

# 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

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## ABSTRACT

Tension in an anterior cruciate ligament graft is greater with the knee in flexion when the angle of the tibial tunnel in the coronal plane is vertical or more perpendicular to the medial joint line of the tibia; however, the relationship of the angle of the tibial tunnel to knee function has not been studied. Greater graft tension may limit knee flexion or stretch the graft and increase anterior laxity. Five surgeons treated 119 subjects by reconstructing a torn anterior cruciate ligament using a double-looped semitendinosus and gracilis graft and a standardized technique. The femoral tunnel was drilled through the tibial tunnel. Radiographs were analyzed for tibial tunnel placement and a clinical evaluation was made 4 months postoperatively. Knees were assigned to subgroups according to the angle of the tibial tunnel in the coronal plane (65° to 69°, 70° to 74°, 75° to 79°, 80° to 84°, and 85° to 89°), with the angle of the latter subgroup being most vertical. Loss of flexion increased significantly from 0.5° to 6.5° and anterior laxity increased significantly from 0.5 to 2.2 mm as the tunnel angle was increased. The average angle of the tibial tunnel varied significantly, 11° between surgeons (range, 69° to 80°). We found a tibial tunnel angle of 75° or more is associated with greater loss of flexion and anterior laxity. Surgeons do not drill the angle of the tibial tunnel in the coronal plane accurately. We

now routinely drill the tibial tunnel at an angle of 65° to 70° in the coronal plane because it may reduce loss of flexion and anterior laxity.

It has been stated that there is a penalty for having forces in an ACL graft that are greater than those in the intact ACL. One penalty of large tensions in the graft may be an increase in anterior laxity if the graft stretches or elongates permanently with cyclic loading.<sup>13</sup>

A study reported by one of us (SMH) showed greater tension in the graft during knee flexion when the angle of the tibial tunnel in the coronal plane is more vertical or perpendicular to the medial joint line of the tibia when the femoral tunnel is drilled through the tibial tunnel; however, the clinical consequences of a vertical tibial tunnel were not determined.<sup>9</sup> Two clinical consequences of a vertical tibial tunnel, and the greater tension in the graft with flexion, may be loss of knee flexion and an increase in anterior laxity from stretching of the graft.

We found no studies published in peer-reviewed journals that investigated the relationship between the angle of the tibial tunnel in the coronal plane and loss of flexion and anterior laxity when the femoral tunnel is drilled through the tibial tunnel. We therefore decided to measure the angle of the tibial tunnel in the coronal plane, loss of flexion, and anterior laxity 4 months after ACL reconstruction in a large series of subjects (119) treated by five surgeons. One objective of our prospective study was to determine whether the angle of the tibial tunnel in the coronal plane is related to loss of flexion and anterior laxity. The second objective was to determine whether surgeons drill the angle of the tibial tunnel in the coronal plane accurately.

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Two authors have commercial affiliations with products mentioned in this study.

## MATERIALS AND METHODS

### Inclusion and Exclusion Criteria

Twelve surgeons who perform at least 75 ACL reconstructions per year were invited to participate in the study. Five surgeons agreed to participate, and they enrolled 20 to 30 consecutive subjects who met the following criteria. For a subject to be enrolled in the study, the knee with the torn ACL had to have, at the time of reconstruction, 1) motion equal to the contralateral knee, 2) no roentgenographic evidence of degenerative arthritis, 3) no ligament injuries to the medial or lateral collateral ligaments that required repair, 4) a normal contralateral knee, and 5) a willingness to be evaluated 4 months postoperatively. Subjects were excluded if the injured knee had a prior reconstruction for a torn ACL.

### Preoperative Data Collection

Patient characteristics, activity level, and injury mechanism were recorded on a standardized worksheet before surgery. The laxity of the ACL, PCL, and medial and lateral collateral ligaments and the motion of the injured knee were evaluated and compared that of with the contralateral knee.

### Surgical Technique

The torn ACL was reconstructed using a previously described arthroscopically assisted technique with an autogenous double-looped semitendinosus and gracilis tendon graft.<sup>2</sup> Briefly, the gracilis and semitendinosus tendons were harvested, muscle was removed, and the two tendons were folded in midsection over an umbilical tape. The tape was used to pull the double-looped graft through a series of cylinders that each increased in diameter by 1 mm. The diameter of the smallest cylinder that freely passed over the graft was used to drill the femoral and tibial tunnels.

In the sagittal plane, the center of the tibial tunnel was aligned 4 to 5 mm posterior and parallel to the slope of the intercondylar roof, with the knee in maximum hyperextension, using a drill guide that referenced off the slope of the intercondylar roof (Howell Tibial Guide, Arthrotek, Inc., Warsaw, Indiana). In the coronal plane, the guide centered the tibial tunnel between the medial and lateral tibial eminences; however, the angle of the tunnel in the coronal plane was drilled according to the surgeon's preference.

The placement of the femoral tunnel was determined by inserting a femoral aimer through the tibial tunnel. The size of the offset of the femoral aimer was specific for the diameter of the femoral tunnel so that the posterior wall was never more than 1 to 2 mm thick. For example, a size 7 femoral aimer with a 4.5-mm offset was used for a femoral tunnel that was 7 mm in diameter, and a size 12 femoral aimer with a 7-mm offset was used for a femoral tunnel that was 12 mm in diameter (Size-Specific Femoral Aimer, Arthrotek, Inc). The tongue-like extension of the femoral aimer was hooked posterior to the intercondylar

roof in line with the axis of the tibial tunnel. The femoral aimer was locked in position by allowing gravity to flex the knee. The flexion angle of the knee where the femoral aimer locks into position varies between knees (65° to 90°) and is determined by the orientation of the tibial tunnel and the geometry of the knee. A 25 to 30 mm long closed-end femoral tunnel was drilled using a cannulated femoral reamer. The thickness of the posterior wall of the femoral tunnel was probed with a nerve hook and was never more than 2 mm thick.

The double-looped semitendinosus and gracilis tendon graft was fixed 18 to 23 mm inside the femoral tunnel by pulling the graft through the knee until the midsection of each tendon was around a fixation post (Bone Mulch Screw, Arthrotek, Inc.). Either the surgeon or assistant manually applied an unmeasured tensile force to the graft with the knee in maximum hyperextension to pre-tension the graft. The graft was fixed inside the tibial tunnel using a washer with 13 spikes and a compression screw (WasherLoc, Arthrotek, Inc.). An unmeasured amount of bone graft was compacted inside the femoral tunnel through a bore in the femoral fixation device to fill voids between the tendon graft and tunnel wall. Bone compaction increases stiffness, increases friction inside the tunnel, and produces reciprocal tensile behavior of the graft with the anterior bundles sharing slightly more load in flexion and the posterior bundles sharing slightly more load in extension.<sup>19,20</sup> Bone compaction was discontinued after reaching the desired tension in the graft, which was determined by displacing the graft with a nerve hook probe.

### Postoperative Care and Rehabilitation

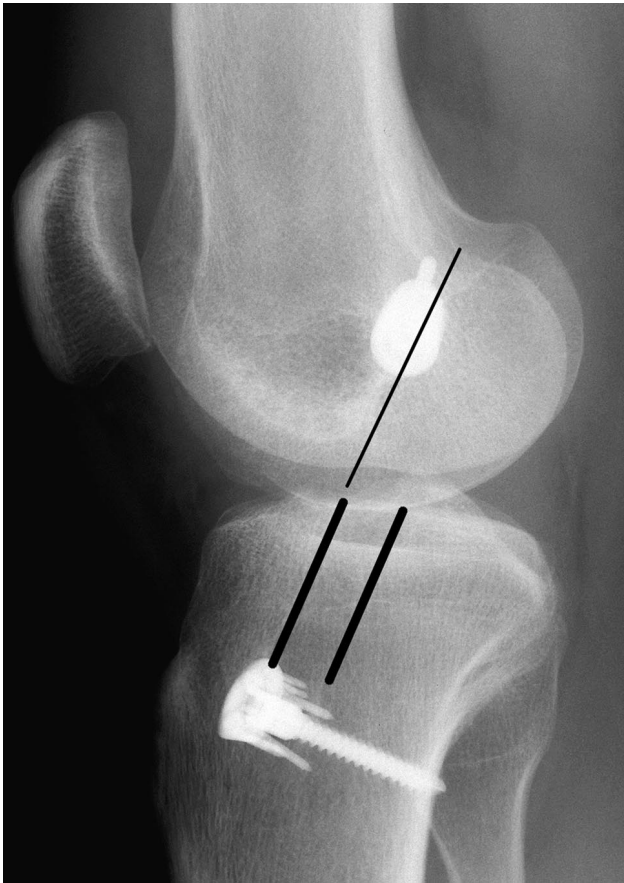
Three surgeons prescribed a knee immobilizer or a range of motion brace, which was used for 1 to 2 weeks after surgery. Two surgeons did not prescribe a brace. Subjects were encouraged to bear weight on the reconstructed limb and use crutches for an average of 2 weeks. Physical therapy was prescribed at the discretion of the surgeon.

### Data Collection 4 Months Postoperatively

*Assessment of Radiographs.* One author (SMH) determined the placement and measured the angle of the tibial tunnel in the sagittal and coronal planes.

The placement of the tibial tunnel in the sagittal plane was analyzed from a lateral radiograph of the knee in full extension to determine whether the graft was placed without roof impingement (Fig. 1). It was necessary to determine whether the graft was placed without roof impingement because roof impingement increases anterior laxity<sup>4,8</sup> and confounds the detection of any relationship between the angle of the tibial tunnel in the coronal plane and anterior laxity. Roof impingement was prevented when the entire width of the tibial tunnel was posterior to the slope of the intercondylar roof.<sup>8</sup>

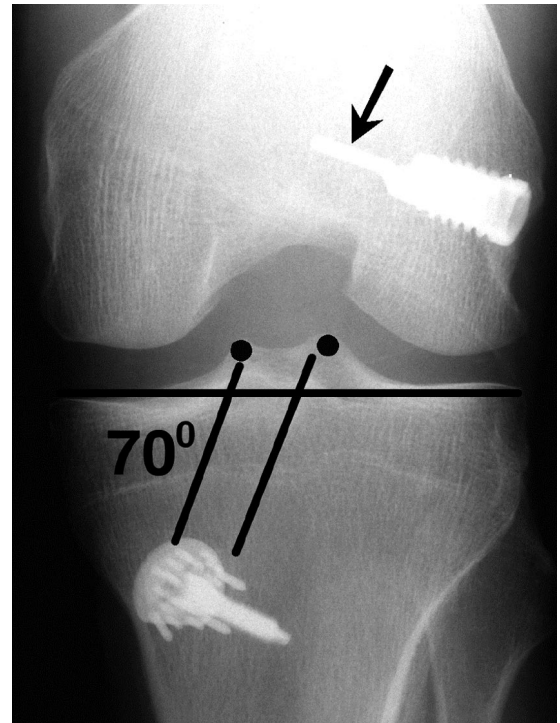
The placement of the tibial tunnel in the coronal plane was analyzed from either an AP or a notch radiograph to determine whether the tibial tunnel was contained be-



**Figure 1.** A lateral radiograph of the knee in maximum extension was obtained 4 months postoperatively to determine whether impingement of the graft by the intercondylar roof had been prevented. Roof impingement was prevented when the entire width of the tibial tunnel (two solid lines) was posterior to the slope of the intercondylar roof (narrow line). The double-looped semitendinosus and gracilis tendon graft was looped around a fixation post in the femoral tunnel, and the free ends of the graft were fixed inside the tibial tunnel with a multiple-spiked washer and compression screw.

tween medial and lateral eminences and to measure the angle the tibial tunnel formed with the medial joint line (Figs. 2 and 3). It was necessary to determine whether the tibial tunnel was contained between the medial and lateral eminences because placement of a portion of the tunnel medial to the medial tibial eminence limits flexion<sup>17</sup> and placement of a portion of the tunnel lateral to the lateral tibial eminence increases anterior laxity,<sup>16</sup> and either of these two placements confounds the detection of any relationship between the angle of the tibial tunnel in the coronal plane and loss of flexion or anterior laxity. The angle of the tibial tunnel was the angle subtended by a line drawn along the axis of the tibial tunnel and its intersection with the medial portion of a line drawn along the plane of the articular surface of the proximal tibia.<sup>6,9</sup>

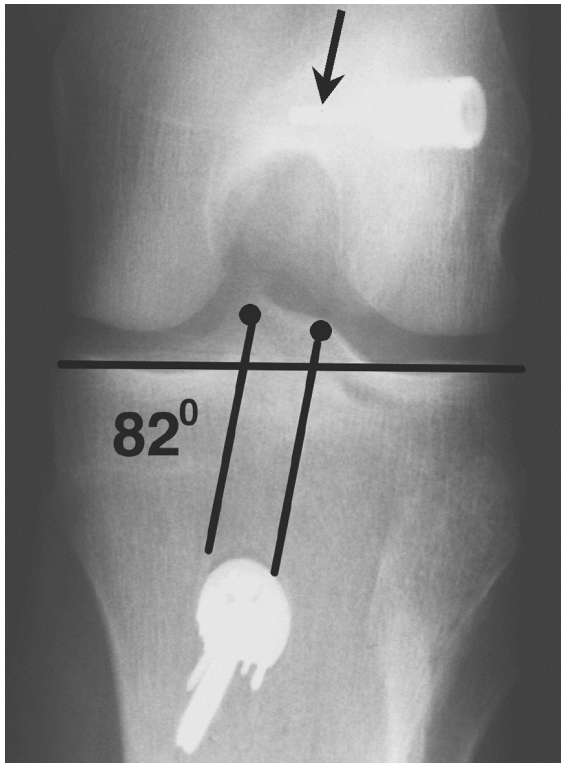
*Assessment of Loss of Flexion, Anterior Laxity, and Clin-*



**Figure 2.** An AP notch view of a left knee was obtained 4 months postoperatively to measure the angle of the tibial tunnel in the coronal plane and to determine whether the tibial tunnel (two oblique parallel lines) was contained between the tibial spines (two black dots). The angle of the tibial tunnel in the coronal plane is measured as the angle subtended by the axis of the tibial tunnel and a line drawn parallel to the medial articular surface of the tibia. In this example, the entire width of the tibial tunnel is contained between the limits of the tibial spines and the angle of the tibial tunnel in the coronal plane was 70°. The longitudinal axis of the femoral tunnel (arrow) and tibial tunnel is collinear because the femoral tunnel was drilled through the tibial tunnel. The axis of the femoral tunnel is at 1:30 on an imaginary clock face.

*ical Outcome.* Loss of flexion was calculated as the difference in flexion between the treated and intact knee as measured with a goniometer. Anterior laxity was calculated as the difference in anterior displacement at 25° to 30° of flexion between the treated and intact knee as measured with an arthrometer (KT-1000 arthrometer, MEDmetric, Inc., San Diego, California) during a maximum anterior load applied manually to the posterior tibia. The Lachman test in the treated knee was graded as having either a firm or soft end point. The pivot shift test was graded as negative if the degree of subluxation in the treated knee was the same as that in the intact knee and positive if the degree of subluxation in the treated knee was greater than that in the intact knee.

We used the International Knee Documentation Committee form to evaluate overall knee function. Knees were graded normal, nearly normal, abnormal, or severely abnormal in seven categories. The categories that were evaluated included the patient's assessment of his or her knee



**Figure 3.** An AP notch view of a left knee with the angle of the tibial tunnel in the coronal plane at 82°. The axis of the femoral tunnel is at 12:30 on an imaginary clock face (arrow). The femoral tunnel and tibial tunnel are more vertical than the knee in Figure 2. (See explanation of lines and dots in legend at Figure 2.)

function, symptoms (pain, swelling, and giving way), motion, stability, crepitus in each knee compartment, harvest site abnormalities, and the single-legged hop test. The lowest grade in any category determined the final outcome for that subject's knee.

**Statistical Analysis**

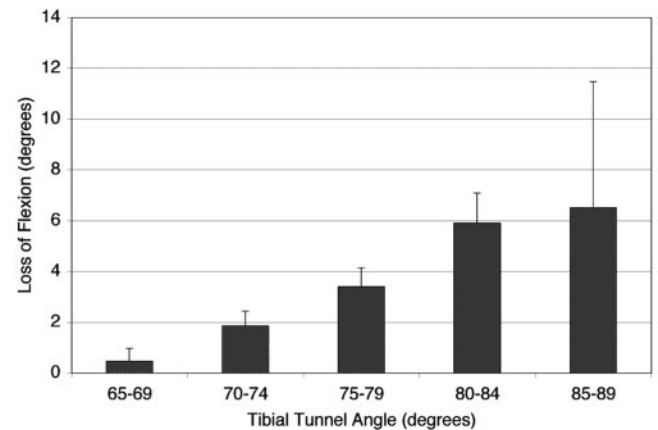
Descriptive statistics (mean ± standard deviation) were compiled for radiographic measurements and clinical outcome parameters for the subjects treated by each surgeon and for all subjects. Knees were assigned to five subgroups according to the angle of the tibial tunnel in the coronal plane (65° to 69°, 70° to 74°, 75° to 79°, 80° to 84°, and 85° to 89°). One subject with a 62° angle did not fit a subgroup and was excluded from the analyses. A one-factor analysis of variance was performed to determine whether there was a significant increase in the loss of flexion as the tunnel angle of the subgroup increased; a significant increase indicated a relationship between the angle of the tibial tunnel and loss of flexion. A one-factor analysis of variance was performed to determine whether there was a significant increase in anterior laxity as the tunnel angle of the subgroup increased; a significant increase indicated a relationship between the angle of the tibial tunnel and

anterior laxity. A one-factor analysis of variance was performed to determine whether there was a significant difference in the average angle of the tibial tunnel between surgeons; a significant difference indicated the angle of the tibial tunnel in the coronal plane was not placed accurately. Post hoc analysis was performed using the Fisher pairwise least significant difference test. Significance was set at  $P < 0.05$ .

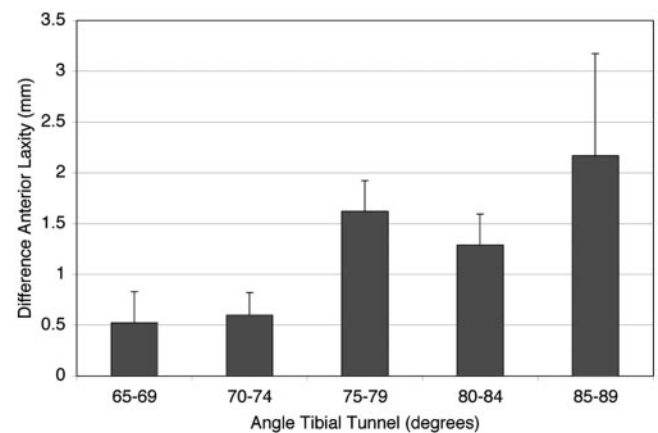
**RESULTS**

**Relationship of the Angle of the Tibial Tunnel to Loss of Flexion**

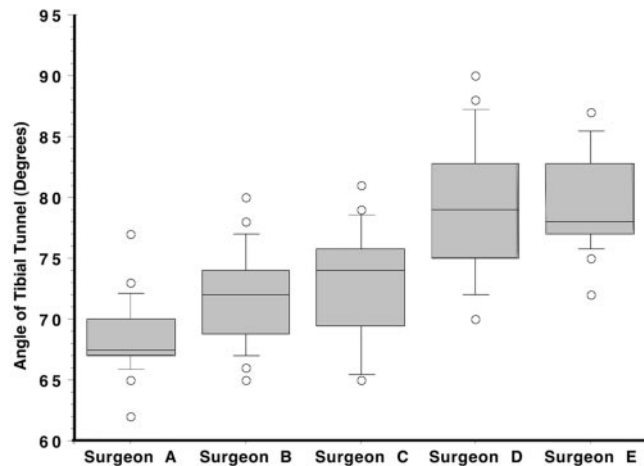
There was a relationship between the angle of the tibial tunnel in the coronal plane and loss of flexion (Fig. 4). Loss of flexion increased from 0.5° to 6.5° as the tunnel angle of



**Figure 4.** Comparison of the average loss of flexion (±SEM) between the reconstructed and contralateral knee according to the tibial tunnel angle in the coronal plane. See text for details.



**Figure 5.** Comparison of the average increase in anterior laxity (±SEM) between the reconstructed and contralateral knee according to tibial tunnel angle in the coronal plane. See text for details.



**Figure 6.** A box plot compares the variability of the angle of the tibial tunnel in the coronal plane for five surgeons. Each box plot is composed of five horizontal lines that display the 10th, 25th, 50th, 75th, and 90th percentiles of the angle of the tibial tunnel in the coronal plane. Wider boxes and error bars indicate more variability (Surgeon C and D). A circle (o) represents a knee with a tunnel angle either below the 10th or above the 90th percentile. The angle of the tibial tunnel was not placed consistently because the average angle of the tibial tunnel for each surgeon was different ( $P < 0.0001$ ). The average angle of the tibial tunnel made by Surgeon A was less than that of the average angles of the other surgeons ( $P = 0.0116$  to  $P < 0.0001$ ). The average angle of the tibial tunnel made by Surgeon B was less than that of Surgeon D ( $P < 0.0001$ ) and Surgeon E ( $P < 0.0001$ ). The average angle of the tibial tunnel made by Surgeon C was less than that of Surgeon D ( $P < 0.0001$ ) and Surgeon E ( $P < 0.0001$ ) (Fisher's pairwise least significant difference test).

the subgroup increased ( $P = 0.0007$ ). The loss of flexion in the subgroups with a tunnel angle of  $65^\circ$  to  $69^\circ$  ( $0.5^\circ \pm 2.5^\circ$ ) and  $70^\circ$  to  $74^\circ$  ( $1.9^\circ \pm 3.4^\circ$ ) was similar ( $P = 0.29$ , not significant) and averaged less than  $2^\circ$ . However, the loss of flexion in the subgroup with a tunnel angle of  $65^\circ$  to  $69^\circ$  was significantly less than the loss of flexion of the subgroups with a tunnel angle of  $75^\circ$  to  $79^\circ$  ( $P = 0.02$ ),  $80^\circ$  to  $84^\circ$  ( $P = 0.0002$ ), and  $85^\circ$  to  $89^\circ$  ( $P = 0.005$ ). Furthermore,

the loss of flexion in the subgroup with a tunnel angle of  $70^\circ$  to  $74^\circ$  was significantly less than the loss of flexion of the subgroups with a tunnel angle of  $80^\circ$  to  $84^\circ$  ( $5.9^\circ \pm 5.2^\circ$ ) ( $P = 0.003$ ) and  $85^\circ$  to  $89^\circ$  ( $6.5^\circ \pm 12.2^\circ$ ) ( $P = 0.02$ ).

**Relationship of the Angle of the Tibial Tunnel to Anterior Laxity**

There was a relationship between the angle of the tibial tunnel in the coronal plane and anterior laxity (Fig. 5). Anterior laxity increased from 0.5 to 2.2 mm as the tunnel angle of the subgroup increased ( $P = 0.01$ ). The increase in anterior laxity in the subgroups with a tunnel angle of  $65^\circ$  to  $69^\circ$  ( $0.5 \pm 1.5$  mm) and  $70^\circ$  to  $74^\circ$  ( $0.6 \pm 1.3$  mm) was similar ( $P = 0.85$ , not significant). However, the anterior laxity in the subgroup with a tunnel angle of  $65^\circ$  to  $69^\circ$  was significantly less than the anterior laxity in the subgroups with a tunnel angle of  $75^\circ$  to  $79^\circ$  ( $1.6 \pm 1.7$  mm) ( $P = 0.009$ ) and  $85^\circ$  to  $89^\circ$  ( $2.2 \pm 2.5$  mm) ( $P = 0.02$ ). The anterior laxity in the subgroup with a tunnel angle of  $70^\circ$  to  $74^\circ$  was significantly less than the anterior laxity in the subgroups with a tunnel angle of  $75^\circ$  to  $79^\circ$  ( $P = 0.007$ ) and  $85^\circ$  to  $89^\circ$  ( $P = 0.02$ ).

**Accuracy of the Angle of the Tibial Tunnel in the Coronal Plane**

The angle of the tibial tunnel in the coronal plane was not drilled accurately (Fig. 6). The average angle of the tibial tunnel varied  $11^\circ$  between surgeons (range, from  $69^\circ$  to  $80^\circ$ ) ( $P < 0.0001$ ). In contrast to not accurately drilling the angle of the tibial tunnel in the coronal plane, every tibial tunnel was placed without roof impingement (that is, posterior to the intercondylar roof) in the sagittal plane and centered between the medial and lateral tibial eminences in the coronal plane.

**Clinical Outcome**

Table 1 describes the average age, the sex distribution, duration of brace use, number of subjects who were rehabilitated with the assistance of a physical therapist, number of knees with a meniscal repair, average angle of the tibial tunnel in the coronal plane, difference in flexion, and difference in anterior laxity between the treated and

**TABLE 1**  
Patient Data and Findings by Surgeon

Surgeon	Patient age	Patient sex	Brace use (weeks)	Physical therapy	Meniscal repair	Tunnel angle (deg)	Tunnel variance (deg)	Loss of flexion (deg)	Anterior laxity (mm)
A	28	10 M 15 F	None	11 of 25	3 of 25	69	9	1	0.7
B	25	10 M 16 F	2.5	4 of 26	None	72	14	0	0.6
C	38	10 M 10 F	None	20 of 20	8 of 20	74	26	2.5	0.8
D	33	16 M 8 F	2	23 of 24	2 of 24	79	29	6	1.5
E	27	12 M 12 F	2.4	24 of 24	None	80	18	5	1.7

intact knee. All of these findings are listed for each of the participating surgeons.

For all subjects, the average loss of flexion was  $3^\circ \pm 5^\circ$ , and the average loss of extension was  $0.5^\circ \pm 2.6^\circ$ . The difference in anterior laxity between the treated and intact knee was less than 3 mm in 86% (102) of the treated knees, between 3 and 5 mm in 13% (15), and greater than 5 mm in 2% (2) during a maximum anterior load applied manually to the posterior tibia. The Lachman test was negative in 98% (117) of the treated knees and the pivot shift test was negative in 96% (114) of the treated knees. The overall International Knee Documentation Committee score for the treated knees at 4 months was normal in 20% (24), nearly normal in 61% (72), abnormal in 16% (19), and severely abnormal in 3% (4).

## DISCUSSION

The most important results from our study were that the angle of the tibial tunnel in the coronal plane is related to loss of flexion and anterior laxity when the femoral tunnel is drilled through the tibial tunnel, and that surgeons do not drill the angle of the tibial tunnel accurately. Before interpreting the results, it is necessary to determine whether two assumptions concerning the methods of the study affect these results.

### Methods Issues

Our first assumption was that a relationship between the angle of the tibial tunnel and loss of flexion and anterior laxity could be detected as early as 4 months postoperatively. The decision to measure loss of flexion and anterior laxity 4 months postoperatively was based on several studies that showed that motion and anterior laxity do not change between 3 months and 2 years<sup>18</sup> and 4 months and 2 years<sup>6,7</sup> after surgery. The assumption was reasonable because we did show, from data collected 4 months postoperatively, that the tibial tunnel angle in the coronal plane is related to loss of flexion and anterior laxity.

Our second assumption is that the lack of standardization of postoperative brace use and physical therapy did not affect the loss of flexion and anterior laxity. This assumption was justified based on four observations. Bracing did not affect loss of flexion because the least loss of flexion occurred when either a brace was used (Surgeon B) or was not used (Surgeon A) (Table 1). Bracing did not affect anterior laxity because the least anterior laxity occurred when either a brace was used (Surgeon B) or was not used (Surgeons A and C). Physical therapy did not affect loss of flexion because the least loss of flexion occurred when physical therapy was either used sparingly (Surgeon B) or was used for every subject (Surgeon C). Finally, physical therapy did not affect anterior laxity because the least anterior laxity occurred when physical therapy was used either sparingly (Surgeon B) or was used for every subject (Surgeon C).

## Interpretation of Results

Anterior cruciate ligament reconstruction is a technically challenging procedure, and attention to the placement of the tibial and femoral tunnels is essential for preventing motion loss and restoring anterior laxity to normal. Although guidelines have been established for drilling the tibial and femoral tunnel for the two-incision technique, in which the femoral tunnel is drilled through a femoral skin incision and not through the tibial tunnel,<sup>3,5,8,16,17</sup> we could not find any studies reported in the peer-reviewed literature that provided guidelines for the single-incision technique, in which the femoral tunnel is drilled through the tibial tunnel.

The single-incision technique requires following distinct guidelines for drilling the tibial tunnel because free placement of the femoral tunnel is not possible when the femoral tunnel is drilled through the tibial tunnel.<sup>9</sup> The maneuverability of the femoral drill is limited because the tibial tunnel is relatively long (40 to 55 mm) and narrow (8 to 10 mm in diameter). Free placement of the femoral tunnel may be clinically important because the placement of the femoral tunnel determines the tensile force in the graft.<sup>1,10,11,14</sup> A femoral tunnel positioned too anteriorly or distally causes abnormal increases in graft tension with flexion that may result in graft failure, loss of fixation, or limited motion.<sup>10,13,15</sup>

Our study of the single-incision technique suggests that flexion and anterior laxity may be improved by accurately drilling the tibial tunnel in the coronal plane. The two subgroups with a tunnel angle of  $65^\circ$  to  $69^\circ$  and  $70^\circ$  to  $74^\circ$  had the least loss of flexion and the least anterior laxity. The three subgroups with a tunnel angle of  $75^\circ$  to  $79^\circ$ ,  $80^\circ$  to  $84^\circ$ , and  $85^\circ$  to  $89^\circ$  had a greater loss of flexion and greater anterior laxity. These findings suggest that drilling the tibial tunnel at an angle less than  $75^\circ$  in the coronal plane and avoiding an angle of  $75^\circ$  or greater may reduce the loss of flexion and anterior laxity.

One limitation of our study is that we cannot conclude that drilling the tibial tunnel at an angle of less than  $75^\circ$  in the coronal plane reduces loss of flexion and anterior laxity because the angle of the tibial tunnel was not randomly assigned to each subject. We did not randomly assign the tunnel angle because the surgeons could not agree at the beginning of the study on the best angle for drilling the tibial tunnel because guidelines were not available. Furthermore, even if each subject had been assigned a specific tunnel angle, it is doubtful that the tibial tunnel would have been drilled at that angle without radiographic control, because our study showed that the angle of the tibial tunnel was not drilled accurately when left up to the surgeon's judgment.

Not randomly assigning the tunnel angle to each subject resulted in an unequal distribution of each surgeon's subjects in the five subgroups. For example, more subjects of Surgeons A, B, and C were in the subgroups with a tunnel angle of  $65^\circ$  to  $69^\circ$  and  $70^\circ$  to  $74^\circ$ , and more subjects of Surgeons D and E were in the subgroups with a tunnel angle of  $75^\circ$  to  $79^\circ$ ,  $80^\circ$  to  $84^\circ$ , and  $85^\circ$  to  $89^\circ$  because the average angle of the tibial tunnel was significantly differ-

ent between surgeons. An unequal distribution of each surgeon's subjects suggests a link between the angle of the tibial tunnel and the judgment of the surgeon. A link between the angle of the tibial tunnel and the surgeon raises the possibility that either the differences in surgical technique, such as tensioning, between surgeons, or the differences in the detection of flexion loss or anterior laxity between surgical centers (detection bias), may be the actual explanation for the relationship between the angle of the tibial tunnel in the coronal plane and loss of flexion and anterior laxity, and not the angle of the tibial tunnel.

We believe it is highly unlikely that differences in tensioning between surgeons explain the relationship. For differences in tensioning to explain the relationship, the three surgeons (A, B, and C) whose subjects had a more oblique tunnel angle, less loss of flexion, and less anterior laxity would each have had to apply the same tension to the graft, while the two surgeons (D and E) whose subjects had a more vertical tunnel angle, more loss of flexion, and more anterior laxity would each have had to apply the same tension to the graft but a different tension than the other three surgeons. Such a systematic series of coincidences is unlikely, especially because the tension was not measured, was manually applied by a variety of surgeons and assistants, and changed after compacting bone into the femoral tunnel.

A similar argument can be made that differences in the detection of flexion loss and anterior laxity between surgical centers is not the explanation for the relationship between the angle of the tibial tunnel in the coronal plane and loss of flexion and anterior laxity. For differences in the detection of flexion loss and anterior laxity between surgeons to explain the relationship, the three surgeons (A, B, and C) whose subjects had a more oblique tunnel angle would each have had to similarly underreport loss of flexion and underreport anterior laxity, while the two surgeons (D and E) whose subjects had a more vertical tunnel angle, would each have had to similarly overreport loss of flexion and overreport anterior laxity. Again, we believe that such a systematic series of coincidences by independent surgical centers is unlikely.

A second limitation of the study is that we did not determine the specific angle for drilling the tibial tunnel in the coronal plane that is related to the least loss of flexion and anterior laxity. Instead, our results determined a range of angles, from 60° to 74°. Although our results suggest that the angle should be less than 75°, it is not known whether the angle should be drilled closer to 60° or to 75°. Drilling the angle of the tibial tunnel at 60° orients the graft nonanatomically because the average angle of the intact ACL is 71° in the coronal plane.<sup>9</sup> Our results and anatomic considerations suggest that drilling the tibial tunnel at an angle of 65° to 70° in the coronal plane may be a reasonable compromise.

A third limitation is that we did not measure the placement of the femoral tunnel postoperatively, which prevented us from determining whether the placement of the femoral tunnel is related to the loss of flexion and anterior laxity. Consistent with the experience of others, we found that neither the angle nor the position of the femoral

tunnel can be accurately measured from the radiographs.<sup>9,17</sup> The measurement accuracy was further complicated in our study by the less distinct sclerotic outline of the femoral tunnel caused by compaction of bone into the femoral tunnel through the femoral fixation device. Computerized tomography and MRI were not used because artifacts from imaging the titanium femoral fixation device obscure the femoral tunnel.<sup>9</sup>

Our study proved that surgeons do not drill the tibial tunnel at the same angle in the coronal plane. The average angle of the tibial tunnel varied 11° (69° to 80°) between surgeons, indicating that the angle of the tibial tunnel was not drilled accurately. One explanation for the inaccuracy is that, at the start of the study, there were no guidelines for drilling the angle of the tibial tunnel. Another explanation is that two surgeons (D and E) preferred to avoid injuring the medial collateral ligament and therefore drilled lateral to the medial collateral ligament, resulting in a vertical tibial tunnel, while two surgeons (A and B) preferred to drill through the medial collateral ligament, resulting in a more oblique tibial tunnel.

These observations have changed the way we drill the angle of the tibial tunnel in the coronal plane. To drill the angle of the tibial tunnel less than 75° and to improve the accuracy in drilling the angle of the tibial tunnel, we now use an alignment rod inserted into a drill hole into the handle of the tibial guide and intentionally drill through the medial collateral ligament. The alignment rod is oriented perpendicular to the long axis of the tibia and parallel to the joint line, which positions the tibial guide to drill the tunnel at an angle of 70°. Surgeon A used the alignment rod and this technique, and the average angle of the tibial tunnel of his subjects was 69°, with less variance (9°) than the other surgeons (Table 1).

Others may not reproduce the results of our study unless they control three factors that are known to affect loss of flexion and anterior laxity. Because placement of the tibial tunnel medial to the tibial eminence causes loss of flexion<sup>17</sup> and placement of the tibial tunnel lateral to the tibial eminence causes anterior laxity,<sup>16</sup> it was necessary to center the tibial tunnel between the eminences in the coronal plane. An analysis of an AP or notch radiograph verified that the tibial tunnel was centered in every knee. Because placement of the tibial tunnel anterior to the intercondylar roof in the extended knee causes anterior laxity from roof impingement,<sup>8</sup> it was necessary to position the tibial tunnel posterior and parallel to the intercondylar roof in the sagittal plane. An analysis of a lateral radiograph with the knee in full extension verified that roof impingement was prevented in every knee. Because slippage of the graft during aggressive rehabilitation can cause anterior laxity, we used strong, stiff fixation methods to attach the double-looped semitendinosus and gracilis tendon graft.<sup>12,19</sup> Only by controlling these three potentially confounding factors were we able to determine that there is a relationship between the angle of the tibial tunnel in the coronal plane and loss of flexion and anterior laxity.

In summary, we have shown that loss of flexion and anterior laxity are greater when the angle of the tibial tunnel is drilled at 75° or more in the coronal plane.

Drilling the angle of the tibial tunnel at 65° to 70° in the coronal plane may reduce loss of flexion and anterior laxity. Surgeons should be aware that it is easy to drill the angle of the tibial tunnel inaccurately. However, the tunnel angle can be drilled more accurately when an alignment rod in the tibial guide is oriented perpendicular to the long axis of the tibia and parallel to the joint line and the tibial tunnel is drilled through the medial collateral ligament.

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