A Force-Sensing Drill for Robotic Skull-Base Surgery

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Technical Summary

Background

The Galen Robot is a hand-over-hand cooperative controlled surgical robotic system used for head and neck surgery. This surgical system brings together the precision and dexterity of a robot with the cognition and intelligence of a surgeon. For surgeries of the skull base, any tremor, jerk, or overshoot could have serious consequences on the patient outcome, including facial paralysis or loss of taste/smell.

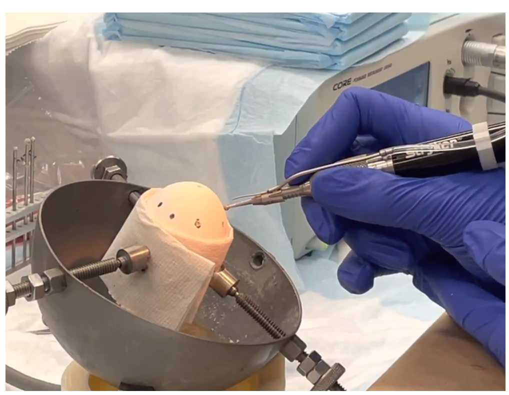
Additionally, the forces applied by the surgeon to the bone during drilling operations require a highly skilled surgeon who is both delicate and precise. A device that can precisely measure a critical range of forces applied during surgery can play a significant role in reducing the rates of complications during otologic surgery.

This device can also be used to train surgeons and evaluate surgical skills. Using the forces measured by this device, virtual fixtures or other haptic feedback can be delivered to the surgeon to improve their perception of the surgical theater.

By the semester's end, we successfully designed and prototyped a mechanical device which utilizes an ATI Nano43 6 DOF F/T sensor to provide tool-tip interaction forces. Next steps for this project are to connect the force sensor and analyze the initial readings.

Process

Our design process started with discussions with surgeons to understand what forces they wanted to measure and why they wanted to know them. Once we identified these targets, we reviewed existing literature to see what existing research and technology existed around this area. We also conducted experiments early in the semester using a force sensor positioned beneath various drilling media (dental stone, eggs, and cadaveric temporal bones) to get a clearer understanding of the range of forces applied during these procedures. Now armed with greater knowledge about the problem we were trying to solve, we began a thorough brainstorming and ideation phase.



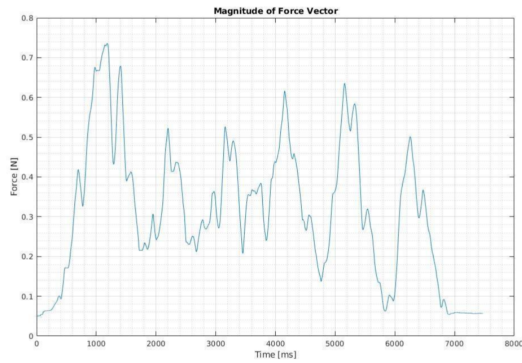


Figure 1: Experimental setup and measurements from early experiments to determine a suitable range of forces for our device.

For several weeks, we came up with many different ideas and reviewed sketches and our technical understanding of the problem with mentors. Our mentors helped us to downselect our ideas so that we could quickly jump to rapid-prototyping. From here, we were frequently iterating on our ideas and presenting new designs or updated prototypes every week. Great feedback from surgeons regarding ergonomics and usability and constructive comments from technical mentors regarding feasibility and manufacturability left us with a lot to explore in our designs between weekly meetings.

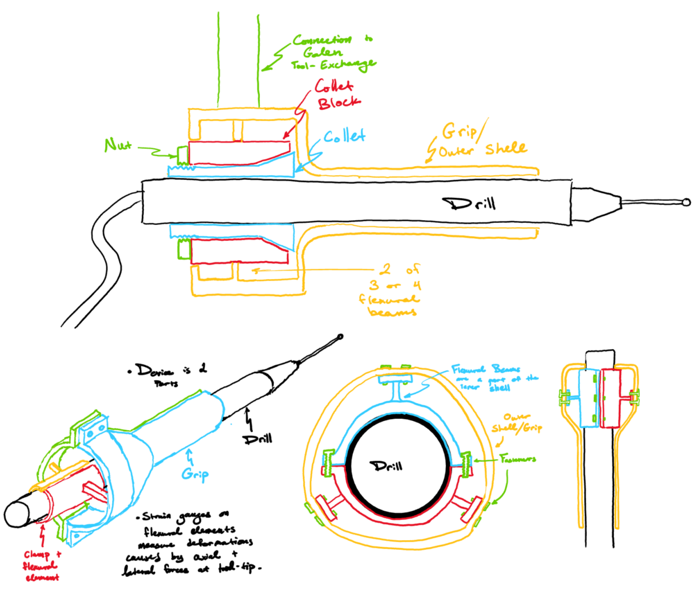


Figure 2: Early-stage sketches and back-of-the-envelope calculations to explore our design.

Initial Design Using Strain Gauges

Our initial ideas were focused around the designs of flexural elements connecting an inner shell clamped to the drill to an outer shell gripped by the surgeon. The deflections in these flexures would be large enough to measure with reasonably sensitive strain gauges because of the large moment arm between the tool tip and the axial position of the flexures along the drill.

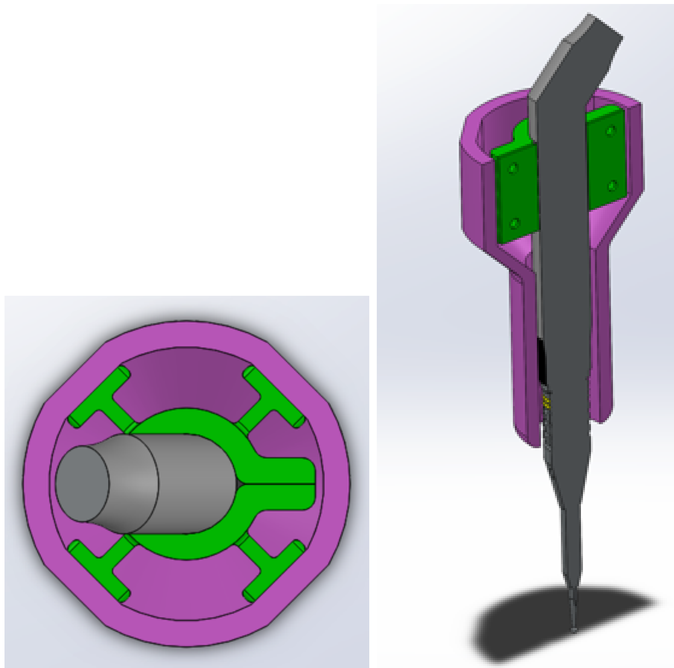


Figure 3: CAD of initial design in SolidWorks.

This design used a lot of very small screws and tight tolerance fits, which made it difficult to assemble. We also received feedback from surgeons that the prototype was almost uncomfortably large and bulky, and while we hoped that more precise manufacturing methods and careful analysis would have led us to a design with a smaller footprint, we decided instead to explore alternative design paths.

Refined Design Using ATI Nano43

We started our alternative design exploration by thinking about how we could incorporate commercial force/torque sensors into our design to help reduce complexity and alter the shape of the grip to maximize comfort and field of view. While researching commercial options, we discovered the ATI Nano43 sensor. Unlike most other sensors used in similar applications, the Nano43 has a ring-shaped design, which allows the sensor to be mounted axially on a tool.

Calibration	Fx,Fy	Fz	Tx,Ty	Tz	Fx,Fy	Fz	Tx,Ty	Tz
SI-9-0.125	9 N	9 N	125 Nmm	125 Nmm	1/512 N	1/512 N	1/40 Nmm	1/40 Nmm
SI-18-0.25	18 N	18 N	250 Nmm	250 Nmm	1/256 N	1/256 N	1/20 Nmm	1/20 Nmm
SI-36-0.5	36 N	36 N	500 Nmm	500 Nmm	1/128 N	1/128 N	1/10 Nmm	1/10 Nmm
	SENSING RANGES				RESOLUTION			

Figure 4: The ATI Nano43 is the sensor used in our final prototype.

The inner diameter of the Nano43 was fortunately just large enough to accommodate the diameter of the Anspach EG1 at the location we planned to mount it. The design is made of three parts. A two-part clamp attaches to the distal end of the sensor and specialized geometry ensures that the clamp is rigidly fixed to the drill at a repeatable axial position upon installation. The grip, which is the part held by the surgeon, attaches to the proximal end of the sensor and includes an attachment point to connect the grip to the Galen robot's tool-exchange system.

Figure 5: Our final prototype attached to the Galen.

The unique geometry of this part was designed based on feedback from surgeons regarding their preferred "neutral" position of the drill relative to the robot. We considered hand position on the grip, position of the robot and the patient, field of view, and the allowable range of motion and manipulability. When the robot's roll and tilt stages are in a neutral position, the geometry of the grip positions the drill in a comfortable neutral position used in the procedures we were targeting. This ensures that surgeons can comfortably reach the full range of motion they are accustomed to without meeting the robot's joint limits.

Figure 6: Ergonomic testing of final prototype

We created configurations with design tables in Solidworks to quickly iterate on parts and make dimensional changes. These techniques made it easier for us to produce multiple prototypes and get ergonomic feedback from our surgeons almost every week.

We also explored options for designing the grip in a way that would prevent overloading the sensor. We envisioned the inner diameter of the grip being precisely fabricated such that slight deflections of the grip caused by the surgeons' applied forces would cause the grip to "bottom-out" on the drill if the applied forces approached the overload limits of the sensor. This would help to prevent permanent deformation of the sensing elements in the sensor. We concluded this was not feasible with the scale of forces (<1 Newton) we expected and conventional manufacturing methods and materials.

Drill Burr Exchange Tool

While designing this device, ease of use for surgeons was of great importance. Some iterations of our grip design restricted access to the part of the drill that is used to exchange the drill burrs, so we decided to design a specialized tool that could reach under the grip to perform the exchanging motions. The part uses rubber strips inlayed in grooves arranged around a conical shape that matches the contour of the drill's nose piece. The user can apply axial and rotational forces to the tool to perform the motions necessary for drill burr removal.

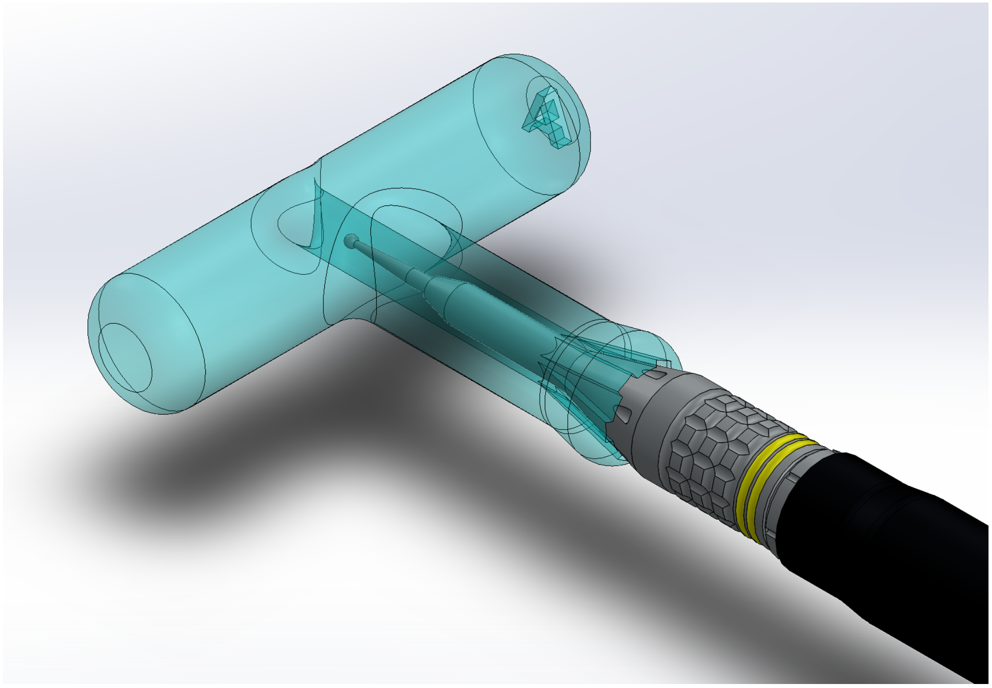


Figure 7: CAD model in SolidWorks of the drill burr exchange tool.

Ultimately, we decided this tool would not be necessary to use because the final design of the grip did not restrict access to the conical part of the nose piece. Glueing the small rubber strips into the tool was also a difficult and tedious task, further justifying our decision to forego additional development.

Results

The system we developed mounts an ATI Nano 43 force sensor and an Anspach EG1 surgical drill to the Galen surgical system. The components have been 3D printed and the screws have been carefully selected to avoid breaking the force sensor. We have uploaded zip files to the course wiki which contain our CAD files and data analysis. The prototype, drill, and force sensor are being stored in Professor Taylor's lab pod over summer 2021.

Management Summary

Team Contributions

Harsha Mohan began the project by conducting a literature review to learn about the state-of-the-art in force-sensing for drilling. In the initial phases of the design process, he designed the experiment to acquire force data, which involved drilling egg shells and a phantom temporal bone. After the experiment was conducted, he analyzed the drilling data and to select an appropriate ATI force sensor for the project. Harsha also contributed to concept generation, design work, and CAD modeling.

Seena Vafaee played a critical role in designing and prototyping the mechanical device, and generated the assembly and manufacturing instructions. He met frequently with our surgeon mentor to get feedback on the mechanical design. Seena also assisted with experimental setup and data collection for the drilling experiments.

We held working meetings 4 times a week, met with each of our mentors once per week, and presented weekly updates at the Galen Research meeting.

Results Compared with Planned Deliverables

At the beginning of this semester, we set out to prototype a device which could provide tool-tip force readings. The first direction we took was to create our own force-sensing elements with strain gauges. In the middle of the semester, we shifted deliverables and decided to integrate the ATI Nano 43 F/T sensor as it would be a faster way to test our force-sensing drill concept. However, this turned out to be a major dependency, as delays in procurement resulted in us not being able to test the functionality of the device. Instead, we focused our efforts on rapid prototyping, ergonomic studies, and documentation. By fall 2021, we hope to accomplish our maximum deliverable, which is to use our device during the eggshell drilling experiments to record the measured forces at the tool tip.

Suggested Next Steps

Upon receiving the ATI control box, the device should be assembled and configured to get readings from the sensor. A simple first experiment to assess the force readings is to fix the device to the Galen and position it such that the drill is parallel with the ground. With the drill in this position, hang a small weight on the drill burr. Compare the force and torque readings and proceed from there.

Eventually, it may be necessary to perform a pivot calibration on the galen to get more precise tool-tip force readings. With a pivot calibration, we can precisely calculate the position and lever arm associated with the tool-tip forces and compare those forces with the readings of our “ground truth” sensor which we used in the initial drilling experiments. It may also be useful to create a new class for the device on the Galen to input the geometric properties and desired gains.

We also see a number of mechanical design improvements that can be made. The current device is relatively difficult to assemble and requires caution as to not drop or break any of the components. For the purpose of research, it would be useful to have a device which is more simple and easy to assemble. If this device is going to be used for bone drilling experiments, an irrigation channel should be integrated into the system. If irrigation is used, sufficient caution must be taken to prevent the force sensor from getting damaged by water.

Lessons Learned

Early on, we learned how to manage our CAD files as both of us worked on the same assembly together. We created a folder on OneDrive and synced that folder to our computers. After each iteration, we would zip all the files for archival purposes.

Throughout the design process, we were experimenting with multiple versions and iterations of parts. Rather than creating new parts for each different modification we wanted to test out, we set up design tables with the dimensions of interest and created multiple configurations of the part in the same Solidworks file.

Technical Appendices

Manufacturing and Assembly Instructions

All .stl and .sldprt files necessary for 3D-printing and a complete design history file are included in the OneDrive folder for this project. 3D-printer training is required to use any 3D-printer in the robotorium.

First, add .stl files to GrabCad Print one at a time. By default, GrabCad Print interprets the .stl files in units of inches. Change the units of each model to millimeters after importing each file.

Tray settings can be adjusted. For final prototypes, I used a slice height of 0.0070 in, but for rapid iterations, you can use larger slice heights to save material and print time. I kept all other tray settings as default.

Model settings may also be adjusted. For final prototypes, I used the dense infill (second from the right), but used the sparsest infill for iterating. I kept all other model settings as default.

Orient the models as shown in Figure 8 to ensure ease of removing the support material. Once the print is done, carefully remove each part from the tray and remove the support material. It is fine to leave some support material in the holes because the holes will be drilled out to a larger diameter anyway. I recommend using the tools shown in Figure 9. If necessary, use the cleanstation bath. I did not need to use the cleanstation for removing support material from the final prototype.

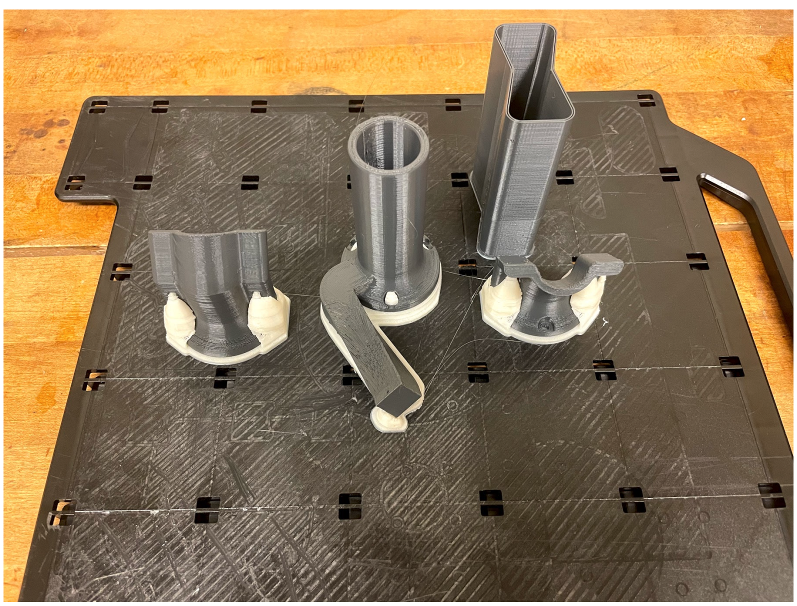


Figure 8: Orientation of models.

Figure 9: Tools used to remove support material and final result.

Use a 3.4 mm drill bit to drill out all through holes on all three parts to produce clearance holes for M3 bolts. Be careful while handling the parts not to crack them, especially if using the lower infill density. Remove any remaining support material.

To assemble the parts, first use 3 socket-head M3 screws to attach the grip to the bottom of the Nano43. Ensure that the grip is oriented in the same way on the sensor as shown in the following images. Be extremely careful with the length of the screws used so that the depth of the hole is not exceeded. This could lead to permanent damage of the very expensive sensor.

Next, use one more socket-head M3 screw to attach the half of the clamp with one hole to the top of the Nano43. Remember to follow the same orientation shown in the images below, and be very careful with your selection of screws so that you do not damage the sensor.

Figure 10: Assembling the grip and first half of the clamp onto the sensor.

Next, insert the drill as shown in Figure 11. Use 4 socket-head M3 screws and M3 nuts to clamp the two halves of the clamp together around the drill. To ensure that the last two screws that go into the sensor can be accessed using the allen key, have the heads of the screws that attach the two halves of clamp on the side of the clamp with two holes that attach to the sensor (see Figure 12). Use two more socket-head M3 screws to attach the remaining holes of the clamp to the top of the sensor.

Figure 11: Intermediate assembly step with drill placed in half-assembled device.

Figure 12: Final steps of assembling the clamp.

A machined adapter exists to fit onto the end of the grip so that it can be attached to the Galen robot’s tool exchange system. The adapter should be able to press onto the grip with ease. If necessary, use a file to shave down the size of the grip so that it can fit into the adapter. The hole size in the .stl is designed so that the panhead M2 screws that connect the adapter to the grip can thread their own hole as you screw them into the plastic.

Figure 13: Attaching the adapter to the grip.

Finally, place the device into the robot and use zip ties and velcro strap for strain relief.

Figure 14: Final assembly (1).

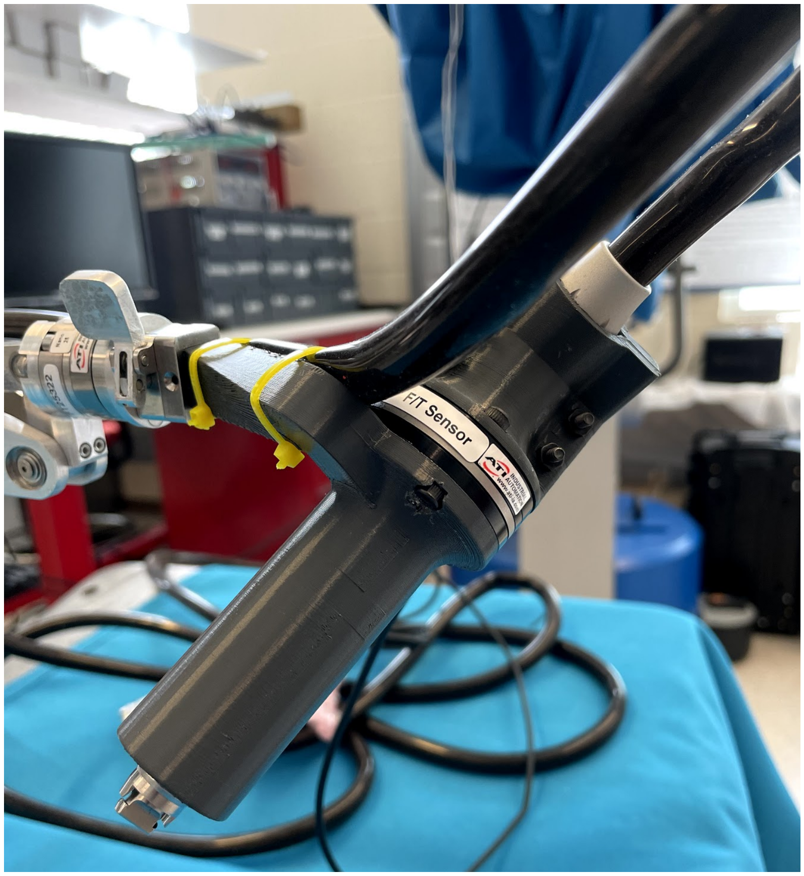
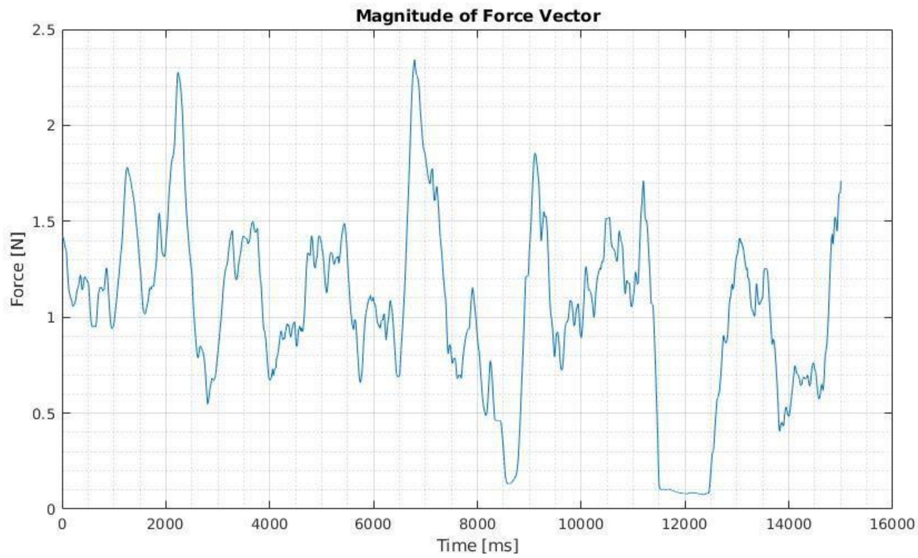
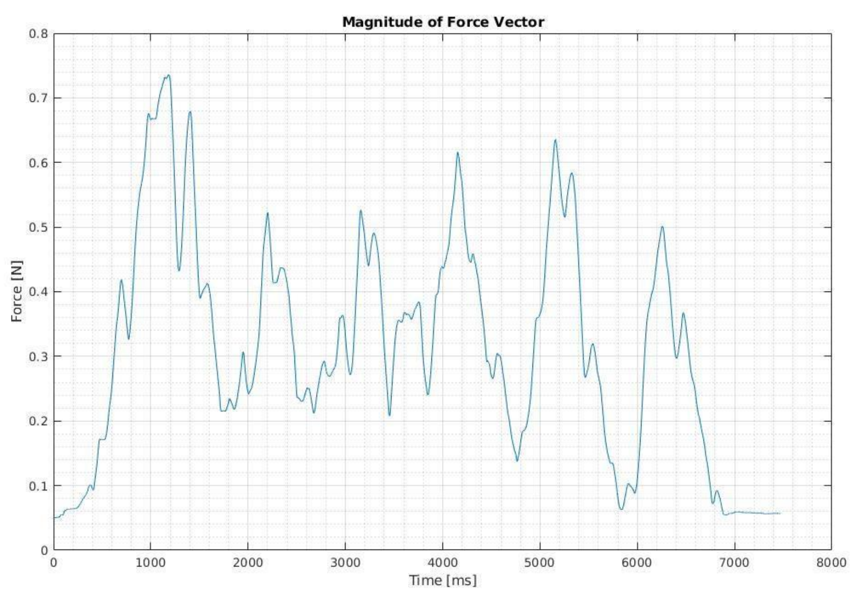


Figure 15: Final assembly (2).

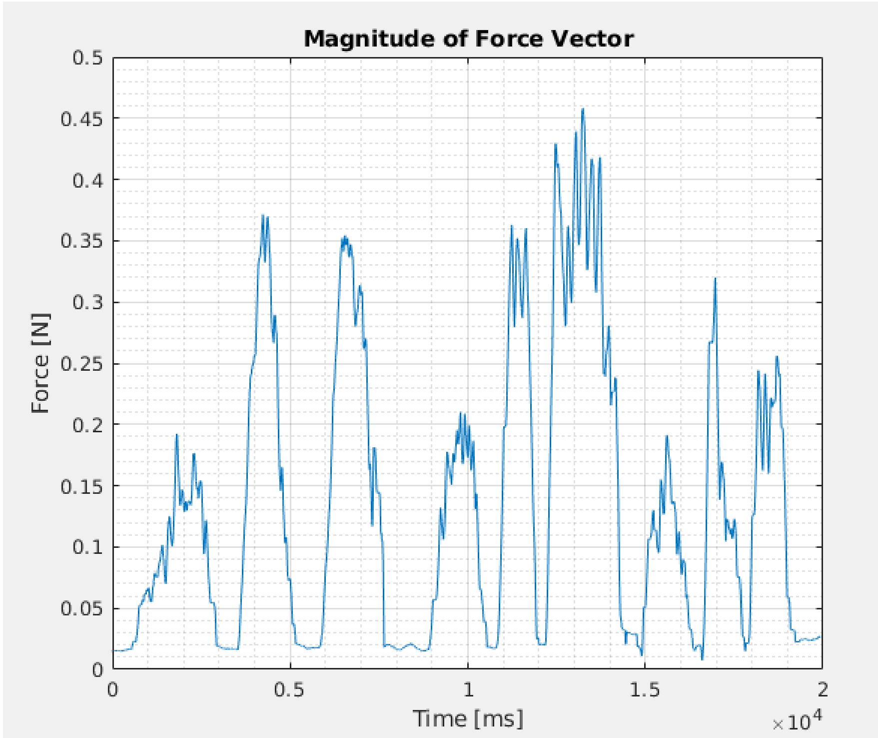
Drilling Experimental Data



Phantom Cordial Mastoidectomy: Aggressive Drilling



Phantom Cochlea: Sensitive Drilling



Egg Shell: Similar to Cochlea

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References

[1] T. B. C Gaudeni, GM Achilli, M Mandala, D Prattichizzo, “Instrumenting Hand-Held Surgical Drills with a Pneumatic Sensing Cover for Haptic Feedback,” Cham, 2020: Springer International Publishing, in Haptics: Science, Technology, Applications, pp. 398-406.

[2] R. M. H Sang, E Wilson, H Fooladi, D Preciado, K Cleary, “A New Surgical Drill Instrument With Force Sensing and Force Feedback for Robotically Assisted Otologic Surgery,” Journal of Medical Devices, vol. 11, September 2017.

[3] J. H. M Hessinger, PP Pott, R Werthschutzky “Handheld Surgical Drill With Integrated Thrust Force Recognition,” presented at the IEEE International Conference on E-Health and Bioengineering, Grigore T Papa University a/Medicine and Pharmacy, Iasi, Romania, November 21-23,2013, 2013.

[4] S. L. Y Guo, JB Mann, “Piezo-Actuated Modulation-Assisted Drilling System With Integrated Force Sensing,” Journal of Manufacturing Science and Engineering, vol. 139, January 2017 2017.

[5] R. L. D Schurzig, A Hyssong, T Rau, RJ Webster III, “Design of a Tool Integrating Force Sensing With Automated Insertion in Cochlear Implantation,” presented at the IEEE/ASME Transactions on Mechatronics, 2012.

[6] I. D. M Louredo, JJ Gil, “DRIBON: A mechatronic bone drilling tool,” Mechatronics, vol. 22, no. 8, pp. 1060-1066, 2012, doi: doi.org/10.1016/j.mechatronics.2012.09.001.

[7] L. W. PJ Berkelman, RH Taylor, P Jensen, “A Miniature Instrument Tip Force Sensor for Robot/Human Cooperative Microsurgical Manipulation with Enhanced Force Feedback,” presented at the IEEE Transactions on Robotics and Automation, October 2003, 2003.

[8] J. R. DL Rothbaum, D Stoianovici, P Berkelman, GD Hager, RH Taylor, LL Whitcomb, HW Francis, JK Niparko, “Robot-assisted stapedotomy: Micropick fenestration of the stapes footplate,” Otolaryngology– Head and Neck Surgery, vol. 127, 5, pp. 417-426, 2002.