# Rehabilitative Haptic Stimulation Device for Sensorimotor Impairment

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## Abstract

With ever increasing numbers of stroke victims, improvements in treatment options for those physically impaired by stroke is dire. Most efforts so far utilize physical rehabilitation as a general technique for recovery. This project aims to simplify these strategies by utilizing the effects of neuroplasticity to help restore function. To do this, we have built an adaptable device for providing vibrational stimulation to regions of an impaired hand. This tool can be used alongside a variety of cortex stimulation methods, including our lab's optogenetic setup used in animal stroke models. We anticipate that through this solution and method, we can demonstrate significant progress in recovering motor function, with the hope that this technology can be translated into meaningful advances for stroke patients.

## Introduction

Broadly, stroke is a medical condition where blood supply is lost to a particular area of the brain [1]. This can happen when a blood vessel becomes occluded by a clot or plaque, which is known as ischemic stroke, or it can occur if a vessel bursts resulting in bleeding, which is known as hemorrhagic stroke. Ischemic strokes account for around 85% of all strokes, although they are easier to treat and less life threatening than hemorrhagic strokes [2]. Ischemic stroke is treated via blood thinning agents to restore proper flow, while hemorrhagic stroke can involve invasive surgery [1]. Regardless of lethality, both variations are likely to result in brain tissue damage, which can severely impact bodily functions.

When a stroke occurs, the loss of blood supply often results in cell death nearby. Additionally, in the case of hemorrhagic stroke, pressure can be exerted on the brain due to bleeding, complicating the issue. Due to the death of neuronal cells, individuals who suffer a stroke will often have impaired neurological function. Oftentimes, this results in some sort of physical disability, which can vary in severity. Following initial treatment of acute symptoms, efforts can be made to help individuals recover from this lack of mobility.

Rehabilitation for stroke is commonly undertaken soon after a patient initially recovers. Most forms of rehabilitation focus on improving physical movement, through various mobility and strength exercises. While this method is highly customizable for different patients, it can take anywhere from several months to a couple years, and full recovery is not guaranteed [3]. Only 10% of stroke survivors recover almost completely, and just 25% recover with minor loss of function. On its own, stroke is incredibly harmful to those it affects. However, perhaps the greatest danger of stroke is just how common it is.

In the United States alone, nearly 800,000 people suffer from stroke each year, about 75% of which are first time incidents [1]. 66% of stroke patients are over the age of 64, and more than half of these survivors suffer from loss of mobility. This means that around 250,000 people annually are being impaired by the effects of stroke. The damage this induces to individual quality of life alone is massive, but it also results in high costs for the families of patients, insurance providers, and the government. Annual rehabilitation costs approximately $11,000, attributing to about 70% of outpatient service costs [4]. Additionally, medications, losses in productivity, and hospital fees cost the United States $34 billion annually [1]. Not only do stroke victims suffer from lifelong sensorimotor impairment, but they also face high costs for rehabilitation techniques that may not work. Because of this, there is a strong need for new and improved options of treatment for stroke patients.

This capstone project aims to explore and create a more efficient method for sensory rehabilitation following stroke. In general, stroke rehabilitation strategies have been fairly stagnant over the years, showing little change from traditional physical therapy. However, there are a number of solutions being developed by research groups around the country. Understanding how these techniques build upon current practices is important to properly define the scope of our study.

Over the years, researchers have made numerous attempts to find novel solutions to treating the underlying neurological issues around stroke. Some studies, such as the one conducted by Wathen et al. used deep brain stimulation (DBS), a method where a neurostimulator and electrode lead are implanted to send regular pulses to deep brain structures, to promote the stroke recovery process in humans [5]. However, while techniques such as DBS have been shown to improve motor function in stroke patients, the mechanism for improved physical ability is still not well known. Despite this, the scientific community has continued to investigate a variety of related methods aimed at recovering loss of function in the limbs, and has attempted to delve further into the mechanisms responsible for these changes.

A similar technique that has been examined several times for rehabilitation use is repetitive transcranial magnetic stimulation (rTMS). This non-invasive tool involves using magnetic coils to induce current in large regions of the brain. Du et al. found that rTMS stimulation in post-stroke patients increased motor ability and caused reorganization in the motor cortex [6]. Liu also found similar improvements in a review of articles that examined rTMS as a therapeutic tool [7]. Learning more about the variety of methods available for motor rehabilitation will hopefully improve our understanding of how and why the brain can recover function from both precise and imprecise stimulation methods.

An alternative to DBS is the non-invasive stimulation method of transcranial direct current stimulation (tDCS) in which current is applied directly to the exterior of the head via electrodes. A handful of studies have utilized tDCS as a treatment for the effects of stroke, by pairing it with physical rehabilitation. One such study by Danzi et al. found that a novel locomotion training method was more successful in patients who were receiving tDCS treatments prior to training than those who did not receive the treatments [8]. A related study by Lindenberg et al. revealed similar results, finding that improved activation of motor regions and enhanced motor function was seen in patients who received tDCS and physical therapy when compared to those who had a sham treatment [9]. Both of these studies illustrate how brain stimulation paired with

physical rehabilitation can bolster traditional stroke recovery techniques. However, research has also been conducted to investigate the role of peripheral nerve stimulation in rehabilitation.

Transcutaneous electrical nerve stimulation (TENS) is a system that consists of an external stimulator and patch electrodes, where electrical pulses are sent through the skin to nearby nerves lying below the surface. This strategy has been shown in several instances to have a short-term effect on stabilizing motor control when applied to limbs affected by a stroke. Studies have shown TENS improves strength in upper limbs and can even be designed into a compact device for mobile usage [10, 11]. TENS has also been paired with physical rehabilitation, and research has shown improvements in lower limb strength and function from this approach [12]. The use of TENS is somewhat limited however, as it can cause rapid muscle fatigue. This is due to the way that electrical stimulation activates motor neurons. Because of this, TENS is not a particularly promising long-term solution for physical impairment.

Developments have also been made to increase sensorimotor recovery through new types of physical therapy. Constraint induced movement therapy (CIMT), where use of an impaired limb is forced through the constraint of working limbs, has been investigated in two studies in rodent models. This method of therapy has seen use in humans, especially in children with impaired upper limb movement. Liu et al. looked at the expression of protein biomarkers indicative of synapse numbers and activation and found that CIMT after stroke resulted in increased motor cortex activation in both hemispheres as well as increased reorganization in the contralesional hemisphere [13]. Nesin et al. found increased synapsing in the ipsilateral hemisphere, along with general pruning across both sides of the brain [14]. Overall, CIMT shows promise as a possible treatment for physical impairment following stroke with research showing possible mechanisms for the method.

Other studies have also found some interesting attributes of neuroplasticity during recovery from stroke. Sun et al. published a review article, hypothesizing that neuroplasticity increases in response to neural damage in order to promote healing and regain of motor function [15]. Similarly, Lim et al. found that while motor performance is decreased in stroke patients, a higher activation of the affected region in the brain is seen [16]. They theorize this may be due to decreased efficiency, though increased activation may also indicate or cause plasticity to increase. Having a basic understanding of the theories around plasticity is important to gain perspective on how my project will fit into the existing landscape of research.

This project builds off of the work conducted by many of these researchers. Our work theorizes that, using principles of neuroplasticity, we can construct a device to assist with passively rehabilitating sensory function in individuals who have suffered a stroke. To do this, we will be using non-human primate (NHP) stroke models who have impaired hand function. Stimulation will be applied to the cortical surface in a healthy brain region not impacted by stroke, while the impaired limb will also receive sensory stimulation. With this, we believe that the stimulated region of the cortex will begin to take over sensory function in the hand, allowing for partial sensorimotor recovery. The focus of this capstone project is specifically to construct a device capable of delivering stimulation to the sensory neurons within the hand.

Several works done within the Yazdan Lab will also be essential for the testing of this device alongside a neural stimulation setup. Specifically, our lab has been working on developing an improved, large scale optogenetic stimulation system for use in NHPs. This setup will play a significant role in this capstone project, as it will be necessary for use and testing. Additionally, proving efficacy of this method in NHP stroke models will be needed to pave the way for potential future use in human patients. In general, proper integration of this design into existing protocols will be needed to conduct an analysis of both this capstone work and further experiments on plasticity and stroke.

## Development of Design Specifications

The design of this project relies on several main components, each of which can be broken down into subcomponents. The primary aims can be summarized as design/prototyping of the physical device, testing with the full system, and experimental work. Each aim includes its own various design specifications, which can be outlined in detail.

The first goal is to construct and optimize a device capable of delivering stimuli to the hand of an NHP using appropriate methods. This broad goal essentially defines the basis of my project, with completion providing the successful creation of a device meeting this need. Within this goal, there are several specific aims to achieve. First, the device has to provide a form of stimulation suitable for NHP experimentation and future translation into human testing. This means that a safe, non-noxious stimulation method will be used in order to satisfy the condition that this device may be used as in a rehabilitative setting. Secondly, the device should be manufactured in such a way that it is easily customizable and reproducible. This is necessary for adapting to different users, who may have varying hand dimensions or require stimulation in different regions of the hand. Thirdly, the material, design, and construction must be done with

NHP testing in mind. This means that all of the components must be robust, and the whole setup needs to be sturdy. Because NHPs are strong and can be unpredictable, precautions need to be taken to prevent harm to the animals and others, and to avoid damaging equipment. Finally, the design also must have a control mechanism, which can be adapted for use with different types of neural stimulation setups (i.e., optogenetic vs. ECoG). This final step will ensure that the device can properly function not only during NHP testing, but also with other systems that it may be used with in the future.

Following the creation of the physical device, there is still a requirement to test its efficacy with cortical stimulation. This will require the design to use a versatile technique for controlling and coordinating tactile stimulation with cortical stimulation. This overarching idea can be divided into a handful of smaller tasks. Firstly, an electronic control scheme will need to be created, which will allow for the tactile stimulation to be altered via different input signals. With this, it will be necessary to establish a flexible way to change these inputs through software programs. It may be beneficial to create a UI for precise control, although this is not necessary. Finally, the device should fit with most possible setups, as flexibility will be key for successful testing and future use. At minimum, the optogenetic setup that is used in our lab will need to be able to interface with the chosen method of control. Overall, laying down a framework for flexible control will be a necessary function for reproducibility and experimentation.

The third and final goal for my design is focused on scientific methodology. That is, developing a series of experiments that can properly quantify the effects of my device when paired with cortical stimulation. This aspect of the project is not an individual challenge, as it will involve several other projects being worked on in our lab. As such, protocols are being developed that utilize all of these works. However, ensuring that this device is constructed to work effectively with the chosen procedures is a must. Additionally, data analysis and further testing in different configurations may become necessary steps, if initial results prove to be interesting or meaningful. This would require additional experimental design steps that can only be determined upon successful completion of this project.

With the general constraints on my project in mind, there are several other important considerations to make. When handling experimentation with any project, there are certain ethical and societal aspects that need to be remembered. For example, my project utilizes animal stroke models, specifically NHPs. The use of NHPs, while common, is still controversial ethically, and protocols used in research are under high scrutiny.

Similarly, any engineered devices used in animal research must be shown to be within ethical/scientific reason. Researching pain pathways in animals may constitute for painful stimuli to be used, but in my project and others, this would be unacceptable. With this in mind, my device will have to adhere to the specific protocols approved by several bodies that oversee the ethical treatment of animal subjects.

Overall, for this project to find success, any uncertainties with safety and efficacy must be addressed. Unbiased and high confidence data collection will be necessary to find meaningful results that could lead to future related research or clinical studies. If this were to be accomplished, additional work will have to be done to account for social, cultural, and economic differences around the globe, in order to improve access to rehabilitative efforts.

Concerning general health, safety, and welfare is important to consider with any device intended for rehabilitation techniques. Specifically, my device needs to have proper safety regulations to constrain the intensity and types of stimulation used. While my design should not have too many safety issues, different types of brain stimulation used alongside my device are more concerning. Generally, my device would not be implemented in individuals without an already implanted electrode array on the cortex, such as some patients receiving treatment for epilepsy. More importantly, animal ethics should be taken into serious consideration, as this is where most of the testing of my device will be taking place. Adhering to animal research guidelines established by the Institutional Animal Care and Use Committee (IACUC) will be essential to ethically design and test my project. These rules are strictly enforced by the Washington National Primate Research Center (WaNPRC), where my research will be conducted. However, attention also needs to be given to ethics regarding use in humans especially, societal, cultural, and economic factors.

While my device is intended to assist populations who have suffered motor impairments from stroke, there are several challenges before this can be done. Both cultural and social problems can impact who has access to rehabilitation devices. Generally, there are not many instances of implantable recovery devices being used in populations outside the majority of the population in the United States. This may make implementing a device difficult in settings that have not had exposure to these kinds of invasive techniques. Similarly, reception to brain implants may not be entirely positive. Until these devices are better understood, challenges will continue to arise with this. Perhaps the most difficult hurdle to overcome is the economic burden of these devices. Rehabilitation strategies for any medical issue are notoriously expensive, resulting in low resource communities having low access to new therapies. Providing new

technologies for medical intervention is exciting but understanding the inequalities that may influence the effectiveness of technology is essential to prevent further disparity in society. Within this project, minimizing the cost of the device could help maximizing accessibility. However, much of the financial burden of a neural stimulation therapy would undoubtedly come from the devices used to stimulate the brain itself. Regardless, minimizing cost of the device would be most ideal for researchers and potential end users down the road.

| Design Specification | Metric | Quantitative Value |
|---|---|---|
| Durable | **STURDY*** | Device cannot be taken apart without tools |
| | **NHP PROOF** | Withstand dropping force at 5m |
| Safe | **NON-NOXIOUS STIMULATION*** | Non-invasive, no painful stimuli |
| | **SHOCK PROOF** | Voltages < 20V, Currents < 10mA |
| Ease of Operation | **COMPATIBILITY*** | Uses own system to communicate with cortical stim setups |
| | **SETUP TIME** | <5 min for wiring and implementation into system |
| | **USABILITY*** | Minimal coding/programming experience required |
| Accessible | **COST** | Final design <$150 to produce |
| Customizable | **DESIGN PROCESS** | < 1 day to produce new design for different users |
| | **MATERIAL** | < 1 week to manufacture altered design |

*Table 1. List of design specifications to be used for this project, with values given for each metric. Note that starred metrics have qualitative rather than quantitative expectations.*

## Materials and Methods

The materials and methods used are focused on the design of this device rather than its implementation in experimentation, which will be done in the future. These steps include scanning, CAD modeling, printing, assembly, as well as circuit design and creation.

Several steps were needed to construct the physical device. First, a handprint was obtained to create a mold that will serve as the area to place and secure the hand. This was done using Crayola air drying clay. When doing this step with NHPs, it was

important that the clay is placed in a sterile bag following creation of the imprint so as to not spread any contaminants. Additionally, the handprint was obtained carefully and safely from an NHP during routine surgery, where the animal was anesthetized. Next, the print had to be implemented into a 3D CAD model. This was done through the use of 3D scanning, which creates a mesh of the scanned surface that could then be manipulated digitally. For this step, a handheld Sense 3D Scanner, provided by 3D Systems, was used. Scanning was done by following the procedures laid out by the manufacturer, although only the top of the clay handprint needed to be scanned. This scan was then imported into Meshmixer software, where a CAD model was created using previously determined measurements and designs. The model was then printed using Hatchbox PLA 3D filament on a Dremel 3D45 3D printer. Additionally, a cover for the print was created to secure the hand in place. This was done by creating a hollow box with one open side with appropriate dimensions to be mounted on top of the printed hand piece. Soft foam was created using a FlexFoam-iT! III kit provided by Smooth-On, which was then placed inside the cover, creating a gentle backing to prevent discomfort.

The next pieces added were vibrational actuators and dampening material. These serve to stimulate the fingertips of the NHP subject, and dampen vibration of individual actuators, preventing interference from noise and unintended vibration. Vibrational actuators were inserted below each finger and supported by struts beneath. Dampening pads are then secured around each motor, between the struts and the handprint base. With these steps finished, the assembly was completed for the handprint base, but electrical components and physical connection to our neural stimulation setup were still needed.

For electrical control of each vibrational motor, an Arduino Uno was used. The exact circuit and breadboard diagrams can be seen in Figures 6 and 7, respectively. With this circuit, a Grapevine Nomad provided by Ripple Neuro is connected to two analog input pins on the Arduino. One input is used to select the motor to run, while the other controls the voltage and intensity of the motor. MATLAB code is used to run the Nomad, and the programmed Arduino is set to respond appropriately to the inputs it receives. The Arduino is necessary to provide the required current and voltage to the vibration actuators, as the Nomad is unable to provide enough power alone. However, through altering the voltage supply, control will still be possible through this original system, allowing for analog adjustments for each motor.

Finally, the handprint base and circuitry can be implemented into our larger rig where an NHP subject sits. This can be done by placing all of the components in a metal shell

that interfaces with the rig using aluminum bars provided by 80/20. The completed device can then be appropriately placed and used in our full rig and neural stimulation setup.

After manufacturing of the full device is completed, work will have to be done to plan testing methods for the system. Following this, experimentation with the entire system can commence. Experimental design will be completed after the whole system is ready for testing.

## Results

While we have yet to test the efficacy of our device, there are a number of important results from the prototyping phase of this project. The process first began with creating a design for the handprint base of the device. The first design was done using a human handprint rather than one from an NHP. In accordance with the aforementioned methods, a handprint was pressed into clay and then scanned using a 3D scanner. The original handprint is shown in Figure 1. This first scan was used to create the CAD model shown in Figure 2. The mode consists of a solid box, with hollow columns underneath each finger. These columns provide space for the vibrational motors to sit, without touching the rest of the model. The box has a small lip on the bottom, to provide room for all necessary circuitry. A dampening pad is attached below this, where struts are inserted to support each motor. These struts are far apart, preventing any possible interference between motors.

*Figure 1. Clay imprint of human hand. This piece was air dried for several days before being scanned and used in the modeling software.*

*Figure 2. The CAD model of the human prototype. Thin metal struts were used to support each motor, as shown in the right image (motors can also be seen on the left at the tip of each finger). The black edge around the base of the prototype consists of a dampening pad, where the metal supports attach.*

This first design was then manufactured and tested. The final print can be seen in Figure 3 below. It was found that attaching the small metal struts to the motors and edges of the dampening pad proved difficult. With this, the design was revised, and an NHP handprint was used in the next prototype.

*Figure 3. The 3D printed human handprint. Due to the size of the model, two separate pieces had to be printed in order to avoid warping. This is evident by the seam near the middle of the hand. Some warping can still occur, as seen in the bottom right corner of the print, although this did not significantly impact the device.*

The obtained NHP handprint was uploaded and edited into a similar design, though with a few different features. First, the size of the design was much smaller than before, because the NHP hand is around half the size of a human hand. Next, to fix the issue of

the struts, the design was altered to include the struts as 3D printed material. They were also widened, allowing for better support of the motors. The finalized design can be seen in Figure 4, with the print in Figure 5. Despite the attempts taken to fix struts, it was found that the printed material could not withstand much force at the joint of the strut and the box, causing the material to break off easily. Additionally, dampening would have to be changed in this design to be at the base of each motor, rather than at the ends of the struts. With these edits in mind, we have been able to develop a final design that we hope to prototype soon.

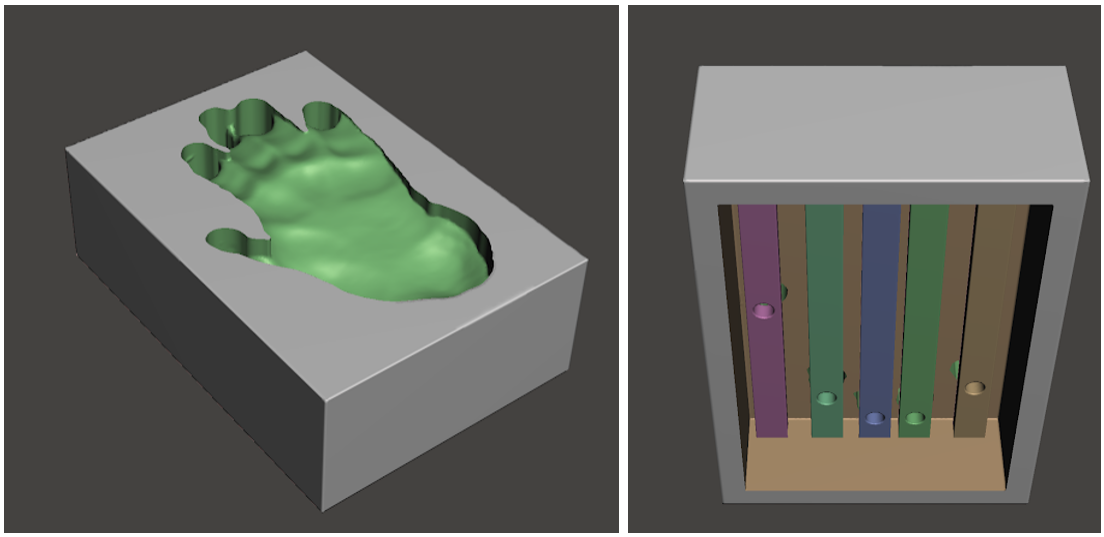

*Figure 4. The CAD model of the first NHP prototype. Note that the metal struts have now been replaced by 3D printed struts that attach to either side of the model. The vibration motors now rest inside the holes in the struts, with epoxy used to firmly set them in place.*

*Figure 5. The first 3D printed NHP prototype. Due to the much smaller size of the NHP handprint, the 3D model does not need to be printed in two separate pieces. Warping is much less of an issue in this design.*

The finalized design of the handprint base is shown in Figure 6. This piece does not incorporate the same designs as before, as it instead relies on several other machined parts for motor placement and stability. Two “wings” are included on the sides of the model, allowing for bolts to be used to secure this portion of the device lower down. Figure 7 shows how the complete design fits together, with each part shown in a different color. The handprint base can be seen in magenta, the dampening pads in teal, a single metal support for the motors in purple, and a metal casing in gray. Each of these components are secured together using bolts, with the exception of the dampening pads, which will use adhesive to attach to the metal support. The cover for this design is not shown. This piece consists of a hollow box with two missing sides. This allows space for the hand and wrist. The cover is 3D printed separately from the handprint base and can be attached using zip ties or Velcro. Inside, the cover is filled with a soft, flexible foam that secures the hand without excessive pressure or discomfort. In general, this design is more modular and flexible than previous configurations. The inclusion of multiple parts allows for increased flexibility in using different hands or subjects, which is important for the end goal of this project. 3D pieces will need to be customized to various hand shapes and sizes, but motors, dampening pads, and the metal shell can all be reused. This design also has more room underneath, allowing for the circuitry to have additional space for wiring.

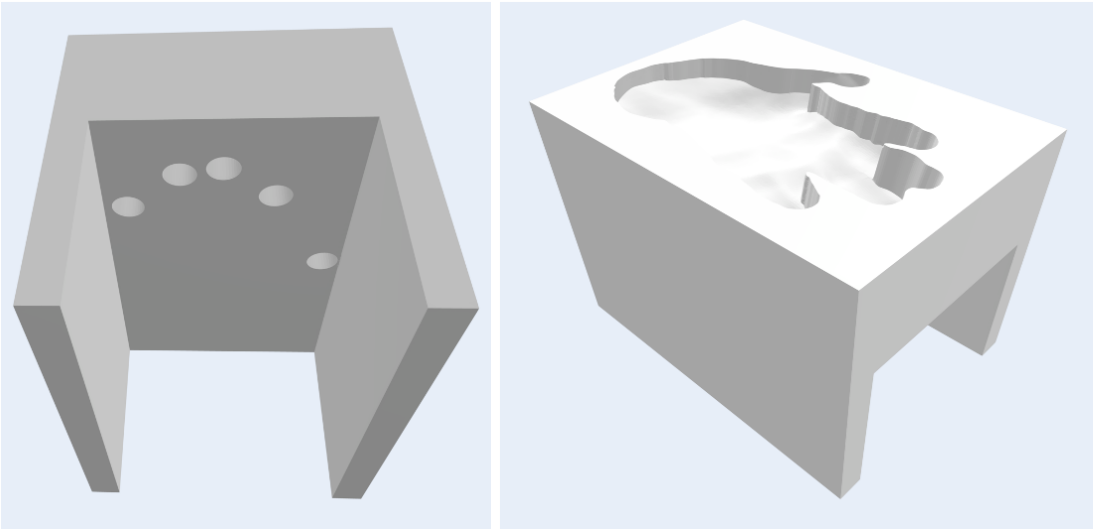

*Figure 6. The final design for the handprint base. Note that the struts have been fully removed in this model, and that 3D printed “wings” are now included. These fit with the full device as depicted in Figure 9.*

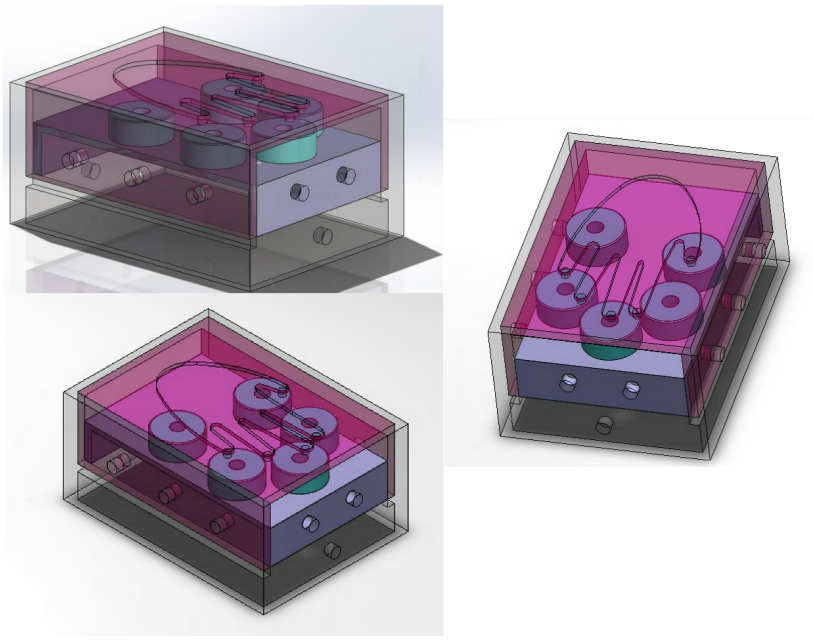

*Figure 7. The finalized physical device. The 3D printed handprint base shown in Figure 8 is shown here in magenta. Teal dampening pads are set underneath the base, with space for vibrational motors (not shown). The pads and motors rest atop a metal support that is machined to provide a via for the wiring. The whole structure is then encased in a 4-sided metal box (top and bottom open), with bolts to hold pieces in place. CAD design and images provided courtesy of Maryam Bahadori.*

With the physical device finalized, circuitry was the next important aspect to consider. Initially, there was some debate on what kind of actuator to use for stimulation. Both linear and vibrational actuators were considered, but ultimately vibrational motors were found to be the smallest and quietest. However, the power requirement of these motors was greater than what the Grapevine Nomad was capable of outputting. This resulted in a need to have a secondary power source for the motors, while still allowing them to be driven by the Nomad. Thus, an Arduino Uno was implemented to output the necessary power to each motor in response to inputs received by the Nomad. The finalized circuit diagram is shown in Figure 8, with a simplified image shown in Figure 9. While the attachments to the Grapevine Nomad are not shown, two analog inputs on the Arduino are used to take in stimulation information. This allows for control of motor selection and motor intensity. Each motor is also a part of a voltage divider circuit, which appropriately adjusts the output of the Arduino to be in the desired range of operation. The Arduino is programmed to automatically interpret varying inputs and output the desired signal to each motor. The control of the stimulation will still be done through MATLAB and the Nomad, but the Arduino acts as a power source for each motor.

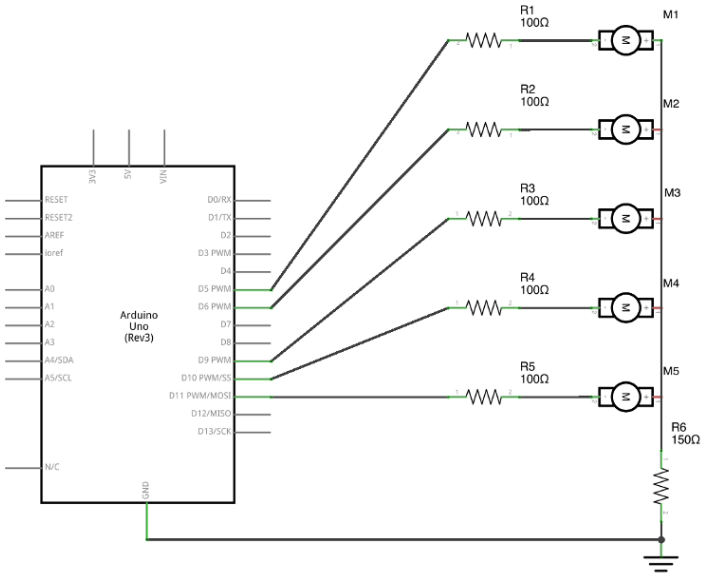


*Figure 8. The diagram for the finished circuit. Each motor is part of a voltage divider circuit that reduces the effective output voltage from a range of 0-5V to a range of 0-3V. Note that the Grapevine Nomad (not shown) would attach to two analog inputs on the left side of the Arduino.*

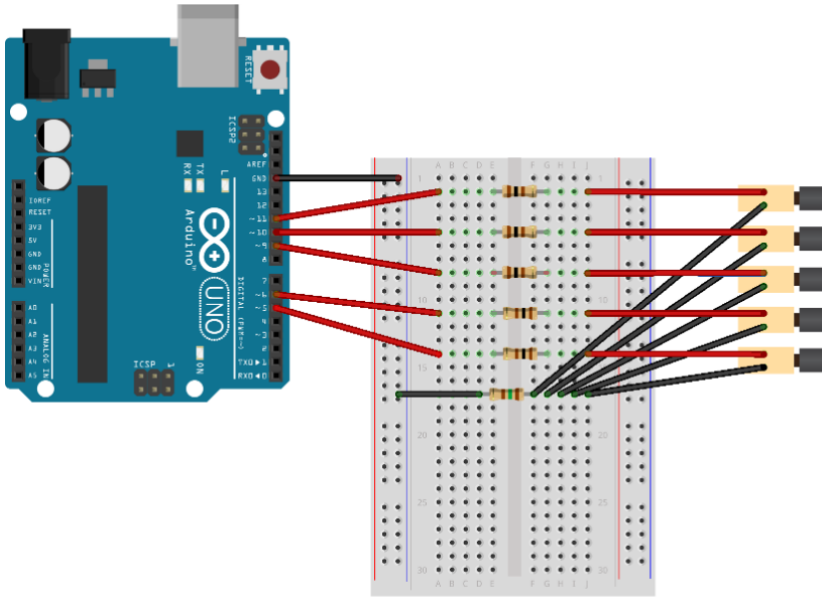

*Figure 9. A simplified diagram, showing how the finished circuit would appear using breadboard connections. The vibrational motors are shown on the far right, with the Arduino on the far left. The Grapevine Nomad (not shown) would be attached to two analog inputs on the lower left side of the Arduino board.*

## Discussion

With the circuitry and physical device designs completed, this device now needs to be manufactured and tested. Unfortunately, the current situation with COVID-19 has made it difficult to finish this entire process, pushing back our timeline. We hope to make any

small, final revisions to the design soon, followed by manufacturing and implementation when the needed resources become available. Additionally, steps are being taken to interface this device with the physical rig for NHP testing. This ongoing work is not depicted here, but it utilizes T-slot aluminum bars and plates to connect with the current system. Following completion of these steps, testing of device controls can be done to ensure that the electronic design functions properly with our established stimulation setup.

Throughout the process of making this device, significant consideration has been made to translation of this technique into human models. While testing will be done using optogenetic stimulation, this methodology has not yet been used in humans. As such, this device will have to work with accepted neural stimulation techniques. In the near future, we hope to test this device with collaborators in humans who have previously implanted ECoG arrays. This will require approval of the device and stimulation procedures, though we anticipate that this should be plausible. Many of these individuals suffer from intractable epilepsy, meaning that they suffer from seizures that traditional medication and treatment cannot assist with. Consideration will need to be given to these patients and this condition, but we hope that our device will be able to demonstrate some level of induced neural plasticity.

Following testing in NHPs and/or humans, success of our device would have several implications. By now, neural plasticity is already a widely accepted phenomenon that shows great potential to be implemented into rehabilitative medicine. While our work will be investigating the ability to rehabilitate neural lesions, a similar principle could be applied to a variety of neurological disorders that degrade brain tissue. As such, proving the use of this device would not only be beneficial for developing a novel stroke recovery strategy, but it may help inspire new methods of treatment for other diseases as well.

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