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Multiple Ligament Reconstruction Femoral Tunnels: Intertunnel Relationships and Guidelines to Avoid Convergence

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Multiple Ligament Reconstruction Femoral Tunnels

Intertunnel Relationships and Guidelines to Avoid Convergence

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Background: Knee dislocations often require multiple concurrent ligament reconstructions, which involve creating several tunnels in the distal femur. Therefore, the risk of tunnel convergence is increased because of the limited bone volume within the distal aspect of the femur.

Purpose: To assess the risk of tunnel convergence and determine the optimal reconstruction tunnel orientations for multiple ligament reconstructions in the femur.

Study Design: Descriptive laboratory study.

Methods: Three-dimensional knee models were developed from computed tomography scans of 21 patients. Medical image processing software was used to create tunnels for each of the primary ligamentous structures, replicating a surgical approach that would be used in multiple ligament reconstructions. Thereafter, the tunnel orientation was varied in surgically relevant directions to determine orientations that minimized the risk of tunnel convergence. The orientation of the anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) tunnels was held constant throughout the study, while the orientation of the fibular collateral ligament (FCL), popliteus tendon (PLT), superficial medial collateral ligament (sMCL), and posterior oblique ligament (POL) tunnels was varied to avoid convergence.

Results: A high risk of tunnel convergence was observed between the FCL and ACL tunnels when the FCL tunnel was aimed at 0° in the axial and coronal planes. Aiming the FCL tunnel 35° anteriorly minimized convergence with the ACL tunnel. No tunnel convergence was observed for the PLT tunnel aimed 35° anteriorly and parallel to the FCL tunnel. To avoid convergence between the sMCL and PCL tunnels, the sMCL tunnels should be aimed 40° proximally in the coronal plane and 20° to 40° anteriorly. During concomitant POL reconstruction, the sMCL should be aimed 40° proximally and anteriorly and the POL 20° proximally and anteriorly. The PLT and POL tunnels aimed at 0° in both the coronal and axial planes had an increased risk of violating the intercondylar notch.

Conclusion: Femoral tunnel orientations during multiple ligament reconstructions need to be adjusted to avoid tunnel convergence. On the lateral side, aiming the FCL and PLT tunnels 35° anteriorly eliminated convergence with the ACL tunnel. On the medial side, tunnel convergence was avoided by orienting the sMCL tunnel 40° proximally and anteriorly and the POL tunnel 20° proximally and anteriorly. The POL and PLT tunnels aimed at 0° in the axial plane had an increased risk of violating the intercondylar notch.

Clinical Relevance: The risk of tunnel convergence with the ACL and PCL femoral tunnels can be reduced by adjusting the orientation of the FCL and PLT tunnels and the sMCL and POL tunnels, respectively.

Keywords: multiple ligament reconstructions; knee; femur; tunnel orientation; tunnel convergence

Knee dislocations are rare but complex injuries.[2] Surgical treatment of the injured ligament structures is reported to result in improved clinical outcomes compared with nonsurgical treatment.[6,9,28,31,34,35] Reconstruction of the cruciate ligaments is widely accepted, whereas repair of the collateral ligaments remains controversial.[29] When indicated, repair of the collateral ligaments has been associated with higher failure rates compared with reconstruction.[27,39] Thus, reconstruction is usually recommended for both cruciate[7,10,12,17]

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and collateral ligaments.[27,39] In multiple ligament knee injuries, it is recommended that all injured structures be reconstructed concurrently to minimize the risk of graft failure and to allow for early knee motion, which promotes healing and decreases the risk of postoperative stiffness.[14,18,24,25]

In recent years, there has been a growing advocacy for anatomic reconstruction of knee ligament injuries. The optimal locations of tunnels for anatomic reconstruction of individual ligamentous structures have been defined by prior studies.[1,5,19,22,26,30,38,41] In addition, several techniques have been described for multiple ligament knee reconstructions.[8,40] Common among each technique is the need to create several reconstruction tunnels in the distal femur, which has a limited bone mass, posing a risk of tunnel convergence. When reconstruction tunnels converge, the reconstruction graft integrity can be damaged and the reconstruction procedure compromised. Additionally, tunnel convergence may result in damage to fixation devices and poor graft fixation, leading to reconstruction failure.

A limited body of literature exists regarding the optimal 3-dimensional tunnel orientation in the setting of multiligament reconstructions. In a previous study, a high risk of tunnel convergence between multiple reconstruction tunnels in the tibia was reported. Therefore, a need to adjust the tunnel orientation during multiligament reconstructions was suggested.[32] Different angles have been suggested in the literature for both medial-sided[4,16] and lateral-sided reconstructions.[3,13,15,20,37] However, to our knowledge, there is no available literature concerning the optimal tunnel orientation for multiple knee ligament reconstructions of all 4 primary ligamentous structures: anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), and posteromedial and posterolateral corners. The aim of our study was to determine the optimal tunnel orientation in the femur when performing multiple ligament knee reconstructions to achieve the desired tunnel length while avoiding tunnel convergence.

METHODS

Imaging Protocol

This study was approved by the Regional Ethics Committee at Oslo University Hospital, Oslo, Norway. A total of 21 patients were included in the study. Computed tomography (CT) was performed using a 16-row scanner (16-slice Brilliance; Philips). The knee was positioned in an extended position with the patella pointing anteriorly. The sequence of scans, at 0.75-mm axial slice thicknesses, was obtained using standard 120-kVp and 250-mAs collection techniques. Each CT scan was exported to an image processing program (Mimics; Materialise) and segmented above a minimum grayscale threshold to remove all soft tissue such that only voxels corresponding to bone remained. The segmented CT image data were combined to produce a 3-dimensional geometric model of the femur for each knee.

The results of prior anatomic and radiographic studies[1,5,19,22,26,30,38,41] were utilized to identify the surface locations (centers of the attachment sites), tunnel diameters, and depths of anatomic reconstruction tunnels for each of the 4 primary ligamentous structures. The original reconstruction tunnel diameters and depths are summarized in Table 1. Mimics software was used to simulate all tunnels, replicating a surgical approach that would be used in multiple ligament reconstructions. Tunnel convergence was defined as the interference of adjacent tunnels (ie, intersection of neighboring tunnel circumferences). A 2-mm clearance between tunnels was defined as the minimum safe distance to ensure a sufficient bone mass for reconstruction. Thus, tunnels were determined to be converging if the shortest distance between their surfaces (circumferences) was less than 2 mm. In this study, all knee reconstruction tunnels for a single-bundle ACL, double-bundle PCL, anatomic posterolateral corner (fibular collateral ligament [FCL], popliteofibular ligament, and popliteus tendon [PLT]), and anatomic posteromedial corner (superficial medial collateral ligament [sMCL] and posterior oblique ligament [POL]) were simulated, representing a knee injury with global laxity and knee dislocation type 4.[36]

The orientation of the ACL and PCL tunnels was held constant throughout the study, while the orientation of the FCL, PLT, sMCL, and POL tunnels was varied to avoid convergence. The starting (neutral) position for the FCL, PLT, sMCL, and POL tunnels was direct orientation along the lateral axis (along the epicondyles). The orientation of the tunnels was expressed in terms of anterior and proximal rotation from the starting position. Anterior rotation of a tunnel was defined as rotation in the axial plane, such that displacement of the end point of said tunnel is in the anterior direction toward the trochlea. Similarly, proximal rotation of a tunnel was defined as rotation perpendicular to the axial plane, such that displacement of the end point of the tunnel is in the proximal direction toward the hip joint. Anterior rotation was performed first, and proximal rotation was performed second. The anatomic frames are represented relative to the femur in Figure 1.

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TABLE 1
Tunnel Dimensions for Ligament Reconstruction in the Femur[a]

Femoral Tunnel	Diameter, mm	Length, mm	Description of Tunnel Position
SB ACL	10	25	A 10 × 25–mm single-bundle reconstruction tunnel was created on the anatomic ACL femoral footprint.[41]
DB PCL	ALB: 11; PMB: 7	25	Two tunnels were created, representing the 2 bundles of the PCL. The distal edge of the ALB was placed adjacent to the articular cartilage, whereas the PMB was centered approximately 8.6 mm proximal to the articular cartilage surface.[19]
FCL	9	25	A 9 × 25–mm reconstruction tunnel was created on the anatomic FCL footprint, which is located 1.4 mm proximal and 3.1 mm posterior to the lateral epicondyle.[22,23]
PLT	9	25	A 9 × 25–mm reconstruction tunnel was created on the anatomic PLT footprint, which is located in the proximal portion of the anterior one-fifth of the femoral popliteal sulcus.[22,23]
POL	7	25	A 7 × 25–mm reconstruction tunnel was created on the anatomic POL footprint.[21,26]
sMCL	7	25	A 7 × 25–mm reconstruction tunnel was created on the anatomic sMCL femoral footprint, which is located 3.2 mm proximal and 4.8 mm posterior to the medial epicondyle.[21,26]

[a]ACL, anterior cruciate ligament; ALB, anterolateral bundle; DB, double-bundle; FCL, fibular collateral ligament; PCL, posterior cruciate ligament; PLT, popliteus tendon; PMB, posteromedial bundle; POL, posterior oblique ligament; SB, single-bundle; sMCL, superficial medial collateral ligament.

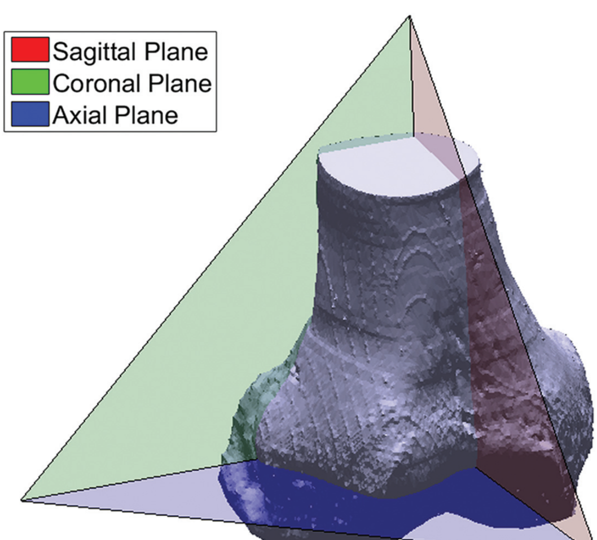

Figure 1. Anatomic frames represented on the distal femur. The tunnels were varied in the axial and coronal planes. The starting (neutral) position was direct orientation along the x-axis (along the epicondyles). For variation in the axial plane, tunnels were directed anteriorly toward the trochlea (maximum 40° from the x-axis); for variation in the coronal plane, tunnels were directed proximally toward the hip joint.

Using MATLAB (The MathWorks), the orientation of the FCL tunnel was varied in increments of 1° from 0° to 40° both anteriorly and proximally, starting from a pure lateral orientation. Forty degrees was chosen as the upper limit of angulation, as a previous study by Shuler et al[37] reported that drilling tunnels at over 40° of angulation resulted in elliptical tunnels and thinning of cortices. Thus, 1600 orientations of the FCL were tested on each patient, and for each orientation, collision or clearance with adjacent tunnels was recorded. Using these data, a collision map was assembled, demonstrating the percentage of patients whose tunnels collided for each orientation. The purpose of the collision map was to reveal "safe zones" or orientations that were statistically unlikely to lead to tunnel convergence. An analogous optimization method was used for the sMCL and POL reconstruction tunnels on the medial side of the femur.

The optimally oriented reconstruction tunnels were then represented using Mimics to ensure that they remained within the surface of the bone, particularly to avoid violating the trochlea and the intercondylar notch. The rate of tunnel collision, distance between tunnels and the intercondylar notch, distance between tunnels and the trochlea, and rate of trochlea and notch violation were recorded.

Statistical Analysis

Thorough summary statistics were reported for each measured distance. Paired t tests were used to compare drilling techniques in terms of the resultant tunnel distances. To assess interrater measurement repeatability, a 2-way random-effects model was used to calculate the single-measures absolute agreement version of the intraclass correlation coefficient (ICC) for each measured distance. Nonparametric bootstrap 95% CIs were reported with each ICC calculation. The ICC values were interpreted as follows: ICC $<$ 0.40 = poor agreement; 0.40 $<$ ICC $<$ 0.75 = fair to good agreement; and ICC $>$ 0.75 = excellent agreement.[11] To assess the measurement reliability in the units of measurement, Bland-Altman 95% limit of agreement analyses were performed. This tool aids in clinical interpretation by determining the average bias and spread of the observed differences between 2 sets of measurements. All statistical analyses were performed with the statistical package R (R Development Core Team; with packages psy and boot).[9]

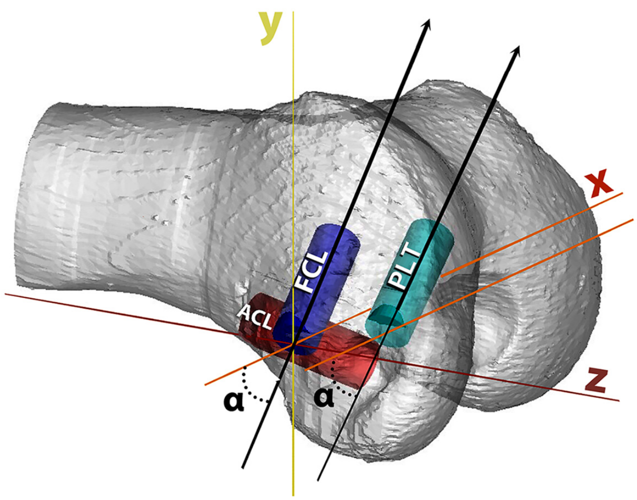

Figure 2. To avoid convergence with the anterior cruciate ligament (ACL) tunnel, the fibular collateral ligament (FCL) tunnel should be aimed 35° anteriorly (with the patient in the supine position, the surgeon's hand should be dropped and the reamer aimed up). The popliteus tendon (PLT) tunnel is shown parallel to the FCL tunnel. α is the angle anteriorly from the horizontal plane (x-axis) = 35°.

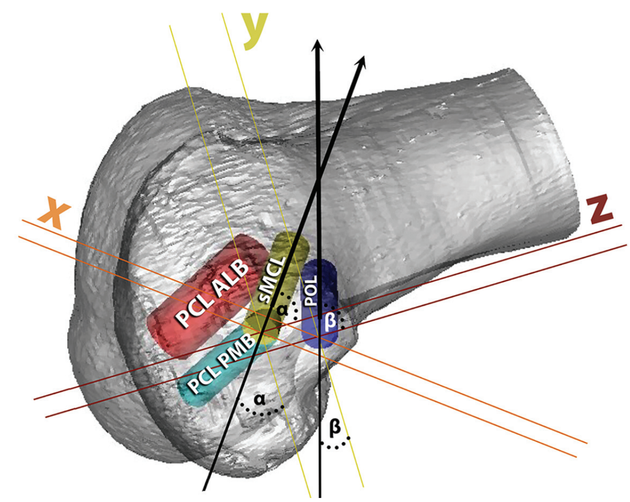

Figure 3. To avoid collision with the posteromedial bundle (PMB) of the posterior cruciate ligament (PCL), the superficial medial collateral ligament (sMCL) should be aimed 40° anteriorly and proximally (with the patient in the supine position, the surgeon drops the hand and the reamer aims 40° up and 40° toward the hip joint). The posterior oblique ligament (POL) should be aimed 20° anteriorly and proximally. α = 40°, β = 20°.

RESULTS

Lateral Knee Reconstruction Tunnels

FCL Reconstruction Tunnel Convergence. Collision between the FCL and ACL tunnels was observed in 100% of the patients when the FCL tunnel was aimed at 0° in both the axial (anterior-posterior direction) and coronal (proximal-distal direction) planes (neutral tunnel orientation). By aiming the FCL tunnel 30° anteriorly, convergence with the ACL tunnel was avoided in 20 of 21 patients (95%). Tunnel collision with the ACL tunnel was avoided in 100% of the patients when the FCL tunnel was aimed 35° to 40° anteriorly and 0° proximally. Proximal angulation of the FCL tunnel was likely to cause collision with the ACL tunnel.

PLT Reconstruction Tunnel Convergence. No collision between the PLT and ACL tunnels was observed, whether the PLT was aimed along the lateral axis (0° in both the axial and coronal planes) or parallel to the rotated FCL tunnel (35° of anterior rotation). However, when aiming the PLT tunnel along the lateral axis, violation of the intercondylar notch was observed in 15% of the patients. No violation of the intercondylar notch or trochlea was observed at 35° of anterior rotation (Figure 2).

Medial Knee Reconstruction Tunnels

sMCL Reconstruction Tunnel Convergence. Tunnel collision between the sMCL tunnel and the anterolateral bundle and posteromedial bundle of the PCL was 76% and 90%, respectively, in the neutral orientation (0° in both the axial and coronal planes). By aiming the sMCL tunnel 20° to 40° anteriorly and 40° proximally, collision with the PCL tunnels was avoided in 18 of 21 patients (86%). For the other 3 patients, other angles for avoiding convergence were found, such that there was a way to avoid convergence in all patients.

POL Reconstruction Tunnel Convergence. Optimization of the POL reconstruction tunnel angle was performed relative to the best optimization orientation of the sMCL tunnel, which was at 40° anterior rotation with 40° proximal rotation (Figure 3). POL tunnel optimization was performed only on the patients for whom the sMCL tunnel did not converge with the PCL tunnels at those angles (n = 18). When the sMCL tunnel was oriented 40° anteriorly and 40° proximally, collision with the sMCL tunnel was avoided in 100% of the patients by orienting the POL tunnel 20° proximally and 20° anteriorly (Figure 3). There was an increased risk of exiting the posterior medial femoral condyle or being too close to the cortex if the POL was aimed 40° proximally.

Relation to the Intercondylar Notch and Trochlea

There was a risk of both the PLT and POL tunnels violating the intercondylar notch when drilled at 0° in both the axial and coronal planes (neutral orientation). Violation of the intercondylar notch was observed in 15% and 5% of the patients for the PLT and POL tunnels, respectively. At the recommended angles, no intercondylar notch violation was observed. The trochlea was not violated at any angulation for either the medial or lateral knee reconstruction tunnels. Distances from the tunnels to the intercondylar notch and trochlea are summarized in Table 2. The distances

TABLE 2
Distances From the Reconstruction Tunnels to the Intercondylar Notch and Trochlea[a]

	Notch			Trochlea		
	Neutral	Optimized	*P* Value	Neutral	Optimized	*P* Value
FCL	7.3 ± 1.9	19.1 ± 2.3	<.001	33.0 ± 3.7	23.7 ± 3.0	<.001
PLT	4.5 ± 2.4	11.3 ± 2.9	<.001	17.9 ± 7.0	10.9 ± 5.5	<.001
sMCL	7.8 ± 2.8	24.8 ± 2.7	<.001	30.4 ± 3.2	24.5 ± 2.9	<.001
POL	5.9 ± 3.0	13.8 ± 3.4	<.001	30.9 ± 3.6	26.9 ± 3.0	<.001

[a]Data are reported as mean ± SD. FCL, fibular collateral ligament; PLT, popliteus tendon; POL, posterior oblique ligament; sMCL, superficial medial collateral ligament.

TABLE 3
Distances Between the Reconstruction Tunnels in Neutral Position and After Optimization[a]

	Neutral			Optimized		
	Patients With Convergence,[b] n	Clearance, mm, Mean ± SD	Clearance, mm, Minimum	Patients With Convergence,[b] n	Clearance, mm, Mean ± SD	Clearance, mm, Minimum
Lateral tunnels						
FCL to ACL	21/21	N/A	N/A	0/21	4.5 ± 1.5	2.4
PLT to ACL	0/21	9.8 ± 2.1	6.4	0/21	17.1 ± 1.7	13.0
FCL to PLT	0/21	7.5 ± 1.7	4.7	0/21	7.0 ± 1.7	4.0
Medial tunnels						
sMCL to ALB of PCL	16/21	2.1 ± 1.3 (n = 15)	N/A	3/21	5.3 ± 3.8	0.8
sMCL to PMB of PCL	19/21	1.3 ± 0.9 (n = 10)	N/A	0/21	5.9 ± 2.7	2.1
POL to ALB of PCL	0/21	8.6 ± 2.5 (n = 21)	3.8	0/18	9.1 ± 3.3	3.9
POL to PMB of PCL	13/21	2.9 ± 2.7 (n = 15)	N/A	0/18	5.9 ± 3.4	2.4
POL to sMCL	0/21	3.7 ± 0.9 (n = 21)	2.4	1/18	3.1 ± 1.0	1.4

[a]The ACL, ALB of the PCL, and PMB of the PCL tunnels were held constant while optimizing the orientation of the FCL, PLT, sMCL, and POL in relation to the tunnels kept constant. ACL, anterior cruciate ligament; ALB, anterolateral bundle; FCL, fibular collateral ligament; N/A, not applicable; PCL, posterior cruciate ligament; PLT, popliteal tendon; PMB, posteromedial bundle; POL, posterior oblique ligament; sMCL, superficial collateral ligament.
[b]Represents the number of patients used to calculate the mean clearance. Only patients with a positive clearance distance were used for these calculations.

between the tunnels after optimization are summarized in Table 3. There was generally a good to excellent ICC for each measured distance (see the Appendix, available online).

DISCUSSION

The most important finding of this study was that there was a high risk of tunnel collision in the femur during multiple ligament knee reconstructions when the ligament reconstruction tunnels for the posteromedial and posterolateral corners were oriented along the neutral axis (0° in both the coronal and axial planes). This study demonstrated a 100% tunnel collision rate between the femoral FCL and ACL tunnels when the FCL tunnel was aimed at 0° in the axial plane (parallel to the joint line) and 0° in the coronal plane (proximal-distal direction). The risk of tunnel convergence between the FCL and ACL tunnels was significantly reduced by aiming the FCL tunnel 35° to 40° anteriorly and 0° proximally. Similarly, the risk of tunnel convergence between the sMCL and 2 PCL tunnels was significantly reduced by aiming the sMCL tunnel 40° proximally and 20° to 40° anteriorly. When performing concomitant POL reconstruction, the risk of tunnel convergence can be minimized by aiming the sMCL tunnel 40° proximally and 40° anteriorly and the POL tunnel 20° proximally and 20° anteriorly.

Posterolateral corner injuries rarely occur in isolation, and persistent posterolateral corner instability increases the risk of cruciate reconstruction graft failure.[24,25] Our results are supported by previous studies that reported a high risk of tunnel convergence during concomitant ACL and posterolateral corner reconstructions when the FCL tunnels were drilled in a neutral orientation (0° in the axial and coronal planes)[3,13,33,37]; previous studies reported that aiming the FCL tunnels anteriorly reduced the risk of tunnel convergence, while the additional proximal orientation of the FCL tunnels ≥20° was reported to further increase the risk of convergence with the ACL tunnel. The anterior angulation was heterogeneous between studies; however, our results suggest that angles from 35° to 40° are safe to avoid tunnel convergence, obtain the desired tunnel length, and avoid violation of the intercondylar notch and trochlea.

On the medial side of the knee, our results suggest that it is necessary to aim the sMCL and POL tunnels both proximally and anteriorly (40°/40° and 20°/20°, respectively) to avoid tunnel convergence and obtain an adequate tunnel length without violating the intercondylar notch and trochlea. Gelber et al[16] reported that aiming the sMCL and POL tunnels 30° in both the axial and coronal planes reduced the risk of tunnel convergence. However, Camarda et al[4] reported that convergence could be avoided by aiming the sMCL tunnel 40° proximally.

We recognize that this study has some limitations. First, the sample size of patients was relatively small and might not be generalizable to the whole population. Another limitation was that not all possible tunnel orientations for the FCL, PLT, POL, and sMCL were evaluated. The maximum angles were limited to 40° based on a previous study by Shuler et al,[37] who reported thinning of cortices and elliptical tunnels when drilled at an angle over 40°. However, 1600 orientations of the FCL, POL, and sMCL were tested on each patient. In addition, not all knee dislocations present global laxity, but this was chosen as a worst-case scenario to highlight the need for adjusting tunnel placement and orientation in multiple knee ligament reconstructions. Another important limitation was that the PCL and ACL tunnels were kept constant in regards to the orientation and tunnel entrance. During surgery, the orientation of the ACL and PCL tunnels can be affected by both the flexion angle and the placement of the portals.

CONCLUSION

Femoral tunnel orientations during multiple ligament reconstructions need to be adjusted to avoid tunnel convergence. On the lateral side, aiming the FCL and PLT tunnels 35° anteriorly eliminated convergence with the ACL tunnel. On the medial side, convergence was avoided by orienting the sMCL tunnel 40° proximally and anteriorly and the POL tunnel 20° proximally and anteriorly. The POL and PLT tunnels aimed at 0° in the axial plane had an increased risk of violating the intercondylar notch.

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