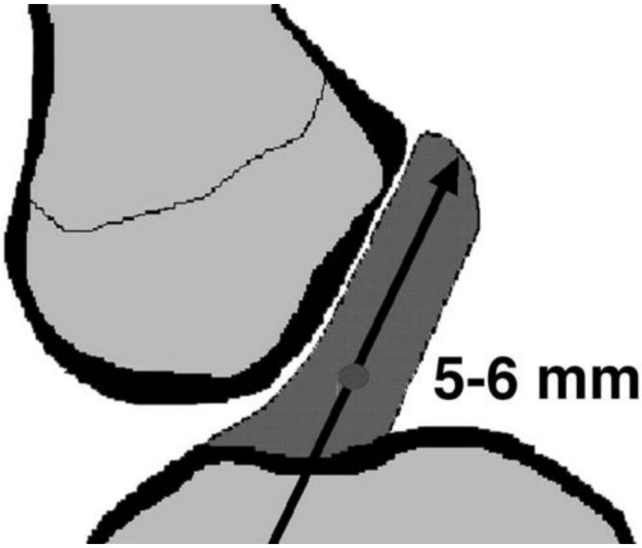

Figure 4 The insertion of the intact anterior cruciate ligament is broad (19-23 mm) and more than twice the sagittal width of the proximal portion of the ligament (10 mm). A round or rectangular graft 8 to 10 mm in diameter cannot replicate the broad insertion of the intact anterior cruciate ligament. Centering the tibial tunnel 5 to 6 mm posterior and parallel to the intercondylar roof with the knee in full extension prevents roof impingement with an 8- to 10 -mm diameter graft. The use of this position places the entire anterior cruciate ligament graft anatomically within the pathway of the intact anterior cruciate ligament and avoids roof impingement without performing a roofplasty.

angle varies from 23° to 60° and knee extension varies from 30° of full extension to 2° of flexion between patients.[8,12,14] Because the correlation between roof angle and knee extension is weak, knees with the same roof angle will extend differently and knees with the same extension will have different roof angles.[15] Therefore, different knees require different placements for the tibial tunnel in the sagittal plane.

Centering the tibial tunnel 5 to 6 mm posterior and parallel to the intercondylar roof with the knee in full extension prevents roof impingement with an 8 to 10 mm diameter graft (Fig. 4). This principle customizes the placement of the tibial tunnel for the anatomy of the knee and prevents roof impingement without performing a roofplasty.[1-3,15-17] The advantages of not performing a roofplasty include lower graft tension, better restoration of anterior laxity, and less stress on the graft and fixation.[18]

In the coronal plane, the intact anterior cruciate ligament is narrow and spindle-shaped, whereas the cross-sectional area of the anterior cruciate ligament graft is much larger (Fig. 5). Magnetic resonance imaging studies of the cross section of the intercondylar notch showed that the intact anterior cruciate ligament is thin and elongated and fits snug between the lateral edge of the posterior cruciate ligament and the medial edge of the lateral femoral condyle.[9] Arthroscopy has shown that the portion of the notch occupied by the posterior cruciate ligament and intact anterior cruciate ligament vary widely. Most notches are "posterior cruciate ligament dominant," where the posterior cruciate ligament occupies more than half of the cross-sectional area of the notch leaving less room for the anterior cruciate ligament graft. The notch is significantly smaller in women than men when matched for height and weight, which means that women require more of

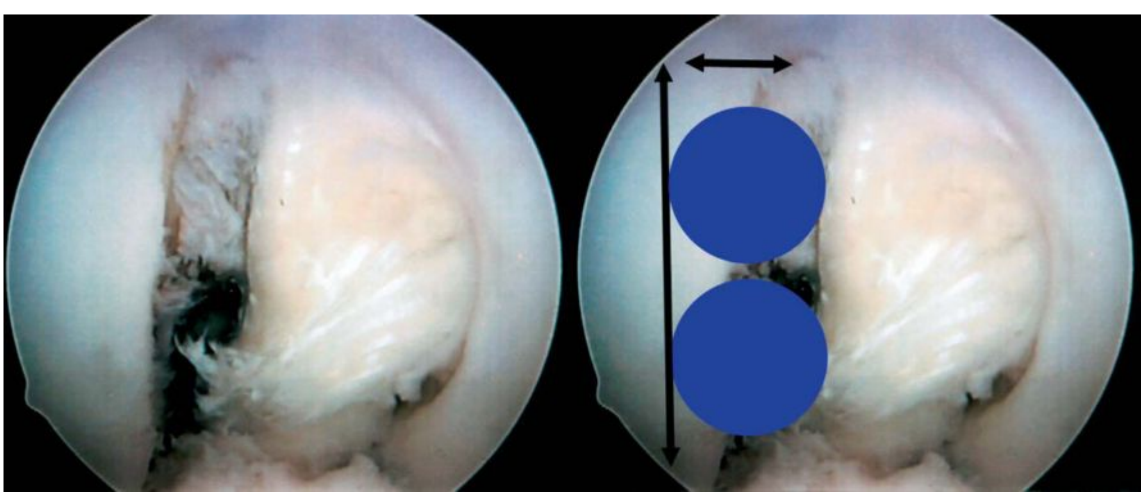

Figure 5 Notches come in many sizes and shapes; however, most notches are too narrow to hold an 8- to 10-mm round soft tissue anterior cruciate ligament graft. The normal anterior cruciate ligament is thin, spindle shaped and much narrower than the cross-section of an 8- to 10-mm graft, (circles) especially in women. Most notches are posterior cruciate ligament-dominant, which means that more than half of the cross-sectional area of the notch is occupied by the posterior cruciate ligament with little room for the anterior cruciate ligament graft (left). Performing a wallplasty (lines with double arrows) until the width between the lateral edge of the posterior cruciate ligament and the lateral femoral condyle exceeds the width of the graft by 1 mm helps prevent posterior cruciate ligament impingement. Widening the notch allows the tibial tunnel to be placed more lateral so that the lateral edge of the tibial tunnel passes through the tip of the lateral spine. (Color version of figure is available online.)

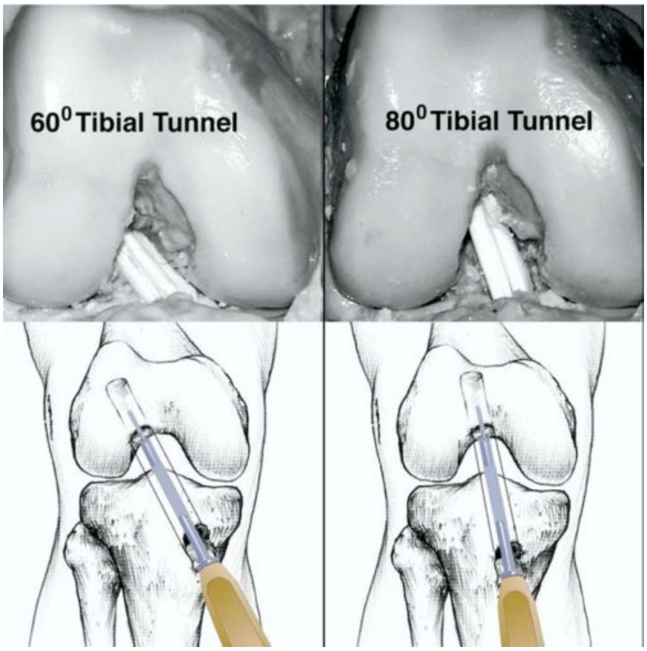

Figure 6 The key tunnel in the transtibial technique is the tibial tunnel because the tibial tunnel determines the position of the over-the-top femoral aimer and the femoral tunnel. When the tibial tunnel is drilled at 60° with respect to the medial joint line the femoral tunnel is placed farther down the sidewall away from the posterior cruciate ligament and the tension pattern in the graft is the same as the intact anterior cruciate ligament. When the tibial tunnel is drilled at 80° the femoral tunnel is placed near the apex of the notch adjacent to the posterior cruciate ligament and the tension pattern in the graft increases abnormally with knee flexion. The tension increase in flexion is caused by the graft impinging against the posterior cruciate ligament which either limits flexion or causes the graft to stretch resulting in increased anterior laxity. (Color version of figure is available online.)

a wallplasty than males for the same diameter graft.[19] Experience coupled with this anatomic understanding suggests that a soft-tissue anterior cruciate ligament graft rounder and larger in cross-sectional area than the intact anterior cruciate ligament requires widening of the notch until the space between that lateral femoral condyle and posterior cruciate ligament exceeds the width of the graft by 1 mm.

Key Tunnel in the Transtibial Technique Is the Tibial Tunnel

The advantage of the transtibial technique is that when the notch is widened and the tibial tunnel is placed correctly in the coronal and sagittal plane, the femoral tunnel is placed correctly automatically. Correct placement of the femoral tunnel means that the anterior cruciate ligament is placed without roof and posterior cruciate ligament impingement, and that the tension pattern in the graft matches that of the intact anterior cruciate ligament. The reason the transtibial technique places the femoral tunnel correctly automatically is that the position of the over-the-top femoral aimer and the position of the reamer are both controlled by the tibial tunnel (Fig. 6).[11]

The feasibility of the transtibial technique to replicate the tension pattern of the intact anterior cruciate ligament was determined by a cadaveric study that analyzed the effect of varying the angle of the tibial tunnel (and femoral tunnel) in the coronal plane on the tension pattern of the anterior cruciate ligament graft (Fig. 6). Drilling the tibial tunnel at an angle of 60° in the coronal plane placed the anterior cruciate ligament graft far down the sidewall of the notch away from the posterior cruciate ligament and the tension pattern of the graft matched intact anterior cruciate ligament. Drilling the tibial tunnel at 70° and 80° placed the anterior cruciate ligament graft more vertical near the apex of the notch and the origin posterior cruciate ligament and the tension pattern of the graft did not match the intact anterior cruciate ligament. With the anterior cruciate ligament graft in the 70° and 80° tibial tunnel the tension pattern increased abnormally with knee flexion. The abnormal increase in graft tension with flexion was abolished by incremental excision of 2 to 6 mm of the lateral edge of the posterior cruciate ligament, which confirmed that posterior cruciate ligament impingement is the mechanism responsible for the abnormal tension increase. Therefore, the tibial tunnel should be placed at angle less than 70° to restore flexion, maintain anterior laxity, and prevent posterior cruciate ligament impingement.[11]

Transtibial Technique for Restoring Knee Extension and Flexion

The success and consistency of the transtibial technique depends solely on correctly placing the tibial tunnel in the sagittal and coronal plane. My preference is to use the 65° Tibial Guide (Arthrotek Inc, Warsaw, IN) (http://www.drstevehowell.com/ezloc_video.cfm) (Fig. 7). The 65° Tibial Guide functions as a 3-dimensional positioning instrument that simultaneously centers the tibial tunnel 5 to 6 mm posterior and parallel to the intercondylar roof with the knee in maximum extension in the sagittal plane, places the tunnel at an angle of 60 to 65° with respect to the medial joint line in the coronal plane, and positions the lateral wall of the tibial tunnel so that it passes through the apex of the lateral tibial spine. The end of the guide is contained by the intercondylar roof, lateral edge of the posterior cruciate ligament, medial edge of the lateral femoral condyle, and the tibial plateau, which is positions the tibial guide wire 3-dimensionally in the anatomic pathway of the intact anterior cruciate ligament. Drilling the tibial tunnel with the knee in full extension customizes the sagittal placement of the tibial tunnel so that it is posterior and parallel to the intercondylar roof in the sagittal plane. Aligning the coronal alignment rod in the handle of the guide parallel to the joint line and perpendicular to the tibia places the tibial tunnel at an angle of 60 to 65° with respect to the medial joint line in the coronal plane. Drilling through the lateral hole in the bullet places the lateral edge of the tibial tunnel through the tip of the lateral tibial spine. The use of the 65° Tibial Guide that keys off the

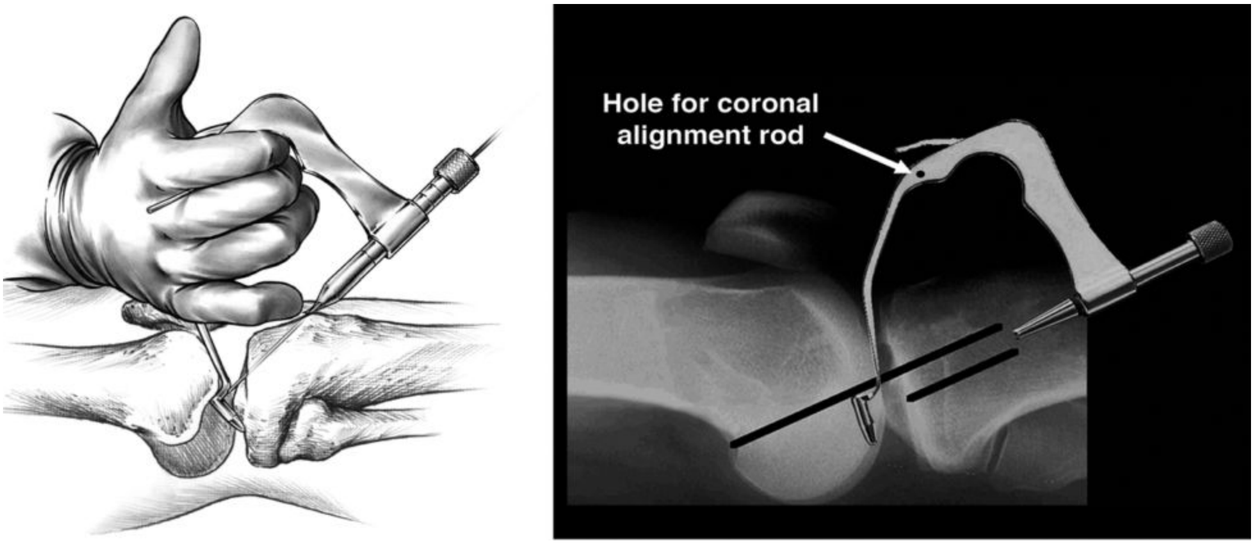

Figure 7 The 65 ° Howell Tibial Guide simultaneously orients the tibial tunnel in both the sagittal and coronal planes. The guide is inserted into the notch, the knee is maximally extended and the surgeon lifts the handle of the guide, which aligns the guide wire 6 mm posterior and parallel to the intercondylar roof. An alignment rod is inserted into the handle of the guide and the guide is rotated until the rod is parallel to the joint line and perpendicular to the long axis of the tibia, which sets the angle of the tibial tunnel in the coronal plane at 65°.

intercondylar roof and a coronal alignment rod reduces the need for inoperative radiography to check to the positioning of the tibial tunnel.

The initial arthroscopic examination of the notch focuses on removing the remnant of the torn anterior cruciate ligament and clearly visualizing the lateral edge of the posterior cruciate ligament (Fig. 8). The tip of the guide, which is 9.5-mm wide, is passed between the posterior cruciate ligament and the lateral femoral condyle. The knee is then gradually extended, examining whether there is enough space between the lateral femoral condyle and posterior cruciate ligament. The notch is then widened from its base to the apex until the 9.5-mm wide tip of the guide easily passes between the lateral femoral condyle and the posterior cruciate ligament. A roofplasty is not performed.

The tibial guide is then reinserted and the knee is placed in full hyperextension (Fig. 7). The heel of the patient's leg is placed on the Mayo stand to maintain the knee in maximum hyperextension. The coronal alignment guide is inserted into the guide, the knee is brought into full hyperextension so that it is parallel to the roof and the coronal alignment rod is adjusted so that it is parallel to the joint line and perpendicular to the tibia (Fig. 9). The guide wire is drilled through the lateral hole in the bullet, which moves the guide wire laterally away from the posterior cruciate ligament. The position of the guide wire is then checked arthroscopically. In the AP view, the guide wire should enter midway between the lateral edge of the posterior cruciate ligament and lateral femoral condyle. In full extension, a probe can be placed between the

Figure 8 Most notches are too narrow to accommodate an 8- to 10-mm round soft-tissue anterior cruciate ligament graft. In this case, the posterior cruciate ligament fills more than half the notch, and there is not enough room for an 8- to 10-mm diameter anterior cruciate ligament graft (A). A wallplasty is performed until the space between the posterior cruciate ligament and lateral femoral condyle exceeds the width of the graft by 1 mm (B). The wallplasty is sufficient when the 9.5 mm wide tip of the tibial guide passes freely between the posterior cruciate ligament and lateral femoral condyle (C). (Color version of figure is available online.)

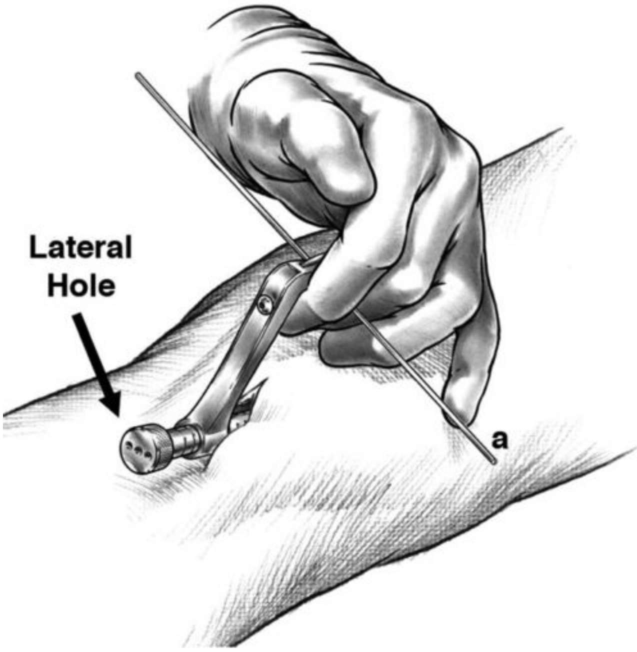

Figure 9 The coronal alignment rod (a) is inserted through the proximal hole on the lateral side of the handle of the tibial guide. The coronal alignment rod is adjusted so that it is parallel to the joint line and perpendicular to the tibia. The guide wire is drilled through the lateral hole in the bullet, which moves the guide wire laterally away from the posterior cruciate ligament and orients the lateral wall of the tibial tunnel through the tip of the lateral tibial spine.

anterior surface of the guide wire and the roof, and there should be 2 to 3 mm of clearance, which indicates that the guide wire is not placed too far posterior.

After drilling the tibial tunnel, an impingement rod is passed into the knee through the tibial tunnel with the knee in maximum hyperextension. Free passage of the impingement rod into the notch indicates no impingement of the anterior cruciate ligament graft against and the posterior cruciate ligament, lateral femoral condyle, and intercondylar roof (Fig. 5). A size-specific femoral aimer with an offset that produces a femoral tunnel with a 1 mm back wall is then inserted through the tibial tunnel. The tip of the femoral aimer is hooked proximal to the lateral wall of the notch and rotated slightly lateral away from the posterior cruciate ligament.

Once the graft is passed, a triangular space should be seen between the posterior cruciate ligament and the anterior cruciate ligament graft at the apex of the notch (Fig. 10). Postoperatively the position of the tibial tunnel in the coronal and sagittal planes should be checked with radiographs (Fig. 11).

Validation of Tibial Guide

One advantage of drilling the tibial tunnel with the knee in full hyperextension with the 65° Tibial Guide is that no manipulation of the knee is required to reduce the knee and drill the guide wire anatomically. Simply extending the knee and placing the heel on the Mayo stand suspends the knee and allows gravity to reduce the tibia on the femur.[17]

A cadaveric study showed that the 65° Tibial Guide placed the tibial tunnel on the posterior half of the anterior cruciate ligament footprint and avoid roof impingement without a roofplasty. Mapping demonstrated a wide variety width, depth and shape of the footprint of the intact anterior cruciate ligament insertion, emphasizing the difficulty in picking the location of the tibial tunnel with use of a point-and-shoot guide and using the anterior cruciate ligament insertion as a target. The consistency of the relationship of the anterior cruciate ligament to the intercondylar roof and the inconsistency of the footprint substantiates the principle of using a tibial guide that keys off the intercondylar roof with the knee

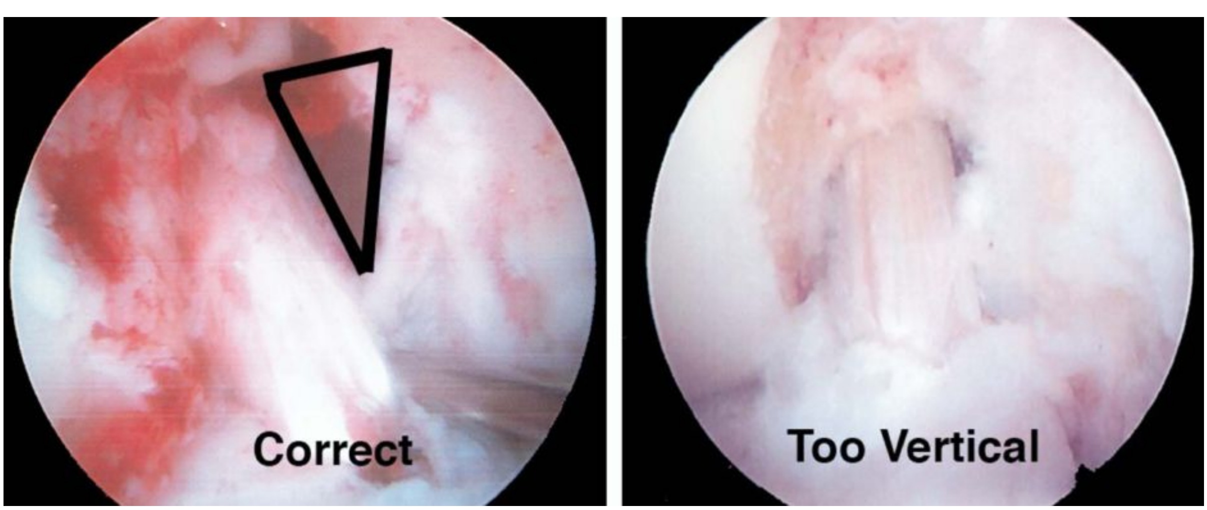

Figure 10 The correct placement of the tibial and femoral tunnel is lateral to the posterior cruciate ligament, which forms a relatively large triangular space at the apex of the notch between the anterior cruciate ligament graft and posterior cruciate ligament (right knee). A vertically placed tibial and femoral tunnel causes posterior cruciate ligament impingement, because there is no triangular space between the anterior cruciate ligament graft and posterior cruciate ligament at the apex of the notch. (Color version of figure is available online.)

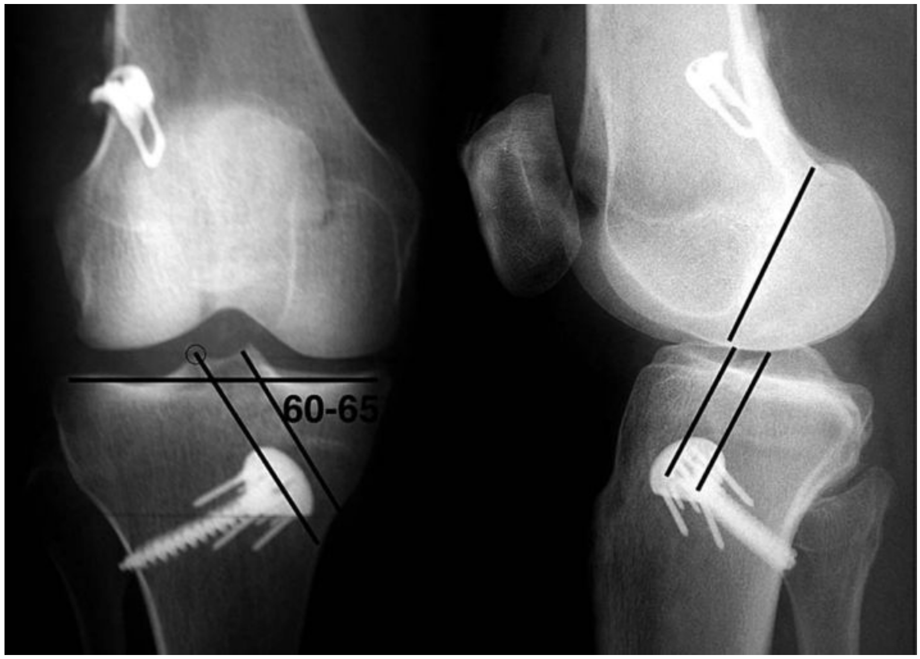

Figure 11 The optimum placement for the tibial tunnel in the coronal and sagittal planes is shown. The lateral edge of the tibial tunnel passes through the tip of the lateral tibial spine (○) and the tibial tunnel forms an angle between 60 to 65 ° with respect to the medial joint line in the coronal view (left). The tibial tunnel is posterior to the intercondylar roof with the knee in extension (right). This patient regained full flexion and extension and remained stable because the anterior cruciate ligament graft was placed without roof and posterior cruciate ligament impingement.

in full hyperextension to select the position of the tibial guide wire.[16]

The use of the coronal alignment guide is preferred over the use of a "clock" as a way of judging whether the femoral tunnel is placed correctly in the coronal plain. A simple experiment can be done to show how imprecise the use of the clock is determining the location of the femoral tunnel in the coronal plane. With the femoral guide wire drilled through the tibial and in to the notch, place the scope through the anterolateral or transpatellar portal, and rotate the 30° arthroscope and camera independently. The "time " formed by the guide wire and the margin of the intercondylar notch will vary 2hours. Repeat the experiment in the anteromedial portal, and observe the maximum and minimum time differs from the view in the previous portal. Therefore, one surgeon's 2-o'clock position may be another surgeon's 1-o'clock position, depending on the choice of portal, rotation of the scope, and rotation of the camera.

Conclusion

Proper tunnel placement is essential for regaining full extension and flexion and for restoring anterior laxity. The complications that are cause by a poorly placed tibial tunnel in the coronal or sagittal plane cannot be overcome by the best graft material, fixation methods or rehab program. Correct tibial tunnel placement in the sagittal plane centers the tibial tunnel 5 to 6 mm posterior and parallel to the intercondylar roof in the extended knee so that roof impingement is avoided without performing a roofplasty. Correct tibial tunnel placement in the coronal plane requires widening of the notch so that the space between the posterior cruciate ligament and lateral femoral condyle exceeds the diameter of the graft by 1 mm, and placing the angle of the tibial tunnel between 60° and 65° with respect to the medial joint line of the tibia. When a femoral tunnel with a 1-mm back wall is drilled through this tibial tunnel the tension pattern in the graft matches the intact anterior cruciate ligament and roof and posterior cruciate ligament impingement is prevented.

References

1. Goss BC, Howell SM, Hull ML: Quadriceps load aggravates and roofplasty mitigates active impingement of anterior cruciate ligament grafts against the intercondylar roof. J Orthop Res 16:611-617, 1998
2. Goss BC, Hull ML, Howell, SM: Contact pressure and tension in anterior cruciate ligament grafts subjected to roof impingement during passive extension. J Orthop Res 15:263-268, 1997
3. Howell SM, Clark JA, Farley TE: A rationale for predicting anterior cruciate graft impingement by the intercondylar roof. A magnetic resonance imaging study. Am J Sports Med 19:276-282, 1991
4. Howell SM, Taylor, MA: Failure of reconstruction of the anterior cruciate ligament due to impingement by the intercondylar roof. J Bone Joint Surg Am 75:1044-1055, 1993
5. Howell SM, Berns GS, Farley, TE: Unimpinged and impinged anterior cruciate ligament grafts: MR signal intensity measurements. Radiology 179:639-643, 1991
6. Howell SM, Clark JA, Blasier, RD: Serial magnetic resonance imaging of hamstring anterior cruciate ligament autografts during the first year of implantation. A preliminary study. Am J Sports Med 19:42-47, 1991
7. Howell SM, Clark JA, Farley TE: Serial magnetic resonance study assessing the effects of impingement on the MR image of the patellar tendon graft. Arthroscopy 8:350-358, 1992
8. Watanabe BM, Howell, SM: Arthroscopic findings associated with roof

impingement of an anterior cruciate ligament graft. Am J Sports Med 23:616-625, 1995
9. Fujimoto E, Sumen Y, Deie M, et al: Anterior cruciate ligament graft impingement against the posterior cruciate ligament: diagnosis using MRI plus three-dimensional reconstruction software. Magn Reson Imaging 22:1125-1129, 2004
10. Howell SM, Gittins ME, Gottlieb JE, et al: The relationship between the angle of the tibial tunnel in the coronal plane and loss of flexion and anterior laxity after anterior cruciate ligament reconstruction. Am J Sports Med 29:567-574, 2001
11. Simmons R, Howell SM, Hull ML: 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. J Bone Joint Surg Am 85:1018-1029, 2003
12. Odensten M, Gillquist, J: Fucntional anatomy of the anterior cruciate ligament and a rationale for reconstruction. J Bone Joint Surg Am 67: 257-262, 1985
13. Howell SM, Clark JA: Tibial tunnel placement in anterior cruciate ligament reconstructions and graft impingement. Clin Orthop 283:187-195, 1992
14. Staubli HU, Rauschning W: Tibial attachment area of the anterior cruciate ligament in the extended knee position. Anatomy and cryosections in vitro complemented by magnetic resonance arthrography in vivo. Knee Surg Sports Traumatol Arthrosc 2:138-146, 1994
15. Howell SM, Barad, SJ: Knee extension and its relationship to the slope of the intercondylar roof. Implications for positioning the tibial tunnel in anterior cruciate ligament reconstructions. Am J Sports Med 23:288-294, 1995
16. Cuomo P, Edwards A, Giron F, et al: Validation of the 65 degrees Howell guide for anterior cruciate ligament reconstruction. Arthroscopy 22:70-75, 2006
17. Howell SM, Lawhorn, KW: Gravity reduces the tibia when using a tibial guide that targets the intercondylar roof. Am J Sports Med 32:1702-1710, 2004
18. Markolf KL, Hame SL, Hunter DM, et al: Biomechanical effects of femoral notchplasty in anterior cruciate ligament reconstruction. Am J Sports Med 30:83-89, 2002
19. Shelbourne KD, Kerr, B: The relationship of femoral intercondylar notch width to height, weight, and sex in patients with intact anterior cruciate ligaments. Am J Knee Surg 14:92-96, 2001