

Original Article

Clinical study of anatomical ACL reconstruction with adjustable oval shaped bone tunnels: a CT evaluation

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Abstract: The purpose of this article was to demonstrate an adjustable oval bone tunnel ACLR technique. Aim of this technique was to fit the direction and shape of the footprint and tendon-bone healing passage (TBHP) which was defined as the passage of the normal ACL insertion embedded in the bone as closely as possible. 30 fresh-frozen human cadaveric knees were used to do the ACL anatomical insertions research. 20 patients underwent adjustable oval bone tunnel surgery and 20 patients were in round tunnel group. The tunnel of the presented technique was first drilled with a small diameter round drill bit. Then according to the direction and area of the remnant insertion fibers, the major axes of oval tunnels were expanded to theoretical value with a bone file. Major and minor axes, positions of bone apertures, and areas were evaluated on CT scans. These results were compared with cadaveric and theoretical values. The distance of major axis of oval femoral and tibial tunnel apertures were 10.42 ± 0.55 mm and 12.63 ± 0.5 mm respectively. There're no statistical significance compared with theoretical distance (femoral: $P = 0.068$, tibial: $P = 0.058$). The distance of minor axis of oval femoral and tibial tunnel apertures were 6.79 ± 0.28 mm and 6.02 ± 0.29 mm respectively. Both of them were longer than theoretical values ($P < 0.001$). Compared with the round femoral tunnel, the major/minor axis ratio of oval tunnel (1.53) was more close to the cadaveric results (1.83, $P < 0.001$). The areas of femoral and tibial apertures were 53.12 ± 1.87 mm² and 54.22 ± 3.21 mm² respectively. Both of them were smaller than the round tunnel area and larger than theoretical areas ($P < 0.001$). We successfully developed the adjustable single oval bone tunnel ACLR technique, which mimic the direction and shape of the tibial and femoral footprints together with the TBHP better than single round tunnel.

Keywords: Adjustable oval tunnels, round tunnels, anatomic ACL reconstruction, CT evaluation

Introduction

Anatomical reconstruction of anterior cruciate ligament (ACL) is an useful method to completely restore the anterior-posterior and rotational stability function of the ligament. The anatomical reconstruction has been become the constant goal of surgeons. Though various techniques have been proposed to reconstruct ACL within its anatomical positions from the aspects of bone tunnel shape, bundle number of the grafts, and the bone tunnels making techniques including anatomical single or double-bundle reconstruction, triple-bundle ACLR, ACLR with oval or rectangular tunnels, transtibial or anteromedial reaming of femoral tunnels, etc., there still exists many problems to be solved.

Several cadaveric studies about ACL indicated that both the femoral and tibial insertions were

of oval shape rather than round shape [1, 2] and the direction of the major axis varies among different individuals. Following these anatomical situation, researchers have been making progress, but still can't fully realize the anatomical ACLR. Several studies have shown that the anatomical double bundle techniques achieve a better stability of A-P translation measured with the KT-1000 and restore a better pivot shift stability compared to a single bundle technique [3, 4]. The advantage of the double-bundle reconstruction is that with this technique the two round tunnels match the oval area of the ACL insertion much better than a single round tunnel does [5]. According to the oval shaped anatomical footprints and the better rotational stability of double bundle ACLR, several researchers have realized that it will be more anatomical to do the oval shaped single bundle ACLR. Recently, technique of oval or

Table 1. Patients characteristics

	Round tunnel (n = 20)	Oval tunnel (n = 20)	P value
Age, y	29.7 (18 to 40)	28.8 (19 to 38)	0.7
Sex, male/female, No.	16/4	15/5	

round rectangular bone tunnel has been reported to do the ACLR [6-8].

Though the oval or round rectangular bone tunnels improved the shape of graft insertion, the key operation skill of currently reported oval or round rectangular bone tunnels studies was that they created the oval or rounded rectangle femoral bone tunnel with oval or rounded rectangle dilators. One risk of the utilization of dilator was that compression of the dilator may break the posterior wall of the bone tunnel. In their study, one patient experienced a partial posterior tunnel wall blowout. The other risk was that once the dilator was knocked into the bone tunnel to expand the aperture, it was impossible to adjust the major axis direction of aperture again if the direction was not satisfied. It was also difficult to make the bone tunnel with the major axis direction alone the individualized footprint. So there still exists some difficulty to ensure both the shape and direction of the graft insertion matched the footprint well. Meanwhile, 0.5 mm extended from the opening of tunnel in joint to the inside of tunnel was also an important factor affecting the tendon-bone healing, which was named as tendon-bone healing passage. In this study, we aimed to present the adjustable single oval bone tunnel ACLR technique, which mimic the direction and shape of the footprint zone better than the single round tunnel. The key point of our skill was that the tunnel was firstly drilled with a small diameter drill bit and then adjusted with the bone file to oval shape step by step according to the footprint or the anatomical landmark. With this adjustable technique, we hypothesis that we could make the femoral bone tunnel as close to the posterior border line as possible without blowout and the tibial bone tunnel as anterior as possible without impingement.

Material and method

Cadaver study

30 fresh-frozen human cadaveric knees (age range, 46-75 years; 15 left and 15 right speci-

mens) were thawed overnight at room temperature and dissected down to the femur, tibia, and joint capsule. The knees were clinically examined to exclude those with previous ligament injury or degenerative joint diseases.

All dissections and markings were performed by a single surgeon. Cadaveric knees were donated to the university donation program.

The medial femoral condyle was cut using an oscillating saw, and all synovial tissue overlying the ACL was removed. The ACL was excised at insertion area and the center and the contour of ACL insertion sites were marked with the mark-pen subsequently. The major and minor axes of both tibial and femoral insertions were measured with a vernier caliper. The center of the femoral insertion were examined with the Bernard and Hertel method and that of the tibia insertion was examined with the Amis and Jakob method. In order to calculate the areas of the attachments, tibial and femoral insertions were photographed with a digital camera (canon) and marked with a measuring scale. The images were then imported into the Adobe Photoshop Elements CS6 software (Adobe Systems, San Jose, CA) to calculate the areas. Briefly, the insertion was divided into many small grids. And the areas were measured according to the measuring scale.

Clinical study

Patients: Written informed consent was obtained from all subjects. This study's design was reviewed and approved by our institutional ethics review board (No. of ethics was IRB00006761-2016139). Between May 2015 and February 2016, 40 patients scheduled to undergo ACL reconstruction were randomized to ACLR with oval tunnel (n = 20) or round tunnel (n = 20) (**Table 1**). The graft diameter of every included patient was 8 mm. All procedures were conducted by a single surgeon. The diagnosis of ACL injury was reached based on a history of knee injury and the results of the Lachman and pivot shift tests, as well as a side-to-side difference of ≥ 3 mm when measured using the KT-2000 arthrometer (MED metric, San Diego, USA). All patients underwent magnetic resonance imaging (MRI) to confirm the diagnosis of an ACL tear. The inclusion crite-

Table 2. Theoretical values of major axis, major/minor and distance expanded by bone file of oval bone tunnels

Diameter of round tunnel and graft (mm)	Minor axis (mm)	Major axis (mm)	Major/minor	Distance expanded by bone file (mm)
7	5	9.8	1.96	4.8
7	6	8.2	1.36	2.2
8	5	12.8	2.56	7.8
8	6	10.67	1.78	4.67
9	5	16.2	3.24	11.2
9	6	13.5	2.25	7.5

ria were unilateral complete ACL tear, and the exclusion criterion included multiple ligament injury or previous knee ligament surgery.

Patient positioning: The patient was positioned in the supine position on the operation table. A tourniquet was placed high on the thigh. The knee could be flexed at an angle from 0° to 130°.

Graft harvesting: Autologous semitendinosus and gracilis (STG) tendons were harvested via a 3 cm oblique incision medial of the tibial tuberosity with a close tendon stripper (Karl Storz, Tuttlingen, Germany). For a four stranded graft, a minimum length of 14 cm for the semitendinosus and gracilis tendons are needed. This length is normally reached in every patient. Graft diameters were measured with round-shaped measuring devices (Karl Storz, Tuttlingen, Germany).

Theoretical value calculation: Theoretical values of the minor and major axes were calculated by assuming good fit between the bone tunnels and the graft. The cross-sectional areas of the bone tunnels, either of oval or round shape, would then be equal to that of the graft, the diameters of which are often 7 mm, 8 mm and 9 mm. According to the area formula of circle and oval, we calculated the major axis when the minor axis was defined as 5 mm or 6 mm. (Table 2) $A_{circle} = \pi \left(\frac{D}{2}\right)^2$ (A_{circle} is the area of the round tunnel. D is the diameter of the round tunnel) $A_{oval} = \pi \left(\frac{Maj \times Min}{4}\right)$ (A_{oval} is the area of the oval tunnel. Maj means major axis. Min means minor axis.). When A_{circle} is equal to A_{oval} , we can deduce calculation formula $Maj = \frac{D^2}{Min}$.

Tibial tunnel: The tibial tunnel was drilled with a tibial tip to elbow guide set at a 45° angle. For anatomical tunnel placement, the tibial stump of the ACL should be left in situ. In cases with no remnants, the anterior horn of the lateral meniscus was used as the landmark. In single bundle ACL reconstruction, the K-wire was placed in the center of the tibial footprint. In the round tunnel group, the tunnel was then drilled with an 8 mm diameter drill bit. In the adjustable oval tunnel group, the tibia tunnel was first drilled with a 5 mm diameter drill bit. According to the direction and area of the remnant insertion fibers, the major axis of the oval tunnel was then expanded to the theoretical value of 12.8 mm step by step with a 4 mm diameter bone file. If the 5 mm tunnel was not anterior enough compared with the footprint, the operator could consider further filing down of the anterior wall. To confirm that the length was equal to the theoretical value, arthroscopic measurement was made manually (Figure 1).

Femoral tunnel: Transtibial technique was used for both round and oval tunnel groups. Using the lateral intercondylar ridge as an anatomical landmark, and taking care not to damage the remnant fibers of the ACL on the femur, a mark was made at the center of the ACL's femoral insertion using a freehand technique and a radiofrequency device at 90° of knee flexion. For the transtibial technique, when the K-wire was placed centrally within the femoral insertion, the small femoral tunnel was penetrated with a 4.5 mm drill bit. Then the whole length of the small tunnel was measured. To create a round tunnel, a wide tunnel was drilled with an 8 mm drill bit up to a suitable length depending on the length of the total tunnel. To create the adjustable oval shaped aperture, we first used the 6 mm diameter drill to create a tunnel which was smaller than the graft diameter. Then in the same manner as that in tibial tunnel creation, the major axis of the oval tunnel was expanded to the theoretical value of 10.66 mm step by step with a bone file by transtibial approach. The posterior wall of the tunnel was measured. About 2 mm was left at the posterior wall of each femoral oval tunnel. Arthroscopic measurement was also applied during the process of tunnel creation (Figure 2).

Adjustable oval shaped bone tunnels for ACL reconstruction

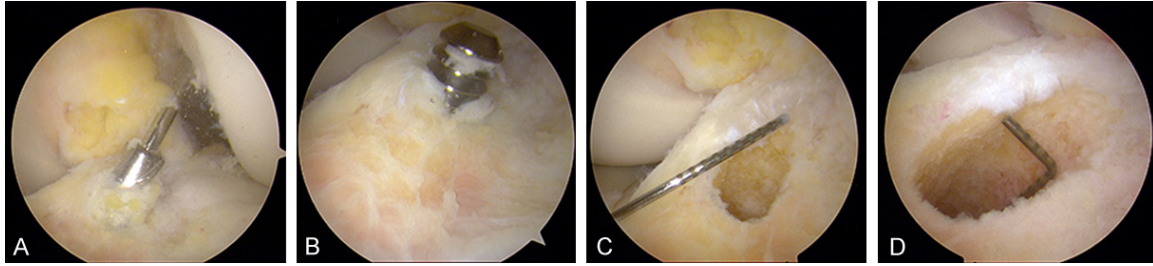


Figure 1. Tibial tunnel creation. A. The tunnel was first drilled with a 5 mm diameter drill bit. B. A bone file was used to expand the major axis of the tunnel. C. To confirm the length equal to the theoretical value, arthroscopic measurement was made manually. D. Showed the oval shaped aperture of the tibial bone tunnel.

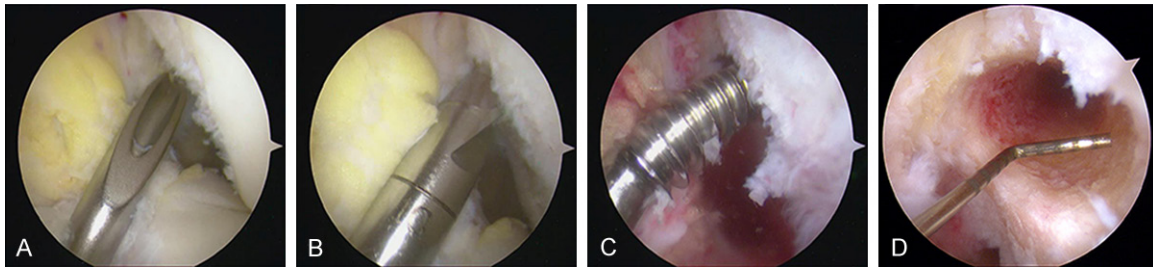


Figure 2. Femoral tunnel creation. A. The femoral tunnel was created with the transtibial technique. B. The 6 mm diameter drill bit which was smaller than the diameter of the graft was used to create the major axis of the tunnel. C. The file was used to expand the major axis of the tunnel. D. Showed the oval shaped aperture of the femoral bone tunnel. Arthroscopic measurement was made manually to ensure appropriate length of the tunnel.

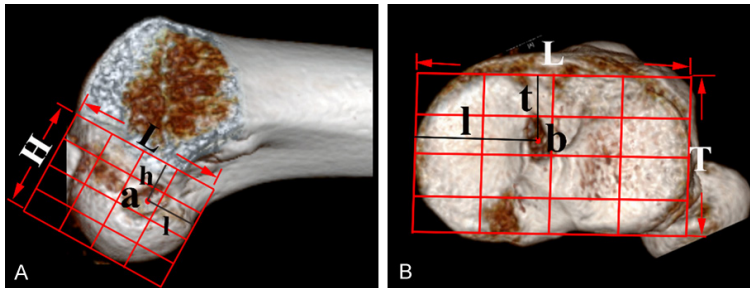


Figure 3. A. The ratios of L:L and h:H were expressed as percentages to describe the femoral tunnel's position according to Bernard and Hertel (BH) method. B. The sagittal tunnel position (percentage) was calculated by $t/T \times 100\%$. The coronal tunnel position (percentage) was calculated as $l/L \times 100\%$.

Graft passage and fixation: After we confirmed the grafts diameter were 8 mm with a round-shaped measuring device, the grafts were passed via the tibial tunnel. At the femoral side, the grafts were secured with a button (Flitack, Karl Storz, Tuttlingen, Germany). After flipping the button, the grafts were pulled back with manual power and the joint was moved several times through the full range of motion. At the tibial side, the grafts were fixed with a bio-absorbable grooved screw (Smith & Nephew

Endoscopy, Andover, MA, USA) of 25 mm length after tensioning the graft in 30° of flexion with manual power. The diameter of the screw was used 1 mm smaller than the diameter of the tunnel.

CT evaluation of femoral and tibial tunnel position: In all patients, computed tomography was performed at one day after the ACL reconstruction to evaluate the femoral and tibial tunnels' position. We obtained 0.6-mm-thick cross-sectional

images (taken perpendicular to the anatomical axis of the femur), which were used to reconstruct the femur and tibia (without any soft tissue) using the AquarisNET (TeraRecon Inc. Foster City, CA, USA) three-dimensional rendering program, and the center of the femoral and tibial tunnels were identified on the reconstructed images. The quadrant method suggested by Bernard and Hertel (BH) grid was used to evaluate the position of the femoral tunnel [9, 10]. The center of the tunnel was

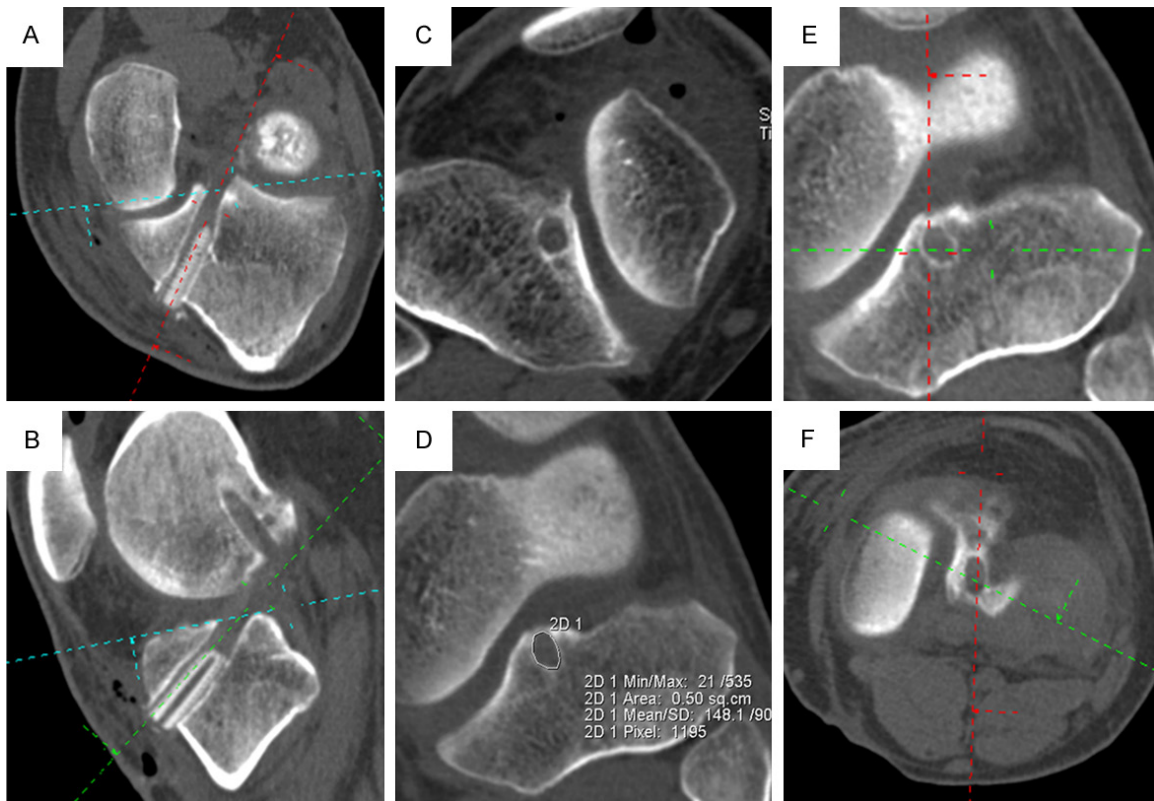


Figure 4. 2D CT scan schematic diagram of measuring distance and areas of tibial tunnel aperture and section of tendon-bone healing passage slice. A and B. Shows the location slice of the tibial tunnel aperture. C. The aperture shape of the round bone tunnel is near a circle. D. The aperture of tibial tunnel perpendicular to the tunnel drilled direction is oval shaped. E. A slice perpendicular to the tunnel drilled direction that was 5 mm in depth away from the aperture identified the oval shaped section of the tendon-bone healing passage. F. The shape of the tibial aperture on the plateau was larger than the bone substance of the bone tunnel caused by the 45° angle of the guider.

defined as point a, and a rectangle was formed using the Blumensaat's line, a parallel line that was tangential to the most inferior margin of the lateral condyle, and two perpendicular lines that were tangential to the shallowest/deepest subchondral contours of the lateral femoral condyle. Using this rectangle, the following four distances were measured: the distance of the lateral femoral condyle on the sagittal plane along Blumensaat's line (L), the maximum height of the intercondylar notch (H), the distance from point a to the deepest subchondral contour of the lateral femoral condyle (I), and the distance from point a to Blumensaat's line (h). The ratios of I:L and h:H were then expressed as percentages to describe the femoral tunnel's position [11].

The position of the tibial tunnel was defined using the method described by Amis and Jakob [12]. Point b represents the center of the tibial bone tunnel aperture. The anterior-posterior

diameter of the tibial plateau was represented as T. The distance from point b to the anterior border of the plateau was represented as t. The medial-lateral distance of the tibial plateau was represented as L. The distance from point b to the medial border of the plateau was represented as l. The sagittal tunnel position (percentage) was calculated by $t/T \times 100\%$. The coronal tunnel position (percentage) was calculated as $l/L \times 100\%$ (Figure 3).

The measurements were performed twice by two experienced residents with an interval of 2 weeks between measurements and we evaluated their Cohen κ coefficient and P value.

CT evaluation of distance and areas of femoral and tibial tunnel aperture and tendon-bone healing passage: In the oval tunnel group, we measured we first identified the femoral and tibial bone tunnels' apertures that were perpendicular to the tunnel drilled direction res-

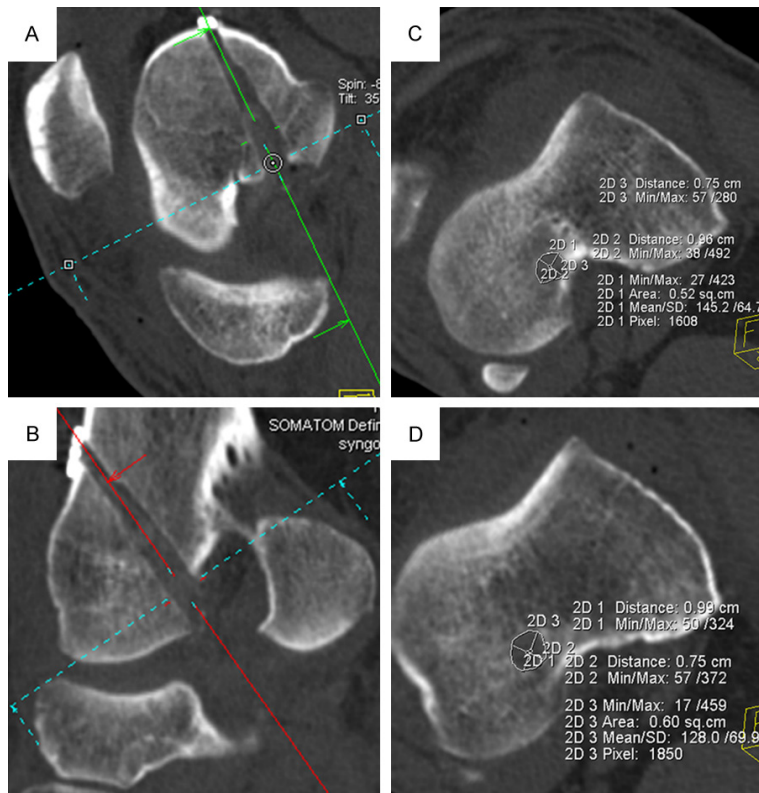


Figure 5. 2D CT scan schematic diagram of measuring distance and areas of femoral oval tunnel aperture and section of tendon-bone healing passage slice. A and B. Shows the location slice of the femoral tunnel aperture. C. The aperture of femoral tunnel perpendicular to the tunnel drilled direction is oval shaped. The value of the major axis, minor axis and area were measured. D. A slice perpendicular to the tunnel drilled direction that was 5 mm in depth away from the aperture identified the oval shaped of the section of tendon-bone healing passage.

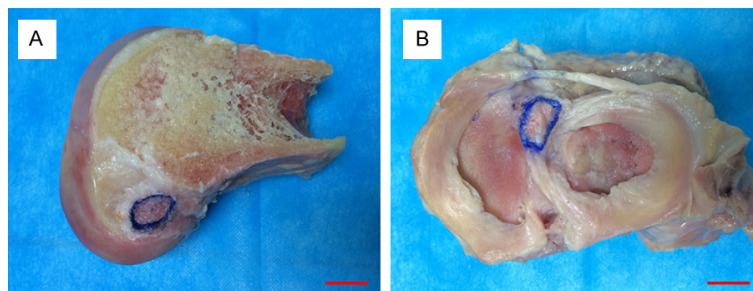


Figure 6. ACL anatomy results from the cadaver study. A. Oval-shaped outline of the femoral insertion. B. Oval-shaped outline of the tibial insertion (scale bar, 1 cm).

pectively using the AquarisNET program. The length of the major and minor axes and the area were measured. Secondly, in order to identify whether the tendon - bone healing passage was repaired to oval shaped, we also made a slice perpendicular to the tunnel drilled direction that was 5 mm in depth away from the

aperture. The area, major and minor axes were measured again. Besides, the major axis of the tibial aperture on the plateau was larger than the bone substance of the bone tunnel caused by the 45° angle of the guider, so the data of the aperture on the plateau was measured too. All of these preparations and measurements were done twice by 2 observers with an interval of 2 weeks between measurements (Figures 4, 5).

Statistical analysis: All results were presented using mean \pm standard deviation. Statistical analysis was performed with independent-samples t tests for comparison of the means between groups. One-sample t-test was used to analyze comparison of the means between groups and theoretical values. The reliability of the CT measured data was evaluated by use of intraclass correlations for interobserver reliability and the Cohen κ coefficient for intraobserver reliability for 2 observers. For statistical analyses, SPSS software, version 16.0 for Windows (SPSS, Chicago, IL), was used and $P < 0.05$ was considered significant.

Results

Cadaver study

The femoral insertion of the ACL was generally in oval shape rather than round shape. The average values of the major and minor axes were 19.32 ± 2.42 mm and 10.52 ± 2.24 mm respectively. The average area of femoral insertion was 155.97 ± 25.21 mm².

The tibial insertion of the ACL was not round either. The average values of major and minor axes were 17.12 ± 2.30 mm and 9.06 ± 1.68

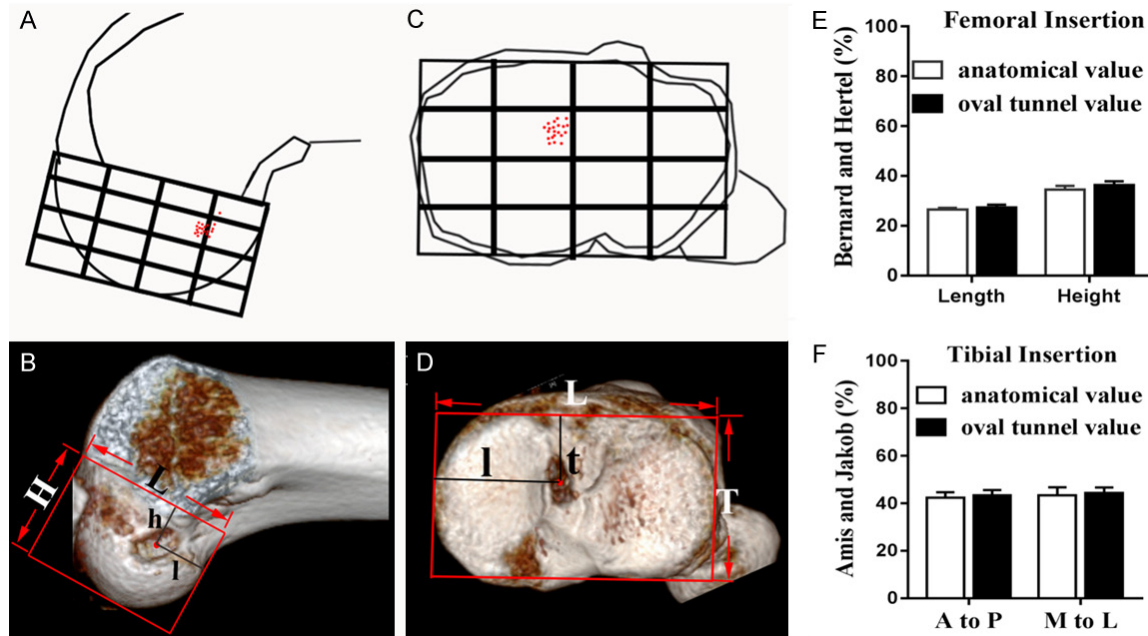


Figure 7. A. Schematic of femoral tunnel centers position of oval bone tunnel group. Each red dot represents 1 case (n = 20). B. The red dot represents the mean femoral tunnel center in the oval bone tunnel group. The value of l/L was $27.38 \pm 2.35\%$ of femoral length and the value of h/H was $36.37 \pm 3.18\%$ of femoral height. C. A Schematic of tibial tunnel centers position of oval bone tunnel group. Each red dot represents 1 case (n = 20). D. The red dot represents the mean tibial tunnel center in the oval bone tunnel group. The value of t/T was $43.46 \pm 2.18\%$ from the anterior margin and the value of l/L was $44.48 \pm 2.21\%$ from the medial margin. E. There's no statistical significance between the center position of oval femoral tunnel aperture and our anatomical femoral insertion location ($P = 0.2$, $P = 0.11$). F. There's no statistical significance between the center position of oval tibial tunnel aperture and our anatomical tibial insertion location ($P = 0.15$, $P = 0.27$).

mm respectively. The average area of tibial insertion was $123.43 \pm 20.53 \text{ mm}^2$.

The center of the femoral ACL insertion was located at $26.42 \pm 2.13\%$ from the deepest subchondral contour of the lateral femoral condyle, and at $34.42 \pm 4.28\%$ from the Blumensaat's line. The center of the tibial ACL insertion was located at $42.42\% \pm 2.25$ from the anterior margin and at $43.48 \pm 3.35\%$ from the medial margin (**Figure 6**).

CT evaluation of femoral and tibial tunnel position in oval shaped tunnel group

The femoral tunnel was located at $27.38 \pm 2.35\%$ from the deepest subchondral contour of the lateral femoral condyle, and at $36.37 \pm 3.18\%$ from the Blumensaat's line. There's no statistical significance compared with our anatomical insertions locations ($P = 0.2$, $P = 0.11$). The center of the tibial tunnel was located at $43.46 \pm 2.18\%$ from the anterior margin and at $44.48 \pm 2.21\%$ from the medial margin. There's no statistical significance compared with our

anatomical insertions locations ($P = 0.15$, $P = 0.27$) (**Figure 7**).

CT evaluation of axes and areas of femoral and tibial tunnel aperture and 5 mm section

Axes and areas of femoral and tibial tunnel aperture in round tunnel group: In the round tunnel group, the diameter of the femoral tunnel aperture was $8.66 \pm 0.17 \text{ mm}$, significantly longer than the diameter of the drill bit (8 mm, $P < 0.001$). The area of the femoral round tunnel aperture was $54.42 \pm 1.19 \text{ mm}^2$, significantly larger than the theoretical area 50.24 mm^2 ($P < 0.001$). The diameter of tibial tunnel aperture was $8.63 \pm 0.11 \text{ mm}$, significantly longer than the diameter of the drill bit (8 mm, $P < 0.001$). The area of the tibial round tunnel aperture on the surface of plateau was $60.43 \pm 3.69 \text{ mm}^2$, significantly larger than the theoretical area 50.24 mm^2 ($P < 0.001$).

Axes and areas of femoral tunnel aperture in oval tunnel group: In the oval shaped tunnel group, the distance of the major axis of femoral

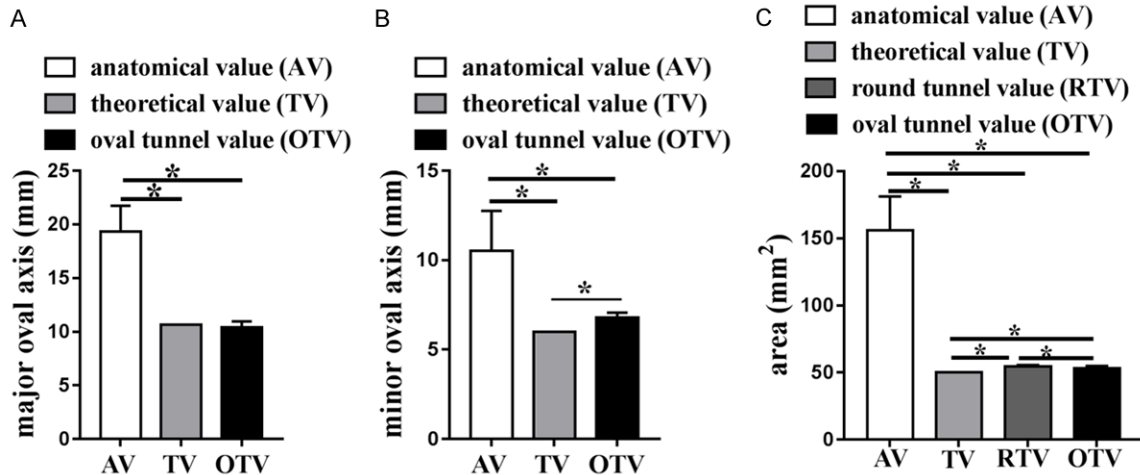


Figure 8. Major, minor axes and areas of femoral tunnel aperture. Both the major and minor axes of oval femoral tunnels were significantly shorter than the anatomical values. The oval major axis matched the theoretical value well. The oval minor axis was statistical longer than the theoretical one. Areas of both round and oval femoral tunnels' apertures were smaller than anatomical area. The area of oval tunnel aperture was statistical smaller than the round tunnel area and larger than theoretical area ($P < 0.001$).

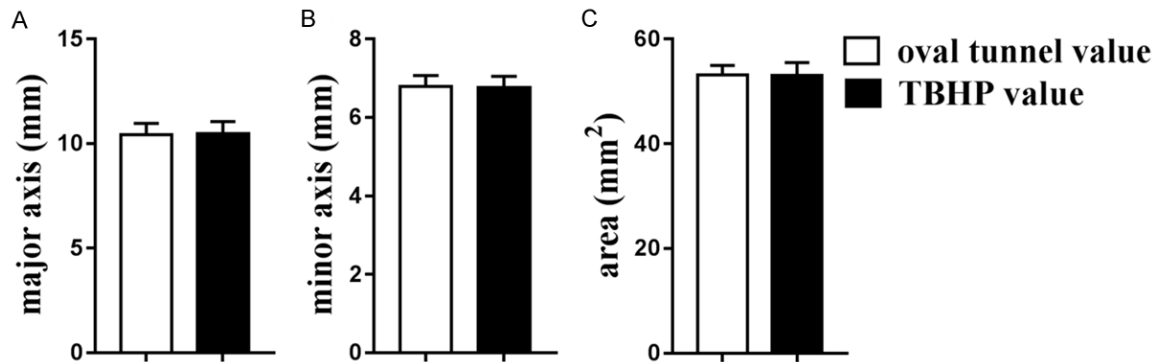


Figure 9. Comparison of major, minor axes and areas of vertical section of femoral tendon-bone healing passage (TBHP) with femoral tunnel aperture. There was no significant difference compared these three parameters of TBHP section with these of oval femoral tunnel aperture.

tunnel aperture was 10.42 ± 0.55 mm. There was no statistical significance compared with our theoretical distance of 10.66 mm ($P = 0.068$). It was significantly shorter than the value of anatomical major axis 19.32 ± 2.42 mm ($P < 0.001$). The distance of minor axis of oval femoral tunnel aperture was 6.79 ± 0.28 mm. It was significantly longer than our theoretical minor axis distance of 6 mm ($P < 0.001$) and shorter than the value of anatomical minor axis of 10.52 ± 2.24 mm ($P < 0.001$). The oval femoral tunnel aperture ratio of major/minor axis (1.53) was significantly smaller than the anatomical major/minor axis (1.83, $P < 0.001$) and higher than the round tunnel ratio which was almost equal to 1 ($P < 0.001$). The area of

oval femoral tunnel aperture was 53.12 ± 1.87 mm². It was statistical smaller than the round tunnel area and larger than our theoretical area of 50.24 mm² ($P < 0.001$). And it was significantly smaller than our anatomical area results of 155.97 ± 25.21 mm² (**Figure 8**).

Axes and areas of femoral tunnel of TBHP in oval tunnel group: The distance of the major axis of vertical section of femoral tendon-bone healing passage (TBHP) was 10.47 ± 0.58 mm. There was no statistical significance compared with our theoretical distance of 10.66 mm ($P = 0.179$) and the oval femoral tunnel aperture value ($P = 0.761$). The distance of minor axis of femoral TBHP was 6.77 ± 0.28 mm. It was lon-

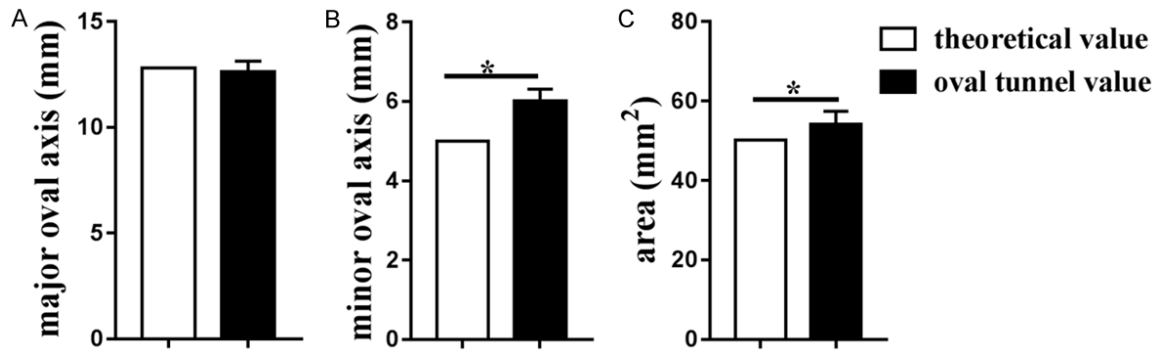


Figure 10. Comparison of axes and areas of theoretical oval tibial tunnel aperture and tibial tunnel aperture perpendicular to the tunnel long axis in oval tunnel group. There's no statistical difference of major axes ($P = 0.058$). The minor axis and area of oval tibial aperture were larger than the theoretical values ($P < 0.001$).

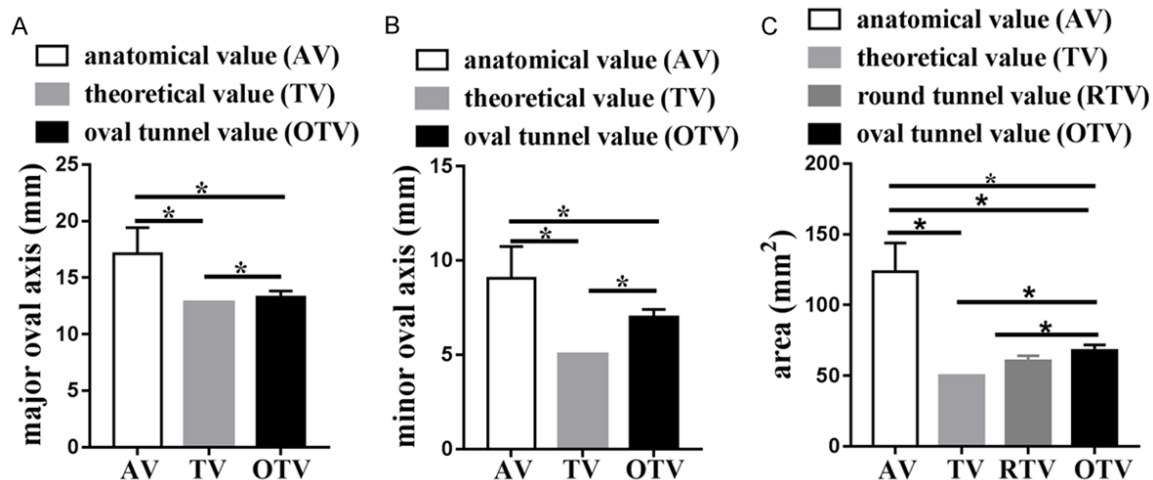


Figure 11. Statistical analysis of axes and areas of oval tibial tunnel aperture on the surface of plateau. A. Major axis of tibial tunnel aperture on the surface of plateau was significantly longer than our theoretical major axis distance of 12.8 mm ($P < 0.001$) and shorter than our anatomical major axis value ($P < 0.001$). B. Minor axis of oval tibial tunnel aperture on the surface of plateau was significantly longer than our theoretical minor axis distance of 5 mm ($P < 0.001$) and shorter than our anatomical minor axis value ($P < 0.001$). C. The area of this aperture was statistical larger than the round tunnel area and larger than our theoretical area of 50.24 mm² ($P < 0.001$). And it's significantly smaller than our anatomical area results of ($P < 0.001$).

ger than our theoretical distance of 6 mm ($P < 0.001$). There was no significant difference compared with the minor axis of oval femoral tunnel aperture ($P = 0.849$). The area of femoral TBHP was 53.02 ± 2.5 mm². It was significantly smaller than the round tunnel area ($P = 0.002$) and larger than our theoretical area of 50.24 mm² ($P < 0.001$). There was no statistical significance compared with the oval femoral aperture area ($P = 0.874$) (Figure 9).

Axes and areas of tibial tunnel aperture perpendicular to the tunnel long axis in oval tunnel group: The distance of major axis of tibial tunnel aperture perpendicular to the tunnel long

axis was 12.63 ± 0.5 mm. There was no statistical significance compared with our theoretical distance of 12.8 mm ($P = 0.058$). The minor axis distance of this aperture was 6.02 ± 0.29 mm, which was significantly longer than our theoretical distance of 5 mm ($P < 0.001$). The area of the aperture was 54.22 ± 3.21 mm². It was statistical smaller than the round tunnel area and larger than our theoretical area of 50.24 mm² ($P < 0.001$) (Figure 10).

Axes and areas of tibial tunnel aperture on the surface of plateau in oval tunnel group: The distance of major axis of tibial tunnel aperture on the surface of plateau was 13.25 ± 0.58 mm. It

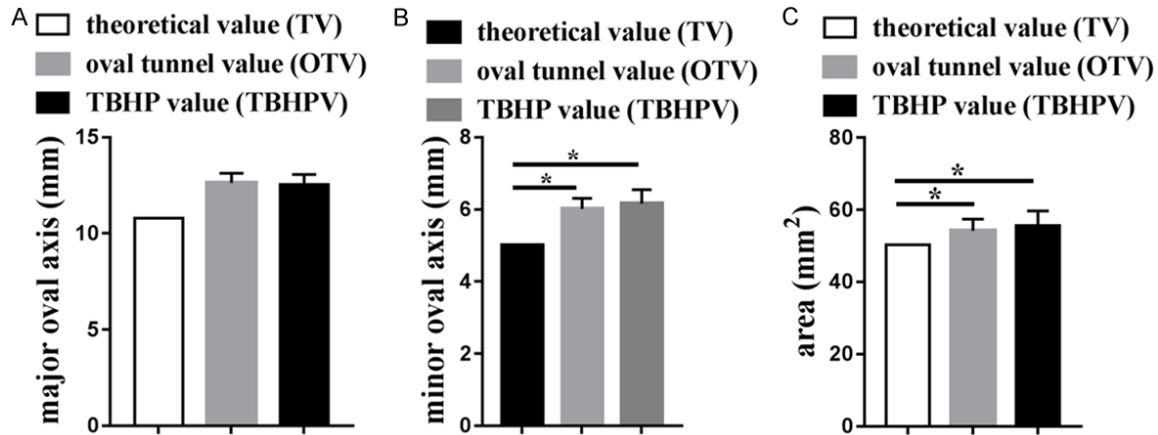


Figure 12. Statistical analysis of axes and areas of tibial tunnel of TBHP in oval tunnel group. A. Major axis of the tibial tendon-bone healing passage (TBHP) was 12.56 ± 0.51 mm. There was no statistical significant difference compared with our theoretical distance ($P = 0.056$) and the oval tibial perpendicular tunnel aperture value ($P = 0.761$). B. The distance of minor axis of section of TBHP was longer than our theoretical distance of 5 mm ($P < 0.001$). There's no significance compared with the minor axis of oval tibial perpendicular tunnel aperture ($P = 0.849$). C. The area of tibial section of TBHP was larger than our theoretical area ($P < 0.001$). There's no statistical significance compared with the tibial perpendicular tunnel aperture area ($P = 0.874$).

was significantly longer than our theoretical major axis distance of 12.8 mm ($P < 0.001$) and shorter than our anatomical major axis value of 17.12 ± 2.30 mm ($P < 0.001$). The distance of minor axis of oval tibial tunnel aperture on the surface of plateau was 7.01 ± 0.4 mm. It was significantly longer than our theoretical minor axis distance of 5 mm ($P < 0.001$) and shorter than our anatomical minor axis value of 9.06 ± 1.68 mm ($P < 0.001$). The area of this aperture was 67.9 ± 3.87 mm². It was statistical larger than the round tunnel area (60.43 ± 3.69 mm²) and lager than our theoretical area of 50.24 mm² ($P < 0.001$). It's significantly smaller than our anatomical area results of 123.43 ± 20.53 mm² ($P < 0.001$) (Figure 11).

Axes and areas of tibial tunnel of TBHP in oval tunnel group: The distance of major axis of the tibial tendon-bone healing passage (TBHP) was 12.56 ± 0.51 mm. There was no statistical significant difference compared with our theoretical distance of 10.8 mm ($P = 0.056$) and the oval tibial perpendicular tunnel aperture value ($P = 0.761$). The distance of minor axis of section of TBHP was 6.16 ± 0.39 mm. It was longer than our theoretical distance of 5 mm ($P < 0.001$). There's no significance compared with the minor axis of oval tibial perpendicular tunnel aperture ($P = 0.849$). The area of tibial section of TBHP was 55.6 ± 4.12 mm². It was larg-

er than our theoretical area of 50.24 mm² ($P < 0.001$). There's no statistical significance compared with the tibial perpendicular tunnel aperture area ($P = 0.874$) (Figure 12).

Discussion

Our cadaveric study indicated that both femoral and tibial insertions of the ACL were in oval shape rather than round shape. Our measurement showed that the average length of major and minor axis of femoral insertion were 19.32 ± 2.42 mm and 10.52 ± 2.24 mm. The average length of the major and minor axis of tibial insertion were 17.12 ± 2.30 mm and 9.06 ± 1.68 mm. Siebold et al. reported that the femoral insertion was of long oval shape and its size was 15 ± 3 mm \times 8 ± 2 mm [13, 14]. Yasuda et al. reported that a footprint of the ACL femoral attachment was in the form of an egg [14]. Ferretti et al. reported that the wide and long distance of femoral attachment was 17.2 ± 1.2 mm \times 9.9 ± 0.8 mm [9]. Mochizuki et al. and Luites et al. reported the shape of the femoral attachment was oval [15, 16]. Iwahashi et al. reported the size of oval shaped femoral insertion was 17.4 ± 0.9 mm \times 8 ± 0.5 mm [17]. The tibial attachment of most anatomical studies was reported to be an average of 10-11 mm wide and 17-18 mm long with an average area of 136 ± 33 mm². These results indicated that the shape of ACL insertion of both westerners

and easterners was oval shaped. Oval bone tunnel reconstruction techniques may be more suitable than the round tunnel reconstruction techniques. The round tunnel reconstruction technique was mainly consider the center location of the insertion. Oval shaped bone tunnel could not only restore the center of the insertion but also the outline to some extent. To achieve anatomical reconstruction, oval shaped bone tunnels should be adapted.

In this study, we successfully developed a new method to create the adjustable oval shaped bone tunnel for anatomical ACL reconstruction. We did not experience any serious intraoperative complications during the operation. The most important advantage was that the tunnel was firstly drilled with a small diameter drill bit and then adjusted with the file to oval shape step by step according to the footprint or the anatomical landmark. With this adjustable technique, we could make the femoral bone tunnel as close to the posterior border line as possible without blowout and the tibial bone tunnel as anterior as possible without impingement. In addition, the utilization of bone file helps to prevent heat-related bone damage and tunnel widening by filing the cancellous bone [18]. Several authors also reported the creation of oval tunnels. Wolf Petersen et al. reported that they developed a technique of anatomical footprint reconstruction of the ACL with oval tunnels and medial portal aimers [6]. Junsuke Nakase et al. reported that they developed a technique of anatomical single bundle ACL reconstruction with rounded rectangle femoral dilator [7]. The key operation skill of these studies was that they created the oval or rounded rectangle femoral bone tunnel with oval or rounded rectangle dilators. One disadvantage of the utilization of dilator was that compression of the dilator may break the posterior wall of the bone tunnel. In their study, one patient experienced a partial posterior tunnel wall blowout (2%). Our adjustable technique could visibly repair the posterior wall of the tunnel with a file step by step again which made it successfully avoid the blow out of the wall. Another disadvantage of dilator expansion was that once the bone tunnel were created with the dilator, it was impossible to adjust the location and the shape of the tunnel. However, with our adjustable technique, surgeons could conveniently adjust the shape and location of the tunnel according to the footprint

and the diameter of the graft. Meanwhile, neither of the above techniques recreated the oval shape of the tibial tunnel. The operation difficulty of making tibial oval shaped tunnel may be responsible.

Our oval shaped bone tunnel matched the footprint much better than the single round tunnel, so it may restore a better rotational stability too. Several studies have shown that anatomical double bundle techniques achieve a better stability of A-P translation measured with the KT 1000 and restore a better pivot shift stability compared to a single bundle technique [3, 4]. Researchers argued that two round tunnels as performed in ACL double bundle reconstruction match the oval-shaped insertion zone better compared to one round tunnel [8]. Besides, many patients had a narrow intercondylar space, which made the optimal anatomical position and the area of the footprint were limited. Therefore, it was difficult to insert a large graft in a bone tunnel with a round shape. When a large round bone tunnel was created, it was more likely that the tunnel crossed over the footprint with roof impingement. However, with an oval shaped bone tunnel, a large major axis section at the limited optimal position could be made easily and roof impingement was unlikely.

In this study, the major axis was mainly created with our adjustable method, while the minor axis was drilled with the round drill bit. With the 3D-CT scanning, we first measured the apertures of the femoral and tibial bone tunnel. Compared with our theoretical values, there's no significant difference of major axis that means our filing adjustable technique was quite accurate. The minor axis was longer than the theoretical value which may be caused by the systematic error of drilling the bone tunnel with the drill bit. The ratio of major/minor of oval shaped tunnel was significantly smaller than the anatomical ratio. Because of the size limitation of the autologous grafts, it's impossible to completely mimic the primary outline of the footprint. The ratio of major/minor of oval shaped tunnel was larger than the round tunnel ratio. Major/minor ratio improvement of oval bone tunnel had been made compared with round bone tunnel values. The ratio of major/minor axis of oval shape made the graft into a more flat shape, which could increase the fem-

oral tunnel major axis size without causing roof impingement. It's also better for the repaired knee to restore more rotational stability.

In order to confirm the tendon-bone healing passage was also oval shaped, we measured relative values of the tunnel 5 mm away from the bone apertures. Compared with the values of bone tunnel apertures, the values of bone apertures had no significant difference of the major axis, minor axis, ratio of major/minor and area. These results indicated that our adjustable technique could not only create the aperture to be an oval shape but also the tendon-bone healing passage. Compared with the round tunnel, increased perimeter of oval shape bone tunnel could improve the contact area between the graft and wall of the tunnel. This may be benefit for the tendon-bone healing after the operation. There's no significant difference between the result of central femoral tunnel location and our cadaveric results measured with Bernard and Hertel (BH) method. The measurements of tibial tunnel center on both sagittal and frontal planes had no statistical significance compared with our cadaveric research measurements. These results mean that both our femoral and tibial tunnel centers are within the anatomical ACL footprints. Junsuke Nakase et al. created the femoral tunnel via an additional low anteromedial portal, which was created with the knee maintained at 90° of flexion. They reported their femoral tunnel central location was 25.3 (\pm SD) 5.8% from the deepest subchondral contour of the lateral femoral condyle, and at 31.8 (\pm SD) 4.3% from Blumensaat's line. The center of the tibial tunnel was located at 40.3 (\pm SD) 2.8% from the anterior margin and at 45.6 (\pm SD) 4.5% from the medial margin [7]. Sebastian Kopf et al. had reported that transtibial ACL reconstruction technique fails to position drill tunnels anatomically in vivo 3D CT study [10]. Their location of tibial tunnels was at 48.0 \pm 5.4% (35.6-59.5%) of the anterior-to-posterior plateau depth and at 47.9 \pm 2.9% (42.2-57.4%) of the medial-to-lateral plateau width. Utilizing a quadrant method, femoral tunnels were positioned at 37.4 \pm 5.1% (24.9-50.6%) from the proximal condylar surface, parallel to Blumen-saat line and at 11.0 \pm 7.3% (6.0-28.7%) from the notch roof, perpendicular to Blumen-saat line. Our tunnel locations were more similar as Junsuke Nakase's report and more anatomical

than traditional transtibial (TT) technique. This result indicated that our adjustable technique could successfully overcome the disadvantage of traditional TT technique and mimic the anatomical range of the attachments.

Conclusion

We successfully developed the adjustable single oval bone tunnel ACLR technique, which mimic the direction and shape of the tibial and femoral footprints zone together with the tendon-bone healing passage much better than the single round tunnel.

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Disclosure of conflict of interest

None.

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