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Original Article

Anatomical single bundle anterior cruciate ligament reconstruction with rounded rectangle tibial tunnel and oval femoral tunnel: a prospective comparative study versus conventional surgery

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Abstract: Conventional anatomical single bundle anterior cruciate ligament (ACL) reconstruction technique with round tunnels could not simulate morphology of native insertion, while studies about ACL reconstruction technique with modified tunnels based on morphology of anatomical insertion are rare. The purpose of this study was to demonstrate an ACL reconstruction technique with rounded rectangle tibial tunnel and oval femoral tunnel and compare clinical outcomes with conventional technique. A prospective comparative study was performed in 80 consecutive subjects who underwent ACL reconstruction with the conventional round tunnels (RT-Group, n=40) or modified tunnels (MT-Group, n=40). For the modified surgery, the tunnel was modified with a bone file based on the anatomical direction and area of the remnant insertion fibers. Graft maturity were evaluated by MR images at 12 months postoperatively and patients were examined for functional scores, physical examinations at 2-year follow-up. The primary variable was the pivot-shift test. No serious complications were experienced in either group. Seventy patients (87.5%) were examined at 2-year follow-up, significant improvements were seen in both groups compared with the preoperative values in terms of all clinical assessments. Tegner scores, pivot-shift test results and SNQ value in the MT-Group were significantly better than RT-Group (*P*=0.04, *P*=0.03 and *P*=0.001, respectively). There were no significant differences in Lysholm scores, IKDC scores, KT-2000 measurements and Lachman tests. We successfully developed the ACL reconstruction technique with rounded rectangle tibial tunnel and oval femoral tunnel, which was superior to conventional technique in terms of postoperative Tegner scores, pivot-shift tests and early graft maturity.

Keywords: Anatomical ACL reconstruction, rounded rectangle tunnels, oval tunnels, pivot-shift, signal/noise quotient (SNQ)

Introduction

Anterior cruciate ligament (ACL) reconstruction has moved to an emphasis on restoring native insertion and location recently to better reconstruct the anterior-posterior and rotational stability function of the knee joint [1-3]. During the past decade, several studies have shown that the anatomical double bundle technique achieve better stability of A-P translation measured with KT-1000 and restore a better pivot shift stability compared to single bundle technique [4-7]. 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 [8]. Several anatomic ACL studies indicated that the femoral insertions were oval or semicircular shape and the tibial insertions were oval or "C" shape [9-12], besides, the cross-sectional shape of quadrupled semitendinosus and gracilis tendons appear to be oval, rather than circular [13]. Restoring the shape of the tibial and femoral insertion has been of great interest coupled with the shape of the graft to reconstruct the ACL [14]. According to the oval shaped anatomical footprints and the better stability of double bundle ACL reconstruction, several researchers have suggested that it will be more anatomical to do the single bundle ACL reconstruction with oval or rounded rectangle shaped tunnel [15-17]. We found that the tibial insertion was flatter than an oval shape along the medial inter-

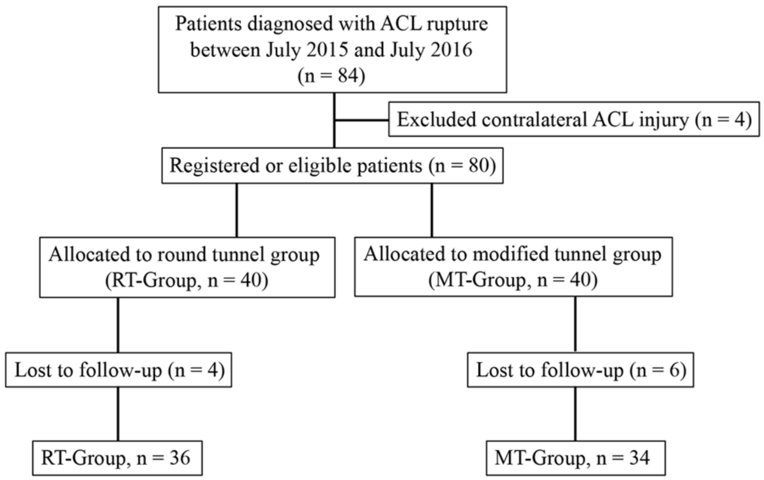

Figure 1. Participant flowchart. ACL, anterior cruciate ligament; RT, round tunnel; MT, modified tunnel.

condylar ridge posterior to the anterior ridge, therefore, we designed an ACL reconstruction technique with a rounded rectangle tibial tunnel and an oval femoral tunnel, which mimic the anatomical orientation and shape of the footprint zone better than the single round tunnel.

MRI was a useful noninvasive tool for evaluating ACL graft remodeling and maturation after ACL reconstruction surgery, several studies investigated the biological healing process of reconstructed ACL using MRI [18-20]. Ntoulia et al. [21] found revascularization of the graft occurs gradually along its length according to signal/noise quotient (SNQ) values on 1.5T MRI after surgery. Tanaka et al. [22] evaluated the entire course of ACL grafts on coronal oblique MR images by the calculation of SNQ between single-bundle (SB), double-bundle (DB), and triple-bundle (TB) reconstructions. In addition, several investigations showed that the lower signal intensity of reconstructed ACL graft is correlated with better clinical outcome [19, 23]. Thus, we calculated the SNQ of MR images to evaluate graft maturity of both technique postoperatively.

The purpose of the present study was to demonstrate an ACL reconstruction technique with rounded rectangle tibial tunnel and oval femoral tunnel and compare the early clinical outcomes and graft maturity with conventional technique. The tunnel was firstly drilled with a small diameter drill bit and then adjusted with the bone file to rounded rectangle shape or oval shape step by step according to the individualized footprint or the anatomical landmark. The primary outcome was the pivot-shift test at 2-year follow-up, as we assumed that the control of rotatory laxity is the main advantage of the modified technique. We hypothesized that our new technique would perform better rotational stability, clinical functional scores and lower SNQ comparing with conventional technique.

Material and methods

Patients

In this prospective comparative study, Patients diagnosed with ACL rupture between July 2015 and July 2016 were included in this study. 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 criteria were unilateral complete ACL tear, age older than 16 years with closed physes and younger than 50 years, the exclusion criterion included multiple ligament injury or previous knee ligament surgery. There were 84 patients met the inclusion criteria, and 4 patients were excluded according to the exclusion criteria (**Figure 1**). The allocation was conducted in a serial consecutive manner, not by randomization: 80 patients were divided into modified tunnel (MT-Group, n=40) or round tunnel (RT-Group, n=40) (**Table 1**). All surgeries were conducted by a single surgery team with uniform standardized procedure. Written informed consent was obtained from all subjects. This study's design was reviewed and approved by ethics committee of our hospital.

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

Table 1. Patient demographics[a]

Parameter	RT-Group (n=40)	MT-Group (n=40)	X^2/t	*p* value
Male (%)	25 (62.5)	28 (70)	0.503	0.478 n.s
Average age in years (range)	29.3±7.2	29.2±8.0	0.088	0.930 n.s
Affected side (%)			1.270	0.260 n.s
Left	15 (37.5)	20 (50.0)		
Right	25 (62.5)	20 (50.0)		
Time from injury to surgery, mo, (range)	2.0 (0.25-60)	4.0 (0.5-51)	1.431	0.152 n.s
Cause of Injury (%)			0.833	0.361 n.s
Contact sport	22 (55.0)	26 (65.0)		
Noncontact sport	18 (45.0)	14 (35.0)		
Associated injuries (%)			1.926	0.639 n.s
Meniscal (medial and/or lateral)	15 (37.5)	11 (27.5)		
Meniscal and cartilage lesions	12 (30.0)	16 (40.0)		
Cartilage lesions	3 (7.5)	5 (12.5)		
None	7 (25.0)	8 (20.0)		

[a]Data as mean (range or standard deviation); categorical variables as frequencies (percentages).

Table 2. Theoretical values and distance expanded by bone file of modified bone tunnels

D (mm)	Minor (mm)	Major (mm)		Major/Minor		Distance expanded by bone file (mm)	
		Tibial	Femoral	Tibial	Femoral	Tibial	Femoral
7	5	8.77	9.8	1.75	1.96	3.77	4.8
7	6	8.04	8.2	1.34	1.36	2.04	2.2
7.5	5	9.91	11.25	1.98	2.25	4.91	6.25
7.5	6	9.38	8.65	1.56	1.44	3.38	2.65
8	5	11.12	12.8	2.24	2.56	6.12	7.8
8	6	9.66	10.67	1.61	1.78	3.66	4.67

rounded rectangle or round shape, would then be equal to that of the graft, the diameters of which are often 7 mm, 7.5 mm and 8 mm. According to the area formula of circle, rounded rectangle and oval, we calculated the major axis when the minor axis was defined as 5 mm or 6 mm. (**Table 2**) $A_{circle}=\pi(\frac{D}{2})^2$ (A_{circle} is the area of the round tunnel. D is the diameter of the round tunnel) $A_{\text{rounded rectangle}}=\pi(\frac{Min}{2})^2+(Maj-Min)\times Min$ ($A_{\text{rounded rectangle}}$ is the area of the rounded rectangle tunnel. Maj means major axis. Min means minor axis). $A_{Oval}=\pi(\frac{Maj\times Min}{4})$ (A_{Oval} is the area of the oval tunnel. Maj means major axis. Min means minor axis.) When A_{circle} is equal to $A_{\text{rounded rectangle}}$, we can deduce calculation formula $Maj=\frac{\pi(D^2-Min^2)}{4Min}$+Min. Similarly, when A_{circle} is equal to A_{Oval}, we can deduce calculation formula Maj=$\frac{D^2}{Min}$ (**Figure 2**).

Surgical technique

Graft harvesting: 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°.

Autologous semitendinosus and gracilis (STG) tendons were harvested via a 3 cm oblique incision 2 cm medial and distal to tibial tuberosity with a close tendon stripper (Karl Storz, Tuttlingen, Germany). No. 2 Ethibond nonabsorbable sutures (Ethicon) were used to weave the grafts into 4 strands, and the graft diameter was measured with a 1 mm interval round-shaped measuring device, after that, the grafts were prepared by hooking and looping to an Endobutton (Fliptack, Karl Storz, Tuttlingen, Germany).

Tibial tunnel: A tip-to-elbow tibial guide (Acufex) was used to establish tibial tunnel for both groups. The drill guide was set at an 45° angle. For anatomical tunnel placement, the tip of the aimer was positioned according to the anterior ridge and medial intercondylar ridge through the anteromedial portal. The anterior horn of the lateral meniscus was used as the landmark in cases with no remnants. In the RT-Group, the tunnel was then drilled according to the diame-

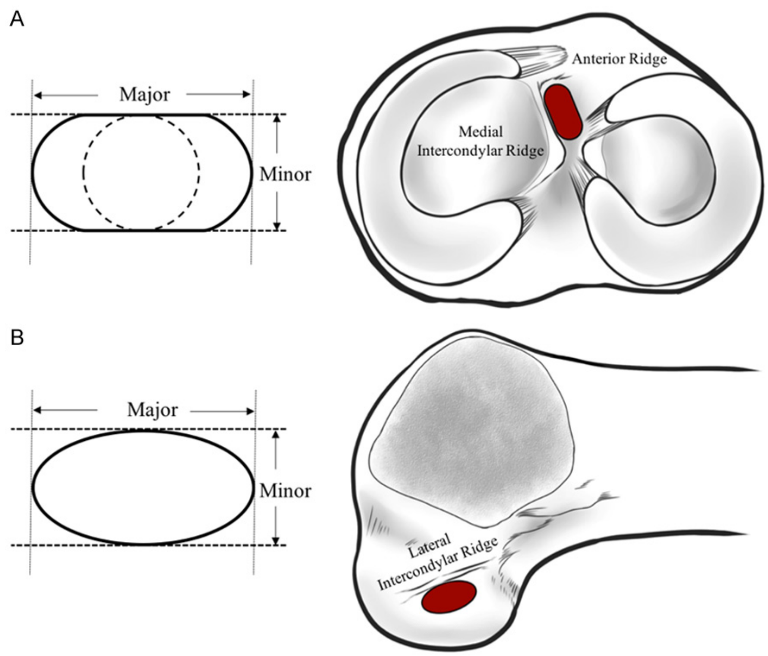

Figure 2. Diagram of tunnel aperture. A. The diagram of rounded rectangle tunnel. B. The diagram of oval tunnel. Major represents the long axis of the tunnel, Minor equals to the diameter of smaller round tunnel.

ter of the graft with a drill bit. In the MT-Group, the tunnel was drilled with a smaller size drill bit (5 mm or 6 mm), to guarantee the distal intra-fixation, we modified about 10 mm long at the articular side of the tibial tunnel, the major axis of the rounded rectangle tunnel was then expanded to the theoretical value step by step with a 4-mm diameter bone file. To confirm that the length was equal to the theoretical value, arthroscopic measurement was made manually (**Figure 3**).

Femoral tunnel: Femoral tunnels of both groups were created with transtibial technique. The lateral intercondylar ridge and remnant fibers of the ACL were used as landmarks on the femur, the knee was flexed to 90° when creating the femoral tunnel, then a 6-mm femoral guide (Smith & Nephew Endoscopy) was inserted through the tibial tunnel and positioned over the native ACL footprint at posterior aspect of the lateral femoral condyle. The guide pin was introduced and drilled through the lateral femoral condyle, after that, a 4.5 mm drill bit was first used to penetrate the thin femoral tunnel and the whole length of the tunnel was measured. To create a round tunnel, drill bit of the same size as the graft diameter was drilled to a suitable length depending on the length of the total tunnel. To create the oval shaped aperture, similarly as tibial tunnel creation, about 10 mm long at the articular side of the femoral tunnel was modified. Firstly, 5 mm or 6 mm diameter drill was used to create a tunnel, then the major axis of the oval tunnel was expanded to the theoretical value step by step with a bone file by transtibial approach. During the adjustment, usually 2 mm was left between the tunnel posterior wall and lateral femoral condyle cortex to avoid posterior wall blowout. Arthroscopic measurement was also applied during the process of tunnel creation (**Figure 4**).

Graft passage and fixation: The graft was passed from the tibial tunnel to the femoral tunnel with the help of 2 leading sutures after the tunnel was created. At the femoral side, the grafts were secured with an Endobutton. At the tibial side, the grafts were fixed with a bioabsorbable intra-fix screw (Smith & Nephew Endoscopy, Andover, MA, USA). The fixation was performed at 30° of knee flexion with the proximal tibia pushed backward. Arthroscopic evaluation was made to ensure the absence of impingement between graft and intercondylar notch before and after fixation.

Rehabilitation: The rehabilitation program for patients of both groups followed a uniform standardized procedure. Each patient wore a brace to keep the leg in full extension after the operation. On the first postoperative day, quadriceps-setting exercises and ankle pump exercises were initiated. The brace was removed at 4 weeks, but patients were allowed partial weight on first postoperative day and full weight bearing thereafter. Range of motion (ROM) was gradually increased to 90° after 1 week, 120° after 1 month and full range of motion within 2 months. Running was allowed after 4 months and returning to contact sports was not recommended until 8 months.

Clinical evaluation: All the clinical evaluations of the subjects were performed preoperatively

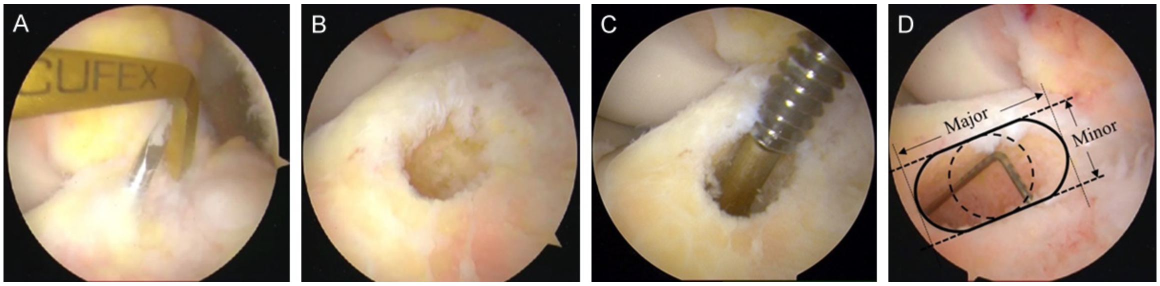

Figure 3. Tibial tunnel creation. A. The tunnel was positioned in the center of the ACL remnants with a tip-to-elbow tibial guide. B. To show the round shaped aperture of the tibial bone tunnel. C. A bone file was used to expand the major axis of the tunnel. D. Arthroscopic measurement was made to confirm the length equal to the theoretical value.

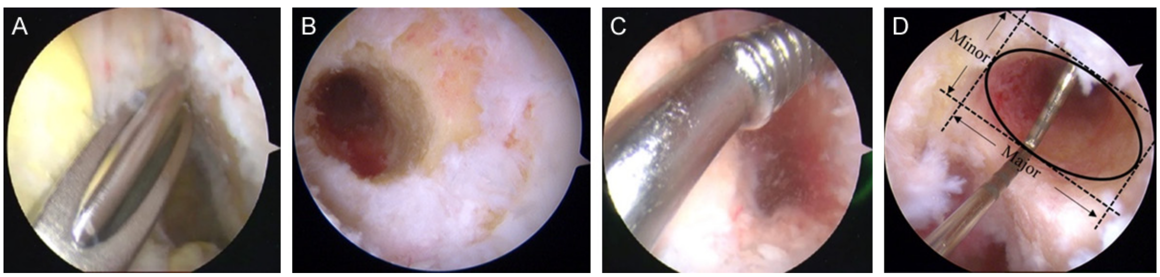

Figure 4. Femoral tunnel creation. A. The femoral guide was placed at the center of femoral insertion. B. To show the round shaped aperture of the femoral bone tunnel. C. To expand the major axis of the tunnel according to anatomical direction with the bone file. D. Arthroscopic measurement was performed to ensure appropriate length of the tunnel.

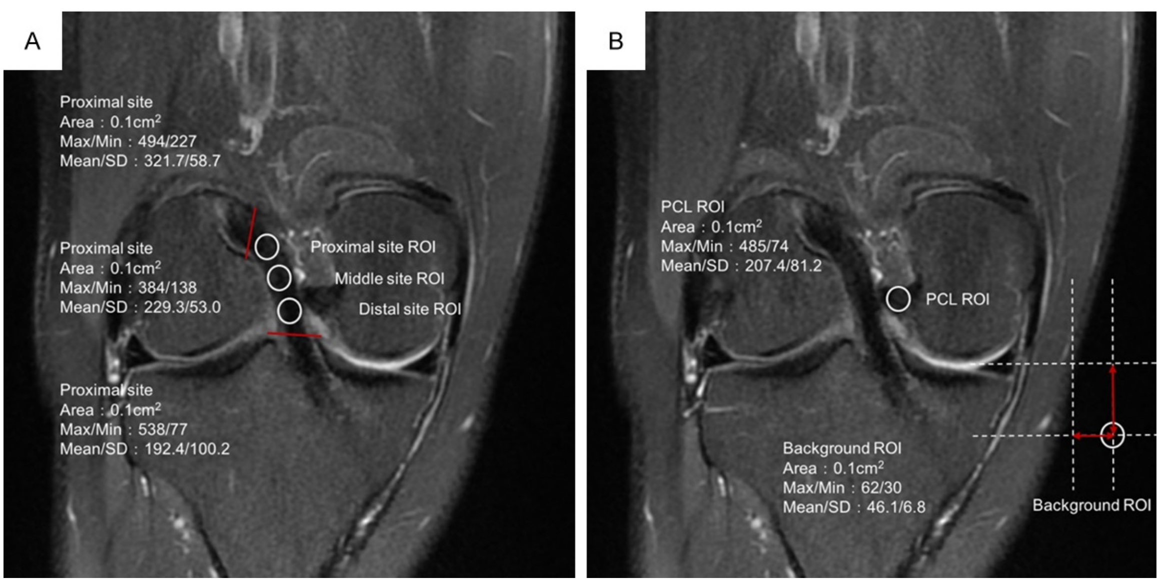

Figure 5. Signal intensity was measured for the intra-articular part of the graft in the coronal oblique image. A. Three regions-of-interest (ROI, area of the circle =0.1 cm^2) were measured independently: the proximal site, the middle site and distal site. B. PCL ROI and background ROI were measured as shown above.

and at 2-year follow-up by an independent, experienced observer. The observer was blinded to the surgery methods. For subjective evaluations, patients were asked about their activity levels referring to Tegner score [24] before operation and at last follow-up. Lysholm scores

Table 3. Analysis of clinical outcomes preoperatively and at 2-year follow-up between two groups[a]

Variables	Preoperative		2-Year Follow-up		*p* value	
	RT (n=36)	MT (n=34)	RT (n=36)	MT (n=34)	Preoperative	2-Year
Tegner score	3.0±0.8	3.1±0.9	5.6±0.9	6.1±0.9	0.55	0.04
Lysholm score	69.7±14.7	75.0±10.4	91.5±5.7	93.3±4.5	0.08	0.16 n.s
IKDC score	70.4±9.7	68.1±10.0	90.2±5.6	90.6±4.4	0.34	0.74 n.s
Manual Lachman, n (%)					0.63	0.22 n.s
0	0 (0)	0(0)	24(66.7)	28 (82.4)		
1+	2 (5.6)	4(11.8)	11(30.6)	6 (17.6)		
2+	30 (83.3)	27(79.4)	1(2.8)	0 (0)		
3+	4 (11.1)	3(8.8)	0 (0)	0 (0)		
Pivot-Shift Tests, n (%)					0.45	0.03
0	0 (0)	0 (0)	23 (65.6)	30 (88.2)		
1+	4 (11.1)	1 (2.9)	12 (31.3)	4 (11.8)		
2+	30 (83.3)	32 (94.1)	1 (3.1)	0 (0)		
3+	2 (5.6)	1 (2.9)	0	0		
KT-2000 Arthrometer SSD (132 N)	4.4±2.2	4.7±2.3	1.3±1.3	1.2±1.0	0.62	0.67 n.s

[a]Data as mean (standard deviation); categorical variables as frequencies (percentages).

Table 4. Multivariable analysis of factors associated with pivot-shift (n=70)

Variables	Odds ratio	95% confidence interval	*p* value
Group	0.21	0.056-0.757	0.02

[25] and IKDC subjective scores [26] were also evaluated at the same time. In terms of objective evaluations, KT-2000 arthrometer test (MEDmetric, San Diego, CA) at 132N were performed to measure the side-to-side difference (SSD) with the knee positioned at 20° of flexion. The Lachman test and the pivot-shift test were also assessed. The Lachman test was graded as 0 (negative) (SSD < 3 mm and hard endpoint), 1+ (SSD of 3 to 5 mm), 2+ (SSD of 5 to 10 mm), or 3+ (SSD > 10 mm). The pivot-shift test was graded as 0 (negative), 1+ (glide), 2+ (clunk), or 3+ (gross) [27].

Radiological evaluation: Postoperative 3-dimensional (3D) computed tomography are performed to evaluate the morphology of modified tunnels within 1 week. MRI images were obtained at 12 months after surgery for each subject with a 1.5-T MRI scanner (GE, Optima MR360, USA). The grafts were evaluated focusing on signal intensity of the MRI. Measurements were performed on PD-FSE images (PACS website, GE Medical System) using the region of interest (ROI) technique. Three intra-articular aspects of the graft were observed in the oblique coronal plane (**Figure 5**): proximal site (close to femoral tunnel), middle site (midpoint of other two sites), distal site (close to tibial tunnel). Area of circular ROIs were 0.1 cm^2. The PCL signal was measured with the region of interest being placed in its midsubstance. The background ROI was placed approximately 1 cm medial and 2 cm distal to the medial joint line. The SNQ of each graft site was calculated with the following equation: SNQ=[signal (specific site of the graft) - signal (PCL)]/signal (background) [28].

All MRI measurements were performed three times by 2 observers who were blinded in terms of patient information and groups, Intra-observer and inter-observer agreement for MRI measurements were evaluated by intra-class correlation coefficient with 95% confidence interval (95% CI).

Statistical analysis

The primary variable in the study was the pivot-shift test. Sample size of each group was determined beforehand by using statistical power analysis. The study was powered to reveal a difference of 1 grade which was assumed clinically important on the pivot-shift test [29]. With a power of 80% and an a of 0.05, calculation results showed that a sample size of 36 patients at least in each group was needed.

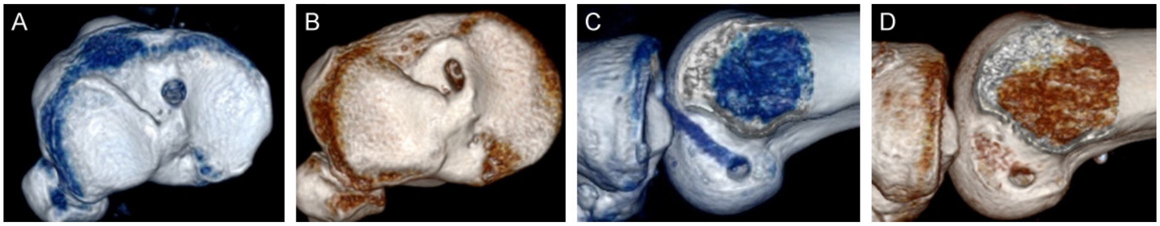

Figure 6. Postoperative 3-dimensional (3D) computed tomography scan showing the morphology of tibial and femoral tunnels. A. A 3D reconstructive view showing the round tibial tunnel. B. Rounded rectangle tibial tunnel. C. Round femoral tunnel. D. Oval femoral tunnel.

Table 5. SNQ Analysis of Coronal Oblique MRI 12 months postoperatively

Variables	RT-Group (n=32)	MT-Group (n=31)	X^2/t	*p* value[a]
Proximal site	4.62±2.76	2.13±1.42	4.514	< 0.001
Middle site	3.62±2.51	2.41±1.63	2.261	0.027
Distal site	4.20±2.80	3.24±2.07	1.545	0.127 n.s
Mean SNQ	4.14±1.93	2.59±1.39	3.648	0.001
Missing values	8	9		

[a]*P* value of corresponding site ROI or mean SNQ between different groups.

Categorical variables between the groups were compared using the X^2 test and Fisher exact test. The independent Student *t* test was used for comparisons of the preoperative and postoperative data within the study groups, as well as signal/noise between two groups. Regarding pivot-shift as dependent variable, patient demographics were evaluated with unconditional multivariate logistic regression analysis. Statistical analysis was performed with SPSS software, version 24.0 (SPSS, Chicago, IL). P < 0.05 was considered significant.

Results

Clinical outcomes

Between July 2015 and July 2016, a total of 80 patients were included in this study, 10 patients were lost to follow up, 36 patients in RT-Group and 34 patients in MT-Group were available for the 2-year follow-up and all the postoperative clinical outcomes were evaluated at the last appointment. There were no differences between the two groups regarding sex, age, affected side, time from injury to surgery, cause of injuries, preoperative subjective scores, or KT-2000 tests, or associated injuries including meniscal and cartilage lesions. Demographic data of patients are presented in **Table 1**.

Neither intraoperative nor postoperative complications were observed. According to the subjective and objective evaluations summarized in **Table 3**, the mean postoperative Tegner scores, Lysholm scores, and IKDC scores were significantly improved in both groups compared with preoperative values (*P* < 0.001), among which the Tegner scores reached statistical difference between two groups (*P*= 0.04). However, no intergroup differences were found for the Lysholm scores, and IKDC scores (*P*=0.16 and 0.74, respectively). Regarding to manual Lachman test, the MT-Group performed better with 28 (82.4%) patients being negative compared to the RT-Group with 24 (66.7%) patients being negative, but there was no statistical difference (*P*=0.22). Postoperative KT-2000 tests of both groups were significantly improved compared with preoperative outcomes (*P* < 0.001) though there was no statistical difference between two groups (*P*=0.67). As for pivot-shift tests, 23 (65.6%) patients in RT-Group and 30 (88.2%) patients in MT-Group had negative result, 12 (31.3%) patients and 4 (11.8%) patients turned out to be glide (1+) respectively, in addition, the RT-group had 1 (3.1%) patient with grossly positive (2+), these findings are significantly different with univariate analysis *P*=0.03 and multivariate analysis *P*=0.02 (**Table 4**).

CT observations and signal intensity of grafts

We found that we have changed the round tibial tunnel into rounded rectangle shape and round femoral tunnel into oval shape on postoperative 3-dimensional (3D) computed tomography scan as we expected (**Figure 6**).

Thirty-two patients in the RT-Group and 31 patients in the MT-Group were obtained for the MRI images. Intra-observer and inter-observer agreement were relatively strong for all patients, with both ICC > 0.85. The SNQ values of the grafts 12 months postoperatively were summarized in **Table 5**. The MT-Group showed a significantly (*P* < 0.001) lower mean SNQ value (2.59±1.39) of the ACL grafts than the RT-Group (4.14±1.93). In terms of independent ROI, The MT-Group had significant lower mean SNQ when comparing with the RT-Group at proximal site (2.13±1.42 vs 4.62±2.76, *P* < 0.001) and middle site (2.41±1.63 vs 3.62±2.51, *P*=0.027). In addition, the MT-Group also revealed a lower SNQ than RT-Group at distal site (3.24±2.07 vs 4.20±2.80) though without statistically difference (*P*=0.127).

Discussion

In this study, we successfully developed a new method to create the rounded rectangle shaped tibial tunnel and oval femoral tunnel for anatomical ACL reconstruction. We did not experience any serious intraoperative or postoperative complications during the operation and until the 2-year follow-up. The outcomes showed our technique could restore higher sports activity level revealed by Tegner scores, better rotational stability evaluated by pivot-shift tests and better early graft maturity assessed by signal intensity on MR images than the conventional technique.

Recently anatomical studies have shown that the direct femoral insertion, tibial insertion and mid-substance of ACL are considered to be oval-shaped, narrow but long "C"-shaped like a belt and a flat ribbon-like structure [30-32], respectively. Several biomechanical studies had reported the importance of matching native ACL footprints as close as possible [33, 34]. Investigations have shown that the anatomical double bundle techniques achieve better stability of anterior-posterior translation and restore better pivot-shift stability compared to the single bundle technique [4, 7], suggesting that two round tunnels would match the oval-shaped or "C"-shaped insertion zone better compared to one round tunnel [17]. However, double bundle technique demands more complicated operating procedure and expensive costs, besides, there still remains controversial about the long-term clinical outcomes comparing to single bundle technique and the macroscopic separation of the ACL into bundles. Emphasis have moved to anatomical ACL reconstruction technique. Several studies reported the creation of oval-like tunnels. Wolf Petersen et al. reported that they developed a technique of anatomical ACL footprint reconstruction with oval tunnels and medial portal aimers [15]. Junsuke Nakase et al. developed a technique of anatomical single bundle ACL reconstruction with rounded rectangle femoral dilator [16]. The key surgery skill of these studies was that they created the oval or rounded rectangle femoral bone tunnel with oval or rounded rectangle dilators, but neither of the above techniques had made an effort to modify the shape of tibial tunnel. Besides, one disadvantage of their dilator expansion was that once the bone tunnel was created with the dilator, it was impossible to adjust the location and the shape of the tunnel. Another disadvantage was that the dilator may magnify the risk of breaking the posterior wall of the bone tunnel [35], but bone file was able to decrease the risk and avoid the heat injury to the tunnel, which was advantageous to tendon-bone healing process. However, with our new technique, the anatomical bony landmarks of anterior ridge and medial intercondylar ridge provide us a rule-based and repeatable procedure and surgeons would be able to adjust the tunnel location and major axis direction with the bone file according to individualized insertion site, we changed the femoral tunnel into oval-shaped and tibial tunnel into rounded rectangle-shaped to match the native oval or "C" shaped insertion. To our knowledge, the tibial plateau and oblique tunnel form a angle in sagittal plane, which made the orifice of tunnel oval-shaped, so does the femoral side. However, the major/minor rate of native ACL insertion is larger than convention round tunnel with oval orifice, and the conventional technique could not change the ACL mid-substance into flat form which count against restoring rotational stability.

Recent cadaveric and histologic studies have found that ACL tibial insertion was closely related to anterior horn of lateral meniscus [3, 31, 36]. We also observed that the conventional round tunnel was easy to injure the insertion of anterior horn of lateral meniscus, especially when the round tunnel is not anatomical positioned or the diameter of round tunnel is large. However, our rounded rectangle bone tunnel could theoretically make less injury to the meniscus as it is rather flat or narrow along the medial intercondylar ridge and matched the footprint much better than the single round tunnel.

The evaluation at 2-year follow-up showed better Tegner scores and pivot-shift results with the MT-Group. We have created a more anatomic insertion morphology, more importantly, we have changed the round form of ligament into flat shaped which fit more closely to the native morphology form along with the changing of tunnels. Similar as the flat shaped designment of paddle, increasing the water contact area to obtain more strength, the flat graft was superior to resisting rotational force, these may explain the higher sports activity level and less positive pivot-shift tests in our new technique.

Better early graft maturity are important for fast recovery and return to sports of injured athletes. Coronal oblique MRI scans made it possible to visualize the entire course of the ACL in vivo [22, 37]. We compared signal intensity of the two groups on the coronal oblique MRI images 12 months postoperatively which supposed to be the early stage of remodeling process but have reached the vascular status of the native ACL [38, 39]. It was believed that the difference in revascularization have a direct influence on the signal intensity changes of the reconstructed graft. The MT-Group showed lower signal intensity at the 12 months follow-up. According to previous studies [18, 28, 40], lower signal intensity indicates less water content and theoretically better maturity and healing of the graft. Besides, it's correlated with patient's good surgical outcome. Restoring the rotational stability was the keystone to successful maturation of the ACL graft. The results of our study indicated that our new technique possessed advantages in terms of early graft remodeling process. Compared with the round tunnel of equal area, increased perimeter of rounded rectangle or oval shape bone tunnel could improve the contact area between the graft and wall of the tunnel. This may facilitate tendon-to-bone healing and nutrients exchange between graft and synovial fluid during remolding process.

Conclusion

We successfully developed a novel ACL reconstruction technique with rounded rectangle shaped tibial tunnel and oval shaped femoral tunnel, which could mimic the anatomical orientation and shape of the tibial and femoral footprints better than round tunnels. The new technique was superior to conventional technique in terms of sports activity level, rotational stability and early graft remodeling process. Long-term follow-up of clinical outcomes and MRI evaluations or biomechanical experiment in vitro could be directions of further investigation.

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Disclosure of conflict of interest

None.

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References

[1] Erickson BJ, Cvetanovich GL, Frank RM, Riff AJ and Bach BR Jr. Revision ACL reconstruction: a critical analysis review. JBJS Rev 2017; 5: e1.
[2] Kim HS, Seon JK and Jo AR. Current trends in anterior cruciate ligament reconstruction. Knee Surg Relat Res 2013; 25: 165-173.
[3] Kusano M, Yonetani Y, Mae T, Nakata K, Yoshikawa H and Shino K. Tibial insertions of the anterior cruciate ligament and the anterior horn of the lateral meniscus: a histological and computed tomographic study. Knee 2017; 24: 782-791.
[4] Aglietti P, Giron F, Losco M, Cuomo P, Ciardullo A and Mondanelli N. Comparison between single-and double-bundle anterior cruciate ligament reconstruction: a prospective, randomized, single-blinded clinical trial. Am J Sports Med 2010; 38: 25-34.
[5] Tiamklang T, Sumanont S, Foocharoen T and Laopaiboon M. Double-bundle versus single-bundle reconstruction for anterior cruciate ligament rupture in adults. Cochrane Database Syst Rev 2012; 11: Cd008413.
[6] Kondo E, Yasuda K, Azuma H, Tanabe Y and Yagi T. Prospective clinical comparisons of anatomic double-bundle versus single-bundle an-

terior cruciate ligament reconstruction procedures in 328 consecutive patients. Am J Sports Med 2008; 36: 1675-1687.
[7] Xu M, Gao S, Zeng C, Han R, Sun J, Li H, Xiong Y and Lei G. Outcomes of anterior cruciate ligament reconstruction using single-bundle versus double-bundle technique: meta-analysis of 19 randomized controlled trials. Arthroscopy 2013; 29: 357-365.
[8] Siebold R and Zantop T. Anatomic double-bundle ACL reconstruction: a call for indications. Knee Surg Sports Traumatol Arthrosc 2009; 17: 211-212.
[9] Girgis FG, Marshall JL and Monajem A. The cruciate ligaments of the knee joint. Anatomical, functional and experimental analysis. Clin Orthop Relat Res 1975; 216-231.
[10] Petersen W and Zantop T. Anatomy of the anterior cruciate ligament with regard to its two bundles. Clin Orthop Relat Res 2007; 454: 35-47.
[11] Odensten M and Gillquist J. Functional anatomy of the anterior cruciate ligament and a rationale for reconstruction. J Bone Joint Surg Am 1985; 67: 257-262.
[12] Guenther D, Irarrázaval S, Nishizawa Y, Vernacchia C, Thorhauer E, Musahl V, Irrgang JJ and Fu FH. Variation in the shape of the tibial insertion site of the anterior cruciate ligament: classification is required. Knee Surg Sports Traumatol Arthrosc 2015; 25: 2428-2432.
[13] Oshima T, Nakase J, Numata H, Takata Y and Tsuchiya H. The cross-sectional shape of the fourfold semitendinosus tendon is oval, not round. J Exp Orthop 2016; 3: 28.
[14] Siebold R. The concept of complete footprint restoration with guidelines for single- and double-bundle ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 2011; 19: 699-706.
[15] Petersen W, Forkel P, Achtnich A, Metzlaff S and Zantop T. Technique of anatomical footprint reconstruction of the ACL with oval tunnels and medial portal aimers. Arch Orthop Trauma Surg 2013; 133: 827-33.
[16] Nakase J, Toratani T, Kosaka M, Ohashi Y, Numata H, Oshima T, Takata Y and Tsuchiya H. Technique of anatomical single bundle ACL reconstruction with rounded rectangle femoral dilator. Knee 2016; 23: 91-96.
[17] Shino K, Mae T and Tachibana Y. Anatomic ACL reconstruction: rectangular tunnel/bone-patellar tendon-bone or triple-bundle/semitendinosus tendon grafting. J Orthop Sci 2015; 20: 457-468.
[18] Biercevicz AM, Akelman MR, Fadale PD, Hulstyn MJ, Shalvoy RM, Badger GJ, Tung GA, Oksendahl HL and Fleming BC. MRI volume and signal intensity of ACL graft predict clinical, functional, and patient-oriented outcome measures after ACL reconstruction. Am J Sports Med 2015; 43: 693-699.
[19] Saupe N, White LM, Chiavaras MM, Essue J, Weller I, Kunz M, Hurtig M and Marks P. Anterior cruciate ligament reconstruction grafts: MR imaging features at long-term follow-up-correlation with functional and clinical evaluation. Radiology 2008; 249: 581-590.
[20] Ahn JH, Lee YS, Jeong HJ, Park JH, Cho Y, Kim KJ and Ko TS. Comparison of transtibial and retrograde outside-in techniques of anterior cruciate ligament reconstruction in terms of graft nature and clinical outcomes: a case control study using 3T MRI. Arch Orthop Trauma Surg 2017; 137: 357-365.
[21] Ntoulia A, Papadopoulou F, Ristanis S, Argyropoulou M and Georgoulis AD. Revascularization process of the bone--patellar tendon--bone autograft evaluated by contrast-enhanced magnetic resonance imaging 6 and 12 months after anterior cruciate ligament reconstruction. Am J Sports Med 2011; 39: 1478-1486.
[22] Tanaka Y, Yonetani Y, Shiozaki Y, Kanamoto T, Kita K, Amano H, Kusano M, Hirakawa M and Horibe S. MRI analysis of single-, double-, and triple-bundle anterior cruciate ligament grafts. Knee Surg Sports Traumatol Arthrosc 2014; 22: 1541-1548.
[23] Figueroa D, Melean P, Calvo R, Vaisman A, Zilleruelo N, Figueroa F and Villalon I. Magnetic resonance imaging evaluation of the integration and maturation of semitendinosus-gracilis graft in anterior cruciate ligament reconstruction using autologous platelet concentrate. Arthroscopy 2010; 26: 1318-1325.
[24] Tegner Y and Lysholm J. Rating systems in the evaluation of knee ligament injuries. Clin Orthop Relat Res 1985; 43-49.
[25] Lysholm J and Gillquist J. Evaluation of knee ligament surgery results with special emphasis on use of a scoring scale. Am J Sports Med 1982; 10: 150-154.
[26] Irrgang JJ, Anderson AF, Boland AL, Harner CD, Kurosaka M, Neyret P, Richmond JC and Shelborne KD. Development and validation of the international knee documentation committee subjective knee form. Am J Sports Med 2001; 29: 600-613.
[27] Hefti F, Muller W, Jakob RP and Staubli HU. Evaluation of knee ligament injuries with the IKDC form. Knee Surg Sports Traumatol Arthrosc 1993; 1: 226-234.
[28] Weiler A, Peters G, Maurer J, Unterhauser FN and Sudkamp NP. Biomechanical properties and vascularity of an anterior cruciate ligament graft can be predicted by contrast-enhanced magnetic resonance imaging. A two-year study in sheep. Am J Sports Med 2001; 29: 751-761.

[29] Ahlden M, Sernert N, Karlsson J and Kartus J. A prospective randomized study comparing double- and single-bundle techniques for anterior cruciate ligament reconstruction. Am J Sports Med 2013; 41: 2484-2491.

[30] Sasaki N, Ishibashi Y, Tsuda E, Yamamoto Y, Maeda S, Mizukami H, Toh S, Yagihashi S and Tonosaki Y. The femoral insertion of the anterior cruciate ligament: discrepancy between macroscopic and histological observations. Arthroscopy 2012; 28: 1135-1146.

[31] Siebold R, Schuhmacher P, Fernandez F, Smigielski R, Fink C, Brehmer A and Kirsch J. Flat midsubstance of the anterior cruciate ligament with tibial “C”-shaped insertion site. Knee Surg Sports Traumatol Arthrosc 2015; 23: 3136-3142.

[32] Smigielski R, Zdanowicz U, Drwiega M, Ciszek B, Ciszkowska-Lyson B and Siebold R. Ribbon like appearance of the midsubstance fibres of the anterior cruciate ligament close to its femoral insertion site: a cadaveric study including 111 knees. Knee Surg Sports Traumatol Arthrosc 2015; 23: 3143-3150.

[33] Herbort M, Lenschow S, Fu FH, Petersen W and Zantop T. ACL mismatch reconstructions: influence of different tunnel placement strategies in single-bundle ACL reconstructions on the knee kinematics. Knee Surg Sports Traumatol Arthrosc 2010; 18: 1551-1558.

[34] Kato Y, Maeyama A, Lertwanich P, Wang JH, Ingham SJ, Kramer S, Martins CQ, Smolinski P and Fu FH. Biomechanical comparison of different graft positions for single-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 2013; 21: 816-823.

[35] Nakase J, Toratani T, Kosaka M, Ohashi Y, Numata H, Oshima T, Takata Y and Tsuchiya H. Technique of anatomical single bundle ACL reconstruction with rounded rectangle femoral dilator. Knee 2016; 23: 91-96.

[36] LaPrade CM, Ellman MB, Rasmussen MT, James EW, Wijdicks CA, Engebretsen L and LaPrade RF. Anatomy of the anterior root attachments of the medial and lateral menisci: a quantitative analysis. Am J Sports Med 2014; 42: 2386-2392.

[37] Staeubli HU, Adam O, Becker W and Burgkart R. Anterior cruciate ligament and intercondylar notch in the coronal oblique plane: anatomy complemented by magnetic resonance imaging in cruciate ligament-intact knees. Arthroscopy 1999; 15: 349-359.

[38] Falconiero RP, DiStefano VJ and Cook TM. Revascularization and ligamentization of autogenous anterior cruciate ligament grafts in humans. Arthroscopy 1998; 14: 197-205.

[39] Unterhauser FN, Bail HJ, Hoher J, Haas NP and Weiler A. Endoligamentous revascularization of an anterior cruciate ligament graft. Clin Orthop Relat Res 2003; 276-288.

[40] Ma Y, Murawski CD, Rahnemai-Azar AA, Maldjian C, Lynch AD and Fu FH. Graft maturity of the reconstructed anterior cruciate ligament 6 months postoperatively: a magnetic resonance imaging evaluation of quadriceps tendon with bone block and hamstring tendon autografts. Knee Surg Sports Traumatol Arthrosc 2015; 23: 661-668.