Background Reading Report:
Building a Workflow for Cooperatively Controlled Robotic Mandibular Surgery

Group 15: Jesse Haworth

Mentors: Dr. Robin Yang, Dr. Francis Creighton, Dr. Russell Taylor, and Andy Ding

Project Summary:

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.

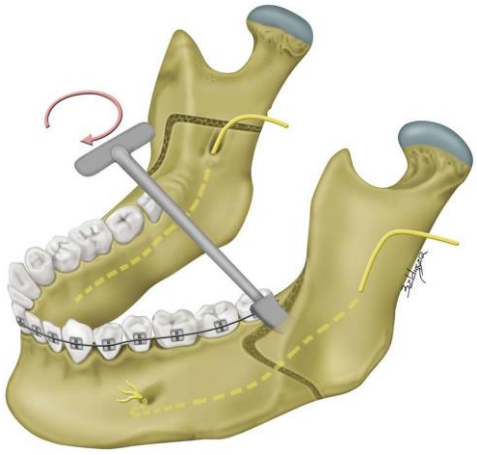

Figure 1. Sagittal cuts on either side of the mandible [2]

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.

Accuracy of haptic robotic guidance of dental implant surgery for completely edentulous arches – Scotty L. Bolding, DDS, MS, FACS, and Uday N. Reebye, MD, DMD – Published in The Journal of Prosthetic Dentistry in 2021 [4]

The first paper that we will review is a clinical study on the cooperative robot designed by Yomi to assist in accurate placement of dental implants (see figure 2). This paper was chosen because this system uses virtual guidance similar to what this project seeks to accomplish and is also meant to be used on the mandible.

Figure 2. Hand Over Hand Robot by YOMI [4]

Most dental implant procedures are done using manufactured physical guides that are designed ahead of the procedure based off patient CT data. Other methods include free-handing the procedure or using image guidance with the free-hand procedures being the least accurate. The physical guide has downsides such as obscuring the target area, requiring longer drill bits, and limited precision due to the hole in the guide needing to be larger than the drill bit. Image guidance requires the physician to look away from the patient to a display, and still relies heavily on the surgeon's coordination.

Yomi designed a system that will hold the drill along with the physician, allowing them to guide the drill placement while the robot reduces hand tumor and can restrict movement when necessary. A splint is screwed into the mandible (or maxilla) and fiducial markers are attached (see figure 3 below). Then the patient's head is scanned again with CBCT to register the relationship between the splint and the bone. Once registration is complete, the fiducials are unattached from the splint, and a secondary arm of the robot is attached in its place. This allows the robot to track the location of the bone without the need for an optical or EM tracking system even when the bone is moved.

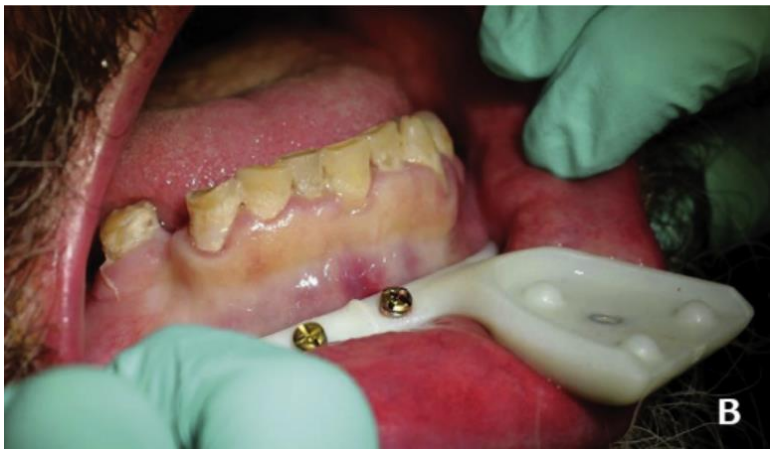

Figure 3. Splint is screwed into the mandible for registration and tracking [4].

The physician can then execute the procedure with the robot preventing them from accidentally deviating from the pre-planned placement for each implant. CT images were then taken after the procedure to compare the angulation and positioning of each implant relative to the original plan.

The results of this study were an average (± standard deviation) angular deviation of 2.56 ± 1.48 degrees, crown placement deviation of 1.04 ± 0.70 mm, apex placement deviation of 0.95 ± 0.73 mm, and an average depth deviation of 0.42 ± 0.46 mm with no adverse events reported. This is approximately on par with the accuracy of current guidance methods such as the physical guides that have been reported on previous studies. The authors argue that this demonstrates their system is safe for use and at least as effective as current solutions. It was also noted by the authors that the average deviations in the mandible were larger than those in the maxilla. This they attributed to the extra movement of the mandible along with the difference in bone density between the two.

My main criticism of this study is that no control was used to directly compare the results of this study. They did compare with the results of other studies, but this does not account for any difference in the patients, physician, or test setup. A future version of this study should include 2 randomly selected groups of patients with one group using robotic guidance and the other using a control such as the physical guide or image guidance. Additionally, a larger sample size than 5 should be used to statistically determine which method is more effective. Granted, the purpose of this paper seems to be to confirm the basic viability of their method, which it does quite well.

Additionally, the study does not go into much detail at all regarding the strategy or mechanisms behind enforcing the virtual guidance, setting up registration, or tracking the bone and tool. There are likely IP reasons behind this, but this does prevent anyone from repeating the study or learning which methods are effective.

For this project, there are a few main takeaways from this paper. First, the idea of using a hand over hand robot to guide a mandibular based procedure is achievable and can improve accuracy compared to free-handed procedures. It is also interesting to note that they used a tracking arm rather than an optical system to avoid any visibility issues with the tracking markers. The difference they discovered in accuracy between the maxilla and mandible indicate that there will be additional difficulties to overcome in improving accuracy of a mandible-based workflow.

Image-Guided Mastoidectomy with a Cooperatively Controlled ENT Microsurgery Robot – Christopher R. Razavi, MD, Paul R. Wilkening, MS, Rui Yin, Samuel R. Barber, MD, Russell H. Taylor, PhD, John P. Carey, MD, and Francis X. Creighton, MD – Published in the Official Journal of the American Academy of Otolaryngology-Head and Neck Surgery Foundation in 2019 [5]

This next paper is a benchtop feasibility study demonstrating cooperative robotic control during a mastoidectomy. It was selected because it utilizes the same Galen system that will be used for this project and demonstrates the system's ability to enforce virtual barriers while cutting bone.

The mastoidectomy is an extremely difficult and time-consuming procedure due to the many critical anatomies that must not be accidentally damaged while drilling. Bone cutting procedures lend themselves well to robotic implementation because of the rigid nature of the tissue. This study is designed to test the basic feasibility of using a cooperative robot to prevent a user from cutting into designated critical areas within bone.

The Galen robot (see figure 4 below) is a 5 DOF system where the user can drive the movement of the end effector by pushing on the attached tool. This allows the machine to filter out any hand tremors, limit the speed of tool motion, and prevent tool movement.

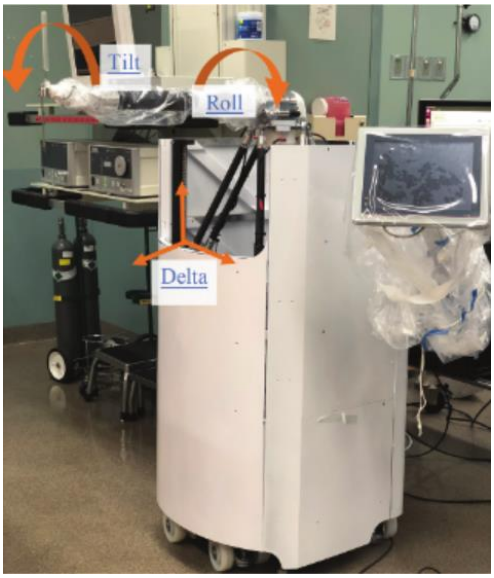

Figure 4. Hand Over Hand Robot System by Galen Robotics [5]

3D Slicer was used to create a pyramid representing the desired cut area on the segmented CT model of the mastoid. By touching 3 points on the physical mastoid phantom, the robot was able to register the desired cut zone to the phantom. An untrained user was then told to cut away the bone without instruction as to where the virtual boundaries were. This was repeated on 5 different phantoms with the results being confirmed by a neurologist who was not present during the drilling. A sample of the results is show in figure 5 below.

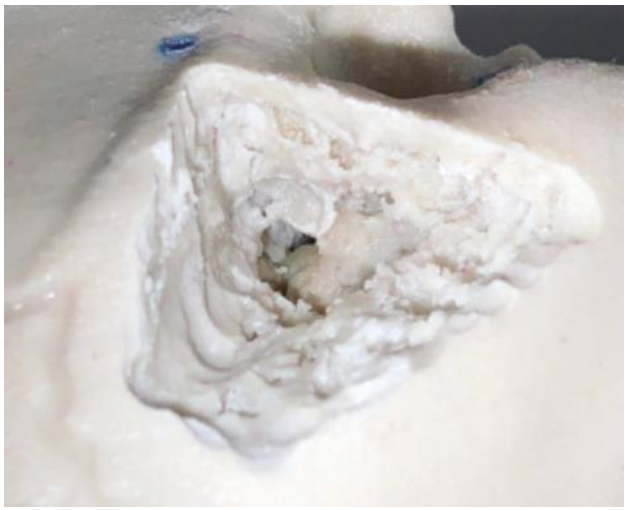

Figure 5. Cut Results When Using Virtual Barriers [5].

All 5 phantoms were successfully drilled within the designated zone with an average completion time of 221 seconds. This is drastically shorter than the corresponding time for a similar procedure on a fully autonomous robot.

One of the weaknesses of this study was that they did not use a direct control to contrast the effectiveness of the system. This could have been a physician performing a specified cut with and without the robot, or by comparing the untrained user using the robot to the physician without the robot. Additionally, the pass-fail metric does not give much detail in quantifying the effectiveness of the methodology. Using CT data to compare the plan to the execution would have allowed calculation of a statistical description for the system's accuracy. Using a larger sample of users and phantom trial would also help to determine the effectiveness of the approach. Like the previous paper, this paper does successfully communicate the feasibility of such a system and encourages further research of the system which could undergo more stringent testing.

The registration appeared to only use a 3-point touch on the model. While acceptable for a feasibility study, this allows much room for error and is not representative of how registration would be done in a clinical system. Using an optical or EM tracking system would have allowed the robot to be able to continue to function even if the bone is moved slightly. Also similar to the previous paper, besides mentioning the used of 3D Slicer, no detail was given as to the technical approach or strategy of enforcing the virtual barriers, which makes it difficult to replicate the studies' results.

This study shows that the Galen robot is capable of enforcing a virtual barrier while performing a cut in bone. In regard to our project, this demonstrates the Galen is a good system to use in our application. The registration approach here, while sufficient for a feasibility study, will need to be changed for our project to be geared towards a clinical application. The paper also shows how a virtual barrier/virtual guidance system removes some of the technical difficulty of an osteotomy procedure given that an untrained subject was used to execute the cut. Implementation of such a system in a mandibular osteotomy could then reduce the dependency of good outcomes on the physician, increasing the quality of care for all who use the system.

Conclusions

Both papers help to demonstrate the feasibility of the kind of solution this project aims to build. The Yomi study demonstrates the robot guidance in a mandibular based procedure and the Mastoidectomy paper demonstrates the use of the Galen robot in performing an osteotomy. The examples given of different registration strategies, tracking strategies, and result measurement approaches will be helpful in designing our system and determining how to calculate its effectiveness. This is a solid base for this project to build on in developing a cooperative robotic system for mandibular osteotomy.

References:

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