Intertunnel relationship in combined anterior cruciate ligament and posterolateral corner reconstruction: An *in vivo* 3D anatomical study

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Intertunnel relationship in combined anterior cruciate ligament and posterolateral corner reconstruction: an *in vivo* 3D anatomical study

Directed by Professor Sung-Jae Kim

The Doctoral Dissertation
submitted to the Department of Medicine,
the Graduate School of Yonsei University
in partial fulfillment of the requirements for the degree
of Doctor of Philosophy

Kwan-Kyu Park

June 2012

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June 2012

ACKNOWLEDGEMENTS

본 논문의 주제에 대해 자료수집을 시작했을 때, 전방 십자인대 및 후외측 구조의 재건에 대한 방대한 주장으로 적지 않게 혼란스러웠습니다. 연구의 진행방향을 제대로 정하지 못하고 있는 상황에서 지도 교수 김성재 선생님의 가르침과 지도로 연구를 진행할 수 있었습니다. 다시 한번 김성재 선생님께 진심으로 감사 드립니다. 또한 이 논문이 있기까지 많은 조언과 지도를 해주신 정형외과학교실 최종혁 선생님, 해부학교실 이혜연 선생님, 재활의학과교실 조성래 선생님께도 깊은 감사를 드리며, 특히 먼 거리에도 불구하고 방문해 주시어 이 연구에 대하여 많은 조언과 가르침을 주신 한림대학교 정형외과학교실 유연식 선생님께 감사의 인사를 올립니다.

지금까지 저에게 항상 큰 가르침을 주신 정형외과학교실의 모든 스승님들과 박사 연구를 진행하는 데에 많은 도움을 주신 동료 및 후배 선생님들, 특히 결정적인 도움을 준 김성환 선생께 깊은 감사의 뜻을 전합니다. 또한 부족한 저를 지금 이 자리에서 일할 수 있는 바탕을 만들어 주신 서울대학교 정형외과학교실 김태균 선생님과 이번 연구에 큰 아이디어를 주신 동 교실 장종범 선생님께도 깊은 감사의 인사를 드립니다.

항상 제 편으로 든든하게 계셔주시는 아버지와 어머니, 저의 결정을 지지해주시는 장인, 장모님 이하 모든 가족 들께 감사의 마음을 전합니다. 마지막으로 항상 뒷받침과 희생을 아끼지 않는 아내 이희연과, 지치고 힘들 때 에너지가 되어주는 딸 서진이에게 사랑의 마음을 전합니다.

앞으로도 모든 선생님들의 큰 가르침을 기억하며, 환자의 진료와 연구에 최선을 다하는 겸손하고 인간적인 의사가 되도록 항상 노력하겠습니다.

2012년 6월

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ABSTRACT

Intertunnel relationships in combined anterior cruciate ligament and posterolateral corner reconstruction: An *in vivo* 3D anatomical study

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(Directed by Professor Sung-Jae Kim)

Combined anterior cruciate ligament (ACL) and posterolateral ligament complex (PLC) injuries are relatively common, and crowded tunneling of the lateral femur condyle area is required in combined ACL and PLC reconstruction. Therefore, tunnel convergence during surgery could occur. However, available studies on this topic are limited. This study sought to elucidate the ranges of angles and distances of lateral collateral ligament (LCL) and popliteus tendon (PT) femoral tunnels that do not violate ACL tunnels during combined ACL and PLC reconstruction and to provide practical guidelines for this operation.

Knee computed tomography images were taken from 14 subjects at 0, 45, 90, and 120°, and three-dimensional anatomical knee models were created using customized software. At 120°, a coin was attached to the anteromedial (AM) portal area. Single- and double-bundle ACL tunneling using the transtibial method for AM bundles and the AM portal method for posterolateral bundles were performed. Femur model cutting was performed at the following angles relative to the transepicondylar axis (TEA) on the horizontal plane from the LCL and PT insertion: posterior 20 (−20°) and 10° (−10°), 0°, and anterior

10 and 20°. The safe angles and distances that did not violate the ACL tunnel or intercondylar notch were determined in the proximal (superior) and distal (inferior) directions.

Generally, the ranges of safe angles increased as the LCL and PT femoral tunnel was positioned in the posterior to anterior direction. When the LCL and PT tunnel was positioned anteriorly to the TEA (10 and 20°), the ranges of safe angles exceeded 40°; however, when the tunnel was positioned posteriorly (−10 and −20°), collision with the intercondylar notch or ACL tunnel occurred. Distances that made tunneling possible at the margin of the safe angle were approximately 35 mm for the LCL and 30 mm for the PT. Collision usually occurred with the AM bundle tunnel. However, convergence with the PL bundle occurred rarely.

We found that LCL and PT femoral tunnels should be directed anteriorly rather than posteriorly on the axial plane. Considering the relationship between LCL and PT tunnels and fixation strength, we believe that tunneling would be safe when the LCL and PT are positioned at an angle of approximately anterosuperior 10°. We admit that there would be differences between the results of our simulation study and those of actual operations. However, our results would help to reduce the incidence of tunnel collisions in actual combined ACL and PLC reconstructions. We believe that our results are meaningful not only in providing practical safe ranges but also in attracting attention to collisions when we perform combined ligament reconstruction surgeries.

Key words: Intertunnel relationship, combined anterior cruciate ligament and posterolateral corner reconstruction, in vivo 3D anatomical study

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I. INTRODUCTION

Combined injury of the posterior ligament complex (PLC) accounts for 11% of all anterior cruciate ligament (ACL) injuries[1-6]. In combined ACL and PLC reconstruction, crowded tunneling of the lateral femur condyle area is required. ACL and PLC femoral tunnel collision may occur at a high frequency rate[7], and bone weakening is also possible because of their close proximity[8]. However, there is only a limited amount of research on such convergence[7,9]. Furthermore, to the best of our knowledge, it is difficult to find a guideline regarding the practical tunneling angle during operation.

Recently, single-bundle (SB) and double-bundle (DB) ACL reconstruction have been used together in ACL construction, and there are differing opinions regarding the position of the ligament femoral footprint and the tunnel position[5-6,10-33]. There is also a difference of opinions concerning the insertion point and angulations when performing lateral collateral ligament (LCL) and popliteus tendon (PT) reconstruction[4-6,34-52]. Opinions also vary regarding the tunnel length and diameter[37,39,46,53]. Due to such recent variability in ACL and PLC reconstruction methods, the degree of collision may vary.

Until now, while performing PLC reconstruction combined with SB or DB ACL reconstruction, we anecdotally experienced tunnel collisions. To avoid this, we are following our own protocol consisting of a fixation angle of anterosuperior 20° for the LCL and PT in PLC reconstruction when combined with ACL reconstruction[37]. However, we felt a need to validate whether this protocol would indeed prevent tunnel collision. Furthermore, we also felt a need to determine the practical ranges of angles and distances for which ACL tunnels and LCL or PT femoral tunnels do not collide. The purpose of the study was to elucidate the practical ranges of angles and distances for LCL and PT femoral tunnels for which ACL tunnel violation does not occur when performing combined ACL and PLC reconstruction. In this study, we used our protocol related to ACL reconstruction as a method including SB and DB ACL reconstruction through the transtibial technique for anteromedial (AM) bundles and the anteromedial (AM) portal technique for posterolateral (PL) bundles.

II. MATERIALS AND METHODS

1. Participants

In vivo measurements were conducted in 14 male subjects without any history of knee pathology or previous injury. The median age of the subjects at the time of the study was 29 years (range, 21–39 years).

2. CT scan and reconstruction of in vivo three-dimensional (3D) anatomical knee models

The subjects' right knees were scanned with a high-resolution CT scanner

(SOMATOM sensation; SIMENS, Germany) with 1-mm slices at three different knee flexion angles (0, 90, and 120°). At an angle of 120°, a coin was attached to the AM portal area to obtain the scans. The files were imported to customized software (Mimics 14.01 software, Materialise NV, Belgium), and 3D anatomical knee models were created (Figure 1A).

A **B**

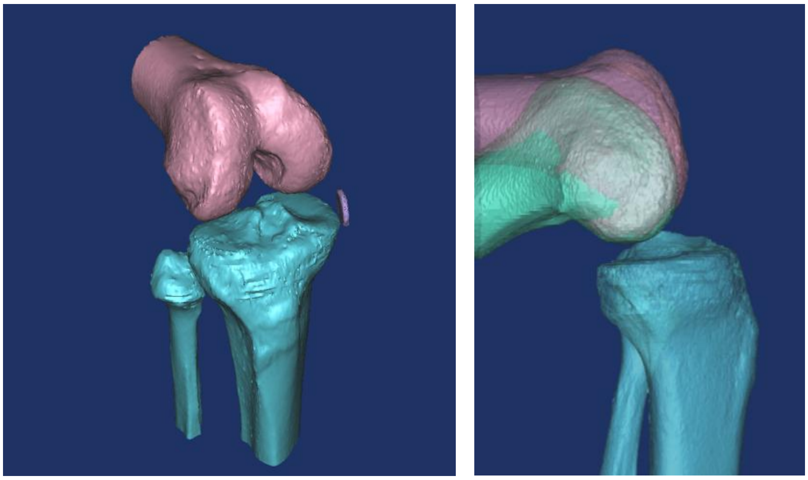


Figure 1. Reconstructed right knee model. In reconstruction knee model, femur is colored in pink, tibia and fibula in sky blue, and coin in purple (A). The 120° and 90° flexed knee models were conjoined based on tibia model (B).

3. ACL tunnels creation

We used the Mimics program to create ACL tunnels, resembling a technique that would be suitable in actual surgery. SB ACL reconstruction used the transtibial method with a 90° flexed knee model, and DB ACL reconstruction used the transtibial method for AM bundles with a 90° flexed knee model and the AM portal method for PL bundles with a 120° flexed knee model. For DB ACL tunnel reconstruction, 90° and 120° knee models were combined as follows. First, the tibia 90° knee model was combined with the tibia of the 120° knee model (Figure 1B). Then, the femurs of the 90 and 120° knee models were substituted with the femur of the 0° knee model. In the combination of 3D images, the mean 3D least square fitting tolerance was 0.075 mm.

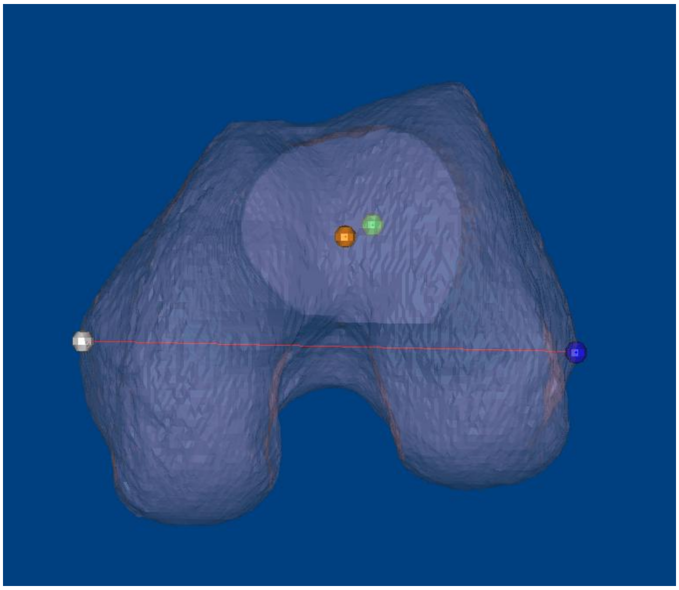


Figure 2. Reference points; blue spot – medial epicondyle, white spot – lateral epicondyle, green spot – center of the femur shaft, orange spot – 1 cm anterior to the top of the intercondylar groove. The transepicondylar line is presented as a red line.

We used the following four points as reference points: medial epicondyle, lateral epicondyle, center point of the femur shaft, and a point 1 cm anterior to the top of intercondylar groove (Figure 2).

The center point of the femur shaft and the point 1 cm anterior to the top of the intercondylar groove were made to overlap on the coronal plane. The femur was rotated laterally to overlap the medial and lateral femoral epicondyles. Regarding the ACL femoral entry point decision, we removed the medial femoral condyle to expose the medial side of the lateral femoral condyle.

A. SB ACL tunnel creation (transtibial method)

In the operating room, we use the following transtibial method for the SB ACL reconstruction on the right side of the knee[5-6,19]. A tibial tunnel was drilled with a 9-mm cannulated reamer and expanded using a 10-mm dilator. A femoral guide pin was positioned the 10:30 position on the right knee at 70–90° of flexion, and the femoral socket was reamed with an 9-mm diameter reamer and enlarged to a depth of 40 mm by using a 10-mm dilator.

In this simulation model, we created a SB femoral tunnel by performing ACL reconstruction using a method resembling the previously presented method. The SB ACL tunnel was created on a 90° flexed knee model. First, the anatomical footprint of the tibial side was positioned on the basis of the investigation of the tibial footprint of the ACL and tibial bony geometry by Punell et al[54]. Then, on the femoral side, the center of the AM bundle footprint was positioned as a quadrant method as described by Bernard and Hartel[55] at approximately 22% of the height of the lateral femoral condyle and 19% along Blumensaat's line as reported by Zantop et al[56]. A 10-mm diameter of simulation cylindrical tunnel was made between two points, and the tunnel was lengthened to the femoral outlet (Figure 3A).

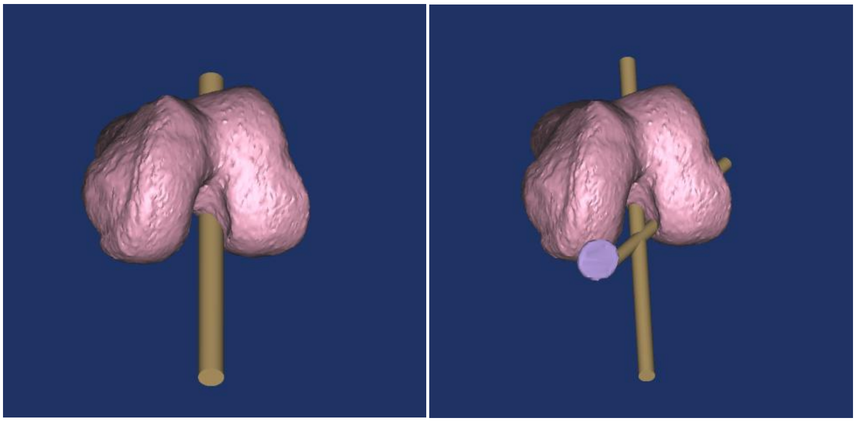


Figure 3. Single (A) and double (B) bundle anterior cruciate ligament tunnels creation. Posterolateral bundle of double bundle anterior cruciate ligament was created based on coin image which is colored in purple.

To confirm that the tunnel was made appropriately in the 3D model, we examined whether the tunnel was positioned at 10:30 compared to the transepicondylar axis (TEA) on the AP view. We also compared the femoral outlet points of simulated tunnels to those on the CT scans of patients who underwent SB ACL reconstruction using our operation technique. First, we compared the femoral outlets of 10 patients who underwent ACL reconstruction with our simulation models. The sample size was calculated under a type I error probability of 0.05 and a power of 0.8. Eighteen was determined to be an effective sample size for the analyses. We added an additional 10 patients and compared the data of a total of 20 patients who underwent ACL reconstruction to those of our 14 simulation models.

B. DB ACL tunnel creation (transtibial method for AM bundles and AM portal method for PL bundles)

In the operating room, we use the following method for the DB ACL reconstruction on the right side of the knee[18-20]. After creating an 11-mm diameter tibial tunnel, a 6-mm over-the-top guide was placed on the intercondylar notch at the 11:00 position. After guide pin placement, an 8-mm diameter reamer was used to drill the AM bundle femoral socket to a depth of 40 mm, followed by a 9-mm dilator. The PL femoral socket was drilled through an accessory AM portal located 1.5 cm medial to the AM portal just above the medial meniscus and 5 mm anterior to the medial femoral condyle. A 6-mm reamer was passed through the PL bundle center located approximately at the crossing point of the ACL attachment long axis and the vertical line drawn at the femoral condyle contact point with the tibial plateau at 90° of knee flexion. The socket was placed at the 9:00 position. With an acceptable position, a 6-mm diameter headed reamer was drilled to a depth of 35 mm, followed by a 7-mm manual dilator.

In this simulation model, femoral tunnels of DB ACL reconstruction were created using a method resembling our operation technique. For DB ACL reconstruction, both 90 and 120° flexed knee models were used; the transtibial technique was used for the 90° flexed model for AM bundle tunnels, and the AM portal technique was used for the 120° flexed model for PL bundle tunnels. The AM bundle tunnel was made using 90° flexed knee model similar to the SB ACL reconstruction technique; however, the diameter was 1 mm smaller than that of the SB ACL tunnel, and the femoral footprint was positioned more superiorly and anteriorly than the SB footprint to position the AM bundle tunnel in the11:00 direction and avoid convergence with the PL bundle. For PL bundles, another cylindrical tunnel was made between the coin image and the center of the PL bundle femoral footprint, which was located at approximately 54 and 29% of the height of the lateral femoral condyle and Blumensaat's line, respectively, as reported by Zantop[56]. This tunnel was lengthened to the femoral lateral cortex side. We examined whether the tunnels were positioned in the 11:00 direction for AM bundle tunnels and the 9:00 direction for PM bundle tunnels relative to the TEA on the AP view. After both AM and PL bundle tunnels were created, the femurs of the 90 and 120° flexed knee models were combined to measure the ranges of angles and distances from the LCL and PT femoral insertions (Figure 3B). There was a mean of 0.075 mm of 3D least square fitting tolerance when the 3D images were combined.

4. LCL & PT reconstruction method and entry point

In our operation protocol, LCL and PT reconstruction is performed as follows[6,37-41]. The lateral femoral epicondyle is first exposed. The position of the patient is changed to lateral decubitus to eliminate the gravitational force of the lower leg in the supine position, and 0.045-in Kirschner wires are provisionally inserted at tentative isometric points. A PT femoral insertion site is placed at the superior margin of the anterior one-third portion of the popliteal sulcus, which is located approximately 15 mm distal to the femoral epicondyle. An LCL femoral insertion site is placed at the anterosuperior lateral femoral epicondyle. Isometricity is confirmed by migration of less than 2 mm during flexion and extension of the knee. A femoral socket 40 mm in depth is created with a 7-mm-diameter cannulated reamer in the anterosuperior direction to the transverse line of the femoral shaft at an angle of 20° for the PT socket and LCL socket. Using a Beath pin, the graft for the PT, which was passed underneath the LCL, is pulled through the femoral socket and then fixed at the femur using a bioabsorbable interference screw.

We positioned the LCL and PT femoral insertion on the lateral femoral condyle area based on our operation technique (Figure 4). Two experienced surgeons selected the LCL and PT femoral insertion points under careful consideration.

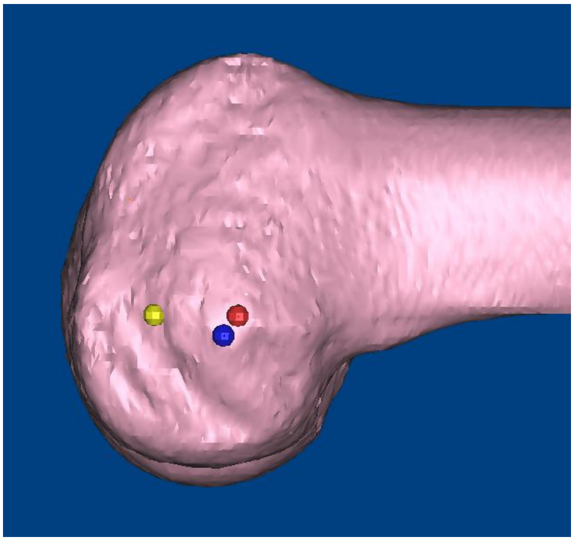
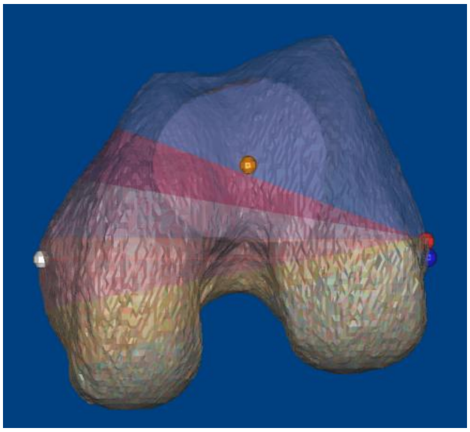


Figure 4. Femoral entry points of the lateral collateral ligament (red spot) and popliteus tendon (yellow spot). The lateral epicondyle is also shown as a blue spot.

5. Measurements of the ranges of angles and distances

To measure the ranges of the angles and distances for LCL and PT femoral insertion, we first overlapped the center point of the femur shaft and the point 1 cm anterior to the top of intercondylar notch intercondylar groove on the horizontal plane. Then, we cut the femur model at angles of posterior 20 (−20°) and 10° (−10°), 0°, and anterior 10 and 20° to the TEA from the LCL and PT entry points (Figure 5A).

A



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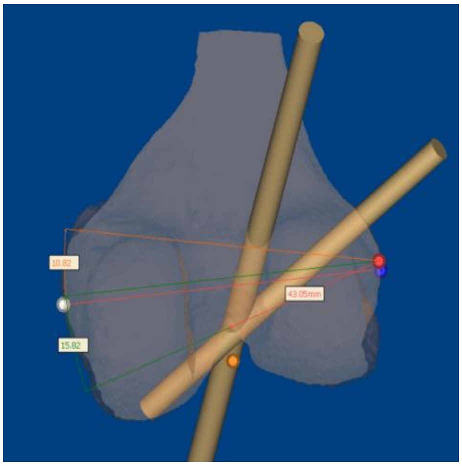

Figure 5. The measurement of ranges of angles and distances from the insertions of lateral collateral ligament and popliteus tendon. (A) The femur model was cut at angles of posterior 20 (−20°) and 10° (−10°), 0°, and anterior 10 and 20° relative to the transepicondylar line (red line) on the horizontal plane from the lateral collateral ligament entry point (red spot). (B) Safe angles and distances that did not violate the anterior cruciate ligament tunnels (cylinders) in the proximal (superior) direction and the intercondylar notch in the distal (inferior) direction using the transepicondylar axis (centered red line) as a reference line were measured.

In each cutting plane, the angles and distances from the LCL and PT femoral insertion point that did not violate the ACL tunnels in the proximal (superior) direction and intercondylar notch in the distal (inferior) direction were measured using the TEA as a reference line (Figure 5B). All measurements were performed by two orthopedic surgeons (KKP and SHK), both of whom were unaware of the consensus information. They were blinded to each other, and they measured each ratio twice over an interval of 2 weeks with subjects ordered randomly. The 95% confidence intervals of intraclass correlation coefficients were 0.90–0.96 for interobserver reliabilities and 0.88–0.94 for interobserver reliabilities. We also measured the ranges of angles and distances from the anatomical point of the LCL, which was inferior to our isometric point in DB ACL tunnels.

6. Statistical analysis

Statistical analysis was performed using the SPSS for Windows statistical package (version 20.0, SPSS Inc., Chicago, IL). A p-value < 0.05 was considered significant. In this study, non-parametric comparisons of outlets of the simulation group and the patients group were performed using Wilcoxon’s rank-sum test.

III. RESULTS

In comparisons of outlets between real operations and simulation of this study, we could confirm that there was no significant differences between the two groups (Table 1). The outlet of real operation was positioned 0.9 ± 5.9 mm anterior to the line between the center point of the femur shaft and the point 1 cm anterior to the top of the intercondylar groove and 2.4 ± 6.6 mm superior to the posterior margin of the lateral femoral condyle. The outlet of simulation of this study was positioned 2.6 ± 3.6 mm anterior to the line between the center point of the femur shaft and the point 1 cm anterior to the top of the intercondylar groove and 4.3 ± 3.7 mm superior to the posterior margin of the lateral femoral condyle. The outlets of our study were included in those of actual operations when presented as the mean and standard deviation (Figure 6).

Table 1. Comparisons of outlets of SB ACL tunnels between real operations and this study[1]

	Real operations (n=20)	Simulation (n=14)	p-value
Anteroposterior[2]	0.9 ± 5.9 (-12 to 10)	2.6 ± 3.6 (-5 ~ 8)	0.478
Superoinferior[3]	2.4 ± 6.6 (-9 to 13)	4.3 ± 3.7 (-4 ~ 8)	0.416

[1]Data are presented as the mean ± standard deviation (ranges) in mm.

[2]When positive, this indicates that the outlet is located anterior to the line between the center point of the femur shaft and the point 1 cm anterior to the top of the intercondylar groove.

[3]When positive, this indicates that the outlet is located superior to the posterior margin of the lateral femoral condyle.

SB:single bundle, ACL:anterior cruciate ligament

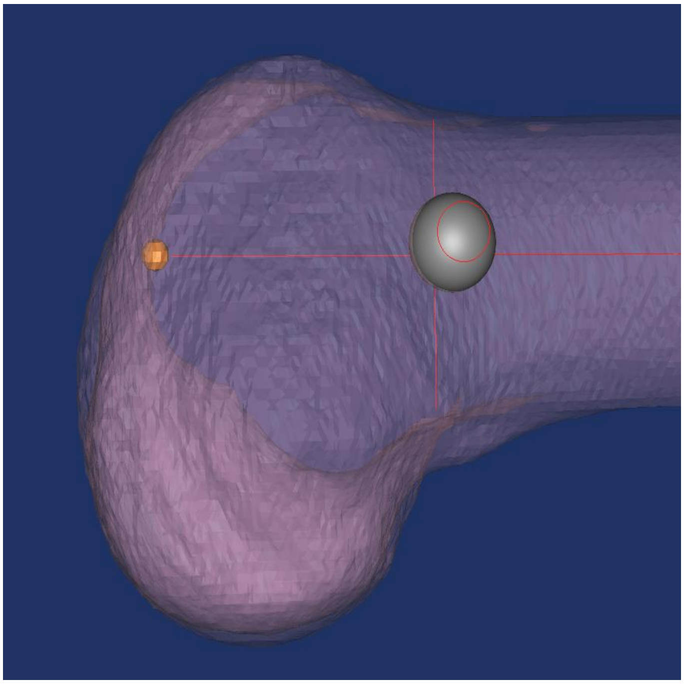

Figure 6. Outlet of real operation and simulation study. The outlet of simulation study (red circle) was included in that of real operation (gray sphere) when presented as the mean ± standard deviation.

In measurement of ranges of angles and distances from insertions of LCL and PT to intercondylar notch or ACL tunnels, generally, the ranges of safety angles of LCL or PT femoral tunnels that did not violate the femoral cortex were higher when the direction of the LCL and PT femoral tunnel was directed posterior to anterior (Table 2 and Figure 7). When the LCL and PT femoral tunnel was directed from 0° to anterior 10 or 20°, the ranges of safe ranges increased (Table

2 and Figure 7-(a), (b), and (c)).When the LCL and PT femoral tunnel was directed anterior to TEA (10° and 20°), the ranges of the safety angles exceeded 40° (LCL 44.0° and PT 49.8° when directed anterior20°and LCL 43.2° and PT 43.5° when directed anterior 10°) (Table 2 and Figure 7-(a) and (b)). However, when the LCL and PT femoral tunnel was directed in the posterior 20 (−20°) or 10° direction, we could not obtain a safe margin or the range was very narrow (Table 2 and Figure 7– (d) and (e)), and collision with the intercondylar notch or ACL tunnels occurred.

When the LCL and PT femoral tunnel was directed from 0° to anterior 10 or 20°, the ranges of safe distances increased (Table 2 and Figure 7-(a), (b), and (c)). In those directions of angles (0°, anterior 10°, and anterior 20°), distances that make tunneling possible at the margin of the safe angle was approximately 35 mm in the LCL and 30 mm in the PT (Table 2 and Figure 10-(a), (b), and (c)). However, within the range of safe angles that did not violate the intercondylar notch or tunnel, longer distances directed toward the medial femoral condyle cortex were possible (Figure 7). Compared to LCL insertion, PT femoral tunnel insertion had a narrower safe angle range when positioned in the distal (inferior) direction because of its distal (inferior) location, but the safe angle range when positioned in the proximal (superior) direction was wider (Table 2 and Figure 7). In the DB ACL reconstruction model, collisions with the LCL or PT femoral tunnel proximally (superior) usually occurred with AM bundle tunnels, indicating that convergence with PL bundles occurred rarely.

Table 2. Ranges of angles and distances for LCL and PT femoral insertion in single- and double-bundle ACL reconstruction[1]

	Single Bundle				Double Bundle			
	Distal (Inferior)		Proximal (Superior)		Distal (Inferior)		Proximal (Superior)	
	Angle (°)	Distance (mm)	Angle (°)	Distance (mm)	Angle (°)	Distance (mm)	Angle (°)	Distance (mm)
LCL								
Posterior 20°	NC	32.0 ± 4.2 (29 ~ 35)	-0.4 ± 2.4 (-6 ~ 3)	30.8 ± 1.7 (28 ~ 35)	18.5 ± 26.2 (0 ~ 37)	36.0 ± 1.4 (35 ~ 37)	0.5 ± 2.1 (-6 ~ 3)	35.4 ± 1.0 (34 ~ 37)
Posterior 10°	1.7 ± 4.1 (-3 ~ 8)	40.8 ± 3.5 (35 ~ 44)	5.9 ± 3.7 (0 ~ 11)	30.6 ± 2.8 (27 ~ 38)	1.8 ± 3.9 (-2 ~ 8)	42.4 ± 3.1 (35 ~ 47)	5.8 ± 5.3 (-3 ~ 13)	32.3 ± 2.3 (28 ~ 38)
0°	11.8 ± 4.6 (4 ~ 20)	41.9 ± 2.3 (38 ~ 45)	13.7 ± 4.6 (7 ~ 22)	30.0 ± 10.9 (23 ~ 67)	11.6 ± 4.0 (4 ~ 17)	42.0 ± 2.4 (38 ~ 46)	10.5 ± 13.3 (-13 ~ 22)	31.1 ± 10.6 (25 ~ 67)
Anterior 10°	21.6 ± 1.0 (20 ~ 24)	35.7 ± 10.0 (23 ~ 47)	21.6 ± 6.0 (12 ~ 33)	37.8 ± 12.7 (24 ~ 72)	22.4 ± 0.9 (21 ~ 24)	42.8 ± 3.3 (38 ~ 48)	23.7 ± 5.8 (16 ~ 33)	33.3 ± 11.8 (24 ~ 72)
Anterior 20°	26.8 ± 4.3 (21 ~ 31)	39.7 ± 12.0 (21 ~ 51)	23.7 ± 8.4 (15 ~ 42)	35.6 ± 13.3 (25 ~ 75)	20.3 ± 2.5 (16 ~ 24)	44.2 ± 6.1 (32 ~ 53)	30.1 ± 5.8 (22 ~ 42)	31.9 ± 13.5 (24 ~ 75)
PT								
Posterior 20°	NC	NC	17.1 ± 4.1 (12 ~ 23)	29.9 ± 2.7 (25 ~ 33)	NC	NC	20.9 ± 1.4 (18 ~ 23)	32.5 ± 1.6 (30 ~ 34)
Posterior 10°	-18.2 ± 2.6 (-21 ~ -14)	37.6 ± 4.3 (33 ~ 42)	23.7 ± 4.2 (20 ~ 37)	30.5 ± 1.8 (27 ~ 32)	-20.4 ± 1.3 (-22 ~ -18)	37.5 ± 2.5 (34 ~ 41)	24.3 ± 2.9 (20 ~ 29)	33.1 ± 1.7 (31 ~ 36)
0°	-8.2 ± 1.1 (-9 ~ -6)	35.3 ± 1.8 (32 ~ 38)	30.4 ± 2.8 (24 ~ 33)	28.9 ± 2.8 (25 ~ 33)	-7.9 ± 1.2 (-10 ~ -6)	35.6 ± 1.6 (33 ~ 37)	30.3 ± 4.3 (21 ~ 35)	30.6 ± 2.6 (28 ~ 35)
Anterior 10°	5.1 ± 1.7 (2 ~ 7)	36.0 ± 1.6 (34 ~ 39)	38.4 ± 2.9 (34 ~ 43)	29.3 ± 3.2 (25 ~ 34)	5.2 ± 3.1 (1 ~ 10)	35.7 ± 1.5 (32 ~ 38)	40.3 ± 2.7 (37 ~ 46)	31.2 ± 2.8 (28 ~ 35)
Anterior 20°	10.2 ± 9.5 (6 ~ 43)	36.1 ± 1.2 (34 ~ 38)	41.4 ± 9.8 (8 ~ 47)	30.0 ± 3.7 (26 ~ 35)	8.4 ± 2.1 (5 ~ 11)	36.9 ± 2.1 (34 ~ 40)	45.2 ± 2.5 (42 ~ 50)	32.6 ± 4.1 (28~38)

[1]Data are presented as the mean ± standard deviation (range) and negative values of angles indicate that angles are oriented to the opposite side..

LCL:lateral collateral ligament, PT:popliteus tendon, ACL:anterior cruciate ligament, NC:non-contributable

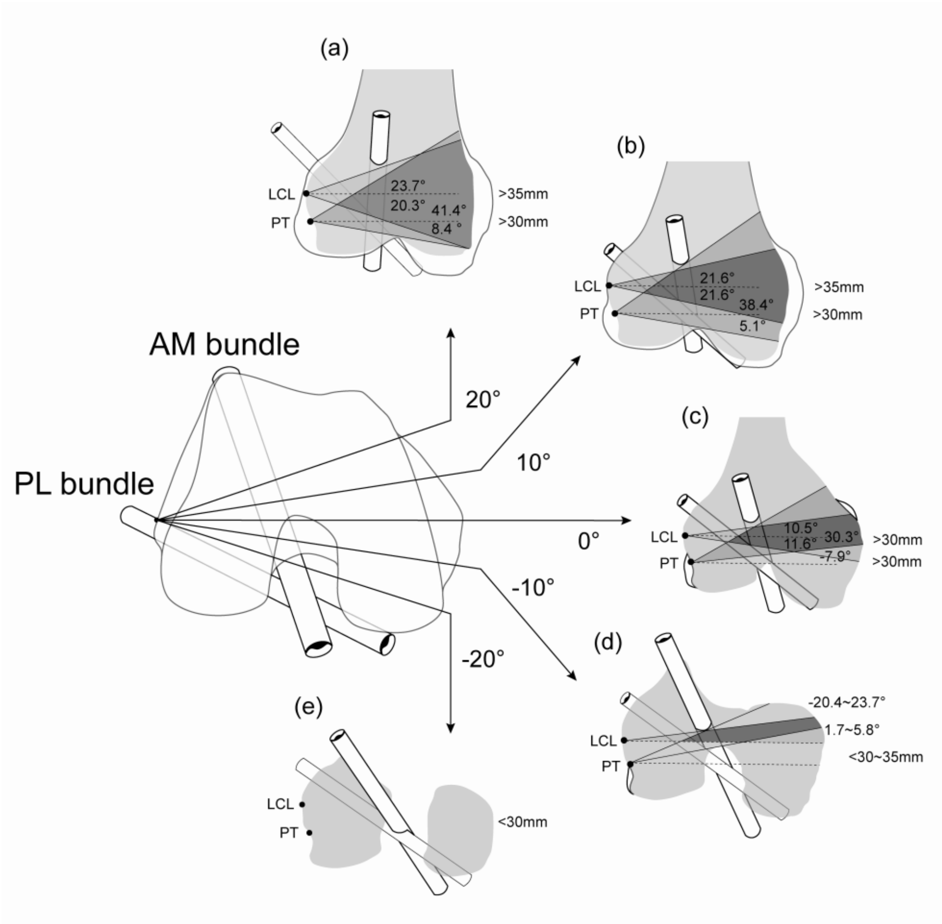

Figure 7. Schematic figure of the ranges of safe angles and distances in each cutting plane. (a) anterior 20° (20°), (b) anterior 10° (10°), (c) 0°, (d) posterior 10° (−10°), and (e) posterior 20° (−20°) relative to the transepicondylar axis on the horizontal plane.

In comparisons of ranges of angles and distances between the method in this study and the method using anatomical footprint we found that the ranges of posterior angles for both the proximal (superior) 10° and 20° directions were significantly smaller than those of our results. In measurement, however, we could observe that the PL bundle tunnel was located more posterior than the AM bundle tunnel on the cutting plane in both the 10° and 20° directions, and thus, there was no violation between the PL bundle and the anatomical footprint of the LCL (Table 3).

Table 3. Comparisons between the method in this study and the method using anatomical footprint in DB ACL reconstruction when the LCL is directed in the proximal (superior) 10° and 20° direction[1]

	Method of this study	Anatomical footprint	p-value
Proximal (Superior) 10°			
Distal angle (°)	22.4 ± 0.9	22.5 ± 1.5	0.887
Distal distance (mm)	42.8 ± 3.3	42.2 ± 3.3	0.650
Proximal angle (°)	22.9 ± 5.0	15.5 ± 9.2	0.014
Proximal distance (mm)	30.4 ± 4.2	29.2 ± 3.6	0.446
Proximal (Superior) 20°			
Distal angle (°)	20.4 ± 2.6	21.4 ± 3.9	0.401
Distal distance (mm)	44.2 ± 6.1	41.8 ± 8.8	0.414
Proximal angle (°)	29.2 ± 4.6	18.1 ± 2.6	<0.001
Proximal distance (mm)	28.9 ± 5.6	28.4 ± 5.6	0.815

[1]Data are presented as the mean ± standard deviation.

LCL:lateral collateral ligament, DB:double bundle, ACL:anterior cruciate ligament

IV. DISCUSSION

The purpose of our study was to elucidate the practical ranges of angles and distances of LCL and PT femoral tunnels that do not violate ACL tunnels when performing combined ACL and PLC reconstruction. In our study, which used an in vivo 3D model, it was determined that LCL and PT tunnels were safe when positioned in the anterior direction on the coronal plane (10° or 20°). On the axial plane, the safe angle range for LCL tunnels was approximately between proximal (superior) 20° and distal (inferior) 20° from the insertion using the TEA as the reference line. The safe range for PT was approximately between parallel to the TEA (0°) and proximal (superior) 30° due to its location that was more distal compared to that of the LCL insertion. In the case of combined LCL and PT reconstruction, if the LCL is positioned distally (inferior) and the PT is positioned proximally (superior), then LCL and PT femoral tunnels could converge, which is why the relationship between the two tunnels must be considered. Therefore, if the LCL and PT were positioned at approximately anterosuperior 10°, then the two tunnels would not converge, and tunnels could be made within a relatively safe angle and distance. Until now, in actual surgery, we made LCL and PT tunnels directed in the anterosuperior 20° direction[37]. In this in vivo 3D simulation study, we were able to confirm that our method did not cause tunnel convergence between the ACL and LCL or PT femoral tunnels. However, the method appears to be safer when we reduce the anterosuperior direction by approximately 10°. If this proves true, then we would be able to avoid tunnel convergence, and the reduced angle could help with the fixation strength as well because it is reported that the fixation strength decreases as the fixation angle increases[57]. This study demonstrated that the safe range for length was generally less than 35–40 mm, especially at the margin of ranges. Within the safety ranges, possible distances that would not violate the far cortex would be longer; however, we believe that it would be safer if we make sure that 40 mm is not exceeded in drilling. In the case of DB ACL reconstruction, PL bundles did not have a significant influence on LCL and PT tunnel convergence.

When the ACL and PLC are reconstructed simultaneously, this could result in crowded tunneling in the LFC. However, we could only find two studies regarding the tunnel relationship[7,9]. Schuler et al. reported in a synthetic femur and cadaveric study that when the lateral tunnel has a length of >30 mm, the incidence of collision exceeded 40%[7]. When the lateral tunnel has tunnel depth of <25 mm and neutral alignment on the coronal plane, it was reported that tunneling was safe at angles >40° on the axial plane[7]. The study was meaningful in that it investigated the issue of ACL and PLC tunnel convergence, but detailed practical ranges of angles were not presented[7]. In addition, we are unconvinced of the feasibility of angles >40° because there is a report that >15° of divergence could weaken the fixation strength[57]. If the angle is too wide, then we must monitor the fixation strength. Moreover, empirically speaking, we had difficulties in tunneling when the angle was wider than 40° on the axial plane because in actual surgery, we experienced pin slippage on the lateral femoral wall when tunneling was directed too proximally. Pujol et al. also documented the possibility of iatrogenic risks concerning femoral cross pins for ACL reconstruction[9]. The authors reported the distance between the cross pin and LCL insertion point and concluded that there is higher iatrogenic risk of collision with the anteromedial portal approach, whereas the transtibial approach appears safer[9]. The authors attempted to suggest the distance between the cross pin and the femur landmark, but practical ranges of angles and distances were not demonstrated.

There are many different opinions regarding the ACL reconstruction method[5-6,10-33], and we could not test all of the available methods. We focused on our protocol and conducted an experiment on SB and DB ACL reconstruction through the transtibial technique for AM bundles and the AM portal technique for PL bundles. This is a potential limitation of our study. Other methods could produce different safe ranges of angles and distances; however, we believe that the general trend would be similar to our results. Regardless, further study is required. Regarding LCL and PT tunnels, there is little consensus on the appropriate reconstructive technique of the lateral tunnel[4-6,34-52]. Some authors have proposed a lateral tunnel from the isometric point of the lateral epicondyle[6,36-41,43-44]; whereas others have suggested the anatomical footprint of the LCL, which is in a small bony depression 1.4 mm proximal and 3.1 mm posterior to the lateral epicondyle, as an entry point[58-59]. Our protocol was based on making the insertion in isometry[6,37-41], and this study was performed using our protocol. Because of current trends toward anatomical reconstruction of the LCL, we also measured the ranges of angles and distances from the anatomical point of the LCL, which was inferior to our isometric point in DB ACL tunnels in the proximal (superior) 10 and 20° direction. We found that the ranges of posterior angles for both the proximal (superior) 10° and 20° directions were significantly smaller than those of the results of this study (Table 3). We observed that the LCL insertion of the anatomical footprint of the LCL is located in the posterior direction, and thus, LCL tunnel met AM bundle tunnel more anteriorly than observed with our method. However, we also observed that the PL bundle tunnel was located more posteriorly than the AM bundle tunnel on the cutting plane in both the 10° and 20° directions, and thus, there was no violation between the PL bundle and the anatomical footprint of the LCL. Caution is needed when using the anatomical footprint of the LCL during reconstruction.

This study has the following limitations. First, it is a 3D imaging study using a method resembling the actual operation. The benefit of a simulation study includes the free formation of virtual tunnels and easy measurement of the ranges of distances and angles. For example, because we could observe all of the crowded tunnels from various angles, especially in DB ACL reconstruction, we believed that great attention would be required when creating multiple tunnels. However, it is possible that the result of the simulation study could be different from that of the actual operation. To compensate for this, we implemented comparisons with the protocol that is applied in actual surgery, and we confirmed that the post-operative CT results were similar to our results (Table 1 and Figure 5). To make our simulation similar to the actual operation, we combined the 120° and 90° flexion knee models (Figure 1) and performed tunneling on each of the PL bundles and AM bundles. Additionally, when we obtained CT scans with the knee flexed at 120°, we attached a coin to mark the medial portal for PL bundle tunneling (Figure 1). Secondly, as was previously mentioned, we investigated the methods used for ACL and PLC reconstruction in actual practice[5-6,12,18,20,36-41]. At the design stage of the study, our focus was not on measuring the distance between the ACL tunnel and LCL or PT femoral tunnel but on presenting the ranges of angles and distances for which LCL and PT femoral tunneling is possible because there are so many different opinions in terms of tunneling angulation[34,39,45-48] and depth and diameter[39,46,53] regarding LCL and PT reconstruction. We have presented the ranges, and our results could be applied to each method. However, because there are different opinions on the possible methods, we believe that additional study is always possible. Third, the insertion points themselves could be inaccurate. There are many controversies regarding the insertion points for each ligament, and some points are known to have low intra- or interobserver reliabilities[60-62]. Therefore, the results may vary depending on the direction of the tunneling. To reduce the inaccuracy, we followed Zantop's study[56] on entry point decision. For LCL and PT insertion, because we could not define isometry points in our simulation study, the entry points were selected by two experienced surgeons based on our surgical procedures[37]. This may not have eliminated all of the variability in the study, and this variability may be amplified in actual operation. Therefore, one option may be to make the safety zone smaller than what it was in our study. Lastly, this study was performed using Korean subjects. There is a difference in the bone size of Asians and non-Asians[63-66]; therefore, our study results must be applied with caution when operating on non-Asian patients and adjustments would be needed.

V. CONCLUSION

The purpose of our study was to provide practical guidelines that could be applied in actual surgery. We found that LCL and PT femoral tunnels should be directed anteriorly rather than posteriorly on the axial plane. Considering the relationship between LCL and PT tunnels and fixation strength, we believe that tunneling would be safe when the LCL and PT are positioned at an angle of approximately anterosuperior 10°. We admit that there would be differences between the results of our simulation study and those of actual operations. However, our results would help to reduce the incidence of tunnel collisions in actual combined ACL and PLC reconstructions. We believe that our results are meaningful not only in providing practical safe ranges but also in attracting attention to collisions when we perform combined ligament reconstruction surgeries.

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ABSTRACT (IN KOREAN)

전방십자인대와 후외방 불안정성의 동시 재건술시 터널 간 관계;
생체 3차원 해부학적 연구

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박 관 규

전방 십자 인대와(Anterior cruciate ligament)와 후외방구조(posterior ligament complex)의 동반 손상은 빈번하며, 두 인대를 함께 재건할 때, 대퇴 외과에 복잡한 터널이 생성되게 된다. 이에 따라 터널 간의 충돌에 대한 우려가 있으나, 이에 대한 연구는 제한적이다. 이 연구는 전방 십자 인대와 후외방 구조의 동시 재건 시 전방 십자 인대의 터널의 손상을 주지 않는 외측 측부 인대(lateral collateral ligament)와 슬와 인대(popliteal ligament) 대퇴 터널의 안전한 각도와 거리의 범위를 알아보아 실제 수술에 도움이 되는 정보를 제공하고자 하였다. 14명의 참가자에서 무릎 컴퓨터 단층촬영을 0°, 45°, 90°, and 120°에서 시행하여 상용화된 프로그램(Mimics 14.01 software, Materialise NV, Belgium)을 이용하여 3차원 해부학적 슬관절 모델을 만들었다. 120°에서는 전내측 포탈(anteromedial portal) 부위에 동전을 부착한 후 촬영을 하였다. 단일다발 전방십자인대 터널은 경경골(transtibial) 방법을 이용하여, 이중다발 전방십자인대 터널은 전내측 다발은 경경골 방법을, 후외측

다발은 전내측 포탈 방법을 이용하여 터널을 만들었다. 대퇴 모델은 외측측부인대와 슬와인대의 대퇴 삽입점에서 수평면(horizontal plane)상 과상간축(transepicydylar axis)에 대하여 후방 20° (-20°), 10° (-10°), 0°, 전방 10° 및 20°의 방향으로 절단을 하였다. 전방십자인대 터널과 대퇴 과간 절흔(intercondylar notch)을 침범하지 않는 외측측부인대와 슬와인대의 안전한 각도와 거리의 범위를 근위부(상부)와 원위부(하부) 방향으로 각각 측정하였다.

전반적으로 안전한 각도의 범위는 후방에서 전방을 향하며 증가하였다. 외측측부인대와 슬와인대 터널이 전방 과상간축에 대하여 전방 (10° and 20°)을 향할 때 안전한 각도의 범위는 약 40° 이상이었으나, 후방(-10° and -20°)을 향할 때는 대퇴과간 절흔(intercondylar notch)이나 전방십자인대 터널과의 충돌이 일어났다. 안전한 각도의 주변부에서 안전한 거리는 외측측부인대의 경우 약 35mm, 슬와인대의 경우 약 30mm 였다. 터널 간 충돌은 전내측 다발 터널과 주로 발생하였으나, 후외측 다발과는 드물게 발생하였다.

이 연구를 통하여 외측측부인대와 슬와인대는 후방보다는 전방을 향해야 할 것으로 사료되었다. 고정 강도를 고려하였을 때, 외측측부인대와 슬와인대 모두 전상방으로 약 10°를 향할 때 안전할 것으로 사료된다. 하지만, 본 연구의 결과는 3차원 모델을 이용한 모델이므로 실제 수술과는 차이가 있을 것으로 사료되며, 실질적인 각도의 제시뿐 아니라 충돌의 위험성에 대한 경각심을 주는 데에 그 의미가 있을 것으로 생각된다.

핵심되는 말 : 터널 간 관계, 전방 십자 인대와 후외방 구조의 동시 재건, 생체 3차원 해부학적 연구