

Development of a 3D-printed Ultrasound-able Anthropomorphic Hip Joint Phantom

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“Development of a 3D-printed Ultrasound-able Anthropomorphic Hip Joint Phantom”

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Abstract

Background: Musculoskeletal (MSK) training constitutes a small percentage of current medical training, but ~20% of healthcare visits in the USA are related to MSK disease. Limited MSK training may contribute to the lack of confidence residents report in performing arthrocentesis and intra-articular joint injections. Previous studies have used expensive commercial models (>\$5000) for resident training, but few have used low-cost, three-dimensional (3D) printed anthropomorphic phantoms. Our objective was to develop an inexpensive, high-fidelity, anatomically accurate, and ultrasound-able anthropomorphic hip joint phantom (UAP) using 3D printing techniques.

Methods: Computed tomography (CT) data obtained from the New Mexico Decedent Image Database (NMDID, New Mexico) were used to create 3D printed molds from segmented layers of tissue from the hip joint. The CT data were segmented by specifying the Hounsfield Units of each tissue using 3D Slicer (slicer.org), creating stereolithographic (STL) files. The STL files were imported into Blender (Blender Foundation, USA) and cleaned to improve the surface topography. Each file was then superimposed over one another. A series of processes was then completed using the *Boolean* and *Solidify* modifiers. This created solid objects of each tissue layer. Once the layers are solidified and cut to a specific size, cubed objects are added and conjoined with the surface mold to create a functional shape that could be used to create a digital casting mold. The files were then exported for printing, with each layer printed separately. The

20 molds were then filled with ultrasound-able tissue mimicking materials (e.g. ballistics gel,
21 silicone). The validation of the model's anatomical accuracy under ultrasound was completed by
22 an attending physician at The Ohio State University Wexner Medical Center.

23 **Results:** The 3D printed UAP was shown to have anatomical accuracy for the following tissue
24 layers: bone, joint capsule, skin, & adipose tissue. The 3D printed UAP costs a total of \$200 to
25 create.

26 **Conclusions:** The development of this 3D printed UAP can provide an alternative to costly
27 commercial models and provide a more equitable means of training residents on MSK-related
28 procedures. Providing learners with an authentic environment to practice without the fear of
29 causing injury or pain to the patient.

Introduction

Musculoskeletal (MSK) training constitutes a small percentage of current medical training, but ~20% of healthcare visits in the USA are related to MSK disease.¹⁻³ Limited MSK training may contribute to the lack of confidence residents report in performing arthrocentesis and intra-articular joint injections.¹⁻⁴ Previous studies have used expensive commercial models (>\$5000) for resident training, but few have used low-cost, three-dimensional (3D) printed anthropomorphic phantoms.⁵ Our objective was to develop an inexpensive, high-fidelity, anatomically accurate, and ultrasound-able anthropomorphic hip joint phantom (UAP) using 3D printing techniques. Reviewing alternative ultrasound-able tissues and their acoustic properties established in the literature⁶ we seek to solve the lack of adequate soft tissue imaging materials used in joint injection models. Therefore, our goal is to develop an ultrasound-compatible anthropomorphic phantom (UAP) model of the hip using 3D printing techniques and to validate the model's anatomical accuracy. This manuscript outlines the steps involved in creating the 3D-printed UAP, including the software, databases, and modeling techniques used. The process presented can be replicated to accommodate other 3D printed UAPs that could benefit from the modeling technique of creating 3D *digital molds*.

Methods

Acquisition of DICOM Data

DICOM data for educational and training purposes can be acquired from multiple sources, including the New Mexico Decedent Image Database (NMDID, New Mexico), the National Institute of Health Cancer Imaging Archive (TCIA, Maryland), or using DICOM scans from consenting patients at an institution. Before selecting the type of DICOM data to request, it is

important to understand the specific anatomical tissues that will be replicated. For example, MRI scans are better suited for use when segmenting soft tissues (e.g., heart, brain, etc.) and CT scans may be better for modeling skeletal structures. The researcher must also consider the pathologies that could be found while segmenting the DICOM data and decide if that dataset is suitable for their phantom. The DICOM data specifically used for the development of this model came from the Cancer Imaging Archive.⁷ Some of the methodologies outlined were inspired by a course reader used for a 3D printing elective course for health science students.⁸

Software Tools

The primary softwares that were used in this process are 3D Slicer (slicer.org), Blender (Blender Foundation, USA), and the proprietary software for the 3D printer, Bambu Studio (Bambu Lab, China). These tools are essential for segmenting the anatomy, creating digital molds, and preparing the structures for printing. Below is a brief summary of the purpose for each software:

- **3D Slicer:** Used for importing and segmenting the DICOM data.
- **Blender:** Used for cleaning up the segmented anatomy to create digital casting molds.
- **Bambu Studio:** Used for preparing the 3D models for printing.

Segmenting Software

3D Slicer is a free open-source segmenting software which allows the researcher to digitally segment out the anatomy. The segmentation software is used to specify density properties from the Hounsfield Units (HU). These are units that are a quantitative scale describing radiodensity.

By selecting for specific HU the researcher can “segment” the specific type of tissue desired (e.g. cortical bones HU is >200).

Importing DICOM Data

Once the software is opened the researcher will import the DICOM files by selecting “Add DICOM data” (Figure 1).

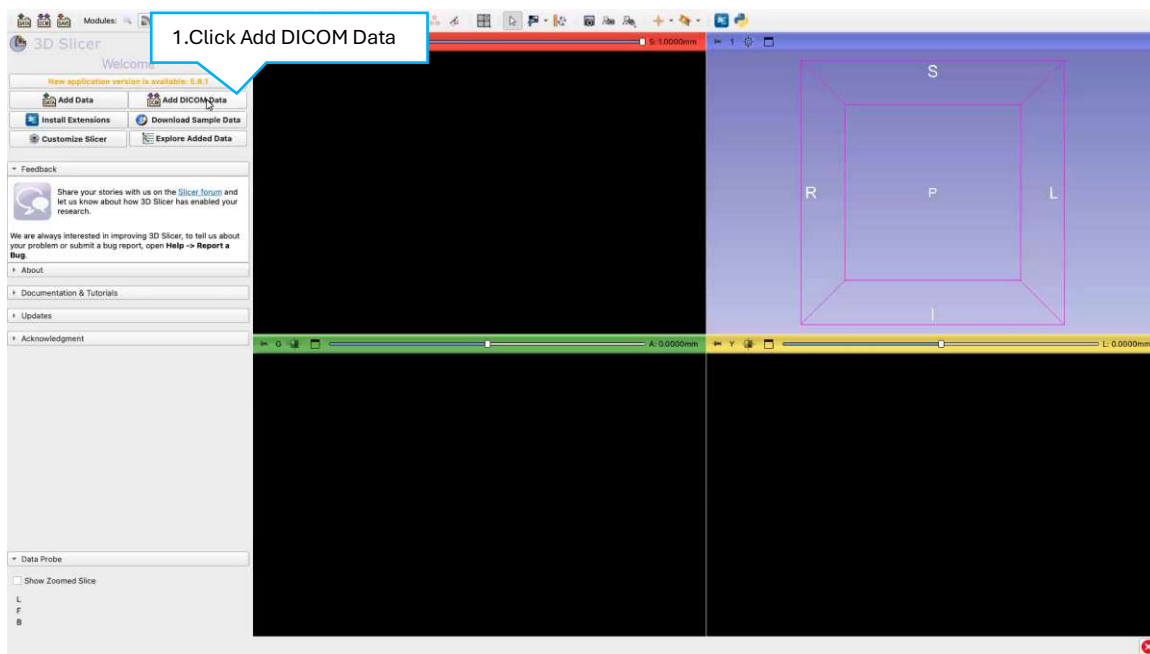
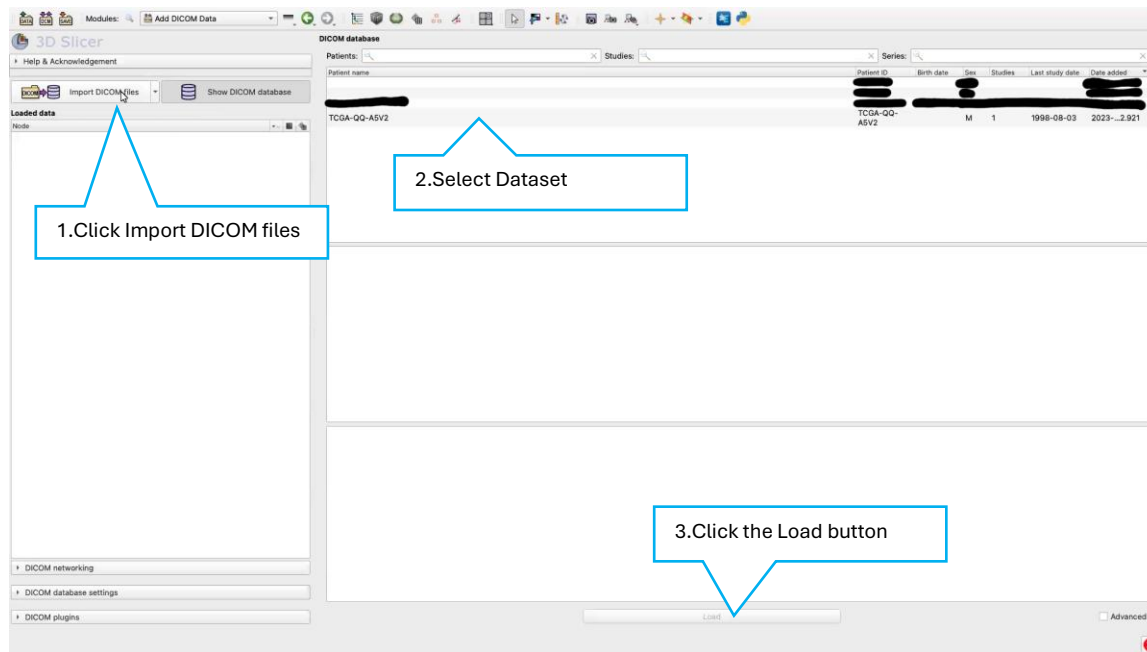


Figure 1 *Adding DICOM Data*

Next, you will click “Import DICOM files”, or you will drag and drop the file dataset (Figure 2). The researcher needs to add the entire folder of the dataset by importing the folder or opening the folder and selecting all the files. Then you will select a specific patient and load the information (Figure 2). Once that is loaded, then you'll see the dataset on the next screen.

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96 Figure 2 *Importing DICOM Data*

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99 *Viewing and Segmenting*

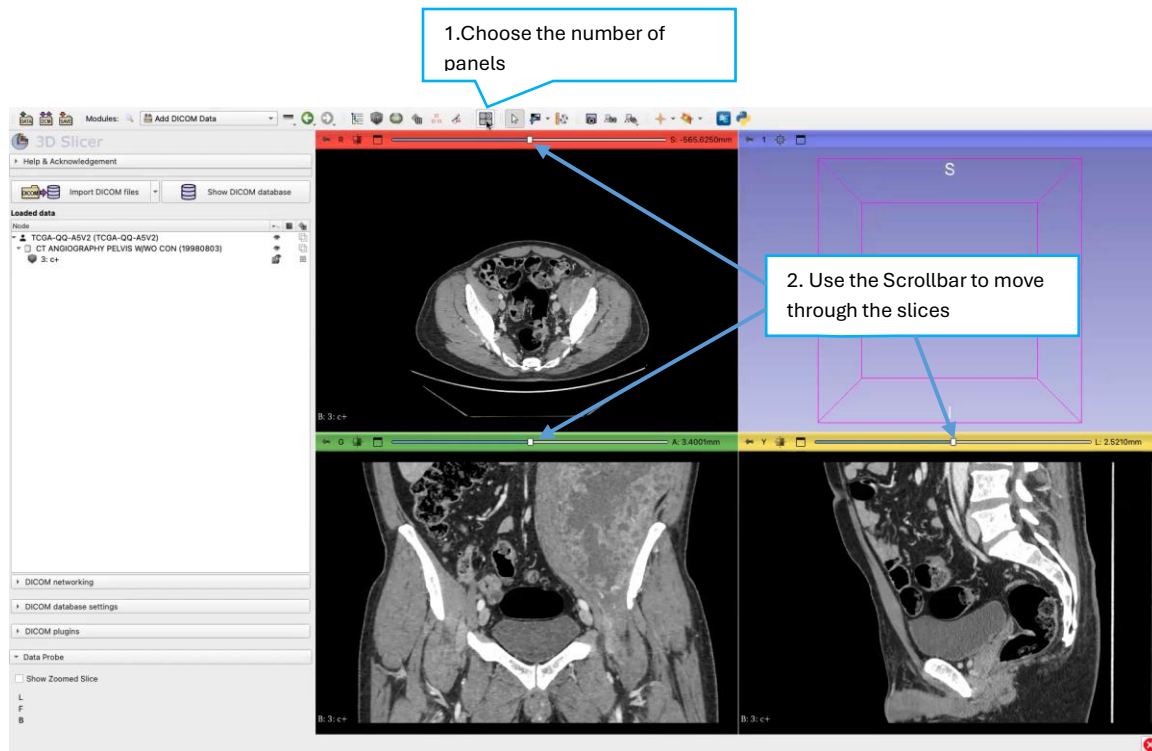
100 The researcher wants to make sure that we have at least 4 panes visible. This allows us to see the
101 axial, coronal, sagittal, and object view. If there are more than 4, go to the top of the window and
102 select the desirable number of panes to display (Figure 3). The scrollbar can be used to move
103 through the individual slices from each plane (Figure 3). The researcher must use these tools to
104 orient themselves with the anatomy. Understanding where structures are in relation to one
105 another (anterior, posterior, superior, etc) is crucial to correctly identifying the pertinent anatomy
106 being segmented.

107

108

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110



111

112 Figure 3 *Orienting the Data*

113

114

115 Next, the researcher will create a region of interest (ROI) to narrow down the area of anatomy
116 they are segmenting. On the top of the screen, select the dropdown menu tab, select converters,
117 and then select crop volume (Figure 4).

118

119

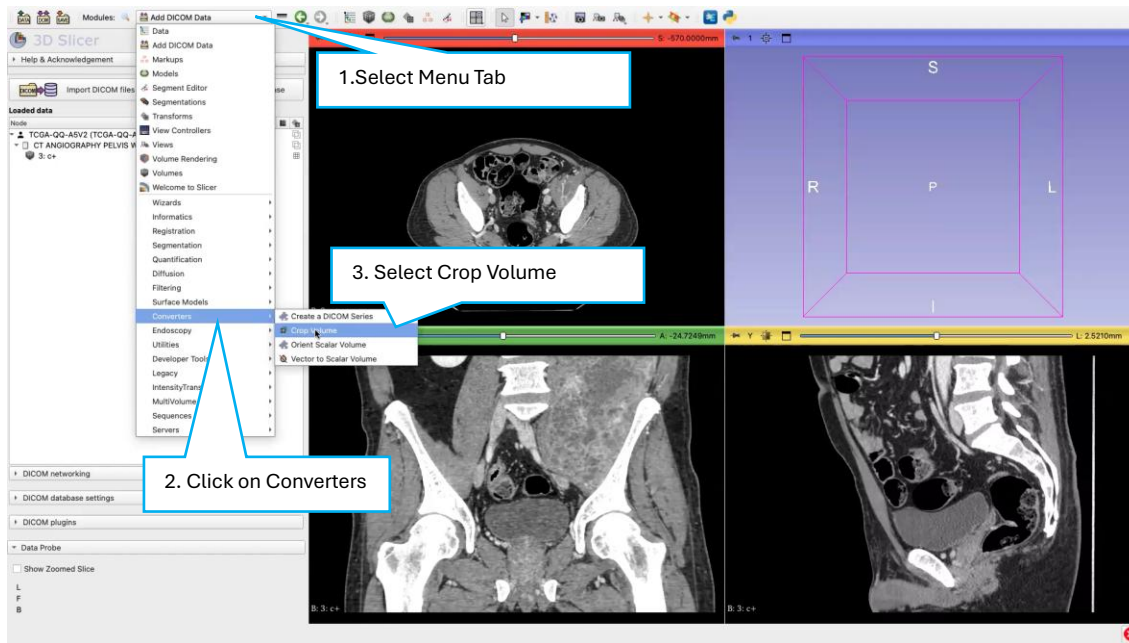


Figure 4 *Crop Volume*

The researcher will then confirm the input volume (c+) and select “create a new ROI” (Figure 5).

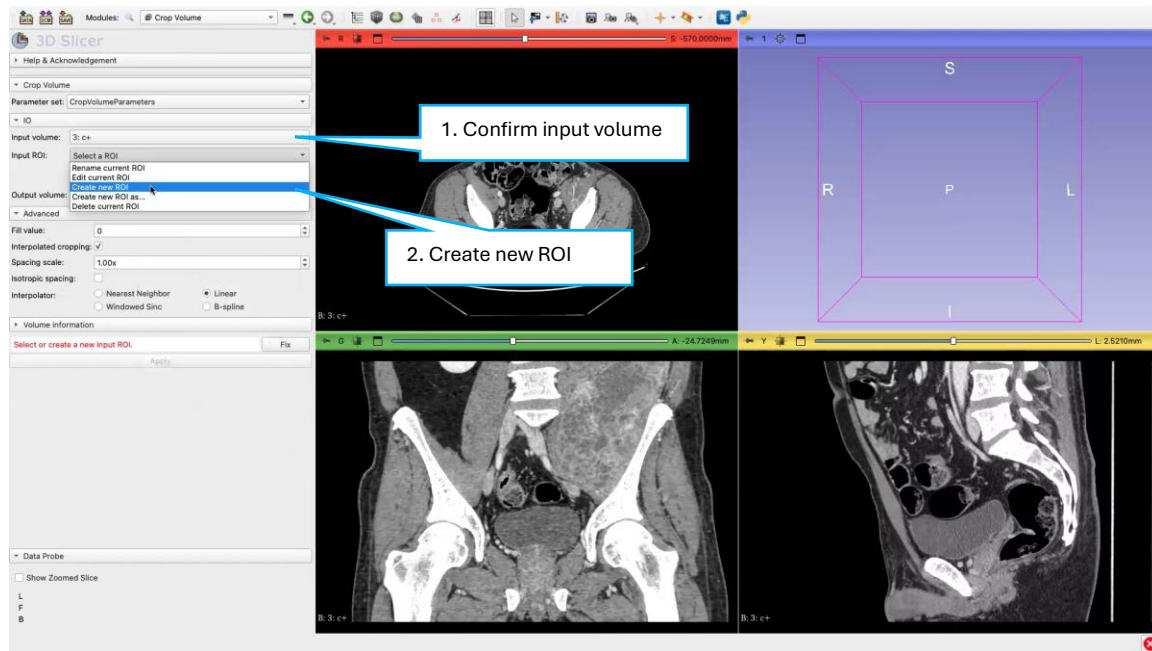


Figure 5 *Creating New ROI*

Next, the researcher will create a new ROI box by focusing on the patient's desired side; for this example, the right side was isolated. By scrolling through the coronal view, the researcher can move the ROI box to slice through the pubic symphysis, as shown on Figure 6. The researcher will repeat this process for the axial and sagittal planes using identifiable landmarks to confirm that the bony anatomy is within the ROI box (Figure 6). The identifiable landmarks will change depending on the anatomical structures you are trying to segment. After confirming the ROI, select "apply".

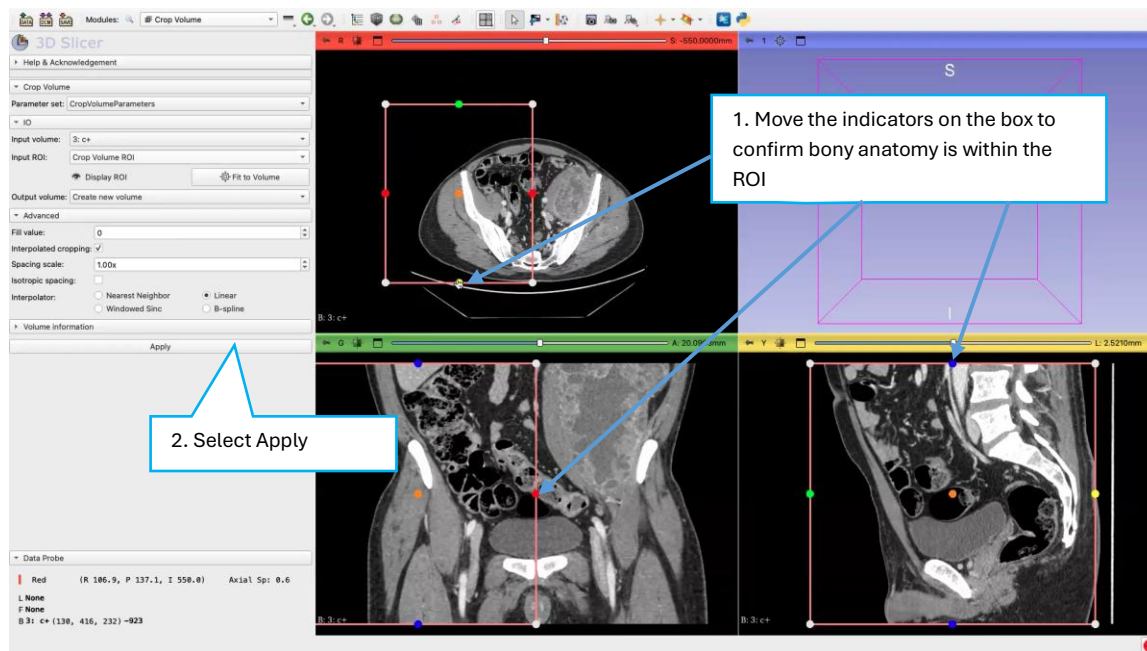


Figure 6 *Confirming ROI*

Next, the researcher will click on the menu tab and select segment editor (Figure 7).

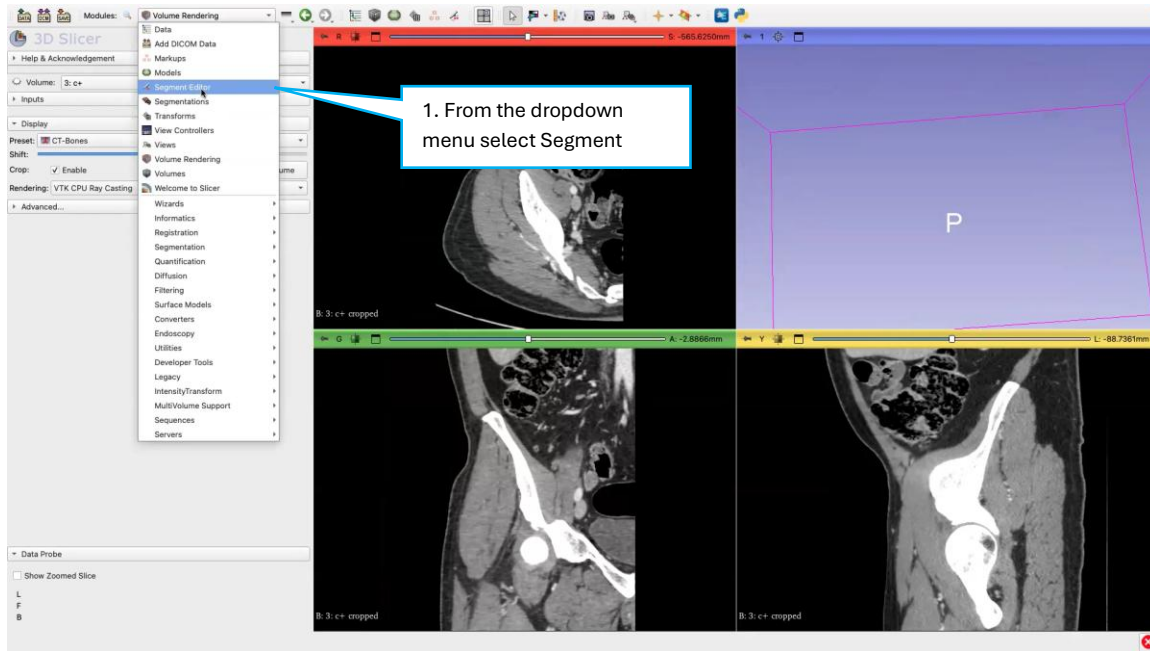


Figure 7 *Segment Editor*

Confirm the source volume, select “add new segment”, then label, and select a color for the segmentation (Figure 8).

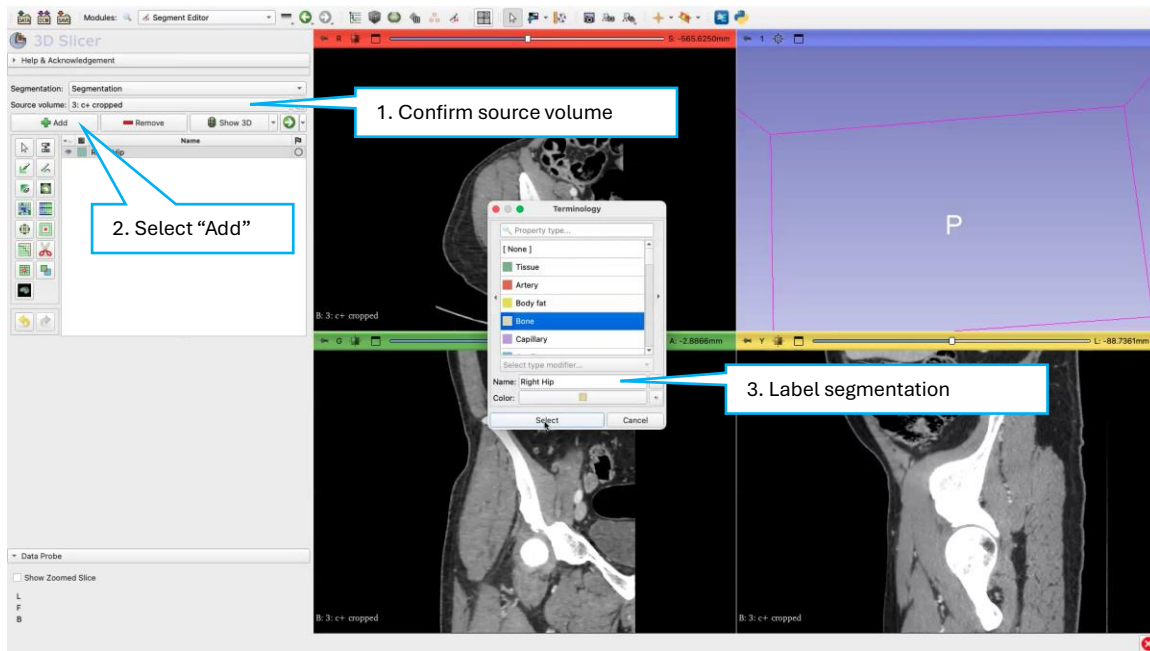


Figure 8 *Labeling Segmentation*

The next step will focus on identifying the HU for the skeleton. To do this, select the “threshold” icon (Figure 9). In the bottom left corner of the screen, observe the HU number that varies depending on the tissue the cursor is overtop (Figure 9). The HU are a quantitative scale describing radiodensity; in other words, structures that are denser will have a higher HU, whereas structures with less density will have a lower HU. Familiarize the HU’s with the bone needing segmenting. Bone will appear in ranges from 55-1000 HU for trabecular and cortical bone, respectively. Remove all the surrounding tissue by adjusting the lower limit of the threshold value until only the bone tissue is highlighted in the color chosen previously, then select apply (Figure 9). Next, move the cursor up to “Show 3D” and select, then center the object in the object view window (Figure 9). Note: *Show 3D* utilizes a lot of computing power, so be sure to deselect the icon when adjusting the *threshold* again for other structures.

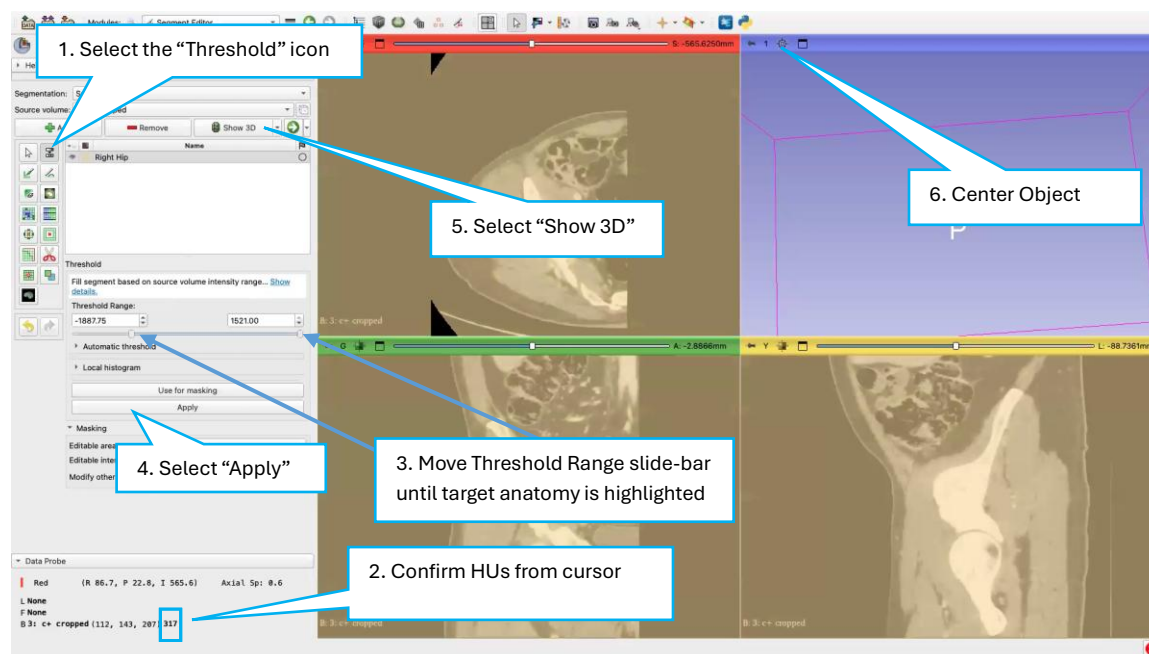


Figure 9 *Adjusting Threshold*

Occasionally, there are some objects that were within the threshold range that we do not want to keep and need to be removed; these are referred to as “mesh islands”. To do so, select “Remove Islands” and apply (Figure 10). All additional islands will be removed (Figure 11).

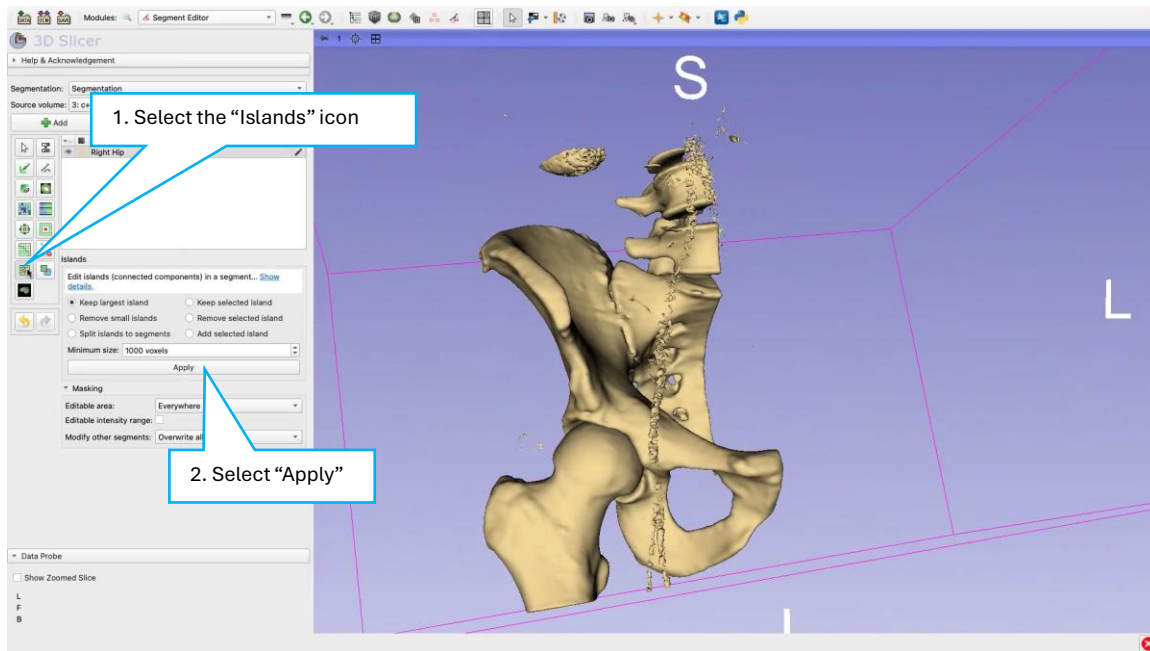


Figure 10 *Removing Islands*

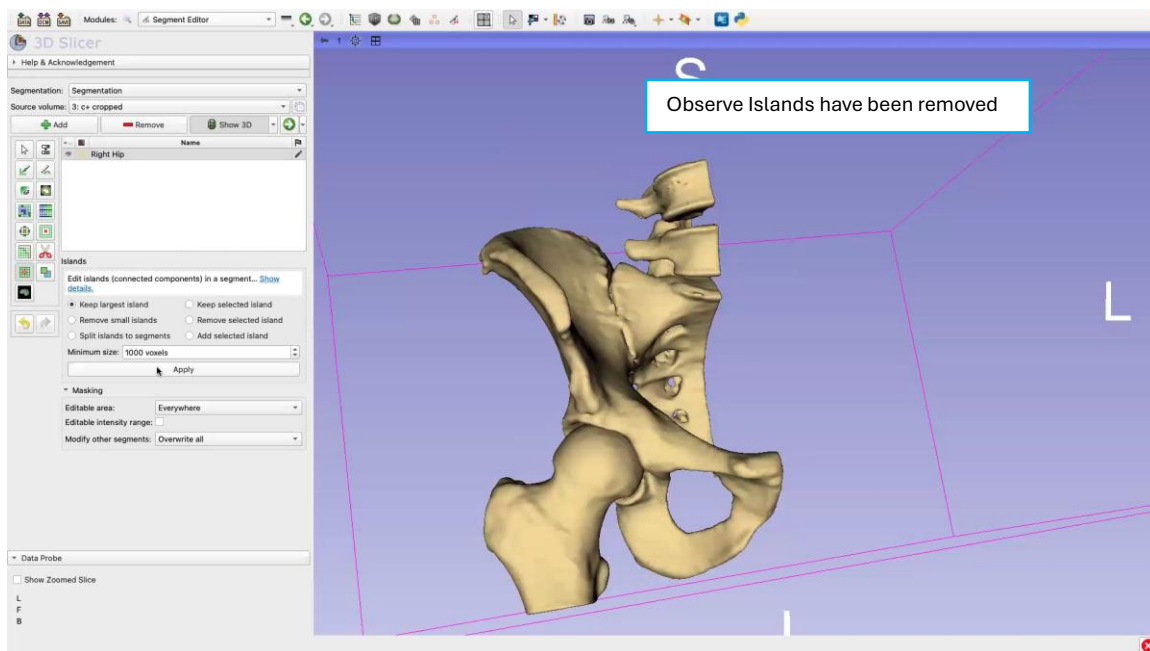


Figure 11 *Islands Removed*

If structures are still attached, the researcher can use the scissor tool to remove objects. Click and hold the left mouse button while circling the additional objects that need to be removed (Figure 12).

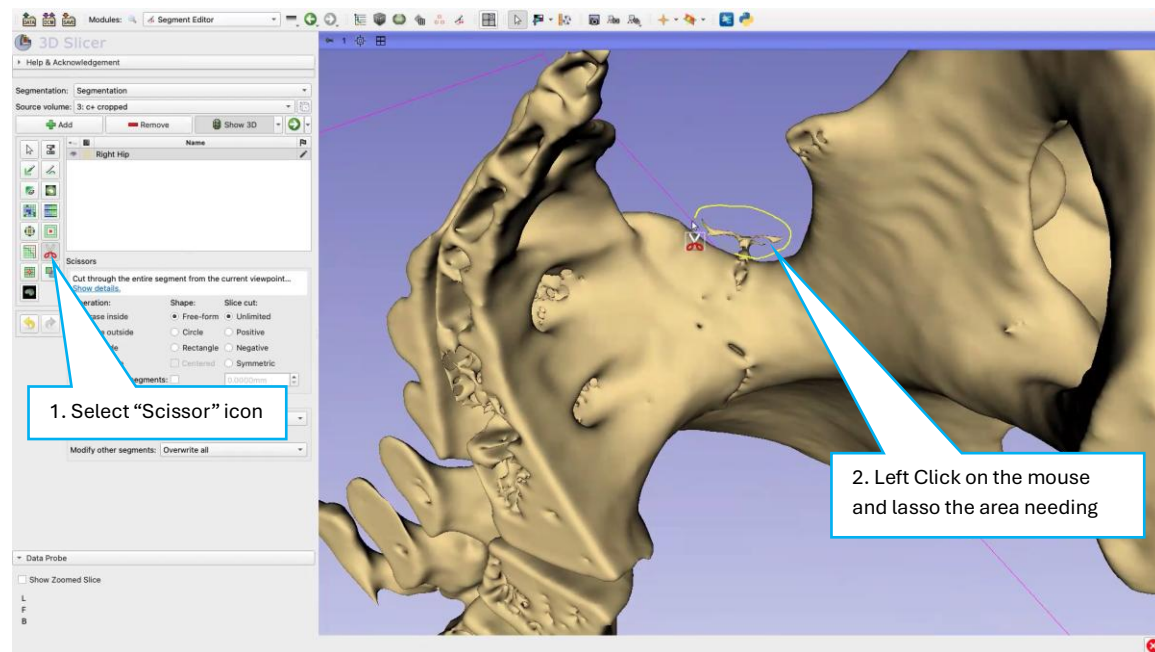


Figure 12 *Scissor Tool*

Once the researcher is satisfied with the segment then save the file as a stereolithographic file (STL) (Figure 13). Save the file in an easily accessible folder as this is the file that will be used in the next software. The researcher can repeat this process for each individual tissue layer (e.g., surface anatomy, muscles, neurovasculature, etc.). This can be either done in separate files or all within the same file.

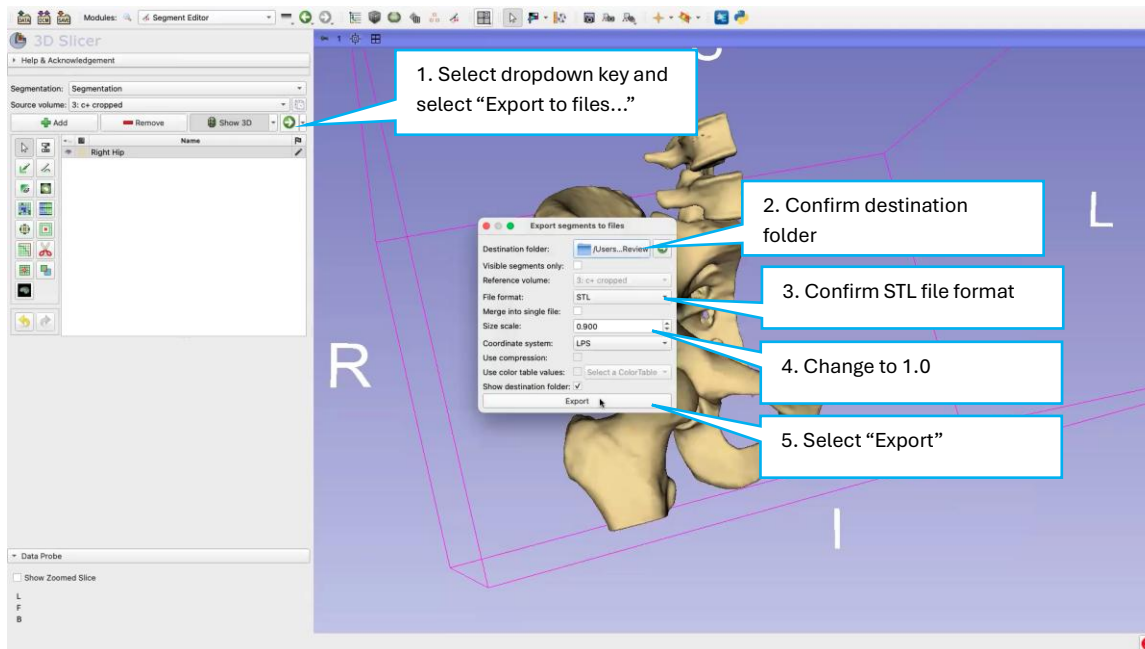


Figure 13 *Exporting STL File*

Meshing Software

The meshing software that will be used is Blender (Blender Foundation, USA), a free open-source software. The STL files from 3D Slicer are imported into Blender and cleaned to improve the surface topography of the object. Next, files will be superimposed on top of each other. A series of processes will then be completed using the *Boolean* modifier (a functional algorithm in blender which cuts specific objects that are in comparison with each other) and the *Solidify* modifier (a functional algorithm that uses the surface topography and expands it). This was done to create solid objects of each specific layer. Once the layers are solidified and cut to a specific size (to match the 3D printer build platform size), cubed objects are then added and conjoined with the surface mold to create a functional shape that can be used to create a casting mold. The files are then exported as STL files and opened within the slicing software (Bambu Studio) to be prepped for printing. Each STL file from each layer will be printed separately.

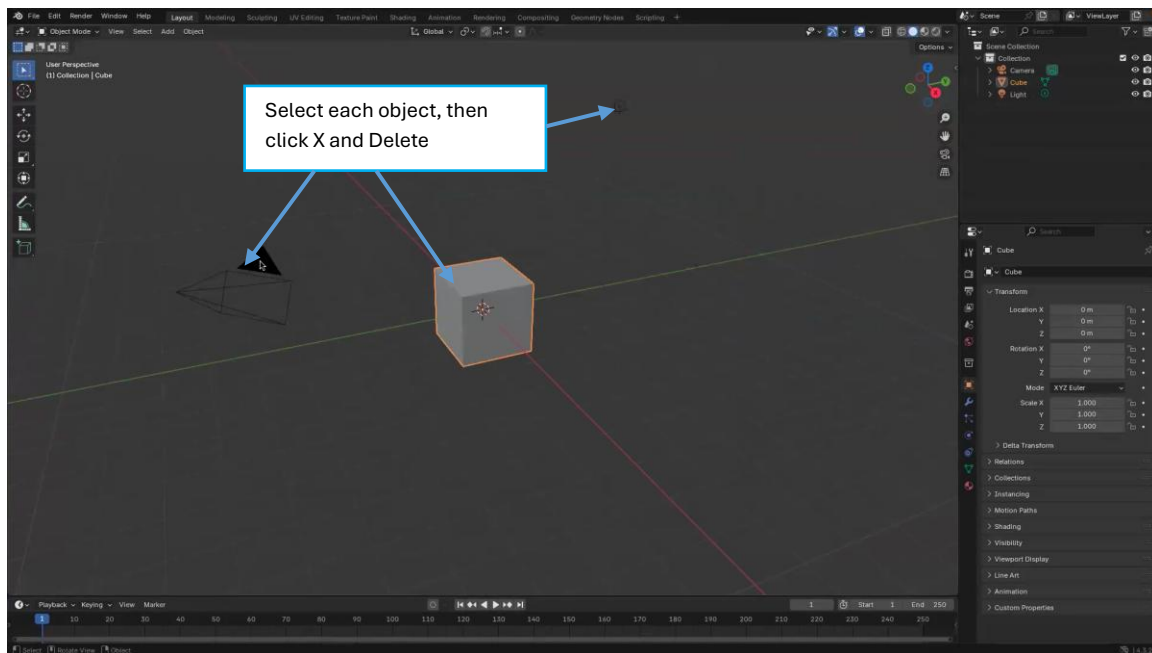
219 Review the keypad controls and shortcuts:

- 220 • Zoom = Scroll
- 221 • Rotate = Press down scroll wheel and drag mouse
- 222 • Pan = Shift + Press down scroll wheel
- 223 • Undo= Cmd+Z(Mac) or Ctrl+Z(PC)
- 224 • Redo= Cmd+Shift+Z(Mac) or Ctrl+Shift+Z(PC)
- 225 • Delete= X
- 226 • Duplicate= Shift+D
- 227 • New Mesh= Shift+A
- 228 • Move Object= G+(X,Y, or Z)
- 229 • Rotate= R
- 230 • Scale= S
- 231 • Join objects= Cmd+J

232

233 *Cleaning Segmented Anatomy*

234 Open the Blender software. Familiarize yourself with the home screen and tools. First, click
235 anywhere on the screen to close the welcome menu, and then select the cube and click X on your
236 keyboard, and select delete (Figure 14). Next, select and delete the camera and the light objects
237 (Figure 14).



238

239 Figure 14 *Setting up Blender*

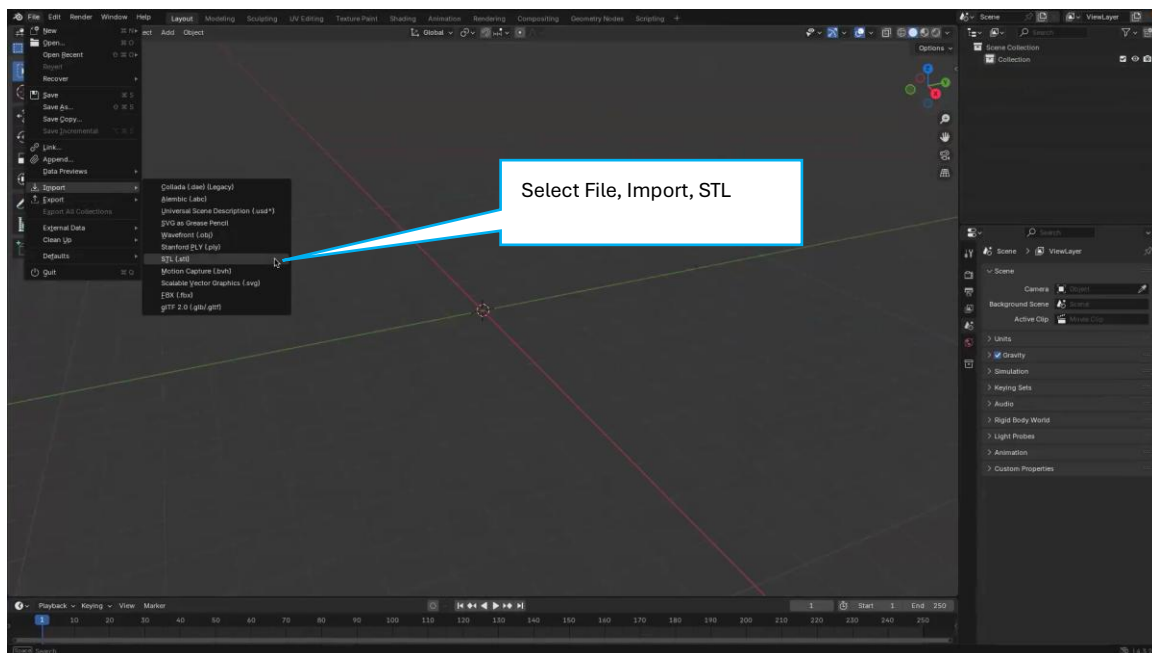
240

241

242 Then select file, import, STL (Figure 15).

243

244



245

Figure 15 *Importing STL*

The object may not appear immediately. Select Object, Set Origin, Geometry to Origin (Figure 16) to center your object at the world origin. The object should now be in view.

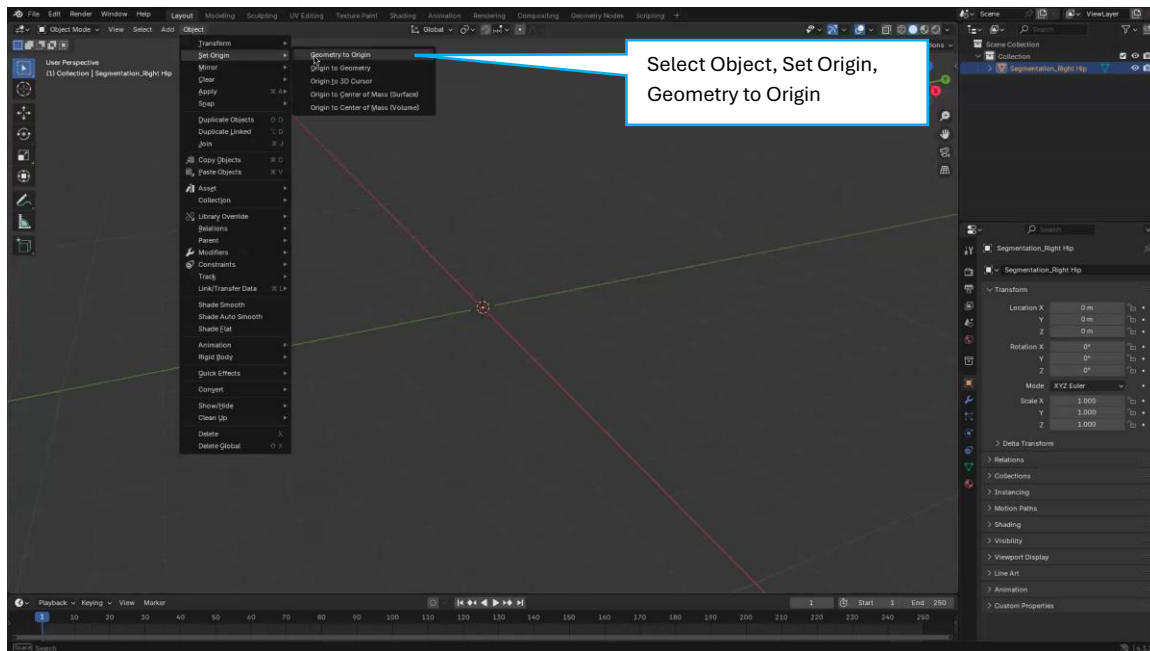


Figure 16 *Centering the Object*

Once the object is in view, notice how smooth the external surface topography is. STL files are just a collection of triangles oriented along an object's surface. These triangles have a specific direction vector (e.g., outside facing, inside facing). These triangles also have edges, vertices, and faces. All these aspects can be manipulated to correct surface defects in the object. Select the dropdown menu and switch to “Edit Mode” (Figure 17).

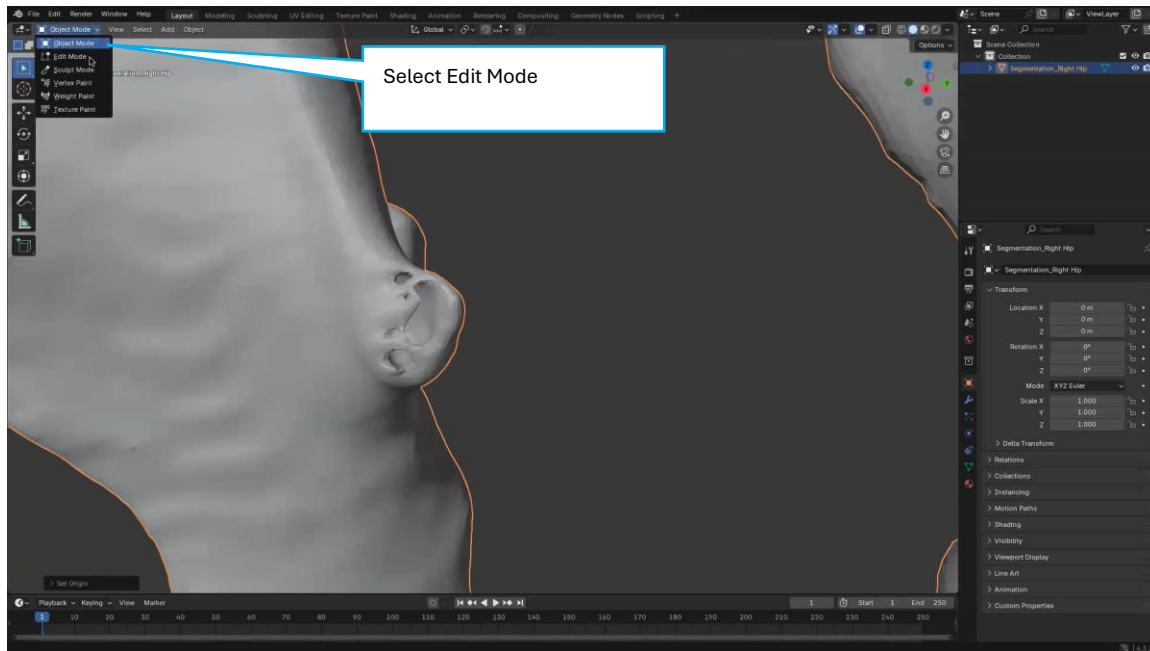


Figure 17 *Edit Mode*

Definitions of common 3D modeling terminology⁹:

- **Faces:** A face is the most basic part of a 3D polygon. When three or more edges are connected, the face is what fills in the empty space between the edges and makes up what is visible on the polygon mesh. The face of a single polygon is shown in grey in Figure 18.
- **Edges:** An edge is another component of a polygon. Edges help define the shape of the models, but they can also be used to transform them. An edge is a line that connects two adjacent vertices. The edges of a single polygon are shown in green in Figure 18.
- **Vertex/Vertices:** A vertex is the smallest component of a polygon model. It is simply a point in a three-dimensional space. By connecting multiple vertices with edges, a polygon is created. These points can be manipulated to create

the desired shape. The vertices of a single polygon are shown in white in Figure 18.

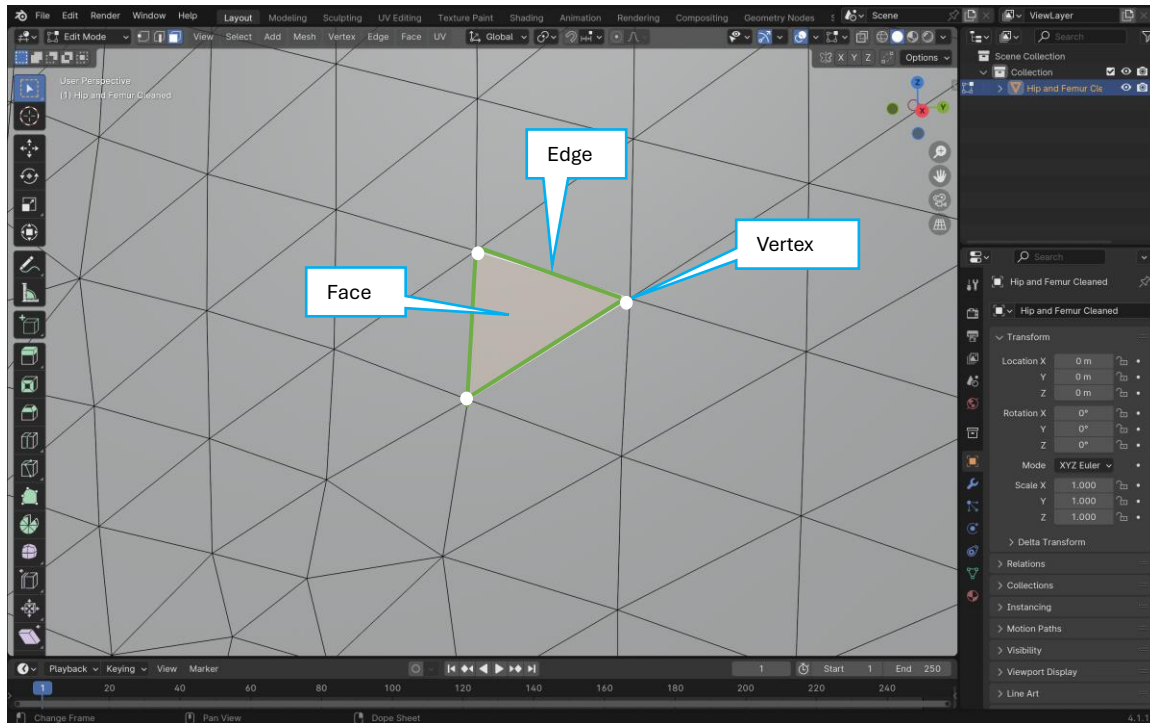


Figure 18 *Faces, Edges, and Vertices*

Select a vertex on any part of the external topographic dataset. Then click select, select linked, and then linked (Figure 19). Notice all the linked vertices are selected. The keyboard shortcut to select all linked vertices after selecting a single vertex is cmd+L (mac) or ctrl+L (windows).

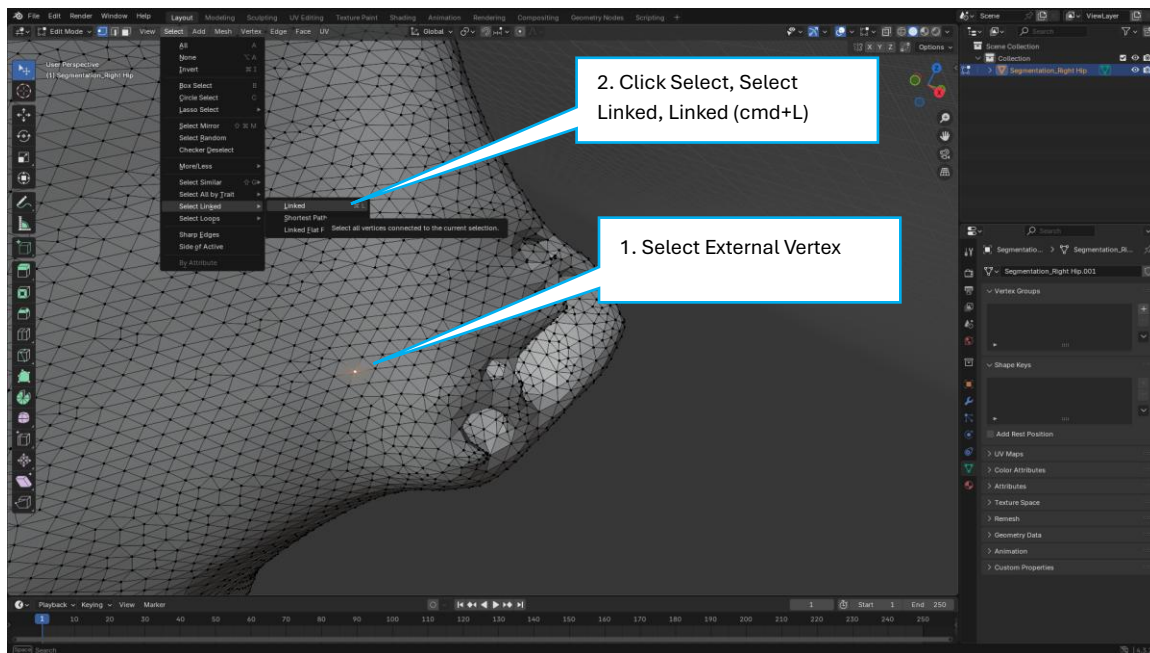
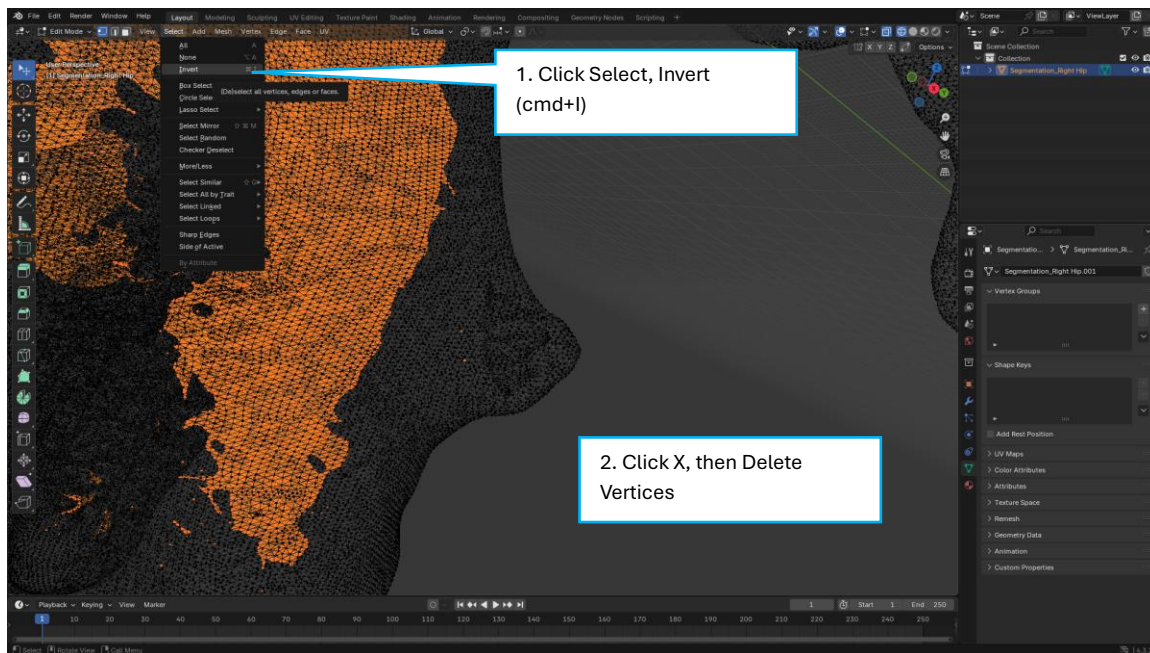


Figure 19 *Selecting External Topography*

Next, click select and then invert (Figure 20). The keyboard shortcut to invert all selected linked vertices is cmd+I (mac) or ctrl+I (windows). Review that all the internal mesh has been selected. Click X on your keyboard and select delete vertices.



298

299 Figure 20 *Deleting Internal Mesh*

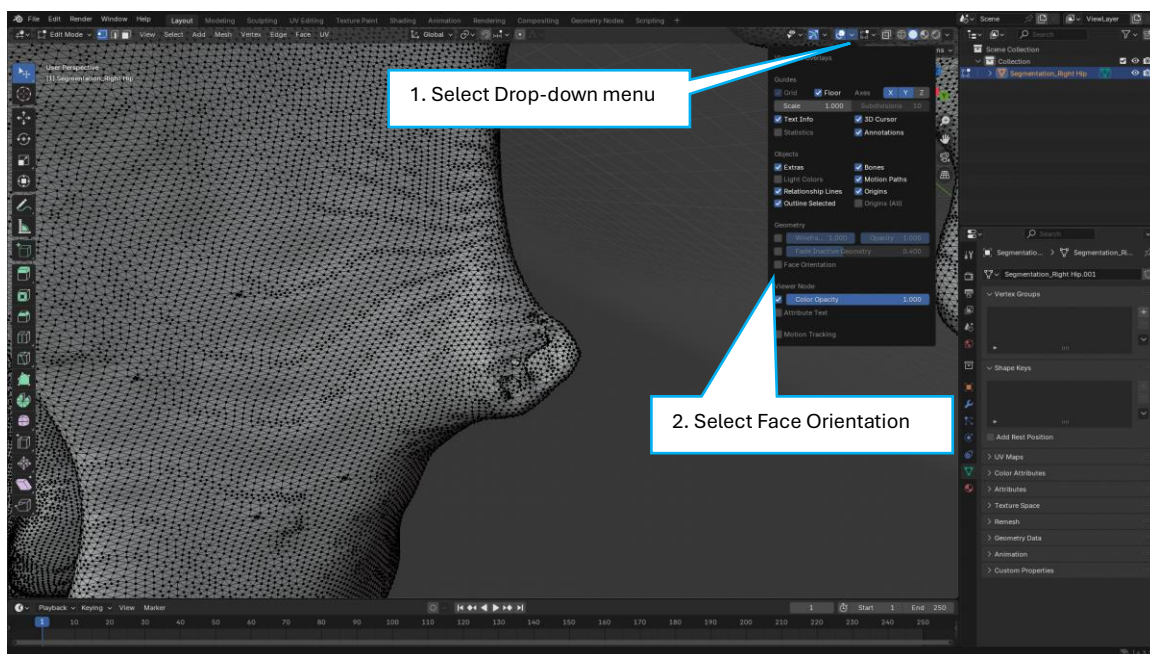
300

301

302 Next, select the overlays drop-down menu and click on Face Orientation (Figure 21).

303

304



305

Figure 21 *Face Orientation*

Left-click and hold the cursor icon until a pop-up window appears, and select the circle icon (Figure 22). The radius of the circle can be adjusted accordingly (Figure 23).

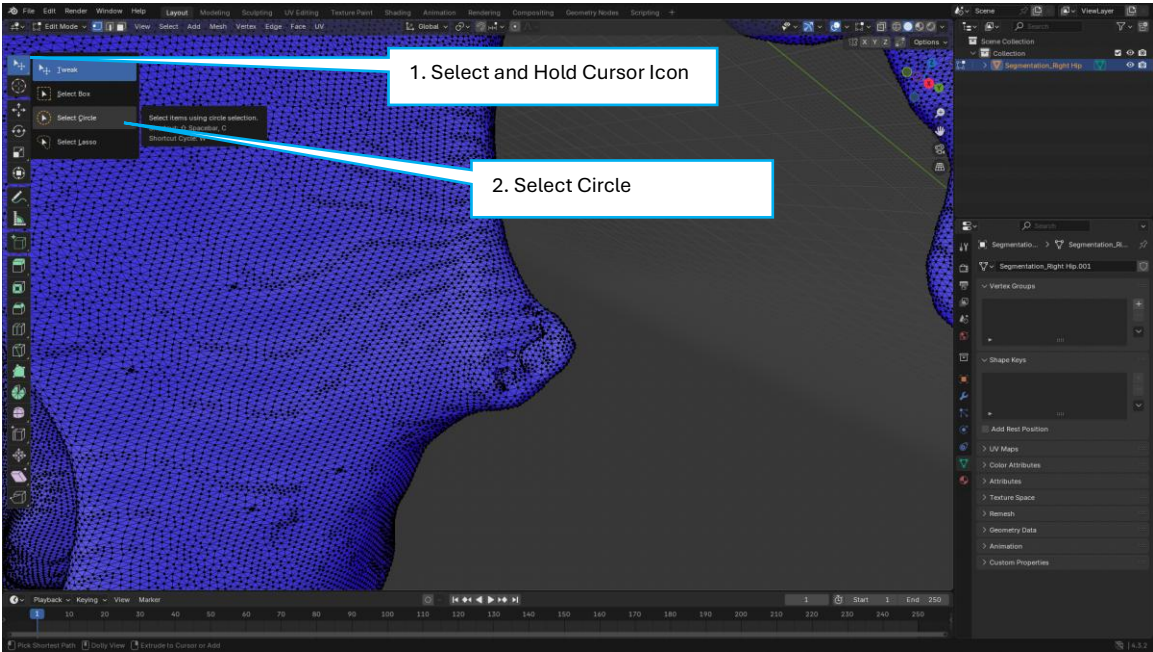


Figure 22 *Selecting Circle Cursor*

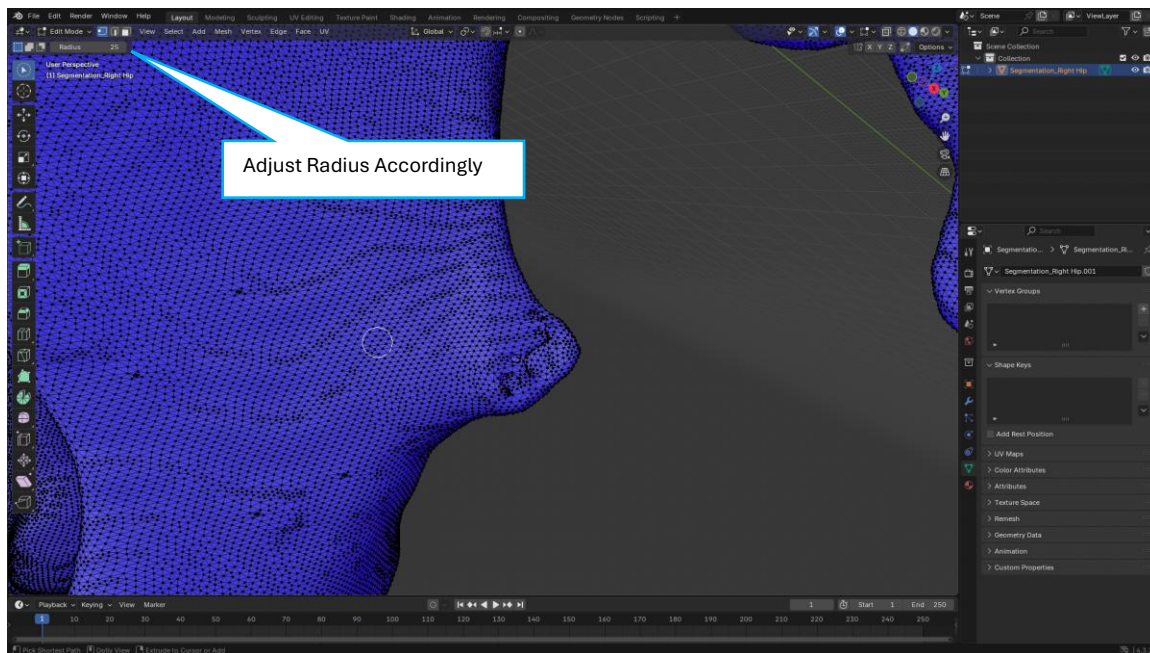
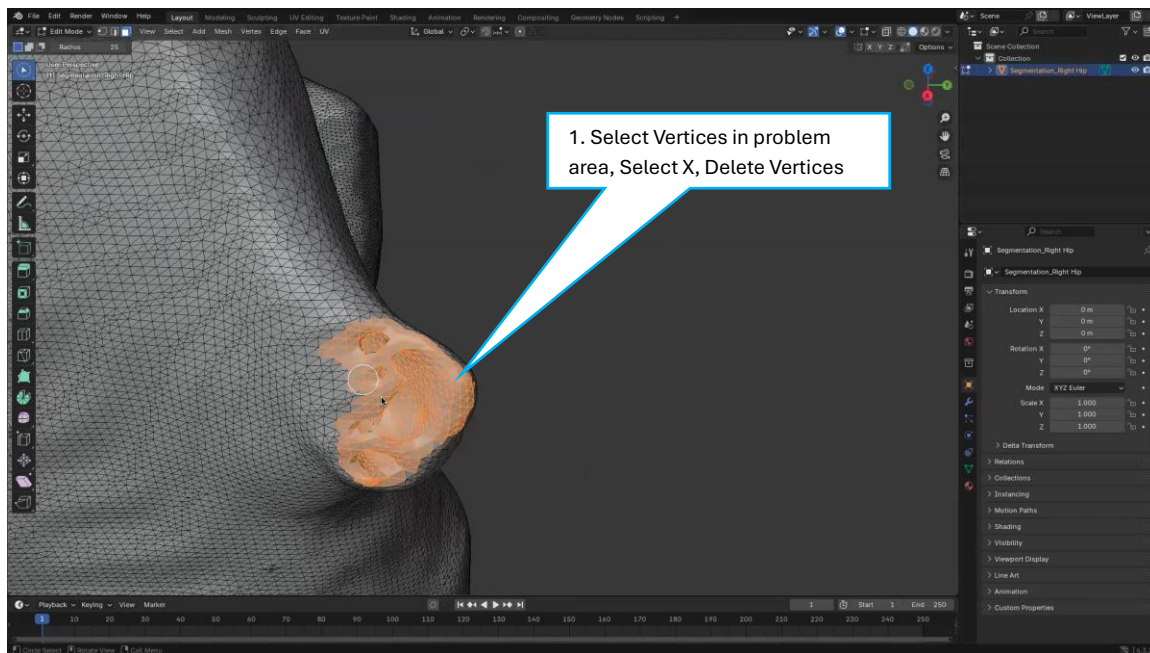


Figure 23 *Adjusting Radius*

Review the anatomical object for areas that present with any defects or need to be cleaned. To clean the topography of the structure, switch between “Sculpt Mode” and “Edit Mode” to remove, smooth, or fill areas within the object. Select the vertices that need to be removed. For areas with an unwanted indentation, move the view multiple times and hold shift while clicking the left mouse button to continue selecting the vertices within one group (Figure 24). Once satisfied, select X and then delete vertices (Figure 24). This will create a hole in the model that can be filled in the next step. Confirm that all attached vertices to the object needing to be removed have been deleted.



329

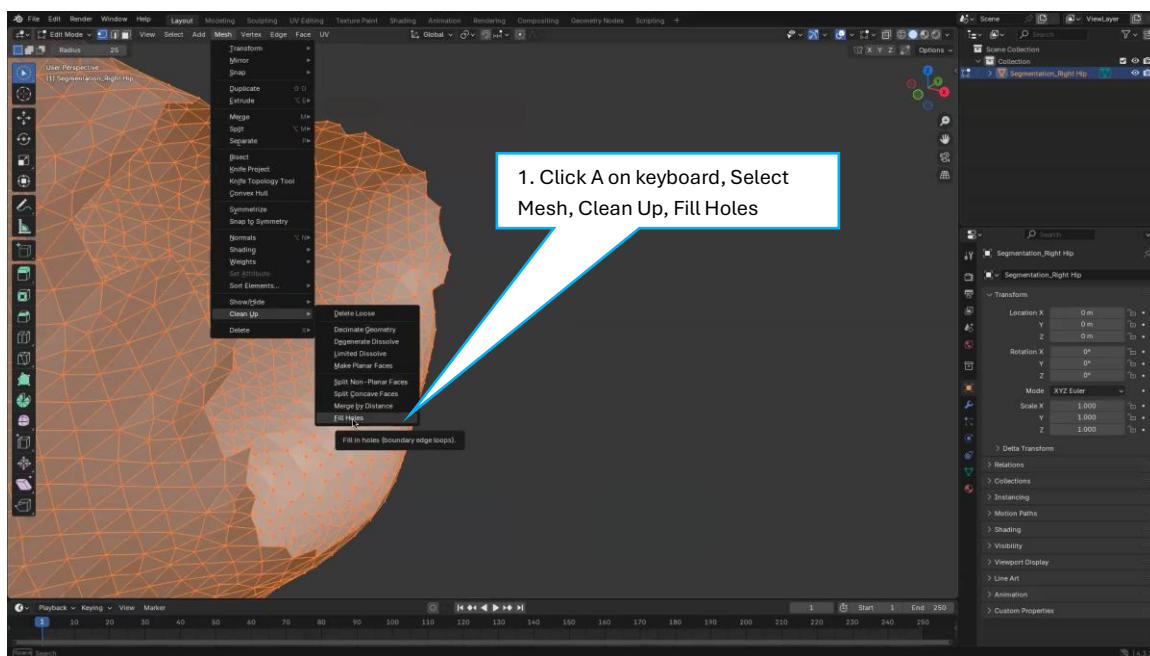
330 Figure 24 *Deleting Vertices*

331

332

333 Next, click A on the keyboard and select Mesh, Clean Up, and Fill Holes (Figure 25).

334



335

336 Figure 25 *Fill Holes*

337

Adjust the fill holes sides (Figure 26) and increase accordingly (>100).

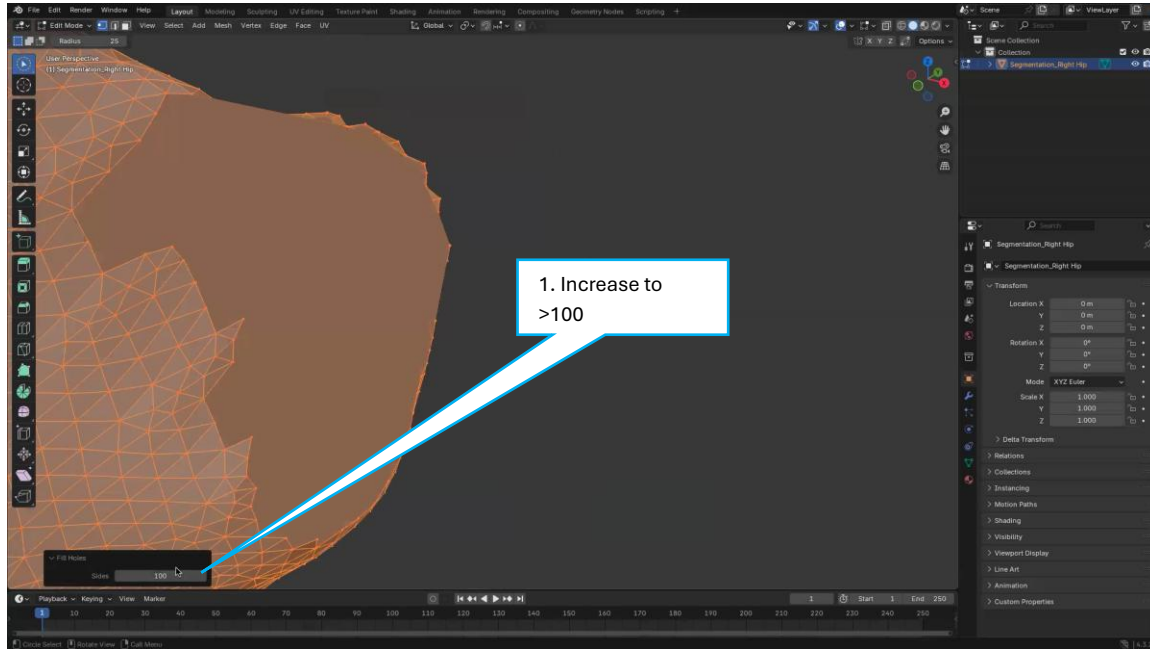


Figure 26 *Fill Holes Threshold*

Select the Face tab and then click on the face just filled on the model. Next, click the Face tab from the menu bar and select Triangulate Faces (Figure 27). The keyboard shortcut to triangulate faces is cmd+T (mac) or ctrl+T (windows).

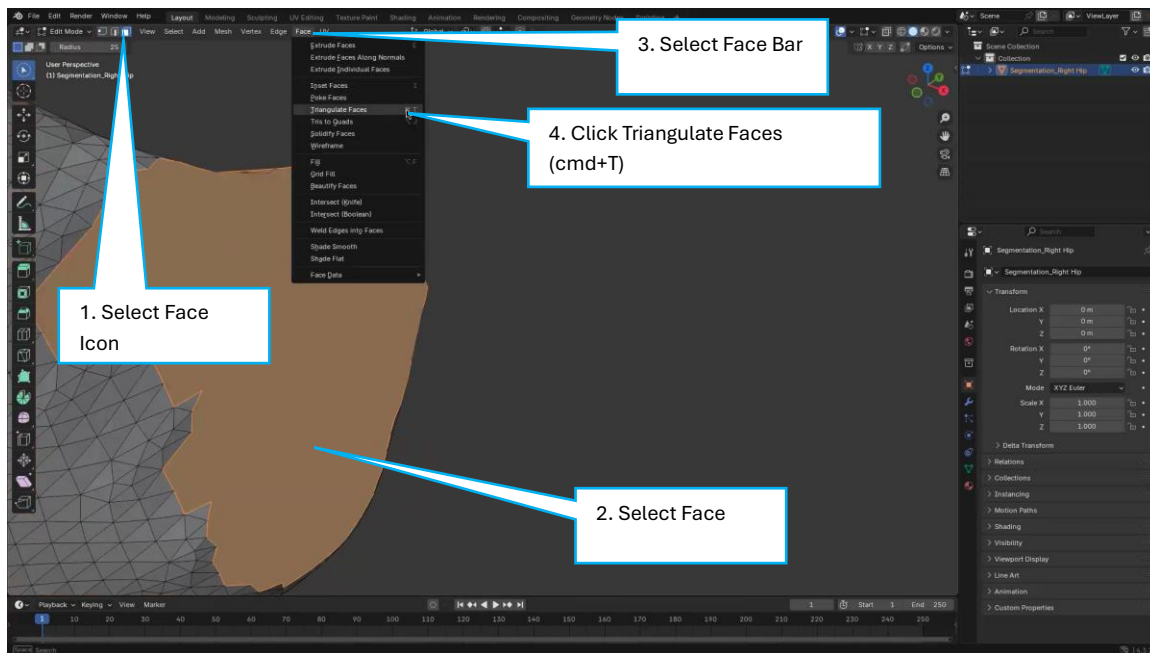


Figure 27 *Triangulate Faces*

Next switch to “Sculpt mode” and click the smooth icon and left-click over the area needing smoothed (Figure 28).

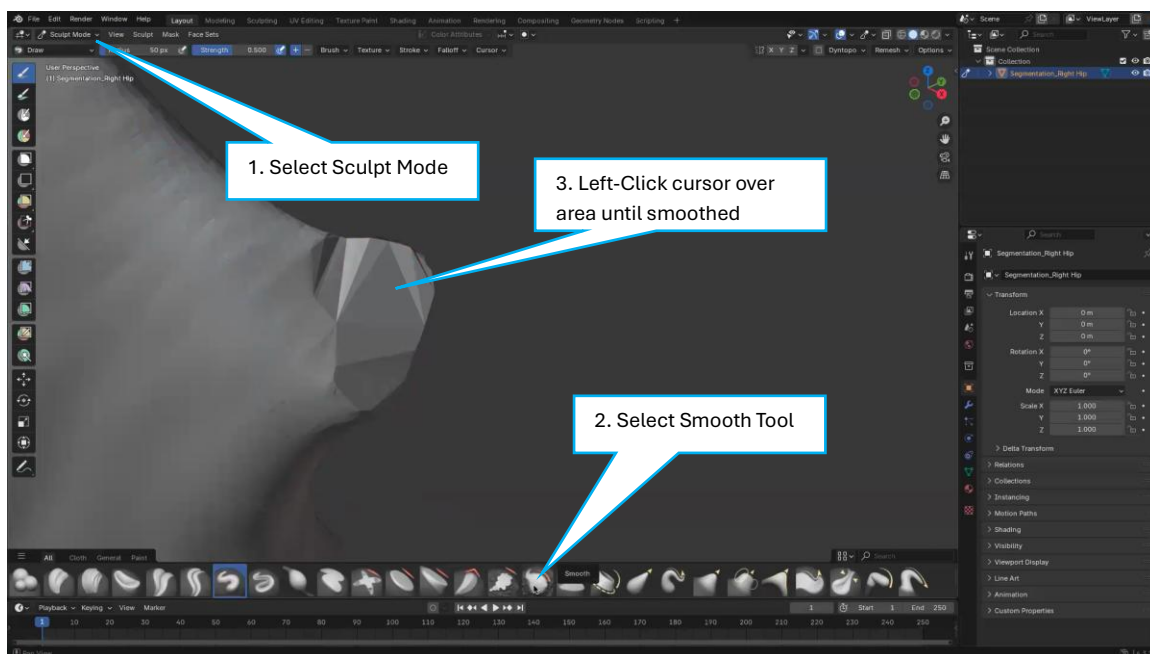


Figure 28 *Smoothing Object*

Repeat these steps (delete problem areas, fill holes, and smooth) until the anatomical object has been cleaned, smoothed, and corrected all over. Once the anatomical object has been edited to your satisfaction, it needs to be exported. Select “Object Mode” and click on the object. Select File, Export, and STL, and save the newly cleaned anatomical object in an easily accessible folder (Figure 29).

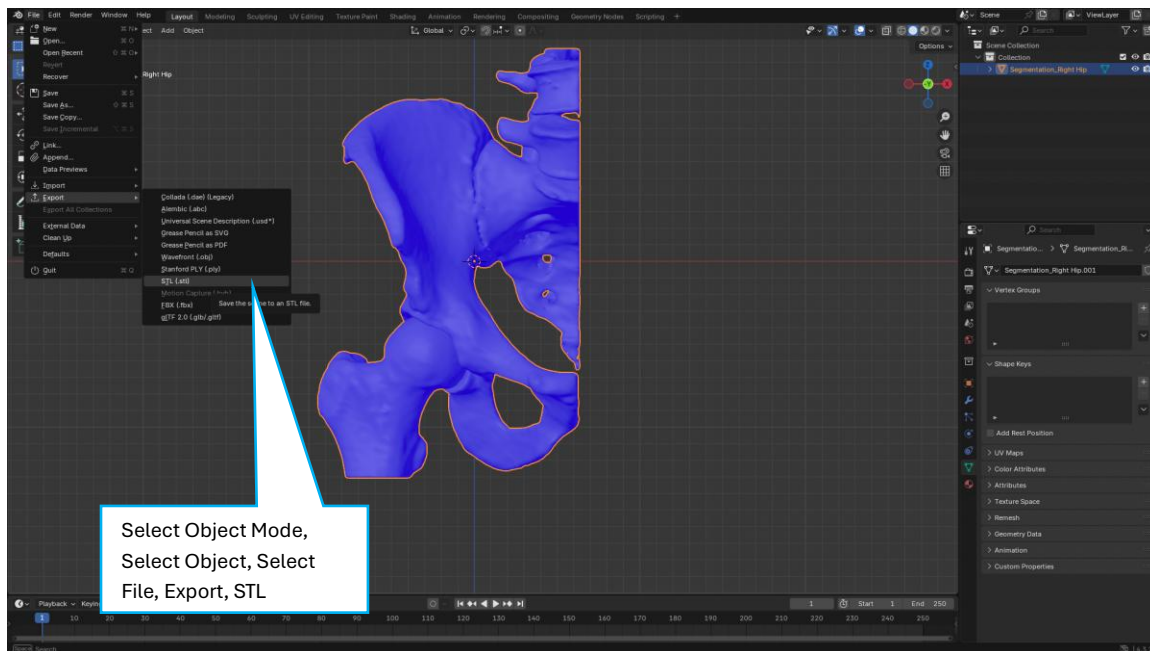


Figure 29 *Exporting STL from Blender*

Repeat the Blender software steps for each additional anatomical segmentation from 3D slicer. For this model, segmentations of the surface anatomy and a separate bone segmentation of just the femur were completed.

374 *Creating Digital Molds*

375 Now that each anatomical segmentation has been cleaned, the next step is to create digital
376 casting molds from this anatomy. This will allow the researcher to create molds that can be 3D
377 printed. These 3D printed molds will then be used to infill the cavity with TMM to simulate
378 various tissues. The first thing to do is cut the objects to correctly match the build plate size of
379 the 3D printer being used. For this demonstration, a Bambu X1 Carbon, which has a build plate
380 size of 256mm² was used. These casting molds can then be 3D printed and used to create UAPs
381 by adding ultrasound-able material into the mold.

382

383 *Orienting the Anatomy*

384 Select “Object Mode” and import the previously cleaned STL files. Repeat this step for all
385 cleaned segmentations until all STL files are imported together. Once the objects have been
386 brought in, bring all the objects to the “world origin”. Select the objects separately and then click
387 the Object bar and select set origin, Geometry to origin (Figure 30). Repeat for each object.

388

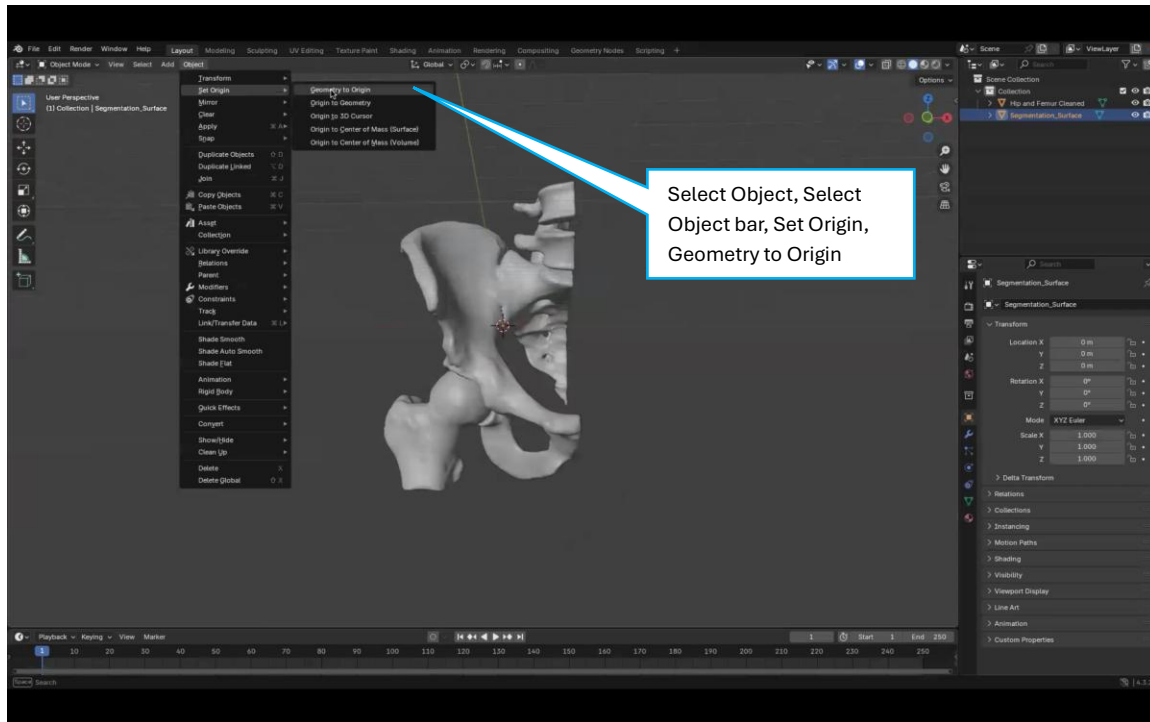


Figure 30 *Importing Objects Together*

The objects will not be anatomically correct in terms of spatial positioning (Figure 31).

The objects are not correctly superimposed over each other because they were segmented and cleaned as separate objects. When they are brought back in and moved to the “world origin” by selecting “Geometry to Origin,” the algorithm moves them based on the center of the object. The next few steps will remedy this issue. Use the directional panel to orient the viewing field (Figure 31).

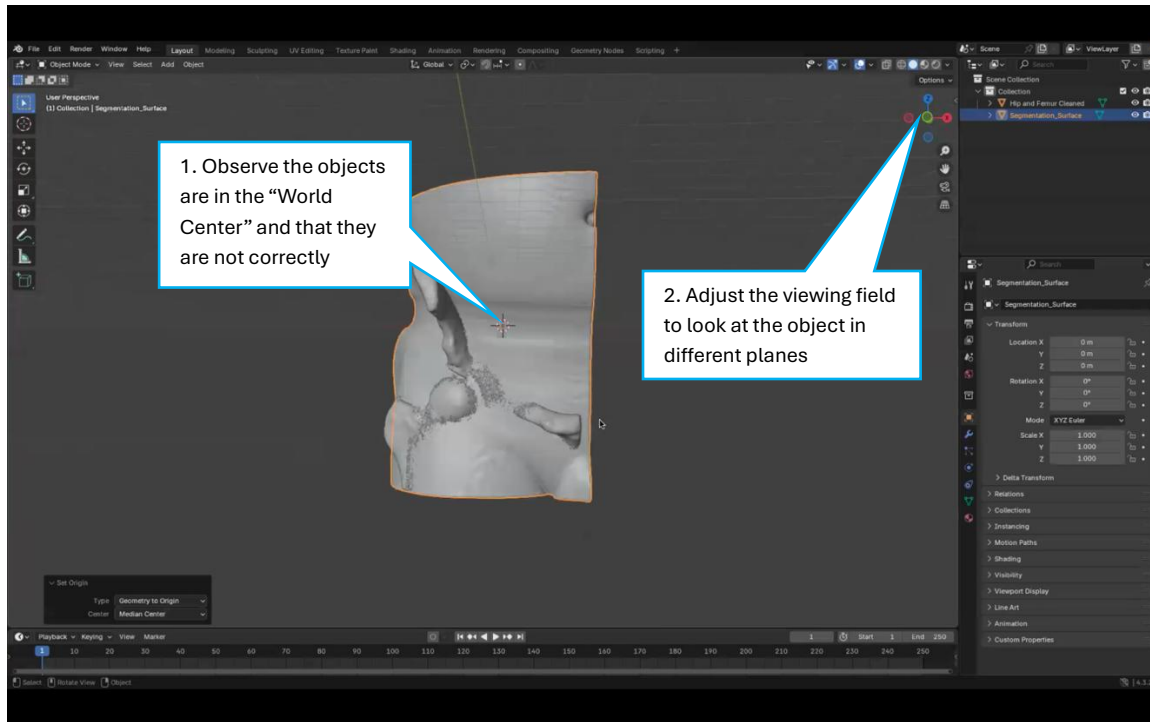


Figure 31 *Adjust Viewing Field*

In order for the objects to be correctly positioned, they will have to be put back into place and confirmed for accuracy with the measuring tool in Blender. Select the object to be moved first in the “Scene Collection” hierarchy to the right of the screen. Press the G key on the keyboard to move the objects. To move the objects in a single plane, select G+(X, Y, or Z) to move them in their respective planes (Figure 32).

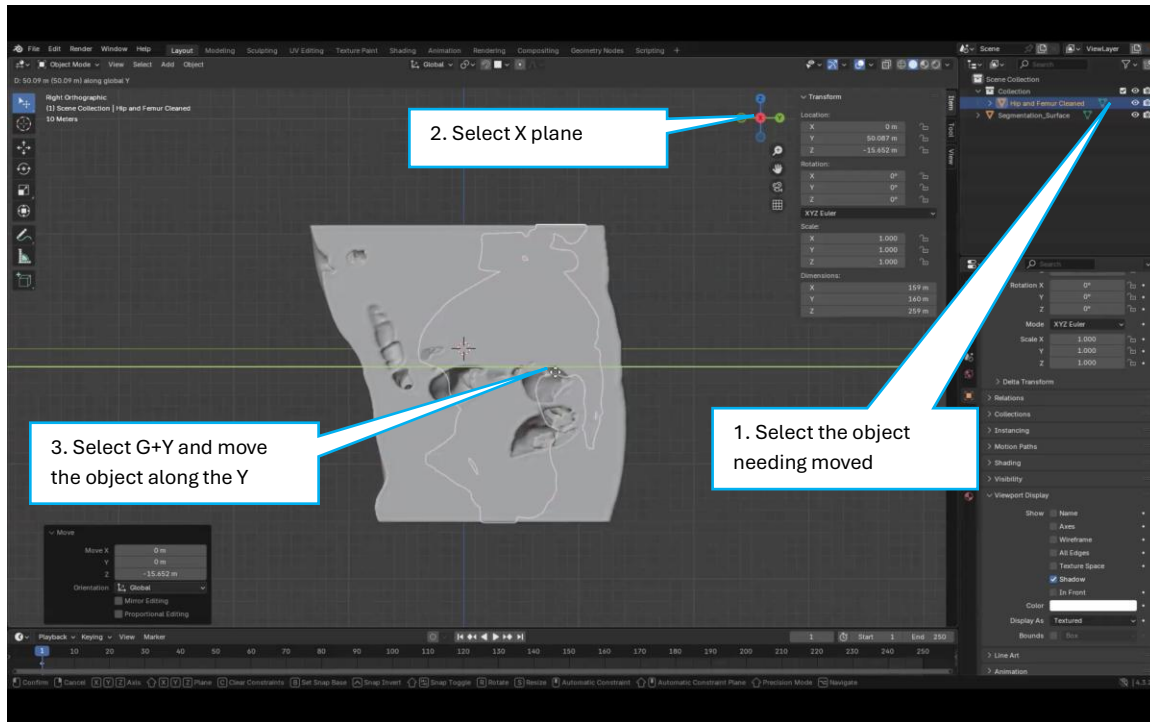


Figure 32 *Moving Objects in a Single Plane*

Next, confirm that the bony anatomy is superimposed completely and there is no part of the bone protruding through the surface anatomy. Move the bone in different planes until the bone is fully enveloped and is in a “generally” correct placement. Measurement can always be verified with the original DICOM data in 3D Slicer. Figure 33 shows the steps involved in using the 3D slicer measuring tool.

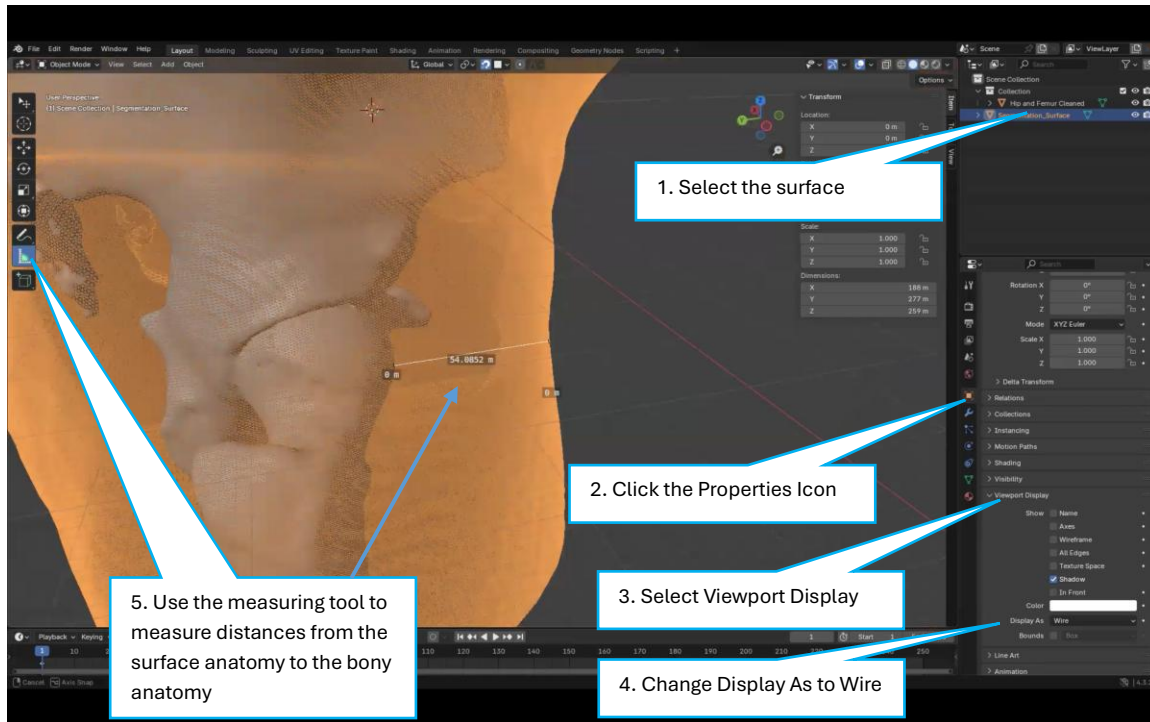


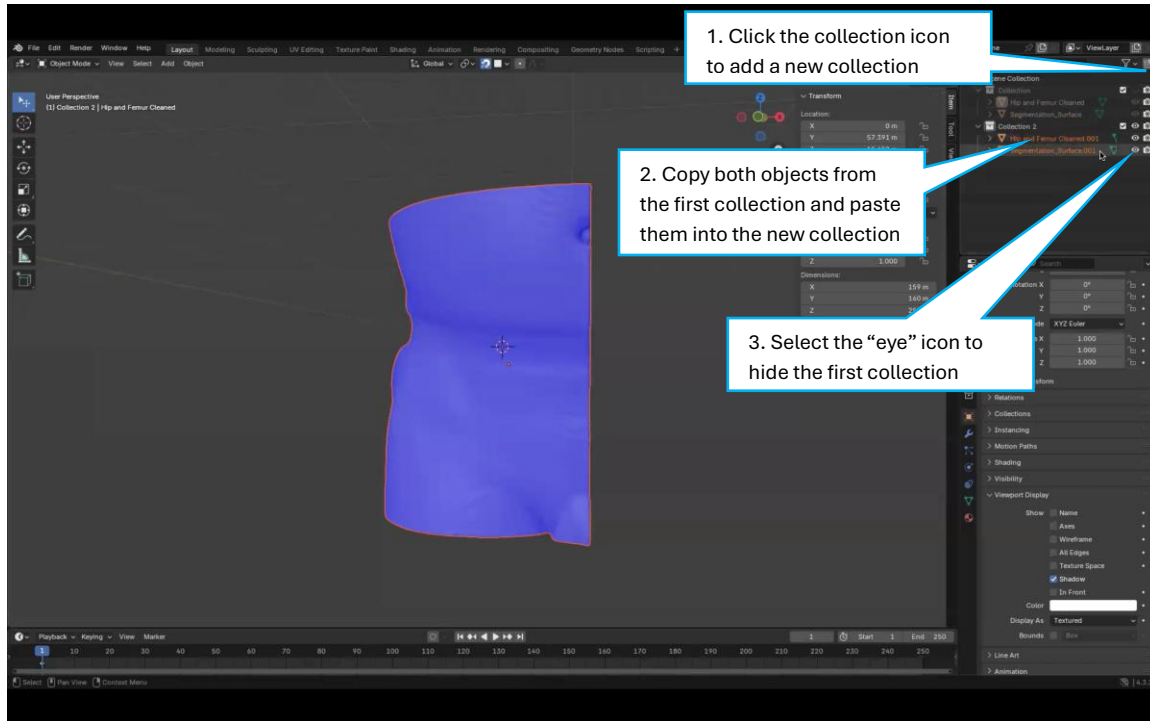
Figure 34 *Measuring Anatomical Placement*

Using the measuring tool in multiple places while moving the bony anatomy will help move the bone into a more accurate placement. The type of UAP the researcher is trying to create will dictate the attention to detail and anatomical accuracy needed for the model. For this UAP, the distance between the surface and the joint capsule is the most important feature required to create a high-fidelity phantom of the hip joint.

Cutting Objects to Size

Create a new Collection and copy and paste the correctly segmented and oriented anatomy into the new collection (Figure 35). Then hide the first section.

444



445

446 Figure 35 *Adding a New Collection*

447

448

449 Next, add a cubed object and scale it to size. Click on the Add bar (shift+A), select Mesh, and

450 select Cube (Figure 36).

451

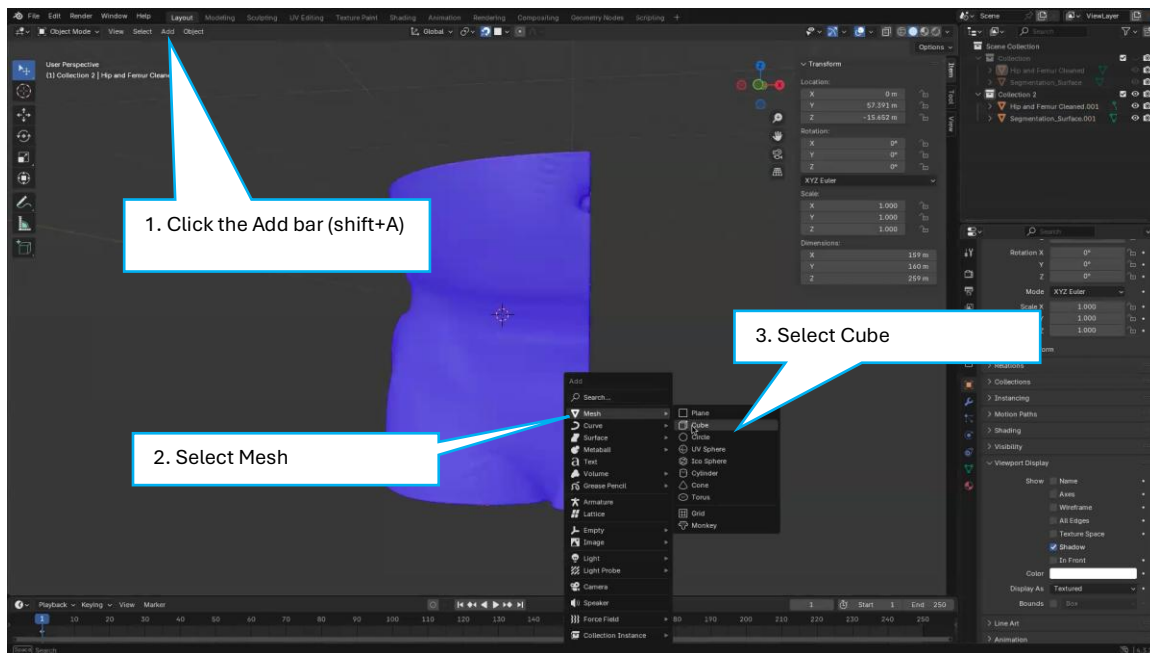


Figure 36 *Adding a Cube*

To scale the object, hold the S key while moving the mouse in a downward motion to increase the size of the cube (Figure 37). Using the scale tool to manually increase the cube size is also another option. Change to cube to be viewed in wireframe (Figure 37).

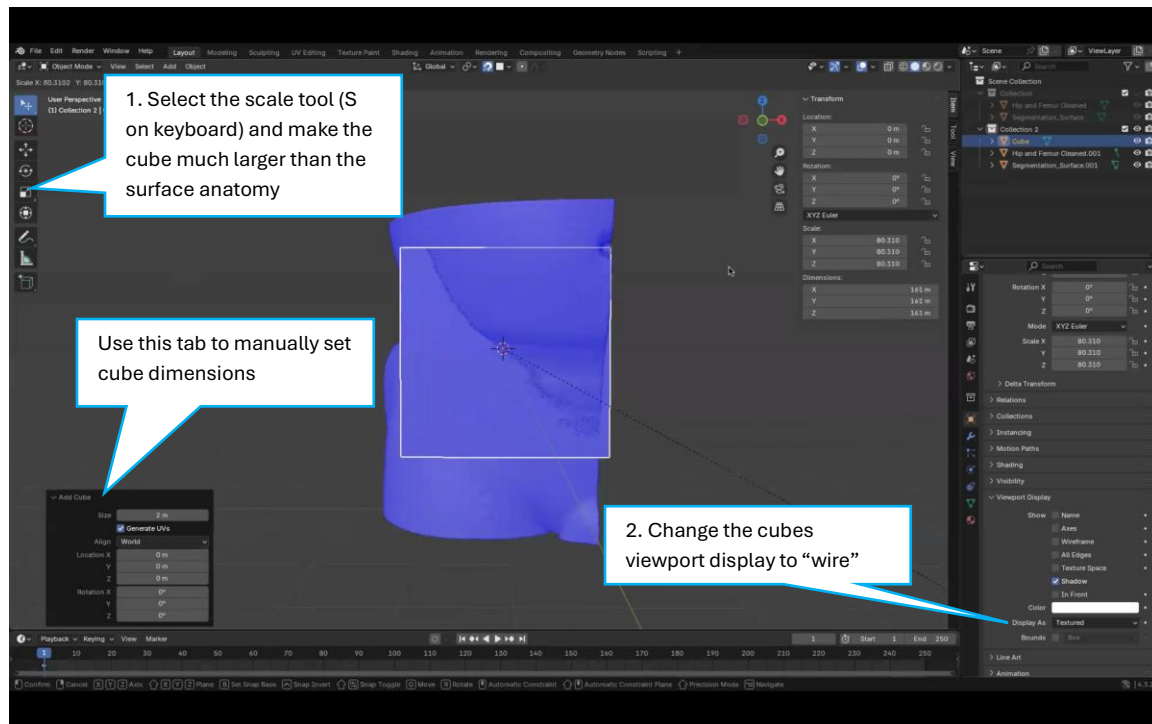


Figure 37 *Scaling the Cube*

A critical thing to consider is the pertinent anatomy needed to create the high-fidelity UAP of interest. In this UAP, the acetabulum, head and neck of the femur, pubic tubercle, and anterior superior iliac spine are considered pertinent bony anatomy. The surface anatomy must be cut to match the bony anatomy. The inguinal crease needs to be visible to the participant to correctly identify the surface anatomy. All of these landmarks are important and need to be visible to the participant when practicing or looking for how to identify the specific anatomy to orient themselves for the procedure. Move the cube to the correct location to cut the anatomy to fit the build plate of the 3D printer (Figure 38). Use the measuring tool as before and measure in the exact dimensions needed for the object to fit on the 3D printing build plate. Next, confirm the cutting cube is oriented to cut the correct surface anatomy (Figure 38). For this model, the only important anatomy is the anterior set of structures, since the procedure is completed using an

anterior approach. In order for the object to fit on the 3D printing build plate, the gluteal and abdominal regions will be taken out.

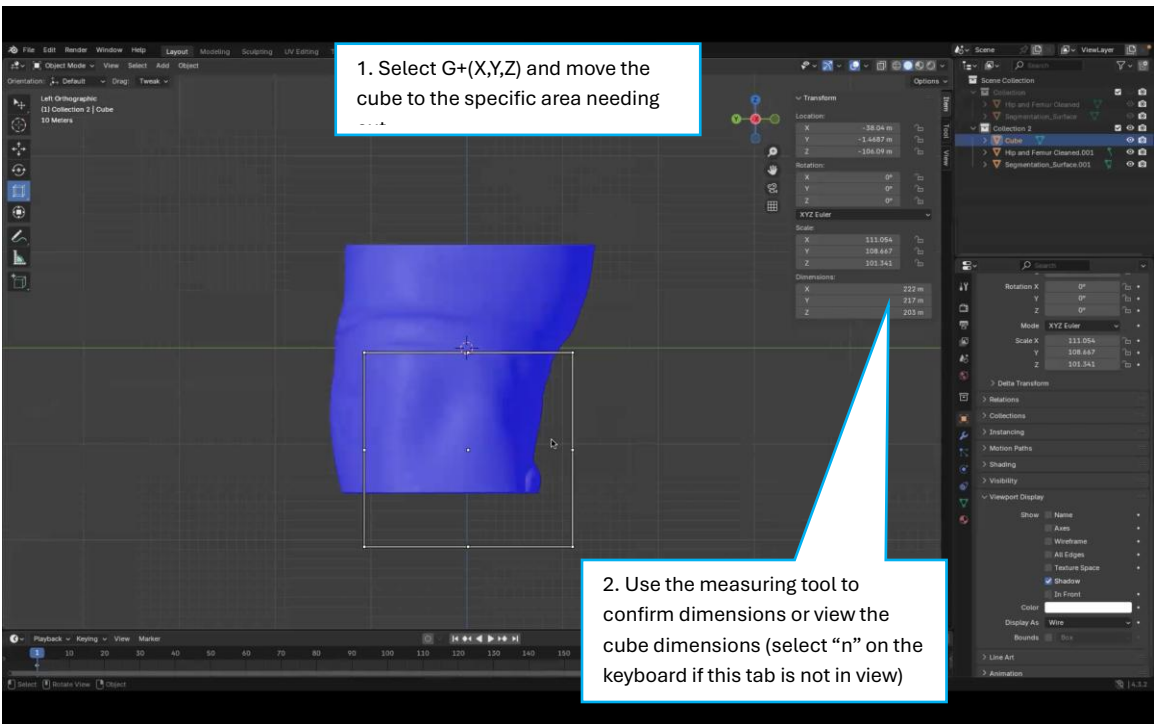


Figure 38 Orienting the Cutting Cube for Surface Anatomy

Confirm the cutting cube is oriented to cut the correct bony anatomy (Figure 39).

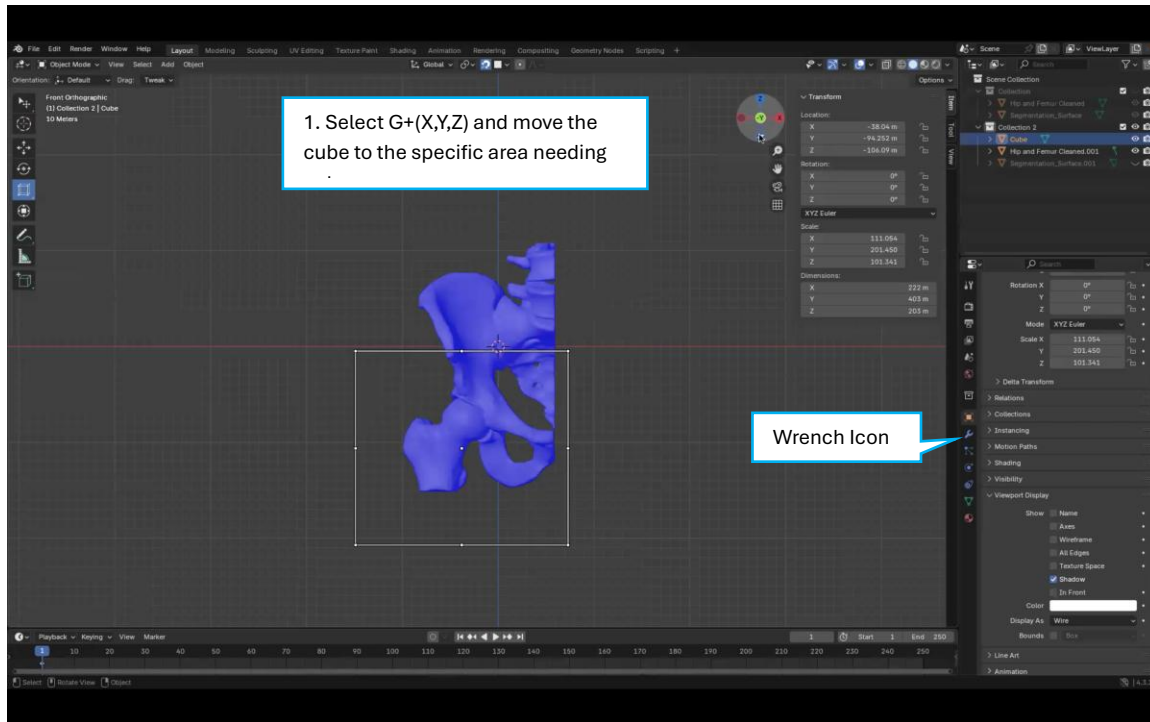
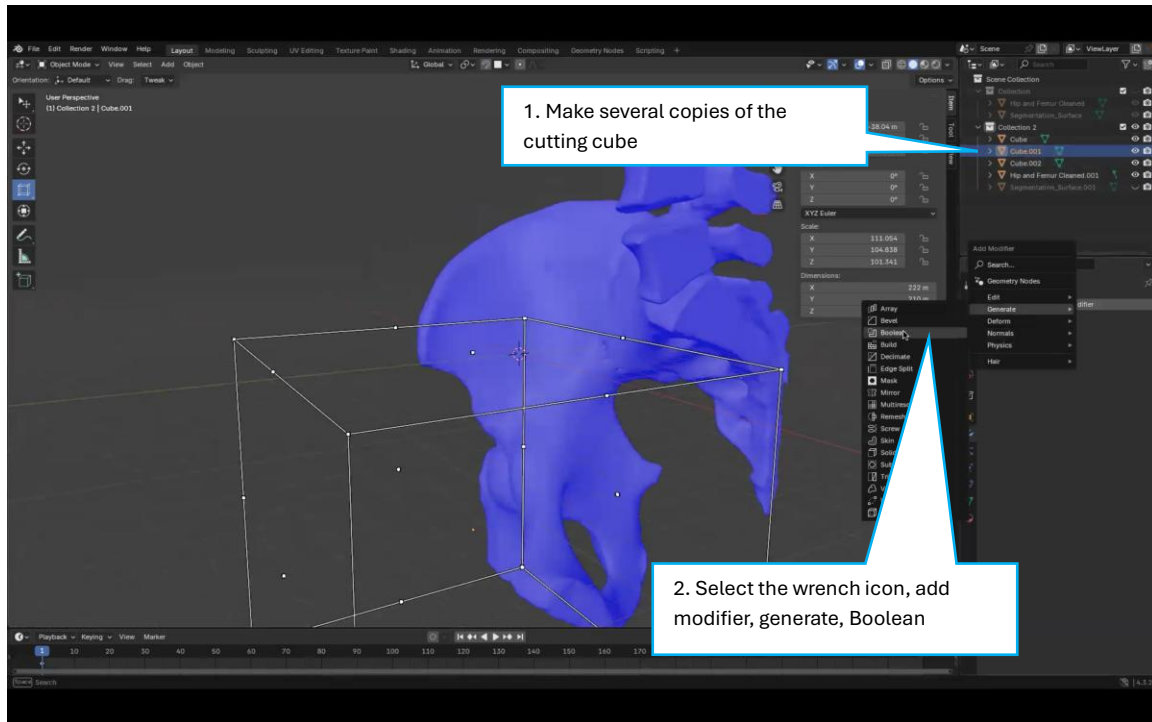


Figure 39 Orienting the Cutting Cube for Bony Anatomy

Once the cutting cube is put into place, make several copies (2-3) of this object (Figure 40). To make a copy, simply right-click on the mouse and select copy (cmd+C) and paste (cmd+V). Select one of the cubes, click the “wrench icon” (Figure 39), and select add modifier, generate, *Boolean* (Figure 40). This *Boolean* modifier is a functional algorithm in blender which cuts specific objects that are in comparison with each other.



495

496 Figure 40 *Creating a Boolean*

497

498

499 Select the intersect tab and select the object being used to imprint/copy within the parameters of
 500 the cube (Figure 41).

501

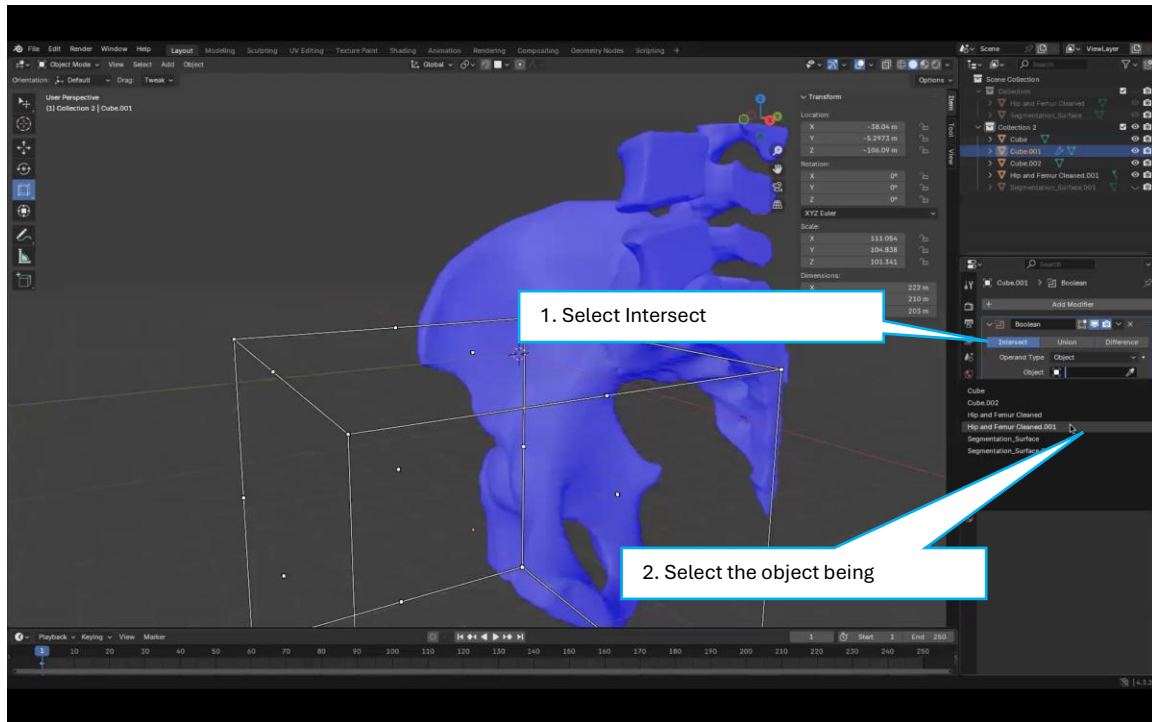
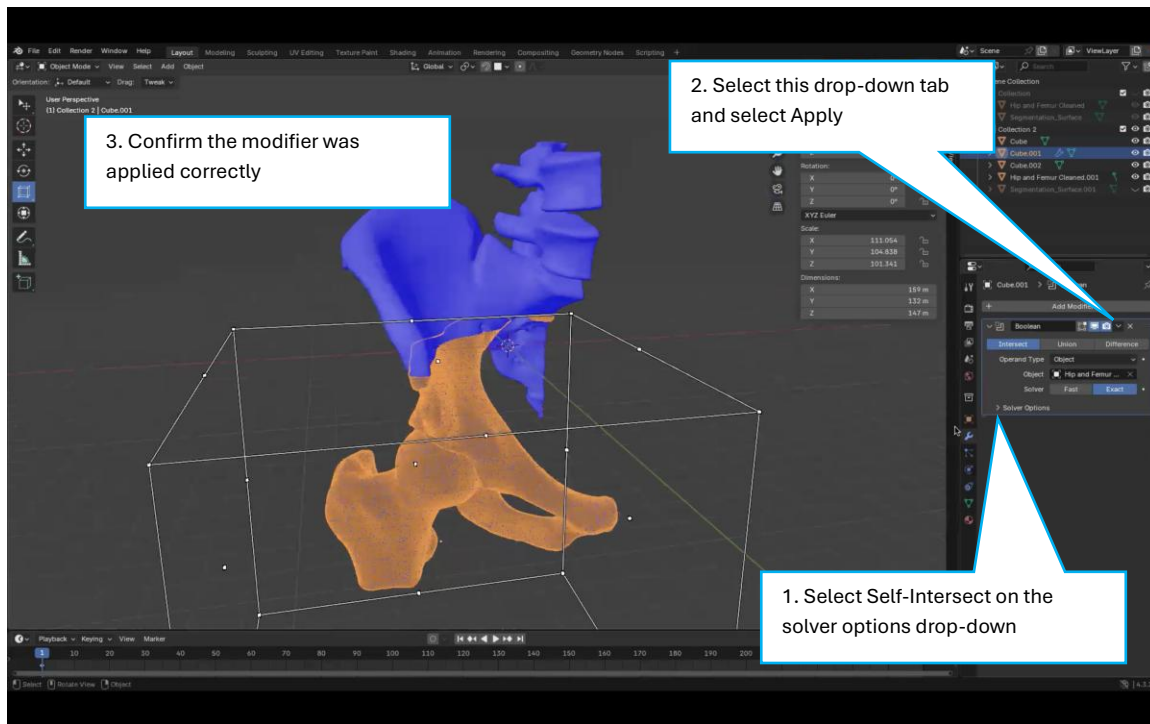


Figure 41 *Intersecting the Bony Anatomy*

If the object doesn't cut correctly, the self-intersection box may need to be selected in the modifier (Figure 42). Select the dropdown tap to Apply the modifier (Figure 42). Confirm the modifier applied correctly by hiding the original object (Figure 42 & Figure 43).



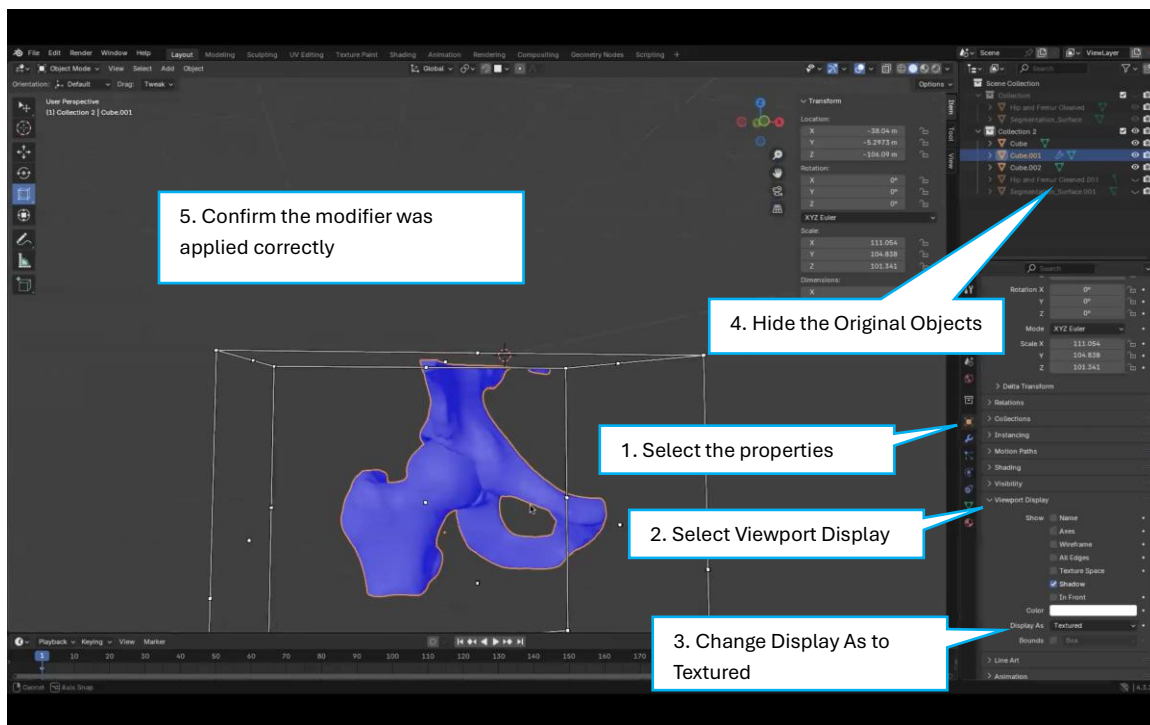
510

Figure 42 *Cutting the Object*

511

512

513



514

Figure 43 *Confirming the Modifier*

Change the name of the cube to an identifiable term (Figure 44). Click the tab bar on the keyboard or select the drop-down menu to change in Edit Mode (Figure 44). Delete vertices from any potential floating objects (Figure 44).

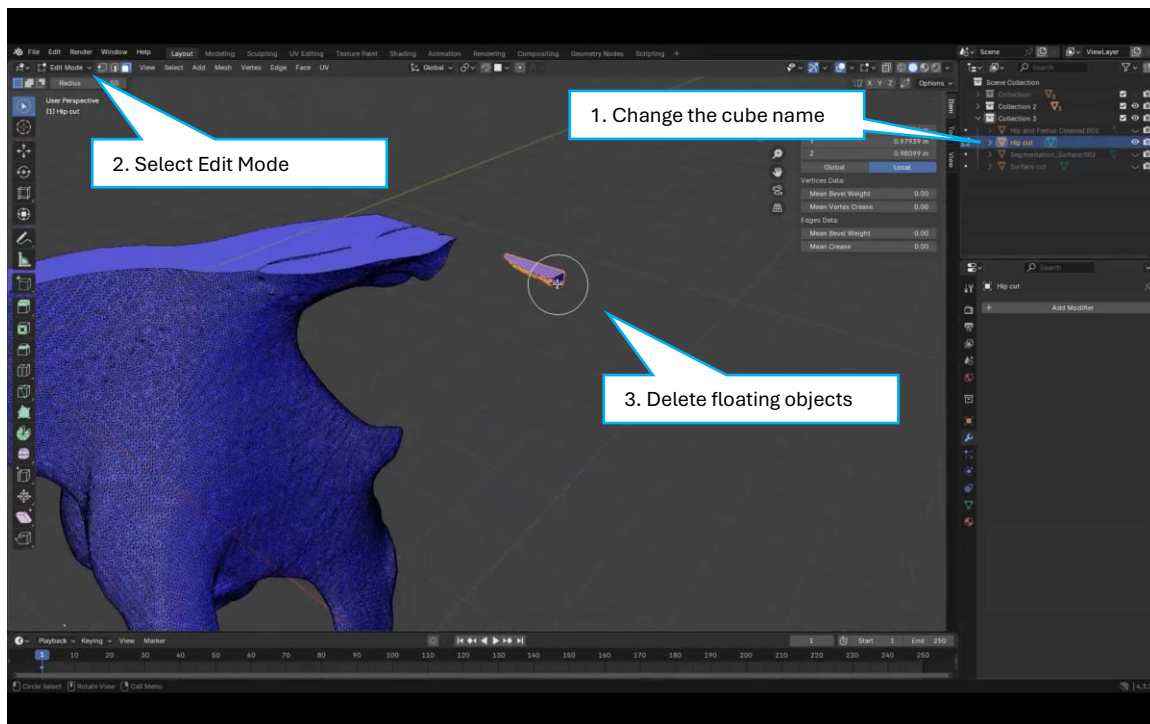
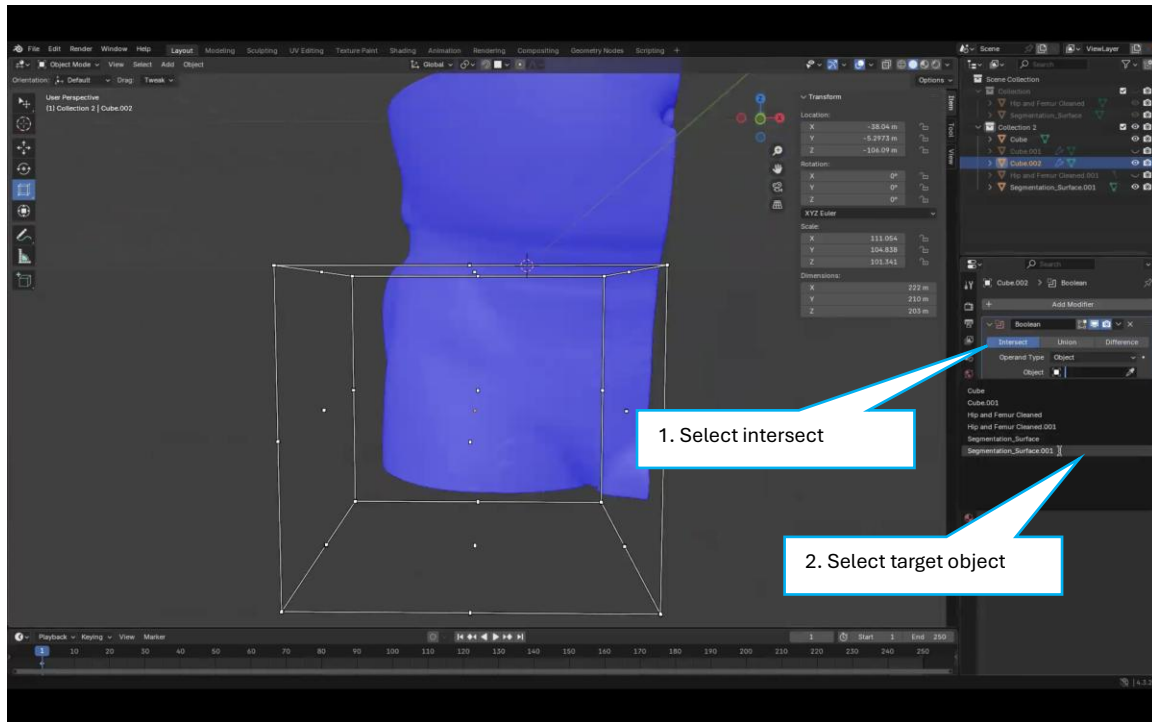


Figure 44 *Deleting Floating Objects*

Repeat the *Boolean* modifier for the surface anatomy using a different cube (Figure 45).



534

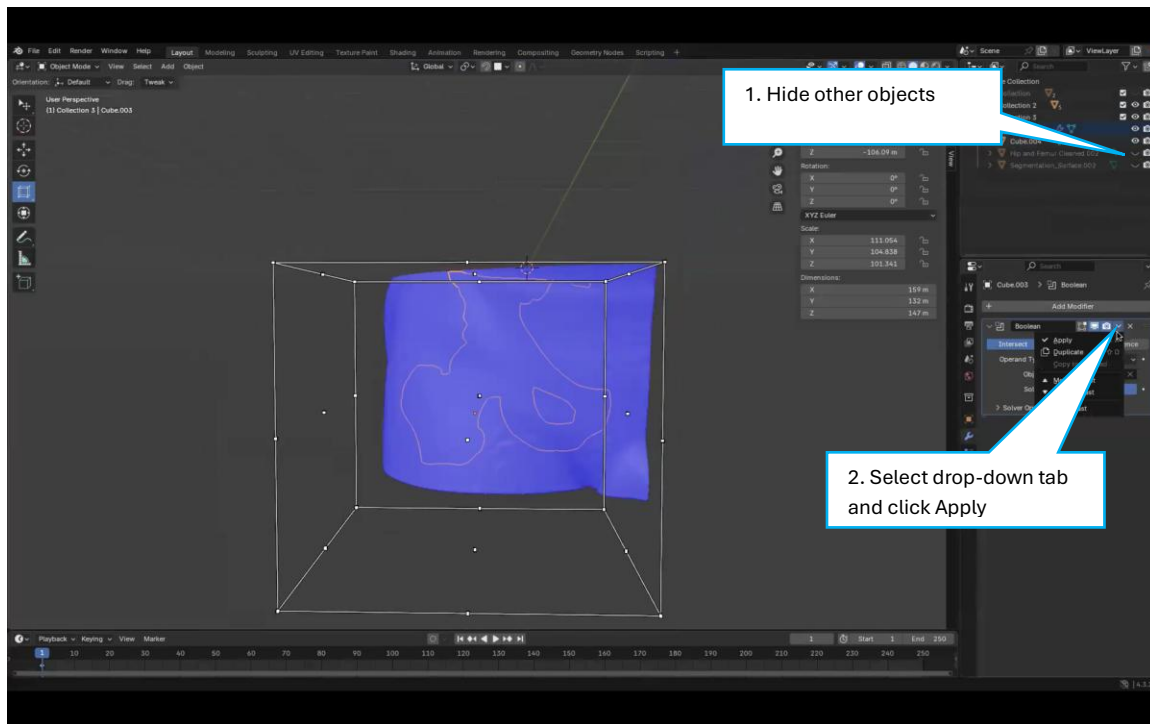
535 Figure 46 *Cutting the Surface Anatomy 2*

536

537

538 Then apply the modifier to the surface anatomy (Figure 47).

539



540

541 Figure 47 *Applying the Modifier*

542

543

544 Add a new collection and copy the newly cut objects into the new collection (Figure 48).

545

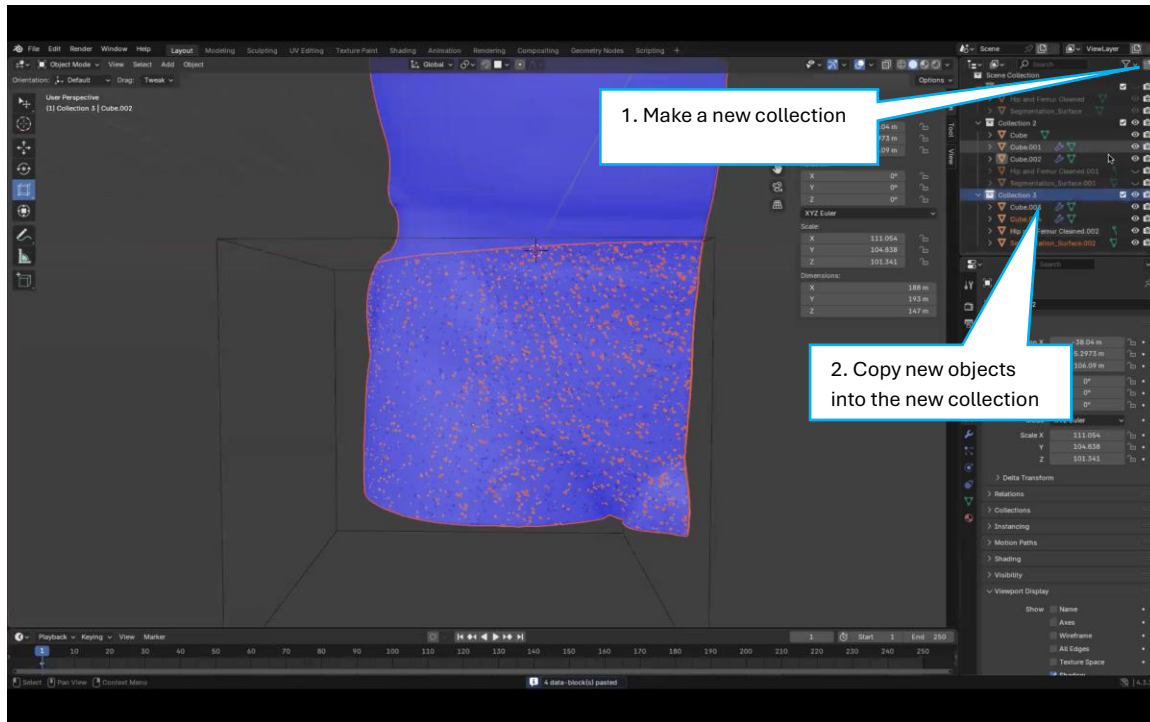


Figure 48 *Copying Cut Anatomy*

Digital Mold Making

Make digital molds of the anatomical structures previously segmented, cleaned, and cut. The *Boolean* modifier will be used several times to cut, copy, and intersect parts of the anatomy. Cutting cubes will also be used to act as a guide, and additional cubes will be added and conjoined with the digital molds to create a functional mold.

First, add a cube and scale it to the appropriate size (Figure 49). Next, change the *Viewport Display* to “wire” (Figure 49). Then move it approximately halfway through the object in the Y plane (Figure 49).

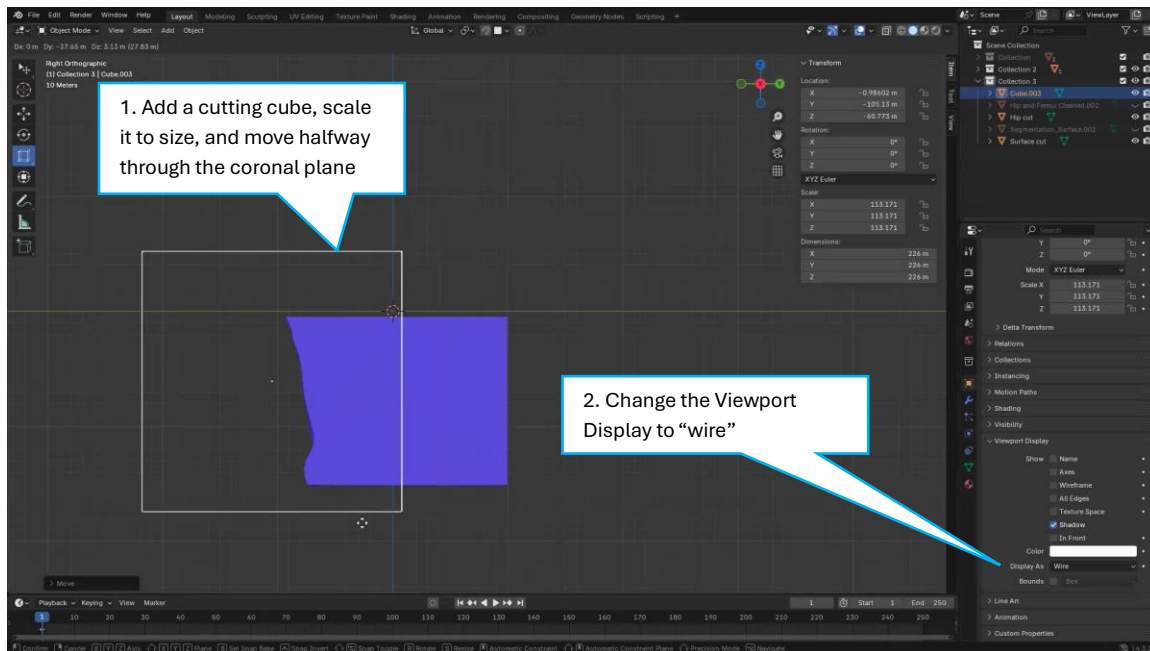


Figure 49 *Adding a Cutting Cube*

Next, make multiple copies of the cutting cube (Figure 50). It is always a good idea to rename objects as more are created to make identifying objects less confusing (e.g., anterior cutting cube). Move the cutting cube in the Y plane (G+Y). Then select the *snapping tool*, and then select Edge (Figure 50). Turn on the *Magnet* (Figure 50).

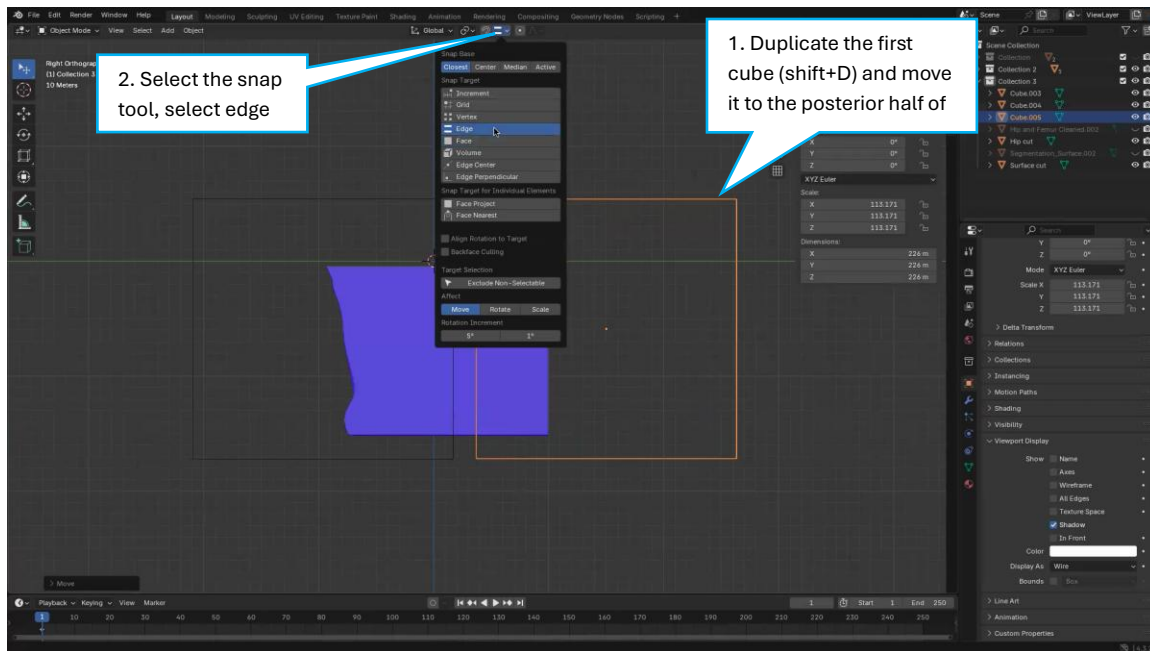


Figure 50 *Snapping Tool*

Select G+control and move the cutting cube until it snaps to the anteriorly placed cutting cube (Figure 51). This is to ensure both cubes are connected to each other. The objects being snapped together is very important when trying to cut objects in half without losing any structures. Make a copy of the posterior cutting cube, then hide the copy (Figure 51).

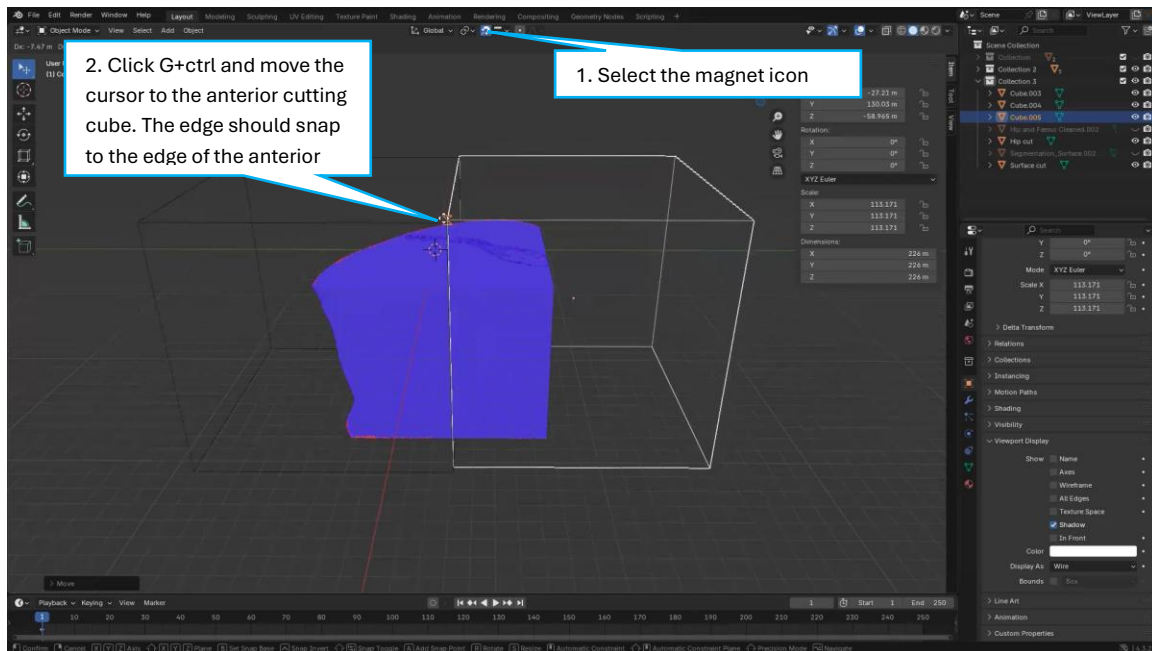


Figure 51 *Snapping the Cutting Cube*

Resize the posterior cutting cube to only include at least an additional 5-10mm from the posterior-most aspect of the surface anatomy. Ensure the posterior part of the bony anatomy is still within this cube (Figure 52).

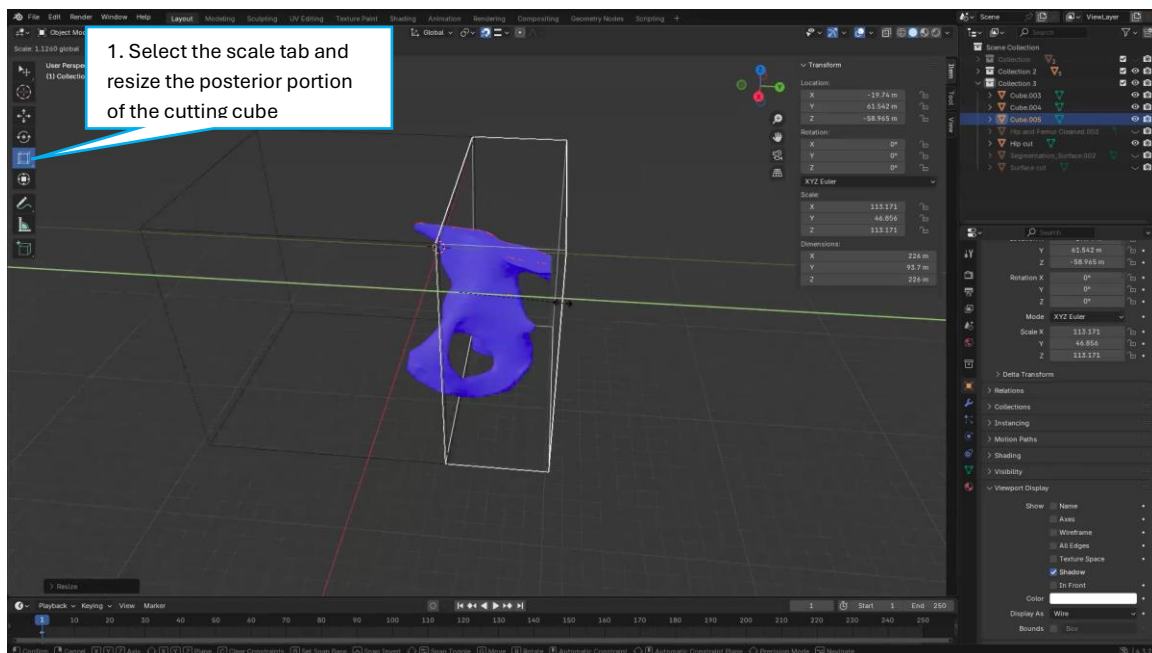


Figure 52 *Resizing the Cutting Cube*

Resize the superior portion of the cutting cube the be just under the top of the surface anatomy
(Figure 53).

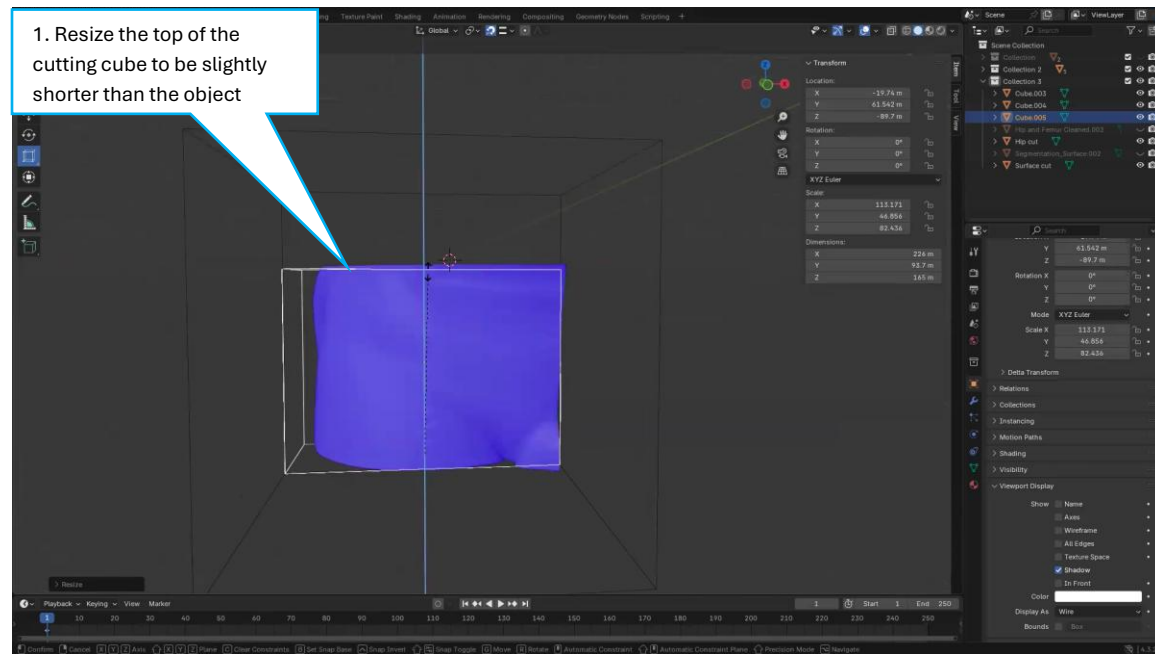
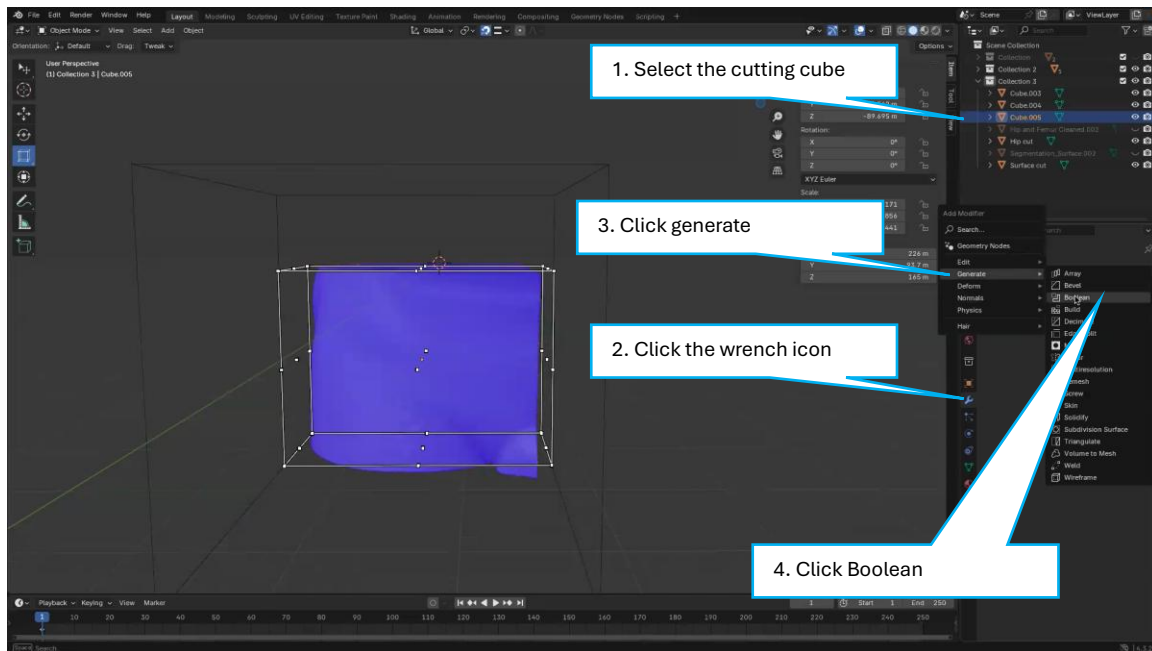


Figure 53 *Resizing the Cutting Cube 2*

Select the cutting cube and add the *Boolean* modifier (Figure 54).



597

598 Figure 54 *Cutting with the Boolean Modifier*

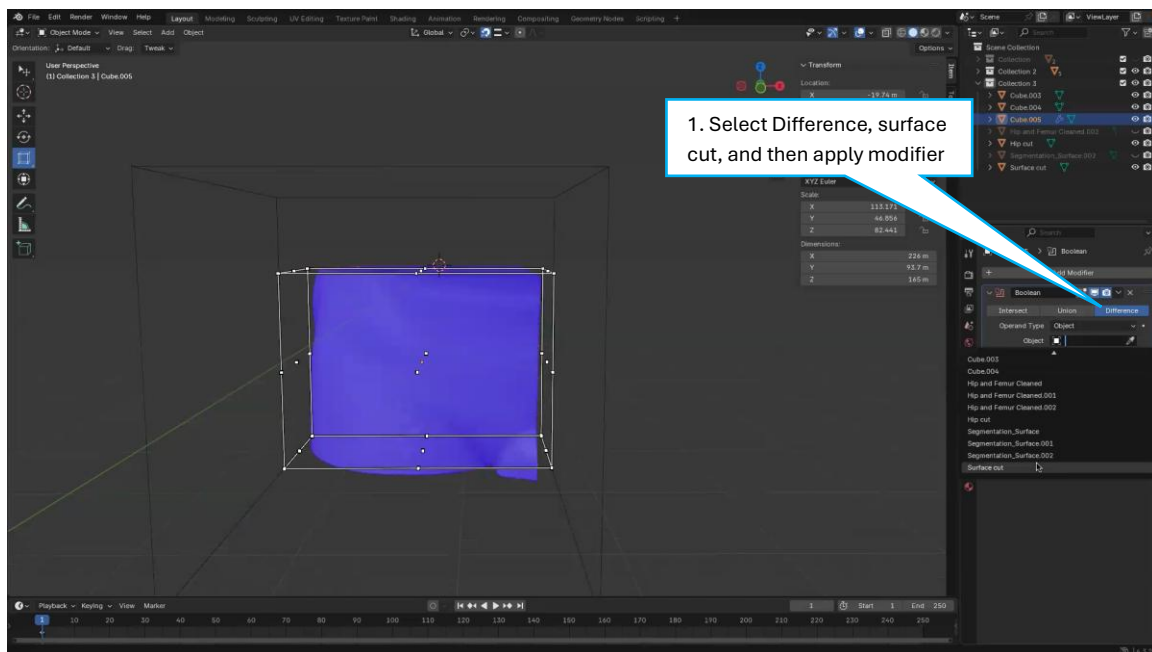
599

600

601 Select Difference and then select the surface anatomy that has been cut previously (Figure 55).

602 Then apply the modifier (Figure 55).

603



604

Figure 55 Cutting with the Boolean Modifier 2

Hide some of the other objects and review the modification. Confirm the modifier has worked appropriately (Figure 56).

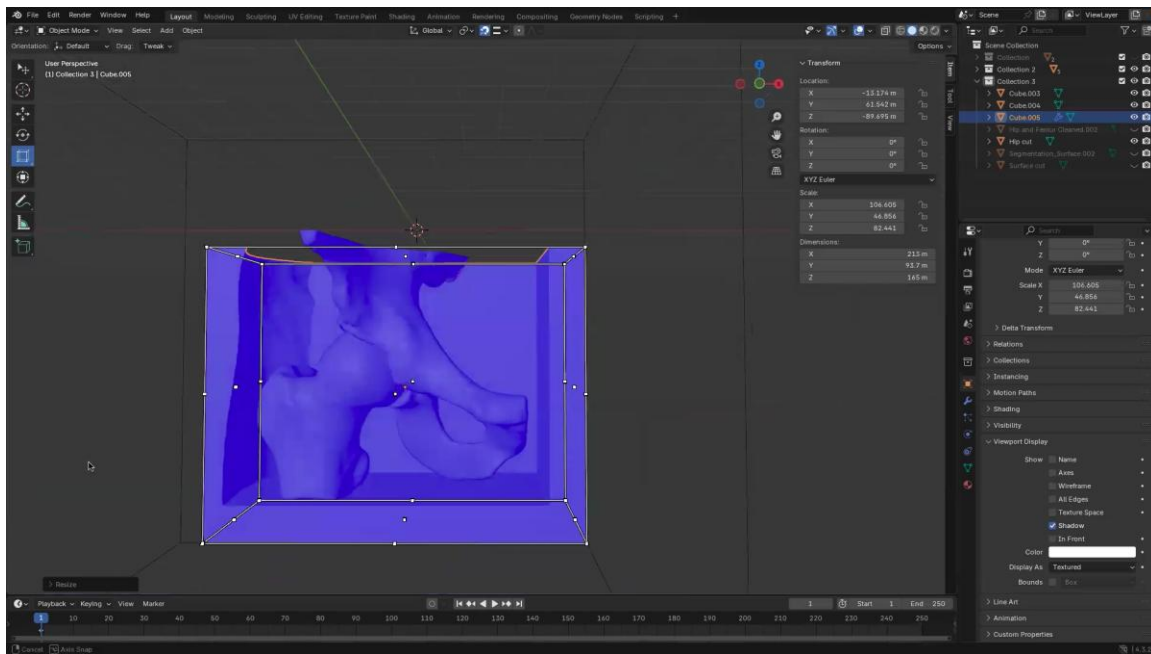
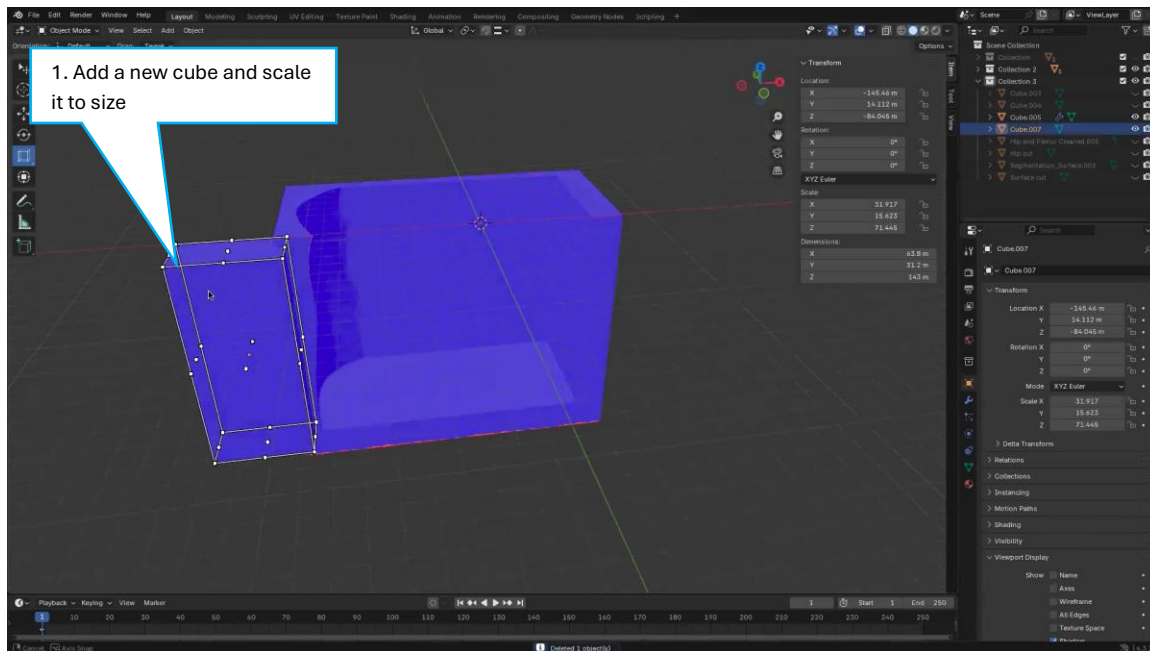


Figure 56 *Viewing the Modification*

Add a new cube and size it accordingly (Figure 57). This new cube will be used to create handles for the mold.



618

619 Figure 57 Adding a Cube for the Mold Handles

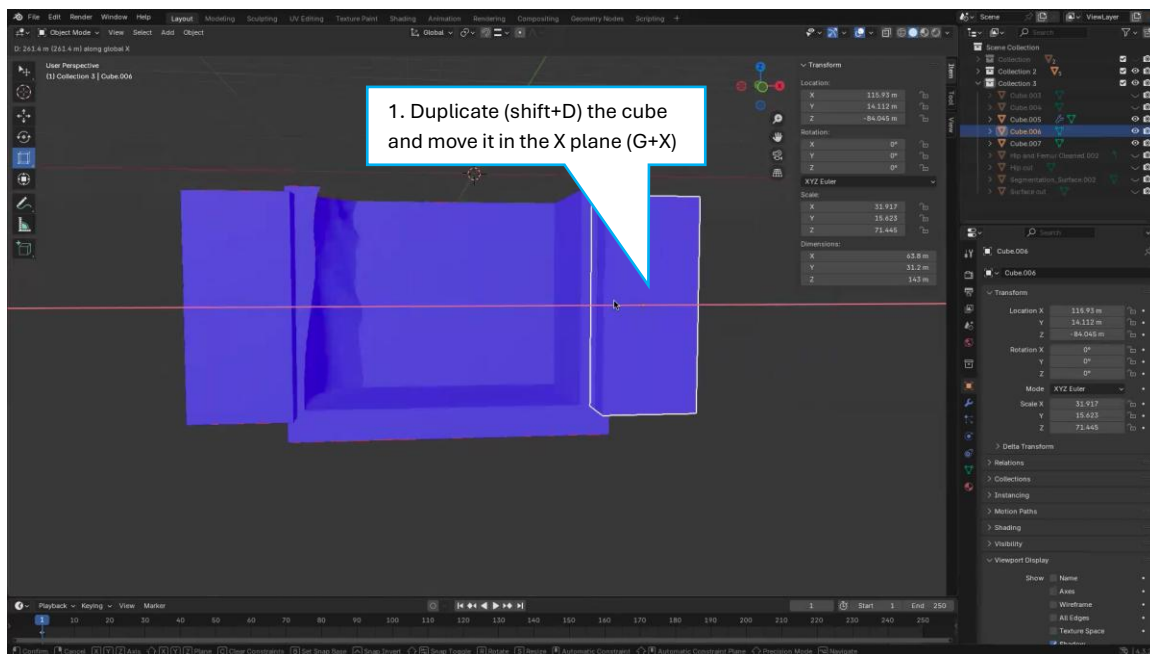
620

621

622 Duplicate the handle cube and move the object in the X plane (Figure 58). Select shift+D, then

623 left click. Then select G+X (Figure 58).

624



625

Figure 58 *Duplicating the Mold Handle*

Orient to look at the object from a superior view to confirm the handle cubes are in the correct placement (Figure 59). Then select both cubes and click cmd+J to join the objects together (Figure 59).

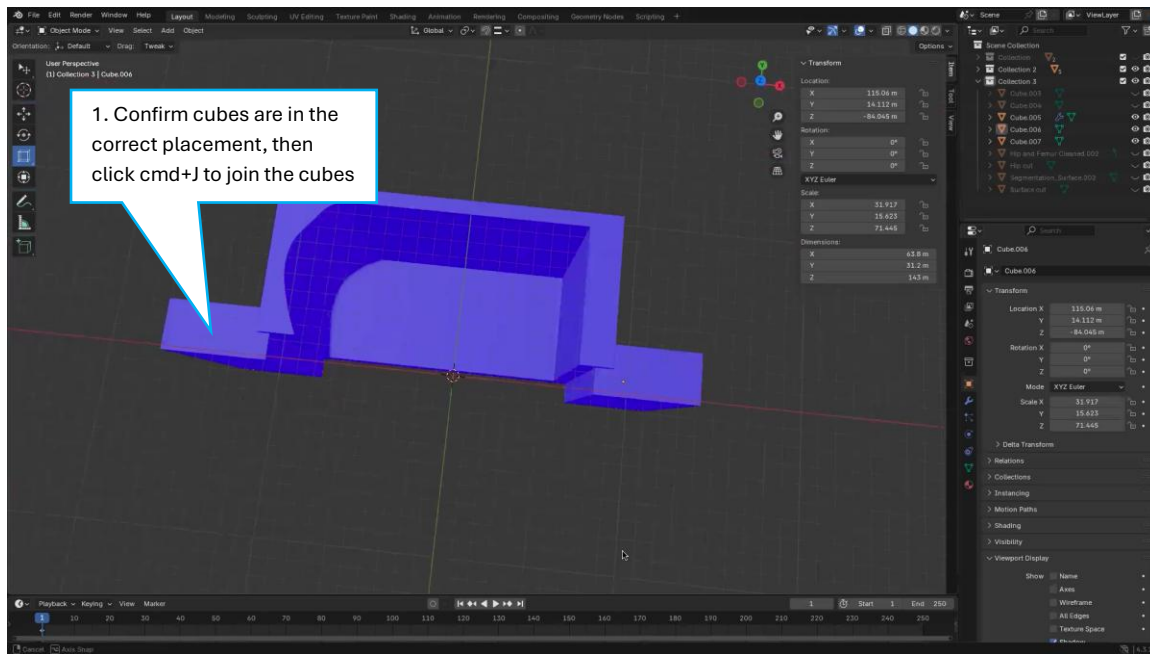
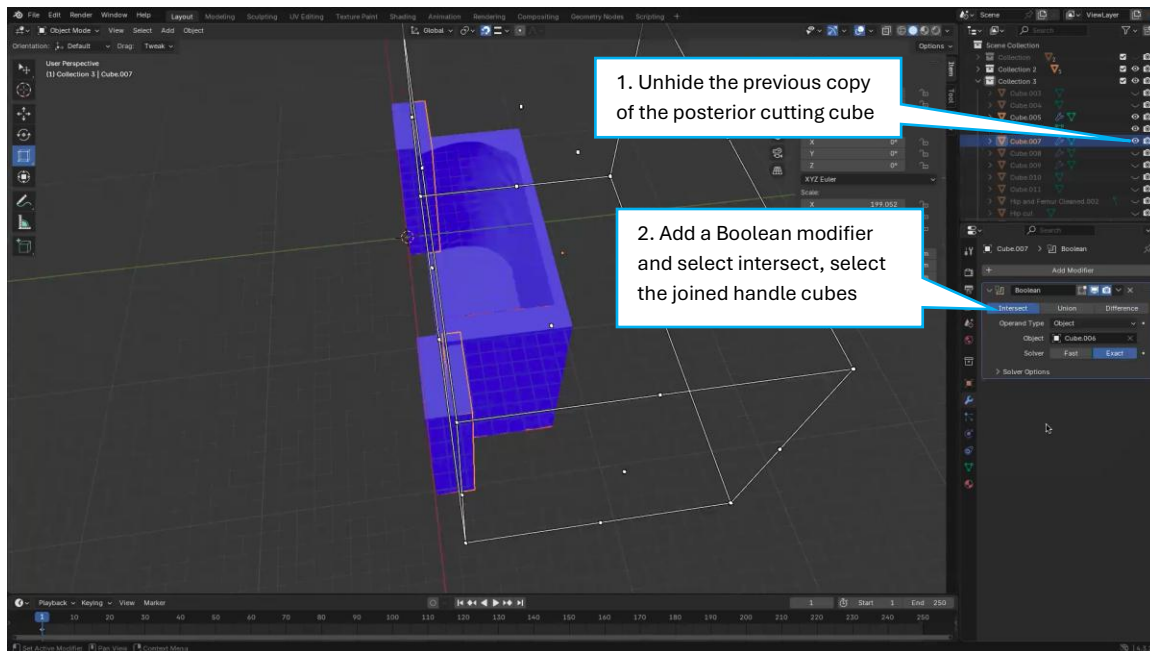


Figure 59 *Reviewing Handles*

Unhide the copy of the posterior cutting cube made previously. Then add a *Boolean* modifier. Select Intersect and select the conjoined handle cubes (Figure 60).



639

640 Figure 60 *Adding a Handle Cutting Cube*

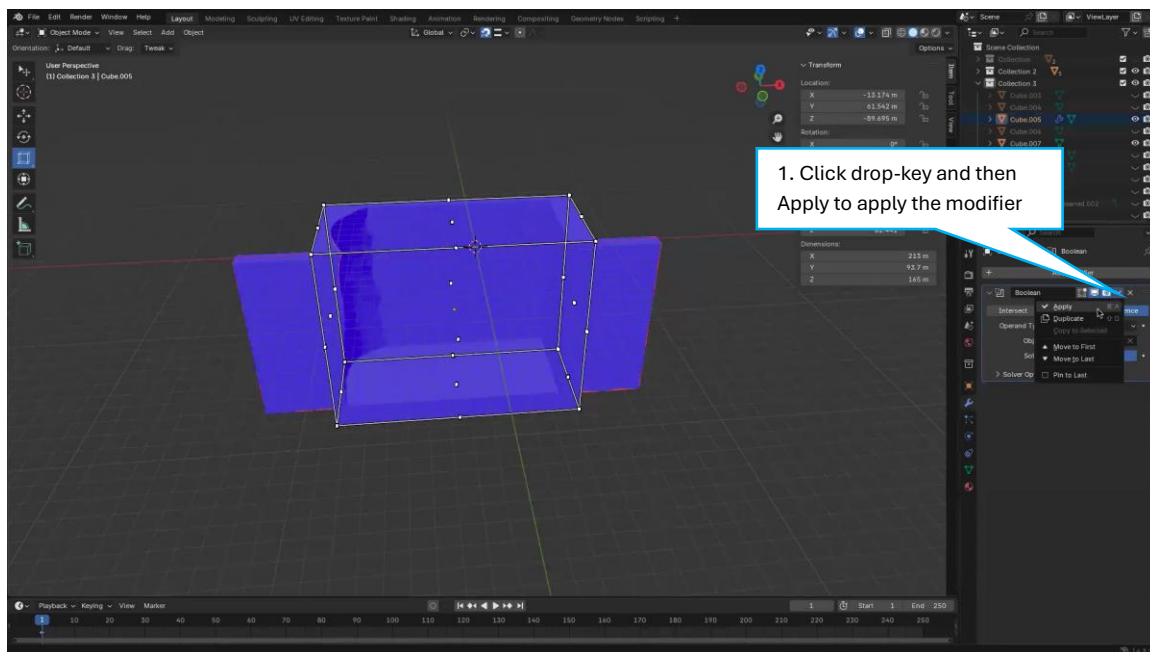
641

642

643 Apply the modifier (Figure 61).

644

645



646

Figure 61 *Applying Modifier*

Then select all three objects in view and click cmd+J to join all three objects together (Figure 62).

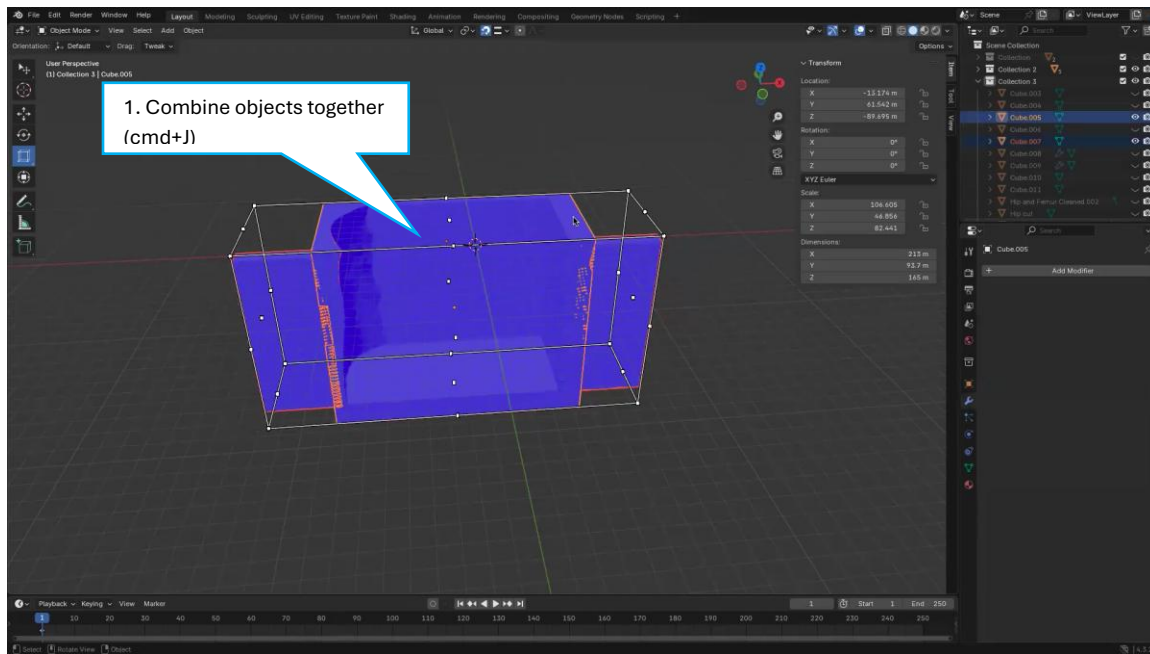


Figure 62 *Combining Objects*

Review the digital mold and confirm it meets the model requirements needed (Figure 63).

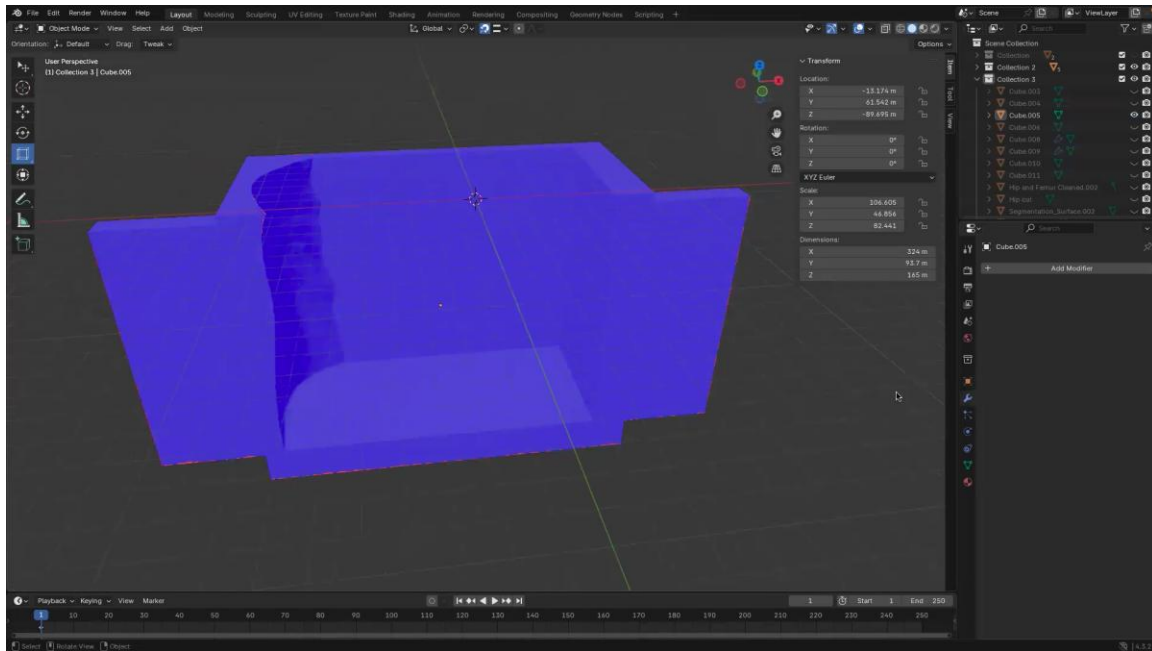


Figure 63 *Reviewing Digital Mold*

Unhide the bony anatomy and confirm the surface anatomy has been correctly molded (Figure 64).

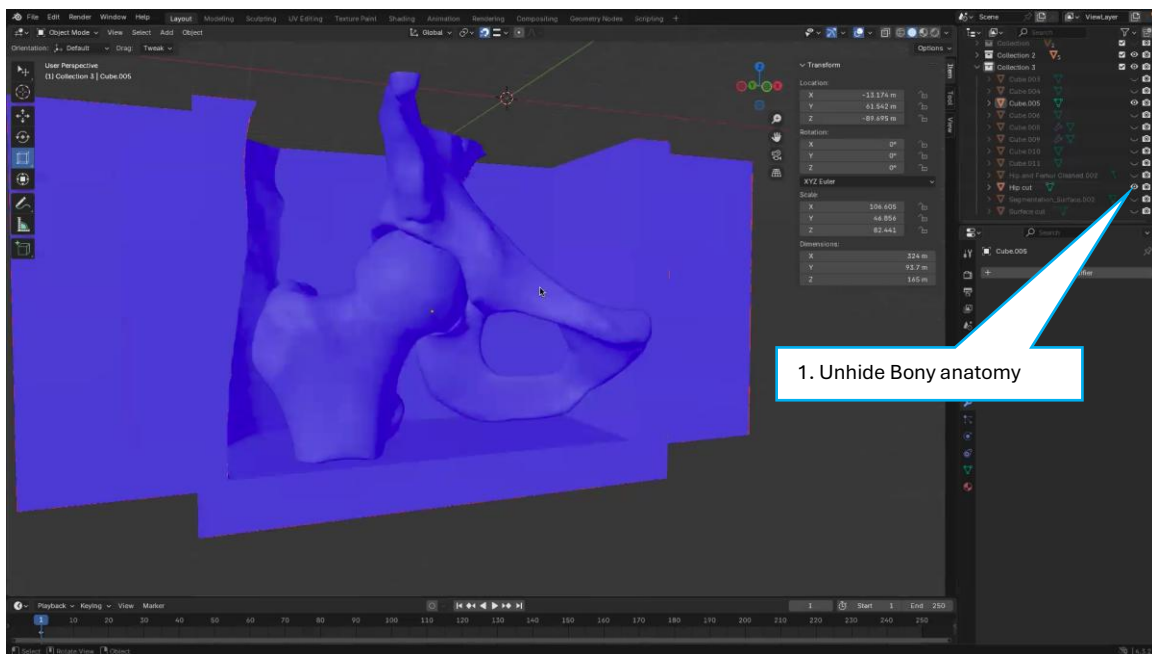


Figure 64 *Reviewing Digital Mold 2*

Next, repeat these steps to create an anterior surface mold. Then create handles for the anterior surface mold (this is why so many copies were made previously). Lastly, the same technique will be used to separate the bottom of the mold. The bony anatomy will be imprinted into the base mold using the *Boolean* modifier for it to have a place to lock in to (Figure 65).

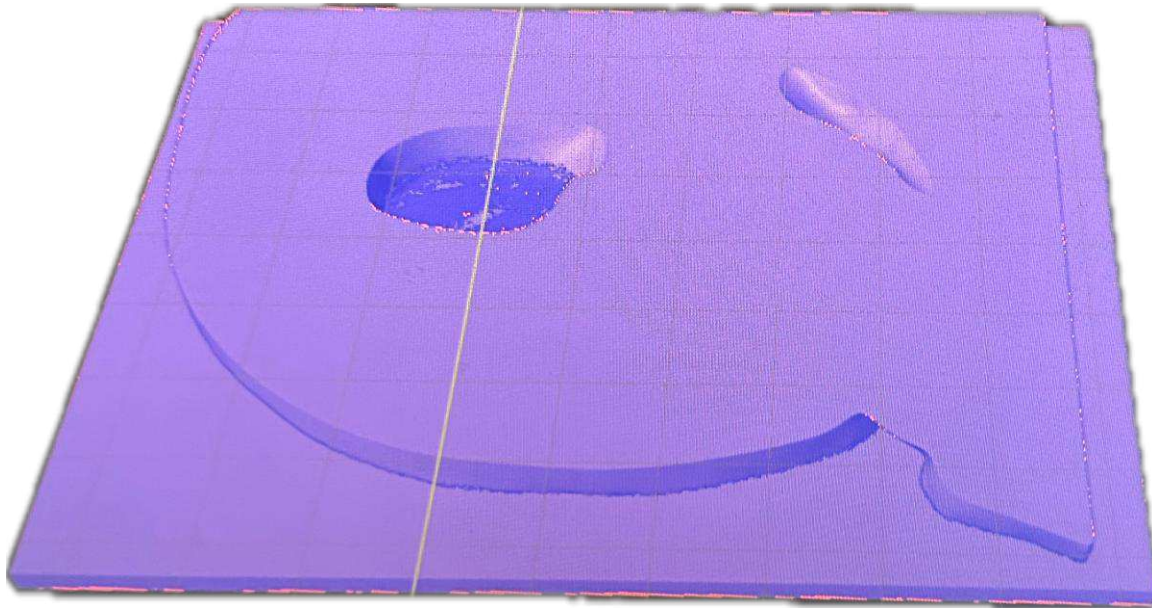
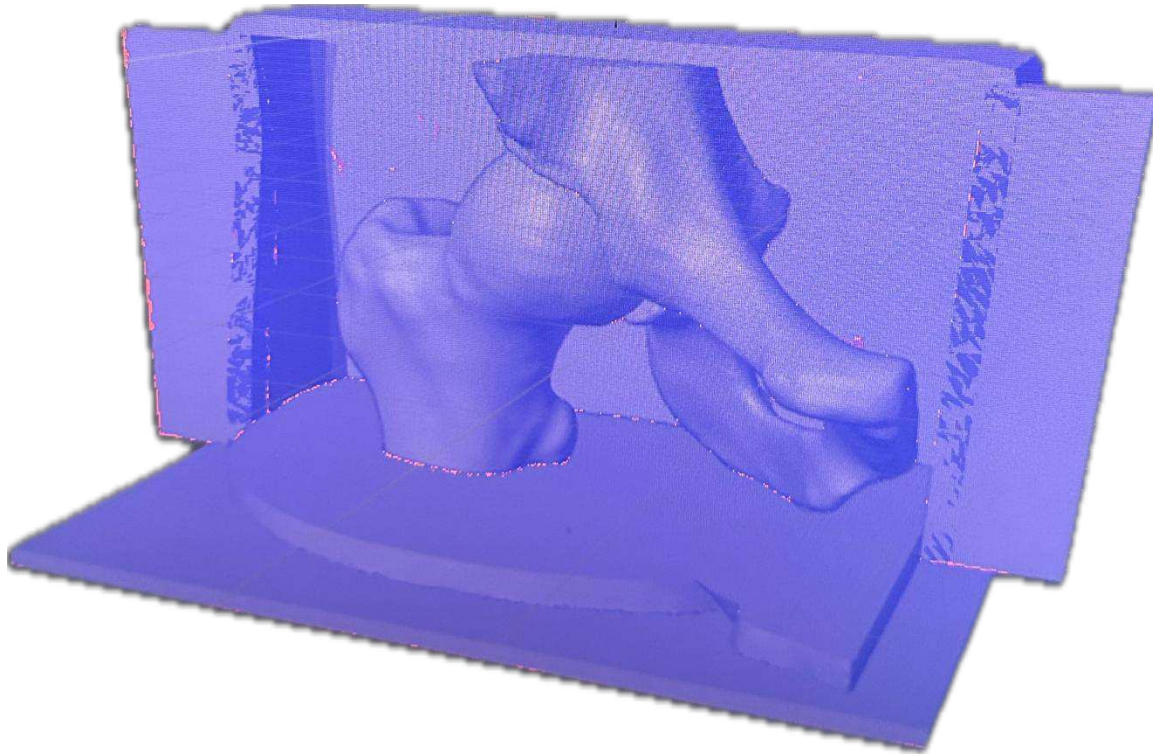


Figure 65 *Digital Base Mold*

Figure 66 shows the final digital mold including the base.



681

682 Figure 66 *Digital Mold*

683

684

685 *Joint Capsule Modeling*

686 Open a new Blender file. Import an STL of just the femur (Figure 67).

687

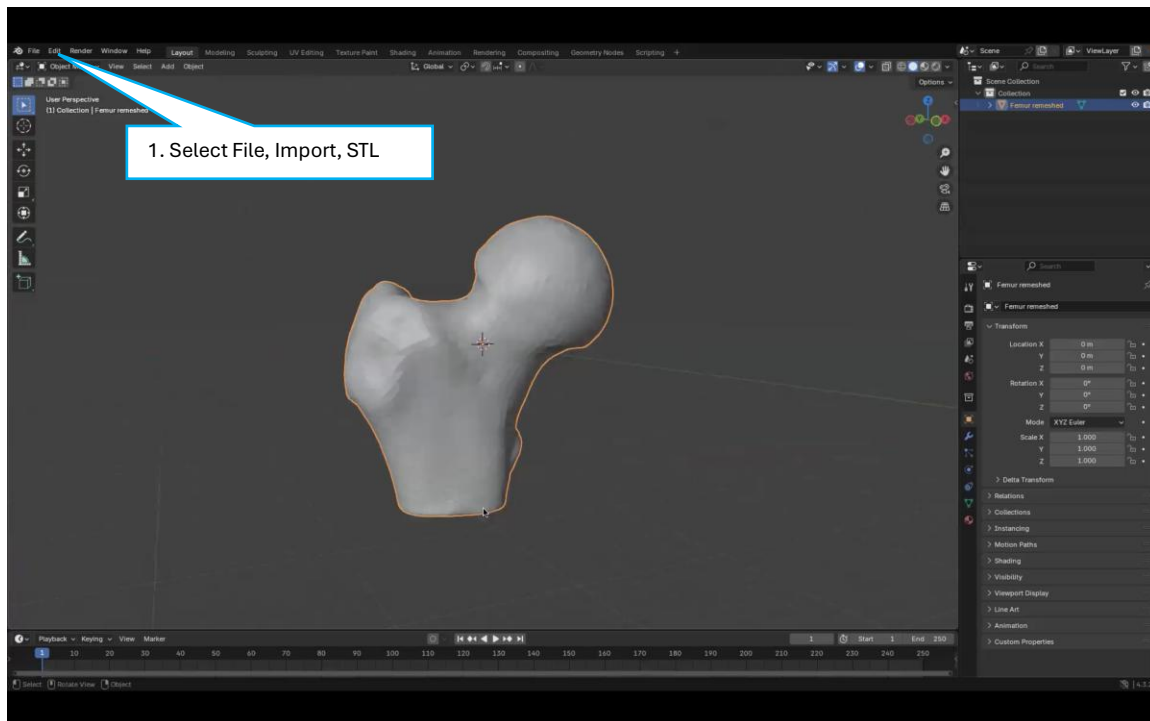


Figure 67 *Importing New Femur*

Make multiple copies of the object (5-10), then select wrench icon, generate, solidify (Figure 68).

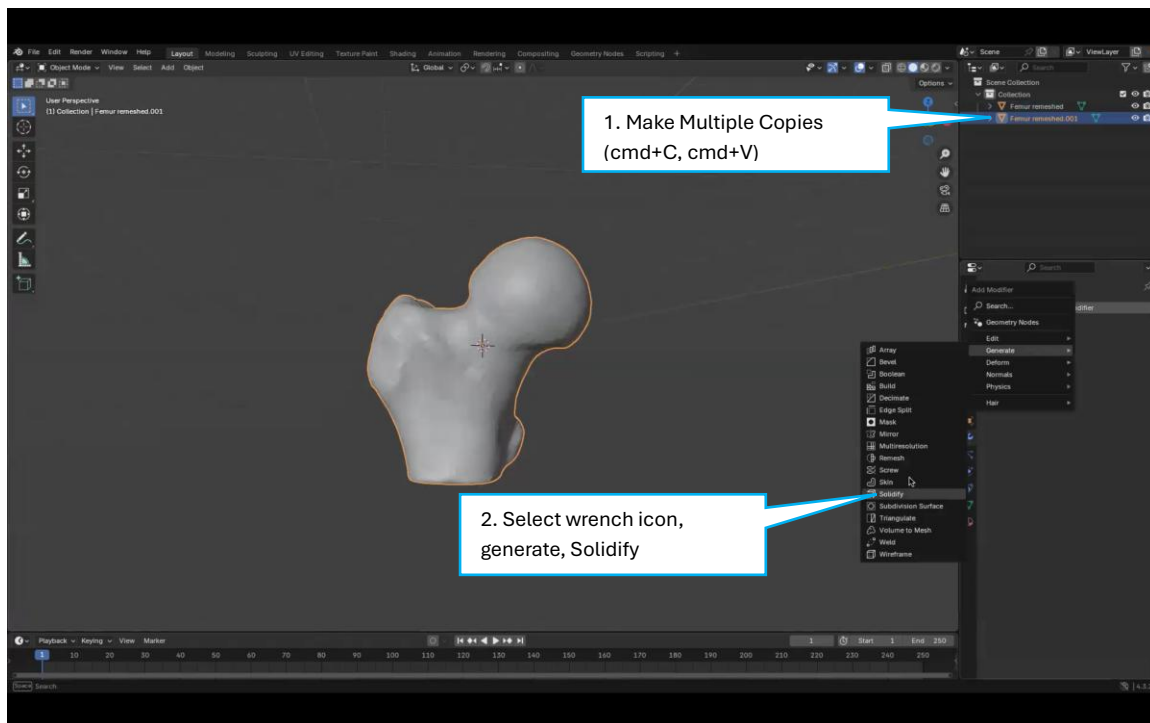


Figure 68 *Solidify Modifier*

Change the “thickness” to 5M (5 mm) and change the “offset” to 1. Then change the viewport display to wire (Figure 69). Apply the modifier.

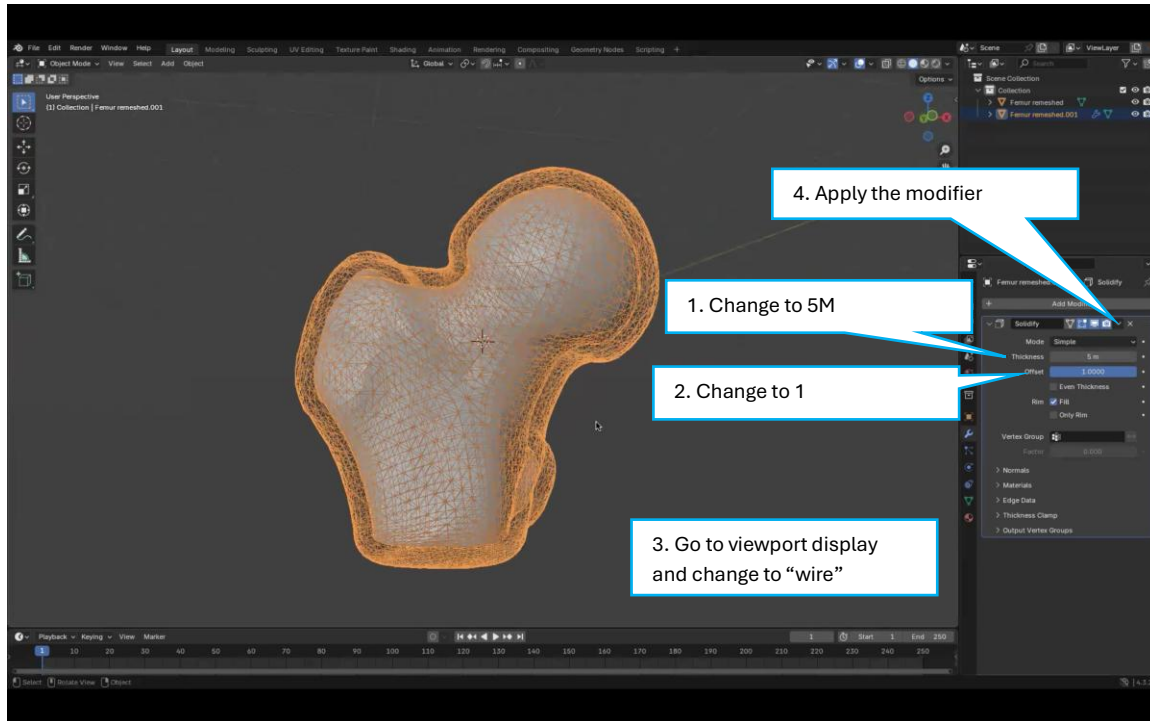


Figure 69 *Viewing Solidification*

Switch to edit mode. Select one external topographical vertex. Select all linked objects (cmd+L).

This is shown in Figure 70.

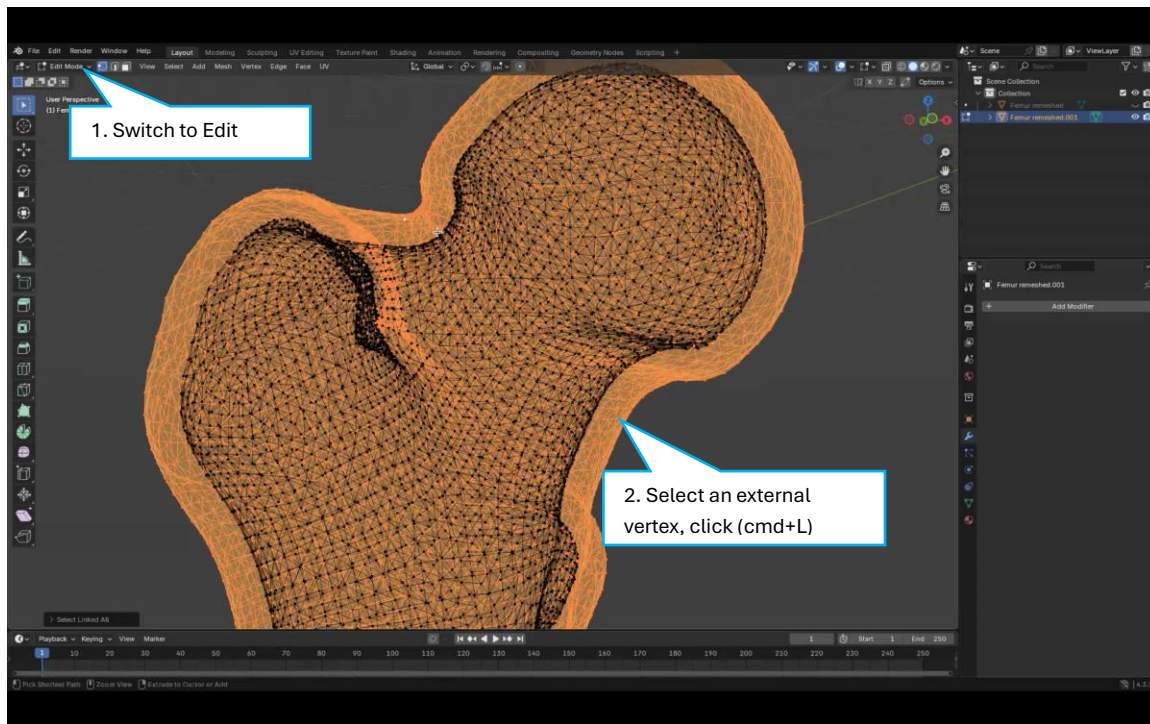


Figure 70 *Selecting External Topography*

Click (cmd +I) and then X and delete vertices (Figure 71).

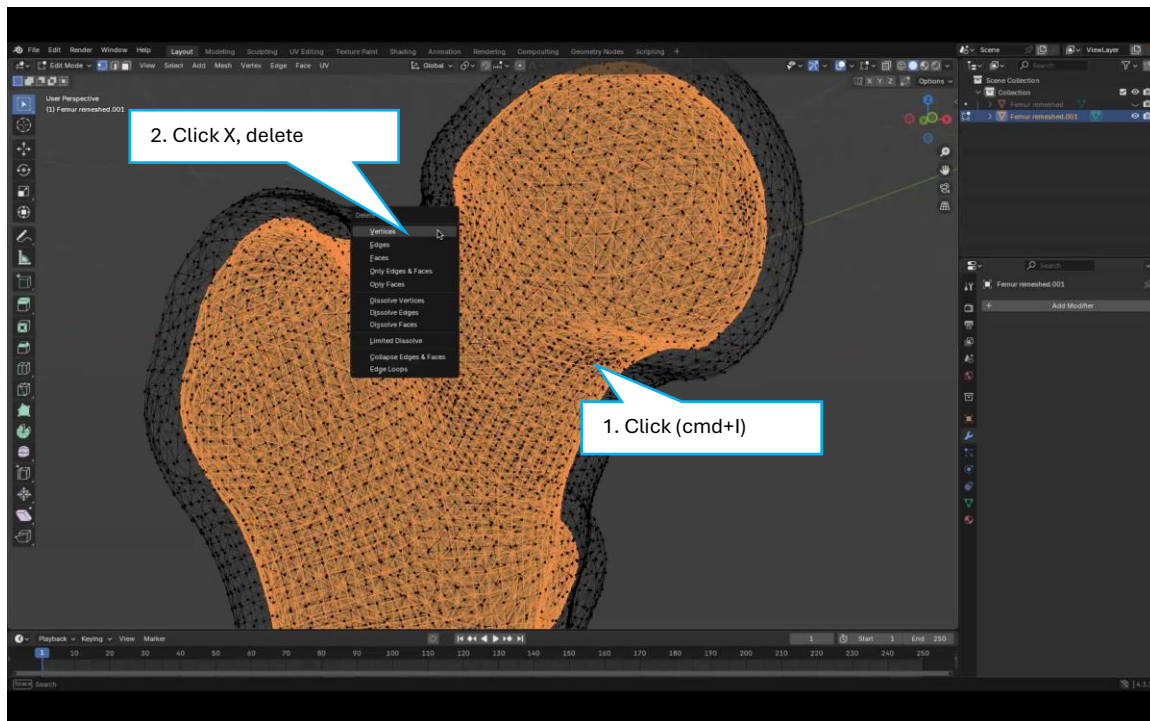
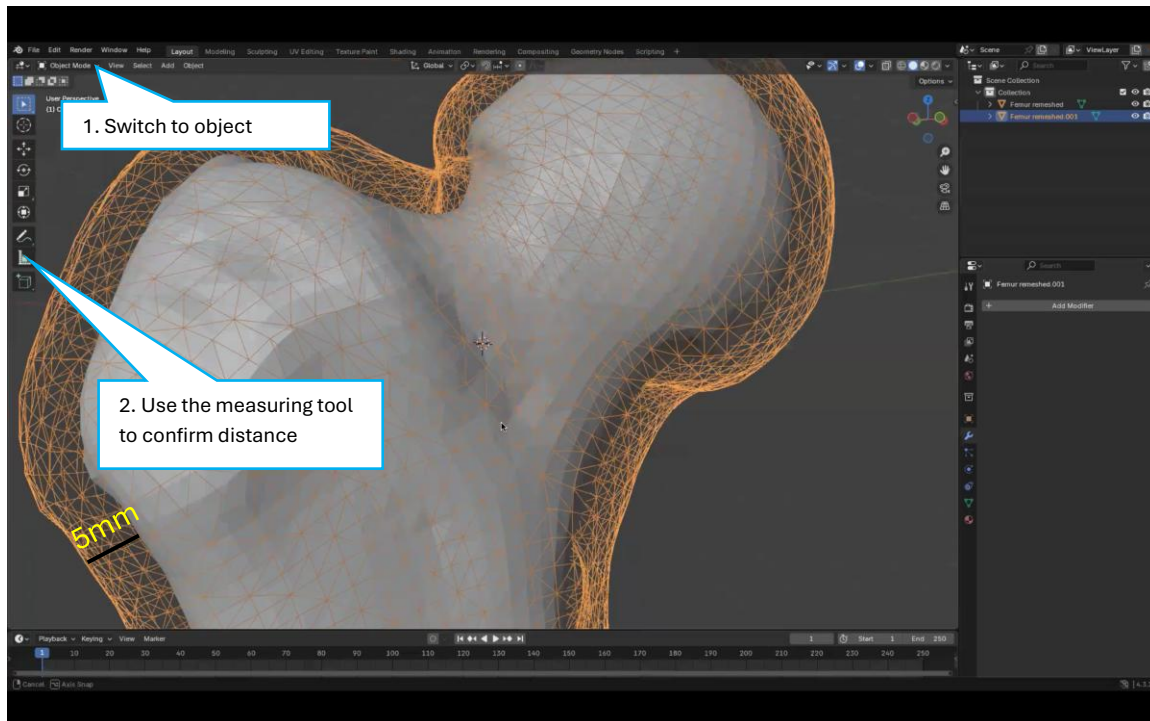


Figure 71 *Deleting Internal Mesh*

715

716 Switch to object mode. Confirm that the internal mesh from the *solidify* modifier has been
717 deleted. Open both objects at the same time and observe the 5 mm difference in the external
718 topography. Use the measuring tool to confirm the difference (Figure 72).



719

720 Figure 72 *Confirming Extrusion Distance*

721

722

723 Add a new cube and move it into place, as shown on Figure 73.

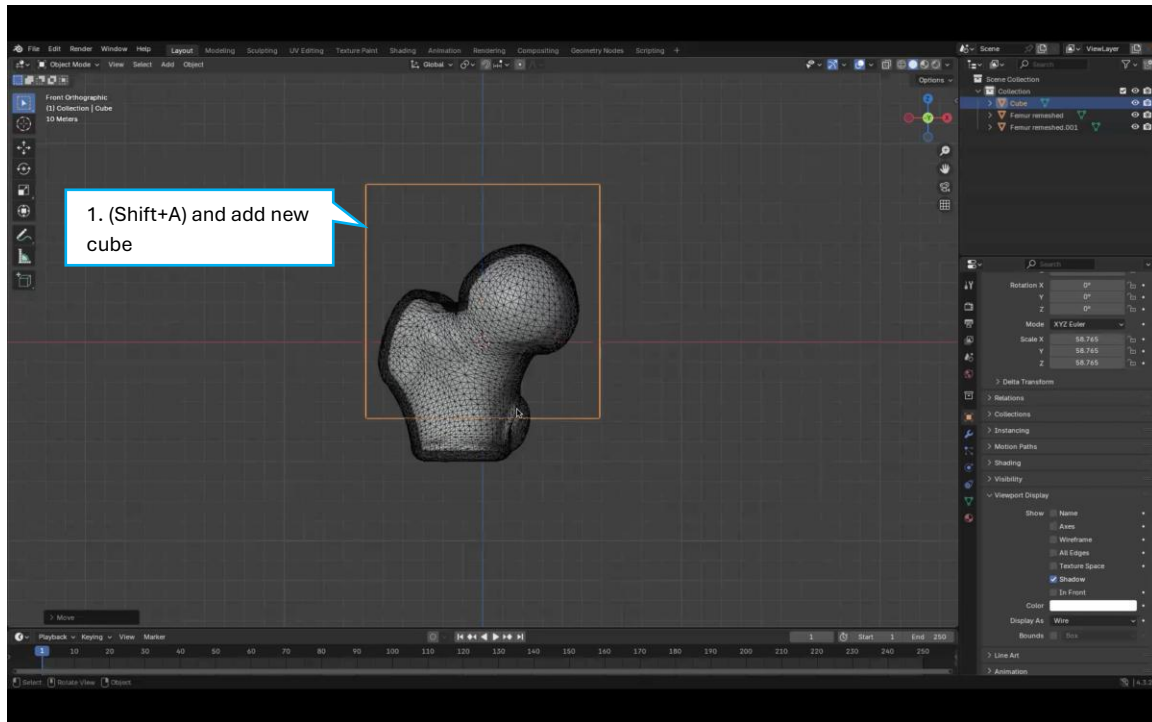


Figure 73 *Inserting a New Cutting Cube*

Once the cube is in place, select the cube. Click the wrench icon, generate *Boolean*. Select intersect, then select “femur remeshed 001” (Figure 74). Click solver options and make sure self-intersection is selected.

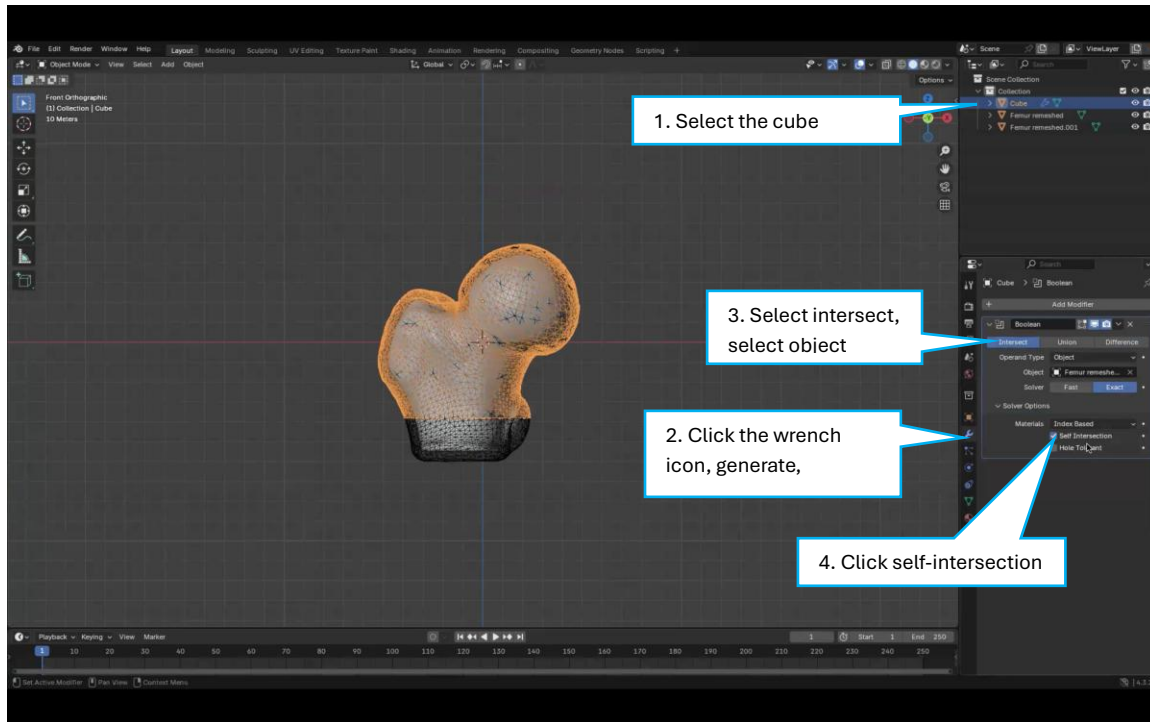


Figure 74 *Applying Boolean Modifier*

Make multiple copies of the objects (2-3). Then apply the modifier. Change the viewport display back to “textured”. Then select the cube that has the applied modifier and combine it with a copy of one of the femurs (cmd+J). Rename any objects that have now changed or been combined. Observe the 5 mm of space between the original femur and the new expanded femur (Figure 75). This will be the distance of space the joint capsule will be. Export the new object as an STL.

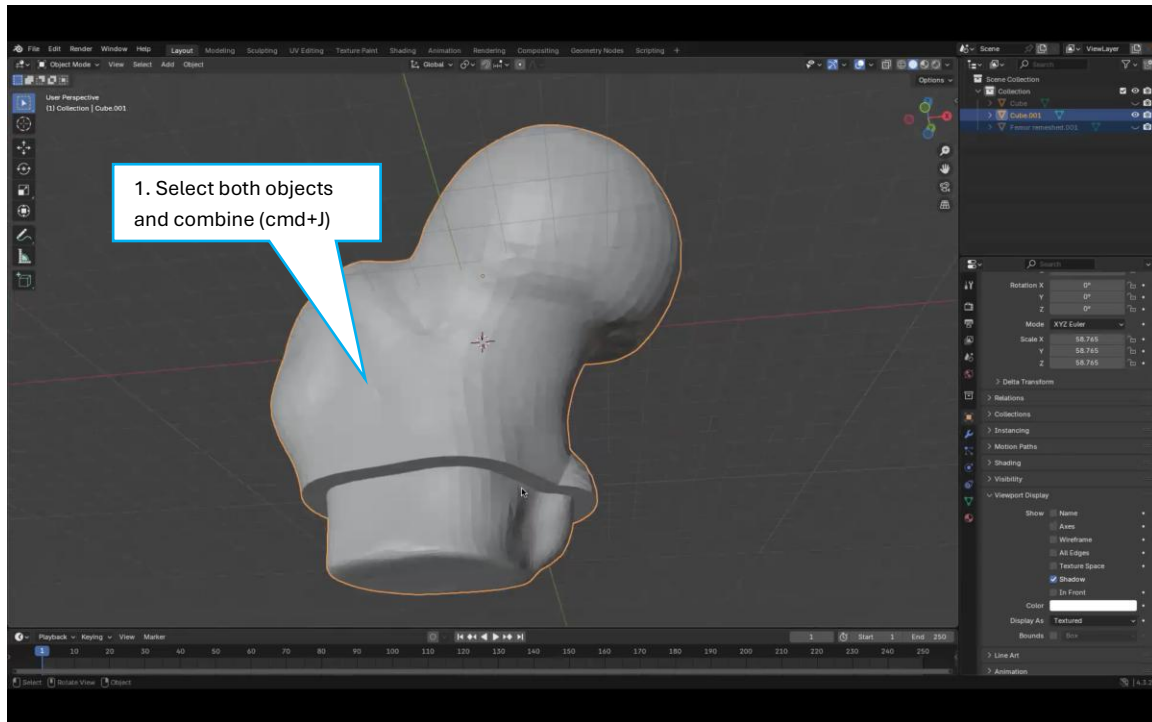


Figure 75 *Combining Objects Together*

Make a copy of the original femur and start a new *solidification* (wrench icon, generate, solidify). Change the “thickness” to 8 mm, select “offset” and change it to 1 (Figure 76).

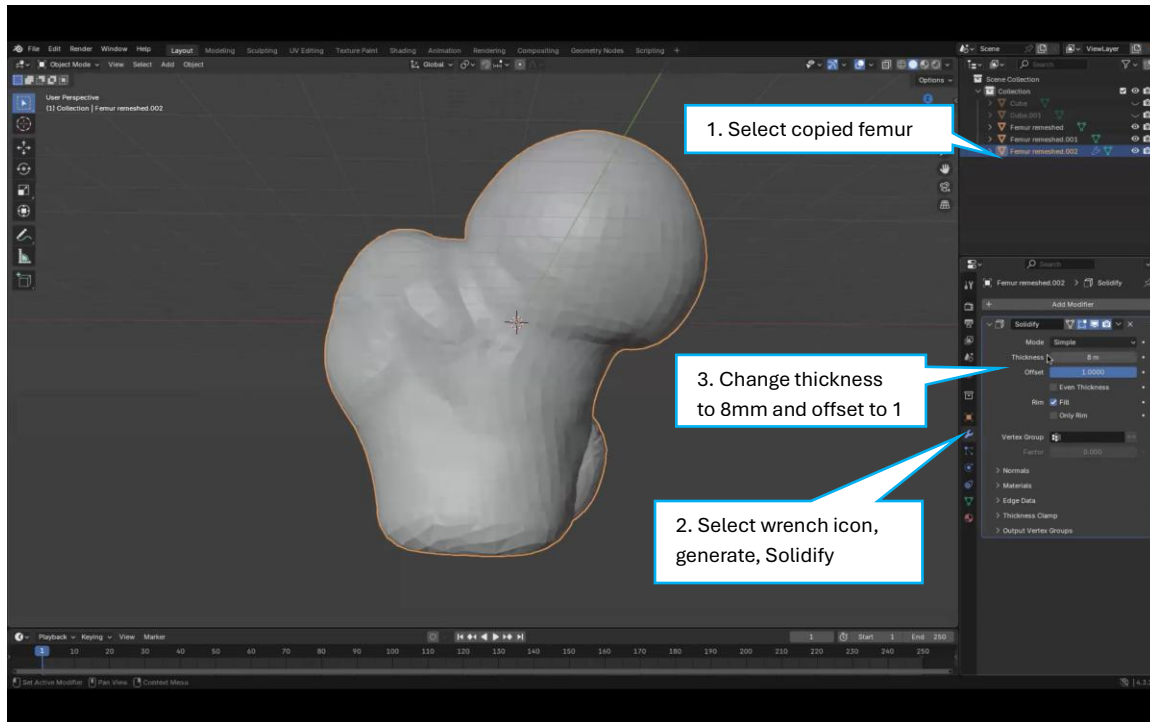


Figure 76 8mm Solidification

The thickness of this *solidification* will dictate the thickness of the tissue-mimicking material that is being used for the joint capsule mold. In this case, there are three additional millimeters from the expanded femur. That means our tissue mimicking thickness will be 3 mm. Go to edit mode, delete the internal mesh as done previously with the new solidification. Complete another *solidification* with an additional copy of the femur and increase the thickness of this layer to be 2-5mm thicker than the second layer. For this example, it is shown to be 13 mm (Figure 77). This will dictate the thickness of the plastic that is 3D printed. Switch to edit mode and delete the internal mesh of this new *solidification*.

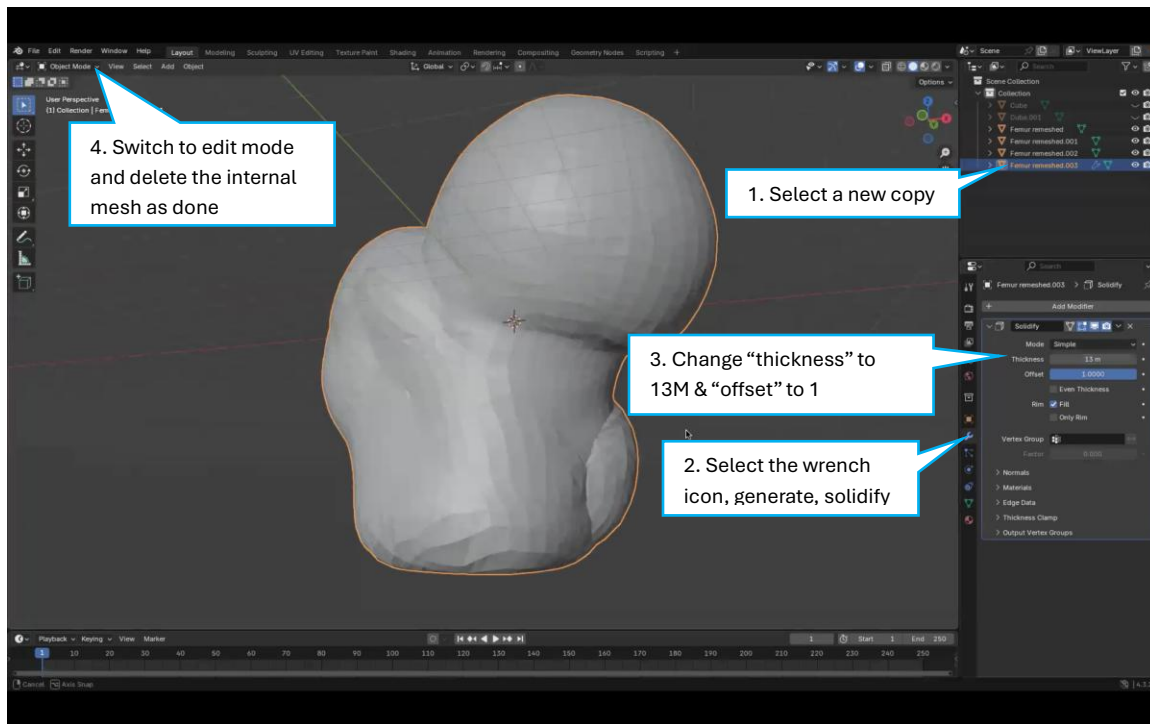


Figure 77 13mm Solidification

Observe the highlighted internal mesh in edit mode in Figure 78.

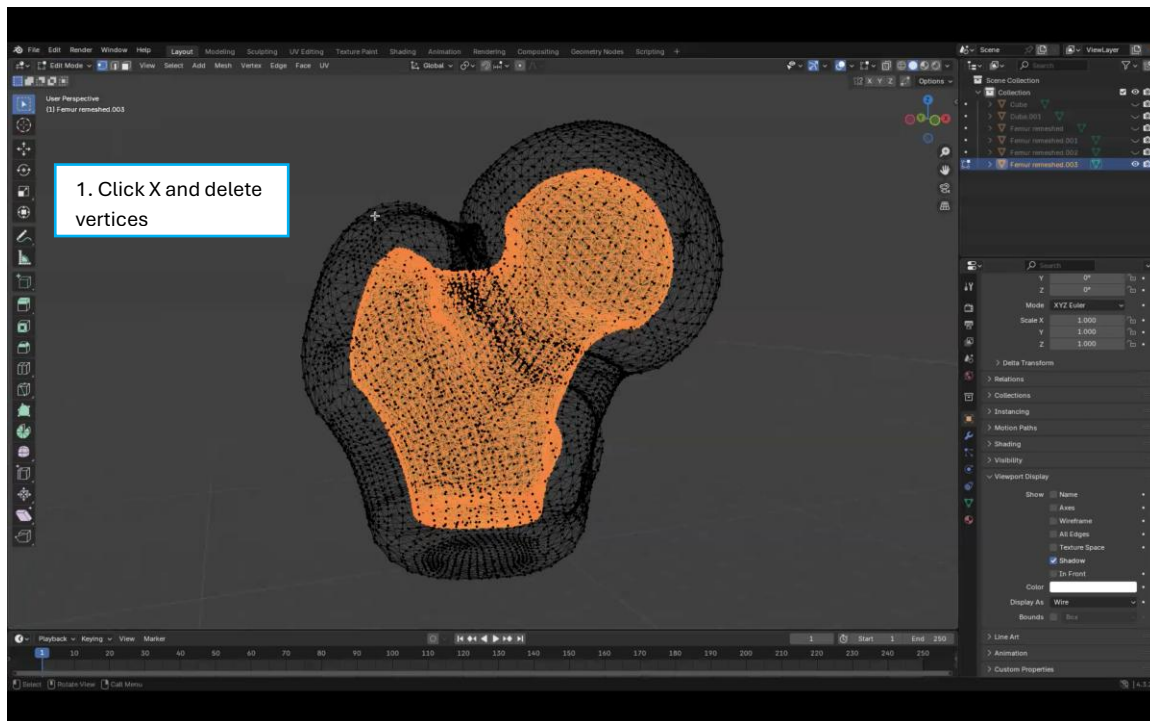


Figure 78 Deleting Internal Mesh 2

Observe the spacing distance between each of the layers, as shown in Figure 79. Use the measuring tool to review the distance between the layers.

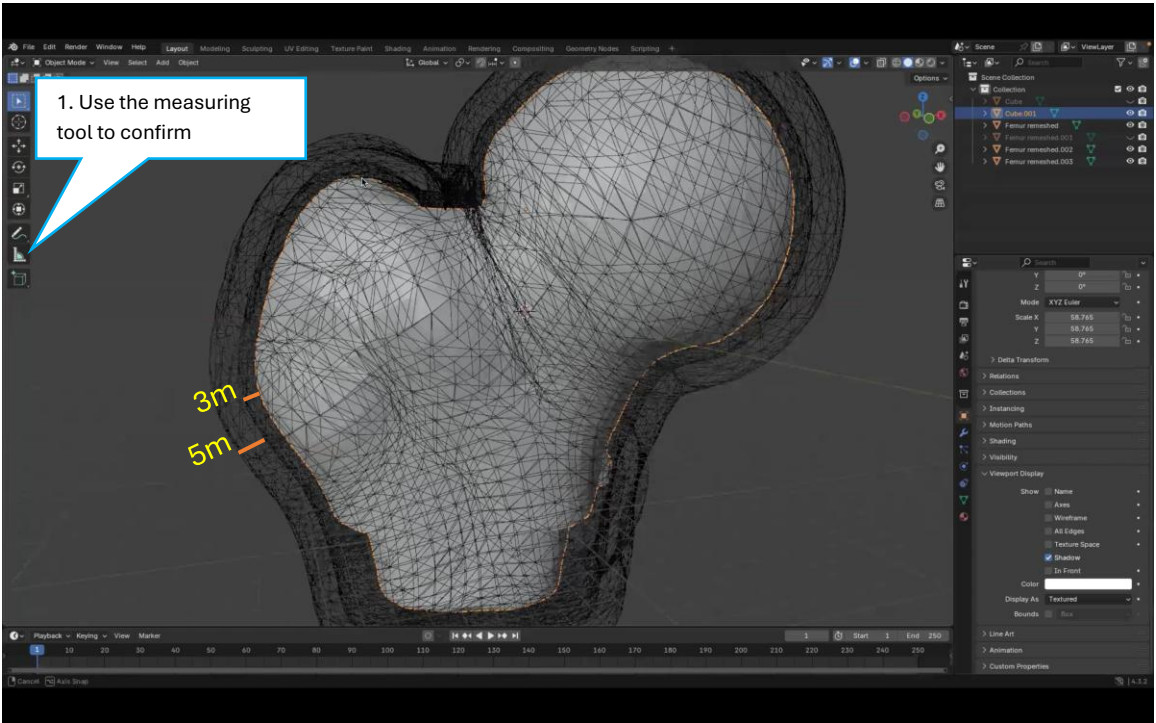


Figure 79 *Measuring Layer Distances*

Select the middle layer. Switch to edit mode. Turn on Face Orientation (Figure 80).

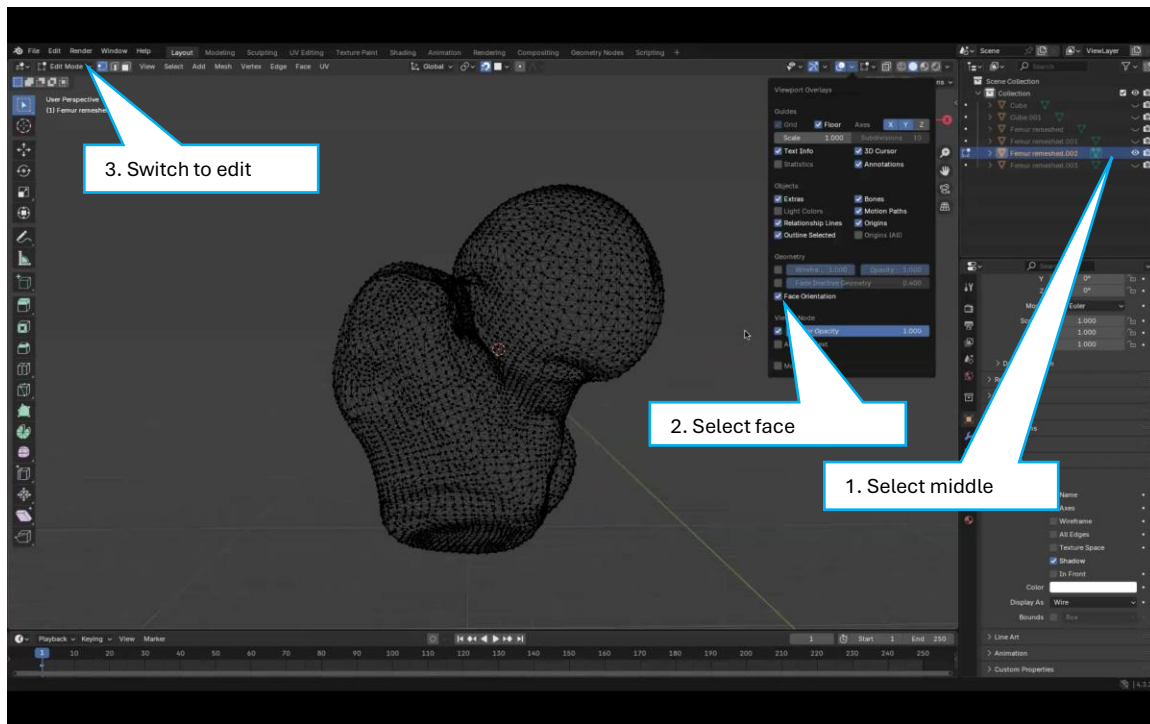


Figure 80 *Face Orientation*

Click A on the keyboard, then select mesh, normal, recalculate outside (Figure 81).

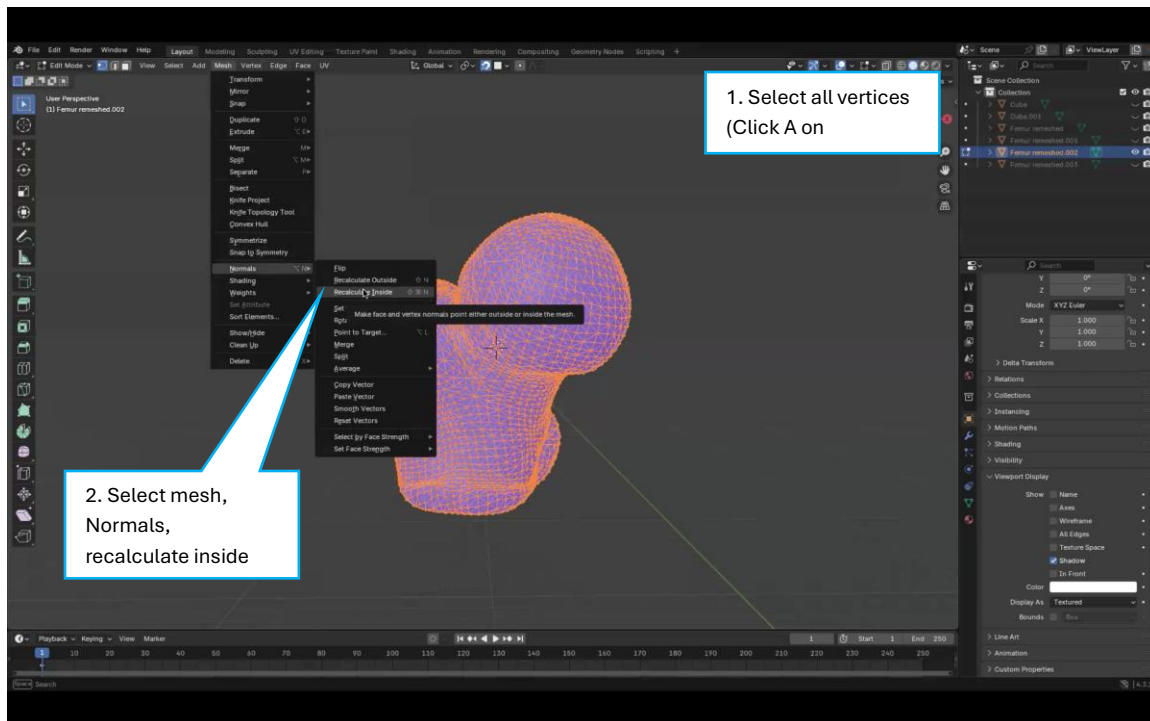


Figure 81 *Recalculating Internal Mesh*

Observe how all the faces have been flipped in Figure 82. This allows the two layers to be combined to make the joint capsule mold. Together, the objects will combine seamlessly, with one being inside the 3-D printed object and the outer layer being the outside of the 3-D printed object.

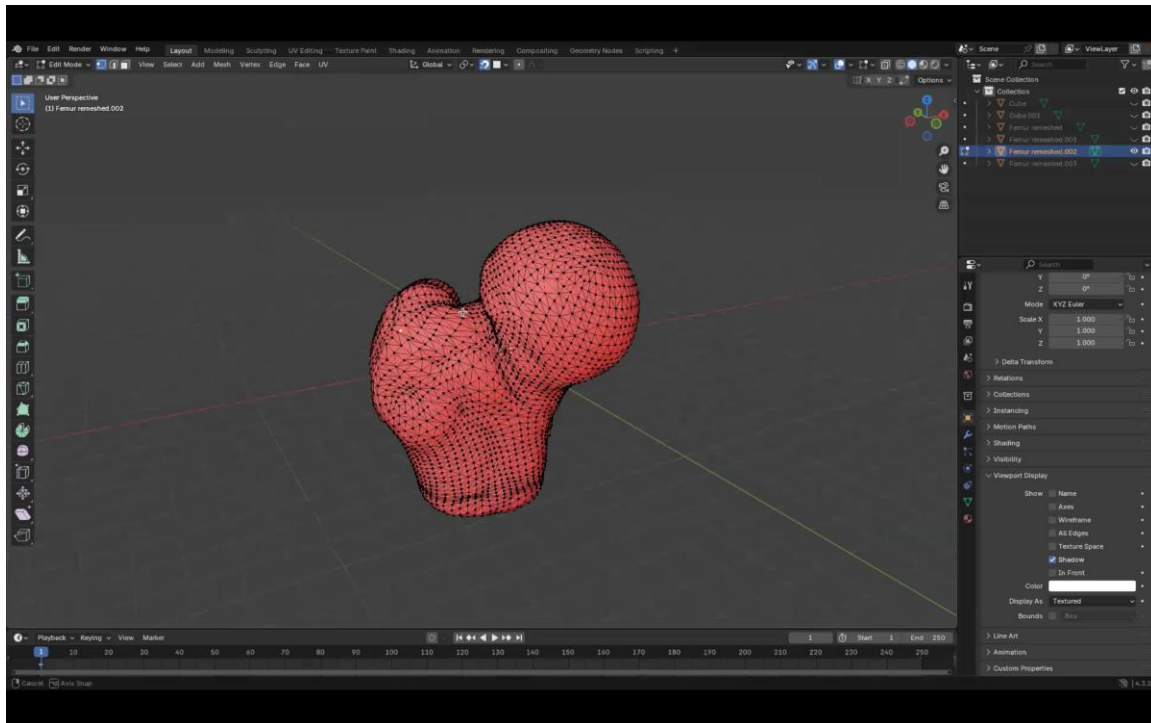


Figure 82 *Observing Flipped Mesh*

Switch to object mode and combine objects together (Figure 83).

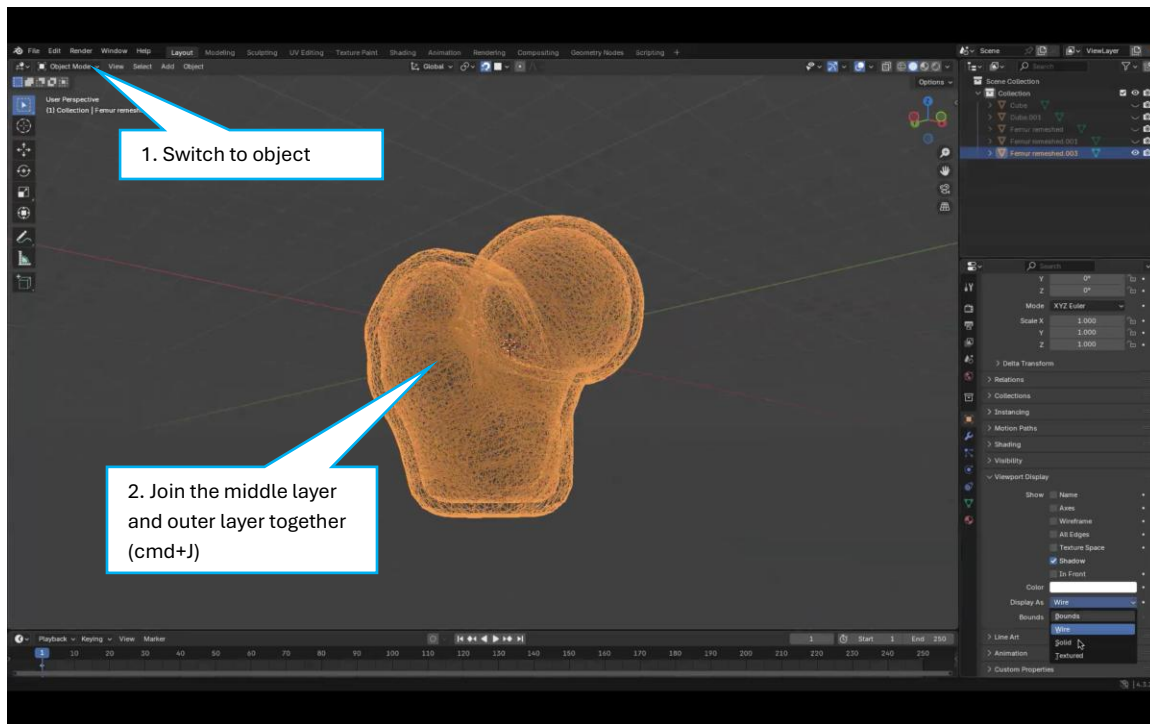


Figure 83 *Combining Solidification Layers*

Once objects are combined, review the object for any defects. Switch to sculpt mode and use various tools to clean the object as done previously with the original segmentation. Observe in Figure 84 the *smooth tool* is being used to clean up the internal mesh of the combined joint capsule mold layers.

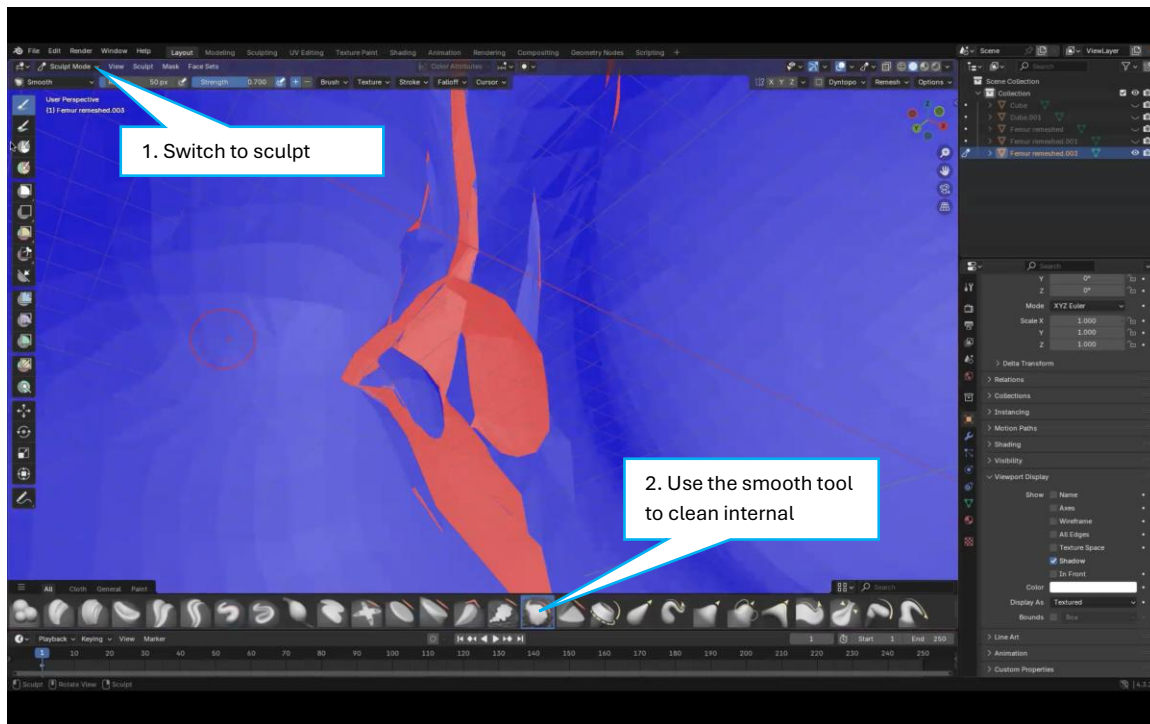


Figure 84 *Cleaning Internal Structures*

Now add a cube to cut the bottom off the joint capsule mold and apply the modification (Figure 85). Make sure to make two copies of this cutting cube.

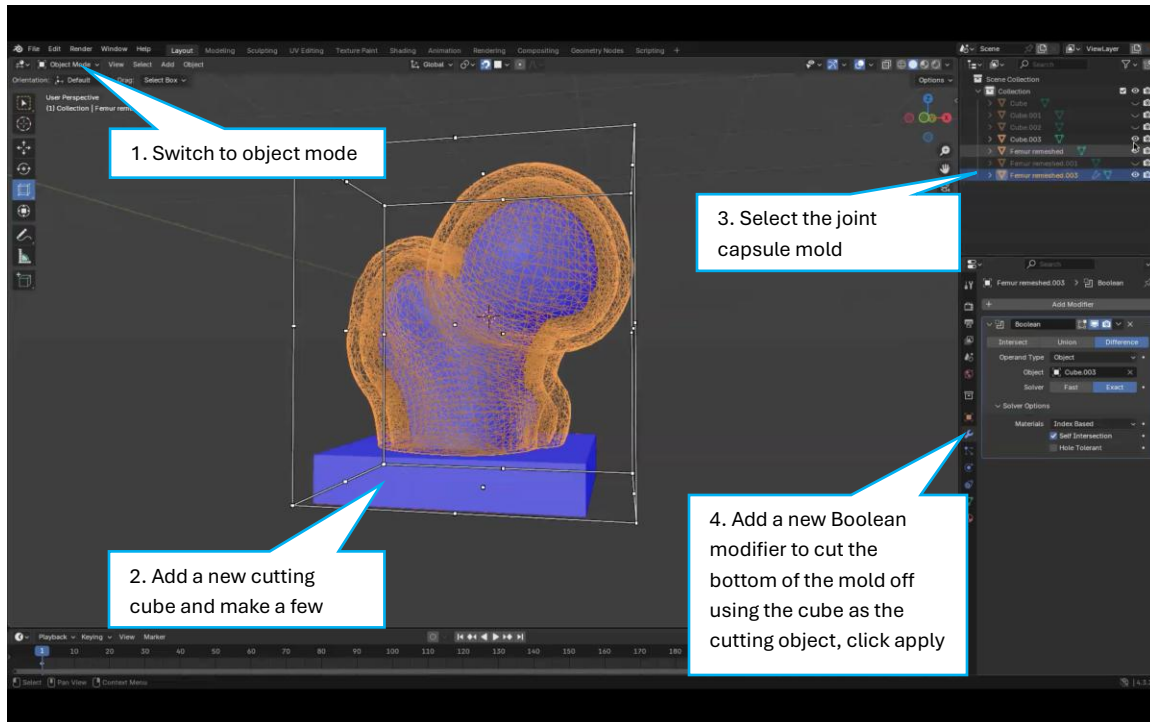


Figure 85 *Creating a Base for the Mold*

Now apply the two modifiers shown in Figure 86 to the cutting cube for both the original femur and the joint capsule mold objects.

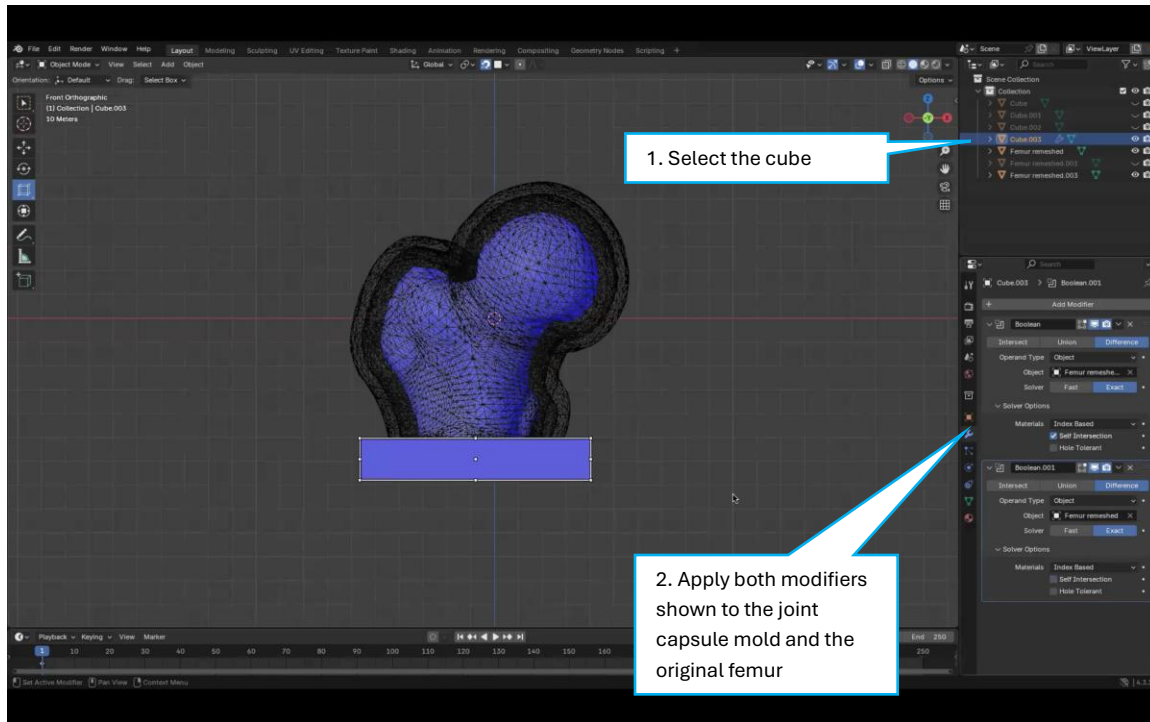


Figure 86 *Cutting Mold into Base*

Observe the cut base (Figure 87). This will be used as the base of the joint capsule mold. Then export the object as an STL.

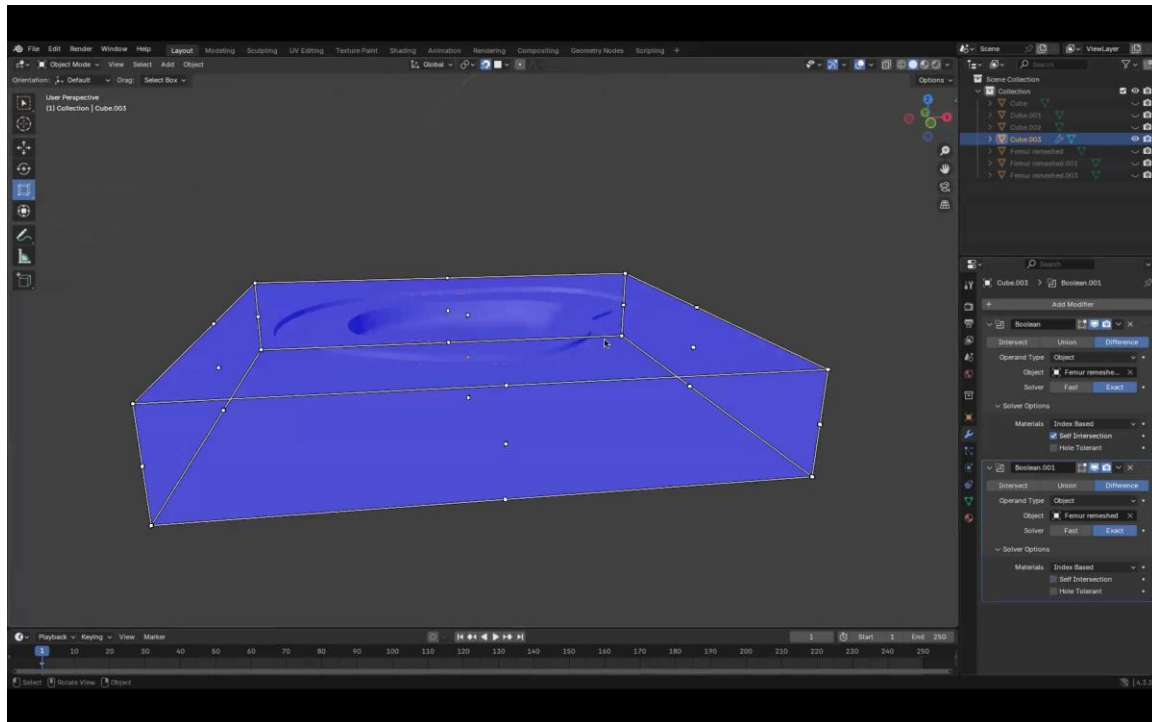


Figure 87 *Observing Cut Base*

Now add an additional cutting cube and move halfway through the joint capsule mold through the coronal plane, as shown on Figure 88.

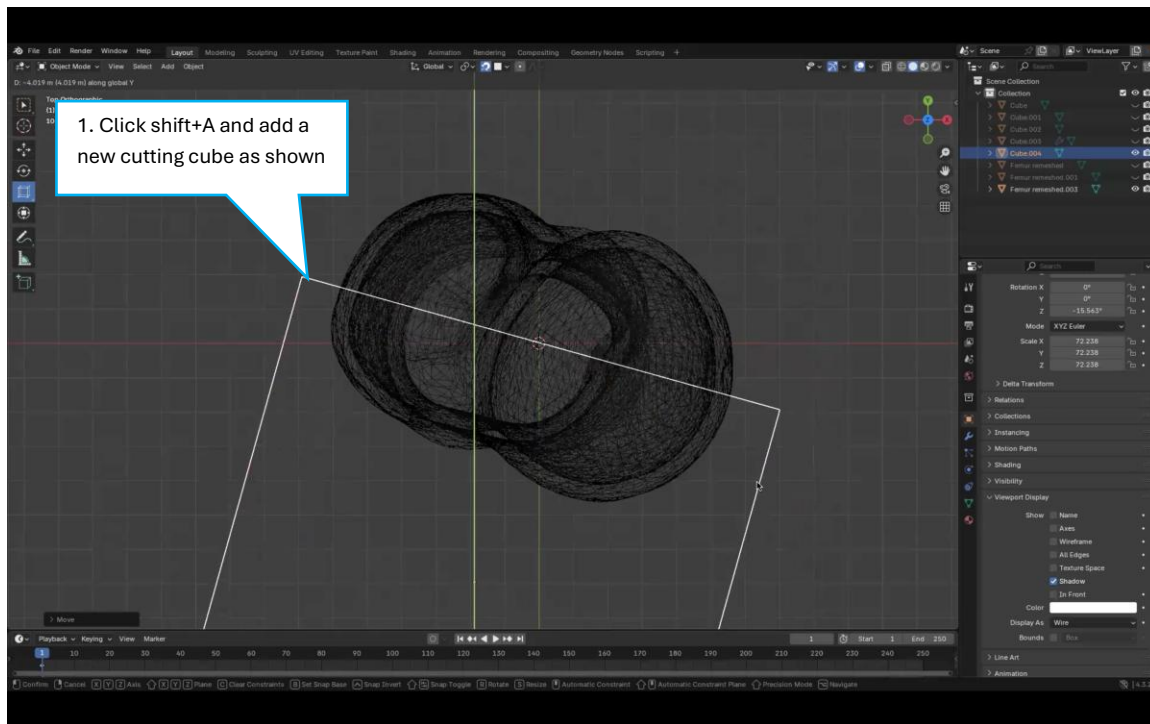


Figure 88 *Adding a Cutting Cube*

Copy the cutting cube and use the *magnet tool* to snap to the adjacent face (Figure 89).

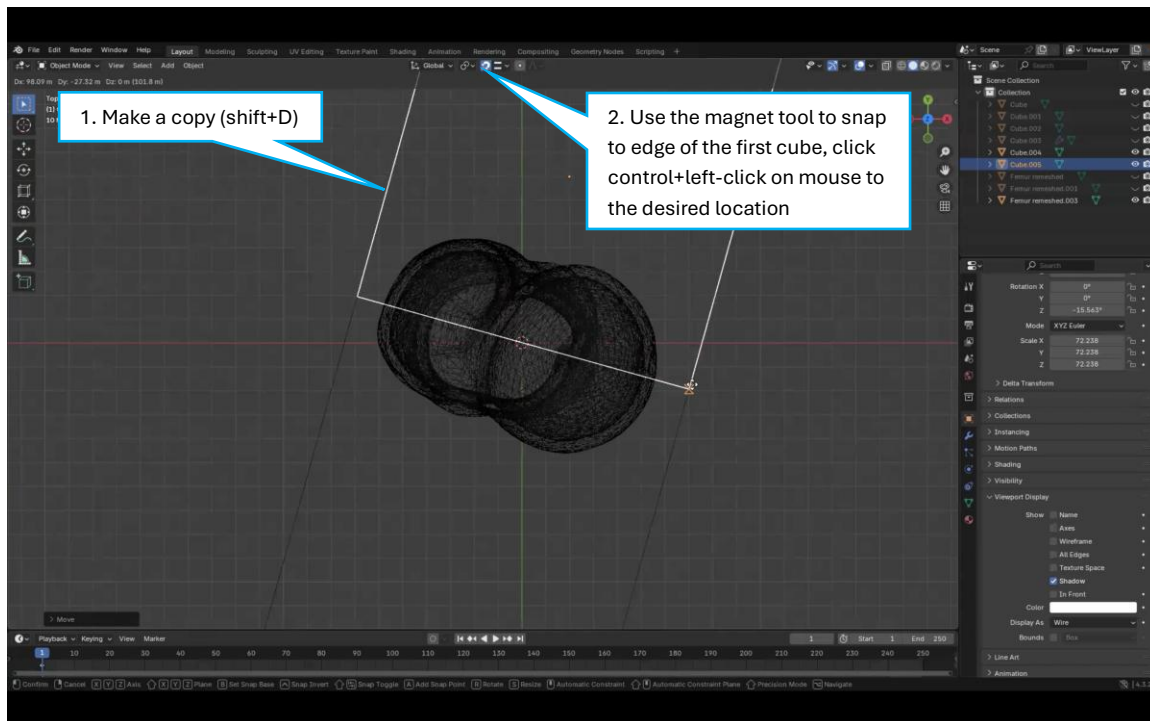


Figure 89 *Snapping Cubes*

Select shift+A and add a Cone mesh. Then orient the cone to the superior surface of the head of the joint capsule of the femur (Figure 90). Add an additional cone that is just a little smaller than the original cone. Create a *Boolean* modifier to cut the smaller cone out of the larger cone.

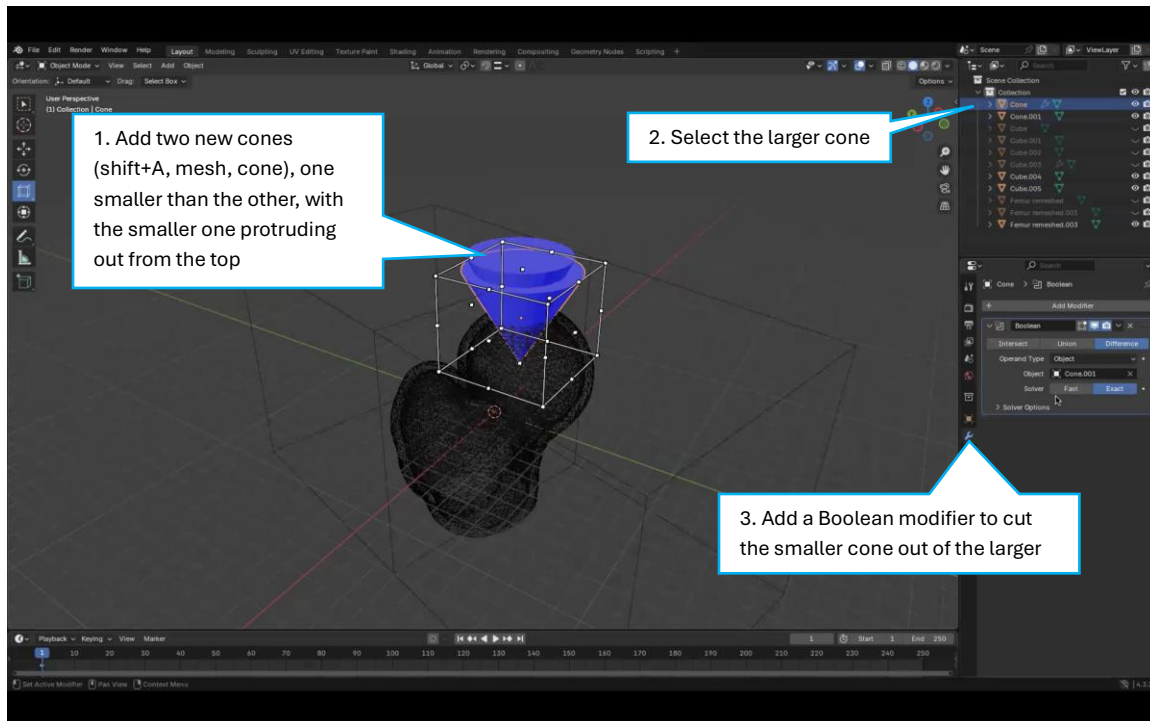


Figure 90 *Adding a Pour Spout*

Observe that the modifier has worked appropriately (Figure 91). Then apply the modifier.

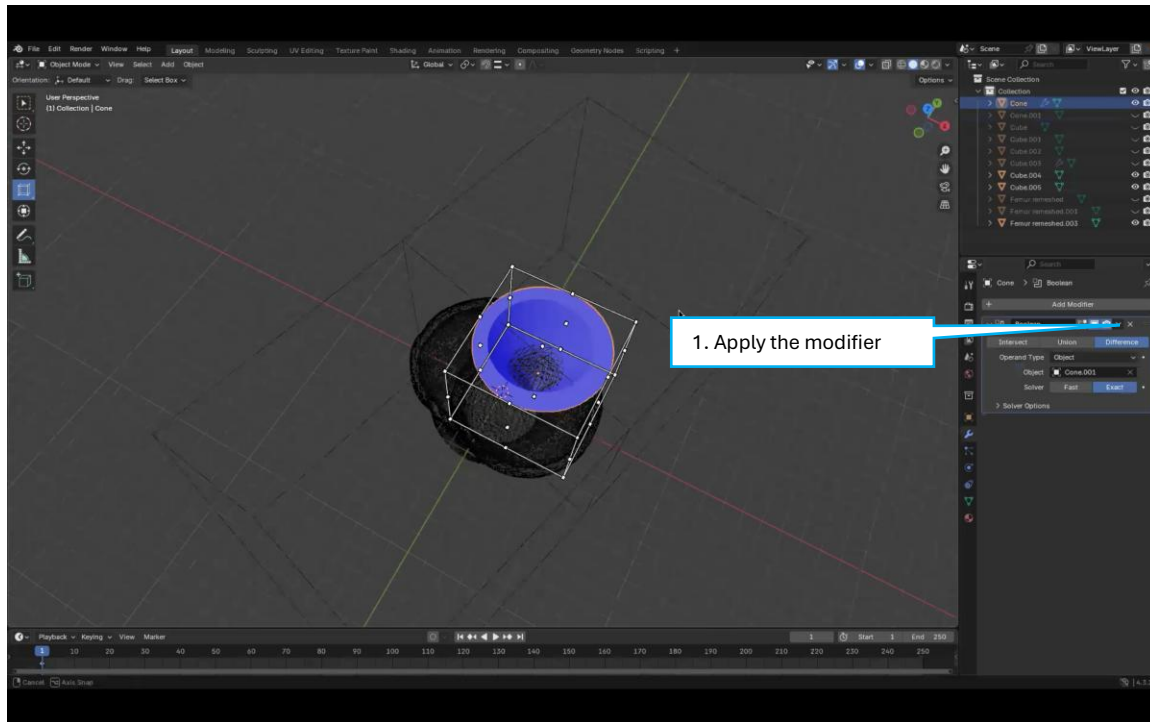


Figure 91 *Confirming Modification*

Now apply a *Boolean* modifier to the joint capsule mold by using the pour spout cone just created. Observe the modification (Figure 92). Apply the modifier.

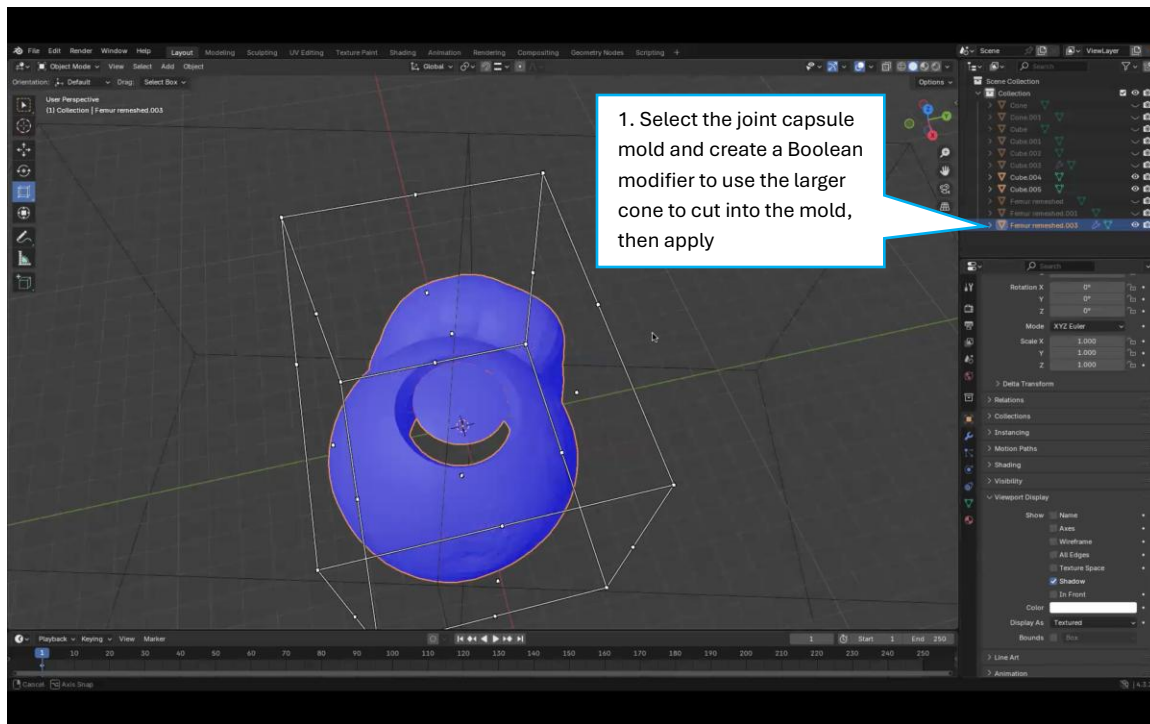


Figure 92 *Confirming Modification 2*

Switch to edit mode and delete the hanging mesh (Figure 93).

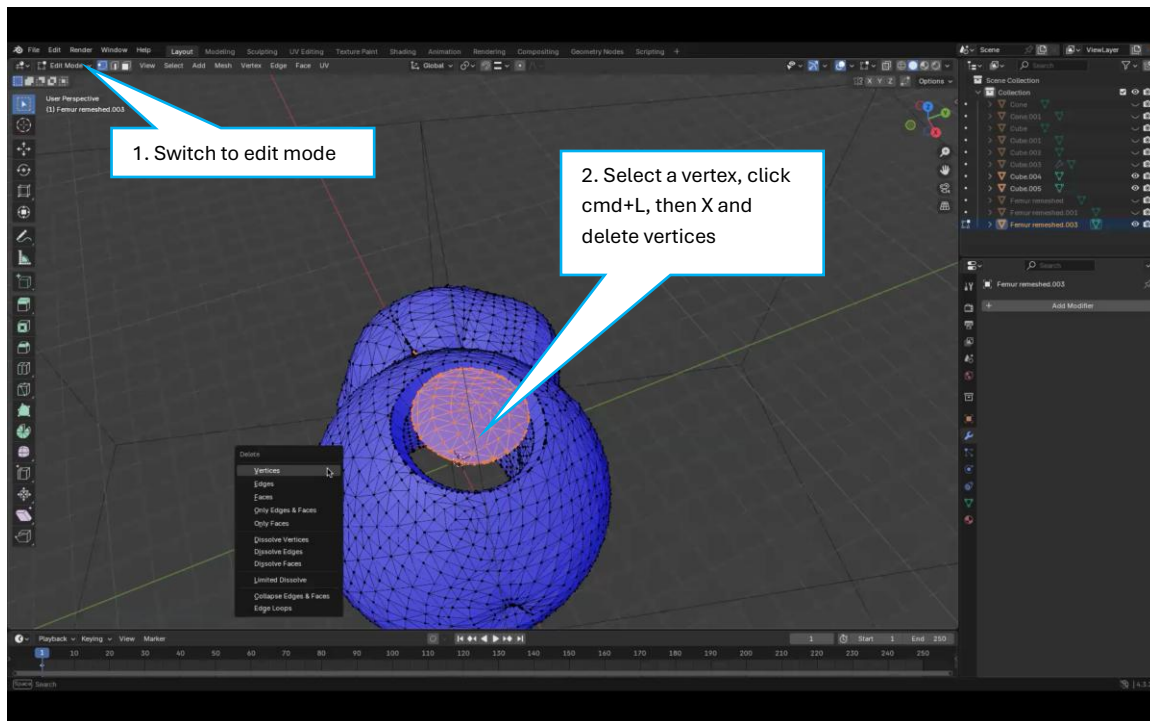
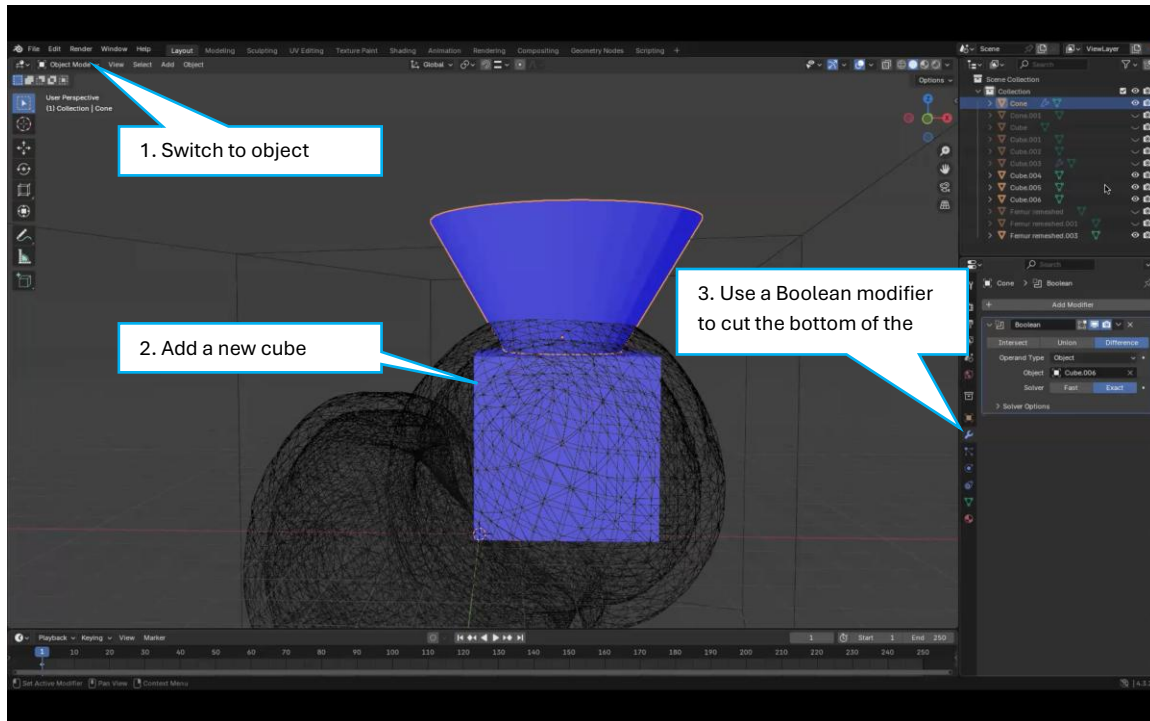


Figure 93 *Delete Hanging Mesh*

876
877 Now use an additional cutting cube to cut the tail end of the pour spout cone (Figure 94).
878



879
880 Figure 94 *Adding Cutting Cube to Pour Spout*

881
882
883 Observe the *Boolean* modification has worked appropriately (Figure 95). Then apply the
884 modification.

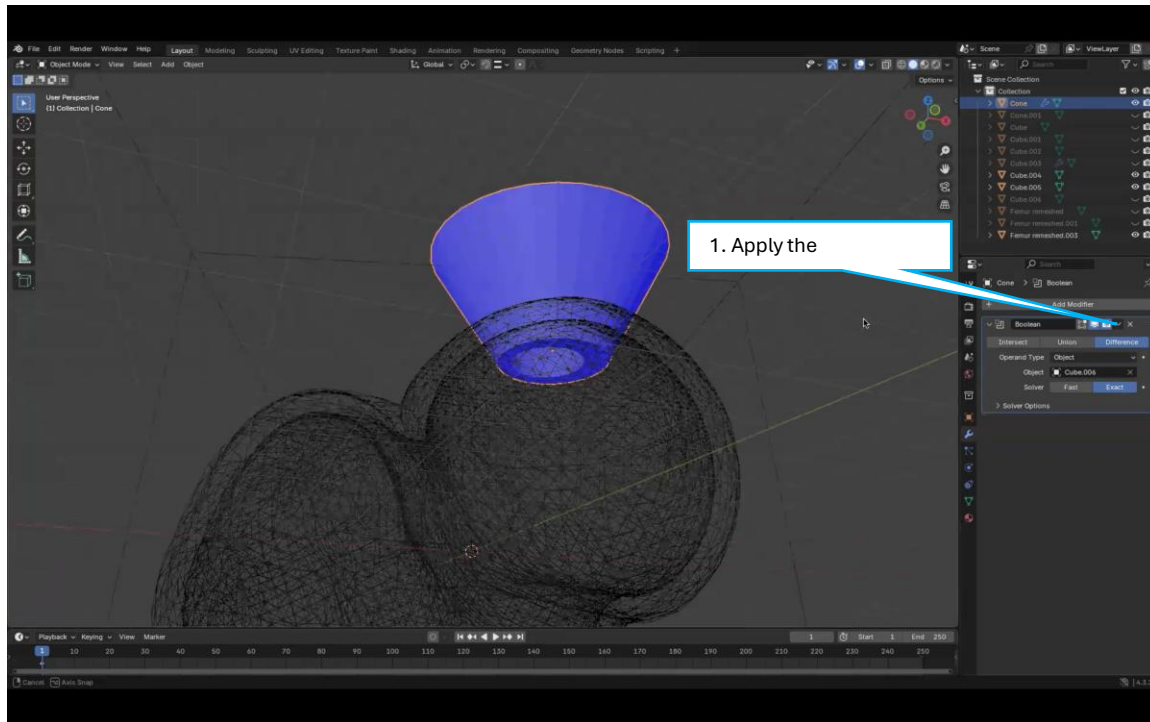


Figure 95 Confirming and Applying Modification

Now repeat the process but using a cylinder to create an air spout just superior to the greater trochanter of the joint capsule mold (Figure 96). Since the tissue-mimicking material being used is in liquid form when poured, the law of fluid dynamics has to be considered. This means the air spout will have to be as tall or taller than the area needing to be filled within the joint capsule mold. Fluid will be displaced evenly and level itself due to gravity.

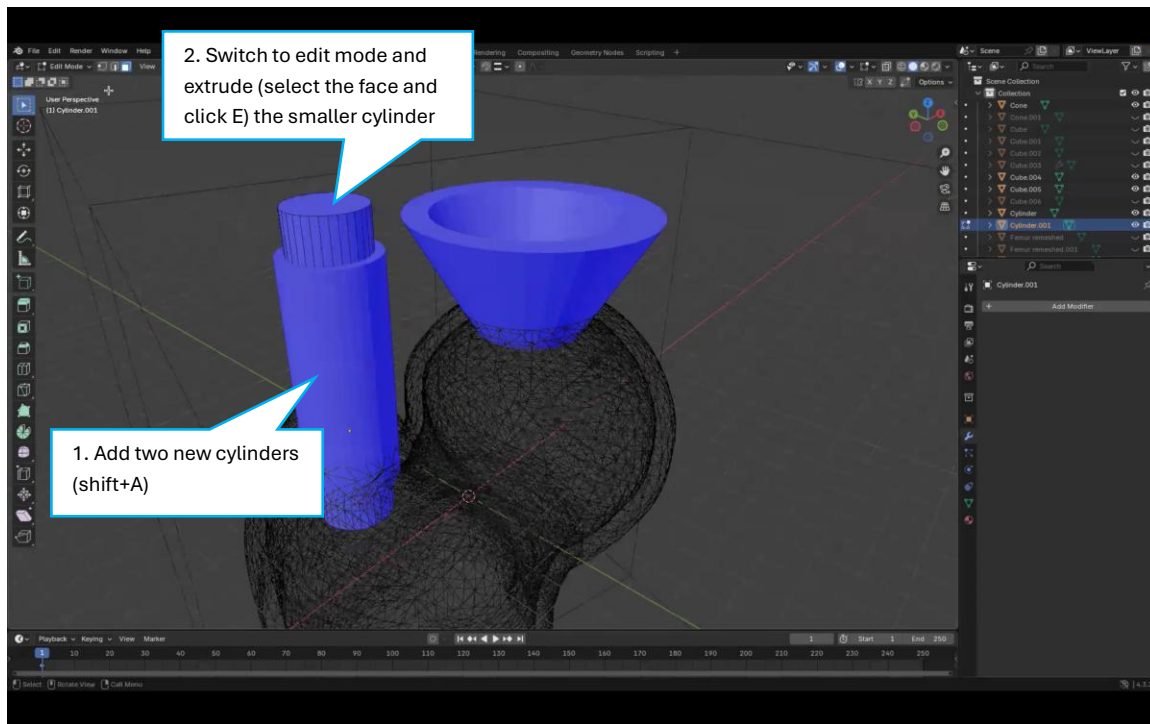


Figure 96 Adding an Air Spout

Use the *Boolean* modifier to cut through the larger cylinder (Figure 97). Then apply the modifier.

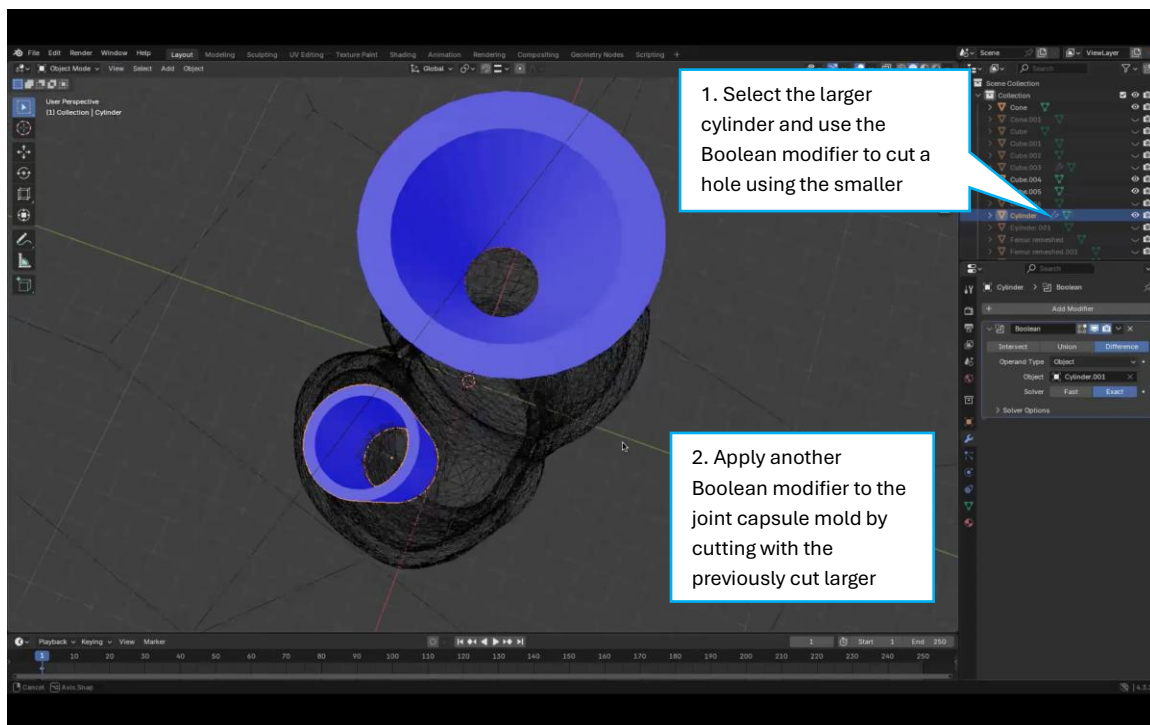


Figure 97 *Cutting Hole in Air Spout*

Then use the *Boolean* modifier to cut through the joint capsule mold with the modified cylinder.

Switch to edit mode and delete the hanging mesh (Figure 98).

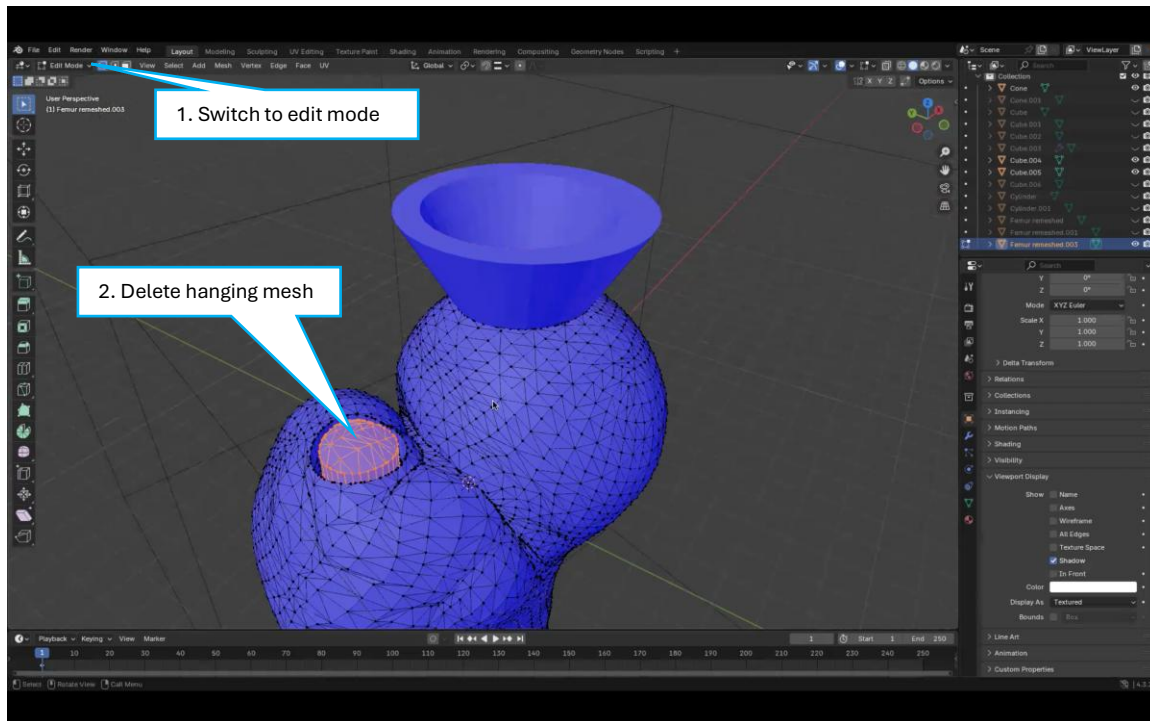


Figure 98 *Delete Hanging Mesh 2*

Switch to object mode, select the pour spout cone, the air spout cylinder, and the joint capsule mold together. Then select cmd+J to join the objects together (Figure 99).

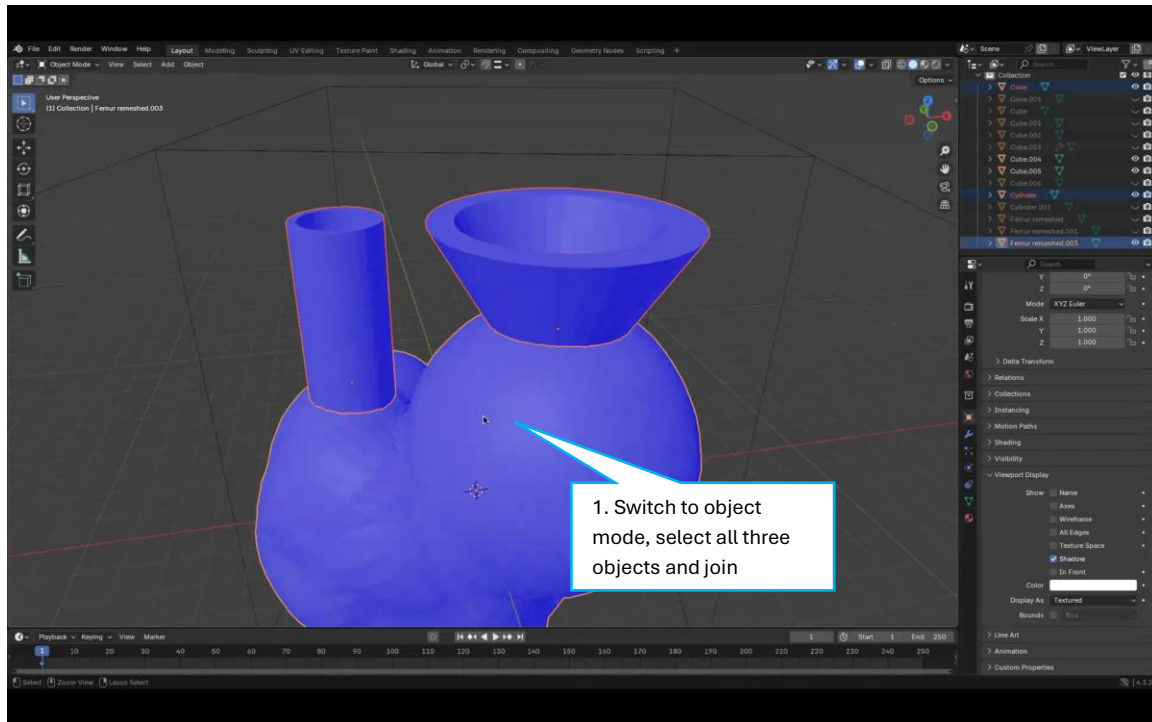


Figure 99 Joining Joint Capsule Mold Objects Together

Now use the larger cutting cube made previously to cut the joint capsule mold into two halves (Figure 100).

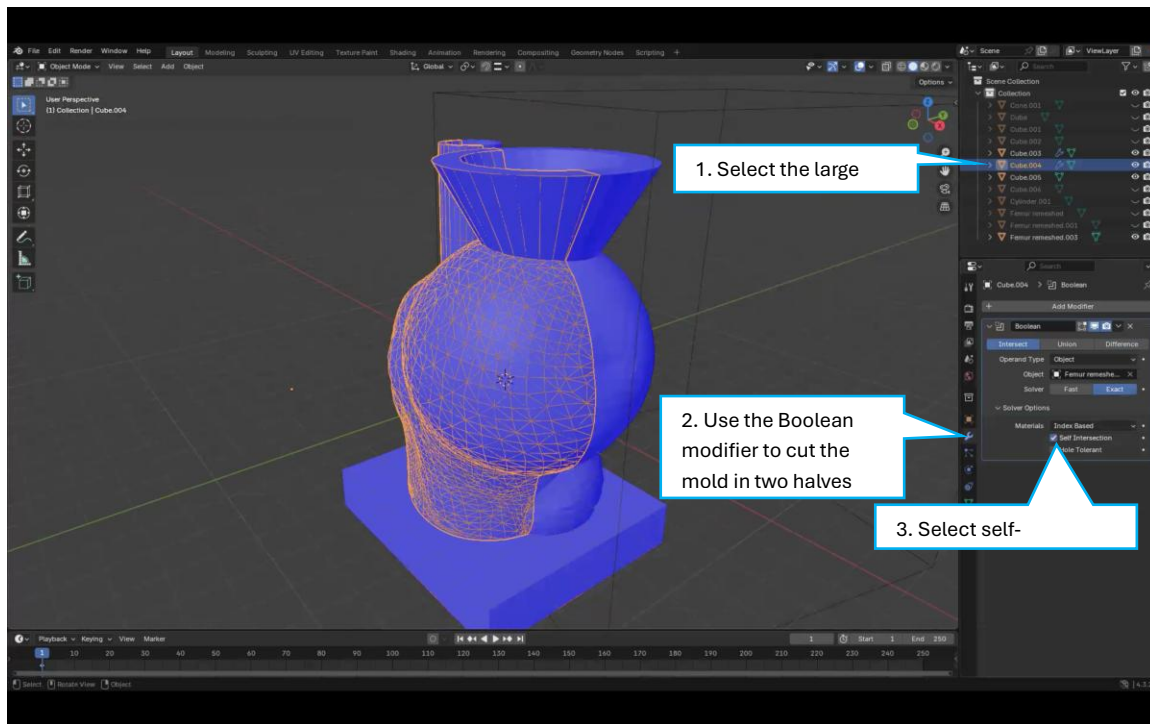


Figure 100 *Bisecting the Mold*

Observe the finished mold with the backpiece and face in view (Figure 101).

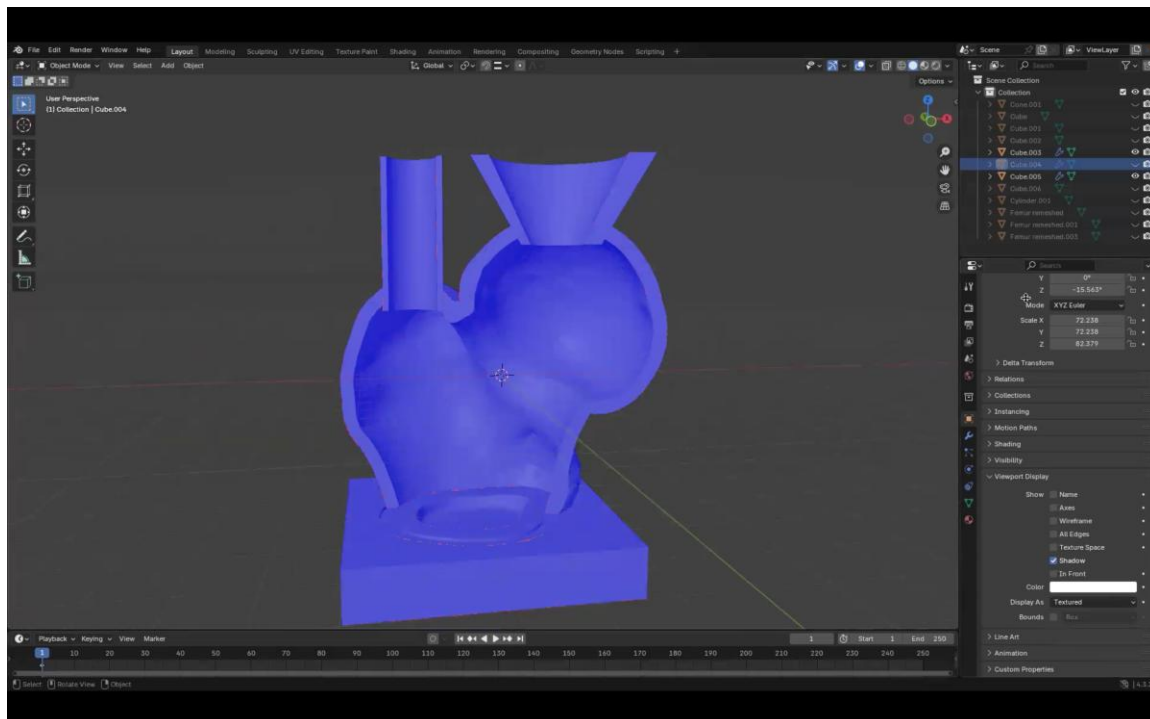


Figure 101 *Reviewing the Joint Capsule Mold*

Observe the final mold with the extruded femur (Figure 102). Confirm all specifications using the measuring tool to ensure the digital mold is functional. Save each object by exporting it as STL's.

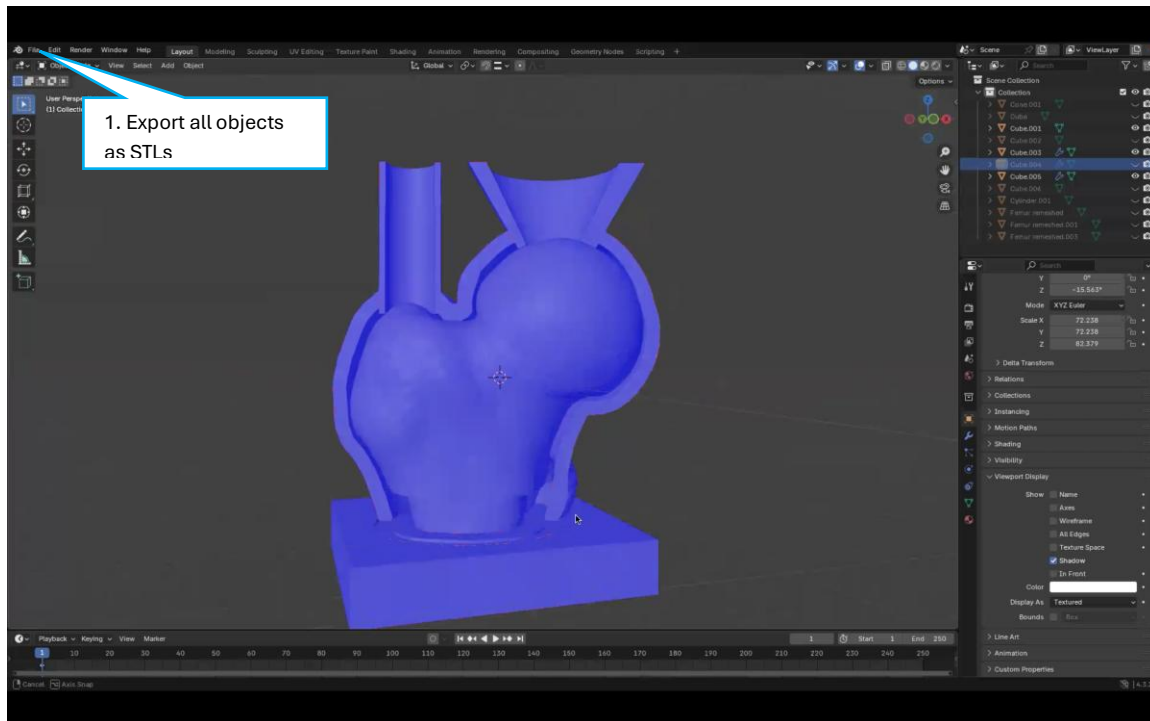


Figure 102 Reviewing the Joint Capsule Mold 2

3D-Printed Model

Once the objects are saved as STLs, the next step is to send them to the 3D printer. The researcher has many options when it comes to 3D printing. If there is not a local 3D printer at the institution, there are likely neighboring institutions or businesses that can print the objects. For this model, a Bambu X1 carbon printer was used. This is a fused deposition modeling (FDM) printer. The type of filament used to 3D print each mold was PLA. This material was chosen for many factors. PLA is relatively cheap (\$10-\$40 per 1000g) and has a melting temperature of

200⁰ C.¹⁰ The melting temperature was important to consider because the TMM being used was ballistic gel, which is melted to 121⁰ C before being poured. Since the PLA is used as the material for the mold, it is important that the mold is able to withstand these temperatures without any defects. To print the objects using the Bambu X1, first open the Bambu Studio. Next, import the STL objects (some larger prints may need to be printed separately). Orient the objects to show minimal overhangs. Enable and add supports, then once satisfied, click slice and print (Figure 103).

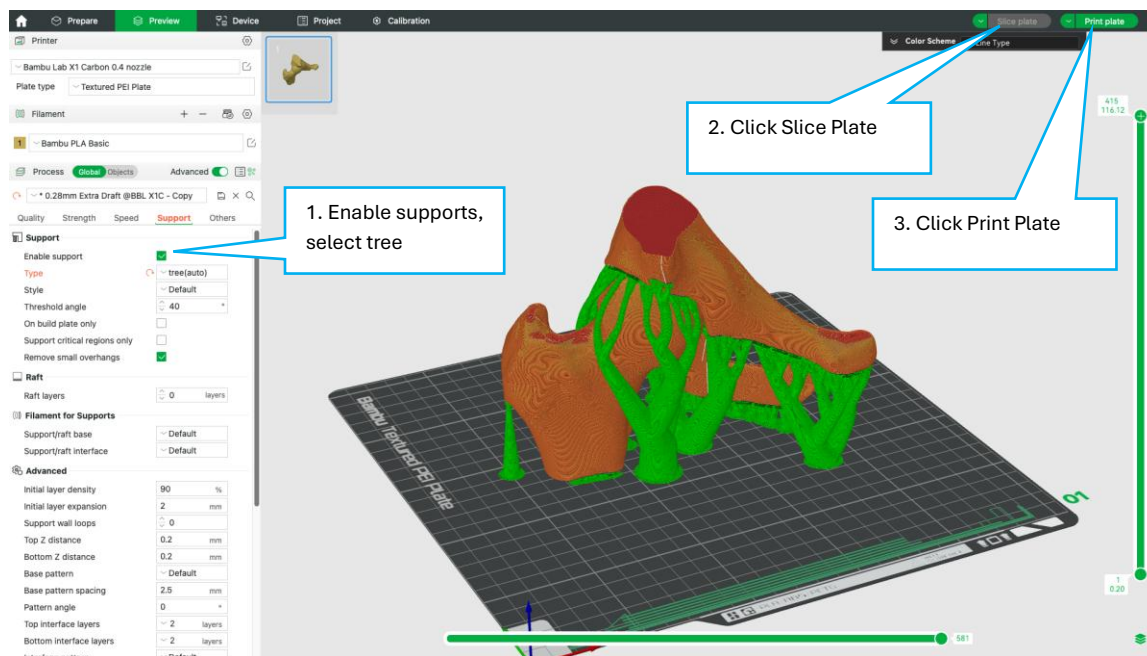


Figure 103 *Preparing Print in Bambu*

In Figure 104 observe the printed surface mold and bony anatomy. In Figure 105 Observe the printed joint capsule mold.

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Figure 1 3D Printed Surface Mold with Hip & Femur



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Figure 2 3D Printed Joint Capsule Mold

978 *Mold Making*

979 There are many steps during the mold making process. Once the objects are 3D printed,
980 they will be pieced together and secured with various tools (tape, clamps, glue, etc.). In Figure
981 106 observe the surface mold with the front, back and base pieces secured together. The handles

added in Blender act as a structure to clamp onto, ensuring the back and front pieces are tightly bound. Hot glue is then added to all the seams to ensure no leaks occur during the curing process. The ballistics gel being used is the DIY phantom gel from Humimic Medical (Humimic Medical, Greenville SC).¹¹ This gel was chosen for its US properties used in other phantom models, where it simulated muscle and adipose tissue.⁵ The gel melts at 250⁰ F (121⁰ C).¹¹ It is bought in solid form and needs to be melted down in order to pour into the surface mold. The gel has to melt at 250⁰ F for four hours to ensure all bubbles are evaporated. A convection oven was used as the heating source and an aluminum pan was used as the vat to hold and pour the melted gel. Once the front, back, and base mold pieces are secured into place, the bony anatomy pieces are added. The slots made previously allow for a snug fit into the base mold. A small amount of hot glue is added to the slots to ensure the hip and femur bones stay in place during the cure. Next a releasing agent is added to the inner walls of the mold (e.g., white petrolatum, releasing agent spray). Once the gel has been heated for four hours the pan of gel is used to slowly pour the ballistics gel into the mold (Figure 106). The gel needs to cool down and solidify for up to 12 hours. Once the gel cools the clamps, hot glue, front, and back mold pieces can be carefully removed.



Figure 106 *Pouring the Ballistic Gel*

Next, the joint capsule mold needs to be filled with the TMM. The TMM selected to simulate the joint capsule was EcoFlex 00-30, which is a flexible and durable silicone.¹² This material was chosen for multiple reasons. The silicone has *self-sealing* properties, which allows for multiple needle sticks. This is very important when considering the containment of joint capsule fluid. Flexibility provides a high-fidelity equivalent to human joint capsule tissue. All of these factors need to be considered when choosing a TMM that fits the researcher's phantom model. The only unknown was the US properties of the material.

Once the front, back, base, and extruded femur were 3D printed they were pieced together using similar materials as before (Figure 107). Silicone arrives in two parts, parts A and B. The formula is a 1-to-1 ratio. A weight scale, multiple cups, hot glue, cleaning towels, and stir sticks are required to mix the materials. First, to prepare the mold, take the base mold and add a small amount of hot glue to the cavity made from imprinting the femur and joint capsule as shown previously on Figure 87. Next, insert the extruded femur into the base mold. Add a

1016 releasing agent (e.g., white petrolatum, releasing agent spray) to the inner surfaces of the molds.
1017 Add the front and back pieces and insert them into the designated slot. Seal all the seams with
1018 hot glue. Non-sulphurated clay can be used at the base to ensure a tight seal (Figure 107). Tape
1019 can also be used around the outside to act as a clamp (not shown in the figure). Now take three
1020 disposable cups. Label one cup as A and one cup as B. The last cup can be left blank or labeled
1021 with a P for pour. Place the weight scale on a flat surface. Place cup A on the scale and tare.
1022 Then use cup A to collect 150mg of part A (this may take a few tries to get correct). Next tare the
1023 scale again using cup B and repeat the process to collect 150mg of part B. Once both cups have
1024 the same amount, pour both into cup P. Use the stirring stick to stir the contents, making sure to
1025 scrape the sides of the cup. Stir for 3 minutes. The cure time is 4 hours, but the contents will start
1026 to set up within 30-45 minutes. Next, use a small vacuum chamber and place cup P into the vat.
1027 Pressurize the pot and let it sit while the bubbles are extruded for 5-8 minutes (this step is not
1028 absolutely necessary, but was found to reduce imperfections in the mold). Now pour the silicone
1029 into the mold slowly until both the air spout and pour spout are filled completely. The silicone
1030 takes 4 hours to fully cure. Next, demold the joint capsule.

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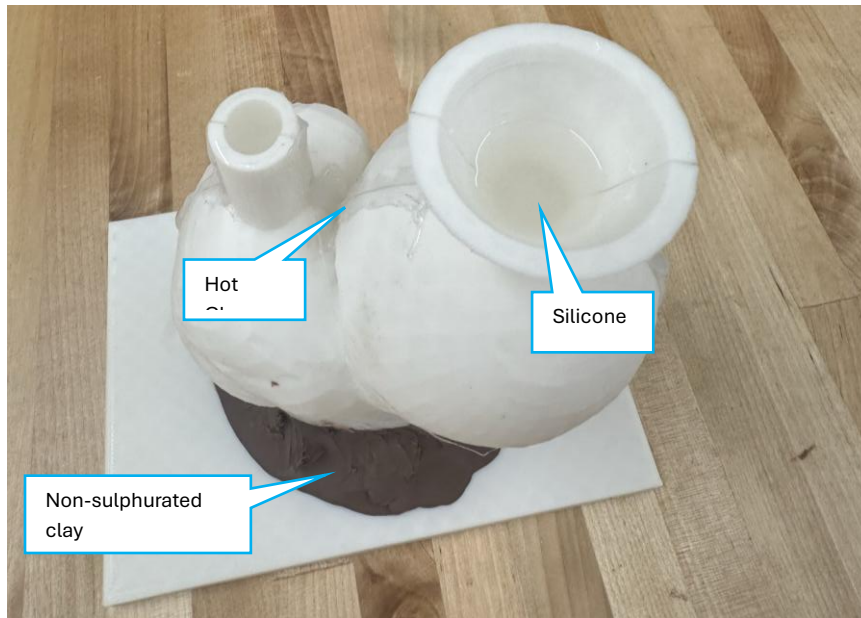


Figure 107 *Pouring the Silicone*

Once the joint capsule is demolded, the additional silicone from the pour and air spouts can be removed with a scalpel blade. Then take the bottom of the mold and de-sleeve the silicone off the extruded femur, and re-sleeve the silicone onto the original-sized femur. This femur was extruded on the inferior surface, and a bevel was added to act as a lock-and-key mechanism once the new silicone is poured (Figure 108).

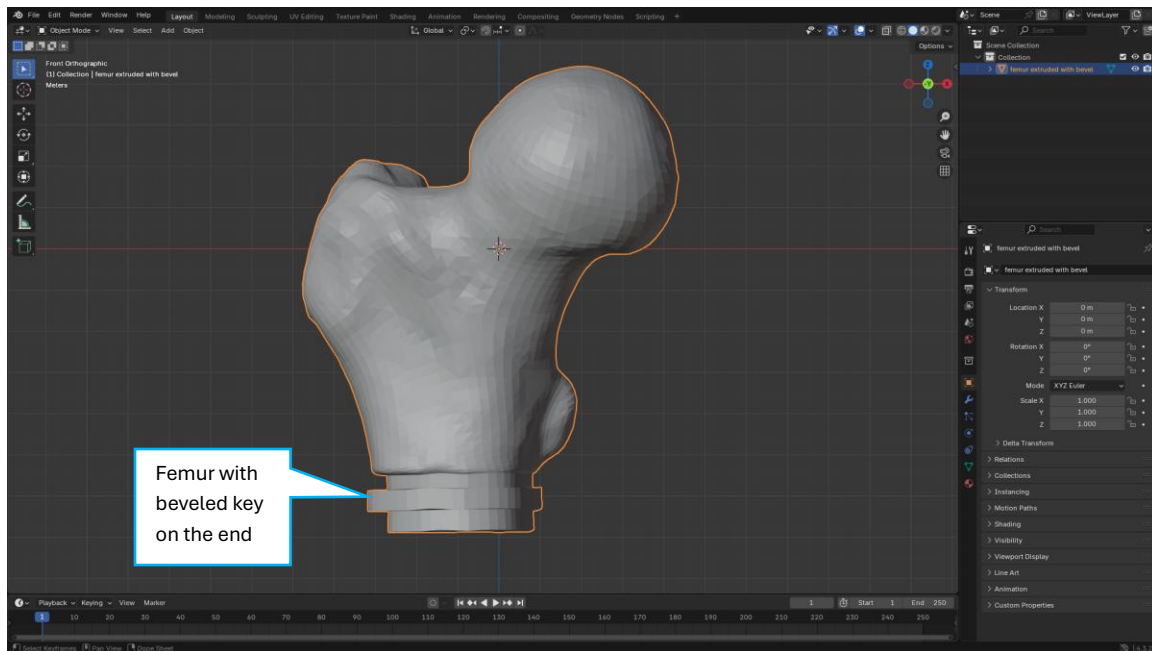


Figure 108 *Femur Extruded with Bevel*

A new digital mold was created that was the same as the joint capsule mold, but with the entire superior surface extruded to act as a base (Figure 109). Put the silicone joint capsule (with the femur inside) into the new joint capsule mold (Figure 109). Pour a new batch of silicone into the mold to cap the bony anatomy.

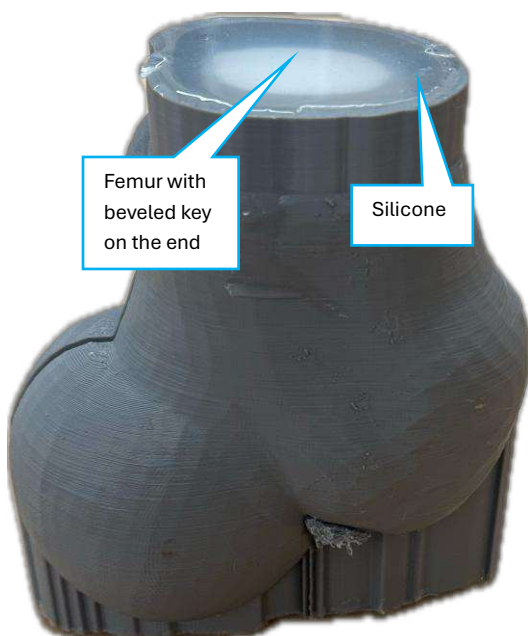


Figure 109 *Capping the Silicone Mold*

Once the silicone has cured, then demold the joint capsule model. In Figure 110 observe the finished joint capsule model.



Figure 110 *Joint Capsule Model*

Next fill the 5mm joint capsule space with saline (this is to simulate the synovial fluid). Take a 50 mL syringe filled with saline and slowly inject into the joint capsule (Figure 111). At the same time use an additional needle with a turn valve and open the valve completely. Place the second needle at the top of the model. This is to ensure that all the air is expelled from the joint capsule space, while the cavity is being filled with saline.



Figure 111 Filling the Joint Capsule with Saline

Validation of Model

The validation of the model was completed by two attending physicians at The Ohio State University Wexner Medical Center. A discussion was also held in order to observe the professional opinion of the physicians. Questions Included: Is the phantom model anatomically accurate? What was your perception of the phantom model? Does the phantom model feel palpably accurate? Do you believe this phantom model can be used to train residents on joint injections/arthrocentesis? What would you change about the model? The model was also compared to a healthy hip joint under ultrasound imaging. When creating a UAP model, the researcher must consider how they will validate the model. Table 1 provides examples of what topics to consider when validating a 3D printed UAP.

1087	Table 1 Validation Checklist
	Validation Checklist
	Needs assessment completed for specific procedure
	Palpation Accuracy
	Needle resistance
	Anatomical accuracy
	Anatomical landmark accuracy
	Realistic acoustic material
	Needle accuracy on the ultrasound image
	Time to perform the procedure
	Necessary anatomical layers and tissues present
	Functionality of the model
	Clinical expert validation
	Training students/residents using a model
1088	
1089	
1090	<i>Prototype</i>
1091	Many iterations of the UAP were made. The first prototype was just the surface mold
1092	with the bony anatomy. Figure 112 shows the first prototype.
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1094	



Figure 112 *Prototype #1*

Figure 113 shows the US imaging of Prototype #1 using a curvilinear probe. The rim of the acetabulum, head of the femur, and neck of the femur were visible. This first prototype was created to verify how the ballistics gel and PLA looked under US. The PLA filament of the bony anatomy appeared as a distinct hyperechoic structure (Figure 113).

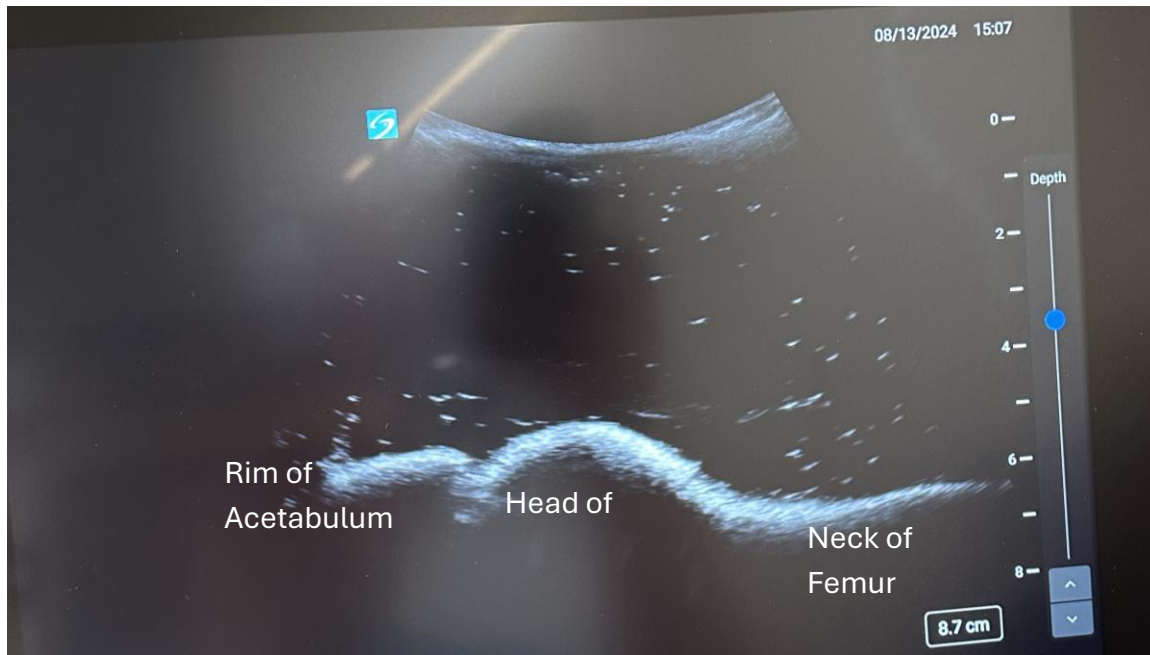


Figure 113 *Prototype #1 Under US*

Next Prototype #2 was made, which included the joint capsule model made previously.

Figure 114 shows the mold just before the ballistic gel was poured. This original joint capsule

prototype was made with a 5mm thick silicone layer.



Figure 114 *3D Printed Mold of Prototype #2*

Figure 115 shows the first US imaging of Prototype #2 using a curvilinear probe. A dense hyperechoic outline of the silicone layer was visible. Needle tracking was successful, but no distinct joint capsule space was visible.

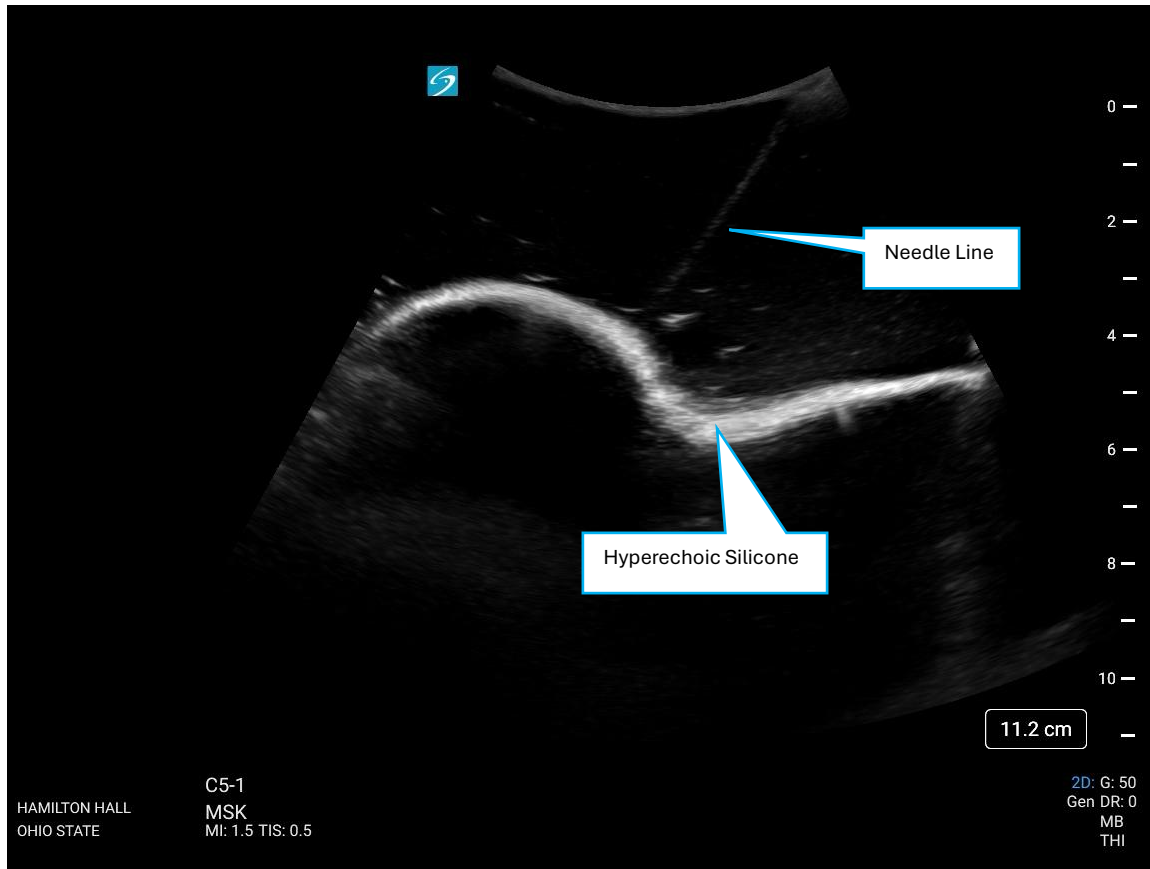


Figure 115 *Initial US Scan of Prototype #2*

Additional models were created to simulate the silicone thickness required for ultrasound impedance. Three models were created, one at 1.6mm thickness, one at 2mm thickness, and one at 3mm thickness. The 3mm thick silicone was the only successful prototype. The durability of the silicone failed in the thinner prototypes. Figure 116 shows the 3D printed 3mm space prototype.

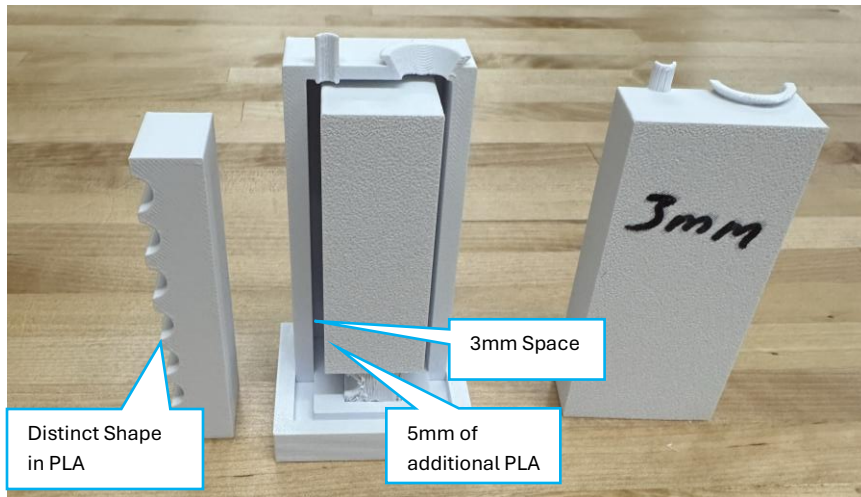


Figure 116 *3mm Silicone Thickness Prototype*

The 3mm prototype was de-sleeved and then resleeved with a distinctively shaped PLA structure shown on the left side of Figure 116. The 3mm space was then filled with saline, and a slab of ballistic gel was added on top to quickly observe the structure under US (Figure 117).

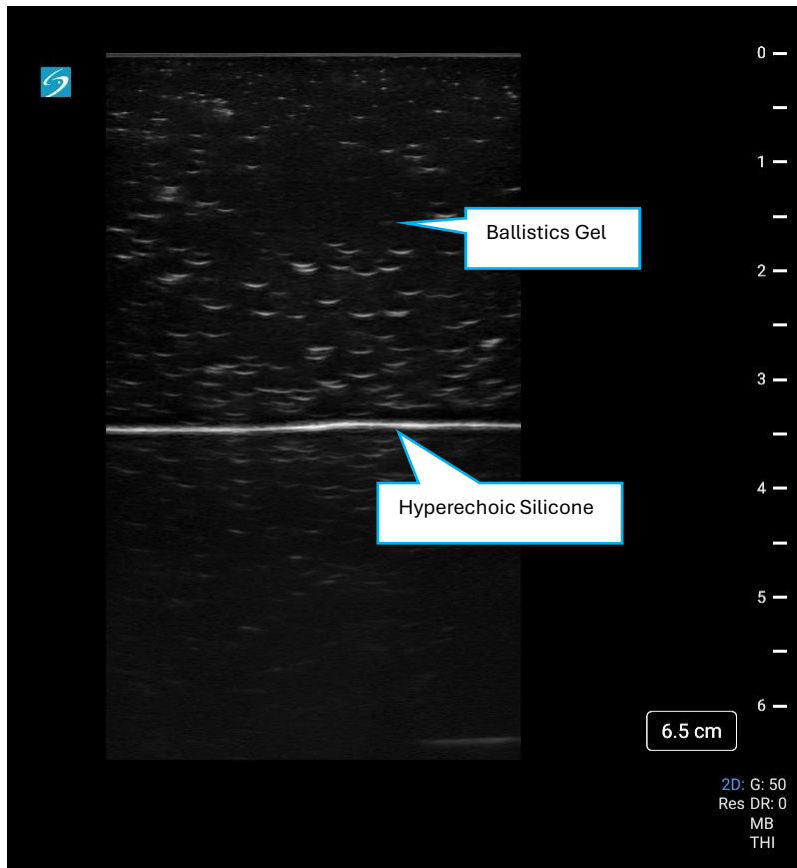


Figure 117 3mm Silicone Thickness Prototype Initial US Scan

The ballistics gel was then removed, and ultrasound gel was added on top of the silicone. This was to act as a medium for the US waves to propagate, since the ballistic gel was not poured. Without changing anything to the 3mm silicone prototype (other than adding US gel in between the silicone and ballistics gel layers) the prototype was scanned again. Figure 118 shows the second US imaging of the 3mm silicone prototype. Here, the US waves propagated through all layers.

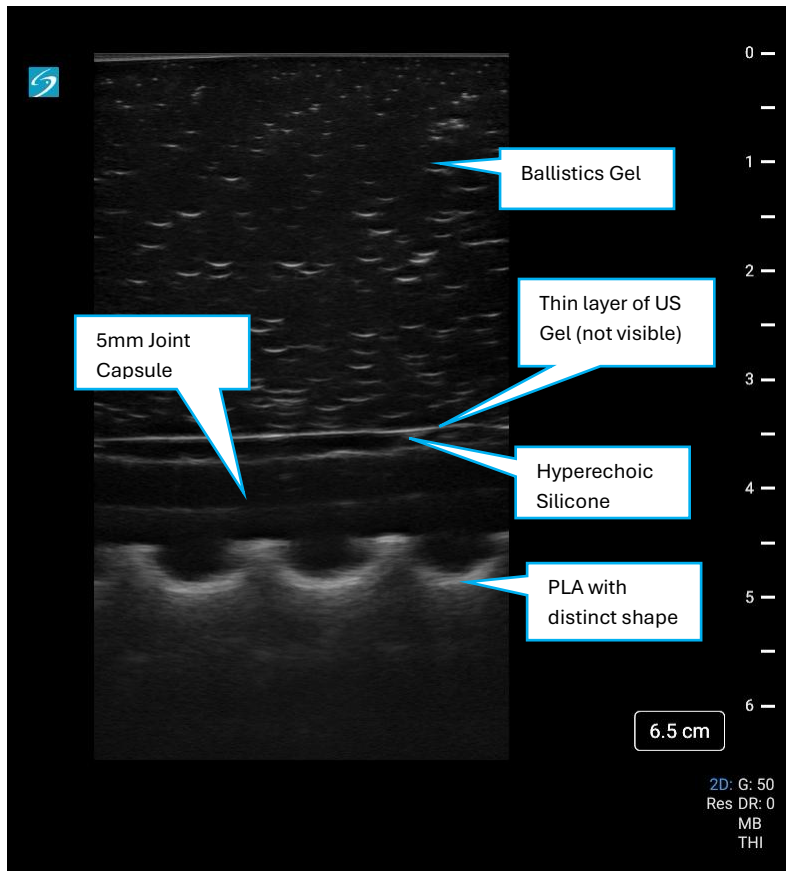


Figure 118 3mm Silicone Thickness Prototype Second US Scan

Prototype #2 was then rescanned after the ballistics gel was carefully removed and US gel was added on top of the 5mm thick silicone. Figure 119 shows the second scan of Prototype #2 with US gel added as a medium.

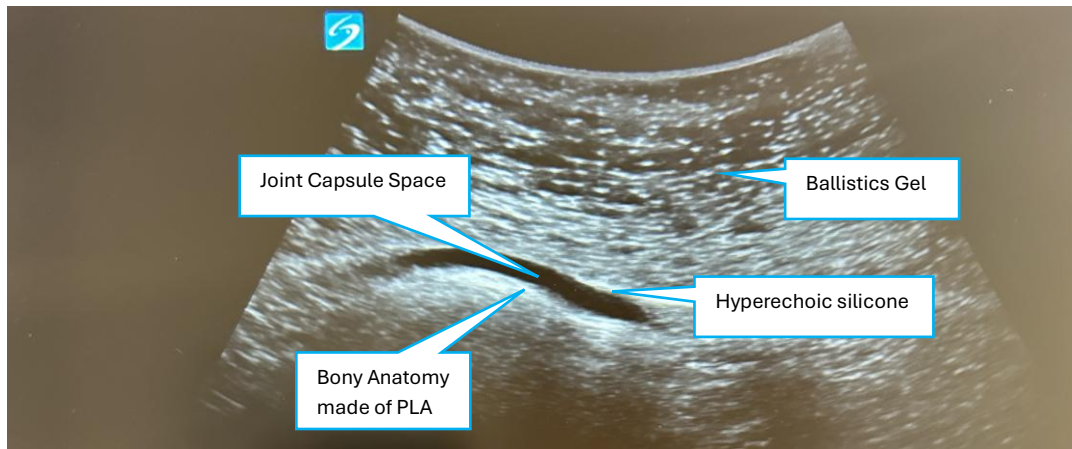


Figure 119 *Second US Scan of Prototype #2*

Results

Final Model

The final version of the model was then constructed. This model was redesigned so that the anterior part of the model could be removed to apply the US gel onto the joint capsule. The final joint capsule mold was remade with a 3mm thick layer of silicone. This was due to the successful 3mm silicone prototype. The 3D printed mold of the redesigned front is shown in Figure 120. The back of the new mold is shown in Figure 121.



Figure 120 *Final Front Mold*



Figure 121 *Final Back Mold*

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Figure 122 shows the back mold just before the addition of the ballistic gel. Sphere impressions were added to act as a lock-and-key mechanism for the front and back pieces. Figure 123 shows the front mold just before the ballistic gel was poured.



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Figure 122 Pouring Ballistics Gel Into Back Mold

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Figure 123 Pouring Ballistics Gel Into Front Mold

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1198 The final version of the 3D printed Hip UAP is shown in Figure 124 once all the parts were
1199 pieced together.



1200
1201 Figure 124 *3D Printed Hip UAP*
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1204 Figure 125 shows the Hip UAP with the front section of ballistics gel removed. The US
1205 gel was added to this layer of the model.
1206



Figure 125 *Hip UAP Without Front Gel Mold*

Lastly, the final Hip UAP was viewed under US. The results are shown in Figure 126.

The model contains the following layers: skin, homogenous muscle/adipose, iliofemoral ligament (joint capsule), joint capsule space, rim of acetabulum, head of femur, and neck of femur.

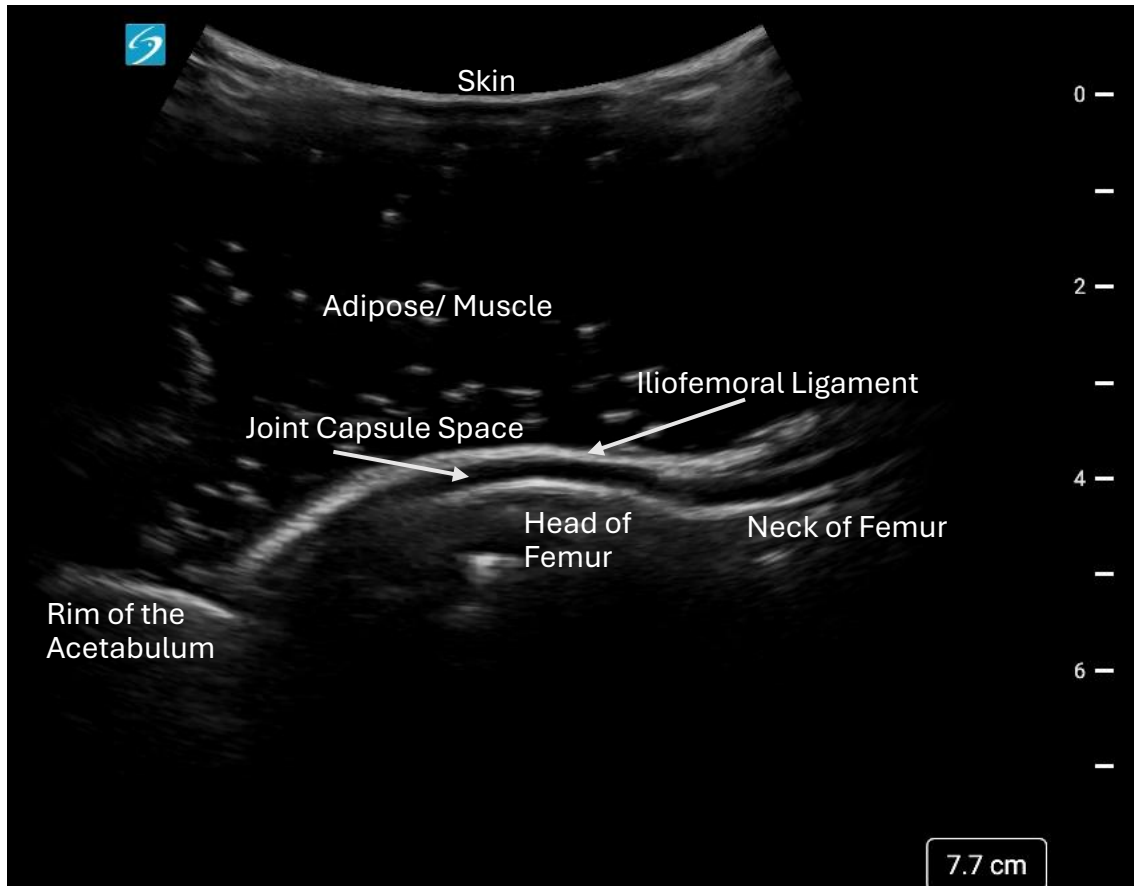


Figure 3 *Hip UAP Ultrasound Scan*

Validation Results

The 3D printed UAP was shown to have anatomical accuracy for the following tissue layers: bony anatomy, joint capsule space, iliofemoral ligament, and skin. The 3D printed UAP cost a **total of \$200 to create**. The majority of the cost was for the price of the ballistic gel needed to create this size of a phantom. Figure 127 shows the comparison between the Hip UAP and a healthy hip joint. Both attending physicians who validated the model confirmed the high-fidelity quality of the model and confirmed the potential benefit in a future injection workshop.

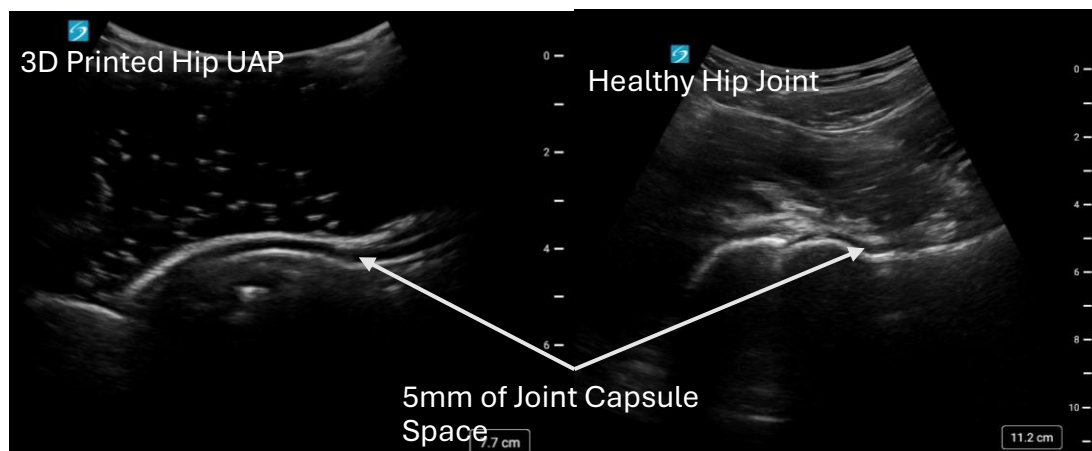


Figure 4 Comparison of Hip UAP to Healthy Hip Under Ultrasound

Discussion

Currently, there are no commercial anthropomorphic hip joint phantom models available. There are several phantom models that are used for joint injection training for the shoulder, elbow, and knee.^{13–16} However, to the best of our knowledge, there are only two Hip UAP models that have been previously made.^{17,18} The first Hip UAP made was a low-fidelity model¹⁹ only containing accurate bony anatomy. Although the beginning concepts of a self-sealing joint capsule were tested using an infant Ambu bag.¹⁹ The second model¹⁷ is very similar to our Prototype #1 shown on Figure 112 and Figure 113, containing accurate surface and bony anatomy. However, to our knowledge, neither of these models has been validated or tested in an injection or arthrocentesis training workshop.

Our model is the first to simulate an anatomically accurate fluid-filled space that is capable of aspiration. This TMM layering can be replicated on other models that require practicing extracting or simulating a fluid under US. The implications behind the development of a 3-D printed joint phantom can be replicated for future models using 3D printing techniques to

create digital casting molds. The lack of methodology in segmenting, cleaning, and preparing 3D models in the literature acts as a barrier to future researchers.⁵ The detailed outline in our methods section was created to remedy this issue. To our understanding, the reason that Prototype #2 failed (Figure 115) when initially scanned was that no chemical bond between the ballistics gel and silicone occurred. This created a small pocket of air between materials. Ultrasound waves have a hard time propagating through air,²⁰ explaining why using the ultrasound gel as a medium helped the sound waves propagate through all the tissue layers. The discovery that a thin layer of ultrasound gel applied on top of silicone can be ultrasound-able g can be replicated in future models. The flexibility and durability of the silicone can be used in many applications that require self-sealable tissue for injection purposes. Many UAP models have been created, but very few have been made and actually tested on a graduate medical education platform.⁵ The Humimic medical gel was chosen specifically for its re-usability. The gel can be heated, and needle marks will disappear from the gel, remelting the cavities the needle left. The shelf life of the Humimic medical gel was also considered. Most homemade ballistics gels can be made cheaper than the cost needed to buy the Humimic medical gel, but the homemade gel is prone to degradation after a few weeks and tends to mold easily. The Humimic medical gel has a shelf life of 3 months and can be remelted and formed up to ten times.¹¹

Conclusions

The development of this 3D printed Hip UAP can provide an alternative to costly commercial models and deliver a framework for graduate education programs. This Hip UAP can also provide more equitable means of training residents on MSK-related procedures and provide learners with an authentic environment to practice without the fear of causing injury or pain to the patient. The methodology of creating digital molds can be replicated to create

1273 anatomically accurate UAPs that can be used to create high-fidelity task training phantoms.

1274 Future work can focus on testing models like this in a graduate medical education training

1275 workshop.

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1279 Educational Research Stimulus Grant.

1280 Ethics Declaration

1281 Not applicable.

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