ORIGINAL RESEARCH

Application of 3D-Printed Personalized Guide for Lateral Femoral Positioning in Anterior Cruciate Ligament Reconstruction of the Knee

Xiaoquan Lan, MMed; Jiajun Huang, MMed; Fangxiao Tian, MMed;
Sizhe Wang, MMed; Caijuan Liu, MMed; Jinyu Wang, MD

ABSTRACT

Objective • This research aims to investigate the effectiveness of 3D computer-assisted customized guided positioning of the lateral femoral tunnel compared to conventional methods for Anterior Cruciate Ligament (ACL) reconstruction surgery.

Methods • A total of 80 patients with a complete ACL tear who underwent arthroscopic reconstruction with autologous tendon transplantation (semitendinosus-gracilis tendon) were included in this study. The patients were admitted to our hospital between March 2020 and January 2022 and were randomly divided into two groups: the conventional group (n = 40) and the personalized guide group (n = 40), based on the positioning method. The conventional group underwent ACL restoration using standard surgical techniques, while the personalized guide group opted for the more precise computer-assisted personalized guide method. The lateral femoral tunnel times were compared between both groups. Additionally, the International Knee Documentation Committee (IKDC) and Lysholm scores were assessed, and the lateral femoral location was evaluated using X-ray imaging at 2 weeks postoperatively.

Results • After surgery, both groups showed a statistically significant increase ($P < .05$) in Lysholm and IKDC scores compared to their pre-surgery scores. However, the two groups had no evident difference ($P > .05$). X-ray evaluation at 2 weeks post-surgery revealed no significant difference between the two groups in NL/ML, AL/BL, α, and β angles ($P > .05$). The preparation time for the femoral tunnel was significantly shorter in the personalized guide group (6.18 ± 0.92 min) compared to the traditional group (15.94 ± 3.12 min) ($P < .05$).

Conclusions • The computer-assisted 3D personalized guide positioning method is more effective in locating the lateral femoral tunnel for ACL reconstruction of the knee and can substantially reduce the positioning time. This study provides valuable insights for clinicians when selecting surgical methods. (*Altern Ther Health Med.* 2023;29(7):360-364).

Xiaoquan Lan, MMed, 3D Printing Clinical Medical Transformation Center; **Jiajun Huang, MMed,** Department of Trauma Microsurgery; **Fangxiao Tian, MMed,** Post medical Follow up Office; **Sizhe Wang, MMed; Jinyu Wang, MD;** Department of Joint and Sports Medicine; **Caijuan Liu, MMed,** Quality Control Office; Chengyang District People's Hospital, Shandong Province, Qingdao, China.

Corresponding author: Jinyu Wang, MD
E-mail: qdcy3d@163.com

INTRODUCTION

The anterior cruciate ligament (ACL) plays a vital role in maintaining knee stability.[1,2] ACL injuries are highly prevalent among articular ligament injuries, with an estimated 100 000 to 200 000 cases per year in the United States.[3,4] If left untreated, ACL injuries can result in knee instability, meniscus, and cartilage degeneration and may eventually lead to serious complications such as osteoarthritis, significantly impacting the individual's quality of life.[5-8] Therefore, repairing the damaged ACL and restoring knee stability is crucial. However, a challenge in ACL repair lies in accurately locating the femoral tunnel.[9-11]

3D printing, also known as additive manufacturing, is a cutting-edge technology that constructs three-dimensional objects layer by layer based on digital models, enabling precise and customized fabrication in various fields, including medicine and surgery.[8-10] Incorporating 3D printing in ACL surgery allows for the creation of personalized guides that enhance surgical accuracy and improve patient outcomes.[10-11] This advancement can transform the process from relying solely on the operator's experience in traditional surgery to implementing computer-assisted precise positioning. Therefore, this research utilizes 3D printing technology in ACL restoration surgery, integrating computed tomography

(CT) and magnetic resonance imaging (MRI) scans to determine the location of the lateral femoral tunnel precisely. The following section elaborates on this innovative approach.

MATERIALS AND METHODS

Study Design and Patient Selection

A total of 80 patients admitted to our hospital between March 2020 and January 2022, diagnosed with a complete ACL tear, underwent arthroscopic reconstruction with autologous tendon transplantation (semitendinosus-gracilis tendon). Based on the positioning method, these patients were randomly divided into two groups: the conventional group (n = 40) and the personalized guide group (n = 40). The conventional group comprised 25 males and 15 females, aged between 19 and 40, with a mean age of 28. On the other hand, the personalized guide group consisted of 26 males and 14 females, with a mean age of 26 and ages ranging from 19 to 37.

Inclusion and Exclusion Criteria

Inclusion criteria were as follows: (1) Patients diagnosed with a complete ACL rupture preoperatively using MRI and demonstrated positive outcomes in the Lachman, anterior drawer, and pivot shift tests; (2) patients without bone deformities in other knee-joint examinations, those hospitalized for more than 1 week after surgery; (3) and those followed up for a full year were included in the study. Exclusion criteria: those who did not meet the inclusion criteria were excluded from this study.

The conventional and personalized guide groups had similar distributions of gender and age, with no statistically significant differences observed ($P > .05$). This study received ethical approval from the hospital's Ethics Committee, and all patients provided informed consent.

3D Printing and Personalized Guide Creation

In the personalized guide group, arthroscopic ACL reconstruction was performed using a 3D-printed personalized guide. A 64-row spiral CT scan and MRI were conducted on the affected knee. The CT and MRI scans were saved in the "DICOM" format and used in conjunction with 3D reconstruction software (Mimics) to generate a 3D model of the knee joint, which was saved in "STL" format. Utilizing the dynamic region generation function of the Mimics software, a preliminary computer-assisted design 3D model of the patient's knee was created. The lateral femoral tunnel localization points were selected, and the relevant parameters were measured during this process.

Modeling Using the 3D Printing. The personalized guide model was designed using 3D-StudioMax software, and the final model was then exported in "STL" file format. The modeling process involved using removable molding plates with a patented fused deposition molding technique to create personalized guide plates and supporting materials. Once the 3D printing process was completed, the printed guide was carefully removed from the working chamber, and the supporting materials were removed.[12,13]

Surgical Procedures

The conventional anterolateral anteromedial approach was used in both groups to access the knee joint. The ipsilateral semitendinosus and gracilis tendons were combined into a single bundle of four strands. For tendon fixation, the Endo button was employed at the external entrance of the femoral tunnel, while extrusion screw fixation and portal screw fixation were used for the tibial tunnel.

Personalized Guide Group. In the personalized guide group, the knee joint was partially cleaned under the arthroscope, and the preoperatively designed and 3D-printed personalized guide plate was placed at 90° of knee flexion. A Kirschner wire served as a guide to drill and position the femoral tunnel. A tibial guide apparatus was used to drill the tunnel on the tibial side. The autologous tendon was smoothed through repeated knee flexion and extension. The tendon, secured with an Endo button collar plate, was then fed into the bone tunnel, and traction was applied to the tendon guideline at the outer tibial tunnel for fixation.

Conventional Group. In the conventional group, the footprint center method was employed to locate the lateral femoral tunnel of the ACL during the surgery. The rest of the surgery was performed similarly to the personalized guide group.

Postoperative Rehabilitation

Following the surgery, ankle pump exercises were initiated as soon as the anesthesia wore off on the day of the surgery. Patients began quadriceps isometric contraction and straight-leg-raising exercises on the first postoperative day. Subsequently, the knee was immobilized in the extension position using a knee brace. Passive knee flexion training commenced 2 weeks after the surgery, starting at 0°~30° and increasing by 30° per week until reaching 120°.

Observation Indicators

(1) Lateral femoral tunnel preparation time: The time taken to prepare the lateral femoral tunnel during the procedure was meticulously recorded; (2) Postoperative knee function evaluation: Postoperative knee function was assessed using the Lysholm Knee Scoring Scale (Lysholm score) and the International Knee Documentation Committee (IKDC) score before the surgery and at three, six, and twelve months following the surgery; (3) Assessment of lateral femoral tunnel positioning: The positioning of the lateral femoral tunnel was evaluated using X-ray imaging two weeks after the surgery.

Measurement Protocol. Several parameters were determined based on the orthopantomography of the knee: (1) ML: length of the femoral condyle; (2) NL: distance between the lateral femoral stop of the reconstructed ACL and the edge of the lateral femoral condyle; and (3) α: angle between the horizontal line of the knee joint and the midline of the lateral femoral tunnel.

On the lateral knee film, (1) BL: length of the Blumensaat line; (2) AL: distance from the lateral femoral stop of the

Table 1. Lysholm score ($\bar{x}$ ± s, points/points) comparison between the two sets of participants.

Groups	Before The Surgery	3 Months After The Surgery	6 Months After The Surgery	12 Months After The Surgery
Regular Group	42.23 ± 2.73	93.13 ± 1.17	93.77 ± 1.07	94.90 ± 0.97
Personalized Guide Group	42.47 ± 1.94	93.23 ± 1.22	93.83 ± 1.15	94.60 ± 0.80
t	0.38	0.32	0.23	1.31
P value	>.05	>.05	>.05	>.05

Note: The "*t*" value represents the *t*-test results for independent samples, while "*P*" indicates the level of statistical significance. A *P*-value greater than .05 indicates no statistically significant difference between the two groups at each time point.

Table 2: The IKDC scores of the two groups were compared ($\bar{x}$ ± s, points/points).

Group	Before The Surgery	3 Months After The Surgery	6 Months After The Surgery	12 Months After The Surgery
Regular Group	45.03 ± 3.44	93.87 ± 1.20	94.03 ± 1.25	94.87 ± 1.11
Personalized Guide Group	44.36 ± 3.50	93.77 ± 1.30	94.17 ± 1.05	95.03 ± 1.00
t	0.45	0.31	0.45	0.61
P	>.05	>.05	>.05	>.05

Note: The "*t*" value represents the *t*-test results for independent samples, while "*P*" indicates the level of statistical significance. A *P*-value greater than .05 suggests no statistically significant differences between the two groups regarding IKDC scores at each time point.

reconstructed ACL to the intercondylar fossa of the femur over the apex of the intercondylar fossa's line; and (3) the angle formed by the long axis of the femoral stem and the centerline of the femoral attempt were measured. The location of the ACL femoral stop in the orthogonal slice was denoted as NL/ML, while the lateral slice location was indicated by AL/BL.[14]

Reliability of Measurements. Two specialized physicians measured all indicators for each patient to ensure accuracy and reliability, and their measurements were then averaged to obtain the final result. When the difference between the measurements of the two specialized physicians exceeded 5%, a specialized professor with a senior title was consulted to perform the measurements, and any discrepancies were resolved.

Statistical Analysis

The data analysis was conducted using SPSS Statistics 25.0 (IBM, Armonk, NY, USA). Kolmogorov-Smirnov tests were performed to ensure the homogeneity of data. The t-test for independent samples (Student's *t* test) was employed to compare the two groups. Normally distributed measurement values were reported as mean ± standard deviation ($\bar{x}$ ± s). For categorical data, the chi-squared test (χ^2 test) was utilized, and the results were presented as [n (%)]. The level of statistical significance was set at $P < .05$.

RESULTS

Incidence of Complications

The surgical procedure proceeded smoothly in both groups, and no intraoperative or postoperative complications were observed.

Postoperative Evaluation of Lysholm and IKDC Scores

Following the surgery, the Lysholm and IKDC scores of both groups showed a significant increase compared to the pre-surgery scores, with a statistically significant difference ($P < .05$). However, there was no statistically significant difference in postoperative scores between the two groups ($P > .05$); refer to Tables 1 and Table 2.

Table 3. Comparison of lateral femoral positioning after the surgery in the two groups ($\bar{x}$ ± s)

Groups	NL/ML	AL/BL	α/°	β/°
Regular Group	0.55 ± 0.02	0.32 ± 0.02	48.09 ± 1.56	31.50 ± 2.24
Personalized Guide Group	0.56 ± 0.02	0.32 ± 0.01	47.97 ± 1.73	31.98 ± 2.29
t	-1.397	-1.303	0. 290	-0.816
P value	>.05	>.05	>.05	>.05

Note: The table presents the mean values ($\bar{x}$) and standard deviations (s) of the lateral femoral positioning parameters NL/ML, AL/BL, α/°, and β/° for both groups. NL/ML: represents the measurement of the lateral femoral positioning of the reconstructed anterior cruciate ligament (ACL) femoral tunnel in relation to the medial side of the femur; AL/BL: represents the measurement of the lateral femoral positioning of the reconstructed ACL femoral tunnel in relation to the intercondylar fossa of the femur; α/°: represents the angle formed by the long axis of the femoral stem and the centerline of the femoral tunnel; β/°: represents the angle formed by the horizontal line of the knee joint and the midline of the lateral femoral tunnel.

Table 4. Comparison of the time required for preparing the femoral tunnel ($\bar{x}$ ± s)

Group	Time required for preparing the femoral tunnel
Regular Group	15.94 ± 3.12
Personalized Guide Group	6.18 ± 0.92
t	18.94
P value	<.05

Note: The table provides the meantime ($\bar{x}$) and standard deviation (s) taken for preparing the femoral tunnel in both groups. The "*t*" value represents the *t* test results for independent samples, while "*P*" indicates the level of statistical significance. A *P*-value less than .05 indicates a statistically significant difference between the two groups in terms of the time required for femoral tunnel preparation.

Evaluation of Lateral Femoral Positioning

At 2 weeks after the surgery, the lateral femoral positioning of the two groups was assessed using X-ray imaging. There was no discernible difference in NL/ML and AL/BL angles between the two groups ($P > .05$); refer to Table 3.

Time for Femoral Tunnel Preparation

Table 4 demonstrates that the time required for preparing the femoral tunnel in the personalized guide group (6.18 ± 0.92 min) was significantly lower than that of the conventional group (15.94 ± 3.12 min), with a statistically significant difference ($P < .05$).

DISCUSSION

Traditional ACL reconstruction is widely regarded as the standard approach, often referred to as the "gold standard," due to its long-standing use and established efficacy.[13] Isometric reconstruction is the preferred technique within traditional ACL reconstruction as it has been shown to provide improved knee stability.[13] However, one important drawback is that it may not fully address rotational stability.[14] On the other hand, the anatomic reconstruction of the ACL emphasizes restoring the ligament graft to its original footprint area with precise diameter and orientation of the tunnel. It improves the anterior-posterior and rotational stability, restoring the knee's normal function.[15,16]

After anatomic reconstruction, ligament repair becomes faster, more durable, and has the potential to cover a larger region of the knee's footprint. This restoration allows for the re-restoration of the ACL's original starting and ending points and its original direction, ultimately contributing to improved knee function.[17] Focusing on these aspects of the reconstruction, anatomic techniques offered the potential for improved outcomes and better restoration of knee function compared to traditional approaches.

The 3D printed model offers a comprehensive view of the fracture status and enables the design of surgical plans to enhance precision and reduce operative time before surgery. Scholars have demonstrated effective clinical results in previous studies using a scale-type 3D-printed guide to assist in cervical pedicle screw fixation.[18] Similarly, in patients with initial joint replacement and lateral femoral extra-articular deformity, 3D printing technology has been shown to simplify the procedure and shorten operative time.[19] The successful application of 3D printing techniques presents new possibilities for precisely positioning the lateral ACL femoral tunnel.

Our study used a combination of 3D CT and MRI to create the patient's knee model on the computer. The reference point for the ACL femoral stop and the tunnel direction were determined based on this computer model. Subsequently, a personalized tunnel guide was designed and 3D printed to determine the femoral tunnel during the surgery. The surgical procedures in both groups proceeded smoothly, with no complications during or after the surgery. Furthermore, the postoperative results, including the Lysholm score, IKDC score, and lateral femoral placement data, showed no statistically significant differences between the two groups.

The group that used personalized guidance exhibited significantly shorter preparation times for the femoral tunnel. This improvement in efficiency during surgery is very beneficial because it reduces the time needed for femoral tunnel preparation. The application of computer-assisted 3D printing technology helps avoid the need for repeated tunnel positioning during surgery, which can occur when relying solely on the surgeon's experience in traditional approaches. Moreover, this technology allows for better control of the tunnel direction, which helps lower the risk of damaging the posterior cortex as the tunnel is too close to the lateral femoral condyle. Consequently, the use of 3D printing technology contributes to reduced surgical trauma.[20] In our study, the personalized guidance group had a significantly shorter preparation time for the femoral tunnel, which improved the surgery efficiency by reducing the time needed for femoral tunnel preparation.

Our results showed that the personalized guidance group experienced significantly shorter preparation time for the femoral tunnel, improving efficiency in surgery. The use of 3D printing technology allowed for better control of the tunnel direction, thereby reducing the risk of damaging the posterior cortex and other complications. These findings support the application of computer-assisted 3D printing technology as a promising approach to enhance surgical precision and reduce operative time in ACL reconstruction, offering new insights for clinicians in selecting surgical methods.

Study Limitations and Future Implications

The primary limitations of the our study include the relatively small sample size and the relatively short follow-up time. These factors may introduce potential bias in the results, and the generalizability of the findings may be limited. To address the limitations and expand on the findings of this study, future research should consider conducting studies with larger sample sizes and longer follow-up periods. Implementing a multicenter approach could enhance the reliability and applicability of the results to a broader population. By addressing these factors, future studies can provide more robust evidence and further validate the effectiveness of computer-assisted 3D printing technology in ACL reconstruction surgery. It may lead to wider adoption and application of this technology in clinical settings, potentially improving surgical outcomes and patient care.

CONCLUSION

In conclusion, using 3D printing technology in ACL restoration surgery for positioning the lateral femoral tunnel has proven effective and efficient, resulting in a significant reduction in positioning time. This study highlights the potential benefits of incorporating 3D printing technology in surgical procedures, providing valuable insights for clinicians and paving the way for further advancements in the field of ACL reconstruction. The promising results encourage future research and implementation of this technique to optimize surgical outcomes and enhance patient care.

DATA AVAILABILITY

The data used to support this study is available from the corresponding author upon request.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

AUTHORS' CONTRIBUTIONS

All authors contributed equally; they read and approved the final manuscript.

FUNDING

No funding was received for this study.

REFERENCES

1. Maniar N, Cole MH, Bryant AL, Opar DA. Muscle Force Contributions to Anterior Cruciate Ligament Loading. [J]. *Sports Med*. 2022;52(8):1737-1750. doi:10.1007/s40279-022-01674-3
2. Nuelle CW, Balldin BC, Slone HS. All-Inside Anterior Cruciate Ligament Reconstruction. [J]. *Arthroscopy*. 2022;38(8):2368-2369. doi:10.1016/j.arthro.2022.06.001
3. Kaeding CC, Léger-St-Jean B, Magnussen RA. Epidemiology and Diagnosis of Anterior Cruciate Ligament Injuries. [J]. *Clin Sports Med*. 2017;36(1):1-8. doi:10.1016/j.csm.2016.08.001
4. Murray MM. Optimizing outcomes of ACL surgery-Is autograft reconstruction the only reasonable option? [J]. *J Orthop Res*. 2021;39(9):1843-1850. doi:10.1002/jor.25128
5. Wang LJ, Zeng N, Yan ZP, Li JT, Ni GX. Post-traumatic osteoarthritis following ACL injury. [J]. *Arthritis Res Ther*. 2020;22(1):57. doi:10.1186/s13075-020-02156-5
6. Sepúlveda F, Sánchez L, Amy E, Micheo W. Anterior Cruciate Ligament Injury: Return to Play, Function and Long-Term Considerations. [J]. *Curr Sports Med Rep*. 2017;16(3):172-178. doi:10.1249/JSR.0000000000000356
7. Beard DJ, Davies L, Cook JA, et al; ACL SNNAP Study Group. Rehabilitation versus surgical reconstruction for non-acute anterior cruciate ligament injury (ACL SNNAP): a pragmatic randomised controlled trial. [J]. *Lancet*. 2022;400(10352):605-615. doi:10.1016/S0140-6736(22)01424-6
8. Saueressig T, Braun T, Steglich N, et al. Primary surgery versus primary rehabilitation for treating anterior cruciate ligament injuries: a living systematic review and meta-analysis. [J]. *Br J Sports Med*. 2022;56(21):1241-1251. doi:10.1136/bjsports-2021-105359
9. Van Der Bracht H, Tampere T, Beekman P, et al. Peak stresses shift from femoral tunnel aperture to tibial tunnel aperture in lateral tibial tunnel ACL reconstructions: a 3D graft-bending angle measurement and finite-element analysis. [J]. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(2):508-517. doi:10.1007/s00167-017-4739-8
10. Clatworthy M, Sauer S, Roberts T. Transportal central femoral tunnel placement has a significantly higher revision rate than transtibial AM femoral tunnel placement in hamstring ACL reconstruction. [J]. *Knee Surg Sports Traumatol Arthrosc*. 2019;27(1):124-129. doi:10.1007/s00167-018-5036-x
11. Balendra G, Jones M, Borque KA, Willinger L, Pinheiro VH, Williams A. Factors affecting return to play and graft re-rupture after primary ACL reconstruction in professional footballers. [J]. *Knee Surg Sports Traumatol Arthrosc*. 2022;30(7):2200-2208. doi:10.1007/s00167-021-06765-8
12. Ganapathy A, Chen D, Elumalai A, et al. Guide for starting or optimizing a 3D printing clinical service. [J]. *Methods*. 2022;206(15):41-52. doi:10.1016/j.ymeth.2022.08.003
13. Henckel J, Holme TJ, Radford W, Skinner JA, Hart AJ. 3D-printed Patient-specific Guides for Hip Arthroplasty. [J]. *J Am Acad Orthop Surg*. 2018;26(16):e342-e348. doi:10.5435/JAAOS-D-16-00719
14. Budny J, Fox J, Rauh M, Fineberg M. Emerging trends in anterior cruciate ligament reconstruction [J]. *J Knee Surg*. 2017;30(1):63-69. doi:10.1055/s-0036-1579788
15. Desai N, Alentorn-Geli E, van Eck CF, et al. A systematic review of single- versus double-bundle ACL reconstruction using the anatomic anterior cruciate ligament reconstruction scoring checklist. [J]. *Knee Surg Sports Traumatol Arthrosc*. 2016;24(3):862-872. doi:10.1007/s00167-014-3393-7
16. Hofbauer M, Muller B, Murawski CD, van Eck CF, Fu FH. The concept of individualized anatomic anterior cruciate ligament (ACL) reconstruction. [J]. *Knee Surg Sports Traumatol Arthrosc*. 2014;22(5):979-986.
17. Kaur M, Ribeiro DC, Theis JC, Webster KE, Sole G. Movement Patterns of the Knee During Gait Following ACL Reconstruction: A Systematic Review and Meta-Analysis. [J]. *Sports Med*. 2016;46(12):1869-1895. doi:10.1007/s40279-016-0510-4
18. Guo F, Dai J, Zhang J, et al. Individualized 3D printing navigation template for pedicle screw fixation in upper cervical spine. [J]. *PLoS One*. 2017;12(2):e0171509. doi:10.1371/journal.pone.0171509
19. Cui D, Yan F, Yi J, et al. Efficacy and safety of 3D printing-assisted percutaneous nephrolithotomy in complex renal calculi. [J]. *Sci Rep*. 2022;12(1):417. doi:10.1038/s41598-021-03851-2
20. Cheng CH, Chuang HY, Lin HL, Liu CL, Yao CH. Surgical results of cranioplasty using three-dimensional printing technology. [J]. *Clin Neurol Neurosurg*. 2018;168:118-123. doi:10.1016/j.clineuro.2018.03.004