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RESEARCH ARTICLE

Biomechanical Comparison of Anatomic *Versus* Lower of Anteromedial and Anterolateral Tibial Tunnels in Posterior Cruciate Ligament Reconstruction

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Objective: In order to reduce the "killer turn" effect, various tibial tunnels have been developed. However, few studies investigated the biomechanical effects of different tibial tunnels during PCL reconstruction. This study aims to compare the time-zero biomechanical properties of anteromedial, anterolateral, lower anteromedial, and lower anterolateral tibial tunnels in transtibial posterior cruciate ligament (PCL) reconstruction under load-to-failure loading.

Methods: Porcine tibias and bovine extensor tendons were used to simulate *in vitro* transtibial PCL reconstruction. Forty bovine extensor tendons and 40 porcine tibias were randomly divided into four experimental groups: anteromedial tunnel group (AM group, $n = 10$), anterolateral tunnel group (AL group, $n = 10$), lower anteromedial tunnel group (L-AM group, $n = 10$), and lower anterolateral tunnel group (L-AL group, $n = 10$). The biomechanical test was then carried out in each group using the load-to-failure test. The ultimate load (in newtons), yield load (in newtons), tensile stiffness (in newtons per millimeter), load-elongation curve, failure mode, and tibial tunnel length (in millimeter) were recorded for each specimen. One-way analysis of variance (ANOVA) was used to compare the mean differences among the four groups.

Results: The biomechanical outcomes showed that there were no differences in the mean tensile stiffness and failure mode among four groups. The ultimate load and yield load of the L-AM group were significantly higher than those of other three groups ($P < 0.05$). For the AM group, its ultimate load is significantly higher than that of the L-AL group ($P < 0.05$), and its yield load is higher than that of the AL group and L-AL group ($P < 0.05$). However, we found no significant differences in either ultimate load or yield load between AL group and L-AL group ($P > 0.05$). There was significant statistical difference in the length of tibial tunnel between anatomic groups (AM and AL) and lower groups (L-AM and L-AL) ($P < 0.05$).

Conclusion: Compared with the anteromedial, anterolateral, and lower anterolateral tibial tunnel, the lower anteromedial tibial tunnel showed better time-zero biomechanical properties including ultimate load and yield load in transtibial PCL reconstruction.

Key words: Posterior cruciate ligament; Tibial tunnel; Ultimate load; Yield load; Zero-time biomechanical properties comparison

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Introduction

The incidence of PCL injury accounts for 44% of acute knee injuries.[1] PCL has an excellent limiting effect on the tibia in the case of both internal and external rotation of the knee joint. Especially in limiting the posterior displacement of the tibia, the role of PCL is irreplaceable.[2] Therefore, when PCL injured, it is particularly decisive to choose a safe and effective method of reconstruction to restore the integrity of the PCL. Nevertheless, since the incidence of PCL injury is lower than that of injury to the anterior cruciate ligament (ACL), the existing research on PCL reconstruction is far from enough.

When tibial tunnel PCL reconstruction is used, the "killer turn" effect is inevitable. The "killer turn" is the sharp angle of the graft at the edge of the proximal tibial tunnel, caused by the traditional anteromedial approach to PCL reconstruction, which may lead to graft abrasion.[3–6] Many scholars hold the view that the sharp "killer turn" is the main reason for failure of PCL reconstruction operations.[7,8] In addition, some authors making use of a three-point bending model of PCL reconstruction came to the conclusion that abrasion at the edge of the tibial tunnel will lead to graft failure.[3,9]

To overcome the "killer turn" effect, several methods have been proposed. The anterolateral tibial tunnel reconstruction was reported by Ohkoshi *et al.*[3] that 95% of the knee function returned to normal, or near-normal, in a short-term follow-up after the operation. The use of the anterolateral tibial tunnel to reduce the "killer turn" effect was identified as the main reason for the favorable results. However, a contrary view is that compared to the traditional anterolateral tibial tunnel, the anterolateral tibial tunnel reduces the compressive force of the graft, which may reduce fixation strength and increase joint translation. Fanelli *et al.*[10,11] described a lower tibial tunnel, which broke the killer turn into two gentle angles by placing the proximal exit of the tibial tunnel below the edge of the tibial plateau. This method has achieved good clinical results. Nevertheless, this method of PCL reconstruction that changes the original anatomical position may change the function of the graft, and there is no consensus on the long-term effect of this method of PCL reconstruction.

At present, the optimal choice of PCL reconstruction about tibial tunnels has not been clarified, and the recommendations are conflicting. To our knowledge, few studies compared the biomechanical properties of the above multiple tibial tunnels simultaneously. This study simultaneously compared the biomechanical properties of anteromedial tibial tunnel (AM), lower anteromedial tibial tunnel (L-AM), anterolateral tibial tunnel (AL) and lower anterolateral tibial tunnel (L-AL) in transtibial PCL reconstruction.

The purpose of this study was to compare the time-zero biomechanical properties of the traditional anteromedial tunnel with those of different reduced "killer turn" tibial tunnels. What is more, the time-zero biomechanical properties of different reduced "killer turn" tibial tunnels were compared. We hypothesized that the AM group had better time-zero biomechanical properties, including ultimate load and yield load, than other groups, as reducing "killer turn" effect weakened the concentrated stress of graft at the proximal tibial tunnel exit.

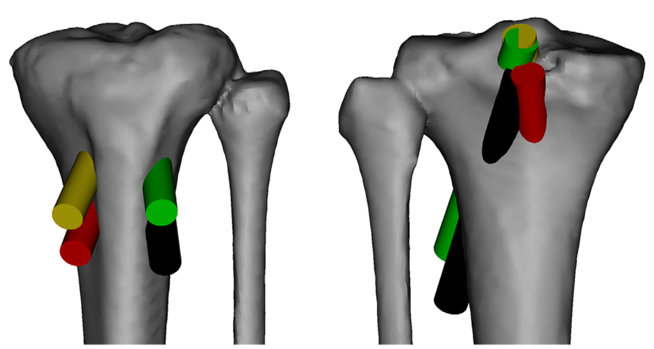

Fig. 1 Schematic of different tibial tunnel placement. Yellow tunnel: AM tibial tunnel; red tunnel: L-AM tibial tunnel; green tunnel: AL tibial tunnel; black tunnel: L-AL tibial tunnel.

Methods

Tibial Tunnel and Graft Preparation

The Regional Ethics Committee of our hospital approved this experiment (D2022-069). Many studies showed that porcine tibias and bovine extensor tendons have similar biomechanical properties with human tibias and tendons, and were commonly used as the materials for constructing transtibial PCL reconstruction models.[12,13] Forty freshly frozen porcine tibias and forty bovine tendons, were randomly divided into four groups(AM, L-AM, AL, and L-AL groups) by random number table. All pig tibias and bovine tendons were preserved at $-20°C$, and defrosted at room temperature over 12 h before preparing the graft and tunnel.

Based on previous studies, a transtibial PCL reconstruction model was established.[14,15] All four groups of tibial tunnels were constructed with PCL tibial aimer drilling guidance system (Arthrex Inc., Naples, FL, USA) at an angle of 50° to the tibial plateau. The entry points of two anteromedial tunnel groups were 1.5 cm medial to the tibial tubercle sagittal line. In the AM group, the proximal tibial outlet was the anatomical footprint of the PCL. In the L-AM group, the proximal tibial outlet was approximately 1.0 cm inferior and 0.5 cm lateral to anatomical footprint of the PCL. The entry points of two anterolateral tunnel groups are 1.5 cm lateral to the tibial tubercle sagittal line. For the AL group, the proximal tibial outlet was the anatomical footprint of the PCL. In the L-AL group, the tibial outlet was approximately 1.0 cm inferior and 0.5 cm lateral to anatomical footprint of the PCL(Fig. 1). The length of all the groups of tibial tunnels was 22–45 mm and the diameter was all 9 mm. The experimental tibia was cut, leaving the proximal end 15 cm.

As for the preparation of the tendon, all the soft tissues were dissected from the tendon and removed. The tendon tissue was then stripped and folded in half to form a double-stranded graft which was 110 mm in length and 9 mm in diameter. All graft diameters were adjusted with the 9 mm diameter tunnel mold until the resistance of graft getting through the mold was moderate. The 110 mm total length included the tunnel length 22–45 mm, and the fixed length of the experimental machine 25 and 35 mm. The grafts were wrapped with 0.9% saline-soaked gauze to keep moist.

Biomechanical Testing

After the prepared graft passed through the porcine tibial tunnel, the clamp was adjusted so that the length of the graft between the clamp and the outlet of the tibial tunnel was 35 mm (the native PCL length was 32–38 mm). The graft was fixed with 9 mm × 25 mm titanium interference screw (Arthrex, Naples, FL, USA) at the entrance of the tunnel and in the direction of the tunnel. To prevent the loss of the fixation effect of the interference screw, its end kept 2 mm outside the entrance of the tibia.

The tibia was fixed in a custom appliance. To obtain a normal anterior declination of PCL with an angle of approximately 70°–80°,[16] the axial direction of the graft loading force was at an angle of 125°–135° to the tibial tunnel in the sagittal plane. The free end of the graft was then clamped firmly to the experimental apparatus. All the materials were used only once in the experiment. Pretension of 20 N at 1 Hz for 10 min was applied to each graft to eliminate tendon viscoelasticity.[17] We used an electronic universal testing machine (AG-X; Shimadzu, Kyoto, Japan) to build a load-to-failure model (Fig. 2). Each graft was loaded until it failed at a rate of 10 mm/min. Ultimate load (N), yield load (N), tensile stiffness (N/mm), load-elongation curve, failure mode, and tibial tunnel length (mm) were recorded for each specimen. Load-elongation curve, limit load, and yield load were recorded directly using the software (Trapezium X; Shimadzu, Kyoto, Japan). The tensile stiffness was defined as the slope of the linear region of the load-elongation curve. The length of the tunnel through the tibia was recorded *via* direct measurement. The failure form of each sample was obtained by visual observation.

Statistical Analysis

Based on pre-experiment data, the minimum sample size in this study was nine, which was calculated by the G*Power software (version 3.1.9, Heinrich Heine University, Düsseldorf, Germany) using the *t* test function (effect size = 1.08; 1-β err prob. = 0.9; α = 0.05). In this study, We used 10 tibial bones and 10 grafts in each group. Therefore, the specimen size in the present study was sufficient. In addition, all statistical analyses were carried out using the IBM SPSS statistical software (version 22.0; IBM, Armonk, NY, USA). One-way analysis of variance (ANOVA) was used to compare the mean differences between the four groups. $P < 0.05$ represented a significant difference.

Result

Failure Mode and Tibial Tunnels Length

Table 1 depicts the graft failure mode. There were no significant differences in the failure mode by using chi-square test (Table 2). The failure modes of each experimental group were due to graft breakage and graft slippage. The tibial tunnel length in anatomic tunnel groups was significantly longer than lower tunnel groups (tunnel length: 397 ± 21 mm in AM group *vs* 324 ± 40 mm in L-AM group [$P < 0.001$], 370 ± 27 mm in AL group *vs* 277 ± 46 mm in L-AL group [$P < 0.001$]). The AM tibial tunnel length showed no difference with AL tibial tunnel length in anatomic group (tunnel

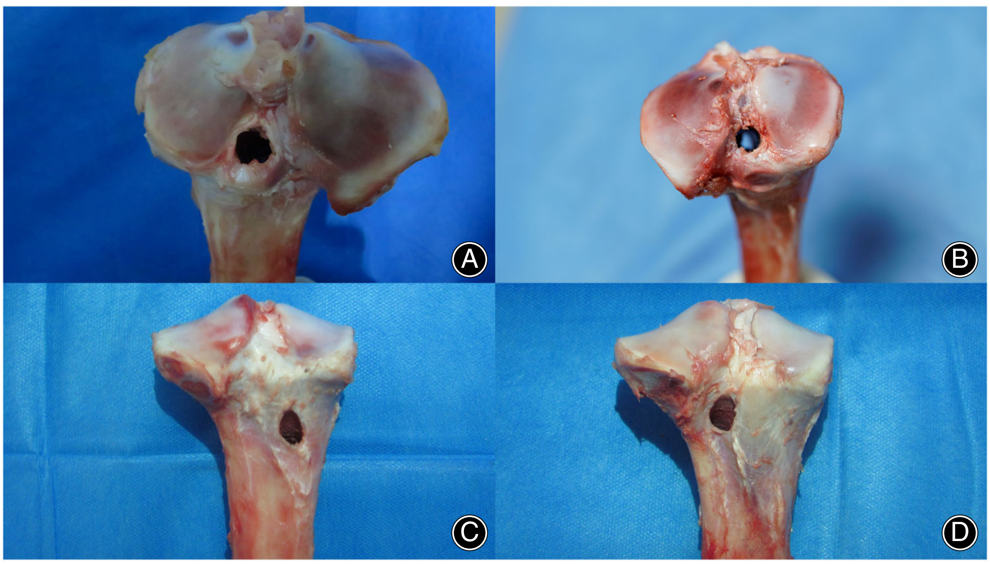

Fig. 2 Proximal exit of tibial tunnel; (A) proximal exit of AM group; (B) proximal exit of AL group; (C) proximal exit of L-AM group; (D) proximal exit of L-AL group.

TABLE 1 Biomechanical results of load-to-failure loading testing

	Mean ± standard deviation			
Biomechanical results	(AM) (n = 10)	(L-AM) (n = 10)	(AL) (n = 10)	(L-AL) (n = 10)
Ultimate load (N)	508.04 ± 53.70	601.76 ± 80.16	390.06 ± 117.18	384.49 ± 112.19
Yield load (N)	399.11 ± 77.42	515.27 ± 92.45	283.26 ± 76.36	296.69 ± 115.58
Tensile stiffness (N/mm)	40.76 ± 10.50	41.8 ± 11.52	48.44 ± 19.82	33.8 ± 9.61
Graft failure mode				
Graft breakage	6	7	3	2
Graft slippage	4	3	7	8

TABLE 2 *P* value of biomechanical comparisons of load-to-failure loading testing

Biomechanical results	AM *vs* L-AM	AM *vs* AL	AM *vs* L-AL	AL *vs* L-AM	AL *vs* L-AL	L-AM *vs* L-AL
Ultimate load (N)	0.007	0.013	0.008	<0.001	0.915	<0.001
Yield load (N)	0.007	0.003	0.013	<0.001	0.986	<0.001
Tensile stiffness (N/mm)	0.835	0.297	0.139	0.372	0.050	0.109
Graft failure mode	0.639	0.371	0.178	0.178	0.639	0.074

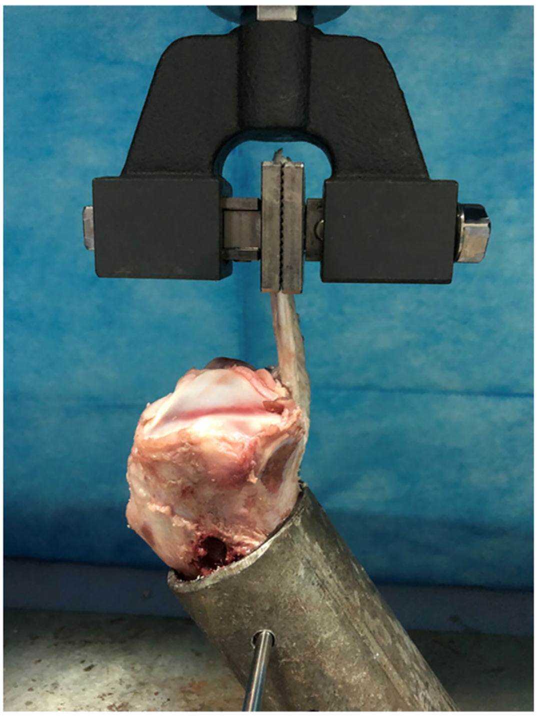

Fig. 3 A specimen was fixed in an electronic universal biomechanical testing machine (AG-X; Shimadzu, KyotoJapan).

length: 397 ± 21 mm in AM group *vs* 370 ± 27 mm in AL group [P = 0.099]). The AM tibial tunnel length was significantly longer than AL tibial tunnel length in lower tunnel groups (tunnel length: 324 ± 40 mm in L-AM group *vs* 277 ± 46 mm in L-AL group [P = 0.008]).

Outcomes of Biomechanical Testing

Ultimate load, yield load, and tensile stiffness obtained from the experiment were shown in Table 1. There were significant differences ($P < 0.05$) in ultimate load, yield load, and tensile stiffness *via* one-ANOVA analysis (Table 2).

The ultimate load and yield load in the L-AM group were significantly higher than those in other three groups (ultimate load: 601.76 ± 80.16 N in the L-AM group *vs* 508.04 ± 53.70 N in the AM group [P = 0.007], 390.06 ± 117.18 N in the AL group [$P < 0.001$], 384.49 ± 112.19 N in the L-AL group [$P < 0.001$]; yield load: 515.27 ± 92.45 N in the L-AM group *vs* 399.11 ± 77.42 N in the AM group [P = 0.007], 283.26 ± 76.36 N in the AL group [$p < 0.001$], 248.02 ± 105.98 N in the L-AL group [$P < 0.001$]). For the AM group, the ultimate load and yield load were also significantly higher than those in the AL and L-AL groups (ultimate load: 508.04 ± 53.70 N in the AM group *vs* 390.06 ± 117.18 N in the AL group [P = 0.013], 384.49 ± 112.19 N in the L-AL group [P = 0.008]; yield load: 399.11 ± 77.42 N in the AM group *vs* 283.26 ± 76.36 N in the AL group [P = 0.003], 248.02 ± 105.98 N in the L-AL group [P = 0.013]). For the AL and L-AL groups, we found no significant difference in either ultimate load or yield load ($P > 0.05$; Fig. 3). Statistical analyses did not show significant statistical differences in tensile stiffness among all groups.

Discussion

The major finding of this study was that the L-AM tibial tunnel provided better biomechanical properties regarding ultimate load and yield load in load-to-failure testing of PCL reconstruction. There were no differences in the mean tensile stiffness and failure mode among four groups. The tibial tunnel length in anatomic tunnel groups was significantly longer than lower tunnel groups.

Anteromedial Tunnel Groups versus Anterolateral Tunnel Groups

Regarding the two anteromedial tunnel groups (the AM and L-AM groups) and the two anterolateral tunnel groups (the AL and L-AL groups), the former exhibited a more superior ultimate load and yield load. A possible explanation for this significant difference is related to the bone surface properties at the distal outlet of the tibial tunnel. Ahn *et al.*[14] compared biomechanical properties of anterior medial tibial tunnel and anterolateral tibial tunnel in PCL reconstruction. We believe that the tunnel entrance formed by the anterolateral tunnel on the surface of anterior tibia is wider and the cortical-tunnel angles are sharper than those of the anteromedial tunnel. Therefore, the biomechanical properties of the failure are worse.

Anatomic Tunnel Groups versus Lower Tunnel Groups

Compared to the AM tibial tunnel, the AL, L-AM, and L-AL tibial tunnels can significantly reduce the sharpness of the "killer turn".[18,19] We hypothesized that the AM group would have better biomechanical properties than other tunnel groups. However, the experimental results did not support our hypothesis. When comparing two anatomic tunnel groups (AM and AL groups) with two lower tunnel groups (L-AM and L-AL groups), we found that the ultimate load and yield load in the L-AM group were significantly higher than those in the AM group. Interestingly, the ultimate load and yield load in the L-AL and AL groups were very close. We believe that the different comparison results are due to different bone structure of the proximal exit of the tibial tunnel in the lower tunnel group on both sides. Hernandez *et al.*[20] believed that there was a linear relationship between bone volume fraction and mechanical properties (Young's modulus, yield strength, and ultimate strength) and that bone volume fraction could be used to estimate the mechanical properties of a bone. According to the distance between the tibial eminence and the distal end of the tibial tuberosity, Krause *et al.*[21] divided the tibial plateau into three equally high levels: proximal, middle, and distal. Subsequently, the proximal and intermediate segments were divided into 10 regions of interest respectively. The histomorphometric parameters of these regions were measured using high-resolution peripheral quantitative CT (HR-pQCT). According to the bone volume fraction supplied in a study by Krause *et al.*, the bone volume fraction at the proximal exit of the tunnel in our AM and AL groups was $12.5 \pm 2.9\%$ (postero-central region of the proximal level) and that in L-AM and L-AL groups was $16.0 \pm 1.9\%$ and $11.8 \pm 5.2\%$ (postero-latero-central and postero-medio-central region of the middle level). There was significant difference in bone volume fraction of proximal tunnel between the AM and L-AM groups. However, there was no significant difference in bone volume fraction at the proximal exit of the tunnel between the AL and L-AL groups. The regionalized measurement of the proximal tibial bone microstructure shown by Krause *et al.* is completely consistent with the results we observed when comparing the experimental groups. Therefore, our results are convincing (Fig. 4).

The Length of the Tunnel

In clinical PCL reconstruction, it is generally believed that the length of the intraosseous tunnel may play a significant role in increasing the strength of bone tunnel to graft fixation.[22] In our experiment, although the length of the tibial tunnel in the AM group was significantly longer than that in other groups, time-zero biomechanical analysis showed that the difference in biomechanical properties obviously did not support this clinical cognition. There was no statistically significant difference in tensile stiffness among all the groups. In a study on anterior cruciate ligament reconstruction, the

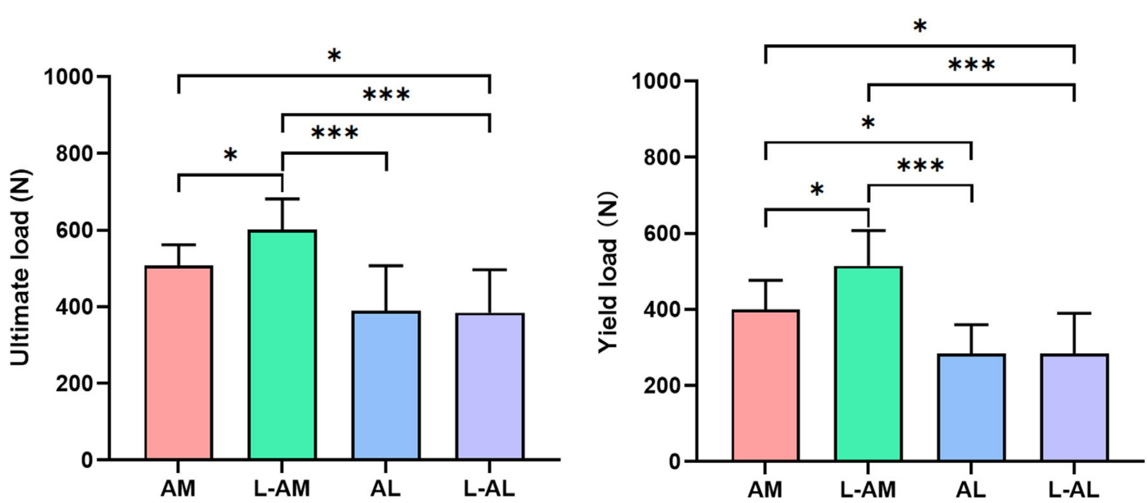

Fig. 4 The difference of ultimate load and yield load among different experimental groups. * $P < 0.05$, *** $p < 0.001$.

effect of tibial tunnel length on the biomechanical properties of the graft was observed. Yamazaki *et al.*[22] used beagle dogs to compare the differences in ultimate load and stiffness at time-zero and exact 6 weeks between the graft-tibial complex in 5 and 15 mm tibial tunnel groups respectively. In this report, after comparing the ultimate load and stiffness at time-zero and week 6, no significant difference was found between the 5 and 15 mm tibial tunnel groups. In another study on anterior cruciate ligament reconstruction, Zantop *et al.*[23] compared the biomechanical effects of a 15 and 25 mm femoral tunnel at 6 and 12 weeks. The results showed no statistically significant differences in ultimate failure load and tensile stiffness between the two groups. Fabbri *et al.*[24] believed that the stiffness of graft should be more correlated to the viscoelastic properties of tendon itself than to the structure of tendon in which the graft is located. In these reports, the effect of the length of the bone tunnel graft-tibial complex on its own stiffness is limited. There is no difference in stiffness and ultimate load among groups in the study by Yamazaki *et al.* and that by Zantop *et al.* However, our results show that the stiffness was not significantly different between the groups while the ultimate load and yield load were different. The difference between our study and theirs was the exit positions of tunnel groups, which was consistent with our finding that different tunnel proximal and distal exit position lead to the various tunnel group differences in ultimate load and yield load.

Limitations

This study comprehensively observed the biomechanical properties of anatomical and non-anatomical tibial tunnels of PCL reconstruction. To our knowledge, our study observed the anterolateral and anteromedial biomechanical properties of lower tunnel, and provided biomechanical evidence for the clinical application of lower tunnel. There are some limitations to our study. First, we used the tendon of porcine tibia and bovine extensor muscle to create an *in vitro* model of PCL reconstruction. These two materials are often used as substitutes for PCL reconstruction, which imparts the experiment better repeatability.[25,26] It has also been documented that the porcine tibia most closely resembles the human tibia that commonly sustain sports injuries,[26,27] nevertheless, there is no denying that animal materials might differ from human specimens. Second, this study focused on the biomechanical properties at time-zero. Since there was no cyclical load to simulate the rehabilitation process, the experiment did not simulate loading during rehab. It may require more clinical studies to prove our findings. Third, we used metal interference screws to fix the graft rather than bioabsorbable screws or polyether ether ketone screws, the reason for which is that the metal interference screws were easier to obtain and more economical. Previous studies have reported similar biomechanical properties during soft tissue fixation with different screws.[12] In addition, in the biomechanical study of tibial soft tissue graft fixation, metal interference screws are often used for soft tissue graft fixation.[27] Fourth, we did not assess the elongation pattern of the graft in this study. Previous studies have suggested that studying elongation patterns helps to understand the local strain of the ligament.[28,29] Also, it gives correct advice on the optimal knee flexion angle during the PCL reconstruction.[30] This study focuses on the effects of different tibial tunnels on graft fixation strength, and it is difficult to evaluate graft elongation patterns based on this biomechanical model. The subsequent studies can further explore the elongation pattern of grafts in different tibial tunnels.

Conclusions

Based on our findings, the lower anteromedial tibial tunnel showed better time-zero biomechanical properties in ultimate load and yield load than the anatomic AM, AL, and L-AL tibial tunnels for transtibial PCL reconstruction. Further clinical and biomechanical studies are still needed to validate our findings.

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Author Contributions

Bo Peng, study design, software, data collections, writing, final corrections. Yuchen Tang and Gengxin Jia, data collections, data analysis, software. Lihu Xu and Bin Geng collections, writing. Yayi Xia and Yuanjun Teng, final corrections, final approval of the version to be published.

Ethics Statement

This study was approved by medical ethics committee of Lanzhou University Second Hospital (No. D2020-19).

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