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Influence of Selected Plane on the Evaluation of Tibial Tunnel Locations Using a Three-dimensional Bone Model in Double-Bundle Anterior Cruciate Ligament Reconstruction

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1. Introduction

Anterior cruciate ligament (ACL) injury is very common in professional athletes and in people who practice sports regularly. ACL reconstruction (ACLR) aims to eliminate knee instability and prevent post-traumatic osteoarthritis[1,2]. Precise assessment of tunnel locations following anterior cruciate ligament reconstruction (ACLR) is of great importance as tunnel locations have been shown to affect clinical outcomes[3,4]. Few studies in the literature which focus primarily on the clinical outcomes of the tibial tunnel position in ACL reconstruction, however the literatures suggest that more anatomical placement of tibial tunnels confers better stability to the knee and some benefit in terms of functional outcomes[5,6]. With respect to the evaluation of tibial tunnel location, a plain lateral radiograph has been originally used to assess the anterior-posterior (AP) location of the tibial tunnel[7–9]. Using a plain lateral radiograph, the center of the tibial insertion point of the ACL was defined as a point along the line parallel to the medial tibial plateau[7] or as a point along the line perpendicular to the tibial axis[10]. In recent years, three-dimensional computed tomography (3DCT) has been used to evaluate the tibial bone tunnel location using a grid method[11–17]. However, the evaluated planes vary among the previous studies[11–17] and there is a concern that tibial tunnel locations may be altered if the selected plane changes. Thus, a unified reliable plane is ideal to discuss and compare the tunnel locations among different surgeons and institutions.

There would be two possible planes for tibial tunnel assessments using a grid method with 3DCT; the plane for tibial tunnel aperture evaluation can be the plane which is parallel to the tibial plateau surface (plane A), or the plane which is perpendicular to the tibial shaft axis (plane B). Although sagittal cutting plane of the femur has been shown to affect evaluation of femoral tunnel locations[18], it still remains unknown how the selected plane affects the evaluation of tibial tunnel locations. Therefore, the purpose of the present study was to investigate the influence of a selected plane on the evaluation of tibial tunnel locations using 3DCT, and to compare the locations of the tibial tunnel apertures between the plane A and B after double-bundle ACLR. The hypothesis was that the results of the tibial tunnel locations would be different between plane A and B.

2. Materials and methods

This study was a retrospective study of prospectively collected data. Consecutive 34 knees of 34 patients (Age at surgery: 26.8 ± 12.4 years, 17 males and 17 females) who underwent anatomic double-bundle ACLR using hamstring tendon autograft in 2015, were included in this study. The inclusion criteria were (1) unilateral ACL injury diagnosed by clinical examination and magnetic resonance imaging, (2) absence of previous knee surgery, and (3) absence of ligament injury to the contralateral knee.

Surgical procedure of anatomic double-bundle ACLR

Anatomic double-bundle ACLR using hamstring tendon autograft was performed by experienced senior surgeons as previously reported[19,20]. The original insertion sites of anteromedial bundle (AMB) and posterolateral bundle (PLB) were identified by using anatomical landmarks arthroscopically. The tibial bone tunnels were created by using the tibial drill guide, and the femoral bone tunnels were created by the transportal technique. The tibial drill guide was adjusted to 45° for PLB and 55° for AMB. The grafts were fixed with a suspensory button for the femur, and a cancellous post screw with a washer for tibial side. Tibial fixation was performed at 0° for the PLB and at 30° of knee flexion for the AMB with manual maximum power.

Data processing

Two weeks following the surgery, 3DCT images (Aquilion 64, Toshiba Medical Systems, Otawara, Japan) were taken for all knees, with a slice spacing of 0.5mm and a resolution of 512 x 512 pixels per image[18]. Bone tunnel of the tibial region was extracted via a manual method using Mimics® (Materialise, Leuven, Belgium). 3D bone models of the proximal tibia were also created. Tibial bone tunnel regions were obtained by a region growing function in the segmentation software on each computed tomography slice to obtain a 3D tunnel volume. These data were transferred to a 3D modeling software software 3-matic® (Materialise) in order to create planes A and B.

Plane A, which is parallel to the tibial plateau surface, was obtained by painting medial and lateral tibial articular surfaces with the function of "wave brush mask" (**Figure 1**). Plane B, which is perpendicular to the proximal tibial shaft axis, was obtained as follows (**Figure 2**). Briefly, the proximal tibial shaft was selected with 10cm width using the function of "wave brush mask". The best-fit cylinder of the selected proximal tibia was automatically created, and the axis of the proximal tibial shaft was obtained. Eventually, plane B was determined. In the proximal-distal direction, both plane A and B was put beneath the aperture of the tibial tunnels where a complete ellipse could be drawn around the tunnels. Additionally, the difference in coronal alignment was evaluated between planes A and B (°).

Evaluation of the locations of tibial tunnel apertures

Locations of the tibial tunnel apertures were evaluated according to the previously reported methods[15,21]. In short, the AP and medial-lateral (ML) edges of the proximal tibial plateau were identified using identifiable landmarks and these points were used to create a grid system on planes A and B, respectively. Each center of the tunnel aperture was then identified within the grid system. Finally, the location was expressed as a percentage of tibial plateau anterior to posterior depth and medial to lateral width using ImageJ (National Institutes of Health, Bethesda, Maryland) (**Figure 3**). The dimensions of the tibial tunnel apertures were also assessed using ImageJ. The diameter (mm) of the major and minor axes of the ellipse were measured in each plane.

To evaluate intra-observer and inter-observer reproducibility of measurements obtained by the ImageJ software, all measurements were performed twice by the same surgeon with more than 2 weeks interval, and another examiner measured once to assess inter-rater repeatability. Intraclass correlation coefficients (ICC) for intra-observer were 0.92 and 0.90 for AMB and PLB in plane A, and 0.93 and 0.95 for AMB and PLB in plane B, respectively. Inter-observer ICC were 0.91 and 0.91 for AMB and PLB in plane A, and 0.92 and 0.94 for AMB and PLB in plane B, respectively.

The study protocol was approved by the Institutional Review Board of our institution (ID No. B190055), and written informed consent was obtained from all patients before their enrollment.

Statistical Analysis

A priori power analysis using G power 3.1 (Christian Albrecht University, Kiel, Germany) indicated that a sample size of at least 17 patients per group was necessary to detect an intergroup difference of 0.1%, in each parameter with effect size of 0.8, an alpha of 0.05 and a power of 80%. A paired t-test was used to compare the data obtained from planes A and B. For all analyses, statistical significance was set at $P < 0.05$. All data were reported as mean ± standard deviation (SD).

3. Results

On plane A, the locations of the AMB and PLB tibial tunnel apertures were 36.1 ± 7.1%, 50.6 ± 6.3% in the AP direction, and 45.0 ± 2.2%, 45.5 ± 1.8% in the ML direction, respectively. On plane B, the locations of the AMB and PLB tibial tunnel apertures were 38.5 ± 6.3%, 52.9 ± 5.7% in the AP direction, and 43.5 ± 2.1%, 43.9 ± 1.5% in the ML direction, respectively. AMB and PLB tunnel apertures in plane A were significantly more laterally located than in plane B (**Figure 4**, AMB; $P = .0021$, PLB; $P = .0006$). Mean differences in the ML direction were 1.5% (95% confidential interval [CI]; 0.5-2.6) in AMB, and 1.7% (95% CI; 0.8-2.5) in PLB. On the other hand, there were no significant differences in AMB and PLB tunnel locations in the AP direction between planes A and B (**Figure 4**). Mean differences in the AP direction were 2.4% (95% CI; -0.9-5.7) in AMB, and 2.4% (95% CI; -0.6-5.3) in PLB. The coronal alignment difference between plane A and B was 16.8 ± 2.2° (range, 13.7-21.3), and plane B was more valgus than plane A (**Figure 5**). On plane A, the diameters of the tunnel apertures were 7.0 ± 0.6 mm and 6.2 ± 0.6 mm in AMB, and 6.0 ± 0.4 mm and 5.3 ± 0.5 mm in PLB (major and minor axes, respectively).

On plane B, the diameters of the tunnel apertures were 7.0 ± 0.6 mm and 6.1 ± 0.5 mm in AMB, and 5.9 ± 0.4 mm and 5.3 ± 0.5 mm in PLB. No significant differences were observed in tunnel diameters between the two planes (AMB major axis, $P = 0.28$; AMB minor axis, $P = 0.19$; PLB major axis, $P = 0.18$; PLB minor axis, $P = 0.25$).

4. Discussion

The most important finding of this study was that the evaluation of tibial tunnel locations was not significantly influenced by the selected plane in the AP direction. Moreover, although statistically significant differences were found in ML direction, the differences in tunnel locations in ML direction was subtle (only a couple of percentages); thus, these differences would not be clinically significant. These findings suggest that both plane A and B can be used in the assessment of tibial tunnel location, and one could assume that the results of the tibial tunnel locations may be compared and discussed using the grid method among different institutions and different studies, as long as the grid is created consistently between the studies. In our opinion, using plane A may be better for assessing the tibial tunnel locations because plane A, which is parallel to the tibial plateau surface, would be clinically more straightforward and the tibial shaft axis is not necessary to determine the plane. This consideration seems to be supported by previous studies using the plane of tibial plateau surfaces[7,15].

In the ML direction, AMB and PLB tunnel apertures were significantly more laterally located in plane A than plane B in the present study. Besides that, plane B was consistently located in more valgus than plane A (**Figure 5**). This coronal plane difference could be because of the morphology of the proximal tibia; the proximal tibia is physiologically varus, and medial proximal tibial angle has been reported to be 87° on average[22–24]. Thus, plane B, which is perpendicular to the tibial shaft axis, can be more valgus than plane A, which is parallel to the tibial plateau joint surface. Moreover, tibial tunnels ran in antero-medial direction from the aperture to the exit. Taken together, one could assume that the tunnel location differences in ML direction could be at least partially attributable to this coronal alignment difference between plane A and B.

Originally, tibial tunnel positions have been assessed using lateral plain radiographs of the knee[7,25]. The method, which was proposed by Amis et al., used the line parallel to the tibial articular surface[7] as a reference, while Staubli et al. reported the use of a line perpendicular to the tibial bone axis[25] as a reference. The limitation of assessment using plain lateral radiographs is that only AP direction can be evaluated, and the rotation of the tibia might affect the results.

In recent years, a grid method using 3D bone models have been used to evaluate the tibial tunnel locations after ACL reconstruction[11,12,14,26,27] (**Table 1**). This grid method with the top view of proximal tibia has been also used for cadaveric studies to evaluate the location of the native ACL insertions[11,13,14,28–30]. A recent MRI-based 3D topographic analysis[30] reported similar locations of native AMB and PLB with these previous studies using 3D CT. A recent systematic review has reported that the weighted mean of the center of native tibial AMB and PLB in 300 knees was 34.7% (the 5th and 95th percentiles; 25.0 and 41.0) and 47.8% (42.8 and 52.0) in AP direction[29], respectively. According to this systematic review, the tibial tunnel locations in the present study were within the anatomical range in the AP direction.

Lertwanich et al.[31] reported high intraobserver and interobserver reliability on the measurement of ACL tunnel locations using 3D reconstructed models. However, these measurements may differ depending on the process of 3D model preparation. Moon et al.[32] has shown that the rotation of the proximal tibia significantly affected the measurement of tibial tunnel location using single-bundle ACL reconstruction, and that the results of tibial tunnel locations significantly shifted to only medial direction but not AP direction when the proximal tibia was rotated in valgus direction. Although they found statistically significant differences, the translation of the tibial tunnel location was within only 3 percentages, thus the differences would not be clinically significant. This study by Moon et al. supports the present results with double-bundle ACL reconstruction.

Several limitations of the present study should be mentioned. First, the present study assessed the tunnel locations in double-bundle ACL reconstruction, but not single-bundle procedure. Nevertheless, we believe that the current results can be transferred to single-bundle ACL reconstruction. Second, only proximal tibial shaft was used to determine the tibial shaft axis. Ideally, the entire tibia would have been needed to determine the accurate tibial shaft axis. But in consideration of radiation exposure, we did not scan the entire tibia. However, we think it would be acceptable to determine the tibial shaft axis by using the proximal tibia.

5. Conclusion

Although the tibial tunnel locations were not significantly influenced by the selected planes in the AP direction, subtle but statistically significant differences were found in the ML direction between the plane A (parallel to tibial plateau surfaces) and plane B (perpendicular to proximal tibial shaft axis) in double-bundle ACL reconstruction. The findings suggest that both plane A and B can be used in the assessment of tibial tunnel locations after ACL reconstruction.

Declaration of competing interest

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Figure Legends

Figure 1. Description of the plane A which was parallel to tibial plateau.

Medial and lateral articular surfaces of the tibial plateau were selected (green) and then the plane A (blue grid), which is parallel to the selected areas, was obtained.

Figure 2. Description of the plane B which was perpendicular to tibial shaft axis.

(a) proximal tibial shaft was selected (green) and the axis of selected area (red line) is automatically created.

(b) the plane B (blue grid), which was perpendicular to proximal tibial shaft axis was created. In proximal-distal direction, the plane B was put beneath the aperture where a complete ellipse could be drawn around the tunnels.

Figure 3. The measurement of tibial tunnel aperture locations using a grid method.

Anterior-posterior and medial-lateral axes were established, and the location of tunnel apertures were expressed as a percentage of the corresponding maximum dimension.

Figure 4. Scatter plots of the tibial tunnel locations using two planes.

(a) Locations of anteromedial bundle (AMB) (b) Locations of posterolateral bundle (PLB)

Figure 5. Coronal alignment difference between plane A and plane B.

An example shows the difference in coronal alignment between plane A and plane B, and the plane B was more valgus than plane A.

Tables

Table 1. Comparison between the current study and the previous studies measuring native ACL tibial footprint and tibial tunnel locations using a grid method with three-dimensional CT images. Values are given as mean ± SD (%). AMB, anteromedial bundle; PLB, posterolateral bundle; NR, not reported

Author (year)	Native ACL/ tunnel	Anterior-Posterior position		Medial-Lateral position	
		AMB	PLB	AMB	PLB
Lorenz (2009)[11]	Native ACL	37 ± 3	48± 3	48 ± 2	50 ± 2
Forsythe (2010)[12]	Tunnel	25 ± 2.8	46.4 ± 3.7	50.5 ± 4.2	52.4 ± 2.5
Lee (2015)	Native ACL	36.7 ± 3.8	42.2 ± 4.2	47.3 ± 1.9	53.8 ± 1.4
Ohori (2017)[26]	Tunnel	25.8 ± 3.1	39.6 ± 4.5	46.7 ± 2.9	46.0 ± 3.0
Taketomi (2018)[27]	Tunnel	25.4	46.2	46.8	46.8
Current study					
Plane A	Tunnel	36.1 ± 7.1	50.6 ± 6.3	45.0 ± 2.2	45.5 ± 1.8
Plane B	Tunnel	38.5 ± 6.3	52.9 ± 5.7	43.4 ± 2.1	43.9 ± 1.5

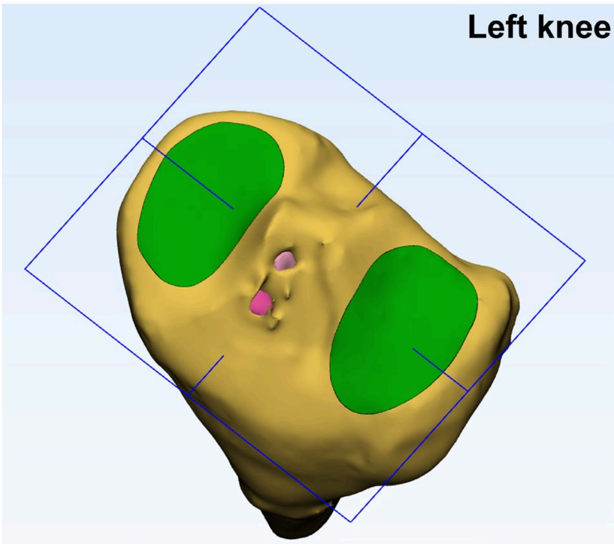

Figure 1.

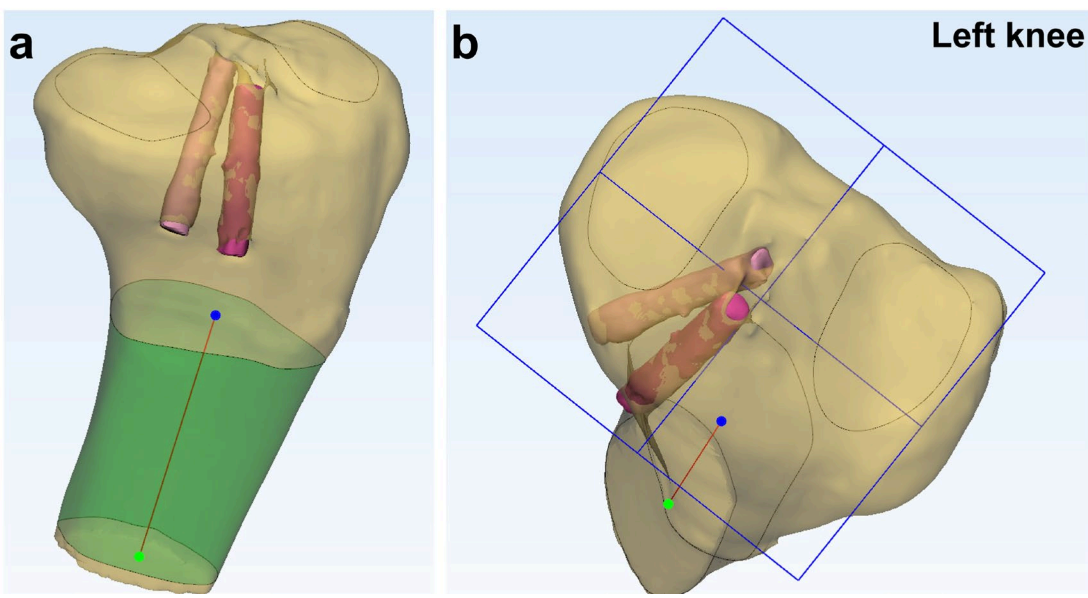

Figure 2.

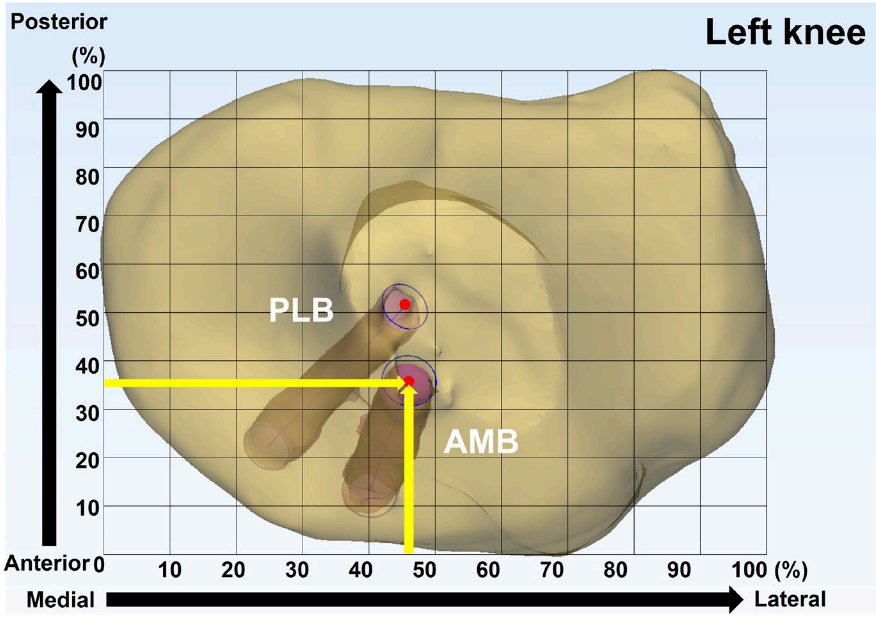

Figure 3.

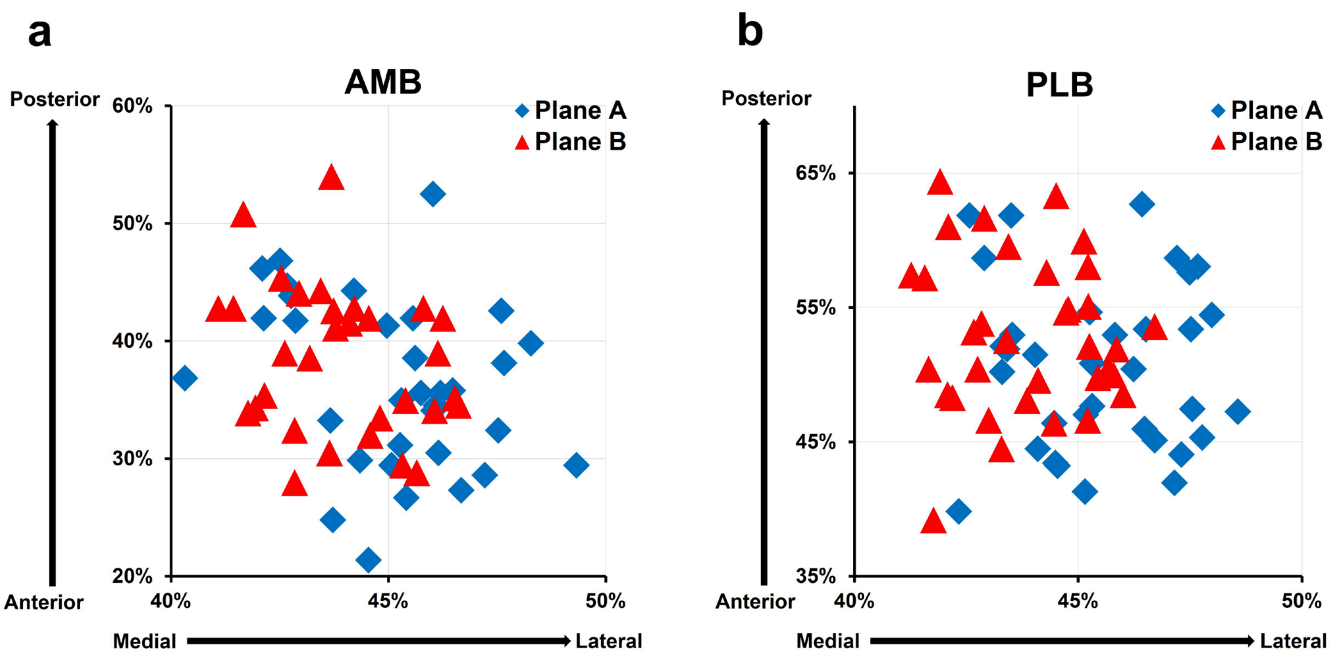

Figure 4.

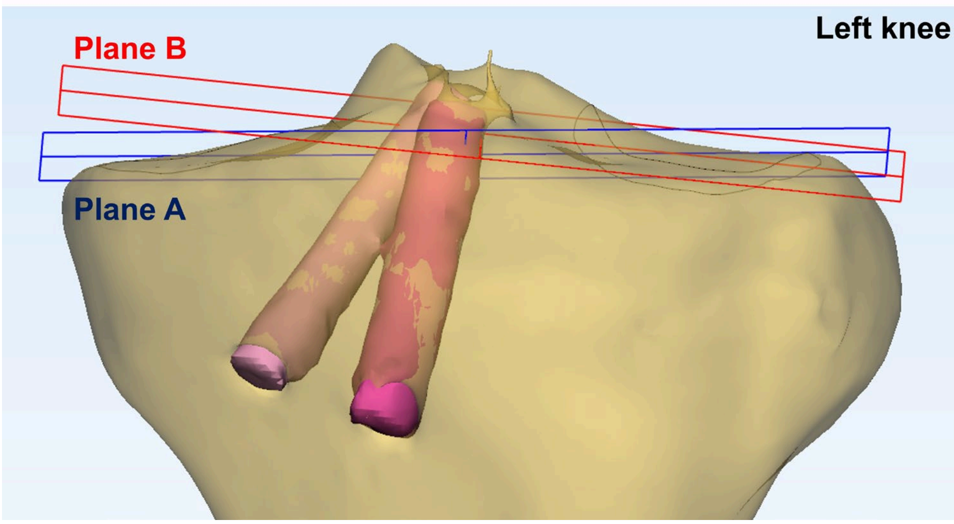

Figure 5.