Better Coverage of the ACL Tibial Footprint and Less Injury to the Anterior Root of the Lateral Meniscus Using a Rounded-Rectangular Tibial Tunnel in ACL Reconstruction

A Cadaveric Study

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Background: To better restore the anatomy of the native anterior cruciate ligament (ACL) attachment and fiber arrangement, researchers have developed techniques for changing the shape of the ACL bone tunnel during ACL reconstruction.

Purpose: To compare the coverage of the ACL tibial footprint and influence on the anterior root of lateral meniscus (ARLM) between a rounded-rectangular tibial tunnel and a conventional round tibial tunnel for ACL reconstruction.

Study Design: Controlled laboratory study.

Methods: A total of 16 (8 matched-paired) fresh-frozen human cadaveric knees were distributed randomly into 2 groups: a rounded-rectangular tunnel (RRT) group and a round tunnel (RT) group. One of the knees from each pair was reamed with rounded-rectangular tibial tunnel, whereas the other was reamed with round tibial tunnel. Coverage of the ACL tibial footprint and areas of ARLM attachment before and after reaming were measured using 3-dimensional isotropic magnetic resonance imaging.

Results: In the RRT group, the average percentage of ACL tibial footprint covered by the tunnel was 70.8% ± 2.5%, which was significantly higher than that in the RT group (48.2% ± 6.4%) ($P = .012$). As for the ARLM attachment area, in the RT group, there was a significant decrease (22.5% ± 5.9%) in ARLM attachment area after tibial tunnel reaming compared with the intact state ($P < .001$). Conversely, in the RRT group, the ARLM attachment area was not significantly affected by tibial tunnel reaming.

Conclusion: Rounded-rectangular tibial tunnel was able to better cover the native ACL tibial footprint and significantly lower the risk of iatrogenic injury to the ARLM attachment than round tibial tunnel during ACL reconstruction.

Keywords: anterior cruciate ligament; anterior root of lateral meniscus; footprint coverage; iatrogenic injury

Anatomic anterior cruciate ligament (ACL) reconstruction has been widely applied to restore native ACL anatomy and biomechanical functions in patients with deficient ACLs and is able to achieve better clinical outcomes compared with nonanatomic ACL reconstruction.[12,21] The key for this technique is to place the bone tunnel accurately within the native ACL footprint, thereby better mimicking the footprint and collagen orientation of native ACL.[10,44]

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With native ACL anatomy being the foundation of anatomic ACL reconstruction, detailed anatomic research regarding native ACL has been performed in recent years,[7,37,38] and the results have shown that native ACL has a flat appearance in terms of both midsubstance and attachments. Quantitatively, the cross-sectional area of the ACL attachments was significantly larger than that of the ACL midsubstance.[7] Based on the anatomic findings and the concept of "anatomic" reconstruction, the graft should be adjusted to being "flat."[37] Theoretically, a flat ACL graft was better able to mimic the anatomy of native ACL, covering a larger footprint area and better restoring the functional properties of native ACL fibers. Nevertheless, in clinical practice, ACL bone tunnels are created by rounded-shaped reamers, and as a result, the shape of the tunnel apertures and the cross section of the graft were all circular rather than flat. Failure to fully restore the attachment sites and collagen orientation of native ACL during single-bundle (SB) ACL reconstruction may result in residual rotational instability postoperatively.[11,13]

Regarding tibial attachment, the mismatch between the bone tunnel and the native ACL attachment could cause iatrogenic injuries to the surroundings, given that the diameter of the tunnel is always larger than that of the minor axis of the ACL tibial attachment.[37,49] Because the anterior root of lateral meniscus (ARLM) attachment is close to ACL tibial attachment, which serves as the lateral border of the latter, and a portion of ACL fibers near its tibial bony attachment has an overlap with the ARLM attachment,[26,40] an ARLM attachment is at risk of being damaged during tibial tunnel reaming. In recent years, a few studies have focused on iatrogenic injury to ARLM caused by round tibial tunnel reaming during SB ACL reconstruction,[19,25,45] and the results showed that the incidence of this injury was 21.7% to 100%, depending on different drilling methods and the diameter of the reamer. Nevertheless, these time-zero studies were based only on cadaveric specimens; whether this injury would cause clinically negative consequences remains to be determined.

To better restore the anatomy of the native ACL attachment and fibers arrangement, several researchers have developed techniques that change the shape of the ACL bone tunnel into oval, rectangular, rounded-rectangular, or "C" shapes, with some satisfactory early clinical outcomes.[6,22,23] In this study, we used a flat-tunnel ACL reconstruction technique developed by Liu et al[20] and Zhang et al.[47,49] Using this technique, the shape of the bone tunnel was adjusted to a rounded rectangle. It was assumed that, by adjusting the shape of the tibial tunnel, the rounded-rectangular tunnel (RRT) would be able to better mimic the flat anatomy of native tibial attachment and lower the risk of damaging the ARLM attachment.

The purpose of this study was to (1) investigate the tibial footprint coverage between the rounded-rectangular tibial tunnel and round tibial tunnel, and (2) compare the influence on the ARLM attachment between the 2 tunnels. It was hypothesized that a rounded-rectangular tibial tunnel would better cover the native ACL tibial footprint and lower the risk of iatrogenic injury to the ARLM attachment than a round tibial tunnel during ACL reconstruction.

METHODS

Specimen Preparation

A total of 16 (8 matched-paired) fresh-frozen human cadaveric knees (5 male and 3 female; mean age, 50.5 years; range, 26-65 years) were used in this study. Cadaveric specimens used in this study were from donations to the Department of Anatomy of Peking University (Beijing, China), and this study was approved by a hospital ethics committee. Left and right knees for each pair were distributed randomly into 2 groups: an RRT group and a round tunnel (RT) group. Specimens with previous knee injury or disease, including ligamentous and meniscal injury or severe cartilage degeneration, were excluded from the study. The knees were stored at −20°C and thawed at room temperature for 24 hours.

3-Dimensional Magnetic Resonance Imaging

Because we created the bone tunnels under arthroscopy, specimens could not be dissected before surgery; hence, we used a 3-dimensional magnetic resonance imaging (3D-MRI) technique, which has been proven to be an effective noninvasive method with good accuracy and reliability, to calculate the relevant parameters.[2] Preoperative MRI scans were performed after the specimens had fully thawed, and postoperative MRI scans were performed directly after surgery. All knees were positioned on full extension and scanned using a high-resolution 3-T magnetic resonance (MR) scanner (uMR 790, United Imaging). The images were collected using a 3D isotropic matrix sequence (Table 1). The Digital Imaging and Communications in Medicine data of MRI scans were then imported into Mimics 21.0 software (Materialise). Significant anatomic components of the tibial plateau, ACL tibial footprint, ACL tibial tunnel, and ARLM attachment site were segmented manually using mainly coronal images and checked simultaneously against the sagittal images by 2 surgeons (J.S. and J.Z.) (Figure 1). Only ACL fibers directly attached to the bones were identified as the ACL tibial footprint; the fibers that overlapped with the ARLM attachment were identified carefully and excluded because these fibers were not attached directly to the tibia (Figure 2).[17,40,43] The 3D models for each structure were then calculated and reconstructed using Mimics software.

The 3D models of postoperative ACL tibial tunnel and tibial plateau of postoperative MR were exported as

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standard template library (STL) files and then imported into the preoperative model. Using STL registration in Mimics and manual adjustment, the postoperative tibial plateau could be matched with the preoperative tibial plateau. The images were then imported into ImageJ software (National Institutes of Health), and the following parameters were calculated: (1) major (anterior-posterior) and minor (medial-lateral) axes and area of native ACL footprint; (2) area of ACL tibial tunnel; (3) footprint coverage of ACL tibial tunnel; and (4) pre- and postoperative ARLM attachment area.

TABLE 1
Parameters of Isotropic 3D-MRI Sequence[a]

Parameter	Value
MRI sequence	Proton density-weighted coronal 3D sequence
Repetition time	1000 ms
Echo time	72 ms
Field of view	160 × 160 mm
Slice thickness	0.80 mm
Interslice gap	0 mm
Resolution	0.8 × 0.8 × 0.8 mm
Matrix size	256 × 0.95

[a]3D, three-dimensional; MRI, magnetic resonance imaging.

Graft Harvest

Ipsilateral semitendinosus and gracilis tendons were harvested by use of a close tendon stripper (Karl Storz). Nonabsorbable sutures (Ethicon) were then used to weave the grafts into 4 or 5 strands. The diameter of the graft was measured by a conventional round measuring device (Karl Storz). The diameter of the graft should be at least 8 mm; in this study, the diameters of the weaved ACL grafts were all 8 mm.

Surgical Procedure

The specimens were visualized arthroscopically, with the femur attached rigidly to a custom-made fixed device. The anteromedial and anterolateral portals were used for instruments and arthroscope, respectively. The ACL was

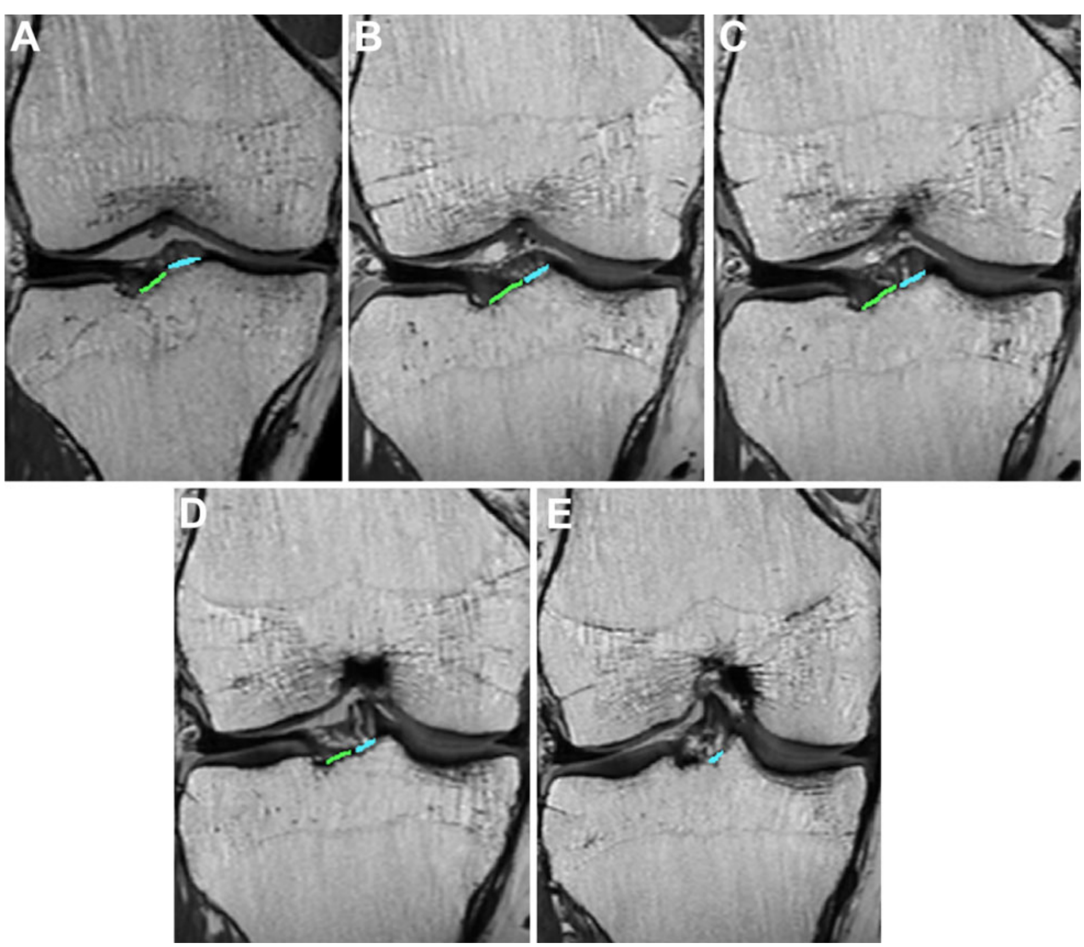

Figure 1. (A-E) The ACL tibial footprint (blue) and ARLM attachment (green) were identified by each slice from (A) anterior to (E) posterior in a 3D-MRI sequence. 3D-MRI, 3-dimensional magnetic resonance imaging; ACL, anterior cruciate ligament; ARLM, anterior root of lateral meniscus.

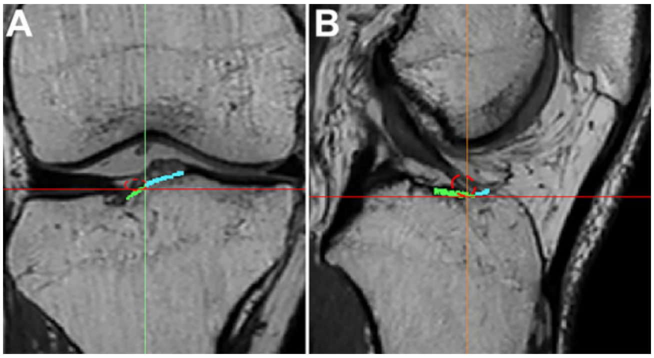

Figure 2. The overlap between ACL fibers and ARLM (dashed red lines). These overlapped ACL fibers were not included as part of the ACL tibial footprint. (A) Coronal view; (B) sagittal view. ACL, anterior cruciate ligament; ARLM, anterior root of lateral meniscus.

visualized, then the midsubstance was cut by a sharp scalpel under arthroscopy. The ACL attachment site and ARLM were fully exposed, with residual ACL fibers carefully shaved to the ACL footprint. A tip-to-tip tibial aiming guide (Acufex Director, Smith and Nephew, Inc.) was used to ream the tibial tunnel for both groups. In addition to the ACL tibial footprint, the following reference points were used as landmarks for tunnel position: posterior border of ARLM, medial tibial spine, anterior ridge, and posterior cruciate ligament. The tip of the aimer was positioned at the calculated center of the ACL tibial footprint. A 2-mm guide pin was then inserted and aimed at the center of the ACL tibial footprint. For the RT group, the pin was overdrilled with a conventional 8-mm round reamer (Cannulated Headed Reamer). For the RRT group, the tibial tunnel was first overreamed with a 5-mm conventional reamer, and then a bone rasp was used to expand the RT to become round-rectangular step-by-step (Figure 3). The key point for this procedure was to rasp the bone tunnel along the long axis of the ACL footprint and match this with its theoretical value, which can be calculated from the previous literature.[47] The bone tunnel was created within the ACL tibial footprint. To standardize the size and shape of the tibial tunnel, a custom-made arthroscopic ruler and dilator of standard size (Figure 4) were applied during the reaming procedure.

All bone tunnels were created by a single orthopaedic surgeon (P.L.) with over 20 years of experience in knee surgery.

Statistical Analyses

An initial pilot study was undertaken with 3 matched knees to determine the sample size calculation for this study. The a priori power analysis was performed with an error probability of 0.05 and power of 0.8 using the G*Power software (v3.1.9.3, F. Faul, Christian-Albrechts-Universität Kiel). The results showed that a minimum sample size of 4 per group was required for testing (see Supplemental Material).

To determine the reliability of MRI evaluation, all measurements were performed twice by 1 observer (J.S.) with an interval of 4 weeks to assess intraobserver reliability, and by 2 independent observers (J.S. and S.R.) to assess the interobserver reliability. The intraclass coefficients were

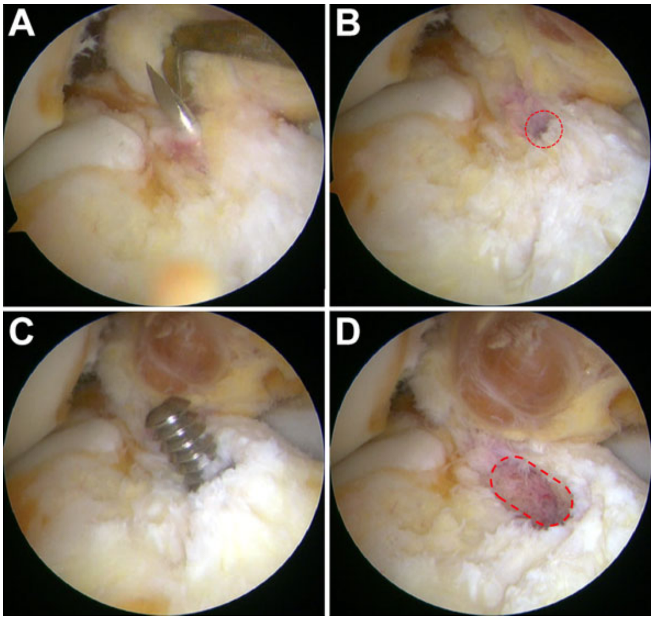

Figure 3. Tibial tunnel reaming in the RRT group. (A) The aimer was placed at the calculated center of the ACL tibial footprint. (B) A small round tunnel was reamed using a conventional reamer. (C, D) The tunnel was adjusted into rounded-rectangular shape using a bone rasp. ACL, anterior cruciate ligament; RRT, rounded-rectangular tunnel.

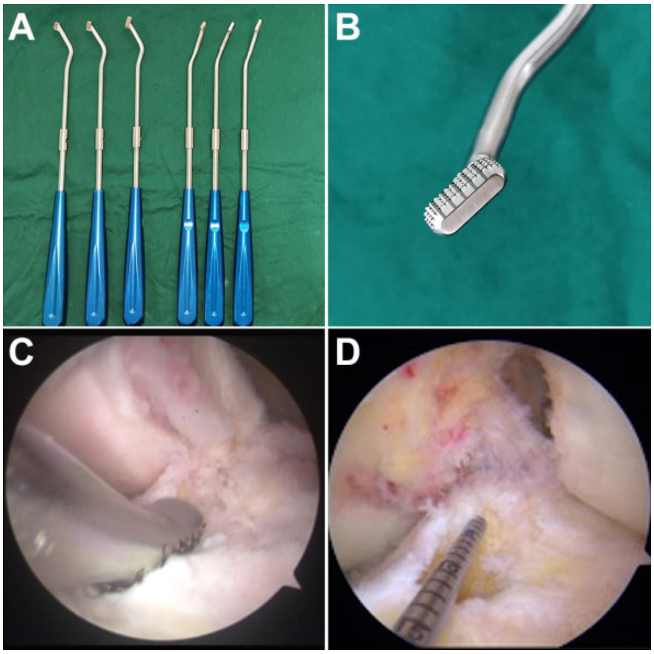

Figure 4. (A-D) Custom-made tunnel dilators of different sizes (A-C) and an arthroscopic ruler (D).

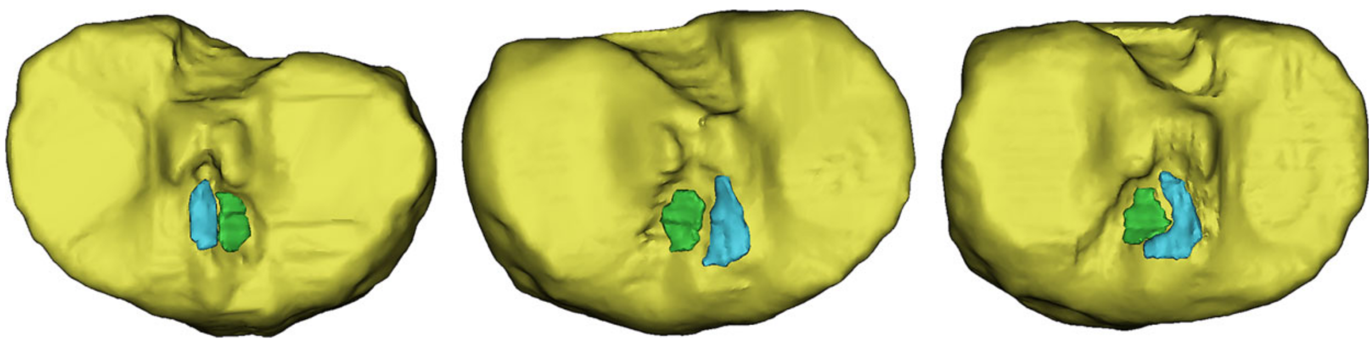

Figure 5. The ACL tibial footprint (blue) in relation to the ARLM attachment (green) in the tibial plateau (yellow) using Mimics software. ACL, anterior cruciate ligament; ARLM, anterior root of lateral meniscus.

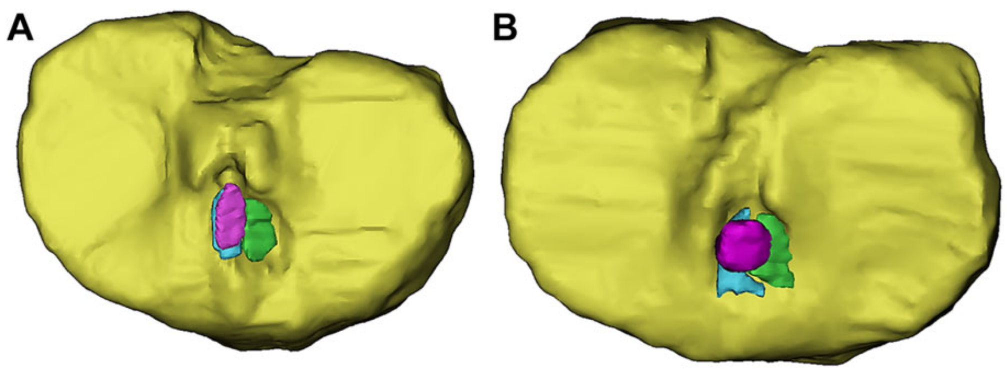

Figure 6. Diagram of footprint coverage in (A) RRT and (B) RT group. The ACL tibial tunnel is shown in purple, the ACL tibial footprint in blue, ARLM attachment in green, and the tibial plateau in yellow. ACL, anterior cruciate ligament; ARLM, anterior root of lateral meniscus; RRT, rounded-rectangular tunnel; RT, round tunnel.

used to assess the intra- and interobserver reliability, which was >0.90 for all measurements.

Statistical analyses were performed using SPSS Statistics 20.0 software (IBM). The paired Student *t* test was used to compare the matched specimens if the data were in normal distribution; otherwise, Wilcoxon signed-rank test was used; $P < .05$ was considered statistically significant.

RESULTS

Parameters of Native ACL Tibial Footprint and ARLM Attachment

The major and minor axes of the native ACL tibial footprint were 14.4 ± 1.0 mm and 5.2 ± 0.4 mm, respectively, with a major/minor ratio of 2.8 ± 0.3. The mean area of the native ACL tibial footprint was 78.1 ± 7.9 mm^2. The mean area of the ARLM attachment was 75.3 ± 9.3 mm.[2] Figure 5 shows the ACL tibial footprint in relation to the ARLM.

Tibial Footprint Coverage in RRT and RT Group

A diagram of ACL footprint coverage in the RRT and RT groups is shown in Figure 6. The mean area of ACL tibial footprint in the RRT and RT group were without significant difference ($P = .401$). However, the mean coverage area and footprint coverage in RRT group were significantly higher than in the RT group ($P = .012$). The mean nonfootprint coverage area of RRT group was significantly lower than that in the RT group (Table 2).

TABLE 2
Footprint Coverage in RRT and RT Groups[a]

	RRT	RT	*P* Value
Native tibial footprint, mm^2	77.8 ± 8.6	78.3 ± 7.8	.401
Tibial tunnel area, mm^2	59.7 ± 5.5	58.8 ± 3.0	.674
Footprint coverage area, mm^2	55.0 ± 5.7	37.7 ± 5.4	**.012**
Nonfootprint coverage area, mm^2	4.7 ± 2.6	21.1 ± 6.8	**.012**
Footprint coverage, %	70.8 ± 2.5	48.2 ± 6.4	**.012**

[a]Data are reported as mean ± SD. Bold values indicate statistically significant difference between groups ($P < .05$). RRT, rounded-rectangular tunnel; RT, round tunnel.

Influence on the ARLM Attachment

After tunnel reaming, all specimens (8/8) in the RT group had injuries to the ARLM attachment. The areas of pre- and

TABLE 3
Pre- and Postoperative Area of ARLM Attachment[a]

	Preoperative Area, mm^2	Postoperative Area, mm^2	Decrease, %	*P* Value
RRT group	75.1 ± 9.7	72.9 ± 8.2	2.7 ± 3.5	.063
RT group	75.6 ± 9.5	58.6 ± 8.1	22.5 ± 5.9	**<.001**
P value	.498	**<.001**	**<.001**	

[a]Data are reported as mean ± SD. Bold values indicate statistically significant difference between groups ($P < .05$). ARLM, anterior root of lateral meniscus; RRT, rounded-rectangular tunnel; RT, round tunnel.

postoperative ARLM attachment in RT group and RRT group are shown in Table 3.

The mean area of ARLM insertions in the RRT and RT group were statistically different ($P = .498$). In the RRT group, the area of ARLM attachment after reaming was 72.9 ± 8.2 mm^2, and the decreased area was 2.2 ± 2.8 mm^2, accounting for 2.7% ± 3.5% of the native ARLM attachment area. The postreaming area was not significantly different from its intact state ($P = .063$). In the RT group, the postreaming area was 58.6 ± 8.1 mm^2, which was decreased significantly compared with its intact state ($P < .001$). The decreased area was 17.0 ± 4.9 mm^2, accounting for 22.5% ± 5.9% of native ARLM attachment area. The postreaming area and decreased percentage in 2 groups were statistically different from each other.

DISCUSSION

The most important finding of this study is that rounded-rectangular tibial tunnel is able to cover a larger portion of native ACL tibial footprint area and reduce iatrogenic injury to the ARLM attachment more than round tibial tunnel.

Recent works by others have shown that anatomic ACL reconstruction was able to achieve better clinical outcomes than nonanatomic ACL reconstruction, indicating that correct tunnel position was critical for ACL reconstruction.[12,21] Because native ACL anatomy forms the basis for anatomic ACL reconstruction, knowing the detailed anatomy of the native ACL footprint is crucial. Recent studies found that the native ACL tibial footprint had a flat appearance. The shape of the ACL tibial footprint could be described as C-shaped, triangular, and oval.[9,37] Quantitatively, the major/minor ratio of the ACL tibial footprint was over 2.0.[37,49] All these findings supported the flat ACL anatomy theory proposed by Siebold.[36]

In conventional ACL reconstruction, the tibial reamer was rounded-shaped, which would create an oval-shaped tibial tunnel. Nevertheless, assuming that the guide was set at 45°, the theoretical major/minor ratio of the tibial tunnel was only 1.41, which was far less than the 2.8 ± 0.3 measured in our study, suggesting the tibial tunnel was not flat enough.

To better reconstruct the flat anatomy of the native ACL footprint, several studies have developed novel approaches in creating oval or rounded-rectangular ACL tunnels.[23,24,32] In this study, we used the technique developed by Liu et al[20] and Zhang et al,[47,49] in which the tibial and femoral tunnels were reamed to become rounded-rectangular shape. The biggest advantage of this technique was that the tunnel was created by a ream-and-rasp procedure so that the shape and location of the tunnel could be adjusted individually.

The center position has always been an important parameter in evaluating whether the tunnel was anatomic for ACL reconstruction.[29,41] However, based on the flat anatomy of native ACL, the shape of the tunnel and how well it matched with the native ACL attachment should also be taken into consideration. In 2011, Siebold[35] developed the concept of "complete footprint restoration," which aimed to reconstruct the maximum area of the ACL footprint. Based on this concept, several studies used footprint coverage as a new parameter to evaluate the matches between the tunnel and the footprint.[3,8,31,33] In this study, we compared the footprint coverage by RRT and RT, and our results showed that, under the same cross-sectional area of the tunnel, the rounded-rectangular tibial tunnel (70.8 ± 2.5%) could significantly cover more of the ACL tibial footprint than round tibial tunnel (48.2 ± 6.4%). Correspondingly, the area of tunnel that extruded the footprint was lower in the RRT group (4.7 ± 2.6 mm^2) than in the RT group (21.1 ± 6.8 mm^2). Previous studies have indicated that restoration of the footprint was crucial for fibers recruited during knee movement and that only the covered footprint would be functional.[16,33] Rounded-rectangular tibial tunnel would therefore be able to recruit more ACL graft fibers and reduce the noneffective footprint coverage. Consequently, RRT could theoretically better improve knee kinematics and clinical outcomes compared with RT. Recent studies have also raised concerns regarding iatrogenic injury of ARLM attachment during anatomic SB ACL reconstruction, as native ACL tibial footprint and ARLM attachment are closely associated with each other.[17,25,27,40,46] Watson et al[45] reported that 66% of the ARLM of human knee specimens were injured during tibial tunnel reaming using a 10-mm diameter reamer. LaPrade et al[19] found that, when using an 11-mm-diameter reamer, the ARLM was injured in all specimens, and the mean decrease of attachment area was 38% compared with the intact state. However, an 11-mm diameter tunnel is extremely uncommon in ACL surgery at our practice. Oishi et al[25] showed that the incidence of ARLM injury using a 10-mm-diameter reamer was 21.7%. In the present study, we found that even using an 8-mm-diameter reamer could result in significant decrease of the ARLM attachment area, which was not recognized in previous studies. This was because the minor axis of the native ACL tibial footprint was only 5.2 ± 0.4 mm, which was far less than the diameter of the tunnel. The tunnel extruding from the footprint could cause injuries to the surrounding tissues, and the ARLM attachment, in particular, is easily damaged as it forms the lateral border of the ACL tibial footprint. This iatrogenic injury could impair the integrity of the ARLM attachment site, reducing the area and, ultimately, the strength of the ARLM attachment site.[19]

Injuries to the ARLM attachment can be of clinical significance. Kodama et al[15] found that a posterolaterally located tibial tunnel aperture increased extrusion of the lateral meniscus after ACL reconstruction, indicating that injury to the ARLM attachment during ACL reconstruction could cause instability of the lateral meniscus. Other studies have shown that injuries to the meniscal root were related to early osteoarthritis and altered knee mechanics.[18,39] Some researchers reported that a complete meniscal root tear was biomechanically similar to total meniscectomy.[1,28] Thus, avoidance of iatrogenic injury to the ARLM attachment is of great significance. Some studies investigated whether double-bundle (DB) ACL reconstruction would reduce this injury, as the tunnels in DB ACL reconstruction were smaller than those in SB ACL reconstruction. Results have shown that the incidence of the injury was lower in the DB group (4.3%-16.7%) than in the SB group (21.7%-50%),[14,25] but there was no significant difference between the 2 groups.

In the RRT group, because the diameter of the tunnel was smaller than the native tibial footprint and the tunnel was created within the footprint by the ream-and-rasp technique, the possibility of tunnel extrusion was reduced. Our results showed that the mean area of ARLM attachment was higher in the RRT group (72.9 ± 8.2 mm^2) than in the RT group (58.6 ± 8.1 mm^2) postoperatively, which verified our hypothesis. Although the postoperative area of ARLM attachment in RRT was lower than its intact state (preoperative area, 75.1 mm^2; postoperative area, 72.9 mm^2), there was no statistical difference between the 2 ($P = .063$), suggesting that our technique could prevent most of the ARLM attachment from injury.

The current study showed the strengths of the rounded-rectangular tibial tunnel in terms of increased footprint restoration and protection of ARLM attachment. Recent studies also presented other advantages using the flat ACL anatomy concept and RRT technique. Zhao et al[50] revealed that a flattened bone tunnel could accelerate tendon-bone healing in the early period after ACL reconstruction in rabbit. Zhang et al[47] showed that a flattened RRT was superior to the RT regarding graft maturity, postoperative Tegner score, and pivot-shift tests. These results suggested that using the flat ACL anatomy concept combined with rounded-rectangular bone tunnel ACL reconstruction technique could better restore the native ACL footprint and improve the clinical outcomes after ACL reconstruction.

We acknowledge some limitations to this study. First, it was a cadaveric study. The average age of the donors was older than the population who underwent ACL reconstruction, which might slightly influence the results.[5] Second, we used 3D-MRI to reconstruct each structure, which was not the gold standard in the current literature. However, as the tunnels were reamed arthroscopically, specimens could not be dissected before surgery, and 3D-MRI has been proven as an effective noninvasive method with good accuracy and reliability.[2,30,34,42] Third, our results showed that RRT could restore a larger portion of tibial footprint than RT, but it still could not achieve complete footprint restoration. This was because the size of the tunnel was determined by the diameter of the hamstring tendon. Future studies need to find ways to obtain a larger graft to completely restore the native ACL footprint. Lastly, current literature reports controversial biomechanical results between the flat-tunnel and RT techniques in ACL reconstruction.[4,48] Whether the RRT technique has biomechanical advantages over the RT technique was not confirmed in the current study.

CONCLUSION

Rounded-rectangular tibial tunnel could better cover the native ACL tibial footprint and significantly lower the risk and extent of ARLM attachment injury compared with round tibial tunnel during ACL reconstruction.

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