Building a Workflow for Cooperatively Controlled Robotic Mandibular Surgery

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I. Abstract

This project aims to improve the safety and accuracy of the Bilateral Sagittal Split Osteotomy (BSSO) procedure using a cooperative robotic system and virtual fixtures. Such a workflow will be the first of its kind for the BSSO and will help pave the way for future cooperative robotic procedures.

II. Introduction

Mandibular osteotomy is a common procedure used to correct an overextended jaw or receding chin [1]. This is done by making a sagittal cut through either side of the mandible as shown in Figure 1 below. During this procedure, the physician must be careful not to damage the alveolar nerve that runs through the mandible [3]. Damage to this nerve can lead to numbness of the chin, lower lip, and lower teeth. According to Dr. Yang, 100% of patients experience a temporary neurosensory deficit following the procedure with 10% of those cases being permanent.

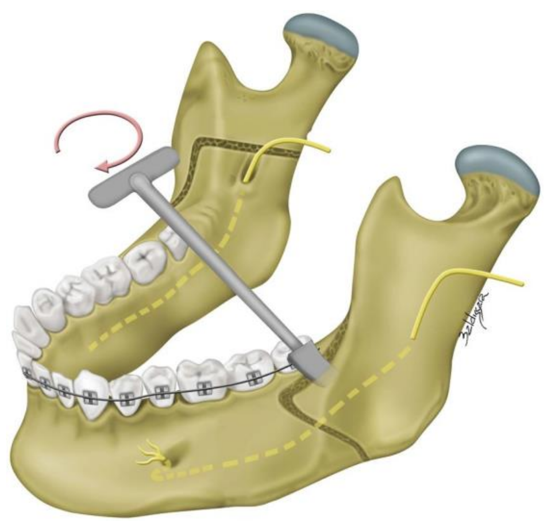


Figure 1. Sagittal cuts on either side of the mandible. [2]

The solution we are investigating is the use of a cooperative robot to enforce virtual guidance. Segmented CT data from the patient will be used by the physician to generate a plan for the ideal mandibular cut which optimizes outcomes and reduces likelihood of damaging a nerve. A “hand over hand” style robot will then work with the physician by reducing hand tremors and ensuring the physician does not deviate from the pre-determined plan.

III. Background

For the BSSO procedure, current standard practice is for the surgeon to execute the cut by hand. A flowchart identifying a typically workflow is shown in Figure 2 below.

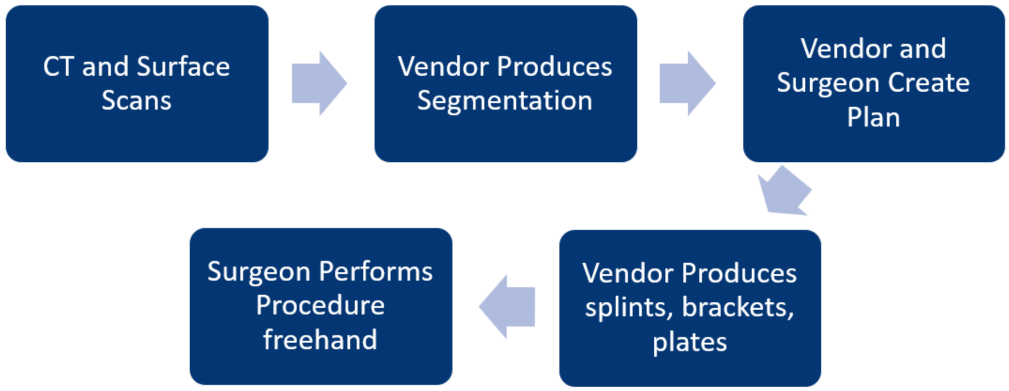


Figure 2. Current workflow for the BSSO procedure.

To begin, a CT scan is taken of the patient's head and a surface scan is taken of the patient's teeth. This is done because many of the patients typically have braces, which will create artifacts in the CT image. The vendor will take the scans and merge them together while producing the segmentation. Using the segmented model, the vendor and the surgeon will create a plan for the BSSO. The vendor will produce splits, brackets, and plates to be used in the procedure. Splints are used to line up the teeth in the desired final position after the cut has been made and before screwing the mandible into place. Brackets and plates are screwed onto the mandible to fix the cut bone into its final position. Once the plan, brackets, and splints are made the physician will execute the procedure by hand by using a drill to cut through the bone.

While no cooperative robotic system has been developed to address the BSSO procedure, there has been work on other cooperative robotic procedure. For this workflow insight was taken from work done on the YOMI dental robot and the Galen robot which are shown in Figure 3.

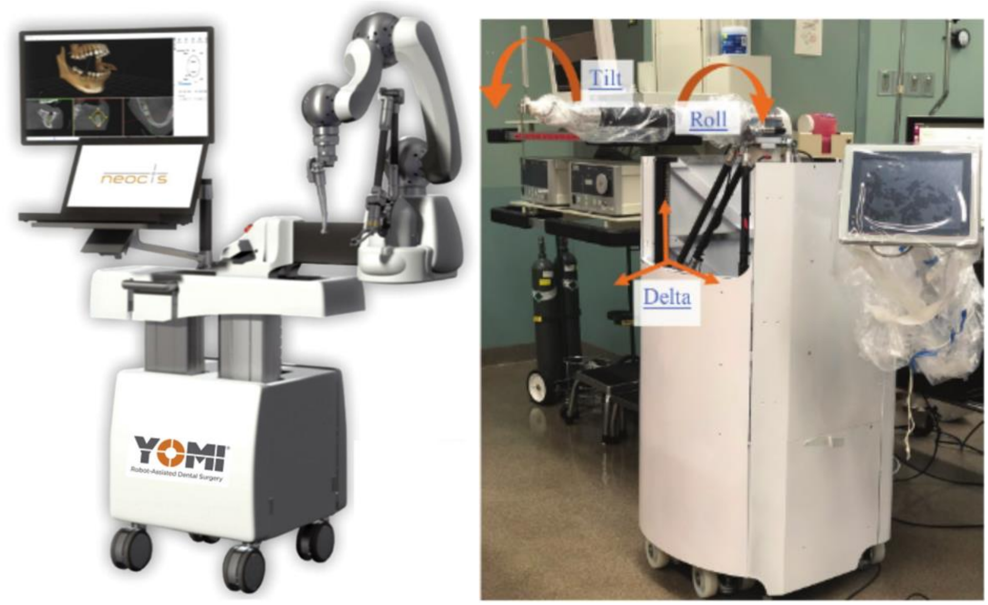


Figure 3. YOMI Dental Robot [4] (Left) and the Galen Robot [5] (Right).

The YOMI robot is designed to assist in the implantation of dental implants into both the mandible and the maxilla [4]. A CT scan is taken of the patient before the procedure which is used to generate a model of the patient's head. The surgeon uses this to create a plan for where each of the dental implants should be placed. During the procedure a splint is attached to the patient's bone using screws. Another CT scan is used to register the relationship between the bone and the splint. A secondary arm of the robot is then attached to the split so it can track the bone's location in space. The primary arm of the robot will cooperatively hold the tool with the physician during the procedure and will guide the physician towards the pre-defined plan using haptics. This results in improved accuracy over free-hand use and similar performance to acrylic guides.

The Galen robot is a 5 degrees of freedom (DoF) system designed to be a general-purpose cooperative robotic platform. An example of this system's potential was shown in a feasibility study where the robot was able to enforce virtual barriers in a mastoidectomy without the need to train the operator on where to cut [5]. Because of the general-purpose nature of the robot, and its demonstrated use in enforcing virtual barriers while cutting bone, this will be the system our workflow is built around.

IV. Technical Summary

a. Mandible Phantom

The first portion of this project focused on the development of a mandibular phantom. This will be needed for testing the system and verifying its performance. Developing such a phantom has additional applications in physician training models and creating other bone phantoms such as a temporal bone for a mastoidectomy.

Fabrication of these phantoms was done using a form of 3D printing called Digital Light Processing (DLP). This process works by curing UV resin one layer at a time with a UV LCD panel. DLP is able to create accurate phantoms from CT segmentations which will preserve anatomical structures better then a casting in dental stone would. Photopolymer resin, unlike thermoplastics used in traditional Fused Deposition Modeling (FDM) 3D printing, does not melt when machined. Additionally, elastic and brittle resins can be mixed to customize the physical properties of the material. Using this as a basis, a mandible phantom can be created that will accurately reproduce patient anatomy and represent the machinability of bone (Figure 4).

Figure 4. 3D Printed Mandible Phantom.

One issue in accurately representing machining bone with these prints is that cancellous bone is not created in the model. This is because the CT segmentation is typically intensity based which is correlated with bone density. Porous structures such as cancellous bone will show up as a lower intensity in the CT images, but even if it was included in the segmentation, it would be printed the same as the cortical bone which would result in one solid phantom which does not accurately represent bone. Another problem that was encountered was the cortical bone in the segmentation showed up thicker than what the physicians expected as shown in Figure 5.

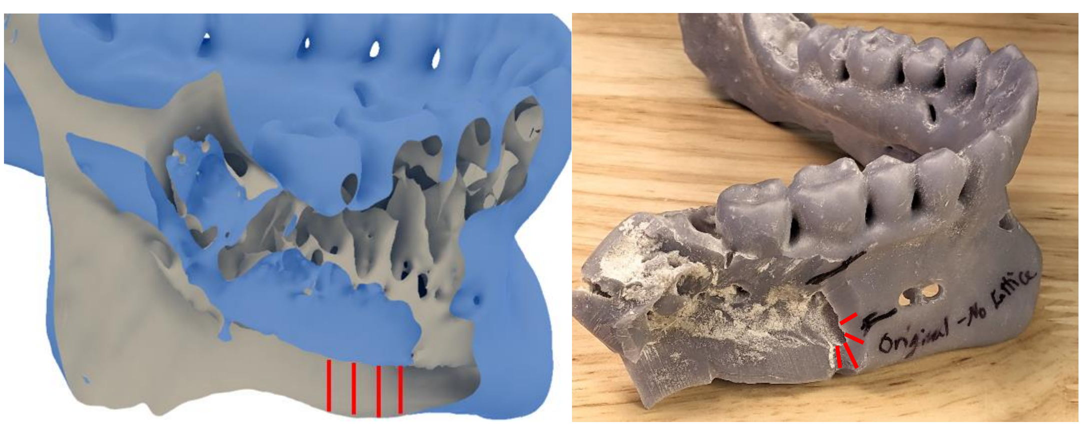


Figure 5. Thick cortical bone in original segmentations.

Two adjustments were made to the model to address these issues. First, the segmented mandible model was shelled out to create an artificial 1mm thick cortical bone. This thickness was selected from a paper that identified the thickest the cortical bone in the mandible is likely to be is 1mm [6]. Second, to represent cancellous bone a lattice structure was generated to fill the internal geometry of the mandible. Both of these features can be seen implemented in the image below.

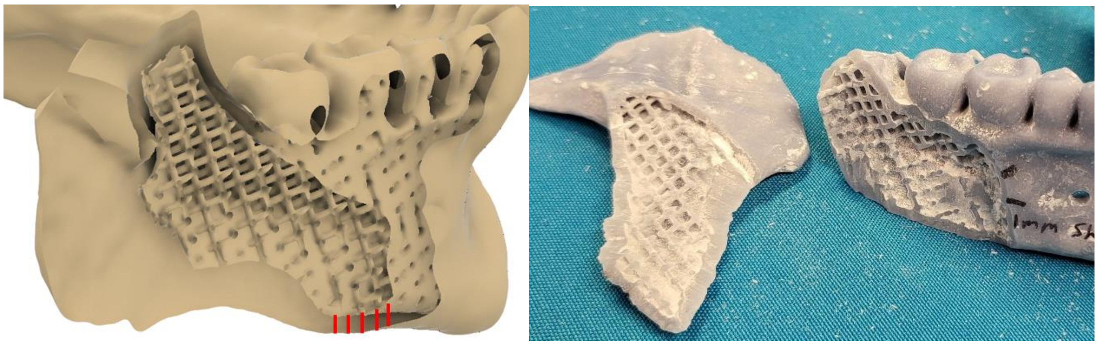


Figure 6. Mandible phantom with 1mm cortical bone and lattice infill.

The lead mentor for this project, Dr. Yang, drilled into these phantoms and verified that their machinability was representative of real bone. A detailed procedure on how these phantoms were made can be found in appendix a.

b. Clinical Workflow

Another aspect of this project is to design a method for implementing the robotic system into the clinical workflow. The current workflow that was shown above in Figure 2 lends itself well to robotic implementation. See the figure below for an outline of the proposed procedure.

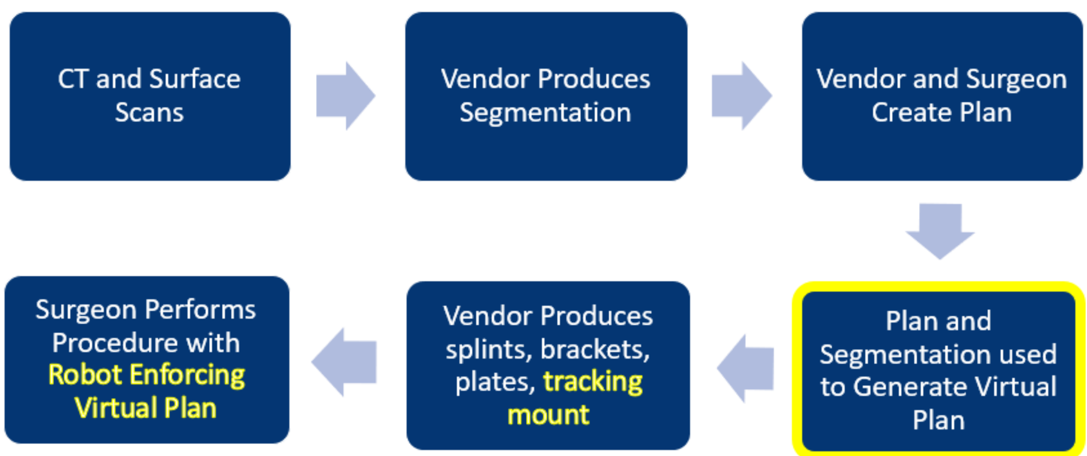


Figure 7. Proposed Clinical Workflow (changes from current workflow are highlighted).

Parts of the workflow that will be changed from the current procedure are highlighted in the figure. Because segmented models and digital surgical plans are already created for the procedure, very little of what the surgeon does will need to be changed. The surgeon's plan can be used to automatically generate virtual guidance that will be enforced by the robot during the procedure. When the vendor creates splits that fit onto the teeth for alignment, a mount for the tracking markers can be created that will fit over the teeth as shown in Figure 8. This will be used so the robot can track the location of the mandible during the procedure. While drilling the physician will operate from one side of the patient with an assistant standing near the patient's head. The robot will reside across from the physician and hold onto the tool with the surgeon throughout the procedure which allows it to enforce the pre-defined plan. An example of this layout is shown in the figure below.

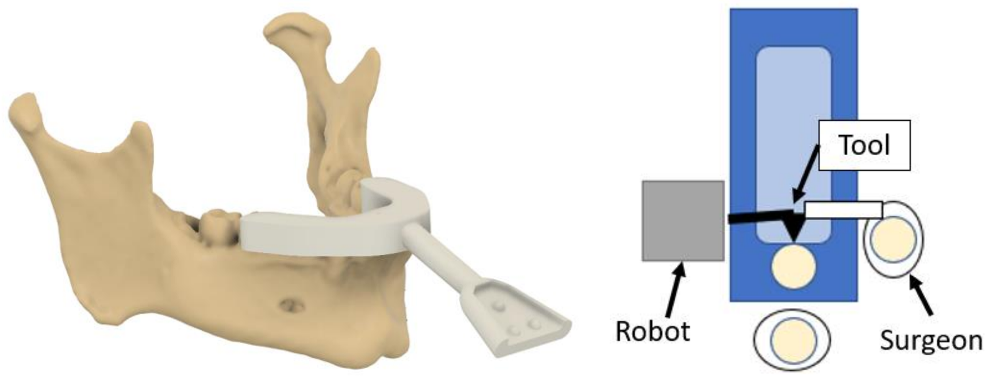


Figure 8. Teeth mounted tracking (Left) and OR layout during procedure (Right).

The aspect of this workflow that is likely to change as the project evolves in how tracking is done during the procedure. As mentioned before, the YOMI robot uses a tracking arm instead of optical markers. This eliminates the risk of the physician accidentally obscuring the markers while operating in the oral window. Given the small operating area, blocking the markers will likely be a problem. Extending the length of the mount's neck could improve marker visibility but will reduce accuracy the further the markers are from the mandible. For now, the project will proceed by using the optical tracking markers to establish the feasibility of the workflow.

c. Bench Testing Workflow

Before building the clinical system, this workflow will need to be tested on the bench. A similar procedure was designed for testing the proposed workflow which is shown in Figure 9 below.

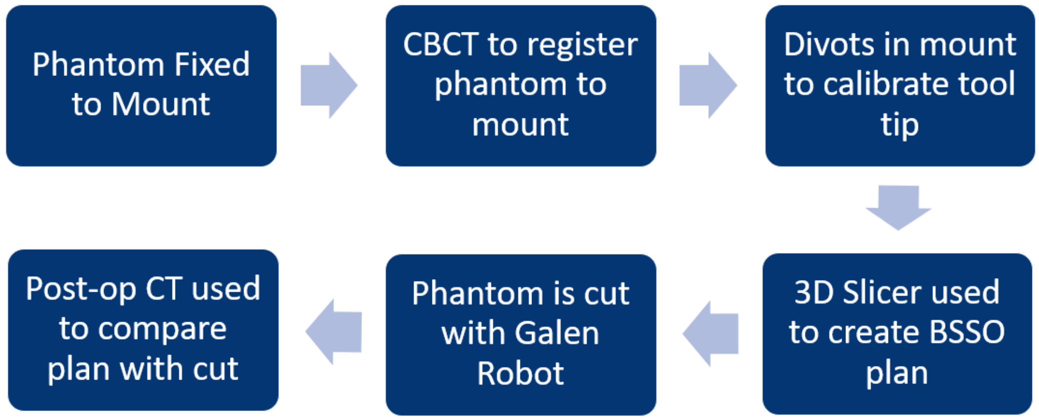


Figure 9. Workflow for bench testing.

To begin, a phantom mandible is screwed into the mounting plate as shown in Figure 10. There is a cutout in the back of the mandible, so it fits securely on the mount. From here the setup can be scanned using Cone Beam CT (CBCT) to register the relationship between the phantom and the optical tracking markers. The markers are laid out in such a way as to represent where the tracking markers would be in the clinical workflow if using the teeth mounted optical markers. Additionally, markers are spaced out as far as possible to reduce tracking error. Tracking markers will also be located on the drill as shown in Figure 11. The drill will be used to perform a pivot calibration using the divots in the corners of the mounting plate to register the relationship between the tip of the tool and the tool's markers.

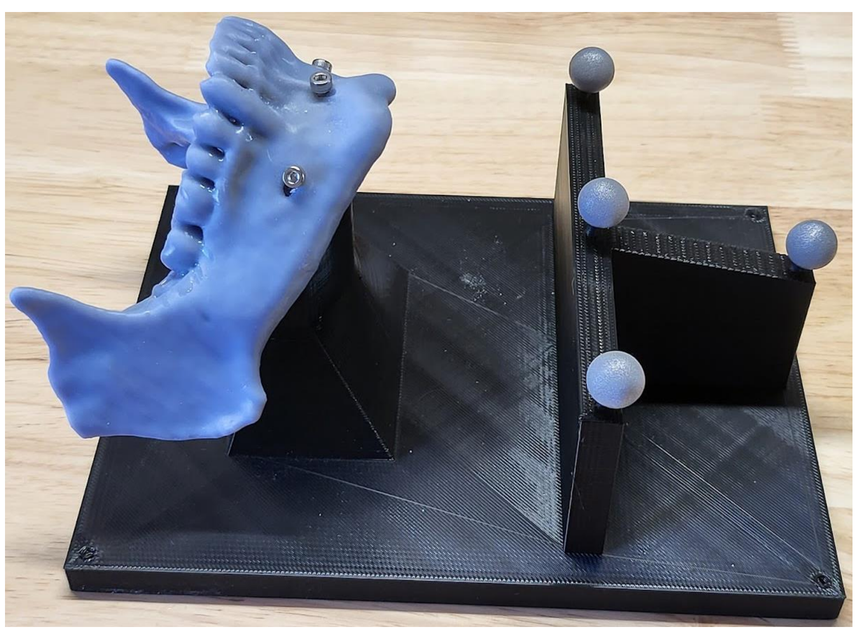


Figure 10. Phantom mounting plate with optical tracking markers.

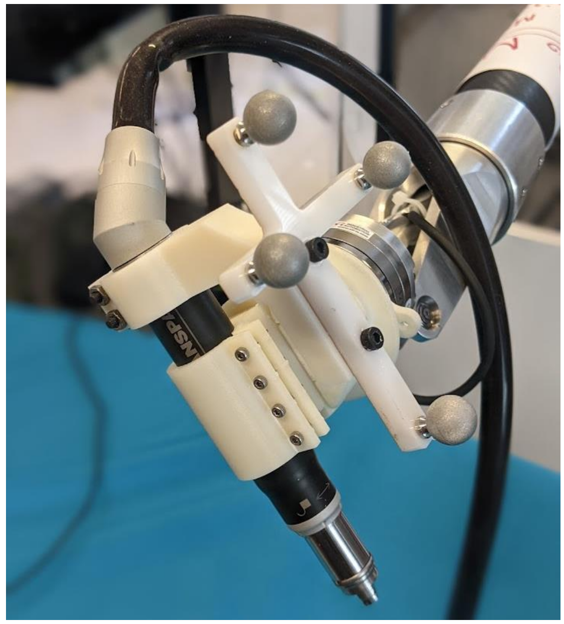


Figure 11. Drill with tracking markers and adaptor.

An adaptor was designed to mount the drill to the Galen robot's end-effector which can be seen in the figure. 3D Slicer can then be used to generate a planned planar cut for the procedure similar to what was done in the Galen Mastoidectomy paper [5]. The Galen can then be used to execute the plan on the mandible phantom. After the operation, the phantom will be scanned again to compare the cut to the plan and measure its deviation. This will be used to compare the effectiveness of the cooperative robotic method to a free-handed operation.

V. **Management Summary**

The only member of Group 15 is Jesse Haworth who was responsible for the following:

- Maintaining meeting minutes and running weekly meetings
- Writing all presentations and reports
- Designing workflows, phantoms, mounts, and adaptors (Anna Goodridge helped with the adaptor)
- Prototyping project components
- Managing project timeline, action items, deliverables, and milestones
- Creating documentation and updating the project wiki

Other participants in the project who were not part of the CIS II class worked on the following items:

- Project advising: Andy Ding, Dr. Robin Yang, Dr. Russell Taylor
- Mandible Segmentations: Sahana Kumar, Niranjan Behera
- IRB Application: Andy Ding, Katie Zhu

The planned deliverables for this project are shown in the figure below.

	Deliverable
Minimum	• 3D printed phantoms that are drillable and similar in feel to bone • Documented approval of phantoms by physician
Expected	• Demonstrable cooperative control robot-assisted mandibular osteotomy • Documented approval of system function by physician
Maximum	• Demonstrated registration between the phantom, CT model, and robot
Summer	• Demonstration of virtual fixtures for robot-assisted mandibular osteotomy • Documentation of virtual fixtures function via CT data • Documented approval of system function by physician

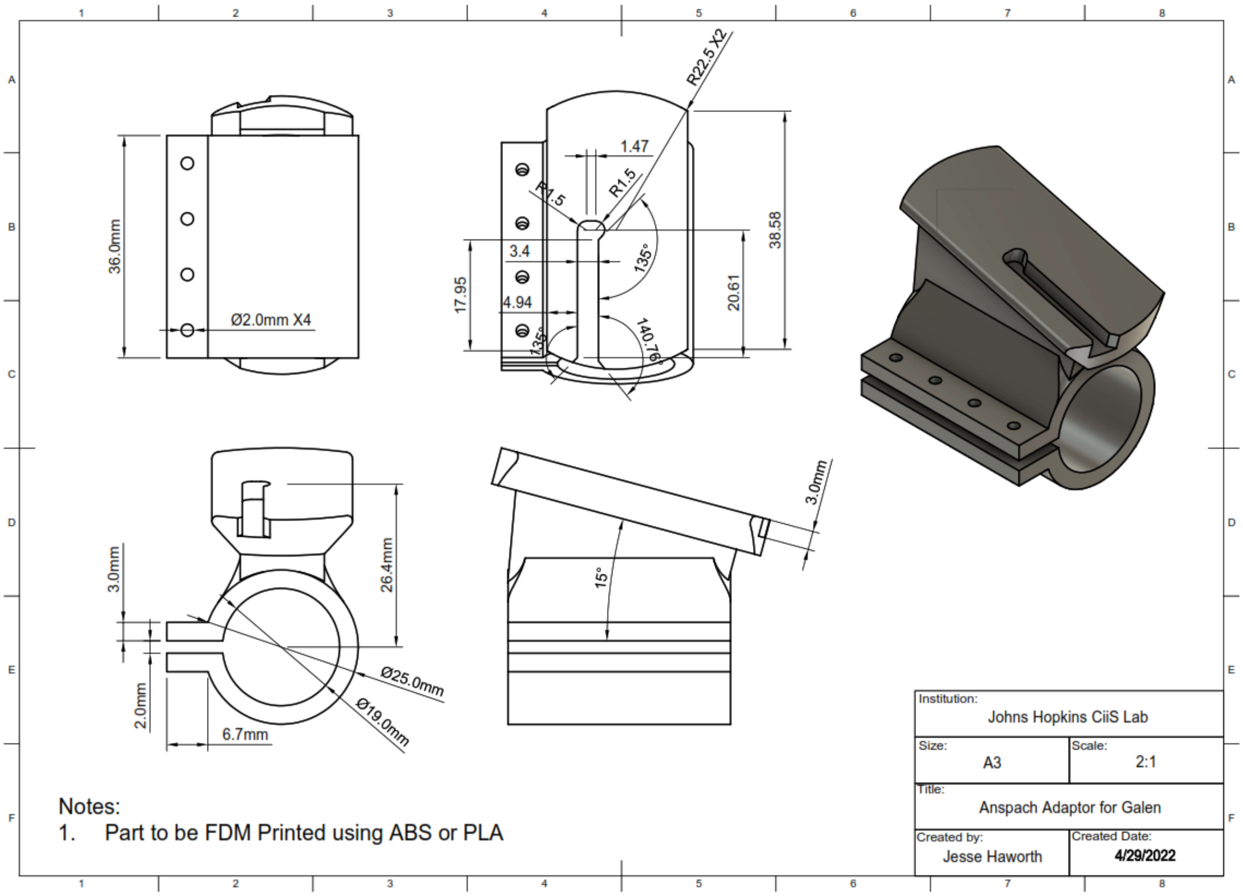
The minimum and expected deliverables will be met this semester, with approval of the system function by Dr. Yang coming the week after the Final Report is due. The Galen robot was down for maintenance for part of the semester which delayed validation of our setup. The maximum deliverable for this semester is not expected to be reached due to needing more training with ROS and the tracking system which made the registration setup take longer than originally planned.

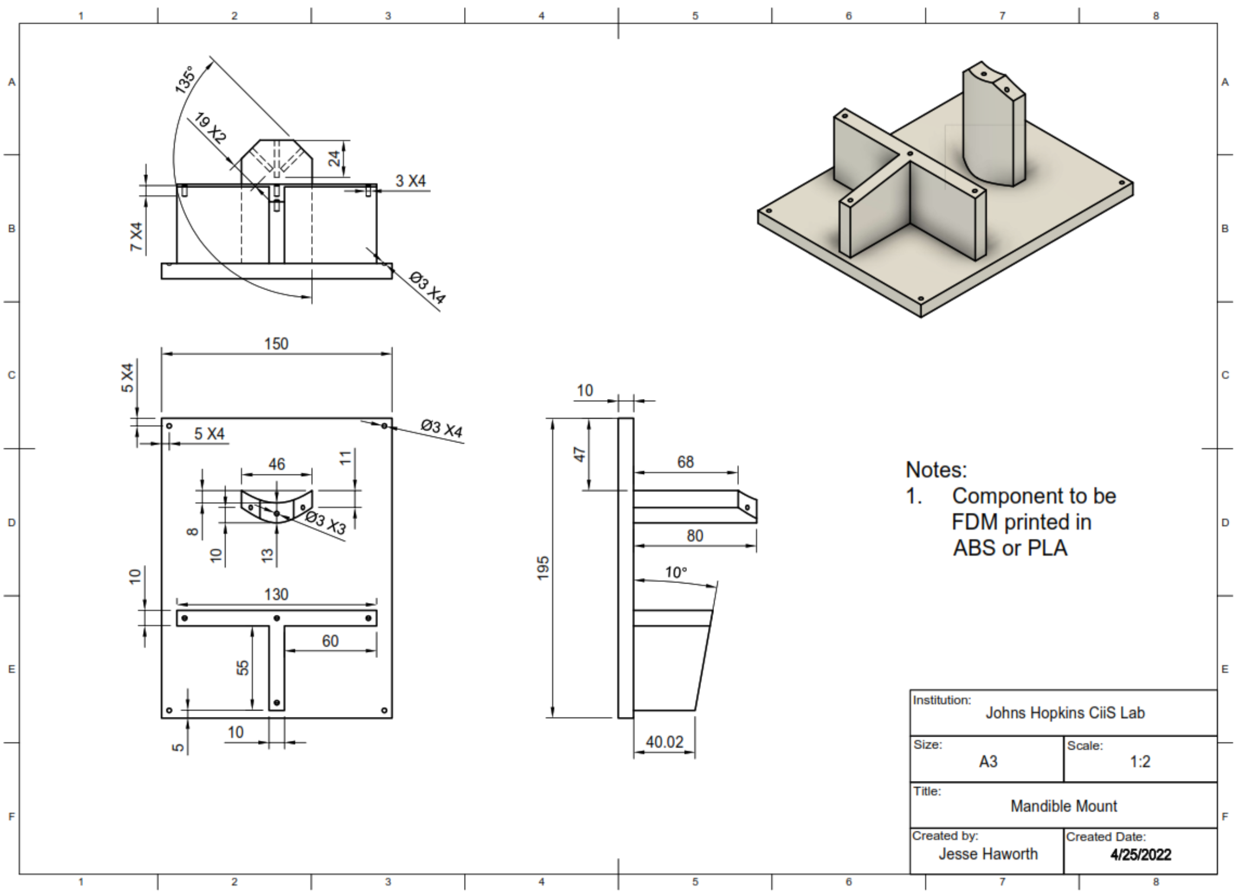
Work on this project will be continued over the summer with the same group. The first items to be completed are integration of the tracking system, followed by completing mandible and tool registration. Following this, work will begin on designing the framework for enforcing the virtual plan. By the end of the summer the team hopes to demonstrate use of the system on the mandible phantoms with performance verified by post-op CT data. In parallel, the phantoms created in the project will be integrated into other projects such as physician training models and robotic mastoidectomy.

This group was able to learn many things during the course of this semester. The main take away was learning about the many components involved in a comprehensive robotic workflow and how they all fit together. These skills will be valuable in the development of any robotic system in the future. We also learned what characteristics surgeons find important to have in a medical bone phantom. As discussed before what was learned in developing these models can be applied to many future projects. Lastly, we learned about the considerations involved in establishing tracking in a robotic platform. We only began to scratch the surface of this but expect the learn much more in the coming months as we develop our workflow.

VI. **Technical Appendices**

a. Component Drawings (Associated CAD files can be found on the project wiki)





135°
19 X2
24
3 X4
7 X4
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150
5 X4
5 X4
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46
11
8
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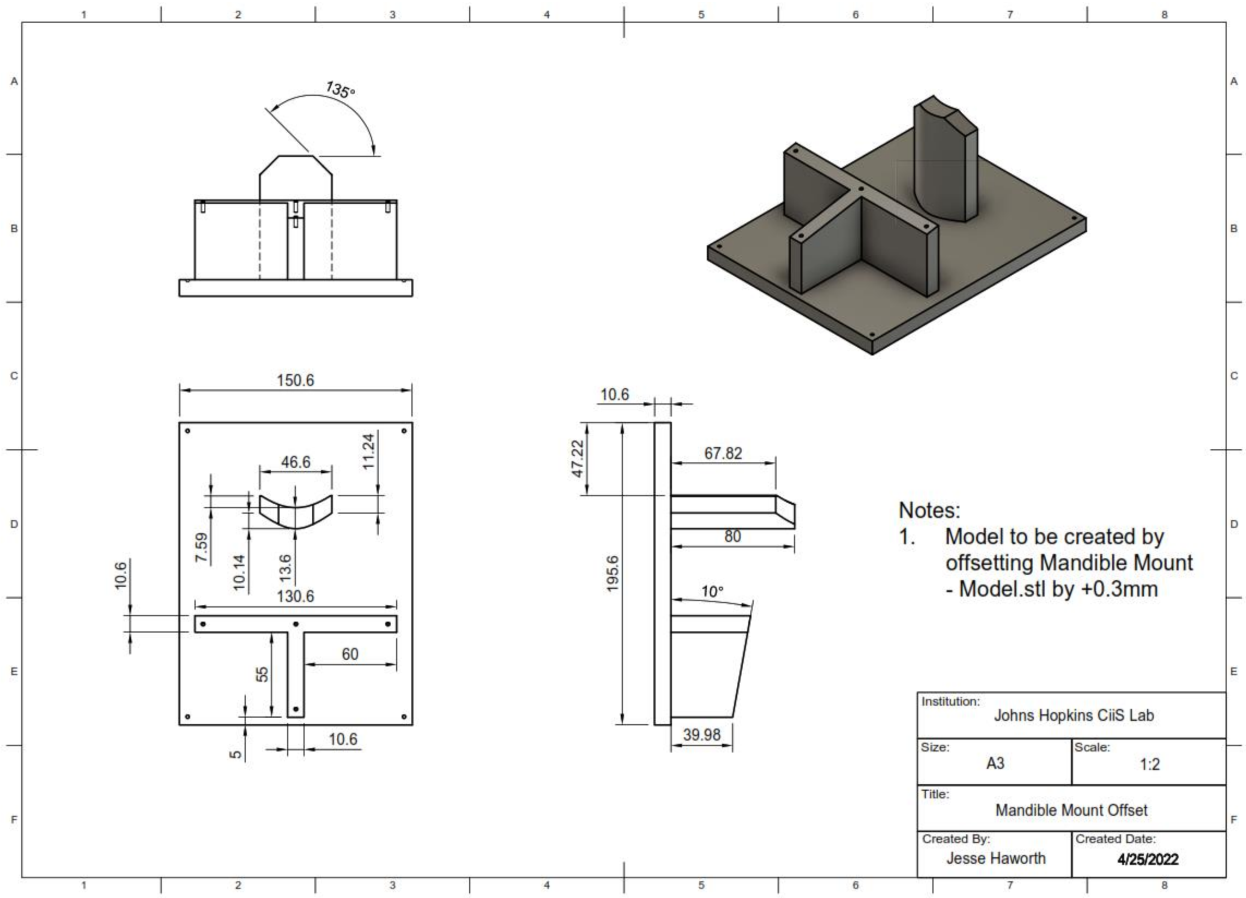
13
Ø3 X3
10
130
60
55
10
5
10
47
68
80
195
10°
40.02
Notes:
1. Component to be FDM printed in ABS or PLA
Institution: Johns Hopkins CiiS Lab
Size: A3
Scale: 1:2
Title: Mandible Mount
Created by: Jesse Haworth
Created Date: 4/25/2022


135°
150.6
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11.24
7.59
10.14
13.6
10.6
130.6
60
55
5
10.6
10.6
47.22
67.82
80
195.6
10°
39.98
Notes:
1. Model to be created by offsetting Mandible Mount - Model.stl by +0.3mm
Institution: Johns Hopkins CiiS Lab
Size: A3
Scale: 1:2
Title: Mandible Mount Offset
Created By: Jesse Haworth
Created Date: 4/25/2022

b. Mandible Phantom Creation Procedure

JOHNS HOPKINS WHITING SCHOOL of ENGINEERING	Mandible Phantom Creation			ciis
	Author: Jesse Haworth	Last Edited: 04/11/2022	Page 1 of 6	

1. **Purpose**
   1.1. The purpose of this document is to outline the procedure for the fabrication of mandible phantoms. These phantoms were designed to replicate the machinability of real bone in the context of a Bilateral Sagittal Split Osteotomy.
2. **Equipment/Software**
   2.1. Anycubic Photon - SLA 3D Printer
   2.2. Flash Drive
   2.3. Fusion 360
   2.4. Glass Bowl
   2.5. Meshmixer
   2.6. Photon Workshop V2.1.26
   2.7. Razor Blade
   2.8. UV Lamp
   2.9. Wire Cutters
3. **Materials**
   3.1. Flexible Resin - Siraya Tech Tenacious 3D Printer Resin Flexible 405nm UV – Clear
   3.2. IPA 99% (or 70%)
   3.3. Mandible STL File
   3.4. Nitril Gloves
   3.5. Paper Towels
   3.6. Rigid Resin - ANYCUBIC 3D Printer Resin, 405nm – Grey (any opaque color will work)
4. **Procedure**
   4.1. Remove internal structures of the mandible.
      4.1.1. Open Fusion 360.
      4.1.2. Import the STL file.
      4.1.3. Select the "Direct Edit" feature under the "Mesh" tab.
      4.1.4. Delete faces that connect the internal structures to outside of the mandible.
      4.1.5. Delete all faces that comprise internal structures of the mandible.
      4.1.6. Select "Finish Direct Editing".
      4.1.7. Select the "Repair" tool and use "Stitch and Remove".
      4.1.8. Right click on the mesh and select "Save as Mesh".
         4.1.8.1. "Format" should be "STL" and "Unit Type" should be "Millimeter".
   4.2. Make model hollow and add lattice.
      4.2.1. Open Meshmixer.
      4.2.2. Import the modified STL file.
      4.2.3. Select the "Edit" tab.
      4.2.4. Select the "Hollow" tool.
      4.2.5. Enter "1mm" as the offset distance.
      4.2.6. Click "Accept".
      4.2.7. Select "Export" and save the hollow mandible file. Make sure to name it in such a way that it can be recognized that it is the hollow version of the mandible.
      4.2.8. Select the "Edit" tab again.
      4.2.9. Use "Separate Shells".

4.2.10. In the "Object Browser" that pops up, select the outside surface. Then click the delete key.
4.2.11. Close the object browser.
4.2.12. Click on the "Select" tool.
4.2.13. Press CTRL + A to select all the faces.
4.2.14. Select the "Edit…" dropdown menu and choose "Flip Normals".
4.2.15. Go back to the "Edit" tab.
4.2.16. Select "Make Pattern".
4.2.16.1. Pattern Type: Lattice
4.2.16.2. Element Dimension: 1mm
4.2.16.3. Element Spacing: 3mm
4.2.16.4. Composition Mode: Intersect
4.2.16.5. Clip to Surface: Deselected
4.2.16.6. Rotate the lattice 45 degrees about the frontal axis.

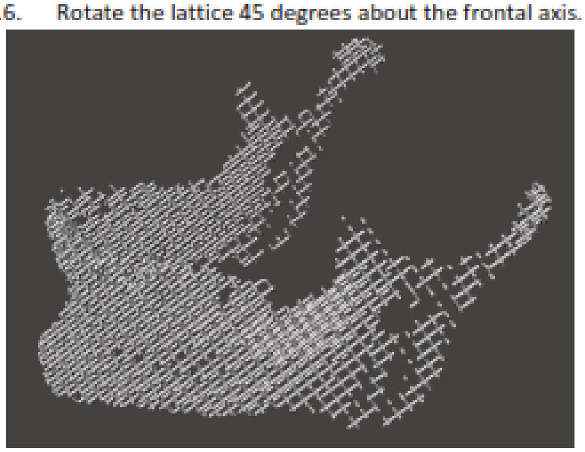

Figure 1. Internal lattice structure.

4.2.17. Click "Accept".
4.2.18. From the Object Browser select the inside mesh (not the lattice) and click the delete key.
4.2.19. Select "Import" and choose "Append".
4.2.20. Select the hollow mesh created previously.
4.2.21. In the Object Browser select both the lattice and the hollow model.
4.2.22. Select "Combine" in the popup menu.
4.2.23. Click "Export" and save the model as an STL file.

4.3. Prepare file for printing.

4.3.1. Open Fusion 360.
4.3.2. Open the Fusion 360 containing the mounting setup.
4.3.2.1. If necessary, use the "Offset Face" tool in the "Solid" tab to increase the size of any surfaces mounting with the mandible phantom. This will ensure the components will mate properly together.

4.3.2.2. Make sure to remove the offset before creating the mounting.

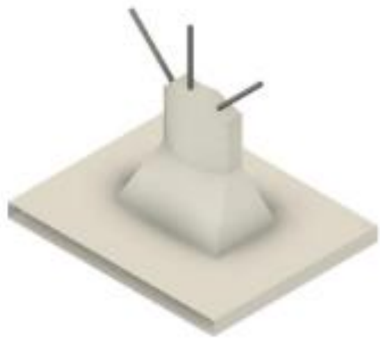

Figure 2. Mounting Setup.

4.3.3. Click "Insert" and then "Insert Mesh".

4.3.4. Select the edited mandible STL file.

4.3.5. Use the "Move" tool to position the mandible onto the mounting plate in the desired location.

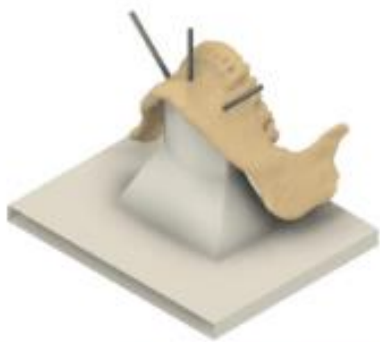

Figure 3. Mandible oriented onto mounting setup.

4.3.6. Ensure the mounting plate and any other relevant bodies (such as the screw axes shown in the picture) are meshes.

4.3.6.1. If not, convert the solid bodies to meshes using the "Tessellate" tool in the "Mesh" tab.

4.3.7. Then use the "Combine" tool in the "Mesh" tab to subtract the mounting from the mandible.

4.3.7.1. Target Body: Select the mandible

4.3.7.2. Tool Bodies: Select any relevant mounting bodies

4.3.7.3. Operation: Cut

4.3.7.4. Keep tool: Selected

4.3.8. Save the resulting body as an STL.

4.3.8.1. Right click on the body.

4.3.8.2. Select "Save As Mesh" and choose STL.

Figure 4. Resulting mandible phantom mesh.

4.4. Print Mandible Phantom

4.4.1. Make sure to use nitrile gloves whenever using the UV Resin or IPA. Clean up any mess using paper towels and IPA.

4.4.2. Prepare an approximately 20% Flexible resin and 80% rigid resin solution.

4.4.3. Pour the solution into the vat of the Anycubic printer.

4.4.4. Open up Photon Workshop

4.4.5. Select "Open" and navigate to the mandible STL file.

4.4.6. Orient the mandible as shown in the picture below.

4.4.6.1. After orienting the mandible, translate it along the Z axis by 5mm.

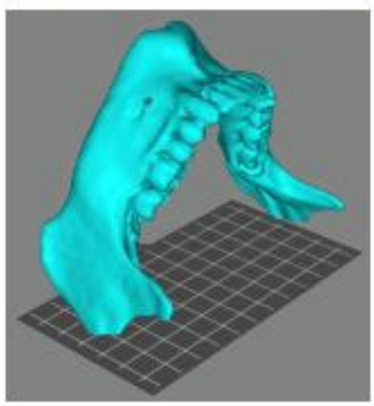

Figure 5. Model orientation in Photon Workshop.

4.4.7. Add support structures on the posterior medial side of the mandible as shown in the picture below.

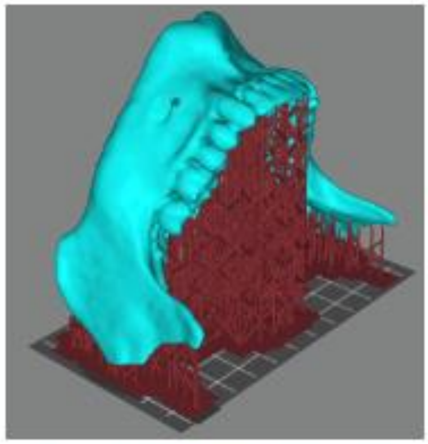

Figure 8. Stupport strutures in Photon Workshop.

4.4.8. Enter the following settings into the slicer:

4.4.8.1. Layer Thickness: 0.050mm

4.4.8.2. Normal Exposure Time: 12 seconds

4.4.8.3. Off Time: 1 second

4.4.8.4. Bottom Exposure Time: 80 seconds

4.4.8.5. Bottom Layers: 6

4.4.8.6. Z Lift Distance: 6mm

4.4.8.7. Z Lift Speed: 3 mm/s

4.4.8.8. Z Retract Speed: 3 mm/s

4.4.8.9. Anti-alias: 1

4.4.9. Click the slice button to finish.

4.4.10. Save the file to a flash drive.

4.4.10.1. Use the file extension ".photon" for the original Anycubic photon printer.

4.4.11. Insert the flash drive into the Anycubic Printer.

4.4.12. Select "Print" and select the prepared slicer file.

4.4.13. Print will finish in approximately 9.5 hours.

4.5. Post Processing

4.5.1. Make sure to use nitrile gloves whenever using the UV Resin or IPA. Clean up any mess using paper towels and IPA.

4.5.2. Use a razor blade to remove the mandible from the build plate.

4.5.3. Break off and discard any support material by hand.

4.5.4. Vigorously rinse the excess resin off of the mandible using IPA in the glass bowl.

4.5.5. Lightly dry the mandible.

4.5.6. Place the mandible under a UV lamp, rotating occasionally.

4.5.7. Repeat until all surfaces are no longer sticky.

4.5.8. Use wire cutters to remove any remaining support structures.

4.6. Testing and Approval

4.6.1. Mandible phantom will be tested by a physician using an Anspach EG1 drill. Physician will verify if mandible machineability is clinically representative.

4.6.2. Signature documenting physician's approval will be recorded below.

Approval of phantom outlined in this procedure:

Name	Signature	Date

Name	Signature	Date

c. Mandible Bench Setup Procedure

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	Author: Jesse Haworth	Last Edited: 04/25/2022	Page 1 of 4	

1. Purpose

1.1. The purpose of this document is to outline the procedure for the fabrication of mandible mounting setup. This setup will be used to test a cooperative robotic workflow for a Bilateral Sagittal Split Osteotomy.

2. Equipment/Software

2.1. Drill
2.2. Drill bits
2.3. FDM 3D printer
2.4. Metric Allen wrench set
2.5. Pliers
2.6. Wire cutters
2.7. Anspach EG1 Dill
2.8. Fluted Router Bit 1.4mm x 12.8mm or similar

3. Materials

3.1. ABS Filament
3.2. Disposable Reflective Marker Spheres – Screw Type
3.3. M2 nuts X4
3.4. M2 x 12 socket head screw X4
3.5. M3 x 12 socket head screw X4
3.6. M3 x 20 socket head screw X2
3.7. M3 x 30 socket head screw X1
3.8. PLA Filament

4. Procedure

4.1. Printing Components

4.1.1. FDM print the Mandible Mount in PLA.
4.1.2. FDM print the Anspach Adaptor in ABS.
4.1.3. Open Fusion 360 and import the Mandible Mount Offset file into the mandible phantom file.
4.1.4. Use the Move tool to position the mandible how it would be when mounted. See Figure 1 for reference.

Figure 1. Mandible position on mount.

4.1.5. Use the Combine tool to subtract the Mandible Mount Offset from the mandible.

4.1.6. Follow the Mandible Phantom Creation procedure for the remainder of the phantom fabrication.

4.2. Post Processing

4.2.1. Use wire cutters to trim off all excess support material from the mandible phantom. Especially be sure to clear off all excess material on the mating surface with the mounting plate.

4.2.2. Using a drill and a set of drill bits, ream out the holes in the mandible phantom until the M3 x 30 socket screw can freely pass through the 3 holes.

4.2.2.1. Make sure to slowly work up in drill bit size as to not fracture the mandible.

4.2.3. Do the same operation on the holes in the Anspach Adaptor until the M2 screws can freely pass though the 4 holes.

4.3. Assemble Components

4.3.1. Insert the 4 M2x12 screws through the holes in the Anspach Adaptor.

4.3.2. Place the M2 nuts on the ends of the screws.

4.3.3. Slide the adaptor over the Anspach as shown in the figure below.

Figure 2. Anspach Adaptor for Galen.

4.3.4. Use an Allen wrench and pliers to tighten the screws until the Anspach cannot move in the adaptor.

4.3.5. Take 4 M3x12 screws and break off the socket heads using wire cutters and pliers.

4.3.6. Using pliers, insert the 4 headless screws halfway into the Mandible Mount with the removed socket end facing up.

4.3.7. Take 4 Disposable Reflective Marker Spheres and thread them onto the screws until they are snug. See figure below for reference.

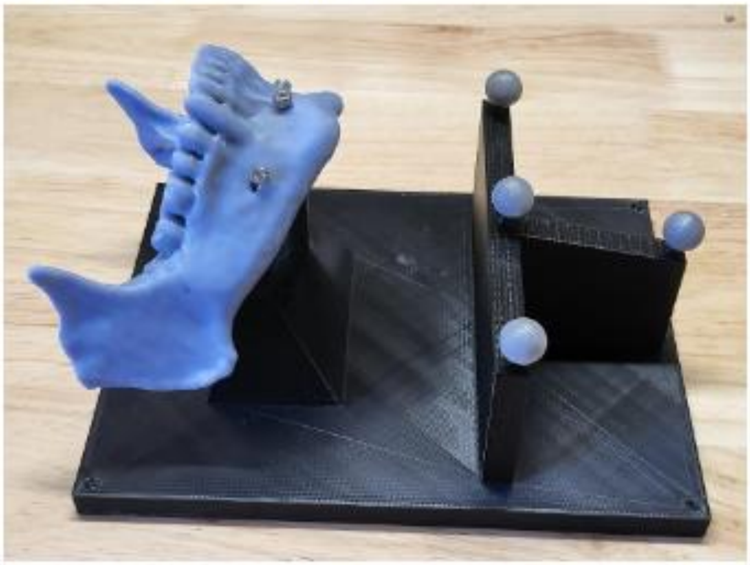

Figure 3. Mandible mounting setup.

4.3.8. Place the mandible phantom on the Mandible Mount as shown in the figure above.

4.3.8.1. If the mandible does not fit, use wire cutters to remove any remaining support material that could interfere with mating.

4.3.9. Using an Allen wrench, screw 1 M3x30 socket screw in the middle of the mandible and 2 M3x20 screw on either side of the mandible as shown in the figure.

4.4. Testing and Approval

4.4.1. Mandible Mounting will be tested by a physician using an Anspach EG1 drill and drill adaptor connected to the Galen robot. Physician will verify if the setup allows for proper execution of the procedure.

4.4.2. Signature documenting physician's approval will be recorded below.

Approval of mounting setup outlined in this procedure:

____

Name　　　　　　　　Signature　　　　　　　　Date

____

Name　　　　　　　　Signature　　　　　　　　Date

VII. References

[1] BSSO Procedure Description: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5392880/

[2] Image of BSSO: https://www.researchgate.net/figure/A-modified-Obwegeser-Dal-Pont-bilateral-sagittal-split-osteotomy-BSSO-technique-was_fig3_335848383

[3] Cortical Bone Thickness in Mandible: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3094736/

[4] YOMI Dental Robot Clinical Study: https://doi.org/10.1016/j.prosdent.2020.12.048

[5] Galen Virtual Fixtures in Mastoidectomy: https://doi.org/10.1177%2F0194599819861526

[6] Average Thickness of Cortical Bone in the Mandible: https://doi.org/10.4047/jap.2012.4.3.146