Mikaela Miranda
Faculty Mentor: Dr Ga Young Kelly Suh
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Cochlear Implantation Computational Modeling: Patient Specific Path Planning for Electrode Insertion

Introduction

Cochlear implantation enables auditory perception in individuals with profound hearing loss by delivering electrical stimulation directly to the auditory nerve, effectively bypassing damaged anatomy and cells within the inner ear that contribute to hearing loss. This targeted nerve stimulation allows the brain to interpret sound signals as if they were natural sounds, leading to improved speech understanding and communication. Despite its clinical success, cochlear implantation remains associated with risks due to anatomical variability and the potential for internal trauma during electrode insertion. Even slight deviations in electrode trajectory can lead to scalar translocation, a complication that occurs when the electrode array deviates from the intended path within the scala tympani and instead shifts into another chamber of the cochlea, such as the scala vestibuli. When the electrode is placed in the incorrect part of the inner ear, hearing performance is significantly and often irreversibly reduced. These placement errors can result in complications such as pain, poor frequency mapping, and long-term damage to delicate cochlear structures.

Background and Significance

However, current surgical techniques are often guided by standardized anatomical landmarks, limiting the ability to tailor electrode insertion to each individual's specific anatomy. Given these risks there is a critical need for personalized surgical planning tools that will accurately reflect each patient's unique anatomy. As noted by Noble et al., who found that "patient specific planning reduced scalar translocation rates from 42% to just 7%" (Noble et al., 2017). By combining MRI imaging and 3D modeling, the creation of patient specific computational path planning becomes a possible and necessary advancement that can significantly improve surgical outcomes for cochlear implantation patients. This proposal aims to develop a computational path planning algorithm that integrates patient imaging data and simulates electrode insertion paths. By identifying the least traumatic and most effective trajectories for each individual, this approach has the potential to significantly reduce surgical risks and improve surgical outcomes for cochlear implantation patients.

Preliminary Work

To date, I have successfully simulated the insertion of a life sized cochlear implant electrode into a pipe shaped 3D model representing the temporal bone. This served as an early test to validate the insertion process. Concurrently, I have created detailed 3D models of the inner and outer ear using MRI scans that I personally segmented. These models will be used in both computational simulations and physical prototypes for future testing. My workflow includes ITK-SNAP for segmentation, Blender and SolidWorks for anatomical refinement, and MATLAB for visualizing and analyzing electrode paths.

In addition, I have refined a Python script capable of processing patient specific segmentations of the temporal bone. The script reads STL models derived from MRI data and interfaces with MATLAB to generate visualizations of the most optimized centerline path for electrode insertion. While the pipeline is currently functional, I am working to improve its adaptability across different cochlear implant devices and STL formats. These advancements have established a strong foundation for the continued development of a patient specific path planning framework.

Proposed Work

Building on this groundwork, I plan to further develop a path planning algorithm that uses patient-specific imaging data to simulate cochlear implant electrode insertion. Using high-resolution MRI and 3D modeling, I will create detailed representations of the cochlea and nearby structures. These models will be exported as STL files and used in simulations. A custom Python script, built with Trimesh, NumPy, and Matplotlib, will process the models, while MATLAB will be used to display and analyze the insertion paths.

The simulation program is designed to model insertion through three key anatomical segments: the temporal bone, the cochlea, and the scala tympani. This allows the system to account for anatomical variation that can affect the safety and accuracy of electrode insertion. The simulations will show how the electrode moves through the cochlear spiral at different angles and along different routes. Each path will be evaluated based on factors such as insertion depth, curvature, force, and proximity to sensitive structures like the basilar membrane and scala vestibuli. The goal is to determine the path that minimizes trauma while ensuring effective cochlear coverage. This approach builds on the work of Vonck et al., who “successfully predicted optimal electrode insertion trajectories in 94% of cases” (Vonck et al., 2019). The workflow uses tools such as ITK SNAP and 3D Slicer, in combination with custom simulation scripts, to transition from medical imaging to surgical planning.

Conclusion

This project aims to address the critical need for safer, more precise cochlear implant surgeries by developing a computational tool that accounts for patient-specific anatomy. By combining medical imaging, 3D modeling, and simulation, the proposed framework has the potential to reduce surgical risks and improve hearing outcomes. The next phase will focus on validating the simulation outputs against physical models and refining the algorithm for broader anatomical use. Ultimately, this work can contribute to the development of personalized surgical planning tools that improve both clinical accuracy and patient quality of life.

References

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