Technical Note

Three-Dimensional Printing of Models of Patellofemoral Joint Articular Cartilage in Patients With Patella Instability for Observing Joint Congruity

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Abstract: Three-dimensional (3D) modeling and printing are increasingly used in the field of orthopaedic surgery for both research and patient care. One area where they are particularly helpful is in improving our understanding of the patellofemoral (PF) joint. Heretofore, morphological studies that use 3D models of the PF joint have primarily been based on computed tomography imaging data and thus do not incorporate articular cartilage. Here, we describe a method for creating 3D models of the articular surfaces of the PF joint based on magnetic resonance imaging. Models created using this technique can be used to improve our understanding of the morphology of the articular surfaces of the PF joint and its relationship to joint pathologies. Of particular interest is our finding of articular congruity in printed articular cartilage surfaces of dysplastic PF joints of recurrent patella dislocators.

Patellofemoral (PF) problems account for up to 45% of knee pain, usually related to altered mechanics or injury to the articular surfaces of the patella, trochlea, or both.[1] Heretofore, clinical understanding of the PF joint has been based almost exclusively on 2-dimensional (2D) images, including axial slices based on computed tomographic (CT) imaging data as originally described by Schutzer et al.[2] However, 3-dimensional (3D) modeling allows us a deeper understanding of the morphology of the PF joint. Studies that have used 3D modeling to understand PF morphology have primarily used CT imaging as the basis for the models, because creating accurate 3D models based on magnetic resonance imaging (MRI) is challenging, although some studies have used MRI.[3-10] MRI is necessary for visualizing cartilage, which is important for understanding the morphology of the true articulating surfaces of the joint. Although PF cartilage can be seen on MRI in 2D, understanding PF articulation in three dimensions (3D) has important implications for understanding PF pain and its treatment. The 3D printing of patella articular cartilage also provides the possibility of quantitating and precisely localizing articular damage. Here and in Video 1 we detail a method for creating 3D models of the PF joint articular cartilage based on MRI to help better understand trochlear dysplasia, related pathologies, and PF joint congruity in the diagnosis and treatment of PF patients, particularly those with recurrent patella dislocations.

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The authors report the following potential conflict of interest or source of funding: D.H.W. reports personal fees from Intellijoint, Globus, and Materise. Full ICMJE author disclosure forms are available for this article online, as supplementary material.

Received February 15, 2023; accepted June 24, 2023.

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2212-6287/23280
https://doi.org/10.1016/j.eats.2023.06.016

Technique

MRI Protocol

To improve resolution, as well as achieve adequate contrast between articular cartilage and surrounding tissue, we use a custom thin section sagittal gradient echo MRI sequence. This sequence has the following parameters—field of view: 150 × 150 × 140 mm^3; matrix: 512 × 380 (interpolated to 512 × 512) with in-plane spatial resolution 0.3 × 0.3 mm; slice thickness: 1 mm; flip angle: 25°; repetition time: 26 msec; echo time: 6.8 msec; acquisition time: ∼5.06 minutes. This sequence maximizes the accuracy of the 3D model produced using MRI data because it maximizes the difference in image intensity between cartilage and other soft tissue. It is imperative to eliminate motion artifact by appropriately stabilizing the study knee using bolsters, stuffing, and any other measures possible, including patient counseling.

Model Segmentation

We use the image processing software Simpleware ScanIP version S-2021.06 (Synopsis, Mountain View, CA) to convert the MRI data into 3D models; however, there are numerous programs that can also be used.[7,9-11] Once the Digital Imaging and Communications in Medicine files are imported, a combination of automated and manual segmentation techniques were used to generate a 3D "mask," which serves as the basis for the model to be printed. First, a thresholding tool is used to isolate the articular cartilage based on image intensity gray-scale value. However, as opposed to segmenting bone from CT images, which is based on tissue density, there is significant overlap between the intensity levels of articular cartilage and other soft tissue.[9] This means that after the thresholding step, there will inevitably be some undesired soft tissue included in the mask, as well as some articular cartilage that is not included in the mask (Fig 1). Thus time-intensive manual editing is required.

The "split regions" tool is used to separate the mask into three new, separate cartilage surfaces: a patella mask, a femur mask, and a tibia mask (Fig 2). The soft tissue that does not fall into these regions is removed from the model. However, as mentioned before, the thresholding step may not include all of the articular cartilage. Furthermore, it is challenging for the algorithm to distinguish borders of regions where 2 articular surfaces are in contact. Thus one is now left with 3 cartilage masks that have to be further refined with manual techniques.

Next, the paint tool is used to edit the mask so that the cartilage on each MRI slice is accurate (Fig 3). This can be a time-consuming process that is nonetheless essential to ensure that the masks are accurate. Special attention should be paid to where the different regions articulate, as well as the bone-cartilage interface.

Because of the MRI sequence used, the sagittal slices have less distance between them than the slices in the other planes, leading to the mask having a pixelated appearance between the slices of the axial and coronal planes. A Gaussian smoothing filter ($\sigma = 1$) is used to smooth the masks. However, although the smoothing filter creates a continuous surface, it may introduce inaccuracies. As such, the masks have to be reviewed

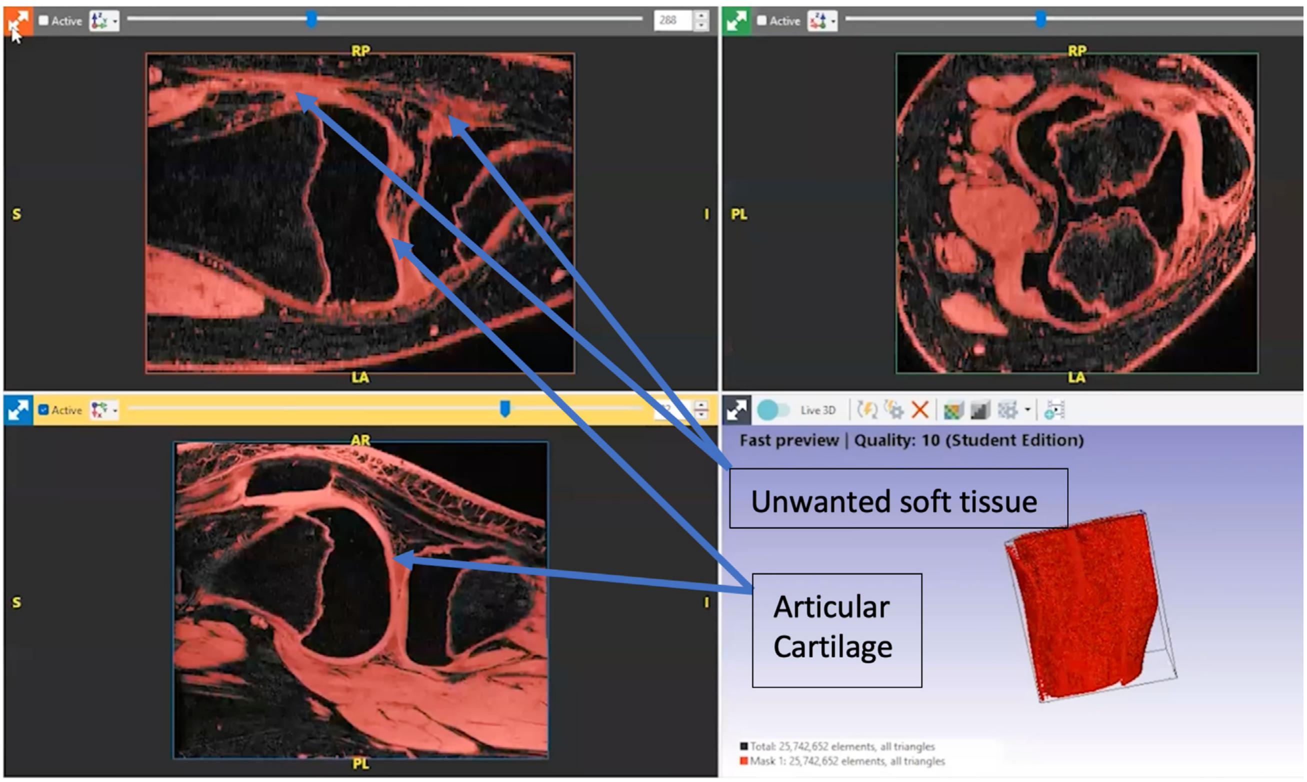

Fig 1. To begin the process of creating 3-dimensional models of the articular cartilage of the patellofemoral joint based on magnetic resonance imaging, a thresholding tool is used to include the articular cartilage within the mask but exclude other tissues. Some unwanted soft tissue is inevitably included, which needs to be removed manually.

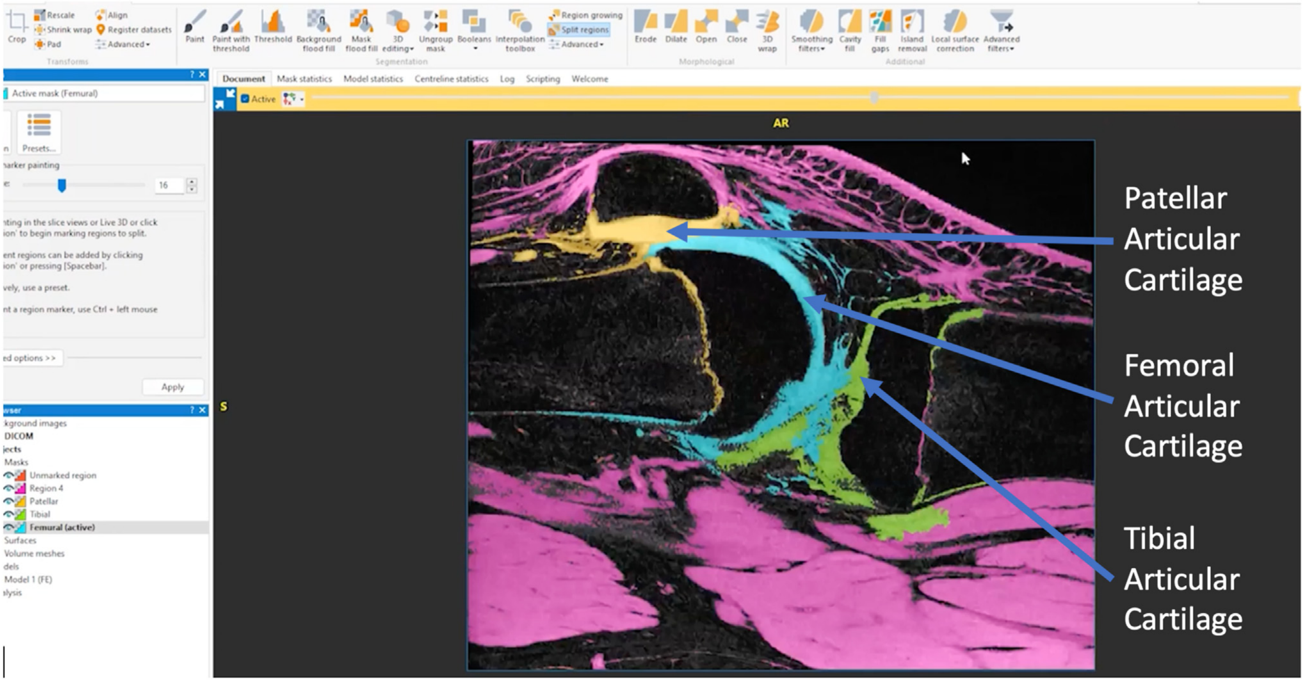

Fig 2. To create a 3-dimensional model of the articular cartilage of the patellofemoral joint, the mask is split into 4 different regions using the "split regions" tool. These regions are the femoral region, patellar region, tibial region, and a region that includes the rest of the tissue (which will not be included in the final model).

again slice by slice for accuracy. The masks are then converted into surfaces, which can be exported into a format compatible with 3D printing software.

The surfaces are embossed with a patient identifier, as well as a marker that indicates where the surfaces articulate with each other. The authors recommend

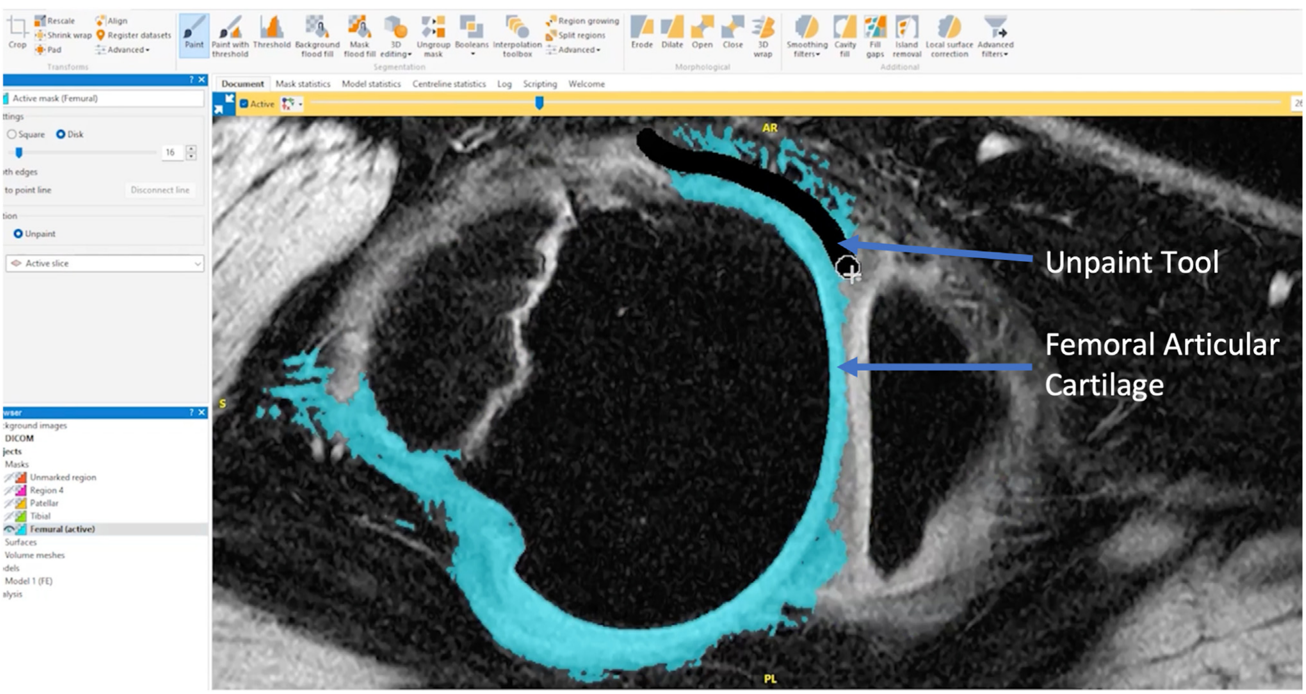

Fig 3. In the process of creating a 3-dimensional model of the articular cartilage of the patellofemoral joint, to ensure that the mask of the articular cartilage of the patellofemoral joint is accurate, the mask is edited manually with the ScanIP paint and unpaint tools.

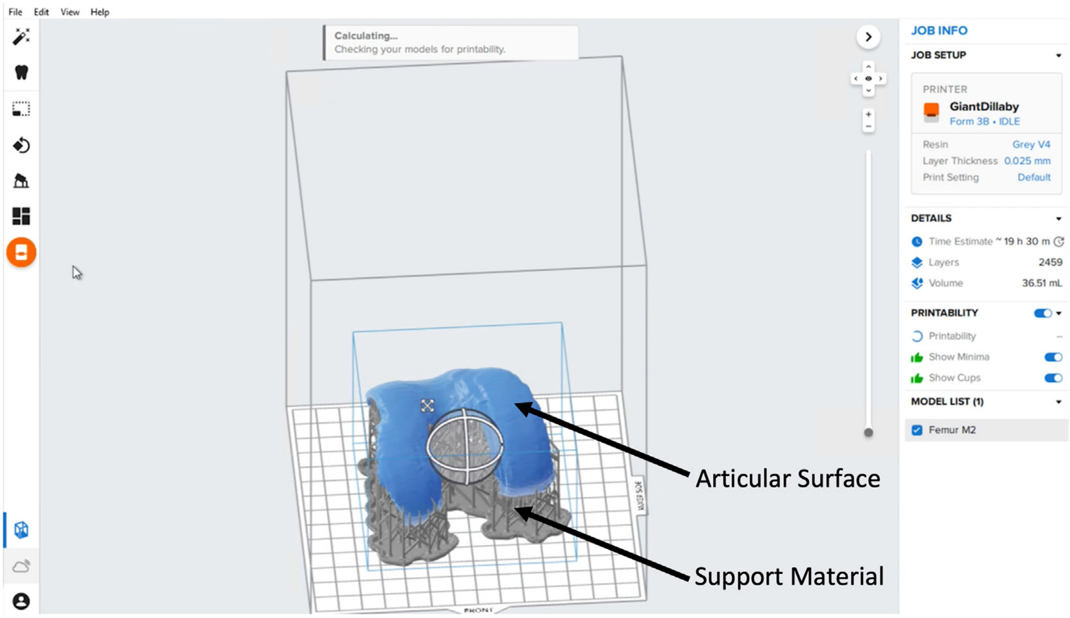

Fig 4. In one of the final steps of creating a 3-dimensional model of the articular cartilage of the patellofemoral joint, the model orientation and support material location is chosen in the software Preform to maximize the accuracy of the articular surfaces of the patellofemoral joint of the final printed model.

placing these markings such that they do not interfere with the articulation. The surfaces are then exported to STL files, which is the format used for 3D printing.

3D Printing

Our lab uses Formlabs (Somerville, MA) Form 3B and 3BL printers. The software Preform (Formlabs) is used to prepare the STL files for 3D printing. First, the print material is selected based on the purpose that the printed models will serve. Next, a high resolution is chosen (sub-millimeter) so that minimal morphological information is lost in the printing process. Finally, the orientation of the print and location of the support material is selected. The authors recommend orienting the print such that the articular surfaces do not have any support material attached to them to maintain the accuracy of those surfaces (Fig 4). The print is then exported to the 3D printer. The authors use a Form 3B or Form 3BL (Formlabs) stereolithography printer, but any printer that can print with high enough resolution (determined by the purpose that the print serves) can be used.

Postprocessing

The following process is specific to Formlabs printers, although many printers have their own required series of postprocessing steps. Once the print is complete, the 3D-printed models are washed in isopropyl alcohol for 20 minutes in a Form Wash (Formlabs). After the wash, the print is allowed to dry at room temperature at least

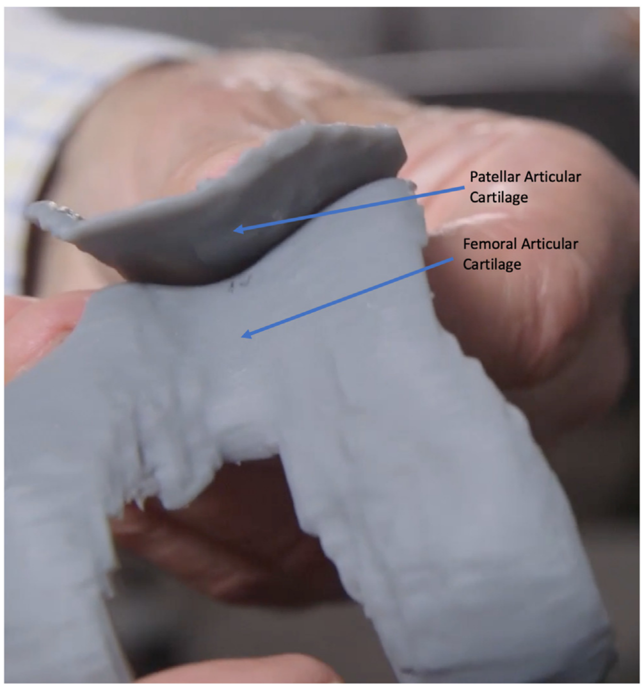

Fig 5. After creating a 3-dimensional model of the articular cartilage of the patellofemoral joint, the models are analyzed for morphological features such as joint congruity.

30 minutes. The print is then placed in a Form Cure, where it is exposed to ultraviolet light for 30 minutes at 60°C. Last, the support material is removed by hand.

Table 1. Pearls and Pitfalls

Pearls	
	Use an MRI sequence that collect data that is high enough resolution to create accurate models
	Having multiple people, including a musculoskeletal radiologist, exam the mask for accuracy will improve the final print
	Print using higher resolution than the imaging data to ensure minimal information is lost in the printing process
	Orient the print such that support material does not contact the articular surfaces
Pitfalls	
	Standard MRI sequences are usually not high enough resolution to be able to create accurate models of articular cartilage
	Many deidentification processes leave metadata that can be used to identify patients
	Failing to check the accuracy of the mask after using a smoothing filter will result in an inaccurate model

MRI, magnetic resonance imaging.

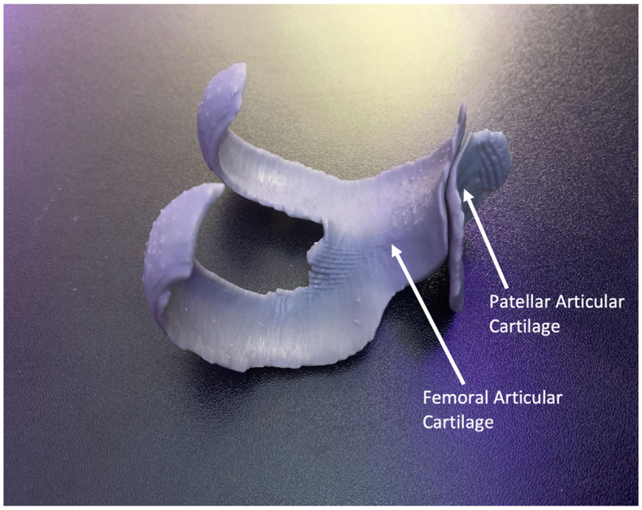

Fig 6. A 3-dimensional printed model of the articular cartilage of the patellofemoral joint based on the magnetic resonance imaging scan of a patient with patellar instability, created through the protocol described in this work. The congruence of the joint is apparent.

The finished articular cartilage prints can be examined for congruity and other morphological characteristics of interest (Fig 5). Pearls and Pitfalls for the entire technique can be found in Table 1.

Discussion

Printing articular cartilage in 3D is technically demanding but important to understand articular surface interactions. We believe that this technique is important for orthopaedic research scientists who study joint biomechanics. In the evaluation of fractures involving articular surfaces and in surgery that alters articular surfaces such as femoral trochleoplasty, preoperative and postoperative understanding of articular congruity, or lack thereof, will likely improve decision-making in selected or particularly complex cases.

Example Findings

In a series of articular cartilage prints of 5 recurrent patella dislocation patients, we have found articular congruity in the PF joints of all 5 patients despite dysplasia (Fig 5, Fig 6, Video 1). This congruity is found at the point where the patella enters the trochlea (based on imaging) and along the patella's likely path within the trochlea. Earlier studies using printed recurrent patella dislocation knees from computed tomography could suggest congruity, but 3D-printed articular cartilage is more definitive because it provides the actual articulating surfaces.[5,8] This consistent finding suggests that deepening trochleoplasty would likely cause articular incongruity in patients with trochlea dysplasia. This illustrates the importance of using techniques that allow for better understanding of the true articular surface of joints.

Acknowledgments

The authors thank Andrew Osborne and Kimberly Conner of the Yale School of Medicine Office of Communications for their assistance with the video. This publication was made possible by the Richard K. Gershon, M.D. Fund at Yale University School of Medicine.

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