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Modified tibial tunnel placement for single-bundle posterior cruciate ligament reconstruction reduces the “Killer Turn” in a biomechanical model

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Abstract

Background: Our previous three-dimensional finite element analysis found that posterior cruciate ligament (PCL) reconstruction in the modified tibial tunneling placement (MTT, 10 mm inferior and 5 mm lateral to the PCL anatomical insertion) could reduce the peak stress of the graft and may reduce the killer turn. The purpose of the current study was to compare the biomechanical results between MTT and traditional tibial tunneling technique (TTT, PCL anatomical insertion) during transtibial PCL reconstruction.

Methods: Fifty-six 3D-printed tibia models and fresh mature porcine flexor digitorum tendons were studied. The PCL reconstruction specimens were randomly divided into TTT group and MTT group based on tibial tunnel placement. A 50 to 300 N cyclic loading was applied using a material testing system. Each specimen completed 2000 cycles at a rate of 200 mm/min and a loading frequency of 80 cycles/min. Load–displacement curves, failure mode, and graft displacement were recorded. Mean maximum contact pressure was measured using a pressure-sensitive film. After cyclic loading test, the surviving grafts were randomly assigned to load-to-failure group or Scanning Electron Microscopy (SEM) group. Ultimate failure load and the appearance of graft abrasion were recorded and analyzed.

Result: During the cyclic loading test, 3 samples in the TTT group, and 2 in the MTT group were excluded because of the graft pullout during the test. Mean maximum contact pressure of killer turn was 9.30 ± 0.29 MPa in the TTT group and 7.27 ± 0.25 MPa in MTT group ($P < .05$). Mean graft displacement was 4.54 ± 0.23 mm in the TTT group and 3.37 ± 3.56 mm in the MTT group ($P < .05$). Maximum failure load was 1886.0 ± 41.83 N in the TTT group and 2019.30 ± 20.10 N in the MTT group ($P < .05$). The SEM analysis showed heavy abrasion and fiber discontinuity in graft in the TTT group, while it showed slight abrasion and fiber arrangement disorders in the MTT group.

Conclusions: The MTT PCL reconstruction significantly reduced stress concentration and graft abrasion as compared with the TTT PCL reconstruction, and it may be a better choice for the reduction of “killer Turn” effect during transtibial PCL construction.

Abbreviations: MTT = modified tibial tunneling, PCL = posterior cruciate ligament, TTT = traditional tibial tunneling.

Keywords: biomechanics, killer turn, posterior cruciate ligament, reconstruction

1. Introduction

Although surgical technique involving posterior cruciate ligament (PCL) reconstruction has advanced in recent years, there are still many unanswered questions regarding the causes of reconstruction failure. The “killer turn” has frequently been documented as a primary drawback of this technique, because it may result in graft abrasion, thinning, and permanent elongation in the sharp graft angulation at the intra-articular aperture of the tibial tunnel.[1–6]

Alternative methods of PCL reconstruction strive to overcome the “killer turn” effect. One of these methods involves performing an inlay technique instead of a transtibial tunnel technique.[7–12] A recent study has shown that there are no clinically important differences between the transtibial and tibial inlay approach for PCL reconstruction.[10,13,14] However, the majority of surgeons prefer transtibial PCL reconstruction. Some research groups have begun to focus on non-anatomic tibial tunnel placement for single-bundle PCL reconstruction to establish a normal anterior–posterior knee laxity patterns during a flexion–extension cycle.

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ZW and YX contributed equally to this work

The authors have no conflicts of interest to disclose.

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Fanelli et al[15–17] have described a modified single-bundle PCL reconstruction technique by placing tibial tunnel outlet on the inferior lateral part of the PCL fovea, which has shown good clinical outcomes. Our previous 3-dimensional finite element analysis found that PCL reconstruction in the Fanelli area, especially 10 mm inferior and 5 mm lateral to the PCL anatomical insertion, could reduce the peak stress of the graft and may reduce the killer turn.

The purpose of the current biomechanical study is to further confirm whether MTT could reduce killer turn as compared with TTT technique of PCL reconstruction. We hypothesized that MTT PCL reconstruction could decrease PCL graft abrasion at the tibial tunnel exit and reduce the "killer turn" as compared with the TTT PCL reconstruction.

2. Materials and methods

This research was approved by the Independent Ethics Committee of West China Hospital, Sichuan University. Fifty-six 3D-printed tibias (metal powders) were included in the study (Fig. 1). The proximal tibial model retains a length of 15 cm. A senior surgeon did the preparation and reconstruction in all specimens. Tibial tunnels of both TTT and MTT were constructed using a transtibial technique in accordance with Acufex PCL guide (Smith & Nephew, Andover, MA). The entrance of the tunnel was placed at the anteromedial surface of the proximal tibia, at midpoint between the posteromedial border of the tibia and the anterior tibial crest, 1 cm below the tibial tubercle. The posterior tibial exit point was in the anatomic PCL footprint of the anterolateral bundle in the TTT group, while 1.0 cm inferior and 0.5 cm lateral to the PCL anatomic insertion site in the MTT group. Porcine flexor digitorum tendons were used as soft tissue grafts. Grafts were harvested from a local butcher, which were stored at −20 °C immediately after harvesting and were thawed for 12 hours at room temperature before testing. The tendon was fashioned to a diameter of approximately 8 mm and braided with No. 2 Ethibond (Ethicon Inc., Somerville, NJ). The graft was passed through the tunnel and fixed with an 8 mm metallic interference screw. The initial graft length from the tibial aperture to the clamp on the load cell was kept at 3.5 cm for each specimen to simulate the intra-articular length of the PCL at 90° of knee flexion.[18] The diameter of the interference screw, the bone tunnel, and the graft were of equal size (Fig. 2).

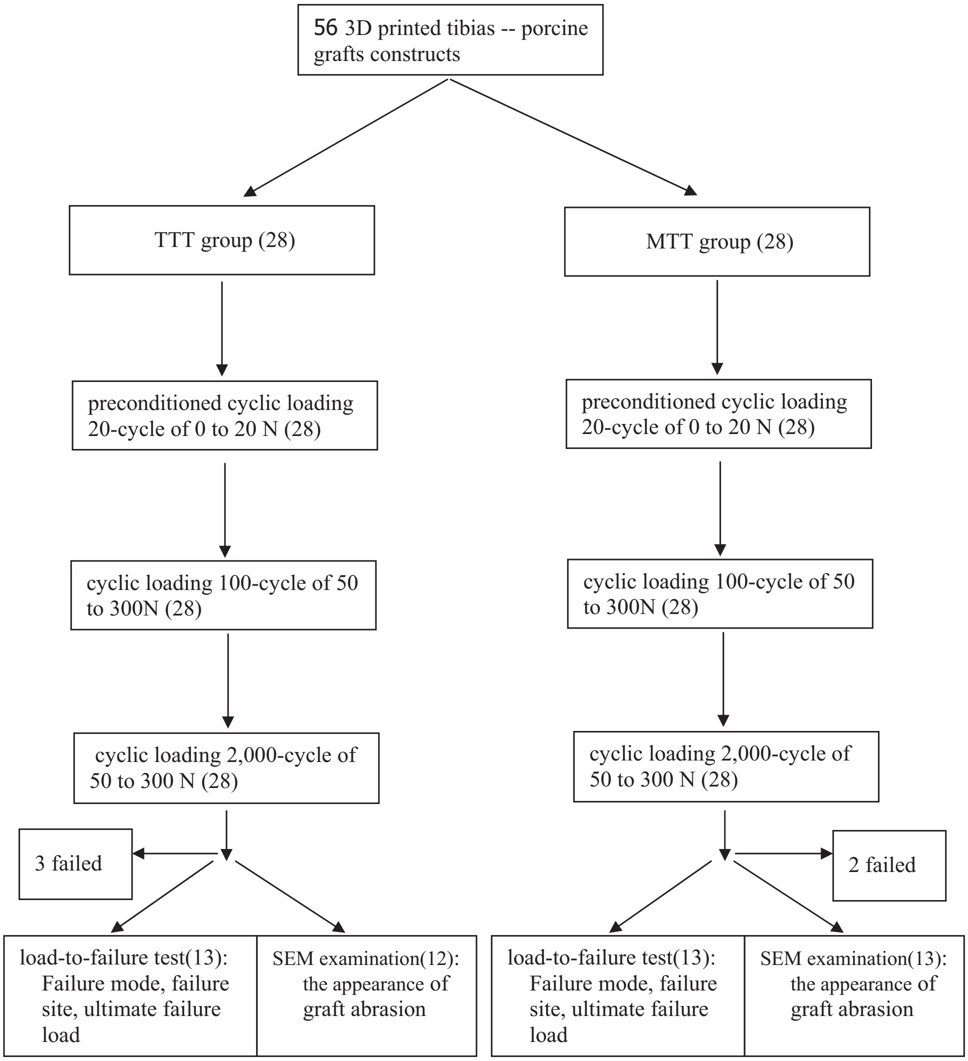

Figure 1. Testing protocol and data obtained.

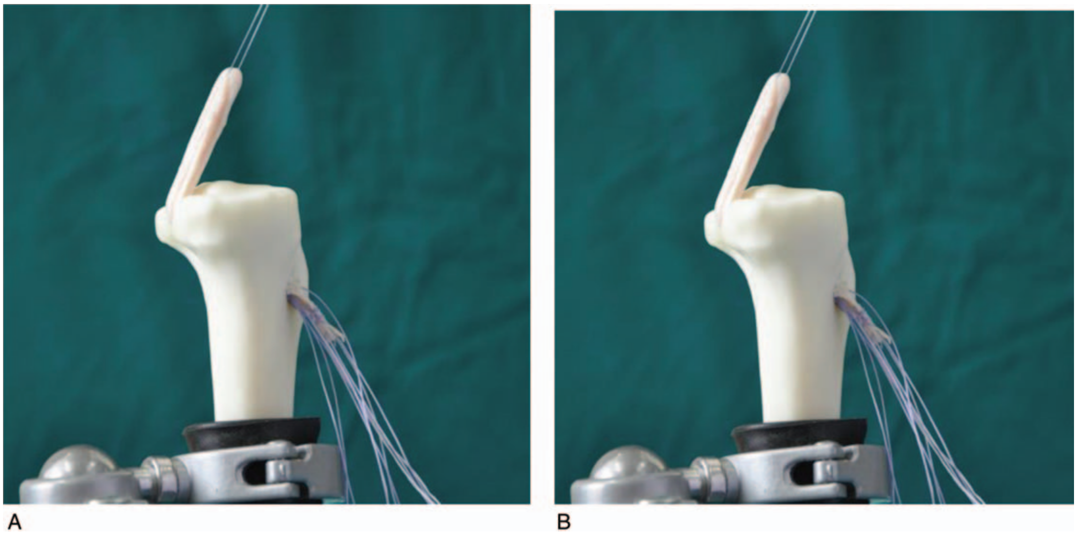

Figure 2. Photograph of TTT and MTT transtibial PCL reconstruction. MTT=modified tibial tunneling, PCL=posterior cruciate ligament, TTT=traditional tibial tunneling.

2.1. Testing protocol

A material testing machine (5565, Instron, Massachusetts) was used for the mechanical evaluation of the constructs. The distal tibia was rigidly fixed on a base platform using a custom-designed clamp. The angle of the tibial shaft could be adjusted, keeping the graft direction approximately 45° to the tibial plateau on the sagittal plane, to simulate the angle in physiological state[5,19,20] and the free graft loop was secured over a shackle bolt and then attached to a testing machine.

All grafts were cyclically preconditioned between 0 and 20 N at a rate of 200 mm/min for 20 cycles prior to testing. The graft constructs were then subjected to 2000 cycles between 50 and 300 N load (Fig. 3). The load is within the general range reported in previously published studies involving cyclic loading, and

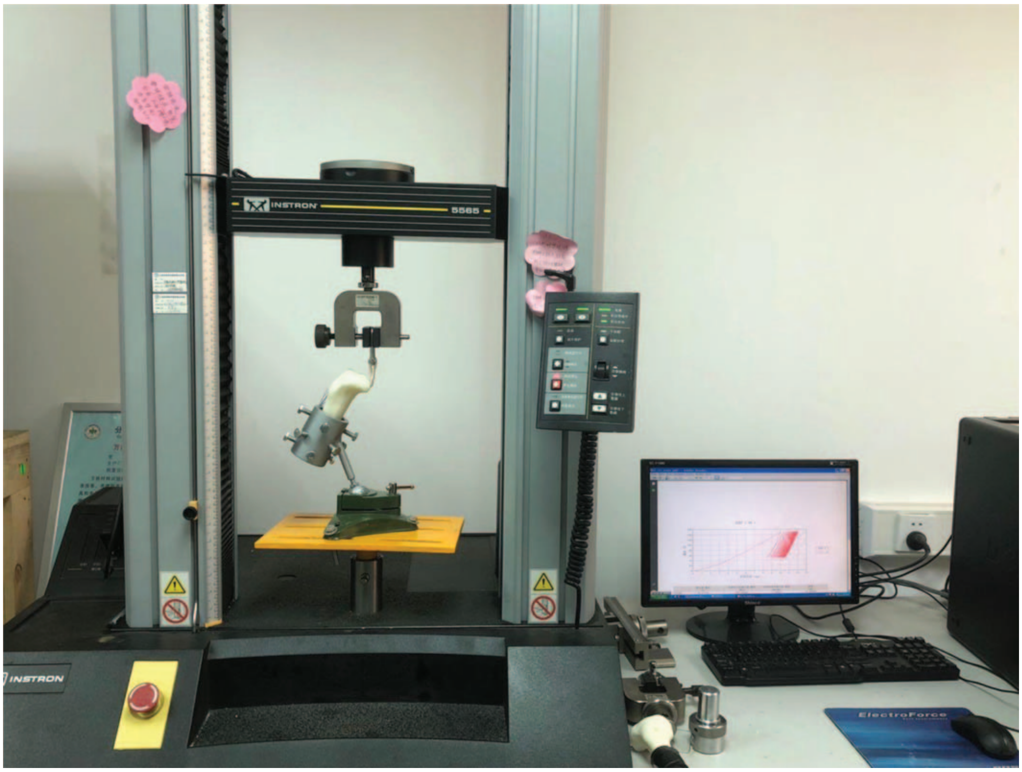

Figure 3. Photograph of the knee specimen used for cyclic loading test using a material testing system. The tibial fixture was adjusted, so that the pull on the free tendon end was at an angle of 45° relative to the tibial plateau.

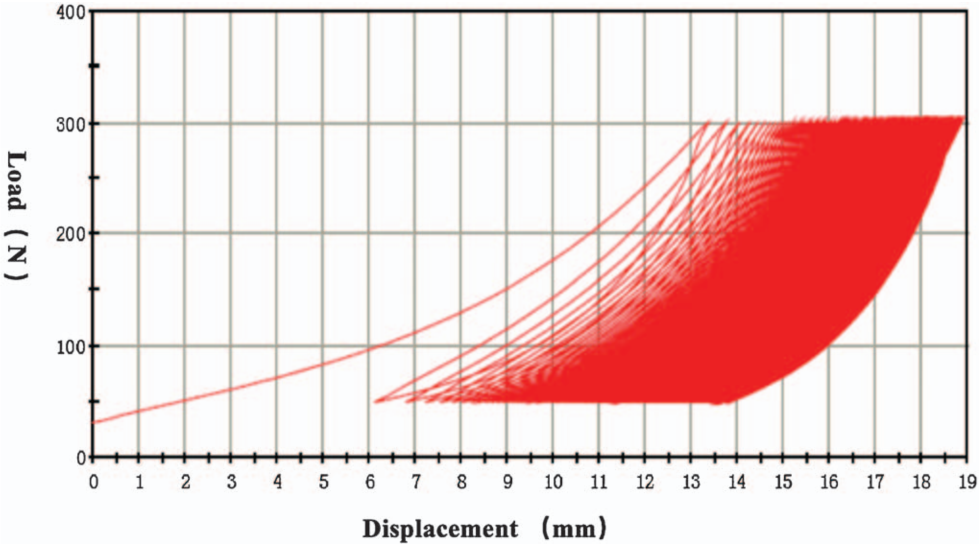

Figure 4. Load–displacement curves.

represents a relatively modest load level in terms of what is believed to occur during an aggressive rehabilitation protocol.[3,21] Cyclic loading was applied at a displacement rate of 200 mm/min and a loading frequency of 80 cycles/min. The loading frequency was similar to that reported in other studies and appears to be within a physiological range of loading. During testing, the graft was continuously moistened with physiologic saline solution. Load–displacement curves (Fig. 4) were continuously recorded during cyclic loading. Failure mode was also recorded in the test. Graft displacement was defined as the difference in graft position between the 20th cycle and the 2000th cycle at a loading of 50 N, which can be calculated from the load–displacement curves. Calculation from 20th cycle is done to reduce the influence of ligament creep and slip. All testing was done at room temperature. Each tibia and graft were used once for the test.

Before test, a pressure-sensitive film (Prescale LW; Fuji Photo Film, Tokyo, Japan) was used to measure local pressure.[22–26] The film was cut into 8 × 10 mm rectangular pieces and placed in the so-called "killer turn" (the tibial tunnel exit, point 1) in both groups and anatomic tibial insertion site of the PCL (point 2) in MTT group. The film was held in place for 100 cycles during tensile loading, and then pulled out for analysis using press analysis system (FUD-8010E). The reference point was checked several times during the experiment to ensure that the film had not moved.

After the cyclic loading test, the surviving grafts (Fig. 5) were randomly assigned to load-to-failure group or Scanning Electron Microscopy (SEM) group. In load-to-failure group, grafts were loaded to failure at a rate of 200 mm/min. Failure mode, failure site, and the ultimate failure load were recorded and analyzed. In SEM group, the graft adjacent to the tunnel exit point (killer turn) was cut off and prepared for SEM examination as described previously.[27] After the preparation, JEOL JSM-6400 SEM was used to study graft abrasion.

2.2. Statistics

Statistical analysis was performed using SPSS version 22.0 (SPSS Inc., Chicago, IL). Continuous data are expressed as mean ± standard deviation. The *t* test for 2 independent samples was used to analyze normally distributed data. The rank-sum test was used for data with heterogeneity of variance and non-normal distribution. Categorical data were compared using the chi-squared test.

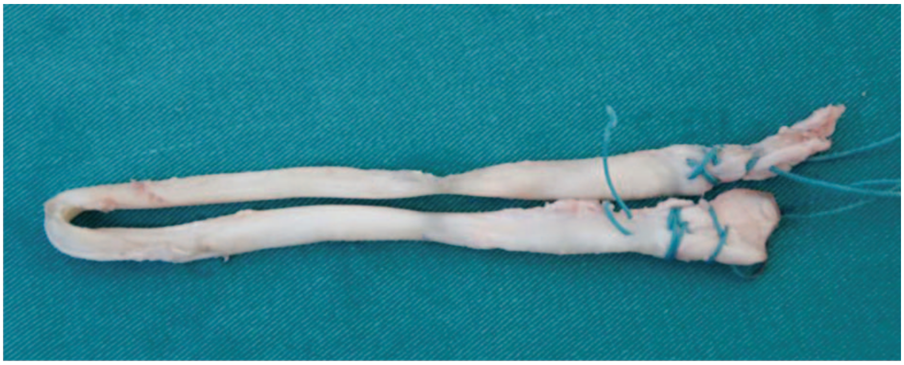

Figure 5. Appearance of graft abrasion after 2000 cycles of 50 to 300 N cyclic loading test.

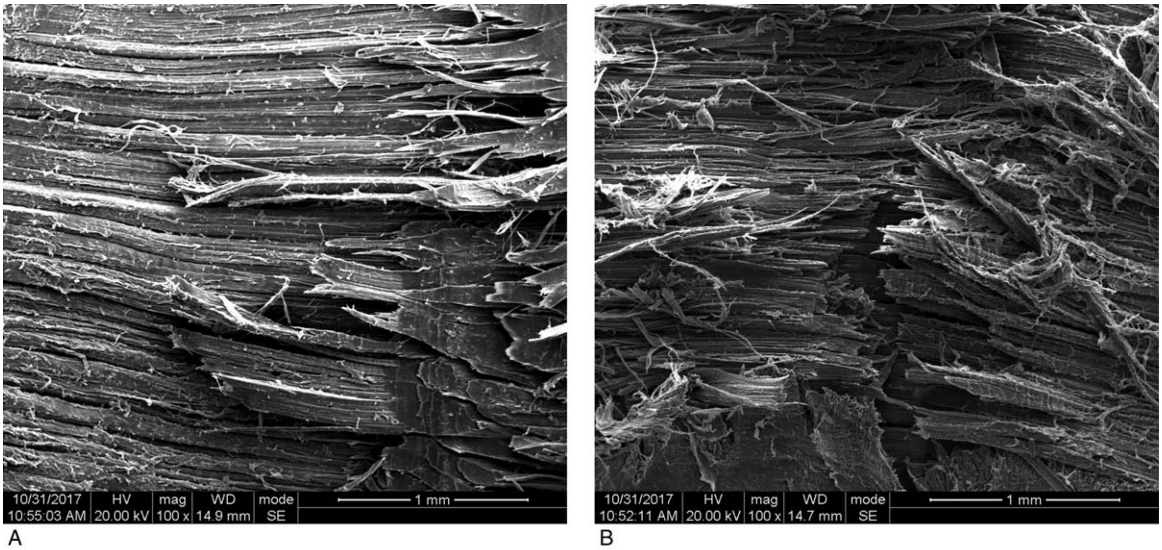

Figure 6. SEM pictures of graft after cyclic loading test showing slight abrasion and simply arranged disorders (A), and heavy abrasion and part of graft fiber discontinuity (B). SEM = Scanning Electron Microscopy.

All statistical analysis was performed on 2-sided tests. A P value of $<.05$ was considered as statistically significant.

3. Results

TTT group: Twenty-eight grafts underwent cyclic loading test and 3 samples were excluded because of the graft pullout during the test. During the follow-up period, 13 surviving grafts were assigned to load-to-failure test, and 12 to SEM examination. Mean maximum contact pressure was 9.30 ± 0.29 MPa and mean graft displacement was 4.54 ± 0.23 mm. Maximum mean failure load was 1886.0 ± 41.83 N. The graft showed heavy abrasion in SEM analysis, and a part of graft fiber showed discontinuity (Fig. 6A).

MTT group: Twenty-eight grafts underwent cyclic loading test and 2 samples were excluded because of the graft pullout during the test. During the follow-up period, 13 surviving grafts were assigned to load-to-failure test, and 13 to SEM examination. Mean maximum contact pressure on point 1 and point 2 was 7.27 ± 0.25 and 0.93 ± 0.05 MPa, respectively. Mean graft displacement and maximum mean failure load was 3.37 ± 3.56 mm and 2019.30 ± 20.10 N, respectively. The graft showed slight abrasion in SEM analysis, and the fibers showed arrangement disorders (Fig. 6B).

Statistically significant differences were observed in mean maximum contact pressure ($t=-28.037$, $P=.000$), mean graft displacement ($t=15.07$, $P<.0001$), and maximum mean failure load ($Z=-4.31$, $P<.0001$) (Table 1).

4. Discussion

The present study compared the biomechanical results between MTT and TTT PCL transtibial reconstruction. The results showed that MTT significantly reduced stress concentration and graft abrasion as compared with the TTT PCL reconstruction, which confirmed our first hypothesis and showed

Table 1

Results after cyclic loading and load-to-failure tests and SEM examination.

	MTT group	TTT group/*Z* value	*t* value	*P* value
Cyclic loading test				
Number	28	28		
Maximum contact pressure, MPa				
Point 1	7.27 ± 0.25	9.30 ± 0.29	–28.037[*]	.000
Point 2	0.93 ± 0.05			
Graft displacement, mm	3.37 ± 3.56	4.54 ± 0.23	15.07[*]	<.0001
Load to failure test				
Number	13	13		
Maximum mean failure load, N	2019.30 ± 20.10	1886.0 ± 41.83	–4.31[†]	<.0001
SEM examination				
Number	12	13		
Image	Graft fiber arranged disorders	Part of graft fiber showed discontinuity		

MTT = modified tibial tunneling, SEM = Scanning Electron Microscopy, TTT = traditional tibial tunneling.

[*] Group *t* test.

[†] Rank sum test.

that MTT technique can reduce the "killer turn" effect as compared with TTT.

We, for the first time, have used 4 indices simultaneously to show the killer turn effect. These include maximum contact pressure of killer turn, SEM appearance, graft displacement, and maximum load at failure. Maximum contact pressure of killer turn reflects a reasonable level of maximal graft compressive force during an exercise. SEM image and graft displacement show the degree of graft abrasion directly and indirectly, respectively. Maximum load at failure is used to explore the tensile strength. The results showed that the maximum contact pressure of MTT group on point 1 (killer turn) is much lower and graft abrasion is lighter than the TTT group during the cyclic loading test, and maximum contact pressure of point 2 in MTT group is too small to be counted. After the cyclic loading test, grafts in MTT group showed significantly higher elongation and lower mean maximum load at failure after surviving 2000 cycles when compared with the grafts in TTT group.

Surgeons often find it difficult to negotiate the killer turn while attempting transtibial PCL reconstruction. The killer turn may cause excess forces within the graft as it turns around the proximal margin of the tibial tunnel exit, thereby, producing abrasion, thinning, and permanent elongation of the graft. Clinically, it could result in increased posterior tibial laxity and construction failure. Theoretically, instead of placing the tibial guide in anatomical position, inferior lateral aspect could convert the acute angle between graft and tunnel to two smooth obtuse angles on the posterior aspect of the tibia. It could explain the reduction in local pressure and decreased abrasion in the killer turn. A smooth groove is present at the posterior lateral of the proximal tibia between posterior tibial intercondylar. The tibial tunnel exit is located on the groove, which is the extended line of anatomical axis of the PCL, along which the graft could pass the PCL's tibial footprint and go through the medial femoral condyle. It reduces the friction between the graft and the bone, thereby decreasing the killer turn, and preventing graft sliding. On the contrary, MTT tunnel inlet is outside of knee capsule, thus, it could avoid damage to the tibial attachment of the posterior capsule and PCL remnants.

Some other techniques have been elucidated in the literature to reduce the killer turn. One of these methods involves using an inlay technique, instead of a transtibial tunnel technique.[7–12] However, a recent study showed no clinically important differences between the transtibial and tibial inlay approach for PCL reconstruction.[10,13,14] Most surgeons prefer an arthroscopically drilled transtibial tunnel technique over an inlay technique to avoid an open procedure and position change during the procedure.[28–30] Another method is making a transtibial tunnel from the anterolateral cortex of the proximal tibia, which allows the surgeon to reduce the sharpness of the acute angle between the tibial tunnel and the intra-articular portion of the graft.[4,24] However, Ahn et al[31] have shown that the anterolateral approach resulted in a tunnel with a wider entrance, a more acute cortex-tunnel angle, and a lower maximal load at failure compared with tunnels created using the anteromedial approach. Another approach described in literature is reducing the killer turn in PCL reconstruction by fixation level and smoothing the tibial aperture,[3] wherein, aperture fixation of PCL graft is required on the femoral side of the graft.

Cyclic testing of cadaver and animal graft tissues has been reported previously, but the test parameters (applied force level, number of cycles, and test frequency) have varied considerably among studies.[3,5,7,21,31–35] Given the relatively wide range of test conditions reported in the literature, we selected a lower load level of 50 N, representing a reasonable level of minimum force in the graft from pretension and an upper load limit of 300 N, representing a relatively during an aggressive rehabilitation program. This is in accordance with previous studies evaluating transtibial PCL reconstructions.[3,35] Although a clinical study has shown that enlargement of tunnel inlet may be a factor underlying the mechanism of "killer turn" causing residual laxity after transtibial PCL reconstruction,[5,36] it couldn't be observed in in vitro biomechanical study. Enlargement of tunnel inlet may occur in the process of tendon-bone healing in vivo because of stress imbalance and abrasion between bone and graft but cannot be seen in vitro. The present study did not measure the tunnel inlet enlargement.

Our study has the following limitations. First, because it is very difficult to obtain fresh cadaver knees in our country, we used 3D-printed tibia models and porcine flexor digitorum tendons in this study. However, 3D-printed tibia models (metal powders) could provide a satisfactory anatomy reproduction and biomechanical properties for us. In addition, both 3D printed tibia and bone are harder than ligaments. In the friction between tendons and bones or 3D printed tibias, it is tendons, not bones or 3D printed tibias, that are worn. Therefore, the use of this material has little impact on the conclusions of this study. The anatomy and function of the cruciate ligament have been reported to be the same between the human and the porcine.[37] Second, this is an in vitro study evaluating the biomechanical properties, which cannot fully simulate the nature of the in vivo environment for a patient undergoing PCL reconstruction in an ideal model. However, our research series consists of 3 parts. We have completed the first part of the three-dimensional finite element study. This is the second part of the in vitro physiology. Next, we will perform clinical research to validate our findings.

In conclusion, MTT PCL reconstruction significantly reduced stress concentration and graft abrasion as compared with the TTT PCL reconstruction, and it may be a better choice to reduce the "killer turn" effect during transtibial PCL construction.

Author contributions

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Supervision: Jian Li, Xin Tang.
Visualization: Xiaoke Shang.
Writing – original draft: Zhiqiang Wang.
Writing – review & editing: Zhong Zhang, Yaxiaer Sulaiman Xin Tang.

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