



Creation of a Three-Dimensional Printed Model for the Preoperative Planning of Hip Arthroscopy for Femoral Acetabular Impingement

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Abstract: We describe a technique that creates a 3-dimensional (3D) printed model from a patient's own computed tomography scan. This introduces an adjunct to conventional imaging for the surgical management of femoral acetabular impingement. The creation of a tactile 1:1 scale model with patient-specific anatomy allows for free manipulation and inspection. This is compared to planar imaging and 3D-reconstructed computer tomography scans, which are limited in their degrees of movement. With a minimal learning curve because of a highly iterative process, no prior experience in 3D printing is required to successfully complete this technique. The primary barrier of entry is the initial start-up cost of a 3D printer; however, the price per print is minimal. These models are valuable clinical tools that can be used in preoperative planning, patient education, and medical trainee learning.

Hip arthroscopy for femoral acetabular impingement (FAI) poses challenges in ensuring accurate cam or pincer resection. Conventional planar imaging and 3-dimensional (3D) reconstruction of computed tomography (CT) scans provide information on the bony structures, although they lack freedom of manipulation and inspection as compared to a tactile 3D-printed model. Ali et al.¹ described the technique of using a 1:1 3D printed model for preoperative planning and intraoperative use; however, currently no literature exists detailing the steps to create a 3D-printed model from a patient's own CT scan.

Three-dimensional printing has become a popular topic in medicine, with innovations looking to improve various aspects of the field, including surgical planning and education.² However, most of these proposed ideas

require further development or are not easily translatable because they require high cost infrastructure and expert knowledge. This article presents a low-barrier technique for creating a 1:1 3D-printed model from a patient's own CT scan with a minimal learning curve. This technique is easily repeatable because of its iterative nature and provides a resource for the physician in preoperative planning, patient education, and medical trainee learning for FAI hip arthroscopy.³⁻⁵

Technique

Selecting the Appropriate Imaging

Optimal imaging for this technique is a high slice count axial CT scan with a soft-tissue view. High slice counts result in greater resolution when creating the 3D model, and using the soft-tissue view creates a higher contrast for the imaging software used later in the process. Ideally for 3D printing, 0.6 mm or 1 mm slices provide the best definition. Once the images have been selected, they will need to be downloaded or transferred as a Digital Imaging and Communications (DICOM) file from your Picture Archiving and Communication System.

DICOMS to a 3D model

When the DICOMS have downloaded or transferred, the next step is to import them into Horos (<https://horosproject.org>; sponsored by Nimble Co LLC d/b/a Purview, Annapolis, MD, USA), a free-to-use DICOM viewer. Within Horos, a DICOM file can be converted to

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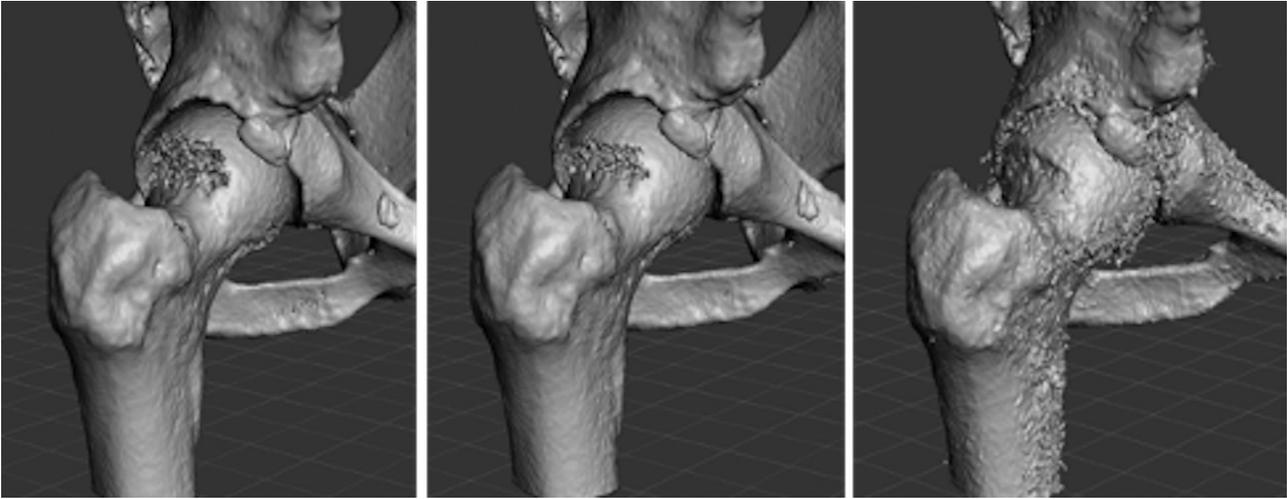


Fig 1. Comparison of Hounsfield unit reference point selection in Horos for the creation of a 3-dimensional model from a patient's own computed tomography scan (left = 320, middle = 220, right = 120). Note incomplete modeling of posterior-superior femoral head on the left, and loss of definition between the femur and acetabulum on the right. Proper balancing of the reference point is crucial in ensuring that proper anatomy is being defined.

a 3D model by using the 3D surface rendering option (Video 1). There are multiple available programs that can be used at this point to convert DICOMs to 3D models. However, Horos' features and it being free to use is well suited to this process. It is important to note that Horos' is only free to use on Mac systems.

Although each program is different, they all rely on setting a reference Hounsfield Value to construct a 3D model from a CT scan DICOM file. A good starting place for this value is 220; then the value can be adjusted from there. If more bone needs to be modeled, the value can be adjusted between 160 and 220, although this often results in a decrease in fine details and definition of joints (Fig 1). If less bone needs to be modeled, the value can be increased up to 350; however, this can create incomplete rendering of the bony structure

(Fig 1). When selecting to find the optimal Hounsfield Value, there may be many small floating islands of modelled material not attached to the bony structure, which can be ignored in this step as they will be removed in the following steps.

Many of these programs also give optional smoothing and resolution options. By introducing smoothing into the equation, the print loses fine details and definition; as a result it is best to leave this at its lowest possible setting. As for the resolution setting, this value needs to be maximized to ensure the greatest detail. Once a suitable model has been created, the file will be exported as a Stereolithographic (STL) file, which will then be imported into Meshmixer (<http://www.meshmixer.com>; Autodesk, Inc. San Rafael, California, USA), a free-to-use 3D modeling software.

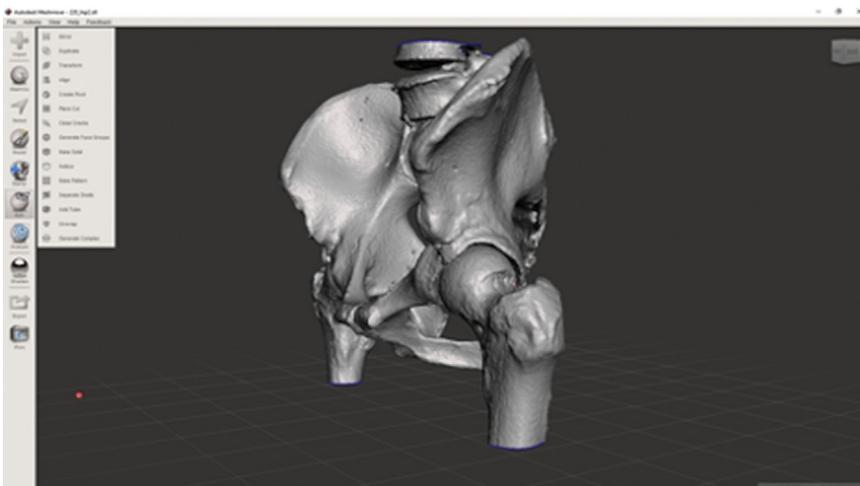


Fig 2. Meshmixer user interface, with "Plane Cut" visible underneath the "Edit" option icon. The "Lasso" tool can be found similarly under the "Select" option icon. These are the primary tools for removing unwanted structures before final model creation and printing.

Table 1. Pitfalls for 3D Printing

Keep filament in a dry environment, PLA is hygroscopic, and it can greatly affect print quality.
Printing via USB thumb-drive allows storage of completed print files for easy re-printing or restarting in case of printer error.
Artifacts on CT will distort the 3D model, this includes prior hardware.
Lower-end computers may struggle with the software and processes, hardware specifications can be found on the websites for the respective programs.
All 3D printers require consistent calibration, if printing issues occur this would be the first step to fix the problem.

3D, 3-dimensional; CT, computed tomography; PLA, polylactic acid.

Preparing the Final 3D Model

In Meshmixer, the STL file of your model that was created by Horos can be imported. The first step of processing the model is to isolate the material that needs to be printed. This can be done with the “Plane Cut” tool under “Edit” or the “Lasso” tool under “Select” (Fig 2). Next it is best to orientate the model to maximize its stability by balancing the center of gravity of the print. To achieve this, the model is positioned using the “Transform” function under “Edit” (Video 1). The next step is to remove excess material and to create a flat bottom surface for the print to begin on, which can be done using “Plane Cut” under “Edit” (Video 1). The amount of bone removed depends on personal preference and what is planned for the surgery, although what is important is creating a flat base to

stabilize the printing of the model. Once all excess bone has been removed from the model, the final step is to fix any errors that occurred through the creation and editing of the model. The “Inspector” tool under “Analysis” can be used to automatically detect and repair all errors, including removing all floating islands of residual bone, and also flattening and repairing any areas missing from the “Plane Cut” or “Lasso” tools used in the previous steps. The final model can be saved by exporting as a STL file.

Selecting a 3D Printer

At this stage, the model is ready to print on practically any 3D printer. However, most printers require the use of their own proprietary software that will turn the STL file into a printing path with X, Y, and Z coordinates specific to the model and make. As a result, the next steps will differ depending on what model of printer is used.

Each printer’s abilities differ from manufacturer to manufacturer, and selecting one is based largely on personal preference. One of the most inexpensive options for high-volume printing is the extruder printer, which uses polylactic acid, because the low price of filament yields a minimal price per print. A 0.9 kg (2 lb) spool costs approximately \$48 USD, and each spool from experience can print on average 7 prints, leading to an average cost of approximately \$5 to \$7 USD per print (Table 1). This type of printer also has minimal

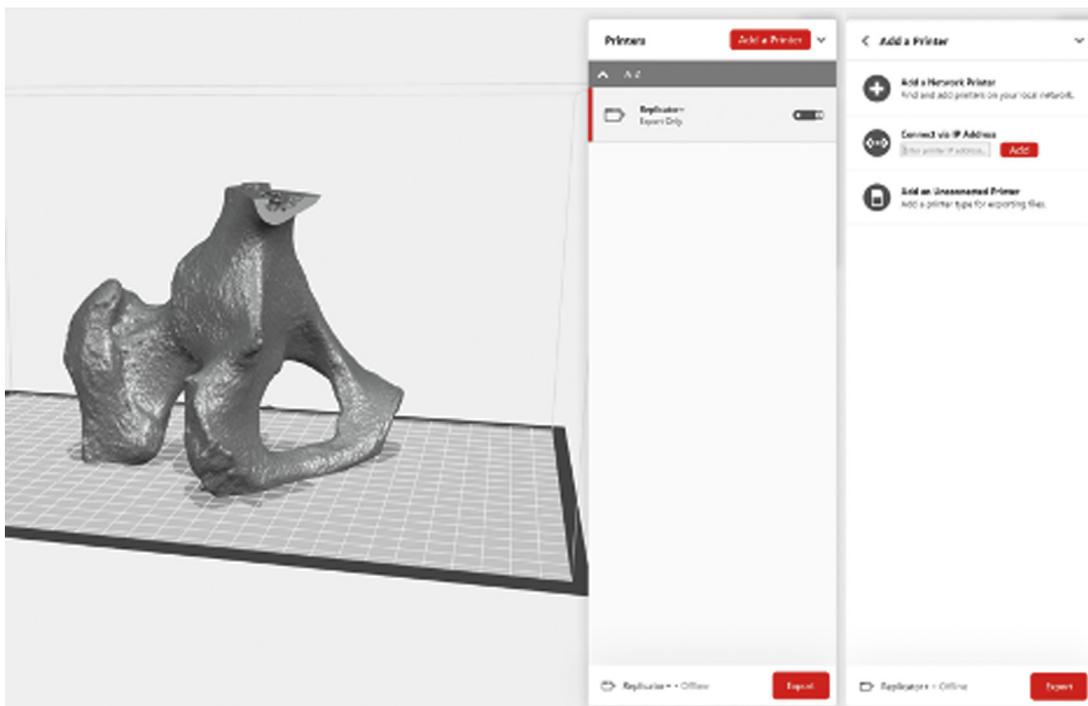


Fig 3. Selection of print options for final 3-dimensional model in MakerBot Print. To print via USB drive, first select “Add a Printer,” then “Add an Unconnected Printer,” and select your printer type. Altering these print settings can result in faster print times, although it typically results in reciprocally decreased print quality.

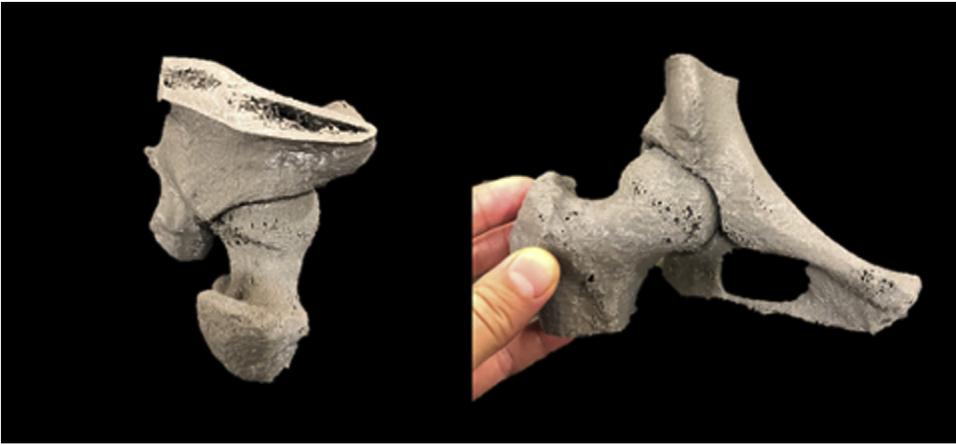


Fig 4. Completed polylactic acid print using a MakerBot Replicator+ printer. Model created using patient's own computed tomography scan, with a 1:1 model ratio.

upkeep and requires a low skill level to print at a satisfactory quality. Our team uses MakerBot Replicator + (MakerBot Industries LLC, Brooklyn, NY) for printing, because it provides a consistent platform that is plug-and-play out of the box and is overall user-friendly. However, if you choose to use another manufacturer, STL files are still appropriate for most printers, although the last step will differ depending on the software the printer uses.

Printing using MakerBot

MakerBot printers use their proprietary software called "MakerBot Print" (<https://www.makerbot.com/3d-printers/apps/makerbot-print>; MakerBot Industries LLC). The STL file exported from Meshmixer can be imported to the MakerBot Print software. To achieve the greatest resolution, while balancing print time, and filament usage, we suggest using the "MinFill" setting, 0% "Infill Density," 0.2 mm "Layer Height," "1 Shell – Very Delicate," "Padded Base + Brims," and selecting "Breakaway Supports." The "MinFill" option alters the amount of infill that is out within the bounds of the 3D model. However, because of the complex organic nature of the model created by the CT of the bone, additional infill leads to unnecessary structures that do not add to the strength of the model. Both the "Infill Density" and "Shell Layers" are also similar in that it will generate additional structures, extending print times and using excess filament. Altering

the "Layer Height" changes the thickness of layers being laid down, because the minimum slice from the CT is 0.6 mm, and any number below this value will have no resolution loss. Despite this, a lower number (i.e., 0.2 mm) leads to smoother transitions between CT slices. Last, selecting for supports ensures that a framework is created underneath any overhangs, which will prevent that collapsing of the model while printing.

At this point, the file is ready to print. Selecting the print button in the lower right corner will allow you to either print with a USB cable attachment, USB drive, or over a network (Fig 3). This can be done by using the "Add a Printer" button and selecting one of the following options. To print via USB drive, select "Add an Unconnected Printer" and select the model you are using (Fig 3). Overall print time varies depending on the size of the model, the printer type, and any deviation from the settings described. However, using this process, an average-sized hip ranges between 14 and 18 hours of print time (Fig 4).

Discussion

Three-dimensional printed models, using a patient's own CT scan, can be accomplished with a minimal learning curve (Table 2). Because of the highly iterative nature of the process, we estimate adequate proficiency in creating these 3D models to take between 5 to 10

Table 2. Advantages and Disadvantages of 3D Printing

Advantages
Minimal learning curve for 3D printing because the procedure is largely iterative
Low cost per model
Tactile model that provides learning tool for patients and learners
Disadvantages
Initial start-up costs can be substantial when acquiring a 3D printer
Quality of model is reliant on the quality of imaging (poor CT scans will create poor models)

3D, 3-dimensional; CT, computed tomography.

Table 3. Pearls for 3D Printing

Some PACS systems do not save all the slices for musculoskeletal CT scans. Asking for the entire scan to be archived will increase the resolution of your models.
Once the process has been mastered, it is quite easy to adapt to modeling other anatomy from CT scans.
Printing several models together on a single build plate can optimize print time over a weekend, although if an error occurs, all models will likely fail.
3D models using this process are printed at a 1:1 scale.

3D, 3-dimensional; CT, computed tomography; PACS, Picture Archiving and Communication System.

Table 4. Cost of Resources for the 3D printing of CT

Resource	Cost (USD)
Software	\$0
Meshmixer	
Horos	
MakerBot Print	
MakerBot Replicator +	\$2,000
MakerBot PLA filament (1 kg)	\$48
Estimated price per print (hip)	\$5-\$7

3D, 3-dimensional; CT, computed tomography; PLA, polylactic acid.

prints. This is based on experience of training other researchers and surgeons to adapt these processes into their own work.

The process can also be adapted to the printing of other CT scans (Table 3). It is important to recognize that the quality of the model is directly proportional to the quality of the CT scans, where higher slice counts will result in a greater resolution of prints. The final model will be at a 1:1 scale of the patient's hip and can provide a tactile representation of their specific morphology. This allows for a model that can be studied before surgery with free movement, as compared to a 3D CT reconstruction, which is often only provided in a single plane of rotation. By allowing for free manipulation of the model, we can use new reference points for identifying levels of resection for FAI osteoplasty. For example, the "birds-eye" described by Ali et al.¹ introduces a new view that shows the lateral extent of cam and pincer deformities.

One of the largest barriers to this technique is the primary start-up cost of a 3D printer (Table 4). However, other printers exist at lower price points; we suggest the MakerBot Replicator + because it is reliable, low maintenance, and requires minimal set-up. After a printer has been acquired, the price per print maintains a relatively low cost, typically \$5 to \$7 when using polylactic acid filament. In conclusion, 3D-printed models for preoperative planning of hip arthroscopy is relatively inexpensive after initial start-up costs and can be accomplished with no prior experience in 3D printing.

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