3D Printing in Medicine

CASE REPORT

Open Access

Patient-specific 3D tibial model: transforming meniscal allograft transplantation and surgical planning

Paula Andrea Sarmiento Riveros[1], Alejandro Jaramillo Quiceno[2] and Rubén Darío Arias Pérez[3*]

Abstract

Background Meniscal allograft transplantation (MAT) restores knee function by replacing a damaged or absent meniscus with a healthy allograft, helping to preserve joint stability, distribute the load, and reduce cartilage degeneration. However, traditional 2D imaging techniques fail to fully capture the knee's complex three-dimensional anatomy, making accurate surgical planning challenging. Computed Tomography (CT)-based 3D printing offers a patient-specific solution by generating anatomically precise tibial models, allowing for enhanced preoperative planning. This is particularly valuable in complex cases involving tibial osteotomy and anterior cruciate ligament (ACL) reconstruction, where precise tunnel positioning is critical to avoid tunnel convergence and ensure optimal graft integration.

Case presentation We present a case study and methodology demonstrating the generation and application of 3D-printed tibial models to assist in MAT, ACL reconstruction, and tibial osteotomy. High-resolution CT scans (slice thickness < 1 mm) were processed using D2P software to create a full-scale 3D model, which was printed using Hyper PLA filament. The 3D-printed model was provided to the tissue bank to optimize meniscal allograft selection and was integrated into preoperative planning to precisely determine tibial tunnel locations and angles, preventing overlap between MAT, ACL tunnels, and the osteotomy site. Intraoperatively, the model served as an accurate physical guide, facilitating osteophyte removal, guided tunnel drilling, and precise meniscal graft placement. Its use improved graft sizing accuracy minimized tunnel convergence, and allowed real-time intraoperative adjustments, which can improve surgical precision and decision-making.

Conclusions The integration of patient-specific 3D-printed models into surgical planning and execution may improve accuracy and efficiency in complex MAT procedures that also involve tibial osteotomy and ACL reconstruction. These models offer detailed anatomical reference points that facilitate more precise graft selection, tunnel placement, and intraoperative decision-making. However, further studies are needed to validate their dimensional accuracy, evaluate clinical outcomes in larger cohorts, and determine their feasibility for routine use in orthopedic practice.

Keywords Three-Dimensional printing, Knee, Meniscal allograft transplantation, Osteotomy, Anterior cruciate ligament reconstruction

*Correspondence:
Rubén Darío Arias Pérez
ruben.arias@upb.edu.co
[1]Knee surgeon, Clinica del Campestre, Medellín, Colombia
[2]Knee surgeon, Salud Sura, Medellín, Colombia
[3]Orthopedic and traumatology resident of Pontifical Bolivarian University, Medellín, Colombia

Background

Meniscal allograft transplantation (MAT) replaces damaged or absent meniscus with a healthy allograft, helping to restore knee function, preserve joint stability, distribute load, and reduce cartilage degeneration [1]. Meniscal loss leads to significant biomechanical disruption, increasing articular cartilage loading, instability, and the risk of early osteoarthritis [2, 3].

The success of MAT relies heavily on accurate preoperative planning, as proper graft sizing and precise placement are essential for restoring normal knee biomechanics and function [4, 5]. To achieve optimal outcomes, the meniscal graft must closely replicate the patient's native meniscus, ensuring effective load distribution and joint stability [2, 5].

Traditionally, surgeons have relied on two-dimensional (2D) imaging techniques, such as magnetic resonance imaging (MRI) and X-rays, to estimate meniscal size. However, these methods often fail to capture the complex three-dimensional (3D) anatomy of the knee, leading to imprecise graft sizing and suboptimal outcomes [6, 7].

When the graft is too tiny, it places excessive pressure on the tibiofemoral joint, accelerating wear and increasing the chances of early graft failure. On the other hand, an oversized graft can lead to impingement and extrusion, where the graft shifts out of place, resulting in joint overloading and potential failure [2]. Thus, achieving an accurate graft size is essential to reduce complications and ensure the graft's long-term success [2].

Computed tomography (CT) imaging provides a three-dimensional view of the tibial plateau, enabling exact measurements, typically within 2 mm of the actual size, 71.9% of the time—an improvement over the traditional method [6, 7]. This enhanced accuracy helps prevent graft size mismatches. It has been estimated that 3D models can reduce outliers in graft selection by up to 83%, significantly minimizing the risk of surgical complications and improving overall outcomes [8].

Filament 3D printing technology presents a cost-effective solution for constructing and replicating bone models from CT data [9]. Developing detailed 3D models of the proximal tibia provides a valuable resource for preoperative planning and surgical decision-making. Patient-specific models allow for more precise allograft selection and placement, increasing the chances of a successful outcome [10, 11].

This study examines the use of 3D-printed proximal tibia models to enhance surgical planning and decision-making in MAT, particularly in complex cases requiring additional procedures such as ACL reconstruction and tibial osteotomy.

Case presentation

Patient

A 35-year-old male patient with 8-degree genu varum and a history of partial medial meniscectomy and anterior cruciate ligament (ACL) reconstruction now presents after a new traumatic episode, resulting in a complex, irreparable medial meniscus tear and ACL rupture. Imaging reveals grade II Kellgren-Lawrence osteoarthritis, with no evidence of tunnel enlargement. Given his condition, the indicated surgical plan includes medial MAT, open-wedge valgus high tibial osteotomy, and revision ACL reconstruction.

3D model creation process

A CT scan of the affected knee with slice thicknesses of 0.7 mm was required. The patient's imaging data was extracted from medical records in the form of DICOM (Digital Imaging and Communication in Medicine) files. To protect patient privacy, these files were anonymized and stored in a secure, protected location. The DICOM files were then imported into D2P™ software (version 1.0.5), though various other software solutions could also be used.

Once imported, automated and manual segmentation techniques were applied to generate a 3D mask of the proximal tibia. The finer the CT slices were, the more detailed and accurate the 3D model became, requiring less interpolation. A 3D mesh was generated from the segmentation mask (Fig. 1) and exported in Standard Triangle Language (STL) format. This file was then imported into Geomagic® Sculpt™ (Version 22) for final surface and geometric refinements prior to 3D printing (Fig. 2). While the initial mesh captured the general anatomy accurately, subtle adjustments were performed to enhance surface continuity and ensure the model's structural integrity and printability.

While the D2P™ segmentation tools generate anatomically accurate models, minor surface smoothing and noise reduction were applied to correct subtle stair-step artifacts and irregular surface transitions introduced during segmentation. Although these adjustments are nearly imperceptible, they help ensure a consistent and clean surface suitable for 3D fabrication. Here, noise reduction refers to the targeted removal of small, non-anatomical surface inconsistencies caused by limited image resolution or imprecise mask boundaries. These modifications were applied conservatively to preserve key anatomical details and avoid any unintended distortion of geometry.

To further ensure model quality, the mesh was carefully inspected for common integrity issues such as open surfaces, duplicate edges, or residual artifacts from the segmentation and mesh generation process. Mesh integrity refers to the structural continuity and correctness of the 3D model. A complete, error-free mesh minimizes

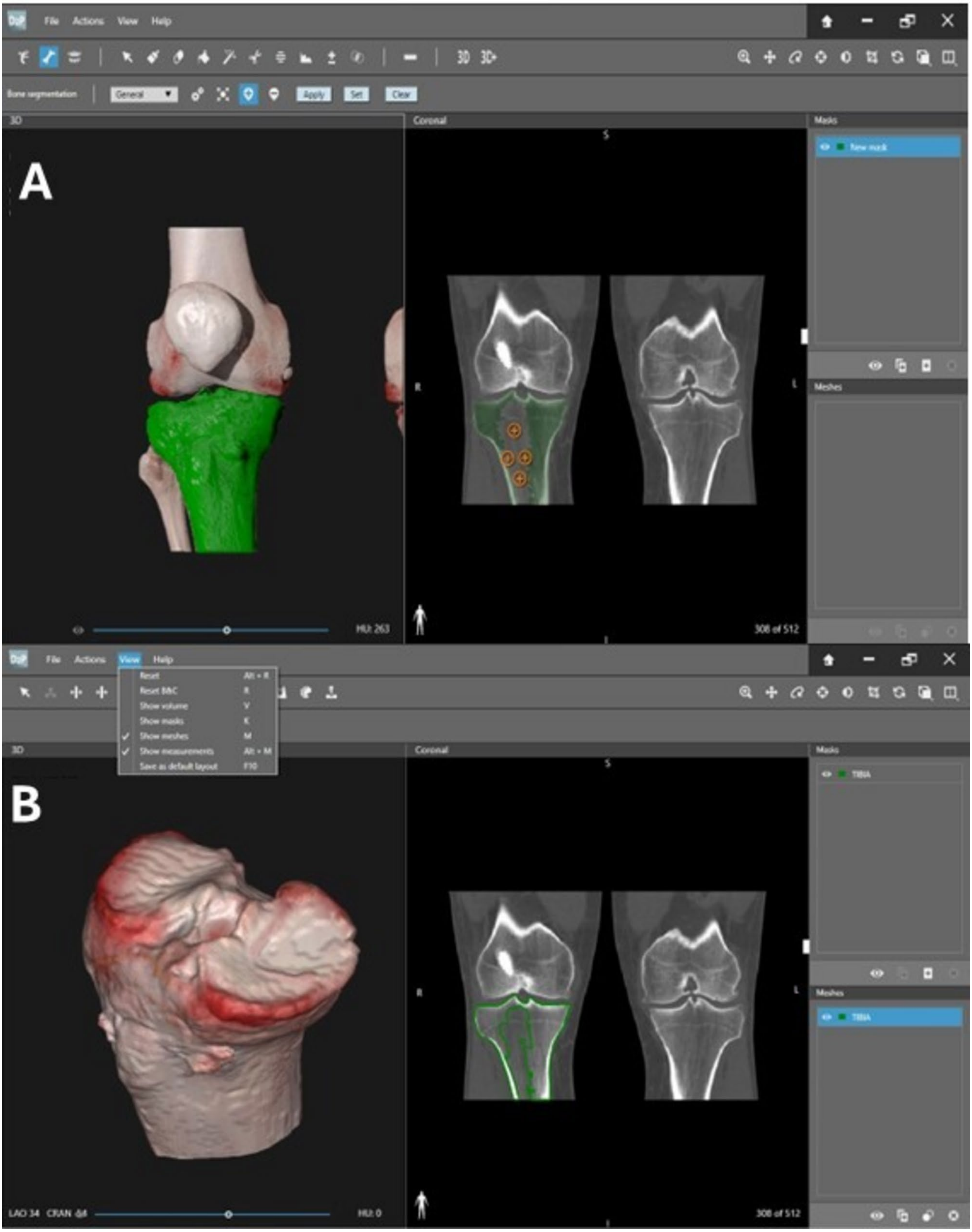

Fig. 1 (See legend on next page.)

(See figure on previous page.)

Fig. 1 Step-by-step workflow for converting DICOM images into a 3D model for preoperative surgical planning. **(A)** Segmentation phase and anatomical slice reference: On the left, a 3D rendering of the knee displays the proximal tibia segmentation mask in green, generated using D2P™ software (version 1.0.5). Green represents the segmented tibia. On the right, two coronal CT slices are shown to illustrate the anatomical level from which segmentation was performed. Green represents the segmented tibia; orange markers indicate segmentation control points. The slice thickness was 0.7 mm. **(B)** 3D mesh generation and export process: The segmented tibial mask was converted into a 3D surface mesh. The left panel shows the final refined mesh of the proximal tibia in light pink, with surface smoothing applied to enhance anatomical fidelity. The corresponding CT slices on the right illustrate the alignment and volume traced by the segmented region (outlined in green). The mesh was exported in STL format for the 3D printing

slicing problems, improves print bed adhesion, and contributes to the overall mechanical stability of the printed structure.

Once the mesh adjustments were completed, the model was processed through a slicer, the final stage before 3D printing. This software converted the STL file into a coordinate-based format (GCODE) compatible with the printer hardware. Ultimaker Cura (Version 3.9) was used for this step (Fig. 3). At this stage, printing parameters such as infill density, support structures, and layer height were carefully reviewed and configured.

The model was then prepared for printing using Hyper PLA (polylactic acid) filament. Although the choice of material is flexible, selecting one capable of capturing fine anatomical detail was essential to avoid loss of morphological accuracy during the fabrication process [12]. The entire workflow—from initial segmentation to the final 3D-printed model—was completed within a single working day.

Preoperative planning using the 3D model

Once the 3D model of the proximal tibia is complete, it is sent to the tissue bank to assist in selecting the appropriate meniscal allograft. By utilizing the 3D model, it becomes possible to accurately select the allograft that best fits the size and anatomy of the proximal tibia. After this, using the 3D model and specialized non-sterile surgical instruments, the team meticulously plans and prepares the tunnels needed for the meniscal transplant and ligament reconstruction. During this process, the precise locations and angles for creating each tibial tunnel are carefully determined, ensuring no overlap between the tunnels (Fig. 4). The tibial osteotomy is first performed on the 3D model, followed by the creation of the MAT tunnels, and finally the ACL. This approach allows for the preoperative determination of drilling parameters (position and angle), ensuring tunnel convergence is avoided across the different procedures.

Intraoperative use of the 3D model

The 3D model is sterilized with a low-temperature process in hydrogen peroxide. Once sterilized, the 3D model is employed intraoperatively as a physical template, guiding essential aspects of the procedure. It supports precise tunnel placement, facilitates osteophyte removal, and ensures accurate positioning of the meniscal graft on the recipient tibia. By predefining the tunnel locations and external entry points, the model helps avoid tunnel overlapping, allowing for real-time adjustments to the insertion of the meniscal roots. This ensures optimal graft integration with the tibia, improving the predictability of the meniscal transplant's behavior and helping achieve the most anatomically accurate placement possible.

The 3D-printed model provides surgeons with a tangible, patient-specific reference, improving spatial awareness and precise tunnel placement during surgery. This is particularly beneficial in complex procedures involving ACL reconstruction and tibial osteotomy, where accurate tunnel alignment is essential to prevent convergence. Additionally, given the variability in osteotomy plate designs (e.g., Tomofix, Arthrex), the model allows preoperative assessment of potential screw interference, enabling surgeons to adjust the osteotomy site if necessary and optimize surgical outcomes (Fig. 5).

After performing the osteotomy, the meniscal transplantation is carried out. A fresh meniscal graft is used, and the transplantation is performed using the double-plug technique. The 3D model assists in adjusting the meniscal allograft to the recipient site (Fig. 5). The meniscal roots are secured to the tibia using a suture anchor for each root. The remaining meniscus is sutured to the capsule using the inside-out technique for the body and anterior horn, while all-inside sutures are used to reinforce the posterior horn fixation. Finally, the ACL reconstruction tunnels are created, with the femoral tunnel positioned at 70 – 30 and the tibial tunnel planned based on the 3D model to prevent tunnel convergence (Fig. 5).

Discussion

The integration of full-scale 3D printing in MAT represents a significant advancement in surgical planning and execution [13], particularly in complex cases requiring multiple concurrent procedures, such as ACL reconstruction and tibial osteotomy [14]. This case demonstrates that patient-specific 3D-printed models, generated from high-resolution CT scans, can enhance donor tissue selection, precise tunnel placement, and intraoperative guidance, all of which are critical factors for optimal surgical outcomes [15, 16].

One of the key aspects of this case was the ability of 3D-printed models to guide tunnel positioning and avoid tunnel convergence, an issue commonly encountered in simultaneous ACL reconstruction, MAT, and tibial osteotomy procedures. Previous studies have emphasized the

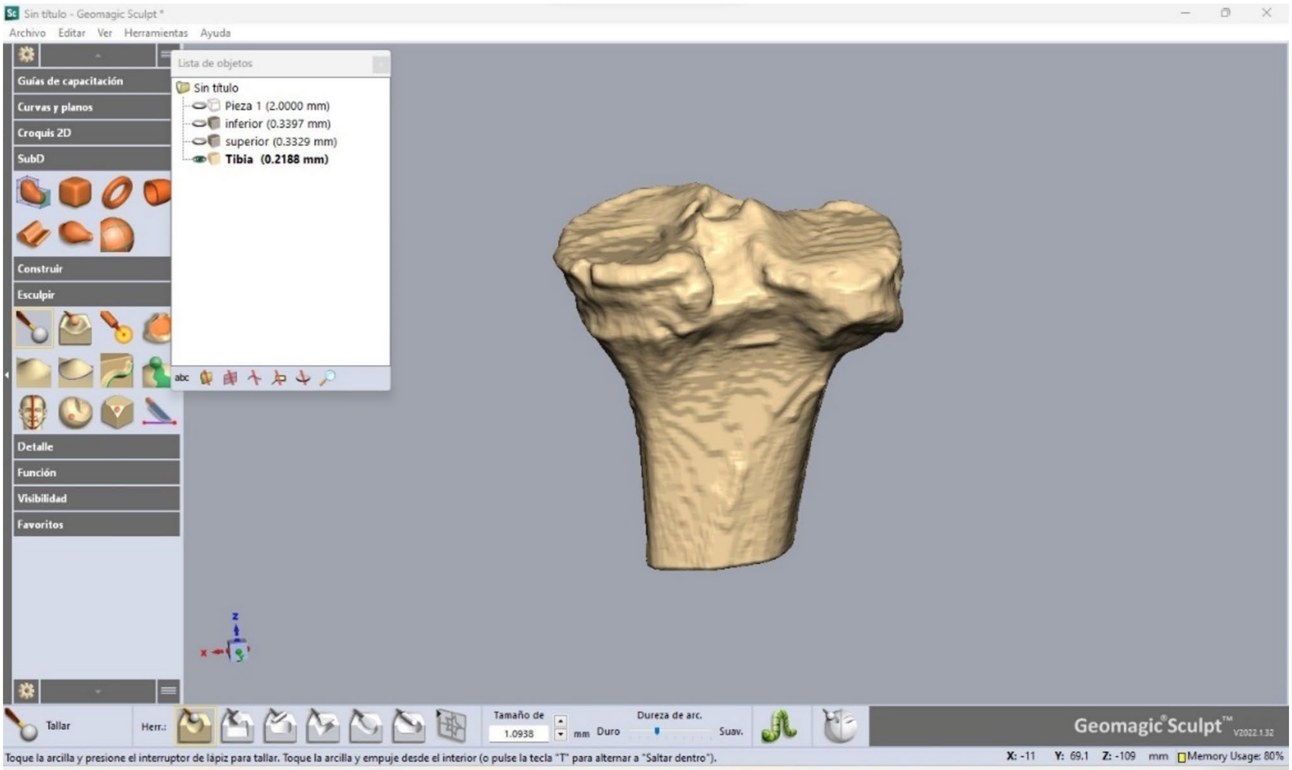

Fig. 2 Final refinements applied to the 3D tibial model before 3D printing. The segmented STL model was imported into Geomagic® Sculpt™ for minor refinements. Surface smoothing and noise reduction were applied to remove subtle artifacts created during segmentation, improving the surface continuity of the model. Mesh integrity was evaluated and corrected to ensure the model was watertight and free of structural errors. The final STL file was exported for printing

risks associated with tunnel overlap, which can lead to graft instability, increased surgical difficulty, and a higher failure rate [17]. Our experience aligns with this, demonstrating that preoperative testing of tunnel positioning on the 3D model allowed us to adjust angulation before drilling in the bone, thereby improving surgical precision and reducing intraoperative challenges.

Another important aspect of this case was the role of 3D-printed models in meniscal allograft sizing and positioning. Meniscal mismatch greater than 10% has been shown to significantly impact knee biomechanics, increasing cartilage wear, instability, and early-onset osteoarthritis [18]. Traditionally, radiographic methods and MRI have been the gold standard for meniscus sizing [4]. However, 2D imaging cannot inherently fully represent the knee's three-dimensional structure, potentially leading to sizing errors and suboptimal graft fit [7]. Both methods have inherent limitations. Radiographs offer a two-dimensional view of a highly complex, three-dimensional structure, leading to potential discrepancies between the measured and actual meniscal size [7]. While MRI improves accuracy in soft tissue assessment, it is not without its challenges, especially when the meniscus is absent, or there are inconsistencies in imaging protocols and observer interpretation [7].

In this case study, the 3D-printed model provided a precise method for ensuring optimal graft fit before transplantation, which is critical for reducing extrusion risk and improving long-term stability. 3D imaging and printing technologies have emerged as promising tools for improving the accuracy of meniscal graft sizing and positioning [6]. The 3D-printed models provide an enhanced view of the knee anatomy [6, 19]. Using such models significantly increases the accuracy of meniscal sizing compared to traditional radiographic methods, helping to minimize both sizing errors and the risk of tunnel overlap [17, 20].

Beyond preoperative planning, intraoperative use of the 3D-printed model provided real-time validation of tunnel positioning and meniscal graft placement. Unlike manual alignment techniques or intraoperative fluoroscopy, which rely on surgeon experience and visual estimation, the 3D model enabled a hands-on approach, improving surgical predictability and reducing human error [9, 10]. This was particularly advantageous when performing multiple concurrent procedures, where small adjustments in tunnel placement significantly influence overall surgical success. Additionally, the 3D-printed model can serve as a valuable tool for surgeons with limited experience in meniscal transplantation, providing

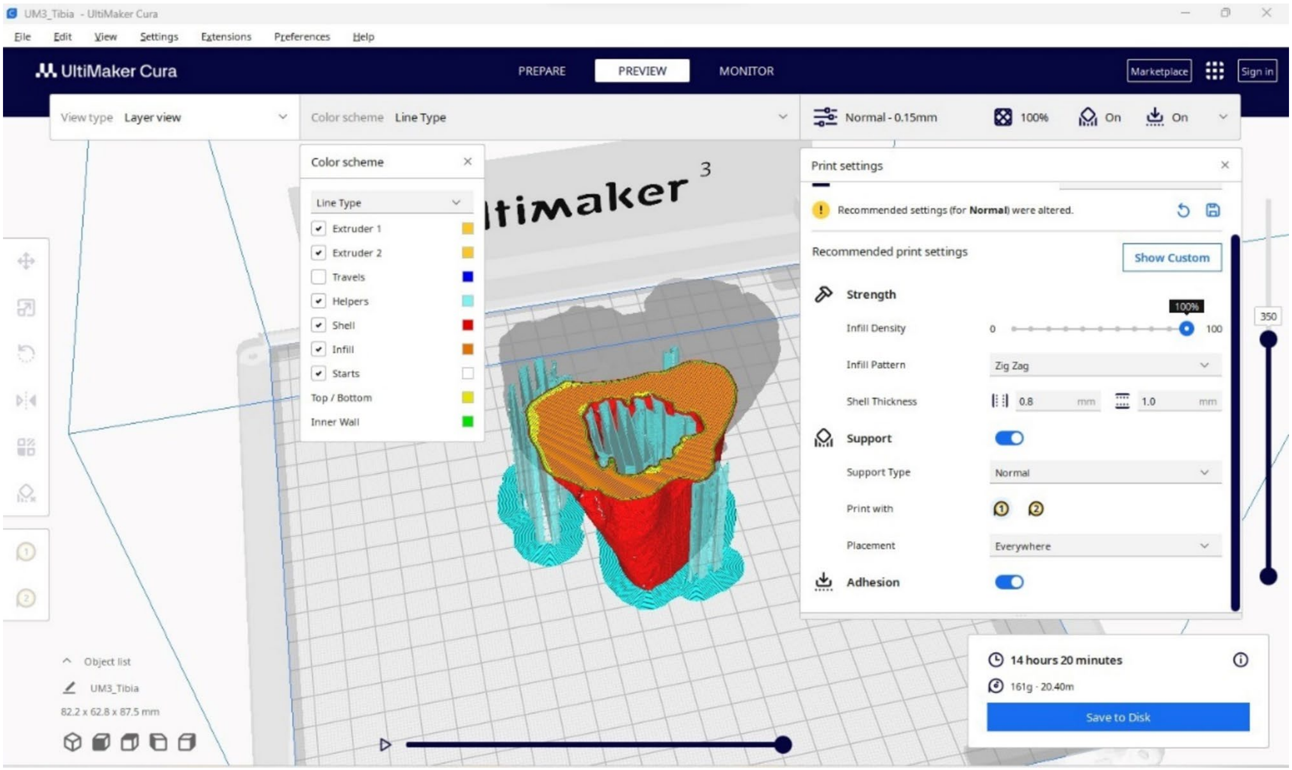

Fig. 3 Following the final mesh adjustments, the STL file was processed using Ultimaker Cura (Version 3.9), a slicing software that converts 3D models into GCODE—a coordinate-based format required by the printer. Key print parameters such as infill density, shell thickness, and support structures were carefully configured to optimize accuracy and stability. Support elements were strategically placed to reinforce overhangs and prevent deformation during fabrication. The model was printed using Hyper PLA (polylactic acid) filament, selected for its balance of dimensional precision, surface detail, and mechanical strength

a tangible reference for graft positioning and tunnel alignment.

Recent studies have highlighted the potential of 3D printing to further improve the precision of tunnel positioning, especially in cases involving combined procedures. DeFroda et al. explored using 3D models for optimizing socket-tunnel positioning in MAT surgeries combined with ACL reconstruction [17]. With the help of 3D-printed guides, surgeons could adjust tunnel angles with greater accuracy, reducing the risk of tunnel overlapping and improving graft stability [19, 21].

The applications of 3D printing extend beyond MAT. In cases of patellar instability, Beitler et al. demonstrated the value of 3D-printed models for preoperative planning, creating anatomical reproductions of knee joints to allow surgeons a more detailed assessment of the tibial plateau [22]. This three-dimensional visualization aids in accurately aligning the meniscal allograft and positioning other structures involved in complex knee surgeries. Similarly, Fernández-Poch et al. showcased the precision of 3D-printed, patient-specific instrumentation for reconstructing bone tunnels in complex knee procedures, reporting minimal deviations in tunnel entry points and angles from the preoperative plan [20].

Despite the demonstrated benefits, this case study had several limitations that must be acknowledged. One of the most notable challenges was the lack of direct dimensional validation between the 3D-printed model and the original CT scan data. Although FDM (Fused Deposition Modeling)-printed models have reported tolerances of 0.1 mm to 0.3 mm [23], ensuring high fidelity, a quantitative comparison between the printed model and digital reconstruction was not conducted in this case study. Future work should integrate 3D scanning techniques or coordinate measuring systems (CMMs) to systematically assess deviations between the printed model and the patient's anatomy, providing a more robust validation of accuracy.

Another critical consideration was the choice of printing materials. While photopolymer resins and polyjet-based polymers offer higher precision and superior surface finish, their high cost, fragility, and extended processing times make them impractical for routine clinical use [24]. In contrast, we selected Hyper PLA due to its balance between affordability, mechanical resistance, and printability, making it a clinically viable alternative [23, 25].

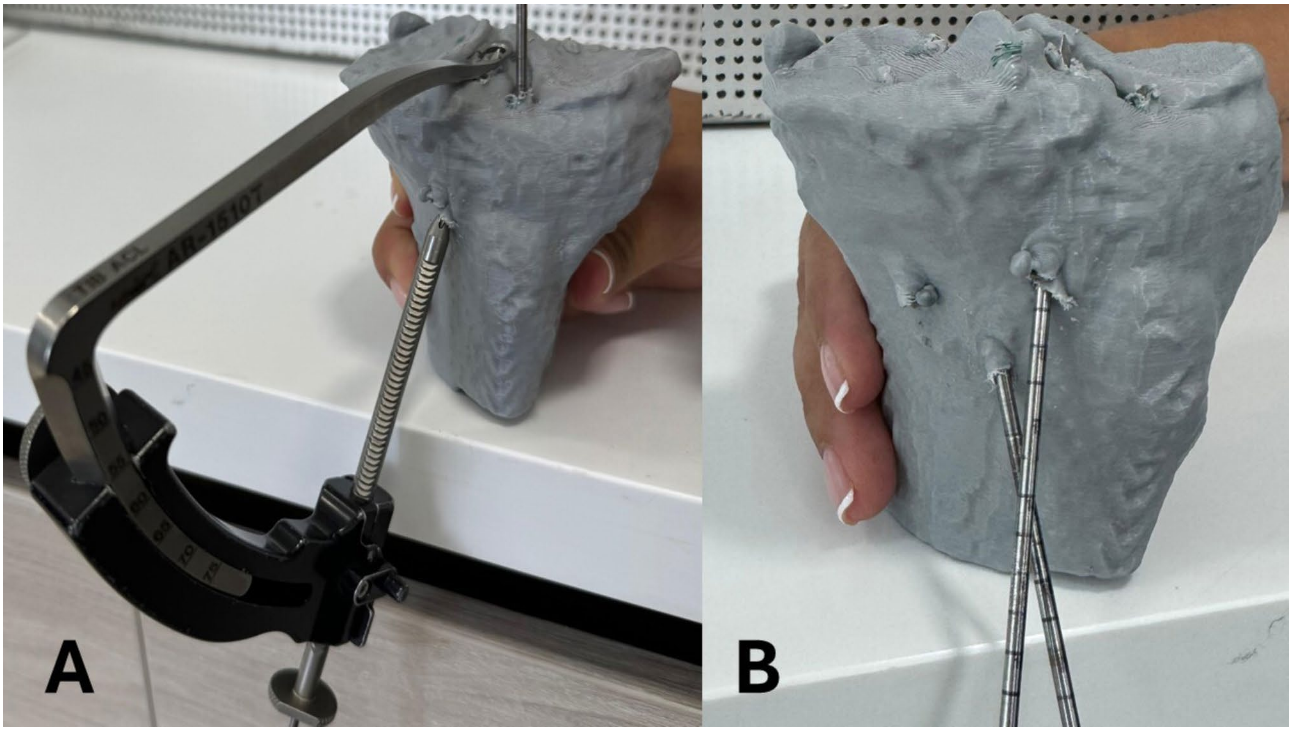

Fig. 4 Example of 3D printing of the proximal tibia as a guide for creating tibial tunnels in the preoperative period. **(A)** Creation of tibial tunnels for the MAT and ACL reconstruction. **(B)** The position of the tunnels is checked to ensure no convergence

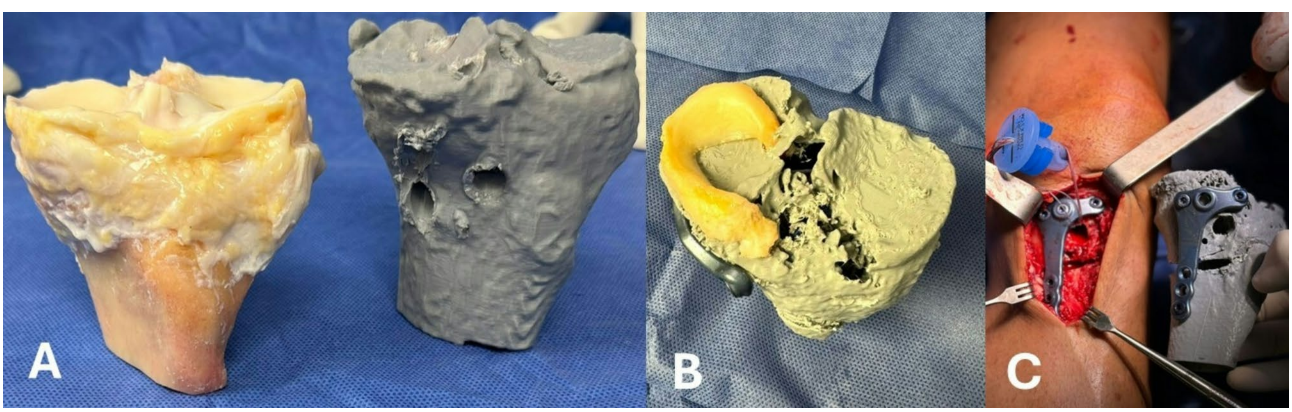

Fig. 5 3D-printed model of the proximal tibia for MAT surgical planning and execution. **(A)** The 3D-printed model of the proximal tibia is used preoperatively to assist in allograft selection, ensuring a graft that closely matches the recipient's anatomy. **(B)** The meniscal allograft is fitted onto the recipient site in the tibia using the 3D model. This process allows surgeons to ensure proper allograft sizing, optimize graft passage, and achieve the most accurate anatomical positioning of the meniscus, thereby reducing the risk of extrusion. **(C)** The 3D-printed model aids in the accurate reproduction of tunnel positioning and angulation during surgery. This ensures that the cutting and drilling parameters (position and angle) are precisely replicated on the patient's bone, avoiding tunnel convergence in ACL reconstruction, tibial osteotomy, and MAT cases

Additionally, the CT scan slice thickness of 0.7 mm was selected to balance anatomical detail and file manageability while remaining within clinically acceptable tolerances for bone-based modeling. Although thinner slices (e.g., 0.5 mm or lower) can capture more intricate details, the improvement in model fidelity does not necessarily translate into higher clinical accuracy due to limitations in 3D printing resolution and material properties. Specifically, with FDM-based printing and the selected material, variations below ±0.5 mm are often indistinguishable in the final model output. Furthermore, acquiring thinner slices substantially increases radiation dose and data size, which can pose practical and ethical limitations in routine clinical workflows. Therefore, a slice thickness of 0.7 mm offered an optimal compromise between image resolution and clinical applicability. Based on the CT resolution and printing tolerances, the expected final accuracy of our 3D printed model is approximately ± 0.7–1 mm, which remained within the range considered acceptable for preoperative bone structure assessment [23, 25].

Additionally, the mechanical properties of the 3D-printed models were influenced by infill density and print orientation, both of which play an important role in model durability and handling stability. A 100% infill density was selected to maximize model stiffness and load-bearing capacity, ensuring resistance during both preoperative planning and intraoperative use. While PLA does not replicate the exact mechanical properties of bone, this configuration provided sufficient structural integrity and minimized deformation risk [25]. Print orientation also proved critical, as FDM-based models display anisotropic behavior due to their layer-by-layer fabrication process [23, 26]. Aligning the long axis of the tibia parallel to the build plate helped improve model stability and reduce the likelihood of delamination or weak points.

Beyond fabrication settings, one of the main implementation challenges was the learning curve associated with digital segmentation and the integration of CT data into printable 3D models. The process requires technical expertise and additional time, which may limit adoption in settings without dedicated personnel or infrastructure. To fully realize the potential of 3D printing in orthopedic surgery, further advancements are needed, including automated segmentation tools, improved graft sizing algorithms, and broader access to preoperative planning platforms. As the field evolves, AI-assisted planning and more affordable printing technologies could streamline the process and enhance clinical outcomes [23, 27].

Finally, several limitations of this study must be acknowledged. Direct dimensional validation between the printed models and native anatomy was not performed, which limits certainty regarding absolute accuracy. Moreover, long-term clinical outcomes related to surgical precision and graft performance were not assessed. Technical requirements such as access to segmentation software and experienced operators may still pose barriers in some clinical environments. While the workflow was completed efficiently in this setting, broader implementation across institutions may require adaptation and training. Future studies should include quantitative accuracy assessments, outcome-based evaluations, and multicenter validation to determine the generalizability, reproducibility, and cost-effectiveness of incorporating 3D-printed models into routine orthopedic procedures.

Conclusion

The integration of preoperative planning with intraoperative precision through patient-specific 3D-printed models may enhance surgical accuracy and efficiency in complex multi-procedure MAT cases. These models provide a detailed anatomical reference that aids in optimizing graft selection, tunnel positioning, and intraoperative execution, particularly in procedures involving tibial osteotomy and ACL reconstruction. While the case presented highlights the potential benefits of this technology. Further studies are needed to quantitatively assess their accuracy, evaluate clinical effectiveness in larger cohorts, and determine the most efficient pathways for their incorporation into everyday orthopedic workflows.

Abbreviations

ACLR	Anterior cruciate ligament
MAT	Meniscal allograft transplantation
2D	Two-dimensional
3D	Three-dimensional
MRI	Magnetic resonance imaging
CT	Computed tomography
GCODE	coordinate-based format
STL	Standard Triangle Language
PLA	Polylactic acid
FDM	Fused Deposition Modeling
CMMs	Coordinate measuring systems

Author contributions

RDAP: Data curation, Writing– original draft, Writing– review & editing, Software, Visualization.AJQ and PASR: Conceptualization, Supervision, Writing– review and editing.

Funding

No funds have been received to support this work.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval

The need for ethics approval was waived.

Informed consent

Informed consent was obtained from the patient to present the case and publish it.

Human/Animal rights

All procedures followed were in accordance with the ethical standards of the committee responsible for human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2013.

Competing interests

The authors declare no competing interests.

Received: 2 January 2025 / Accepted: 28 April 2025
Published online: 06 May 2025

References

1. Ozeki N, Seil R, Krych AJ, Koga H. Surgical treatment of complex meniscus tear and disease: state of the Art. J ISAKOS. Jan. 2021;6(1):35–45. https://doi.org/10.1136/JISAKOS-2019-000380.
2. Gilat R, Cole BJ. Meniscal allograft transplantation: indications, techniques, outcomes. Arthroscopy. Apr. 2020;36(4):938–9. https://doi.org/10.1016/J.ARTHRO.2020.01.025.
3. Jaramillo Quiceno GA, Sarmiento Riveros PA, Arias RD, Pérez, Jaramillo FG. Meniscocapsular release technique to reduce chronic and challenging

bucket-handle meniscus tear, *J ISAKOS*, vol. 9, no. 3, pp. 418–421, Jun. 2024, https://doi.org/10.1016/J.JISAKO.2024.02.013
4. Cavendish PA, DiBartola AC, Everhart JS, Kuzma S, Kim WJ, Flanigan DC. Meniscal allograft transplantation: a review of indications, techniques, and outcomes, *Knee Surg Sports Traumatol Arthrosc*, vol. 28, no. 11, pp. 3539–3550, Nov. 2020, https://doi.org/10.1007/S00167-020-06058-6
5. Haunschild ED, Gilat R, Okoroha K, Cole BJ. Failure of Meniscus allograft transplantation. Oper Tech Sports Med. Mar. 2020;28(1):150713. https://doi.org/10.1016/J.OTSM.2019.150713.
6. Beeler S, et al. Meniscus sizing using three-dimensional models of the ipsilateral tibia plateau based on CT scans– an experimental study of a new sizing approach. J Exp Orthop. Dec. 2020;7(1). https://doi.org/10.1186/s40634-020-00252-8.
7. McConkey M, et al. Radiographic sizing for meniscal transplantation using 3-D CT reconstruction. J Knee Surg. 2011;25(3):221–6. https://doi.org/10.1055/s-0031-1292651.
8. Beeler S, et al. Three-dimensional meniscus allograft sizing-a study of 280 healthy menisci. J Orthop Surg Res. Feb. 2020;15(1). https://doi.org/10.1186/S13018-020-01591-Z.
9. Thiruchandran G, Dean O, Alim D, Crawford A, Salim O. Three-dimensional printing in orthopaedic surgery: A review of current and future applications. J Orthop. Jan. 2025;59:22–6. https://doi.org/10.1016/J.JOR.2024.07.013.
10. Anderson PA. 3D Printing for Education and Surgical Planning in Orthopedic Surgery, *3D Printing in Orthopaedic Surgery*, pp. 55–63, Jan. 2019, https://doi.org/10.1016/B978-0-323-58118-9.00006-3
11. Dong C, Petrovic M, Davies IJ. Applications of 3D printing in medicine: A review, *Annals of 3D Printed Medicine*, vol. 14, p. 100149, May 2024, https://doi.org/10.1016/J.STLM.2024.100149
12. Mahmood A, Akram T, Chen H, Chen S. On the evolution of additive manufacturing (3D/4D Printing) technologies: materials, applications, and challenges. Polym (Basel). Nov. 2022;14(21):4698. https://doi.org/10.3390/POLYM14214698.
13. Sarmiento Riveros PA, Jaramillo Quiceno A, Arias Pérez RD, Velásquez López M, Arango MV. Mejía Henao, Three-Dimensional printing guided for double meniscal allograft transplantation. Arthrosc Tech. Apr. 2025;103542. https://doi.org/10.1016/J.EATS.2025.103542.
14. Ejnisman L, Helito CP, De França Camargo AF, Rocha BA, Baptista AM, de Camargo OP, Three-dimensional printing in orthopedics: where we stand and where we are heading. Acta Ortop Bras. 2021;29(4):223. https://doi.org/10.1590/1413-785220212904245927.
15. Zaffagnini S, Romandini I, Filardo G, Dal Fabbro G, Grassi A. Meniscal allograft transplantation, anterior cruciate ligament reconstruction, and valgus high tibial osteotomy for meniscal-deficient, unstable, and varus knees: surgical technique and clinical outcomes, *Int Orthop*, vol. 47, no. 10, pp. 2523–2535, Oct. 2023, https://doi.org/10.1007/S00264-023-05846-2
16. Zaffagnini S, Grassi A, Romandini I, Marcacci M, Filardo G. Meniscal allograft transplantation combined with anterior cruciate ligament reconstruction provides good mid-term clinical outcome, *Knee Surg Sports Traumatol Arthrosc*, vol. 27, no. 6, pp. 1914–1923, Jun. 2019, https://doi.org/10.1007/S00167-018-5078-0
17. DeFroda S et al. Jun., Optimizing Socket-Tunnel Position for Meniscal Allograft Transplantation Combined With ACL Reconstruction: A 3D Model Analysis, *Orthop J Sports Med*, vol. 12, no. 6, 2024, https://doi.org/10.1177/23259671241246277
18. Dienst M, Greis PE, Ellis BJ, Bachus KN, Burks RT. Effect of lateral meniscal allograft sizing on contact mechanics of the lateral tibial plateau: an experimental study in human cadaveric knee joints, *Am J Sports Med*, vol. 35, no. 1, pp. 34–42, Jan. 2007, https://doi.org/10.1177/0363546506291404
19. Meng M, et al. Clinical applications and prospects of 3D printing guide templates in orthopaedics. J Orthop Translat. May 2022;34:22. https://doi.org/10.1016/J.JOT.2022.03.001.
20. Fernández-Poch N, et al. Three-dimensional-printed patient-specific instrumentation is an accurate tool to reproduce femoral bone tunnels in multiple-ligament knee injuries. Int Orthop. May 2023;47(5):1213–9. https://doi.org/10.1007/s00264-023-05712-1.
21. Arn Roth T et al. Sep., Deep-learning based 3D reconstruction of lower limb bones from biplanar radiographs for preoperative osteotomy planning, *Int J Comput Assist Radiol Surg*, vol. 19, no. 9, pp. 1843–1853, 2024, https://doi.org/10.1007/s11548-024-03110-5
22. Beitler BG, et al. Three-Dimensional printing of the patellofemoral joints of patellar instability patients. Arthrosc Tech. Mar. 2023;12(3):e401–6. https://doi.org/10.1016/j.eats.2022.11.023.
23. Grgić I, Karakašić M, Glavaš H, Konjatić P. Accuracy of FDM PLA polymer 3D printing technology based on tolerance fields. Processes. Oct. 2023;11(10). https://doi.org/10.3390/PR11102810.
24. Kumat SS, Shiakolas PS. Design, inverted vat photopolymerization 3D printing, and initial characterization of a miniature force sensor for localized in vivo tissue measurements. 3D Print Med. Dec. 2022;8(1):1–14. https://doi.org/10.1186/S41205-021-00128-2/FIGURES/11.
25. Adrover-Monserrat B, Lluma J, Luis-Torres B, Jerez-Mesa R, Travieso-Rodriguez JA. Bringing Medical Model Scans into Reality through 3D Printing: Materials and Manufacturing Parameters, *Key Eng Mater*, vol. 956, pp. 117–126, Sep. 2023, https://doi.org/10.4028/P-YHS3PA
26. Qamar Tanveer M, Mishra G, Mishra S, Sharma R. Effect of infill pattern and infill density on mechanical behaviour of FDM 3D printed Parts- a current review. Mater Today Proc. Jan. 2022;62:100–8. https://doi.org/10.1016/J.MATPR.2022.02.310.
27. Olawade DB, Marinze S, Qureshi N, Weerasinghe K, Teke J. The impact of artificial intelligence and machine learning in organ retrieval and transplantation: A comprehensive review, *Curr Res Transl Med*, vol. 73, no. 2, p. 103493, Apr. 2025, https://doi.org/10.1016/J.RETRAM.2025.103493

Publisher's note