Technical Note

# 3D Printed Models of Trochlear Dysplasia and Trochleoplasty Simulation for Trainee Education

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**Abstract:** Trochlear dysplasia is a major contributor to patellofemoral instability and subsequent failure of isolated soft tissue reconstruction procedures in the treatment of recurrent patellar dislocation and/or subluxation. Trochleoplasty procedures aim to address abnormal osseous trochlear morphologic factors that contribute to patellar maltracking. However, teaching these techniques is limited by the lack of reliable training models for trochlear dysplasia and trochleoplasty simulation. Although a cadaveric knee model of trochlear dysplasia for trochleoplasty simulation has been recently described, cadaveric knees are less amenable for use in trochleoplasty planning and surgeon training because of the absence of reliable, natural dysplastic anatomic relationships, such as suprapatellar spurs due to the rarity of dysplastic cadavers and the high cost of cadaveric specimens. Furthermore, readily available sawbone models represent "normal" osseous trochlear morphology and are difficult to modify and bend due to their material composition. Given this, we have developed a cost-effective, reliable, and anatomically accurate three-dimensional (3D) knee model of trochlear dysplasia for trochleoplasty simulation and trainee education.

## Introduction

Patellofemoral instability is a relatively common condition that accounts for 2-3% of all knee injuries and has been attributed to a host of soft tissue and osseous factors, including limb malalignment, abnormal muscle tensioning and retinacular restraints, and trochlear dysplasia.[1-3] Of these, trochlear dysplasia has been identified as one of the greater risk factors predisposing to recurrent instability and treatment failure following soft tissue reconstruction—most commonly of the medial patellofemoral ligament (MPFL)—alone.[2-5] Numerous variations on the deepening trochleoplasty procedure have been proposed and utilized to address abnormalities in osseous trochlear anatomy that contribute to patellar maltracking, such as abnormally flat trochlear grooves with midline elevation of the trochlea to reduced lateral facet height to selective depression of the supratrochlear "bump" with underlying cancellous bone undermining and osteochondral flap elevation for increased cartilage preservation.[4,6,7] Surgical planning and decision-making for patellofemoral instability, particularly the decision to include procedures, such as trochleoplasty and tibial tubercle osteotomy (TTO) for extensor mechanism and patellar tracking vector realignment, have traditionally been observed for select, severe cases of trochlear dysplasia, with positive associated outcomes.[6] Furthermore, teaching of these techniques is complicated by the absence of reliable training model platforms and considerable individual variation in dysplastic trochlear morphology. Although a simple and reproducible cadaveric knee model of trochlear dysplasia and trochleoplasty simulation has been described,[8] cadaveric knees are less amenable for

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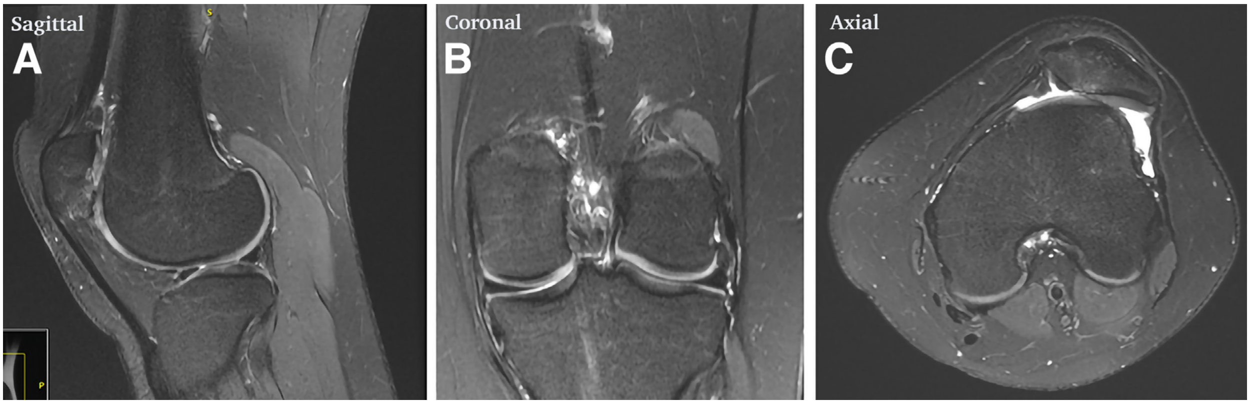


**Fig 1.** MRI from a 23-year-old female patient with patellofemoral instability showing sagittal (A), coronal (B), and axial views (C) of knee cartilage thickness of 3 mm with a displaced patella.

use in preoperative trochleoplasty planning and training due to the absence of reliable, natural dysplastic anatomic relationships and the high cost of cadaveric samples. We developed a cost-effective, reliable, and anatomically accurate three-dimensional (3D) knee model of trochlear dysplasia in the context of recurrent patellofemoral instability for trochleoplasty simulation and trainee education.

## Technique

### Development of the 3D-Printed Model

Models of a distal femur with trochlear dysplasia are generated using computed tomography (CT) imaging of a patient with recurrent patellofemoral instability. Segmentation of bony anatomy is performed with Materialise Mimics (Leuven, Belgium), and articular cartilage is generated using anatomical reference (Fig 1). The entirety of the distal femur as far proximal as to the junction of the distal femoral diaphysis and metaphysis is segmented. The bone part is hollowed to 1-mm wall thickness to facilitate a low amount of plastic melting during the routing part of the procedure (Fig 2). Bone and cartilage parts are exported as separate stereolithography (STL) files to prepare for 3D printing.

### Model Fabrication

Models are printed using material extrusion 3D printing technology on an Ultimaker S5 printer (Utrecht, Netherlands) using acrylonitrile butadiene styrene (ABS) and thermoplastic polyurethane (TPU) filament materials for the bone and cartilage parts, respectively (Fig 3; Video 1). To model cancellous bone, 15 mL of a 2-part rigid water blown foam, FOAM-iT!8 (Smooth-On, Macungie, PA) is mixed 2:1 parts by weight, according to the manufacturer's instructions, poured into the hollow bone cavity, and left for 20 minutes to set. It is then cut flush with the end of the model with a coping saw and left to cure for 2 hours.

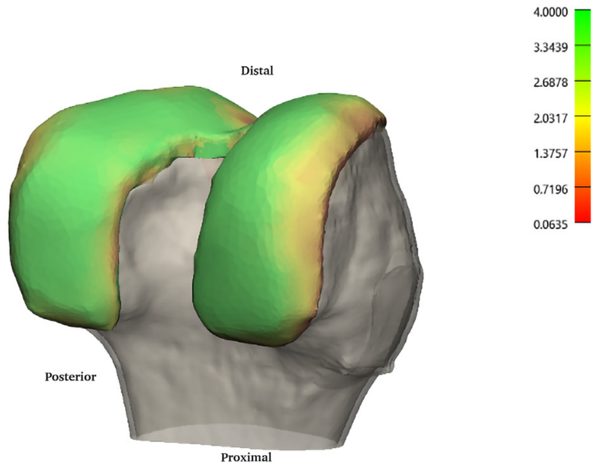


**Fig 2.** Thickness map of articular cartilage originally obtained from the MRI of a 23-year-old female patient with patellofemoral instability showing 1-mm bone thickness.

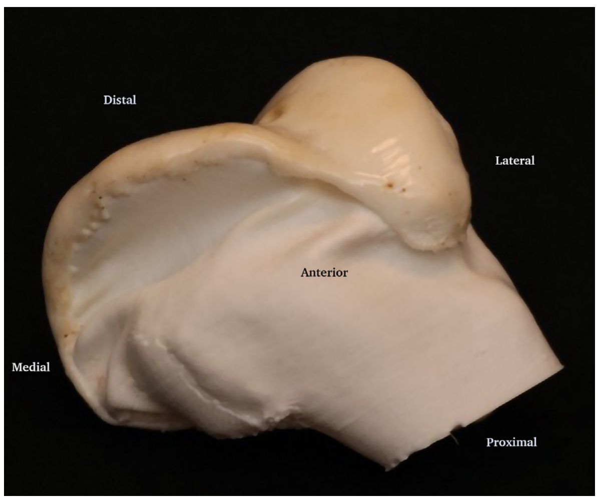


**Fig 3.** Deformed 3D-printed model of a distal femur due to heat polishing prior to filling with rigid foam, as the material from which the model is printed fails to retain its shape with application of heat in the absence of this rigid water-blown foam.

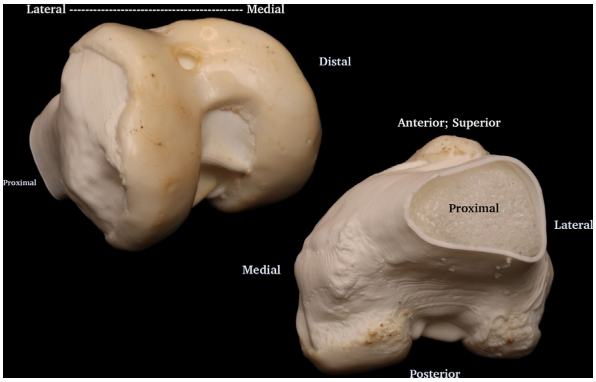


**Fig 4.** 3D-printed model of a distal femur from a 23-year-old female patient with patellofemoral instability with flame polished cartilage and foam filled interior.

The foam density is approximately 0.128 g/cm$^3$. Rapid movements with a blowtorch are then performed over the TPU surface to achieve a smooth finish (Fig 4; Video 1). The rigid foam also aids in shape preservation of the modeled bone during the cartilage-smoothing process. In the absence of this foam material, softened ABS will deform from the original shape.

3D-printed suture anchors were developed in tandem to facilitate the fixation of cartilage to the bone after routing (Fig 5). Anchors are designed in Solidworks (Dassault Systèmes, Waltham, MA) and printed using powder bed fusion 3D printing technology on a Formiga P110 Velocis printer (EOS, Krailling, Germany) with PA2200 (Nylon 12) material.

The raw material cost per printed model is low—though overhead costs related to software access, segmentation, printing, engineering, and postprocessing time, and indirect costs associated with machine and hardware acquisition and use must also be considered and raise the relative production cost of the models—and fabrication time is on the order of hours (Table 1). As such, the model enables plentiful training models for this and similar types of orthopedic procedures.

### Simulated Trochleoplasty Procedure

The pliable materials used in the construction of this trochlear dysplasia model allow for easy ex vivo modeling of supratrochlear spur recession using a high-speed burr or drill (Video 1). Following recession of the subchondral bone below this supratrochlear spur, 3D-printed suture anchors may be easily affixed to span the trochlea for continued groove tampening and stabilization (Fig 6). The final, burred product, thus, undergoes similar surgical modification as one might perform in vivo (Fig 7).

## Discussion

Procedure simulation and practice are essential to surgical education, particularly concerning complex, less common procedures such as trochleoplasty. Despite this, few reliable, accessible, and reproducible models of trochlear dysplasia have been developed and described on which trochleoplasties may be taught to and practiced by trainees to develop this skill set. As this procedure has inherent implications for cartilage health and joint stability, proper surgical technique and education regarding surgical decision-making in the care of this patient population are crucial.

3D printing enables the reproducible and cost-effective development of models that accurately reflect the aberrant morphology of true trochlear dysplasia patients for whom trochleoplasty and other osseous anatomy-altering procedures may be indicated. By

**Fig 5.** 3D modeled and printed suture anchors showing tapered threads, 12 threads per inch, and 4.75-mm diameter and 1-inch length.

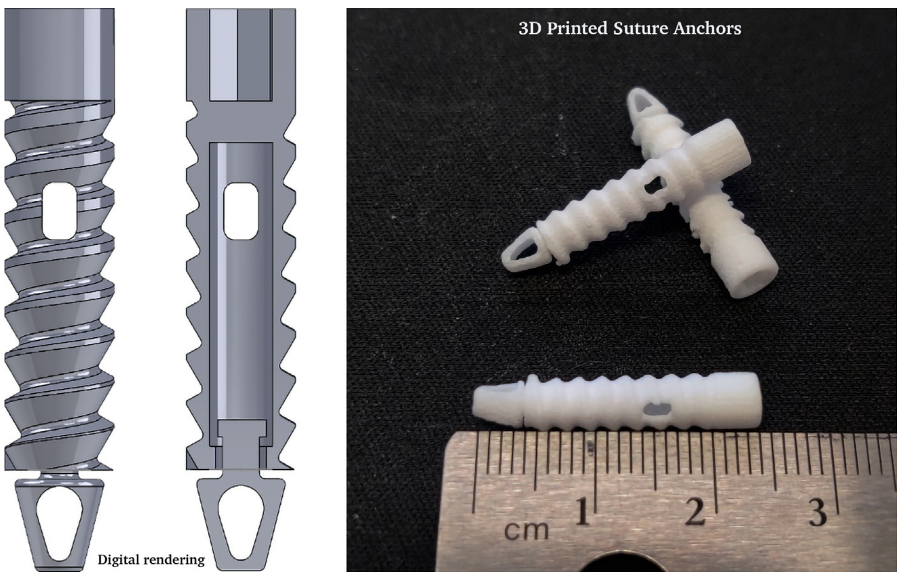

**Table 1.** Cost Breakdown

| Part | Unit Cost |
|---|---|
| ABS | $1.84 |
| TPU | $1.34 |
| FOAM-iT!8 | $0.35 |
| Suture Anchors (3/set) | $0.15 |
| Total Material Cost per Knee | $3.53 |
| Overhead Cost per Model | ~$15 |
| Total Overall Cost | $20.53 |

ABS, acrylonitrile butadiene styrene; TPU, thermoplastic polyurethane.

harnessing this technology, models of the distal femoral trochlea may be reliably produced and used in both general—skills acquisition by trainees—and individualized—patient-specific, therapeutic—surgical preparation. Similar modeling techniques have been described to facilitate and improve preoperative planning and trainee education in the realms of recurrent anterior shoulder instability[9] and arthroscopy simulation.[10] We describe the creation of a flexible, reliable 3D-printed model of trochlear dysplasia that can be easily modified

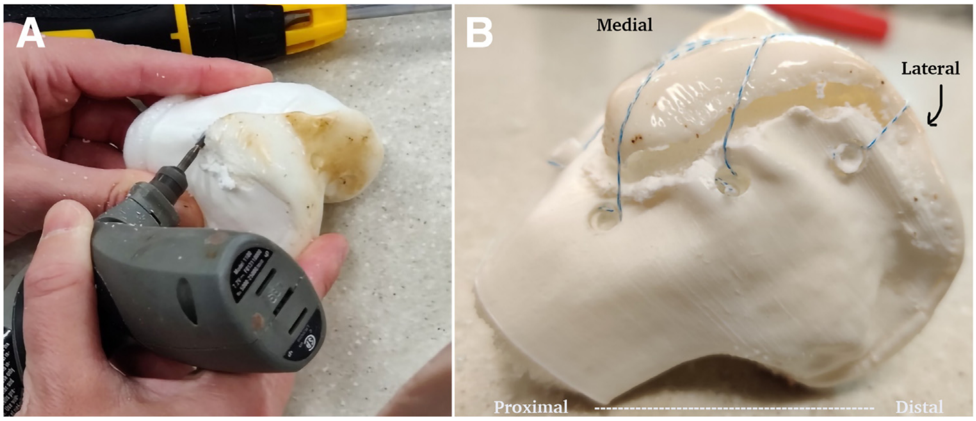


**Fig 6.** Simulated trochleoplasty on a prototype model of a distal femur from a 23-year-old female patient with patellofemoral instability.

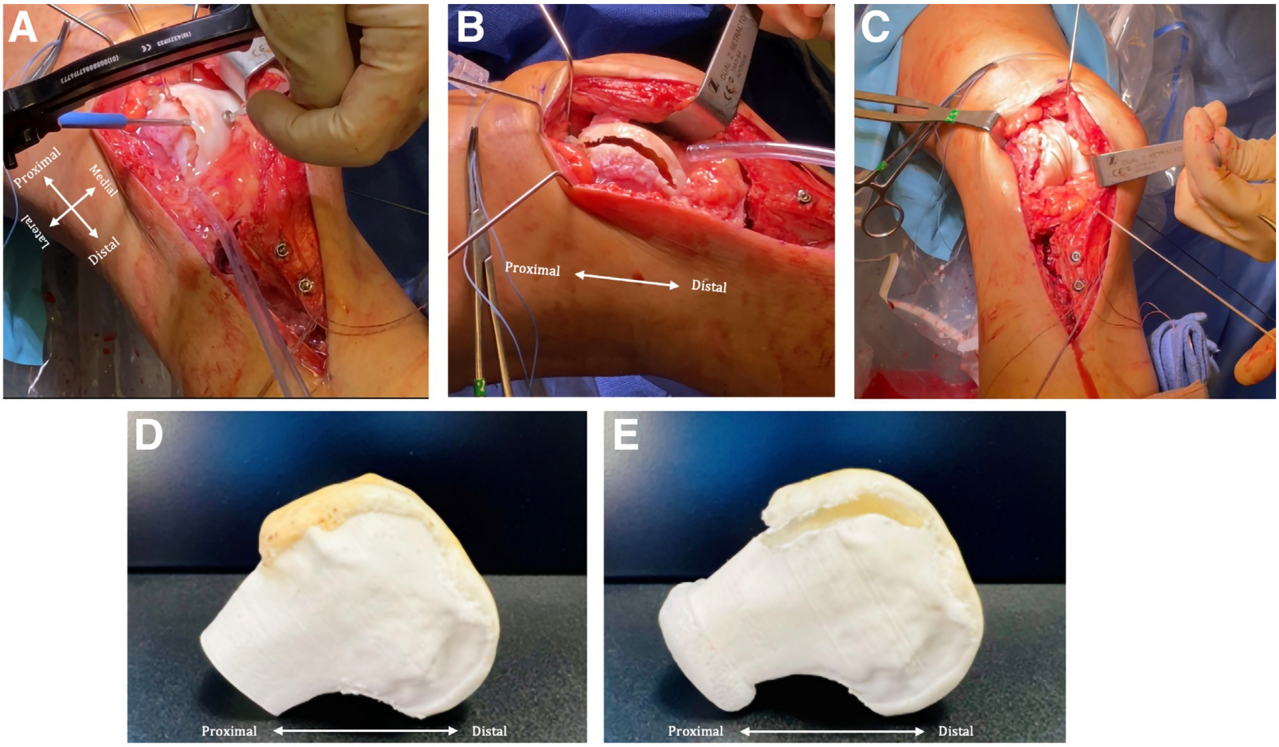


**Fig 7.** (A) Intraoperative view of trochleoplasty, with burr-based resection of the medial supratrochlear bump, while protecting the chondral surface. (B and C) Completed trochleoplasty prior to anchor fixation. (D) 3D-printed anatomic model of a dysplastic trochlea with a 9-mm supratrochlear bump. (E) Ex vivo 3D anatomic model trochleoplasty.

**Table 2.** Advantages and Disadvantages

| Advantages | Disadvantages |
| --- | --- |
| Fills unmet need for pliable, modifiable model of trochlear dysplasia incompletely addressed by sawbone and cadaveric modeling paradigms | Requires 3D printer and knowledge of 3D segmentation and printing techniques |
| Low cost to manufacture | Additional time required to print and perform post-3D printing model processing |
| Anatomically accurate model of trochlear dysplasia | Requires CT for 3D model generation |
| Ability to produce as many models as needed for training purposes | Model may deform, resulting in loss of morphologic accuracy, if appropriate post-processing (foam treatment) is not applied |
| Reliable model using flexible materials for procedure simulation | |
| Ability to simulate procedure in varied morphologic presentations of trochlear dysplasia | |
| High face validity | |

to simulate trochleoplasty procedures by trainees of different levels. This addresses an inherent limitation of existing model systems, including cadaveric samples, which overwhelmingly represent normal osseous knee morphology due to the relative rarity of trochlear dysplasia in the general population. Traditional sawbone models, which also reflect normal osseous morphology, comprise nonpliable materials, and are less amenable to trochleoplasty simulation. Accompanying components such as suture anchors may be subsequently printed for use, as described herein.

The advantages of the use of 3D-printed models of trochlear dysplasia for trochleoplasty simulation are many (Table 2), although it is not without limitations. Although the unit cost of model manufacturing is low, this practice requires access to a 3D printer, knowledge of 3D segmentation and printing techniques, and CT imaging for patients from whose scans models are to be generated. Surgical decision-making and planning for recurrent patellofemoral instability and trochlear dysplasia has conventionally been predicated upon the use of anteroposterior, lateral, and Merchant or axial view radiographs rather than advanced imaging such as CT scans[5,11]. However, the use of advanced imaging has become increasingly popular in the appraisal of trochlear morphology and patellofemoral anatomic relationships. As the use of advanced imaging becomes increasingly commonplace in guiding surgical intervention, so too may 3D reproductions generated from these DICOM files.

Surgical simulation is critical to surgical education and preoperative planning.[10] Herein, we describe the production of a cost-effective, reliable, and anatomically accurate model of trochlear dysplasia and trochleoplasty simulation. This model and technique may be used as a teaching aid for trainees, adapted for the various iterations of trochleoplasty that have been devised and described, and applied to individual patients for surgical planning.

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