Knee Extension and its Relationship to the Slope of the Intercondylar Roof

Implications for Positioning the Tibial Tunnel in Anterior Cruciate Ligament Reconstructions

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ABSTRACT

This study determined that knee extension (range, -30° to 2°) and the slope of the intercondylar roof (range, 26° to 46°) vary widely between knees in both men and women. We found a weak relationship between knee extension and the slope of the intercondylar roof ($r^2 = 0.207$); therefore, roof angle cannot be predicted by clinically measuring knee extension.

Clinical relevance: A knee with a given degree of extension can have a variety of different slopes to the intercondylar roof. Knees with the combination of hyperextension and a vertically oriented slope to the intercondylar roof are “unforgiving” because they require a more posterior position for the tibial tunnel to avoid roof impingement and an extensive roofplasty. If the surgical objective is to minimize the extent of the roofplasty and avoid roof impingement, then consideration should be given to customizing the placement of the tibial tunnel to account for variability in knee extension and roof angle when reconstructing the anterior cruciate ligament. Studies have shown that isometric graft placement can be achieved with this surgical approach.

It is generally acknowledged that improper intraarticular placement of an ACL graft can lead to an unsatisfactory clinical result. Roof impingement occurs when an ACL graft prematurely contacts the intercondylar roof before the knee reaches terminal extension. Roof impingement can cause excessive tensile loads in the graft, effusions, extension deficits, and recurrent instability in patients with ACL reconstructions.1,2,4,7,8,11,13-20,22,28,29 Placing the tibial tunnel posterior to the intercondylar roof with the knee in full extension and performing a roofplasty to accommodate the volume of the graft avoids roof impingement and its complications.18,19,26

What constitutes proper intraarticular placement is less universally agreed on.25 Several authors have proposed that there is one location for positioning the tibial tunnel that can be used in all knees.5,9,23 We believe that it is necessary to adjust the placement of the tibial tunnel to account for variability in the slope of the intercondylar roof and knee extension to minimize the extent of the roofplasty and avoid roof impingement.11,19 For example, a knee that hyperextends and has a more vertical slope to the intercondylar roof will require a more posterior placement for the tibial tunnel than a knee that extends to 0° and has a more horizontal intercondylar roof. An argument can be made for customizing the placement of the tibial tunnel if there is wide variability in knee extension and roof angle among patients.

One purpose of this study was to determine the variability of knee extension and roof angle among patients. A second goal was to determine if there is a difference in roof angle and knee extension between men and women. A third goal was to determine if knee extension can be used to predict a patient’s roof angle. Based on these anatomic observations, we propose guidelines for positioning the tibial tunnel that avoids roof impingement while minimizing the extent of a roofplasty.

MATERIALS AND METHODS

Patient selection

Thirty-three subjects (17 men and 16 women) between the ages of 18 and 40 were recruited for the study. Each
patient denied having a previous injury to the knee or treatment to include immobilization, crutches, roentgenograms, or surgery. A clinical examination was normal. Permission was granted for us to obtain a lateral roentgenogram of their knees in maximum extension.

Roentgenographic technique

The patients were positioned supine on the x-ray table and the heel was placed on a foam bolster so that the popliteal fossa was suspended 10 cm above the table. The patient was instructed to relax the leg, allowing gravity to maximally extend the knee. A 14 X 17 inch cassette was centered on the knee. The x-ray beam was directed medial, parallel to the joint line. Roentgenograms were repeated until the lateral projection of the medial and lateral condyles were superimposed. Measurements were made from films in which the offset of the medial or lateral femoral condyle was 6 mm or less.

Interpretation of roentgenograms

Three measurements were made from each film. First, knee extension was determined by the angle formed by the intersection of lines drawn parallel to the posterior cortex of the femur and tibia (Fig. 1). Second, the angle of the intercondylar roof was determined by the intersection of the lines drawn parallel to the posterior cortex of the femur and the intercondylar roof (Fig. 1). The level of the tibial joint line was defined by a line between the most superior points of the anterior and posterior margins of the proximal end of the tibia. A 10-mm wide tibial tunnel was drawn at the level of the tibial joint line so that the anterior border of the tibial tunnel was in line with the slope of the intercondylar roof (because the roentgenogram was magnified 20%, the true tunnel diameter was 8 instead of 10 mm). Third, the location of the central axis of the tibial tunnel was calculated by measuring the distance from its intersection at the tibial joint line to the anterior end of the line of the tibial plateau. This distance was then divided by the length of the tibial plateau, and the result expressed as a percentage (Fig. 2). Independent measurements were made of each film by both authors.

Statistical analysis

Simple regression was used to determine the interobserver reliability of the measurements made by each author, and to determine the relationship between knee extension and roof angle. The Kolmogorov-Smirnov test was used to determine if the measurements of knee extension, roof angle, and the position of the center of the tibial tunnel were normally distributed. The mean, standard deviation, and 95% confidence interval were used to describe the variability of the three anatomic measurements. The 95% confidence interval provides a range of means derived from a small sample that allows us to be 95% confident that it contains the mean of a larger, parent population. The confidence interval is considered imprecise if there is a wide range of means. Additional sampling is required if accuracy is to be improved. The confidence interval is considered precise if the range of means is narrow, which permits significant inferences to be drawn about the larger, parent population. Comparisons between men and women were made using an unpaired t-test. An 80% power analysis was calculated for insignificant differences to determine the number of samples required to detect the mean difference in roof angle, knee extension, and location of the tibial tunnel between the men and women. Statistics were performed on a personal computer (Macintosh 840 AV, Apple Computer, Inc., Cupertino, CA) using Statview IV (Abacus Concepts, Inc., Berkeley, CA) and Primer of Biostatistics 3/e, version 3.0 (McGraw Hill, New York, NY).

RESULTS

Measurement reliability

Regression analysis of the measurements from the two authors revealed that knee extension ($r^2 = 0.846, P < 0.0001$)
Figure 2. The tibial joint line was chosen as the reference plane for determining the position of the center of the tibial tunnel (CTT). The joint line was defined by the most superior points of the anterior (A) and posterior (P) margins of the tibia. A 10 mm wide tibial tunnel was drawn with the anterior border of the tibial tunnel in line with the slope of the intercondylar roof. The distance from the central axis of the tibial tunnel to the anterior end of the tibial joint line was measured (A-CTT). The position of the center of the tibial tunnel was calculated by dividing this distance by the length of the tibial plateau (A-P) and expressing the result as a percentage.

(Fig. 3) and roof angle were reliably measured ($r^2 = 0.630$, $P < 0.0001$). There was a moderately strong relationship between the two authors in their selection of the position for the center of the tibial tunnel ($r^2 = 0.702$, $P < 0.0001$).

Normality

The distribution of the measurements of knee extension ($P > 0.9999$), roof angle ($P > 0.9999$), and position of the center of the tibial tunnel ($P > 0.9999$) did not differ significantly from a calculated ideal normal distribution. These measurements described a normal distribution providing evidence that the selection of knees used in this study was representative of the normal knee population.

Variability between knees

There was considerable variability in the degree of knee extension ranging from $2^\circ$ of flexion to $-30^\circ$ of hyperextension with a mean of $-10^\circ \pm 5.7^\circ$ and a 95% confidence interval of $-8^\circ$ to $-12^\circ$. The roof angle varied from $26^\circ$ to $46^\circ$ with a mean of $35^\circ \pm 4.6^\circ$ and a 95% confidence interval of $34^\circ$ to $37^\circ$. The position of the center of the tibial tunnel varied from 26% to 55% from the anterior edge of the tibia with a mean of $40% \pm 5.8%$ and a 95% confidence interval of 38% to 42%.

Comparison of men and women

There was no significant difference in knee extension, roof angle, and tibial tunnel placement between the male and female knees. The 80% power analysis predicted that an enormous sampling of 567 knees would be required to detect a 1° difference in extension, 100 knees to detect a 2° difference in roof angle, and 644 knees to detect a 1% difference in the mean tibial tunnel placement between the men and women (Table 1). Based on our sample size, the power analysis confirms that there is a very low probability that we have inadvertently failed to detect a significant difference between the men and women.

Relationship of knee extension to roof angle within knees

There was a significant but weak correlation between knee extension and roof angle ($r^2 = 0.207$, $P < 0.008$) (Fig. 4). Roof angle could not be reliably predicted by measuring the degree of knee extension. A knee with a given degree of knee extension was almost as likely to have a vertical roof
as a horizontal roof (Fig. 5). For example, the eight knees with 12° to 13° of hyperextension had a variety of roof angles ranging from 32° to 44°.

**DISCUSSION**

Statistical analysis established that the distribution of the knee extension, roof angle, and tibial tunnel location measurements were normal. There was no significant difference in the means of the three knee measurements obtained from the men and women. The confidence intervals were narrow, providing a precise description of the mean knee extension, roof angle, and tibial tunnel location for the larger, parent population. Using roof angle as an example, the mean and standard deviation of the roof angle in our study was 35° ± 4.6° (N = 26), which is identical to the roof angle of 35° ± 4.7° in the larger study of normal knees N = 115) by Scuderi. 26 The same roof angle exists in knees with a torn ACL (36° ± 4.5°, N = 25)26 as well as in reconstructed knees (36° ± 3°, N = 48).19 Because our measurements had a normal distribution, a precise 95% confidence interval, and agreed with measurements from other studies, we are justified in making statistical inferences of the general population of knees based on our sample.

We found a weak relationship between the angle of the intercondylar roof and the maximum extension of the knee. This means that a surgeon cannot rely on measuring knee extension in the office or operating room as a method to predict roof angle. Knees with identical knee extension can be expected to have different slopes to the intercondylar roof. The roof angle can only be measured from a roentgenogram and has been shown to vary widely, from 23° to 60°3,26

Customized placement of the tibial tunnel to account for individual variations in knee extension and roof angle has been effective in minimizing the extent of the roofplasty and preventing roof impingement.15,17,19 In this technique the tibial tunnel is positioned posterior and parallel to the slope of the intercondylar roof with the knee in full extension. The variables of knee extension and roof angle are both simultaneously accounted for because the tibial guide keys off the intercondylar roof and the tibial pin is drilled with the knee in maximum extension.11,12 Our study supports the application of these guidelines for selecting the tibial tunnel location in both men and women.

Our clinical experience has proven that an acceptable length change of the suture (3 mm or less25) can be achieved during isometric testing when the tibial tunnel placement has been customized.15,17,19 Cadaveric studies have also shown that acceptable graft excursion profiles can be achieved for a wide range of tibial tunnel placements,10,24,27 including the customized placement of the tibial tunnel.2 This explains why large variations in the sagittal location of the tibial tunnel can occur when the surgeon does not consider anatomic variability and relies only on the isometer to help select the location for the tibial tunnel.15,19

Other reconstruction techniques have stressed that there is one “ideal” position for the tibial tunnel that can be used for every knee. It has been recommended that the tibial tunnel be placed eccentrically5 or centrally9,23 within the ACL insertion stump. These techniques do not adjust the position of the tibial tunnel for individual variations in knee extension and roof angle because the tibial guide keys off the tibial plateau rather than the intercondylar roof and the tibial guide pin is drilled with the knee in flexion rather than extension. Assum-

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**TABLE 1**

Comparison of parameters between male and female knees

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean ± SD</th>
<th>95% Cl</th>
<th>P</th>
<th>Power analysis</th>
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<tbody>
<tr>
<td>Extension (deg)</td>
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Figure 4. There was a weak relationship ($r^2 = 0.207, P = 0.008$) between the measurement of knee extension and the roof angle within a knee. Knee extension cannot be used to predict the roof angle. A knee with a given degree of extension can have a variety of different roof angles.
ing that the tibial tunnel is always placed in the same location, the surgeon will have to vary the magnitude of the roofplasty among patients if roof impingement is to be avoided. Roof impingement has been inconsistently eliminated when one position for the tibial tunnel is used.\(^1,7,8,13,14,17,19-22,28\)

The surgeon has a difficult time judging the adequacy of the roofplasty because the graft-roof relationship cannot be seen with the knee in full extension.\(^11,13,14,17-19\) Bone removal from the roof is often too conservative and incomplete. The complications of roof impingement, which include recurrent effusions, extension deficits, and graft failure, may result.

The “unforgiving knee” is a term that we have originated to identify a knee that, when reconstructed, may have a higher propensity for failure because of a tendency to place the tibial tunnel too far anteriorly (Fig. 6). The unforgiving knee is diagnosed by a lateral roentgenogram taken with the knee in maximum extension. Unforgiving knees hyperextend and have a slope to the intercondylar roof that is near vertical. These knees require a more posterior placement for the tibial tunnel than knees that do not hyperextend or have a more horizontally oriented roof angle (compare Figs. 5 and 6).

In summary, knee extension and roof angle were reliably measured from lateral roentgenograms taken with the knee in maximum extension. There is considerable variability among patients in their maximal knee extension and the slope of the intercondylar roof. These two factors influence the placement of the tibial tunnel if the surgeon’s objective is to minimize the extent of the roofplasty. Consideration should be given to customizing the position of the tibial tunnel to account for differences in anatomy. This technique does not have to be modified for men or women. The combination of a vertical slope to the intercondylar roof in a hyperextended knee

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Figure 5. Both knees have the same extension (-5°) but different slopes to the intercondylar roof, resulting in different positions for the tibial tunnel. A, to minimize the extent of the roofplasty and avoid roof impingement the tibial tunnel is aligned posterior and parallel to the intercondylar roof. The posterior margin of the tibial tunnel is at the base of the medial tibial eminence (0). B, the tibial tunnel has been moved more posteriorly than in A because the intercondylar roof is more vertical (28° compared with 38°). The anterior margin of the tibial tunnel is now at the base of the medial tibial eminence (0) instead of the posterior margin.
defines the unforgiving knee. The unforgiving knee requires a more posterior placement of the tibial tunnel if a permanent flexion contracture or late graft rupture is to be avoided.

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REFERENCES


Figure 6. A, this knee has a failed ACL reconstruction. The cause of the graft failure is not evident from the lateral roentgenogram taken in flexion. The position of the tibial tunnel (parallel lines) is similar to the location of the tibial tunnel in Figure 5A. B, the lateral roentgenogram of the fully extended knee is diagnostic of the unforgiving knee. The unforgiving knee hyperextends (in this example, 12° of recurvatum) and has a vertical slope to the intercondylar roof (in this example, 25°). The entire tibial tunnel is anterior to the intercondylar roof resulting in severe roof impingement. C, a revision ACL reconstruction was performed. The graft was sheared at the level of the tibial plateau because of a guillotine effect by the intercondylar roof. The intraoperative roentgenogram verifies that the position of the tibial tunnel was customized to account for the degree of extension and roof angle. The new tibial tunnel is posterior to the intercondylar roof at the level of the tibial plateau. An impingement rod freely passes into the intercondylar notch confirming that roof impingement has been eliminated before inserting the graft.