Haptic Interface for Sensorimotor Retraining Study

Project 14

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Table of Contents

Abstract

Disorders such as focal hand dystonia is an acquired disorder in which an individual cannot distinguish sensory stimulation or control individual fingers. The brain of individuals with this disorder tends to recognize the fingers as one unit. The goal of our project is to create a device that will help to retrain these individuals. Use of our device should encourage neural re-organization in cortical centers by retraining the patient to perceive with and use each finger separately. We are designing a device that will produce vibrotactile stimulation in individual fingers and register a user response. The device will be interfaced with a computer that can alter the sequence and challenge level of stimulation to create engaging, rewarding tasks and therapies.

Executive Summary

Our project is focused on retraining individuals with hand disorders such as focal hand dystonia. Experimental testing already done on this disorder shows that patients can be retrained through repetitive, fine motor practice of the fingers. This can be accomplished through a device that provides individual stimulation of the fingers followed by a response by the user. There exist devices for tactile stimulation, and our goal is to create something that will be cheap and effective for retraining.

There are several requirements that have been specified by the customer such as low cost, portability, and robustness. We have given highest priority to the product being cheap yet effective. We have related all of the customer requirements to the engineering specifications in a QFD chart. Based on these relations, we were able to rank each specification in order of importance.

We have created a detailed project timeline to aid in keeping our project on schedule. A few important dates in the timeline include the selection of the final design, completion of the prototype, and the design expo. The first few weeks of designing our product will involve rapid prototyping. This approach will allow us to test multiple designs, while fine tuning the mechanisms we hope to employ in our product. Our goal is to have a functional prototype ready two weeks before the design expo. This will give us time to test our prototype and fix any malfunctions. The total budget for this project is $400. The main costs of the project include rapid prototyping materials and final prototype materials.

Through brainstorming, we have created numerous ideas of what our project could look like. We have created a FAST diagram, Morphological chart, and a Pugh chart to help aid in our brainstorming. We combined our ideas into five concepts, and then chose the two most functional designs. One of these is a glove with motors on it to create vibrations at specific points on the fingers. The other design is four separate finger holders that vibrate independently.

The purposes of this report are to present research already done for the project, outline the customer requirements and the engineering specifications, provide a detailed project plan and timeline, and provide the direction in which the project is headed.

1. Introduction

The primary sponsor for our project is Dr. Michael Merzenich, UCSF Center for Integrative Neuroscience and Posit Science Corp. Dr. Merzenich's research over the past three decades has been primarily concerned with brain plasticity. He is also a founder of Posit Science Corp which provides computer-based exercises to keep the brain fit during the aging process. His research has been an integral part of our early design process. The primary contact for our project is Professor Brent Gillespie, University of Michigan.

Focal hand dystonia is a "neurological movement disorder characterized by involuntary muscle contractions, which force the body into abnormal, sometimes painful, movements or postures" [3]. Research specifically shows that patients with focal hand dystonia cannot distinguish between separate sensory stimulation of individual fingers, and contraction of one finger will cause all four fingers to contract. This disorder is caused by repetitive, near simultaneous, finger movements that lead to de-differentiation of finger representation in the brain [5]. The disorder is frequently seen in musicians, specifically string players whose instrument requires them to hold their hand in a curled position. Individuals that don't have the disorder have specific separate regions in the brain that control movements of each finger. Individuals with focal hand dystonia experience a merging of the separate control regions into one large region, which causes a loss of finger specific somatosensory sensation [6].

The goal of the project is to design a device that provides sensorimotor retraining for individuals that have dystonia. From our research we have learned that due to the neural plasticity of the brain it is possible to re-differentiate the merged finger control section of the brain into individual subsections. Our device will provide programmable, computer controlled stimulation to the patient's fingers. The patient will then have to respond to the stimulation by clicking a button. We have researched the possibility of varying the frequency, amplitude, interval, and duration of the vibrations to provide the user with a challenging and rewarding experience.

The prototype we are planning to build will operate under electronic control of the vibratory stimulation, with the possibility of interfacing the device with a computer. The final product will have a computer program which will be capable of varying the vibrational stimulation and increasing the difficulty as the patient improves. There will be four separate input buttons, one for each of the patient's fingers. The buttons will operate similar to a mouse clicker, which when pressed will provide the necessary input to the device.

Our goal is for individuals with focal hand dystonia to have a cheap and convenient way to retrain their sensorimotor capabilities. The device should be comfortable, providing a relaxed interface for the hand and it should also be robust enough to endure constant use. Through use of our device, we want patients to be able to completely re-distinguish control and sensation of the fingers in the brain, thus regaining individual control of their fingers. Our product will be marketed to physical therapists that treat focal hand dystonia and similar disorders. Our device will provide an affordable and effective way for therapists to retrain patients and expedite the healing process.

2. Information Search

2.1. Research of methods and experiments

Since our project is focused on focal hand dystonia, it was necessary for us to learn more about this disorder as well as current treatments and retraining techniques. We also looked into similar devices that have been used in research as well as retraining devices for other diseases.

Our research started with the website of PositScience, our current sponsor [1]. This gave us an idea of what products PositScience has already produced as well as what direction we should go with our product. Next, we researched focal dystonia to obtain a knowledge base regarding the disorder. We found a few useful articles including an article by Blumenfeld [2] and information from the Dystonia Foundation website [3] which summarized basic symptoms and causes. From these articles we learned about the causes and symptoms of focal hand dystonia. With this general background in focal dystonia we focused on specific research in this field

Our sponsor, Dr. Michael Merzenich, has done extensive research on how the brain reacts to focal dystonia, as well as research on retraining methods using humans and animals. In order to learn more about the disease, as well as similar diseases, and the research that has been done our group split up thirteen articles given to us by our primary contact, Professor Gillespie.

A group of these articles discussed focal hand dystonia in more depth. Spengler et al. [4], Byl [5], Mckenzie [6], and Merzenich [7] all discussed the responses to simple tests of the hands of healthy subjects and the hands of subjects with focal dystonia. From these tests they determined that the parts of the brain from which the individual fingers were controlled started to overlap in a person with focal dystonia. Also, they observed that the subjects with focal dystonia showed some recovery of their motor skills in response to retraining. Buonomano [8], Wright [9], and Dobkin [10] focused on the functions of the brain in patients with focal dystonia or similar diseases. Plasticity of the brain was discussed and that the brain can be retrained to do certain tasks. In Merzenich [11], Wang [12], and Xerri [13] animal research was presented. Parts of the animal's brains were lesioned or "rewired" to simulate certain diseases. The animals all started showing a recovery of these skills after being retained by methods involving repetition and rewards. We then researched current methods for treating this disorder.

Research was done on different methods of retraining people who have focal dystonia, as well as similar diseases which cause the loss of use of a part of the body. Volpe [14] discussed the idea of using robotics to aid in recovering stroke victims, their research showed that it can be a useful training technique. Altenmuller [15] focused more on musicians who had focal dystonia and had retrained themselves using a splint to restrain working fingers and force the fingers affected by focal dystonia to complete the tasks. Reference [16] by Byl contained a presentation on retraining people who had focal dystonia. The presentation explained methods for retraining including retrieving small items from a well and using Braille cards to play games. After learning about these retraining methods we researched some existing devices similar to our potential prototype.

We first looked into vibrotacticle devices currently in production. The Engineering Acoustic's C-1 and C-2 tactors [18] are used by pilots, scuba divers, and astronauts. These small vibrotactile devices can be sewn into clothing or seats and will alert the individual by a vibrotactile stimulation instead of (or along with) visual or audio cues. Similar to these were the R-1 Rototactor [19] and the R-2 Rototactor [20], these were smaller and the information about their vibration characteristics was given. This information, given in the form of a graph was very useful for us to estimate the vibrational characteristics we will use for our prototype. Using some of this information we formulated our own graph of the potential characteristics on our prototype, Figure 1. The table accompanying the graph, Table 1, displays how different characteristics of an eccentric motor and an electric toothbrush relate, and which characteristics we can independently control.

Figure 1: Graph of Motor Characteristics

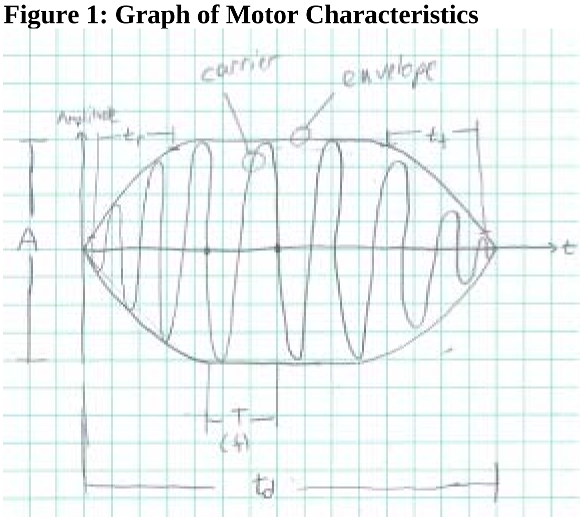


Table 1: Relation of Characteristics

	Eccentric Motor	Elecric Toothbrush
We can Control	F_0	F_0, A
Function of F_0	t_r, t_f, A, t_d	t_r, t_f, t_d

A = Peak to peak amplitude of carrier/amplitude of envelope
T = Period of Carrier
F_0 = 1/T frequency of carrier
t_r = Rise time 10% to 90% A
t_f = Fall time 90% to 10% A
td = Time duration of envelope

2.2. Test to quantify duration between stimuli

We determined an important fact to know is how well a person without focal hand dystonia can distinguish between stimulations of separate fingers. Specifically, we wanted to know how the interval between stimulations influences the user response. Along with the help of Professor Gillespie, we devised a ramp and ball experiment in an attempt to quantify the time interval. The ramp had two slots near the bottom where the user would feel stimulation from the rolling ball.

Initially we created a device out of aluminum rods and clay as seen in Figure 2. After running the test on three subjects, we did not find any conclusive results, and we determined that the test was most likely flawed due to the bounce of the ball when it went from the slanted ramp to the flat ramp where the fingers were located. The length of time between stimuli varied from 22.3 to 31.9 milliseconds. There were four different durations of time between impulses corresponding to four different heights from where the ball was released.

Figure 2: Initial test setup for determining perception of stimuli

We decided that a new test setup would provide more accurate results. Upon the suggestion of Professor Gillespie, we used a rubber tube with holes cut in it to create our second test setup. This new setup allowed for the ball to be dropped from either end with relative ease, it can be seen in Figure 3. We had people stand on both ends of the tube and then one of them dropped a marble through the tube. As soon as the stimulus was felt, the subject removed his or her hand to prevent them from determining which side the ball was dropped when the ball re-crosses the subject's fingers.

Figure 3: Second setup to test perception of stimuli

We ran the test at 5 different times between stimuli, varying from 20.1 to 26.5 milliseconds with 3 iterations at each speed and 4 test subjects. The times between stimuli were calculated using the mass of the ball and the height from which it was dropped. The times were constrained by the length of the tube. We determined that even at the fastest duration of 20.1 milliseconds, it was possible to tell in 3 out of 4 subjects which finger was stimulated first. It was noted for the other three subjects that it was becoming much harder to tell which finger was stimulated first. Although our test did not allow the ball to be dropped from greater heights, we can begin to predict that this duration of 20.1 milliseconds is approaching the limit of perception for people without focal hand dystonia.

There is no concrete data to report for our experiment other than the fact that 3 of the 4 subjects correctly identified every time which finger was stimulated first and the fourth subject was only incorrect on the fastest trial.

2.3. Mechanoreceptors of the hand

There are a total of 17,000 tactile units in the skin area of the area. These tactile units play an important role in determining the relation between impulse discharge and perceptive experience. There are 4 different types of tactile units in the hand: two fast-adapting, FAI and FAII, and two slow-adapting, SAI and SAII. Through experimentation it was found that there is a non-linear relationship between the intensity of the stimulus and the perceived intensity in the brain. This indicates that the central nervous system performs non-linear transformations on the stimulus. Thus, a lighter stimulus may be perceived as a stronger stimulus after being transformed in the central nervous system. Vallbo [24]

The four types of mechanoreceptors are each specialized to detect vibratory stimulations originating from different frequencies. The FA receptors respond best to stimuli that provide ramp and off skin indentation, which involves turning up the frequency and removing the stimulus. SA receptors, on the other hand, respond better to ramp and hold stimuli, which involve turning up the frequency and holding it on the skin. Through experimentation, it was determined that FAI units are most sensitive to vibratory stimuli at 30-40 Hz, FAII units have sensitivity at 60-100 Hz, and both SA units respond at frequencies less than 15 Hz. However, both FA and SA units are sensitive to vibratory stimuli. In general, the Type I units could detect small and well defined receptive fields, while the SA units can detect large receptive fields with remote stimuli. It is believed that the optimal condition during active touch for texture discrimination is at frequencies between 10 and 80 Hz. Since FAI units are active at 30-40 Hz, these receptors seem specialized for texture discrimination. On the other hand, because SAI units are highly sensitive at low frequencies (less than 15 Hz), it is believed they are specialized for automatic regulation of touch pressure. Toma [23] Since the goal of our project is more oriented toward touch regulation and not texture discrimination, we it would be ideal to stimulate the SAI receptors. Thus, ideally we will try to provide a stimulus that operates at a frequency of 15 Hz. If this is not possible, however, vibratory stimulation can still be detected at other frequencies. Therefore, we will run the motors at a frequency that provides the most efficient power response.

The density of tactile units in specific regions of the hand also is a factor in determining the necessary threshold stimulus needed for sensation. Specifically, the relationship is that there is a higher threshold for sensation in the palm where there is a lower density of tactile units. However, there is a higher density of tactile units in the fingers, corresponding to a lower threshold for stimulation. Thus, it is important for our device to provide stimulation in the fingers where sensitivity is the highest, and not in the palm where sensitivity is lower.

3. User Definition

We determined that there are three users for our device: Dr. Michael Merzenich, physical therapists, and people with focal hand dystonia.

The first user, Dr. Michael Merzenich, is our project sponsor. He wants to market this device to physical therapists that have patients with focal hand dystonia. He has done research about what tests need to be performed, and how tests will run using our device.

The second user is a physical therapist with patients who have focal hand dystonia. The physical therapist is the user who will determine if this product is a useful tool. If the physical therapist does not see a use for this, then they will not attempt to use it with, or sell it to their patients.

The third user is the patient with focal hand dystonia. This user is very important for us to consider when designing the device. Since the dystonia patient is the person who will actually be using the device, then they have certain things that they will deem more important. Comfort and ease of use will be especially important to this user.

4. Customer Requirements and Engineering Specifications

The customer requirements for our project were loosely defined. The primary requirement is that the device can retrain a user with focal hand dystonia. The important characteristics that we have determined with our customer are that the device is cheap, portable, robust, and that it can eventually be interfaced with a computer. It needs to be easy to use and control, comfortable, and have the ability to be both rewarding and challenging.

It was emphasized to us that keeping the cost of the device at a minimum is an important factor. The device is to be marketed to physical therapists to aid in retraining patients. They will not be interested if the product is too expensive. Keeping the device portable enough to be used at a desk was also emphasized. After doing our research, we determined that making the device comfortable for the user is also something that our customer wants. Since tension in the hand one of the causes of dystonia, it would be counterproductive if the device caused extra tension in the arm.

Table 2: Customer requirements and engineering specifications in order of importance (high to low)

Customer Requirements	Engineering Specifications
Retrains User	Vibratory Stimulation
Cheap	Isolation of Vibrations
Portable	User Response
Robust	Materials
Easy to use / control	Duration of Vibration
Comfortable	Ability for Computer Interface
Challenging	Shape
Rewarding	Amplitude, Frequency and Interval of Vibrations
	Electrical Requirements

We decided to make a QFD diagram in order to rank the customer requirements, and to relate the relevance of our engineering specifications to these customer requirements. The QFD can be seen in Appendix A, while Table 2 shows the customer requirements from most to least important and the engineering specifications from most to least important as determined from our QFD analysis.

4.1. Vibration characteristics

It was made clear to us by Professor Gillespie that in order to stimulate the fingers, and retrain the user, small tactile vibrations are desired. There are two main aspects of the vibrations that are important. The most important is isolating the vibrations between the fingers. The second is controlling the vibration. We determined that there are four things that are potentially important to control: the duration, amplitude, frequency, and the interval between the vibrations. This can be seen from our research as shown in Figure 1 on Page 3.

4.1.1. Isolation of vibrations

In order to run a beneficial test, each finger needs to be stimulated separately. To accomplish this, we will need to be sure that there is an isolation of the vibration between each finger. The test will not be effective if two adjacent fingers are feeling the same vibration. The idea of the test is to stimulate two different fingers, at different times, and then have the user respond with which finger was stimulated first. If two fingers were being stimulated at the same time, then even a user without dystonia would not be able to distinguish the stimulations. For example, if one were to place a vibrating cell phone next to another cell phone that wasn't vibrating, it would be almost impossible to determine which cell phone was actually vibrating. This is due to the fact that the vibrations are transmitted through the contact point of the two phones.

4.1.2. Characteristics to control

The most important characteristic to control on our device is the duration of the vibration. In order to make the test challenging for users at different stages, there needs to be less of a detectable difference between stimuli. Closely related to this, and second most important is the interval between vibrations. These two characteristics allow for a simple change of the test to make it more or less challenging for users in different stages of retraining. The amplitude and frequency can also be important to control. They can make the finger feel more or less of a vibration when it is stimulated. This also keeps the challenge level of the test appropriate for the user at the stage of retraining that they are in. Although these are both important to control, it is also important to keep the cost down. If it is too expensive to include these functions of the vibration in our design, then they may be deemed unnecessary.

4.2. User response

In order to run the test, there needs to be a way for the user to respond as to which finger was stimulated. This response should be a simple motion without much movement, such as a mouse click. It should allow for an immediate response when the fingers are stimulated. This feedback allows a computer program to acknowledge that the patient is making progress on the test that is being performed in terms of how long it took, and whether the user was correct.

4.3. Materials

The materials of the device affect the cost, robustness, and comfort of the device. In terms of robustness, we need something that can be used for numerous cycles without failing. At the same time, we do not want to over-design it to the point that we use unnecessary, costly parts. Since we are only creating small motion in the parts, we must determine where the largest forces are, and the magnitude of the forces. We will then choose the cheapest design and materials that can withstand the forces without failure.

4.4. Ability for computer interface

The ability for computer interface allows the device to be easy to use and control, and it is what will allow for the test to be the most challenging and rewarding. Our prototype does not necessarily have to be connected to a computer, but it needs to have the vibrations controlled electronically, and have the response monitored electronically. This will provide the ability to interface our product with a computer.

4.5. Shape

The shape of our device is important for meeting several of our customer requirements. Mainly it affects the comfort and the portability of the device. In terms of comfort, we need to have support for the entire hand and allow the hand to fit naturally on the device. If the fingers have to stretch to get to the correct place, or if there is extra tension in the wrist or arm, the device could be ineffective and harmful. In order for the device to be portable, we need to make sure that it can easily be put on a desk, since the device will be used in conjunction with a computer. This means trying to restrict the size of the device to something that is about the size of a mouse pad. The shape also affects the cost of the device. Choosing a smaller shape with less material may create a more effective final design.

5. Concept Selection

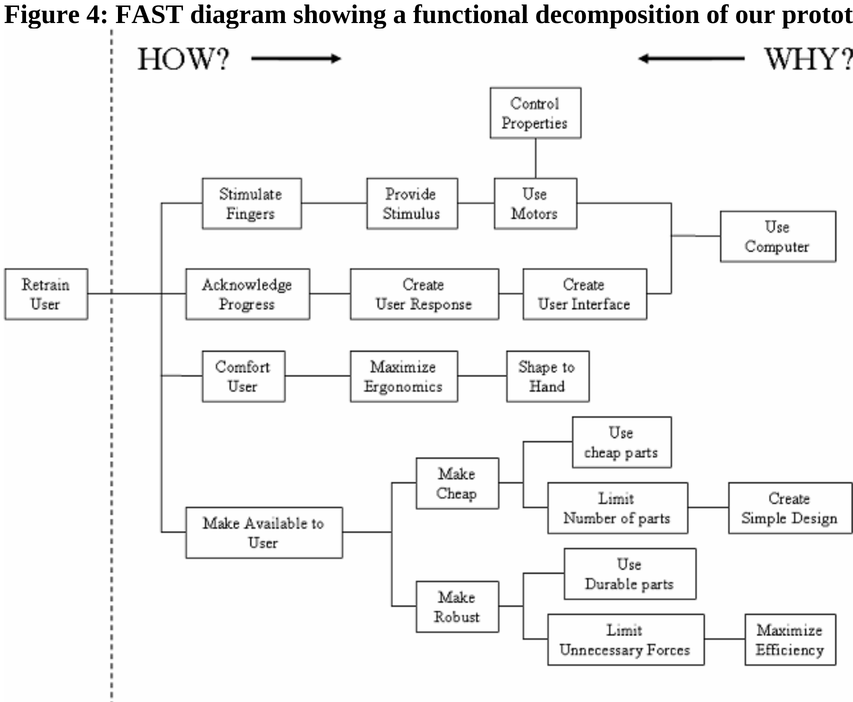
5.1. Concept generation

In order to generate our concept, we organized our functions and requirements using a FAST diagram and a Morphological chart. The FAST diagram shows how the functions of our prototype relate to each other by relating how a function is performed and a why the function is performed. The morphological chart shows the different design concepts for each function of the device. We generated concepts through brainstorming functions, and how the functions could be met. Thereafter, we categorized the concepts and began to narrow down the list.

5.1.1. FAST Diagram

The basic and most important function of our project is to retrain a person with focal hand dystonia. In order to do that, we determined four necessary functions of the device: stimulating the fingers, acknowledging progress, encouraging the user, and making the product available to the user. From these basic functions, we proceeded to determine how each function could be performed. We were broad in defining the functions so that we did not eliminate any ideas based on our initial concept ideas. Instead of characterizing a function as being a vibrating motor with an eccentric mass, we characterized the function as being a stimulus. The goal in creating the FAST diagram was to define all of the functions of our device to retrain the user, and to determine what our design areas are. The complete FAST diagram can be seen in Figure 4, below.

Figure 4: FAST diagram showing a functional decomposition of our prototype

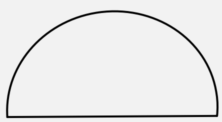
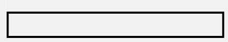
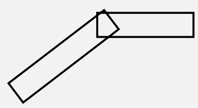
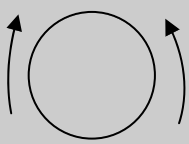
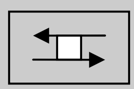
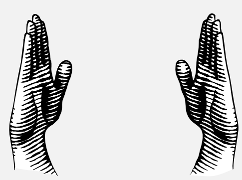


Although there are four functions that stem from the basic goal of retraining the user, we determined that there are three main areas of our design that impact the overall function. These areas are the type of stimulus, the user response mechanism, and the shape of the product. The final area that we had on the FAST diagram was to make the product available to the user. This is important, but we did not want to limit our brainstorming efforts with trying to be cost-effective and only creating designs that had cheap materials. We decided that this area served as a tool to help narrow down our choices, instead of fostering new ideas.

5.1.2. Morphological Chart

After creating a FAST diagram, we created a Morphological chart, which can be seen below in Figure 5. We decided to categorize the functions as the three main areas that we determined with the FAST diagram. We used the shape, the type of stimulation, and the type of user response. In each of these we had several different ideas of how the function could be performed. Since each function is somewhat uncorrelated to the other functions, we decided that this was the best method to represent our ideas. Instead of constricting ourselves to a specific shape, or a specific stimulus, we were able to expand our ideas for the primary functions of the device.

Figure 5: Morphological chart showing functions and design concepts

Function	Concept 1	Concept 2	Concept 3	Concept 4
Shape	Dome 	Flat 	Slanted 	Form Fitting 
Type of Stimulation	Vibration 	Rotational Direct Contact 	Linear Direct Contact 	Air 
Type of User Response	Mouse Click 	Button 	Other Hand 	

5.1.3. Classifying Design Concepts

After creating the FAST diagram, and the Morphological Chart, we started to combine our ideas and develop rapid prototypes. We sat down in brainstorming sessions after having come up with our own ideas and sketches. After sharing the idea, we then built off of the concept to create another concept and continued to find new ways that the concept might work. After brainstorming in this fashion, we came up with five categories of ideas. The figures for the concepts are shown in the next section. This is a brief overview of the five categories.

One category fell along the idea of having bendable parts that vibrated, much like a mouse button with a motor attached underneath. There are two versions of this concept. One version has a slanted shell, and one has a flat shell. The second category was one that had direct contact as a stimulus, with separate buttons for the user response. There are also two concepts in this category. One idea is to have buttons that move up and down, and the other is to have rotating brushes that move back and forth to create a stimulus. The third category contained ideas that used some form of motor on a track to create the stimulus. One design was a flat track, and the second was a rotating motor that created a stimulus. The stimulus would either occur as a part of the movement of the button on the track, or occur after the track was in place. The fourth category had the motors attached to the hand. This was in the form of something that rested on the table, or something be worn as a glove. The final category of ideas had compressed air as the stimulus. The air would pass through a valve in order to stimulate the fingers in different places. Concept Evaluation and Selection

5.2. Concept Evaluation and Selection

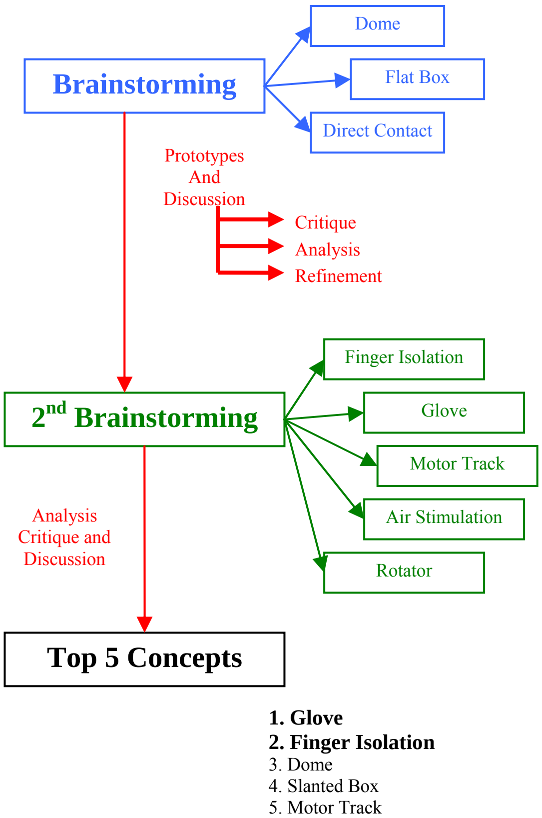
5.2.1. Concept Evaluation Criteria

To evaluate the concepts we generated during brainstorming, we have determined a set list of criteria that we would like the final design to meet. The most important criteria are that it is cheap to produce, it is portable, and it is robust. It needs to be cheap so that it can be manufactured at a low cost and so that it is widely accessible to people who need to use it. It also needs to be portable and robust so the user can use the device at home, and it will last a long time. We also want the device to be easy to use and comfortable for the user. This device needs to be something that the user enjoys using so that he can effectively and efficiently retrain himself. For the device to work at its full potential there needs to be isolation of vibration stimulation between the different fingers. A vibration in one finger should not be felt in another finger, or it will ruin the test. We also would like the device to be easy to manufacture. This will keep the price of the device low, thus making it accessible to a wide range of operation. Also, if it is easy to manufacture, there will be less of a chance of a device being made that is faulty.

5.2.2. Brainstorming flow chart

The brainstorming flow chart can be seen in Figure 6 below. It diagrams how we had an initial brainstorming session from which we generated 3 design ideas, we then analyzed and refined these ideas, then we held a second brainstorming session where we generated 5 new ideas, and finally we narrowed down to our top 5 design ideas. This method of having two brainstorming sessions allowed us to integrate good ideas from our initial session into our new designs. We were also able to eliminate the bad aspects of our original ideas to create more functional designs.

Figure 6: Brainstorming flow chart



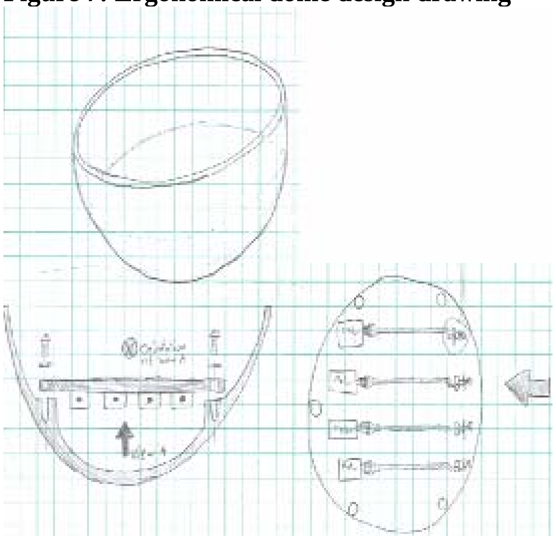
5.2.3. First brainstorming concepts

After our initial brainstorming period, we had three basic designs that explored the visceral, behavioral, and reflective levels of the design process. Each design was unique in that one was a dome shape, one was a flat box, and one involved direct tactile stimulation of the fingers. The next step was to make drawings and prototypes of each design to better understand the pros and cons of each idea.

5.2.3.1. Ergonomical dome shape design

The dome shape appealed to the ergonomical and aesthetical sides of our design. This design was generated mainly to provide a comfortable position for the user's hand, while also being pleasing to the user's eye. We created drawings for this design, and decided to produce vibrotactile stimulation through a plastic button, and the user would respond by clicking on a button that was separate from the stimulation. We also created a rapid prototype using a rubber ball and cardboard. The prototype revealed that the design was comfortable for the user, but it was not easy to produce. We decided it would be very difficult to create a dome shape using the manufacturing techniques we have at our disposal and there would be difficulty connecting the vibration motors to the dome. Although, if the device were to be mass produced, manufacturing would be easier as it could be made by molding. Also, this design only provided one point of stimulation on the fingers, but one of our goals is to have multiple stimulation points. A drawing of the dome design can be seen in Figure 7 below.

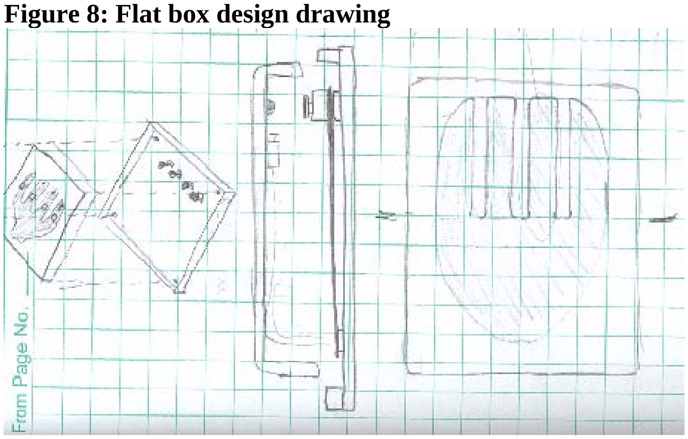
Figure 7: Ergonomical dome design drawing



5.2.3.2. Flat box design

The flat box design was made to satisfy the manufacturing side of our design. This design would be easy to produce, but it would not be ergonomical for the user's hand. The stimulation would be generated by an eccentric motor and felt through a thin piece of plastic, the user would then respond by clicking down the same button. The outside shell of this design could be easily removed to expose all of the components if the device were to malfunction. This design would not be comfortable for the user, however, in that it would force the user to place their hand flat on the top of the box. We decided the hand naturally prefers a curved position as when using a mouse. To improve this design, we incorporated the ergonomics of the dome shape by placing the fingers on a slant from the palm. A slanted design would provide a more comfortable position for the user's hand, but it would not be as difficult to manufacture as the dome. A drawing of the flat box design can be seen in Figure 8 below.

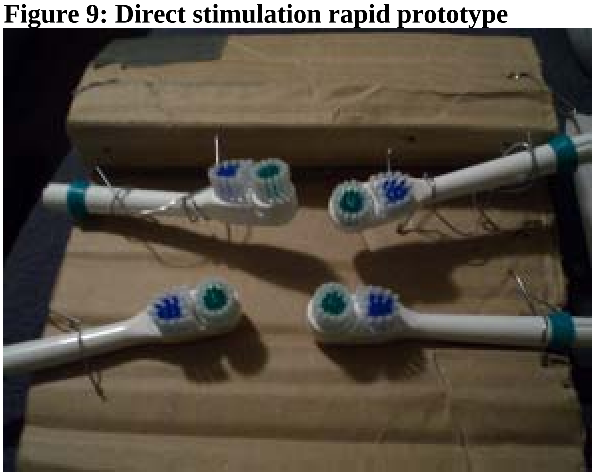
Figure 8: Flat box design drawing



5.2.3.3. Direct vibrotactile stimulation design

The direct tactile stimulation design was created to be functional and easy to use. This design, shown below in Figure 9 involved having two discrete vibrotactile stimulation points for each finger. There would be no plastic cover separating the vibration motor from the fingers. The stimulus would be created by brushes moving back and forth controlled by a scotch yoke mechanism. This design would ensure separation of vibrations for each finger. The buttons for the user response would also be separate from the stimulation. We created a rapid prototype for this design using cardboard, toothbrush heads, and paper clips. The prototype showed us that the design effectively separated the vibrotactile stimulations, and it was ergonomical for the user. We decided, however, that this design would be hard to manufacture, costly to produce, and not robust. There were a number of small pieces, such as the scotch yoke mechanism, which could easily break when being used. The number of small pieces also added to the cost in manufacturing of the design.

Figure 9: Direct stimulation rapid prototype



5.2.4. Second brainstorming concepts

After creating these three designs, we analyzed the pros and cons of each, and held a second brainstorming session. During the second session, our aim was to create designs that incorporated the pros of each of the initial three designs, and to create more unique designs. We developed designs which involved total finger isolation, a glove, motor movement on a track, air stimulation, and motor movement on a rotating arm. Again we made drawings of these designs and evaluated them at the three levels of design.

5.2.4.1. Total finger isolation design

The total finger isolation design involved separate units for stimulation of each finger. This would ensure that stimulation of one finger would not be felt in another finger. The separate units could also be organized into different configurations for different size hands. It would be easy to manufacture, as the device is essentially four discrete boxes for each finger. This design, however, does not provide a comfortable position for the user's hand. The user would have to place their palm flat on the table, while their fingers are slightly elevated in each unit. To improve this negative aspect of the design, we envisioned a rubber pad that could be included with the units where the user could place his wrist. This would effectively place the rest of the user's hand on the same plane as the fingers. The design for total finger isolation can be seen in Figure 11.

Figure 10: Finger Isolation Rapid Prototype

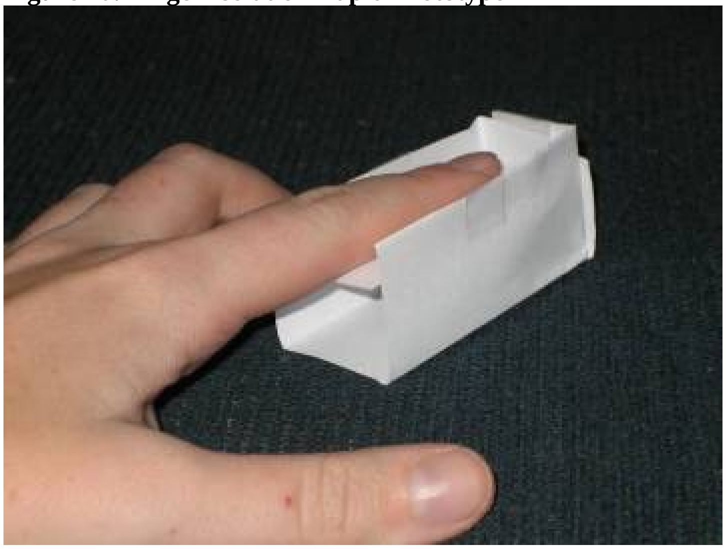
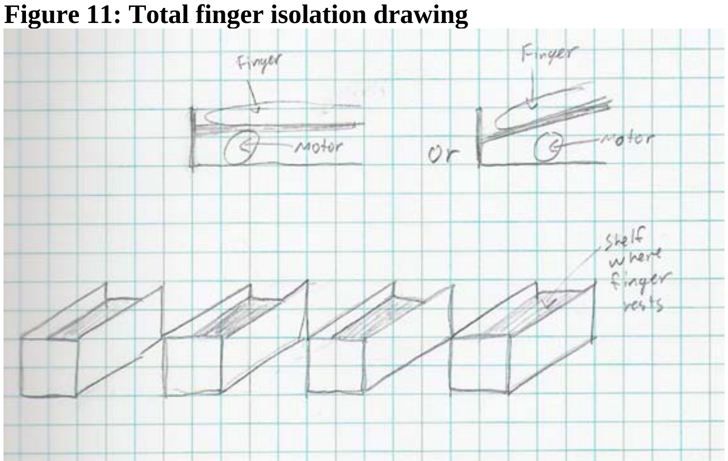


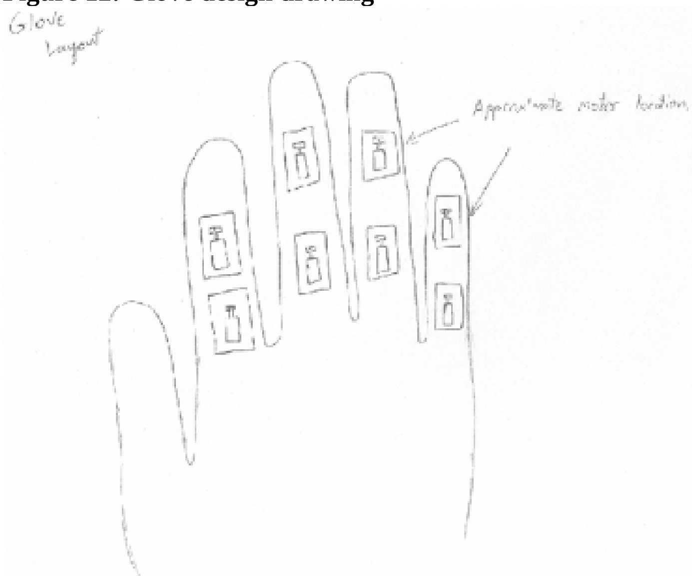
Figure 11: Total finger isolation drawing



5.2.4.2. Glove design

The glove design is essentially a glove with vibration motors attached to each of the fingers. We feel that this is our best design right now. It effectively integrates all the important aspects of our device, and it combines the best elements from our previous designs into one. It provides total isolation of finger stimulation and there can be multiple stimulation points on each finger. It also allows the user to place their hand in whatever position he/she feels is the most comfortable. This design would also be relatively easy to manufacture due to the minimal number intricate moving parts. The major drawback to this design is that one glove can not be used by both hands. If an individual is afflicted with dystonia in both hands, they would have to buy two gloves for each hand. A drawing of the glove design can be seen in Figure 12.

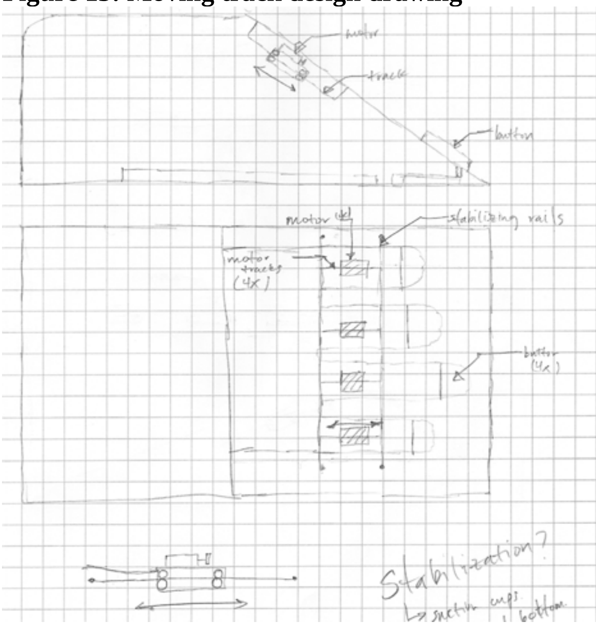
Figure 12: Glove design drawing



5.2.4.3. Moving track design

One design element that many of our design ideas were lacking was a way to provide multiple vibration stimulation points for each finger, thus, we created a design that involved placing the vibration motor for each finger on a moving track. Essentially, the vibration motor would be attached to a car on a track. The car could move up and down the track according to computer input, therefore allowing any point on the finger to be stimulated. We thought that this could easily be incorporated on the slanted box design, while also improving the functionality of the slanted box design. The main drawback to this design comes from the number of moving parts and small components involved in the device. The car and track design is not very robust; specifically the possibility of the car breaking down is very high. The vibration motor would have to be connected to the car, thus when the motor vibrates the car would also vibrate. Also, it would be very difficult to manufacture all of the small components involved in the design. This design also violates the requirement of isolated vibration stimulation. The tracks for the motors would have to be connected to the outer casing, thus the tracks could transmit the vibration for one finger to another finger. A drawing for the moving track design can be seen in Figure 13.

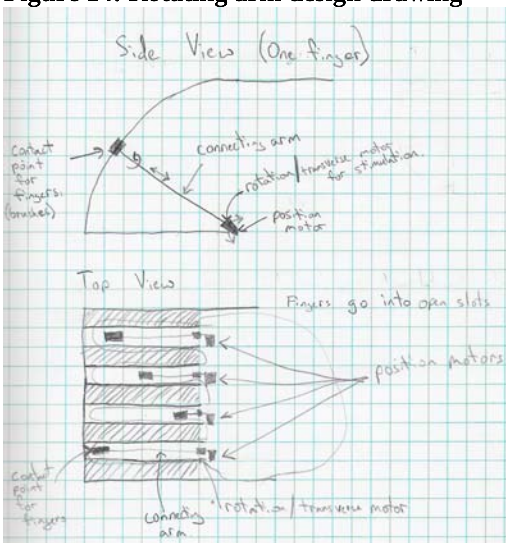
Figure 13: Moving track design drawing



5.2.4.4. Rotating arm design

We created another design that focused on multiple stimulation points for the finger. This design involved a brush on the end of a rotating arm, which was connected to a turning motor. The stimulation would result from the end of the brush sweeping up and down the finger or by rotation of the brush. This design improved on the car and track design in that it effectively separated the vibration stimulation of each finger. After analysis, however, it proved to be impractical in many respects. The brush on the end of the rotating arm would cause unnecessary torque on the arm, and decrease the expected lifetime of the component. Also, the number of moving parts would increase the risk of the device breaking down due to component failure. The number of parts also would add to the expected cost of the entire device. A drawing of the rotating arm design can be seen in
Figure 14 on page 18.

Figure 14: Rotating arm design drawing



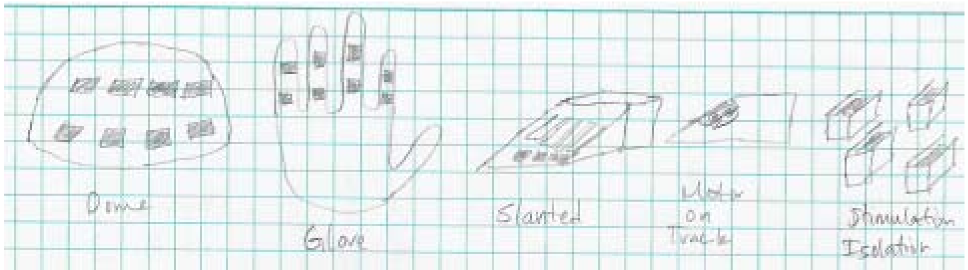
5.2.4.5. Pneumatic design

To initiate more creative thinking, we also created a unique design that utilized jets of air as stimulation for the fingers. The outside shell would have multiple holes for each finger, and each hole would be connected to a tube that would supply the air flow. The air jets effectively eliminate the problem of isolating the vibration from the motors, while also providing a mechanism with few moving parts. This design, however, was impractical regarding air supply and air flow generation. Specifically, the device would require an air compressor to generate the necessary air flow. It would be expensive and impractical to include an air compressor with each device.

5.2.5. Pugh Chart

The Pugh chart in Figure 15 provides an effective method for evaluating the top five concept designs. Each design at the top of the chart is analyzed against a list of design requirements. If the design meets the specified requirement it gets a plus, if not it gets a minus. The pluses and minuses are summed up at the bottom of each column, and a score was tabulated for each design. The glove design proved to be our most effective design according to the list of requirements we generated.

Figure 15: Pugh chart for top five designs



Design Number	**1**	**2**	**3**	**4**	**5**
Cheap to produce	-	+	+	-	+
Portable	+	+	+	+	+
Robust	+	+	+	-	+
Easy to use / Control	+	+	+	+	+
Vibration Isolation	-	+	-	-	+
Comfortable	+	+	+	+	-
Easy to manufacture	-	+	+	-	+
Multiple Stimulation Points	-	+	-	+	-
Sum +	4	8	6	4	6
Sum -	4	0	2	4	2
Total	0	8	4	0	4

5.2.6. Top Five Designs

Our top five designs, in order of importance are the glove, the isolated fingers, the slanted box, the dome, and the motor on a track. To arrive at our top five designs, we thoroughly analyzed the pros and cons of each of the ideas we generated during our two brainstorming sessions. We analyzed how the designs of the second session improved on the first, and how the ideas from both sessions were related to each other. The top five concepts are effective, feasible, and low cost. We also created a Pugh chart, seen in Figure 15 on page 17, to assist in narrowing down our ideas.

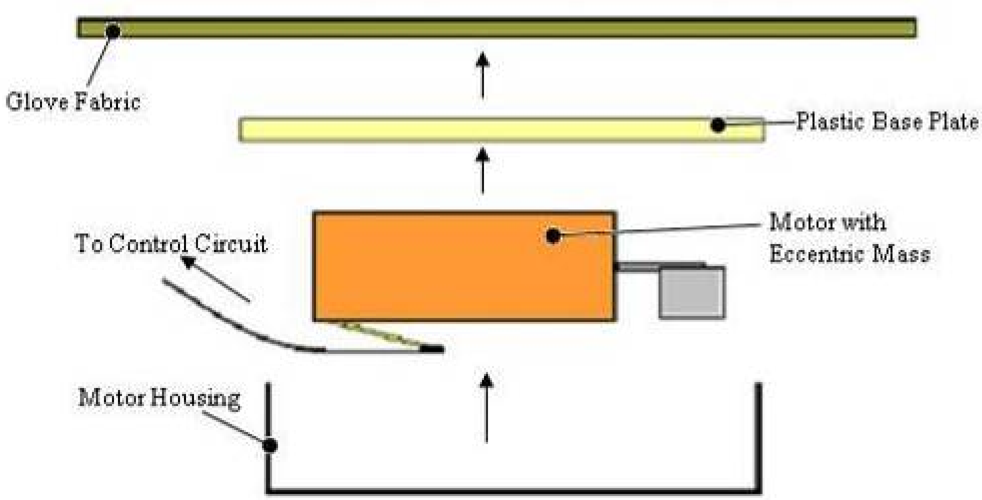
5.3. Selected concept

The selected concept is a design which consists of a glove with integrated tactile displays. The glove will be made from a thin flexible material, similar to a biking glove or a golf glove. A final product would be easily modified for various sizes and would be offered for both the right and the left hand. In this concept, each tactile display is a small eccentric mass vibrating motor, such as what can be found in cell phones. A basic layout of the glove is shown in Figure 17, on page 20. Figure 16 shows a mockup of a glove with the motors attached.

Figure 16: Motors with an eccentric mass will be attached to the glove in the locations shown

The motors which we will use are approximately 5/8 in. long by 1/4 in. wide inches in size, allowing two to be attached to each finger in the glove. These will be attached to the glove on the underside of the hand on the proximal and medial (base and middle) sections of the finger. The motors will be bonded to small plastic base plates which will in turn be attached to the glove. These plates provide good support for each motor, and also help to prevent the eccentric mass from contacting the fabric of the glove. They also will better transfer the vibratory stimulation to the finger. These plates will be no larger than 3/4 in. by 1/2 in. by 1/16 in. thick. When a motor is activated the user will feel the vibration through the plate and glove fabric. A motor housing could also be incorporated into each of the vibration units to protect the motors from the environment. A schematic of this type of unit can be seen in Figure 17 below.

Figure 17: Diagram of motor connection to glove



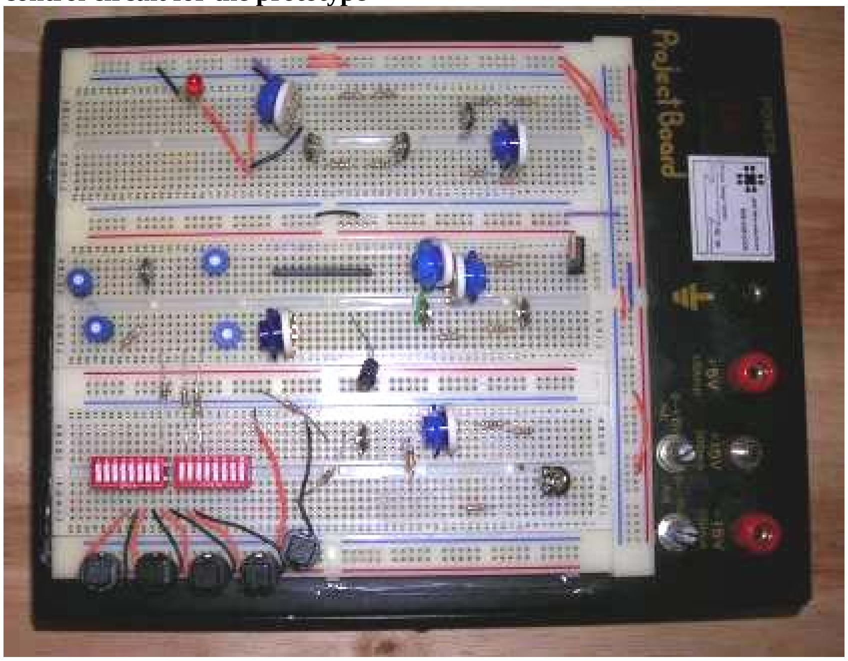
Since each motor is attached separately, this design can easily be adapted to a variety of hand sizes. The small size of the motors (Figure 18, below) and their placement on each finger allow for some flexibility in the glove fingers and lets the user to choose the most comfortable orientation for his hand. This also allows us to stimulate different parts of a single finger.

Figure 18: Small size of motors allows for easy placement on the glove, flexibility, and comfort for the user

As discussed earlier, other concepts that we generated incorporated buttons for user response into the same device which housed the tactile displays. In this concept the device which accepts the user response will be separate. For our prototype, a separate control unit will be built which will house these buttons, as well as the electronics which control the motors on the glove. An operator will input a sequence of stimulations into the circuit, and the user will respond by clicking a button which corresponds to the finger which was stimulated first. Depending on the user's comfort and rehabilitation level, these buttons can either be operated by the hand which is not being retrained, or the hand wearing the flexible glove.

The control unit for the prototype will either be a circuit built on an electronics project board as seen in Figure 19, below, or a manufactured case containing a circuit board and electronics. The case control unit for our prototype will most likely be produced from plastic or aluminum. The wires connecting the motors in the glove to the control unit will be routed together across the glove to the wrist, and then to the unit. The exact placement of the wires has not yet been determined. Although the control circuit for the prototype has not yet been designed, the control unit should be smaller than six by six inches square and less then two inches thick. Power will be supplied by either battery or a power source, such as what can be found on the electronics project board.

Figure 19: An electronic projected board such as this may used to build a control circuit for the prototype



The advantage of this concept design is that it is simple, cheap, and easy to use. The combination of the small motors and the flexible glove provide an ergonomic interface which allows comfortable motion of the hand. Gloves could be manufactured specifically for this application, or existing gloves could be modified and fitted with the appropriate hardware. The small motors are inexpensive at $ 1.00 a piece, and if ordered in bulk they can cost even less. Other small vibrotactile displays, such as the tactors presented earlier (on Page 2) in the paper, could be used instead of eccentric mass motors, but they are more expensive and difficult to obtain.

In a future production product, the tactile displays in the glove could be directly connected to a computer via a USB port. It would then be software controlled, and the user could respond using keyboard buttons or a mouse. This would entirely eliminate the need for a separate control unit, further decreasing cost.

The low cost and simplicity of the final product will allow the design to be produced in several sizes and for both hands.

6. Engineering Analysis

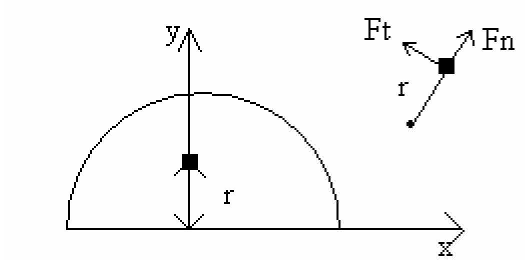
We determined that there were four factors of our design that we needed to analyze. We needed to determine how the voltage of the motor relates to the force of the motor, how the system of the motor/plate/finger works and relates to perception, and how to design a circuit that will make the device work for a variety of inputs. After this, we did a failure and manufacturing analysis of our device to try to identify problems before and during the manufacturing process.

6.1. Force Analysis

In order to characterize the force that will be provided by the motors, we made a free body diagram of the motor, and then calculated the force as a function of time and the angular velocity. The angular velocity is a function of the voltage across the motor.

Because the motor provides vibration by using an eccentric mass, we began by determining the center of mass location of the eccentric mass. This distance from the axis of rotation will be referred to as *r*, given by: $r = \frac{4R}{3\pi}$ because the mass is approximately a half-cylinder as seen by Figure 20, below.

Figure 20: Coordinate system for eccentric mass force calculations



At steady state, the tangential force of the motor is equal to zero, and the normal force can be described by the equation shown below.

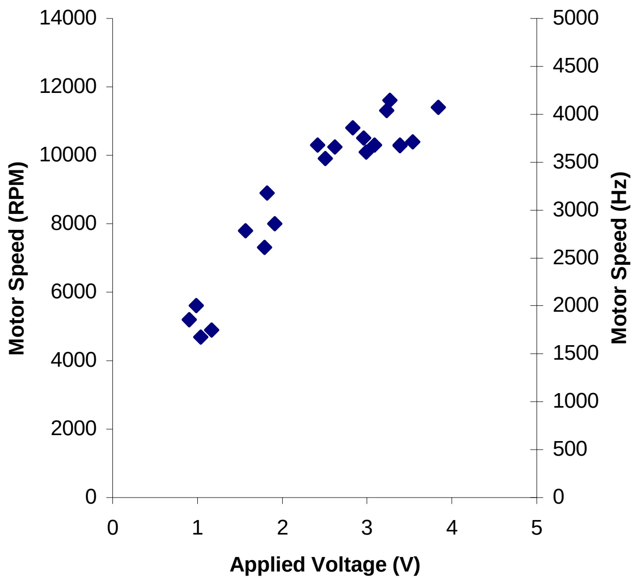
$$F_n = ma_n = m\frac{v^2}{r} = mr\omega^2 \qquad \text{Equation 1}$$

By determining the force at two times, we can determine how the x and y-axis forces relate to the normal force. They are time-varying forces with a difference in phase angle of 90 degrees. When the y-axis force is at a maximum, then there is no x-axis force. We only need to look at the y-axis force in order to do our analysis, since we are only moving the motor in one direction. The y-axis force can be shown by Equation 2, below, where *M* is the mass of the eccentric mass, and *ω* is the angular velocity of the motor.

$$F_y = F_n \sin(\omega t) = Mr\omega^2 \sin(\omega t) \qquad \text{Equation 2}$$

Our control of the angular velocity comes from controlling the voltage across the motor. This is actually equated by using the motor constant, which we experimentally calculated from a series of tests on the motor. We measured the speed using a tachometer that can see the difference in light from a mark on the motor. We ran the motor at 15 different speeds to get the results. The results of this experiment can be seen below in Figure 21.

Figure 21: Motor speed v. applied voltage to determine K_b



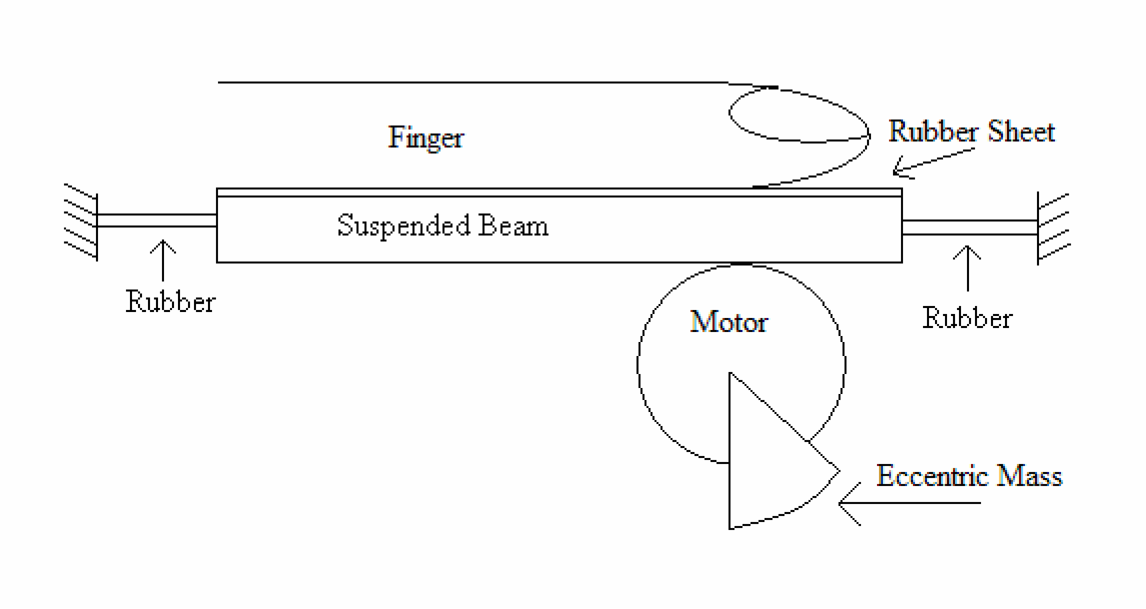
This relation is $\omega = \frac{e_b}{K_b}$, where e_b is the back emf across the motor, and K_b is the motor constant.
We found that we do not have a completely linear system for the motor speed to the applied voltage. We will show in Section 6.2, we want to run the motor at the fastest speed for maximum force, we only need to know the maximum speed, which is about 12000 RPM, or 1257 rad/s.

From all of these calculations we have determined the maximum force of our motor. The mass of the motor is $1.74 \cdot 10^{-3}$ pounds. The radius, r, is 0.0531 inches. The maximum force is about 0.38 pounds force.

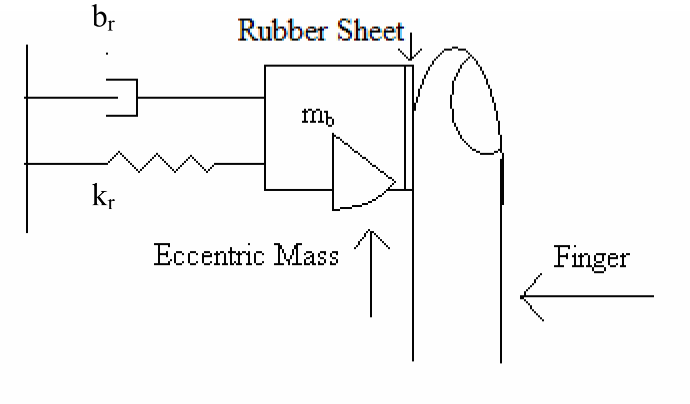
6.2. System Analysis

One necessary factor of our prototype is that the user can feel the stimulation from the motor. To determine this, we set up a system of mass, springs, and dampers to represent our prototype. Our prototype can be seen as a motor with an eccentric mass putting a force on a suspended beam, attached on both sides by a sheet of rubber, and separated from the finger by a sheet of rubber. A diagram of this decomposition is shown In Figure 22.

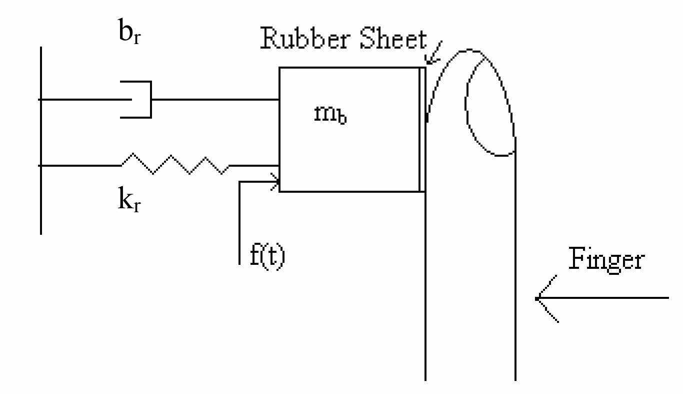
Figure 22: Model of the isolation design system and simplification steps



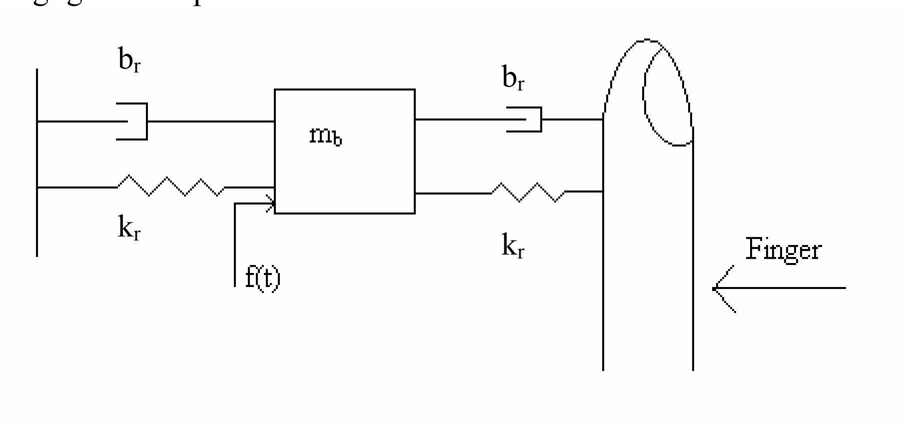
We then began to decompose this complicated model by representing the fixed beam with a mass and the rubber, on its ends, by a spring and damper, with the eccentric mass, rubber sheet, and finger still their original forms.



Next, the eccentric mass is replaced by a force, which has been described earlier.

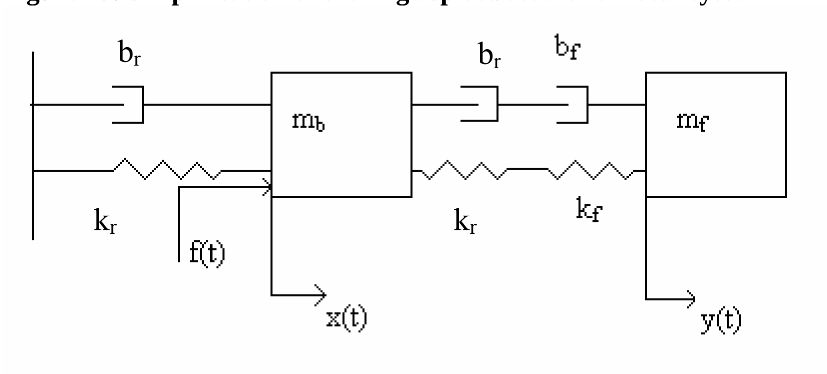


The rubber is then replaced with another spring and damper. There is no mass because it is negligible compared to the other variables.



Lastly, the skin of the finger is represented by another mass, spring, and damper. From Howe [26] and Lundström [25], we can see that although both the skin and finger can be characterized by mass spring damper systems, it has not yet been experimentally determined what this system is. Lundström provides us with some values for b_f, k_f, and m_f, which we will use later in the analysis. Lundström also provides information about the natural frequency of the skin. This natural frequency is about 200 Hz, which is close to the maximum operating range of our motor. The decomposed system can be seen below in Figure 23.

Figure 23: Simplification of the finger/plate/eccentric motor system



Using this system we set up two equations to represent the system, Equations 3 and 4.

$$m_f \ddot{y} = -\frac{k_f k_r}{k_f + k_r}(y - x) - (b_f + b_r)(\dot{y} - \dot{x})$$ Equation 3

$$m_b \ddot{x} = -k_r(x) - b_r(\dot{x}) + (b_f + b_r)(\dot{y} - \dot{x}) + \frac{k_f k_r}{k_f + k_r}(x - y) + f(t)$$ Equation 4

Using Laplace transforms, we then found Equations 5 and 6. Then solving equation 5 for X and substituting it into equation 6 we could find the transfer function of the system (Equation 7), relating the displacement of the finger to the force contributed by the motor.

$$X((b_f + b_r)s + \frac{k_f k_r}{k_f + k_r}) = Y(m_f s^2 + (b_f + b_r)s + \frac{k_f k_r}{k_f + k_r})$$ Equation 5

$$X(m_b s^2 + b_r s + (b_f + b_r)s + k_r + \frac{k_f k_r}{k_f + k_r}) = F + Y((b_f + b_r)s + \frac{k_f k_r}{k_f + k_r})$$ Equation 6

$$\frac{Y(s)}{F(s)} =$$

$$\frac{1}{(m_f s^2 + (b_f + b_r)s + \frac{k_f k_r}{k_f + k_r})(m_b s^2 + (b_f + 2b_r)s + (k_r + \frac{k_f k_r}{k_f + k_r})) - (s(b_f + b_r) + \frac{k_f k_r}{k_f + k_r})^2}$$

Equation 7

For our system to be most effective we need to maximize the transfer function, however we only can change some of the variables. To maximize the transfer function we need to minimize the denominator. Since we can change the mass of the beam, m_b, we decided to focus on minimizing that variable. The mass of the beam, m_b, is inversely related to the natural frequency squared, ω_n, (Equation 8), which means we need to focus on maximizing ω_n.

$$m = \frac{k}{\omega_n^2}$$ Equation 8

The natural frequency, ω_n, is also related to many of the material properties (Equation 9). C is a constant equal to 4.73 for a fixed beam [27]. E is the Young's Modulus, I is the moment of inertia, ρ is the density, A is the cross sectional area of the beam and L is the length of the beam.

$$\omega_n = C\sqrt{\frac{EI}{\rho A L^4}}$$ Equation 9

One way to help maximize ω_n, is to maximize E/ρ. Both of these are material properties, so using CES selector [28] we found E and ρ for some different materials; these have been compiled in Table 3.

Table 3: Comparison of materials for plate

	ρ (lb/ft^3)	E (10^6 psi)	E/ρ
Aluminum	167.5	11.5	0.071
Steel	490	30.2	0.061
Plastic	56.2	0.18	0.0032
Rubber	58.4	0.0004	0.000007
Wood	45.6	0.25	0.0055

From this table the maximum value of E/ρ is from aluminum and, therefore, is the best choice of material for the beam in our prototype. Also from Equation 5, to help maximize ω_n we will minimize the length, making it as short as possible in our design calculations.

6.3. Electrical component analysis

We decided to use an OOPic to control our device. This allows for the device to be easily set to run with a variety of test conditions. We had to determine how to connect the OOPic to our device to get the motors to work successfully. The OOPic is connected to a 9 volt power source at the power input, and it will supply 5 volts across the motors via its power outputs. From the OOPic to the circuit board, there is an I/O line with a minimum voltage (V_{OH}), of 2.7 volts. The maximum current (I_{OH}) running through the I/O line is 0.4 mA.

We determined from the results of section 6.1 that we need a current of approximately 80 mA for our motor to run at an ideal speed. Thus, to achieve this current, we will employ a transistor in our circuit. We will use the PN2222A transistor for our circuit, which has a max current (i_c) of 1 A. The voltage (V_{BE}) necessary to turn it on is 0.6 Volts. To activate the transistor, we had to calculate a resistance to place between the OOPic and the transistor. We determined the resistance by calculating the potential difference between the OOPic and the transistor which was 2.1 Volts. We then divided this voltage by the max current coming from the OOPic and calculated a resistance of 5.25 kOhms. We will achieve this resistance by including one resistor between the OOPic I/O line and the transistor. The resistance equation is shown in Equation 8 below.

$$R_1 = \frac{V_{OH} - V_{BE}}{i_{OH,\max}} \qquad \text{Equation 8}$$

Originally, we designed our circuit to include a potentiometer between the voltage source for the motor and the motor itself. This potentiometer was included to achieve the desired 80 mA current across the motor. However, we plan to run the motors only for short periods of time to achieve a short vibratory stimulus. Thus, when we tested the motor near actual operating conditions, we could not ramp them up to the desired current in the short time period. When we removed the potentiometer, though, we were able to achieve the desired current. We will not be including a potentiometer or any other resistor between the voltage source and the motor in our final circuit design. This allows for the motor to be run at its maximum speed, which can then be varied to be slower with a pulse-width modulation.

6.4. Failure and manufacturing analysis

In order to help us determine the potential failures of our device, we created a failure mode and effect analysis diagram, as seen in Table 4. We determined that largest area of concern arises from the parts that are glued together, and the response button. We should be able to conduct enough tests to ensure that our device will work with the bonds that we have, but we cannot necessarily be certain that the device will function properly. This is why the glued connections are of the most concern.

Table 4: DFMEA diagram

Part # and Functions	Potential Failure Mode	Potential Effects of failure	Severity	Potential Causes	Occurance	Tests	Detection	Recommended Actions	RPN
Component Structure -holds all the parts	fracture/fatigue, vibration transfer	device is unusable, device is uneffective	7, 5	cracks formed, units are touching	1, 3	run numerous times	6, 1	use stronger material, trim and weight components	42, 15
Metal Plate -mount for the motors	bonding failure	motor does not vibrate the finger	7	glue is not strong enough	3	run numerous times	1	use stronger bonding material	21
Rubber Holder - keeps motors in place, acts as support for plate	bonding failure, fatigue	motor is not kept in place	7	glue is not strong enough, rubber cannot withstand forces	3	run numerous times	2	use stronger bonding material, use thicker rubber	42
Response Button - allows for user response	short/open circuit, fatigue	user cannot respond	6	bad connection, overuse	3	run numerous times, ensure good connection	3	solder connections well, create tight fit so connection must be formed	54
Circuit Board - keeps cicuit in place to control motors	short/open circuit	motors do not run, user cannot respond	7	bad connections	2	test circuit for good connections	1	solder connections well	14
OOPic - allows for test administrator input	program failure	input cannot be changed by the user	6	program is altered from original	2	provide effective program, test	2	provide instructions on what to change in program	24

In order to design for manufacturing and assembly, we applied several principles of design. We decided to mount both motors onto the same rubber piece. This should not affect vibration, but it makes one less part that has to be assembled. We also had all of the connections happen in open spaces along the assembly process. For example, the rubber will be attached to the roof of the PVC structure. We have a standardization of the four units so that only one template needs to be made for all of them. This will allow for an ease of manufacturing, as only one process needs to be done for all four components. We also kept the parts symmetrical about one axis, which allows for the product to be manufactured without worry to orientation. We included notches on the sides of each component to allow for the alignment of the rubber on the top of the device. This will ensure uniformity in manufacturing.

7. Final Design

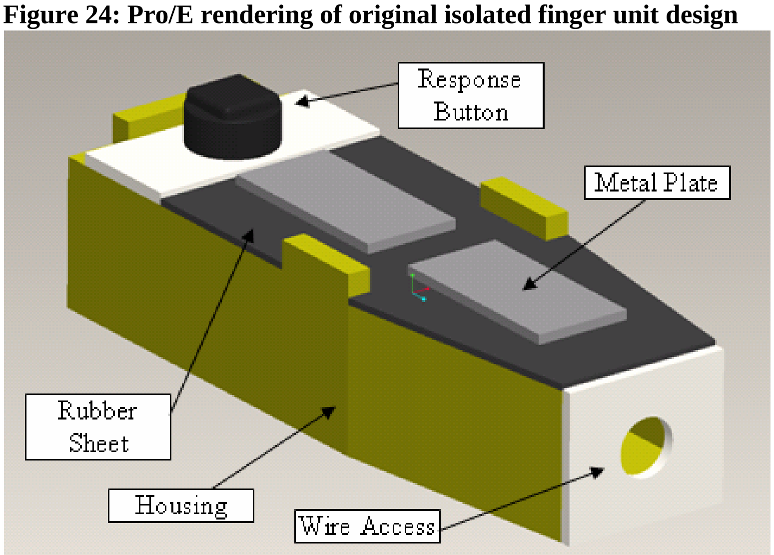
After reviewing our selected concept with our sponsor, we have been directed to focus more on the external unit, rather than solely on a form fitting glove. For our final design we will focus on producing a prototype of the individual finger units, the concept discussed in section 5.2.3.1, and if time permits we will also construct our original selected concept, the form fitting glove. By creating two different prototypes we are providing our sponsor with more testing options.

7.1. Isolated finger unit design

The isolated finger unit design fulfills the customer requirements, including that it is able to help retrain the user, it is made from inexpensive materials and processes, it is portable, and it is easy to use. It also fulfills the majority of the engineering specifications, including that it provides stimulation to the user, it easily isolated vibrations between fingers, it allows for a user response, it is made from readily available and inexpensive materials, and that is has the ability to interface with a computer.

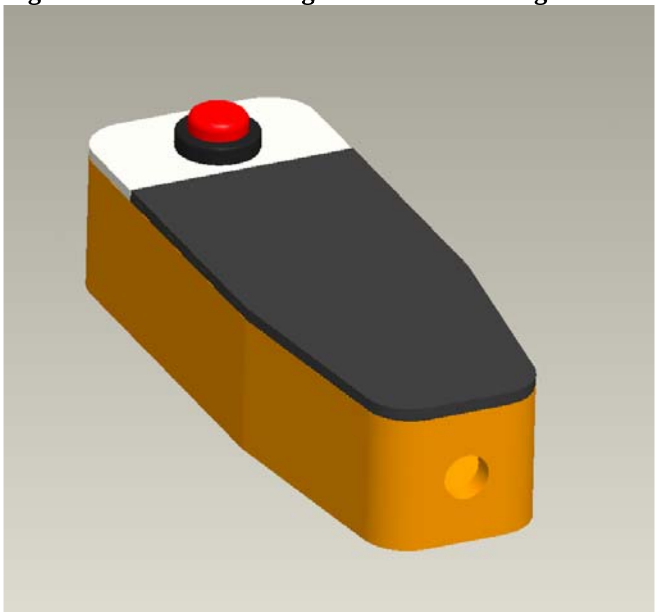
Four prototype units will be produced, one for each finger. These units can be arranged by the user on a desk to best fit his or her hand. Since the units are identical, the system can be easily used by both right and left handed persons. The original CAD model of one of the units is shown in Figure 24, below.

Figure 24: Pro/E rendering of original isolated finger unit design



After discussions with Professor Gillespie, we decided to make the units more visually pleasing, as well as eliminating possible cues. To this end, we eliminated the sharp corners of the units. The three ridges on the top of the units were also eliminated. A second rubber sheet was also added to cover the aluminum plates. All of these changes helped to make a more aesthetically pleasing product. A CAD rendering of the final design is shown in Figure 25.

Figure 25: Pro/E rendering of final isolated finger unit design

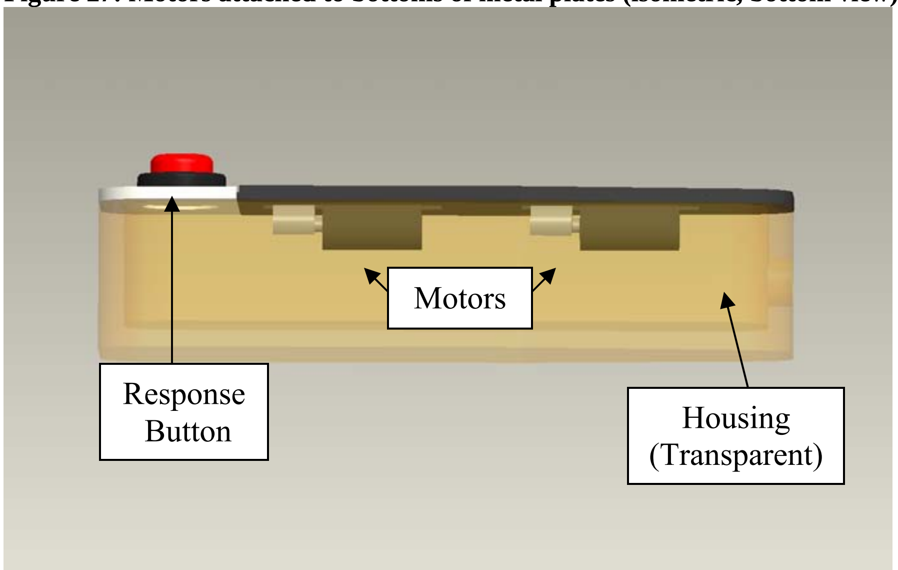


The units are arranged so that the response button is away from the user and the user places his or her finger tip on the rubber sheet close to the button, as seen in Figure 26. These metal plates will be made from aluminum as determined by our engineering analysis discussed in the preceding section. Once the user receives the stimulation, he indicates which finger was first stimulated by pressing the response button on the corresponding finger unit.

Figure 26: Finger placement on top of units

Each unit consists of a base, machined from a PVC block. A thin rubber sheet is attached to the top of the base. Bonded to the top of the sheet are two small metal plates which transmit the force from two eccentric motors to the finger. These plates act as the beams used in the engineering analysis. A final rubber sheet covers the top of the unit. The motors are bonded to the bottom of plates as shown in Figure 27. Having two motors in each unit creates multiple stimulation points on one finger. The approximated stimulus location can be selected to best fit the user's retraining needs.

Figure 27: Motors attached to bottoms of metal plates (isometric, bottom view)

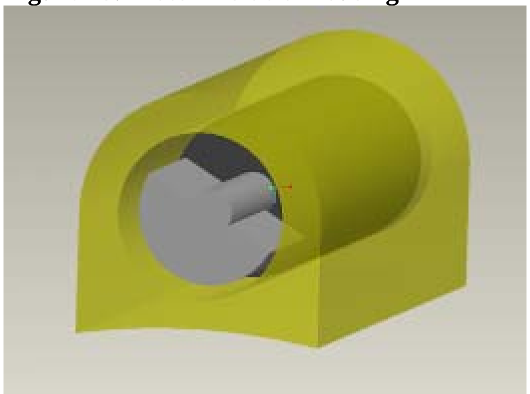


Wires from the response button and motors will group together and feed out of the wire access. The wire groups from each unit are grouped again several inches from the units and routed to the control circuit. The button support plate will be made from a plastic sheet which was purchased earlier in the project. All components will be attached using a strong LOCTITE brand adhesive designed for bonding aluminum, rubbers, and plastics. Additional rendering of components and engineering drawings for the housing and rubber sheets can be found in Appendix B.

7.2. Form fitting glove design

If time permits we plan to create a second prototype using our original selected concept of a form fitting glove with eccentric mass motors attached to the fingers. Like the isolated finger unit design, two motors will be attached to each of the four fingers of a skin tight glove. For our purposes we will be using a golf glove. The motors will be encased in simple polymer housings (see Figure 28) and will be attached by fabric pockets sewn to the underside of the glove fingers.

Figure 28: Motor inside of housing

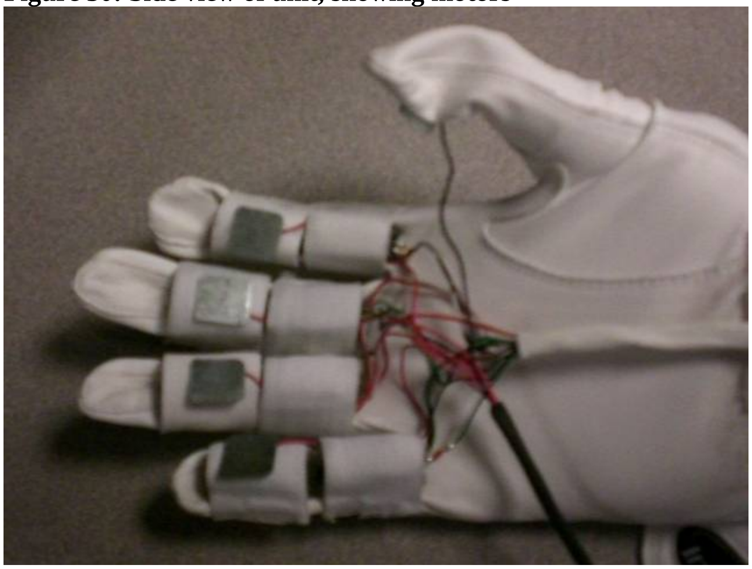


As shown in this figure, there is a concave side of the hosing (bottom in figure) which would be the side which contacts the finger. This shape allows for greater stability in securing the housing to the glove. These housing will be manufactured from scrap PVC left over from the isolated finger units. The motor is tightly fitted to the inside of the housing and secured by a strong adhesive. These motor and housing units will attach in the approximate locations shown in Figure 29 below.

Figure 29: Approximate placement of motors shown on concept prototype

The final prototype was made from a flexible form-fitting golf glove. The motors in housings are placed inside of elastic bands on each of the fingers, as seen in Figure 30. The wires are routed from the motors across the hand. Instead of buttons to input a user response, electric contact pads are used.

Figure 30: Side view of unit, showing motors

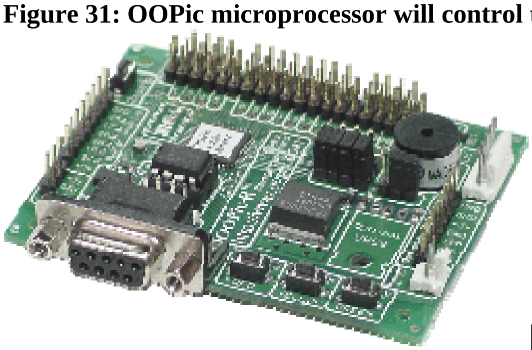


7.3. Electric circuit

7.3.1. Motor Control

We will be controlling the action of the motors using an Object-Oriented PIC (OOPic), which is a microcontroller specifically designed for robotics shown below in Figure 31. The OOPic uses a library of objects for the controlling language.

Figure 31: OOPic microprocessor will control the prototype



[29]

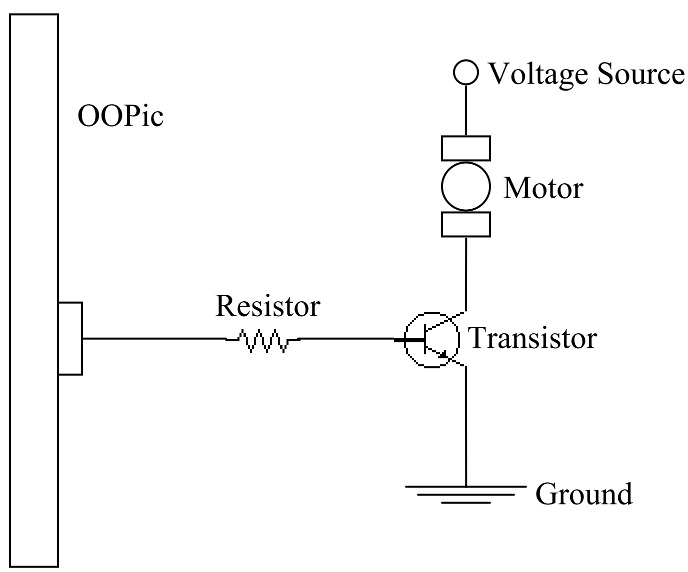
There are a wide range of objects that perform different operations on the motor. There are four main operations we are currently employing in our program, which are oDIO1, oPWML, oWire, and oEvent. The object oDIO1 controls the input from the user by managing an I/O line integrated into a virtual circuit. For example, different user inputs can be programmed to perform different tasks through oDIO1 by monitoring the electrical state across the circuit. The object oPWML controls the motor output, by providing a low-speed output with a variable size pulse width. Essentially, this object will control the speed of the motor, which also relates to the force of the motor, as explained earlier. The object oWire takes the value from the Input property and copies it to the Output property. The object oEvent calls a sub procedure. The oWire combined with the oEvent will be used to create the response and input properties of the device.

7.3.2. Circuit Design

As mentioned in the analysis section, we will use a PN2222A transistor with a 5.25 kOhm resistor for our circuit, which will be connected to the OOPic and a 5 V voltage source.

The PN2222A transistor has three input leads named C, B, and E. The C lead is connected to the motor, the B lead is connected to the OOPic I/O line, and the E lead is connected to ground. Our circuit will also contain a resistor which connects the B lead to the OOPic I/O line. The circuit is diagrammed in Figure 32 below. This circuit will be made on a breadboard that will be separate from the device. Wires from the motor will be connected to the breadboard which will contain the circuits. A ribbon cable will be connected to the breadboard and then connected to the OOPic. This model will be used for both the isolated units design and the glove design.

Figure 32: Circuit Schematic

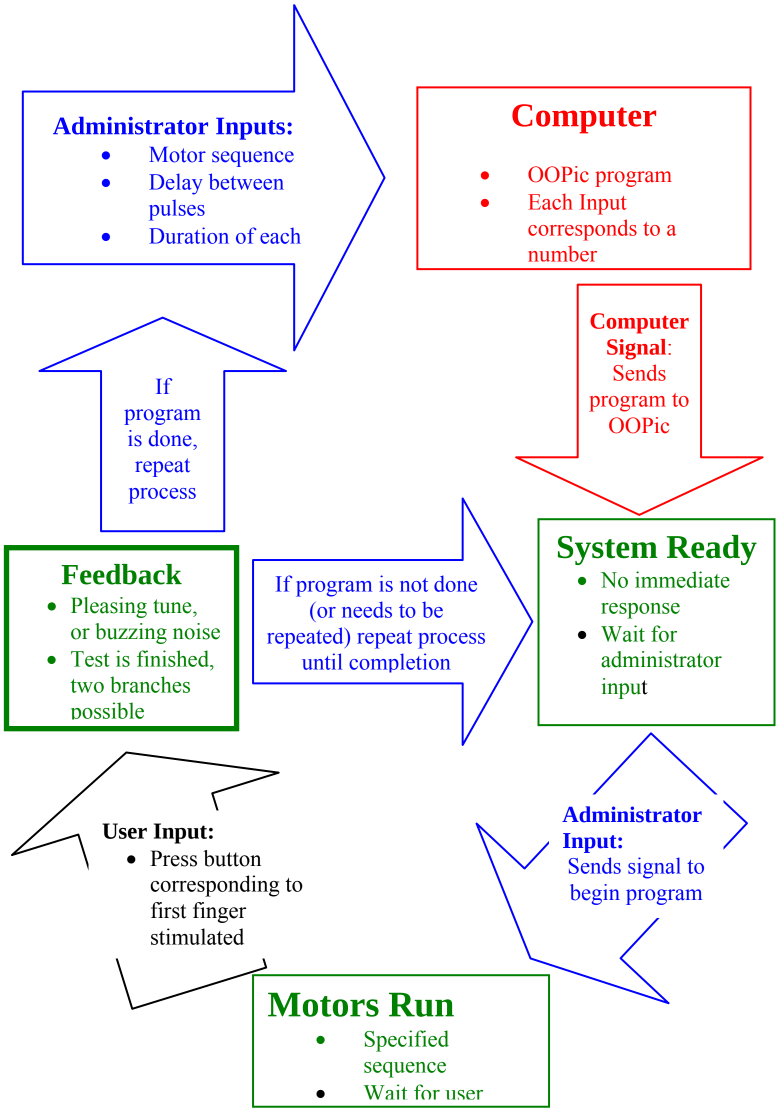


The majority of the circuit is contained in a small housing which also incorporates the administrator input buttons. It allows for both designs to be used with the same circuit through connectors for the buttons and for the connections to the motors.

7.3.3.Sequence of Events

We have decided on a set sequence of events which the program will run through while controlling the motors. It consists of the OOPic sending the motor sequence to the motors, the administrator deciding which program to run, the user experiencing a stimulus, and feedback to the user. To better illustrate this sequence of events, we have created a diagramming outlining how the program will work, it is shown in Figure 33 below.

Figure 33: Diagram of the Sequence of Events



7.4. Bill of Materials

Below in Table 5 is our tentative bill of materials. The PVC, rubber, wire, and vibrator motors have already been ordered. The rest of the electronic components are being ordered by Professor Gillespie. The aluminum sheet will be ordered shortly. The rest of the materials used in the project have already been provided, so they are not included below. This could change as we find new potential flaws and better processes in our design and manufacturing.

Table 5: Bill of Materials

Quantity	Part Description	Purchased From	Part Number	Price (each)
2 feet	PVC (Type I) Rectangular Bar 1-1/4" Thick, 1-1/2" Width	McMaster-Carr*	8740K27	$10.40/feet
0.2 feet	Commercial-Strength Neoprene Rubber Film, .031" Thickness, 36" Width	McMaster-Carr*	1875T21	$13.37/feet
20	Tiny Vibrator Motor	Electron Goldmine**	G13566	$1.00
1	Alloy 3003 Aluminum Sheet	University of Michigan		$0.00
90 feet	22 gauge wire	Radio Shack		$5.99
2	Prototyping Board	Radio Shack		$3.29
16	5.25 kohm resistor	University of Michigan		$0.00
16	TIP 112 transistors	University of Michigan		$0.00
1	ooPIC-R hardware object	University of Michigan		$0.00
				Total = $144.08

*http://www.mcmaster.com
**http://www.goldmine-elec.com

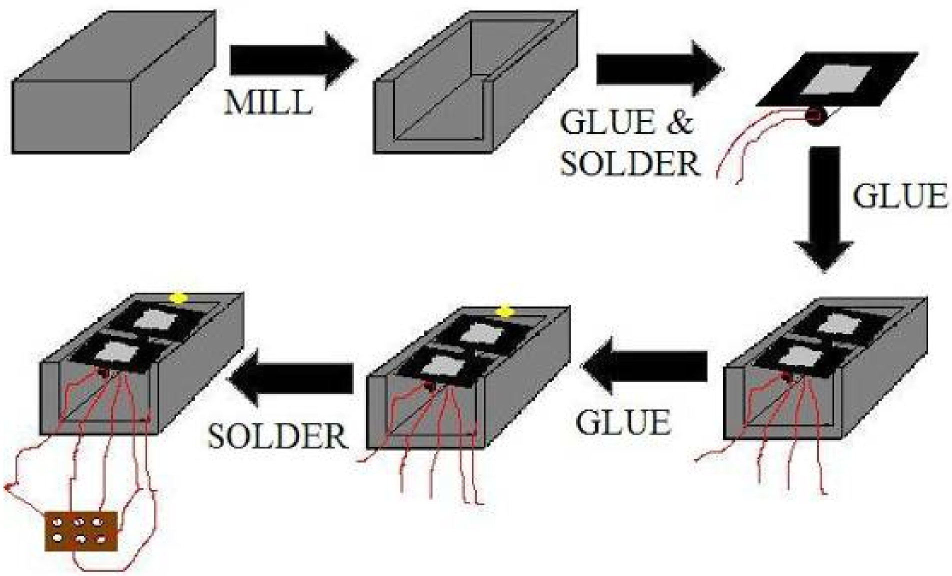
8. Manufacturing and Testing Plan

In order to manufacture our prototypes, there are two main parts that we have to consider. We have the physical devices, and we have the OOPic program to write. Most of the consideration and time will be devoted to manufacturing the physical devices. As we have explained, we will be making two prototypes. One will be the isolated fingers design and one will be the glove design. The OOPic program will be the same for both devices, and only one OOPic will be necessary to control both of the devices. It will be plugged into the appropriate circuit board.

8.1. Isolated finger unit manufacturing

A diagram of how the isolation design will be manufactured can be seen below in Figure 34. We will manufacture the isolation units from PVC blocks. We will order precut blocks with dimensions of 1.25x1.5x4 inches. From these blocks we will face each end with the mill, and then mill out the interior and top of the design that we specified earlier using a ½ inch end mill. Then we will reposition the mill and trim the bottom edges where the blocks are at an angle. After that, we will drill out the holes that the buttons will lie in for the user response. We will then attach the motors to the plates using superglue. The leads of the motor will be snapped off to allow for the motor to sit flat on the plate. Some insulation may be provided to ensure that there is not a short. We will cut out the hole in the rubber for the plate, and then attach the plate to the rubber using superglue. The side of the plate with the motor will face towards the rubber such that the motor lies in the hole that was created. The rubber will then be attached to the PVC using adhesive. The buttons will be inserted into the holes and the wires will run underneath the metal plates. Then the front cover of the device will be attached. This will be made from scrap material from the prototyping process. The wires running to the motor and the buttons from the circuit board will be attached prior to attaching the rubber to the PVC block.

Figure 34: Manufacturing Diagram



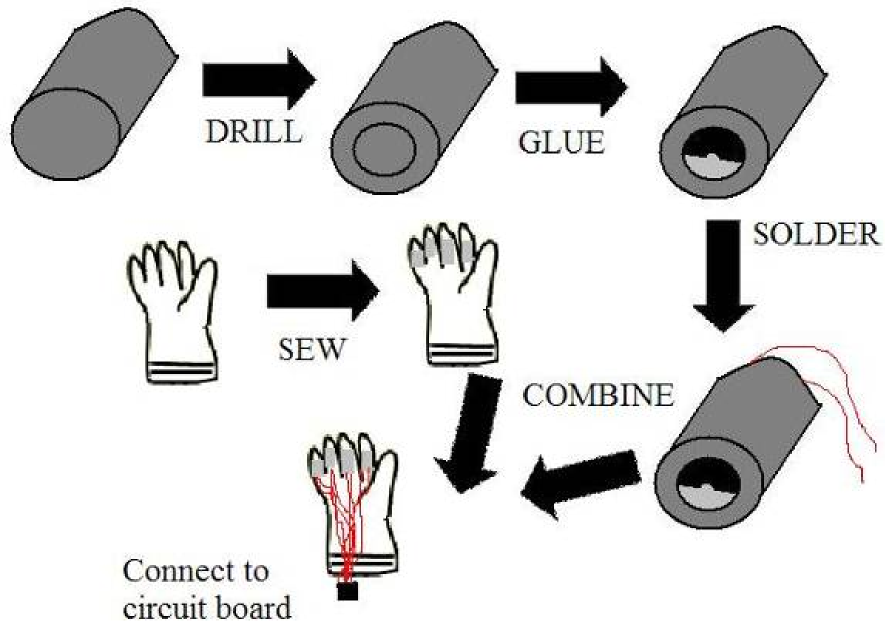
We will also manufacture a wrist support that will be designed to fit a normal wrist. It will be cushioned, so the exact shape is not as important.

We will build all four finger sections so that the device can serve as a fully functioning testing tool before it potentially goes into mass production. This will allow Posit Science to make sure that our device actually does what they have hypothesized. Each finger will have the wires connecting the motors running from the base. They will be attached together and then connected to the circuit board. The circuit will be soldered onto a circuit board so that it can serve as a way to run tests.

8.2. Form fitting glove manufacturing

In order to manufacture the glove, we will use a golf glove, and the spare PVC from manufacturing the isolation design. This will allow the prototype to be cheap and readily available for use. The golf glove allows for the freedom of movement of the fingers, and it allows the motors to be placed at precise points. We will cut the PVC into cubes that are just larger than the size of the motor, and then sand them down to be a curved shape. The exact shape is not very important. Then we will drill holes that are the size of the motor in the PVC. The motor will be press-fit, and possibly glued into the housing. We will sew elastic bands onto the golf gloves. Then the motor housings will be put into the golf gloves. The wires from the motors will be wrapped together and then run to the circuit board. This will allow the hand to freely move and allow for the glove configuration to be used with multiple inputs. By wrapping the wires, it will be much less stressful for the user to use the device. The manufacturing diagram for the glove is shown in Figure 35.

Figure 35: Manufacturing Plan for Glove Design



8.3. OOPic Programming

We created a program using the OOPic software. This program allows the user to have four possible tests. The program can be seen in Appendix C. These would most likely alternate between two fingers, and allow the user to determine which finger was stimulated first. The program has to be setup in the computer by specifying which fingers are involved, the delay between pulses, and the duration of each pulse. All of this information can be set at the top of the program, for easy access to the administrator. Then the administrator would be able to push one of four buttons to have one of the four pre-programmed tests sent to the motors. The user would then be able to respond by pressing the button at the top of the units. This could be repeated as many times as necessary alternating which finger is stimulated first.

8.4. Changes for mass production

The production processes of both devices would have to be varied if our prototype went into mass production. The blocks would still be able to be milled out from PVC blocks. It might be cheaper to fasten PVC plates together to use less material, depending on how many products were produced. The components that were bonded with adhesive may have to be bonded in a different fashion. They might be fused together in some manner.

The adhesive is the main thing that would have to be changed in both processes. The adhesive would not necessarily have to be eliminated, but a stronger, industrial-style, adhesive would be necessary to make sure that the device did not fail with any users. Adhesive will function for long enough for our prototype, and will allow Posit Science to run the tests that are necessary for them.

The electrical components of our device will also need to change for mass production. A connection to a computer will be necessary. This would most likely be easiest in the form of a USB cable. The electrical circuit would also need to be changed. Our device can function because Posit Science knows the tests that they want to run, and can have individual contact with the users. If the device went into mass production, then the device would have to be fully automated from a computer program. This setup was out of the scope of our project, which is why we used the much simpler to program OOPic device.

8.5. Testing plan

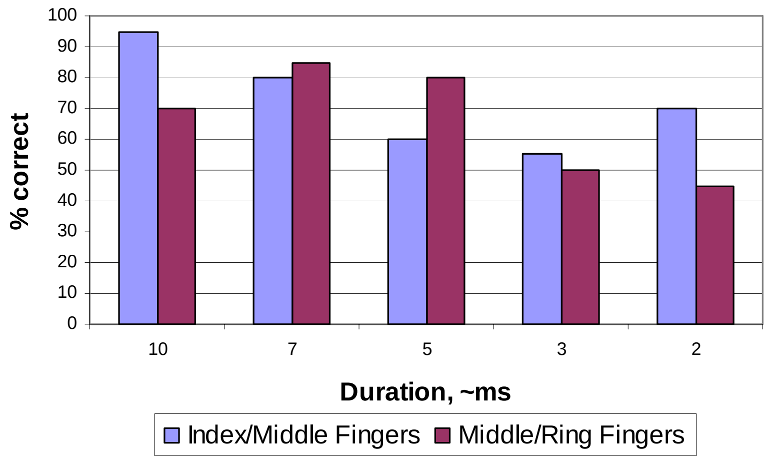
In order to test our device, we will perform numerous runs of potential tests with human subjects. First we will run the motors without any interaction with human fingers to observe how well they work, and ensure that all of the connections are solid connections that will not break down with use. We will then run the programs that we made to make sure that they work as expected. This may or may not be done with interactions to fingers. During this phase we will also observe how the delay in the program relates to the actual delay of the motors and then provide that information to Posit Science.

After all of the tests to ensure that the device works and if there is enough time, then we will run the experiment that we ran before with the motors. This will help to show that our device works, and see if there is a threshold of how long of a delay can be felt. It will also test the limitations of our device. We will be able to observe the minimum running time of a motor so that it provides stimulation.

9. Testing and Design Validation

In order to test our design, we conducted a similar experiment to the one that was discussed in Section 2.2. We used each of our group members as test subjects, and we conducted 5 tests at 5 different speeds for each subject. The speeds in this case referred to the duration that the stimulus was felt, instead of the length of the delay between stimuli. We conducted tests on both the index and middle fingers, and the ring and middle fingers. We varied which finger that was stimulated first, and the user had to respond as to which finger was stimulated first. The results of this experiment can be seen in Figure 36. We found that it was generally tougher to distinguish between vibrations in the ring and middle fingers, and that it was harder to distinguish between vibrations at faster speeds. It also seemed that there was an ideal duration between vibrations at which the difficulty level was the greatest.

Figure 36: Preliminary results from sensorimotor testing



During the Design Expo, we ran the experiment with four random tests programmed into the OOPic. The tests were conducted with 64 participants, with approximately 5 tests done per person. We only kept a record of whether or not the participant was correct. It generally seemed that it was harder to distinguish between vibrations when two motors that were one finger apart were stimulated. We ran the tests at a duration of about 7 ms. The overall percent of correct answers was 58%. There were 291 total tests done.

The testing of our group members and expo participants helped to show the durability of our device. The testing went smoothly, and the device still functioned after all of the tests. Since we were only running a few motors for all of the tests, it showed how that repeated use can be done with our prototype.

10. Potential Improvements

In testing our prototype and seeing other people's reactions during the Design Expo, we were able to determine many improvements that could be made for our product design.

One main improvement should be updating the connectors between the units and the programming board. We modified connectors to serve our electrical purposes, and the current connector pins are very fragile. If our device were to be made for mass production, the pin connection would be changed to a USB connection to a computer, so the connector issue would no longer be a problem. Another improvement is the membrane thickness. We could have used a much thinner rubber membrane. This would allow for less damping of the vibrations which would ensure that the stimulus was felt at the point that it was meant to be felt. The wires running to the bottom of the units was another design improvement that could be made. The wires often vibrated, and it was hard to distinguish the vibration since the whole hand felt it through the wires. This could easily be fixed by having the wires go out the front of the units near the fingertips, instead of at the base of the palm. The final improvement for the units is to have a connection already made for the motors instead of a solder joint. This would allow for more durability and robustness of the device. It would also ensure that the motors do not short.

For the glove design, one improvement is to have a stronger connection between the motors and the wires. This can be accomplished by having more stress relief in the wires, and by using stronger wire that will not break as easily. Another improvement is to sew the wires into the glove so that they do not be seen. Two pieces of material would be necessary for this design. The main problem with our glove design is that it was not versatile enough for multiple hand sizes. The final improvement is to make the glove out of a more elastic material that would easily stretch over any user's hand.

11. Conclusion

The goal of our project is to create a device that assists in retraining patients afflicted with focal hand dystonia and similar disorders. Research indicates that due to the neural plasticity of the brain, retraining is a viable option. Retraining needs to consist of repetitive, fine motor practice of the hand afflicted with focal hand dystonia. Currently there are no devices that specifically target sensorimotor retraining of the hand in patients with focal hand dystonia, however, there are abstract techniques used to cure this condition. Our device will induce vibrational stimulation of the fingers causing the patient to respond with a button input.

To further study the effects of stimulation of the fingers, we designed an experiment to test the tactile acuity of individuals without focal hand dystonia. The results of this experiment indicate that it is much harder to correctly determine the order of finger stimulation with a decreasing time interval between tactile stimulation.

The most important customer requirements are that it is cheap and effective at retraining the user. We translated all the customer requirements to engineering specifications, thereby allowing us to construct a relationship matrix. The relationship matrix provides a method to determine the overall most important aspects of the design.

The most effective design technique for our project will be rapid prototyping. We plan to create multiple designs utilizing cheap materials to determine which design is most effective. The direction of our project is currently headed toward more specific prototyping over the next couple weeks. We have estimated the costs we will incur over the design process, and we expect the total budget to be under $400. The bulk of the costs we expect will come from the materials needed for making prototypes of the design.

The concept generation process involved creating a FAST diagram, a morphological chart, and classifying the ideas generated from brainstorming. To better understand the designs we generated, we created drawings and rapid prototypes for a few of the ideas. The ideas we synthesized from the brainstorming process were critiqued and analyzed to determine the most important aspects of each design. We held two brainstorming sessions to create more effective ideas after determining the flaws encountered after the first session. We were then able to choose our top 5 design ideas based on the results of the Pugh chart.

By comparing the top 5 designs to a list of specific requirements, we determined the best design concept. We want to further analyze the mechanical requirements for the glove design because it is out most functional design. We envision two eccentric motors being attached to each finger of the glove with a small casing around each motor for protection. The electrical wiring that will control the eccentric motors on the glove will be wired through a project board. There are many advantages to this design such as it is cheap, comfortable, portable, and easy to use.

Through our engineering analysis, we were able to model the motion of the motor, beam, and finger system using a simple free body diagram. Through this analysis, we were able to determine what type of material we wanted to use for the beam. In conjunction with our mechanical analysis of the system, we also analyzed the electrical circuit we will use to control the motors. We determined we needed an OOPic microprocessor to control the activity of the motors, and we would also need a resistor and transistor to achieve the desired current through the motor.

We also created CAD drawings of our selected concept to better visualize what our design will actually look like. We can also use these drawings to aid us in manufacturing the different components in the shop. To aid in the manufacturing process, we also created manufacturing plans for the individual units and the glove design.

Prototype manufacturing and testing have now been completed. We have found many areas of improvement for the prototype design. The electrical improvements we would suggest are improving the connections between the motor units and the control boards and improving the solder connections between the wires and the connectors. Also, the emergence of the wire groups from the units should be moved to the far end of the unit relative to the hand. We found that the wires transmitted slight vibrations to the hand which may have skewed the results. To improve the mechanical operation of the device, a thinner membrane should be used to cover the top of the units to allow for better transfer of vibration stimulation to the fingers. The membrane we used was to thick which caused extensive dampening of the vibrations.

Testing at the design expo revealed that the device is robust, easy to use, and challenging to the user. Thus far, the device has been used in 291 tests and still functions properly. It is also easy to use. After giving the participant brief instructions on how to use the device, he or she could easily complete the requested testing. We also noticed that the testing was challenging and rewarding to the participants. If a participant did poorly the first time tested, he or she would want to do a second test to improve. Usually, if a participant repeated the test, he or she would improve the second time.

We have designed and built a device that should be effective in completing a sensorimotor retraining study on individuals with hand disorders such as focal hand dystonia. Our glove design could also be utilized as a second testing device, and possibly marketed one day to the public if the testing finds that sensorimotor retraining is an effective procedure.

References

[1] *PositScience*. 2007. Posit Science Corporation. 12 January 2007. http://www.positscience.com/

[2] *Focal Dystonia of the Hand, and what the Brain has to do with it.* 16 Feb. 2006. Henrike Blumenfeld. 11 January 2007. http://serendip.brynmawr.edu/bb/neuro/neuro01/web2/Blumenfeld.html

[3] *Dystonia Medical Research Foundation*. 2004. 22 January 2007. http://www.dystonia-foundation.org/defined/.

[4] Spengler, Friederike, Roberts, Timothy P.L., Poeppel, David, Byl, Nancy, Wang, Xiaoqin, Rowley, Howard a., Merzenich, Mike M. "Learning transfer and neuronal plasticity in humans trained in tactile discrimination" *Neuroscience Letters.* 232 (1997) 151-154

Research was performed on healthy human subject as well as humans with focal dystonia. Magnetic source imaging was using to evaluate how the brain responded to repeated multi-finger stimulation. It was determined where the brain was being stimulated for this to occur. The results were also compared to animals which have undergone the same testing.

[5] Byl, Nancy N., Srikantan S. Nagarajan, Michael M. Merzenich, Tim Roberts, and Alison McKenzie. "Correlation of Clinical Neuromusculoskeletal and Central Somatosensory Performance: Variability in Controls and Patients with Severe and Mild Hand Dystonia." *Neural Plasticity*. 9.3 (2002): 177-203.

The authors researched the differences in neuromusculoskeletal performance and somatosensory responses of healthy subjects versus focal hand dystonia subjects with mild to severe hand dystonia. They hypothesized that there should be measurable problems in sensory processing and motor control due to dedifferentiation of the cortical somatosensory organization of the hand. To test this hypothesis, they performed a number of different clinical test procedures on healthy test subjects and subjects with focal hand dystonia. They concluded that patients with focal hand dystonia experienced strong somatosensory degradation of the hand that directly affects sensorimotor functions. There are also different degrees of focal hand dystonia, ranging from dystonia to mild dystonia, thus, sensorimotor retraining must be specialized to the individual.

[6] McKenzie, A.L., S.S. Nagarajan, T.P.L. Roberts, M.M. Merzenich, N.N. Byl. "Somatosensory Representation of the Digits and Clinical Performance in Patients with Focal Hand Dystonia." *American Journal of Physical Medicine & Rehabilitation*. 83 (2003): 737-749.

This article presented research done to investigate the somatosensory organization of the hand in the brains of focal hand dystonia patients using magnetoencephalography. The authors also researched the sensorimotor functions of the hand in patients with focal hand dystonia. The researchers performed experiments such as magnetoencephalography measurements and assessments of physical variables, sensory discrimination, motor speed, and quality of life. They concluded that patients with focal hand dystonia experience a decreased representation of individual fingers in the brain. There is evidence, however, that patients can recover from focal hand dystonia with repetitive, fine motor practice which will lead to expansion of finger representation in the brain.

[7] Merzenich, Michael M. and Sanger, Terence D. "Computational Model of the Role of Sensory Disorganization in Focal Task-Specific Dystonia." *J Neurophysiol* 84 (2000): 2458-2464.

This paper presents a model of sensorimotor function as a computation. It explains how the sensorimotor system works as a closed loop system. It explains that task-specific dystonia arises due to instabilities in the loop. It generally starts as something that is not as serious and then continues to worsen into a serious disorder. The computation allows for a computer simulation of the disorder.

[8] Buonomano, Dean V., Merzenich, Michael M. "Cortical Plasticity: From Synapses to Maps" *Annual Review Neuroscience.* 1998. 21:149-86.

This paper discussed in depth how the brain can be retrained. Plasticity was the main idea of this paper, and where in the brain this can occur. Using mapping as the technique the plasticity process was understood better.

[9] Wright, Buonomano, Mahncke, and Merzenich. "Learning and Generalization of Auditory Temporal-Interval Discrimination in Humans." *The Journal of Neuroscience.* May 1997: 3956-3963.

This paper discusses a study which focused on the learning ability of the brain, and how it relates to hearing. In the study subjects were subjected to two short sounds at a determined interval. Over time subjects were shown to be able to distinguish discrete sounds at increasingly closer intervals. The study demonstrates the effectiveness of perceptual learning.

[10] Dobkin, Bruce H. "Functional Rewiring of Brain and Spinal Cord after Injury: The Three Rs of Neural Repair and Neurological Rehabilitation." *Current Opinion in Neurology* 13. (2000): 665-659.

This article explains what goes on in the brain when there has been an injury to the neurons. It explains that the brain can be retrained with enough practice at doing movements. Also neural transplantation is possible to repair the brain. The combination of replacement and regrowth can then be aided by rehabilitation to fix the brain.

[11] Merzenich, Michael. "Seeing in the Sound Zone." *Nature.* Vol. 40, April 2000: 820-821.

The article discusses a study in which scientists "rewired" the brains of ferrets, connecting the visual nerves to the auditory part of the brain and the auditory nerves to the visual part of the brain. The ferrets' brains were able to adapt and retrain, so that they were able to sear and hear

as normal. This study demonstrates the plasticity of the brain, and its ability to be remapped by use of rewarding training.

[12] Wang, Merzenich, Sameshlma, and Jenkins. "Remodeling of hand representation in adult cortex determined by timing of tactile stimulation." *Nature.* Vol. 378, November 1995: 71-75.

This paper discusses a study which demonstrated the plasticity of the brain. The study showed that in owl monkeys, repeated and nearly simultaneous stimulation to two or more fingers resulted in the loss of distinction between fingers by the brain. This is similar to focal hand distonia which can be found in humans.

[13] Xerri, Merzenich, Peterson, and Jenkins. "Plasticity of primary somatosensory cortex paralleling sensorimotor skill recovery from stroke in adult monkeys." The American Physiological Society.

In this study, adult owl and squirrel monkeys were trained to receive treats from wells of varying diameter and depth. Lesions, simulating a stroke, were then cut in the part of the brain which used tactile perception to guide movement of the hand. The monkeys were initially unable to retrieve the treats after the induced stroke. Through repeated and rewarding training, the monkeys were able to restore their original ability to retrieve the treats from the wells.

[14] Volpe, Bruce T., Hermano I. Krebs, and Neville Hogan. "Is robot-aided sensorimotor training in stroke rehabilitation a realistic option?" *Current Opinion in Neurology*. 14 (2001): 745-752

This article discussed the possibility of using robotic devices to reduce impairment and increase motor power in patients who have experienced a stroke. The goal of the authors' study was to test whether or not therapists equipped with robotic devices would enhance the rehabilitation of sensorimotor skills. They concluded that robotic devices favorably influenced the motor retraining of injured patients.

[15] Altenmuller, Eckart. "Focal Dystonia: advances in brain imaging and understanding of fine motor control in musicians" *Hand Clinics.* 19 (2003) 1-16.

This article examines focal hand dystonia in musicians. Musicians are one of the common groups that suffer from focal hand dystonia. Rapid finger movement and stressful hand positions over a long period of time can lead to this disease. There have been musicians who have retrained themselves to recover from this disease using different methods. One example is a splint that restrains the working fingers and forces the finger affected by focal dystonia to complete simple tasks.

[16] Byl, Nancy N. "Aberrant Learning Associated with Upper Extremity Overuse: Intervention Strategies." CSM, Opryland, TN. 6 February 2004.

This is a presentation about methods of retraining for people with focal hand dystonia that was given to clinicians. It covers the how the disorder is developed, and what the science is behind the disease. It also provides examples of a training program which includes activities such as retrieving small items from a small well, playing games like dominos or scrabble with Braille cards, and reading letters and words in a Braille book.

[17] *Tactuator: A new device for sensory substitution.* 1999. Tan, Hong Z. 17 January 2007. http://www.ecn.purdue.edu/HIRL/projects/tactuator.htm

[18] *Vibrotactile Tranducers andDisplays*. 2004. Engineerign Acoustics, Inc, 3 February 2007. http://www.tactileresearch.org/rcholewi/files/C_2_Spec_Sheet_IITSEG_2.pdf

[19] *R-1 Rototactor.* 2002. Steadfast Technologies. 3 February. 2007. http://www.tactileresearch.org/rcholewi/files/R1_Rototactor.pdf

[20] *R-2 Rototactor*. 2002. Steadfast Technologies. 3 Frebruary. 2007. http://www.tactileresearch.org/rcholewi/files/R2_Rotactor.pdf

[21] Debus, Becker, Dupont, Jang, Howe. "Multichannel vibrotactile display for sensory substitution during teleoperation" 2001 International Symposium on Intelligent Systems and Advanced Manufacturing, Newton, MA, 28-31, October.

[22] *Logitech iFeel Mouses.* 15 March 2001. Daniel Rutter. 2 February 2007. http://www.dansdata.com/ifeel.htm

[23] Toma, Shinobu and Yoshio Nakajima. "Response characteristics of cutaneous mechanoreceptors to vibratory stimuli in human glabrous skin." *Neuroscience Letters* 195.1 (1995): 61-63.

[24] Vallbo, A.B. and R.S. Johansson. "Spatial Properties of the population of mechanoreceptive units in the glabrous skin of the human hand." *Brain Research* 166.2 (1980): 353-356.

[25] Lundström, Ronne. "Local Vibrations – Mechanical Impedance of the Human Hand's Glabrous Skin." *Journal of Biomechanics* 17.2 (1984): 137-144.

[26] Howe, R.D. and A.Z. Hajian. "Identification of the Mechanical Impedance at the Human Finger Tip." *Journal of Biomechanical Engineering.* 119 (1997): 109 – 114.

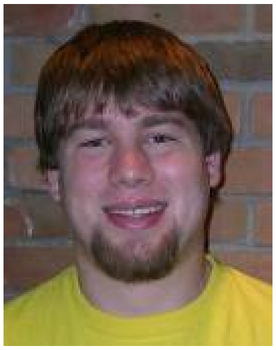
[27] Rao, Singiresu S. <u>Mechanical Vibrations.</u> 2nd Edition. Reading, MA: Addison-Wesley, 1986.

[28] CES Selector Version 4.6.1. Cambridge, United Kingdom: Granta Design Limited, 1991.

[29] "OOPic Home Page." <oopi.com> Savage Innovations: 2007.

12. Team Bios

Kevin Bielawski



Kevin is completing his third year in mechanical engineering at Michigan. It was in his hometown of Lansing where he first became interested in mechanical engineering. His mother took him to a design fair at Michigan State University, and he thought that it was very interesting. He is currently a trumpet player in the Michigan Marching band, and he is a member of Pi Tau Sigma, the mechanical engineering honor society. In the summer of 2006, Kevin worked as an intern at Caterpillar, Inc. in sound and cooling research, and he plans to work there again in the summer of 2007. Kevin plans to complete his undergraduate degree in mechanical engineering, and then continue with mechanical engineering by earning a Master's degree in the SGUS program at Michigan. He then plans to get a job with a large company and live someplace warm.

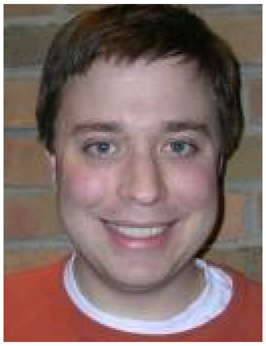
Chris Bogan

Chris is currently a fourth year mechanical engineering student. He is from Battle Creek, MI where he attended Lakeview High School. Chris was originally interested in mechanical engineering because he had a strong affinity for math and science and he liked the idea of designing new technology for companies. In the summer of 2005, he had an engineering internship at Eaton Corporation where he worked on the assembly line efficiency of EGR units. He is a member of the mechanical engineering honor society Pi Tau Sigma, and was also a four year member of the Michigan Marching Band in the trumpet section. He is currently planning to attend Medical School after he completes his undergraduate degree.

Annie Fyfe

Annie is currently in her fourth year studying mechanical engineering. She is from Tahoe City, CA where she attended North Tahoe High School. She had an internship at D.C. Cook Nuclear Plant where she worked in rotating equipment, and predictive maintenance. She is involved with the Society of Women Engineers, Michigan Marching Band, and Michigan Outdoor Adventures. After graduation, she hopes to continue to work in the energy industry, eventually doing research for the Department of Energy.

Ben Przeslawski



Ben is a fourth year student in the mechanical engineering program. After working at a Co-op at TRW Automotive during the winter semester in 2006, he plans to graduate in December 2007. Since his youth, growing up in Saline, MI, he has always known that he would attend the University of Michigan. From a young age he has had an interest in building things and loved working with toys such as Lego's and Erector Sets. He continues this passion as an active member of the University's SAE Baja Racing Team, where he is responsible for the design and manufacturing of the car's gearbox. Ben plans on pursuing a Master's degree after his graduation.

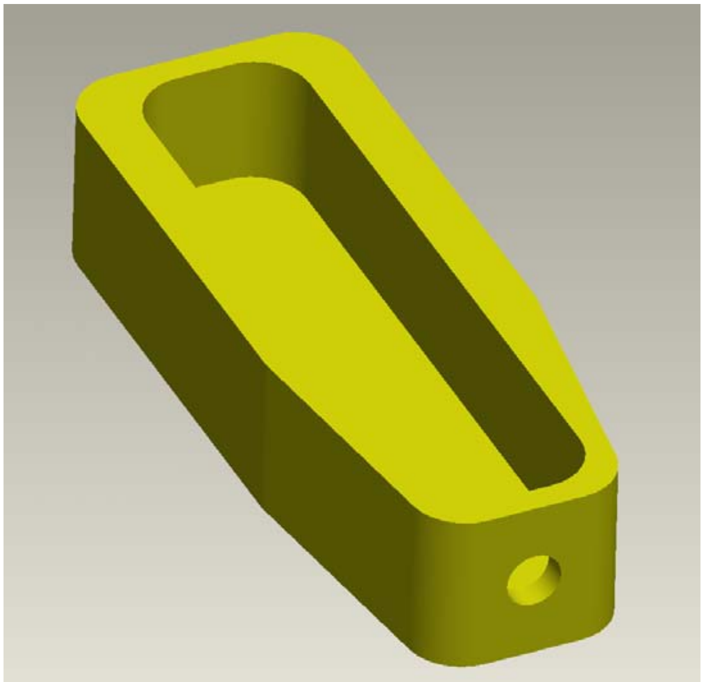
Appendix A

Project QFD

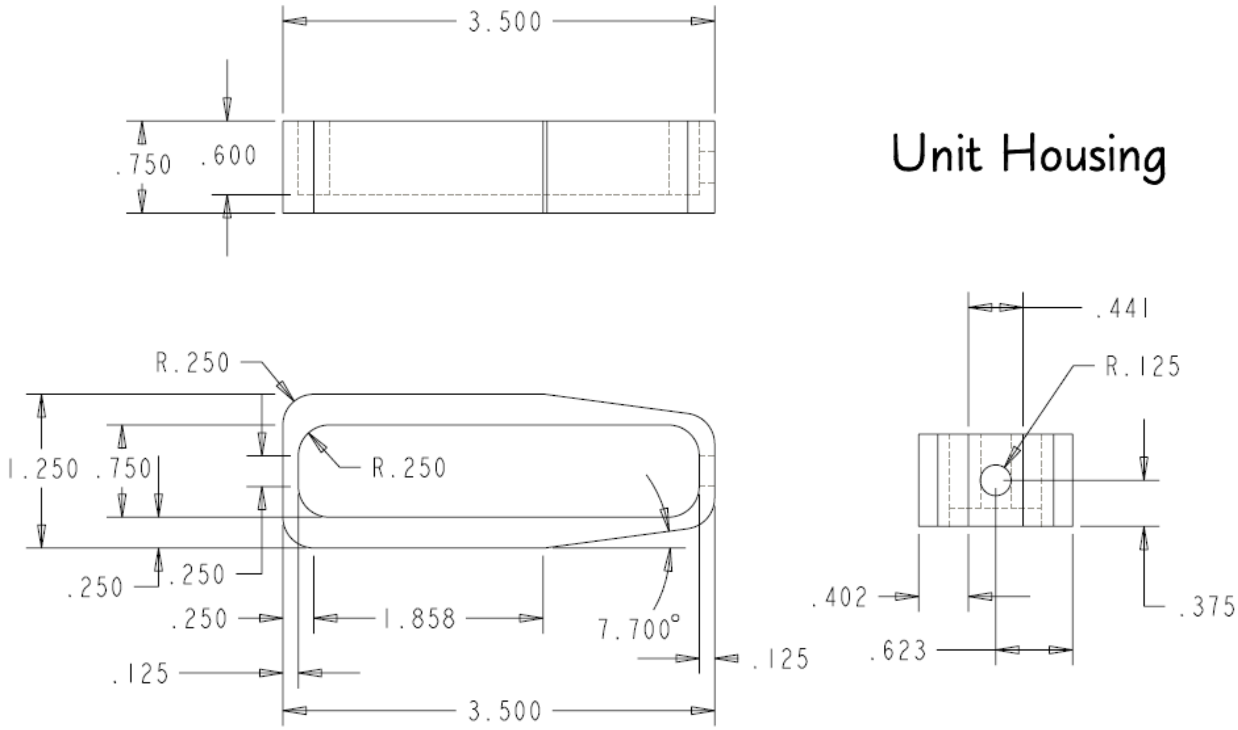
	Weight*	Vibratory Stimulation	Ability for Computer Interface	Isolation of Vibrations	Multiple Stimulations per Finger	User Response	Materials	Shape	Duration of Vibration	Amplitude of Vibration	Frequency of Vibration	Interval of Vibrations	Color	Electrical Requirements
Cheap	4	9	3	9	9	1	9	3	1	3	3			1
Portable	3	1		3	1			9						3
Robust	3	9		3	1	3	9	1	3	3	3	1		
Easy to use / Control	3		9		1	9		1						3
Retrains User	4	9	3	9	3	9			9	3	3	9		
Comfortable	2	1				3	9	9	1	1	1		1	
Rewarding	1		9			3								
Challenging	2	3	3	1	1				9	9	9	9		
Total		110	66	92	59	85	81	63	69	53	53	57	2	22
Normalized		0.14	0.08	0.11	0.07	0.10	0.10	0.08	0.08	0.07	0.07	0.07	0.00	0.03

Appendix B

Unit Housing Render

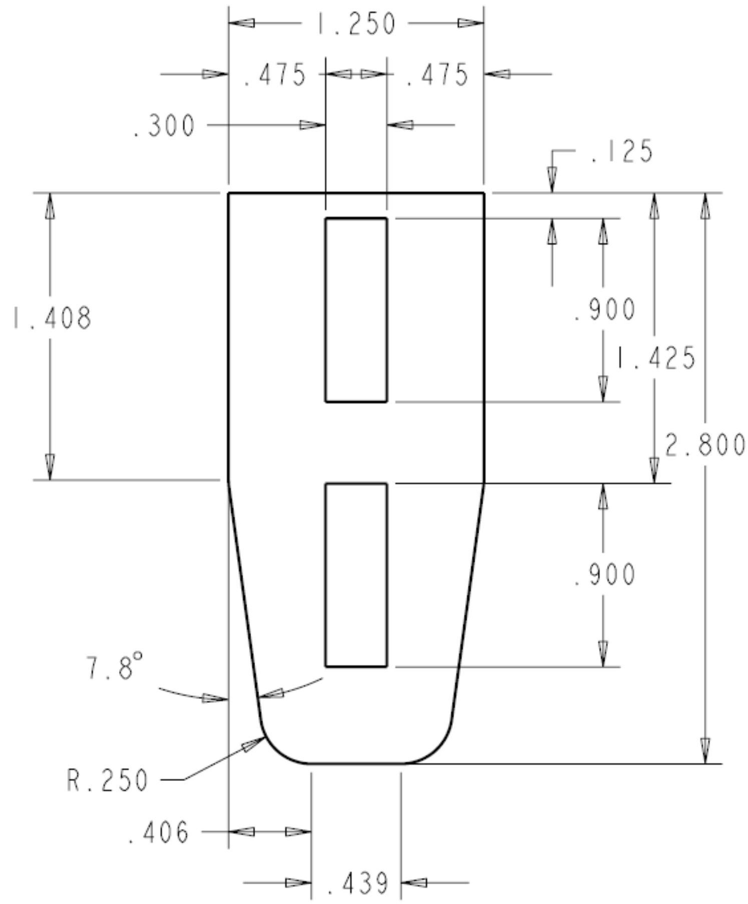


Unit Housing Drawing



Rubber Sheet Render

Rubber Sheet Drawing



Appendix C

OOPic Program

```
'This program controls four sequences of operations
'This program is to be used with the isolation units
'Four Tests can be programmed at the top by changing the:
'                    motor duration, motor delay, motor ioline #, and motor dutycycle
'motor duration = length of time each motor runs
'motor delay = delay inbetween each motor vibration
'motor ioline # = which motors run: 'a' is first and 'b' is second
'                                         see chart for appropriate ioline numbers
'motor dutycycle = essential power of the motor, controls the perceived force

'The top lines of code can be used to change the four previously mentioned variables

'Connection requirements:
'          Vibration motors are connected to iolines 1-4 and 28-31
'          User inputs are connected to iolines 8-11
'          Administrator inputs are connected to iolines 12-15

'See lines 70 through 108 to set the variable for your test

Dim RunMotor1 As New oEvent
Dim RunMotor2 As New oEvent
Dim RunMotor3 As New oEvent
Dim RunMotor4 As New oEvent

Dim MotorInput1 As New oDIO1
Dim MotorInput2 As New oDIO1
Dim MotorInput3 As New oDIO1
Dim MotorInput4 As New oDIO1

Dim UserInput1 As New oDIO1
Dim UserInput2 As New oDIO1
Dim UserInput3 As New oDIO1
Dim UserInput4 As New oDIO1

Dim Motor1a As New oPWML
Dim Motor1b As New oPWML
Dim Motor2a As New oPWML
Dim Motor2b As New oPWML
Dim Motor3a As New oPWML
Dim Motor3b As New oPWML
Dim Motor4a As New oPWML
```

```
Dim Motor4b As New oPWML

Dim Wire1 As New oWire
Dim Wire2 As New oWire
Dim Wire3 As New oWire
Dim Wire4 As New oWire

Dim MotorDuration1 As New oByte
Dim MotorDuration2 As New oByte
Dim MotorDuration3 As New oByte
Dim MotorDuration4 As New oByte

Dim motor1dutycycle As New oNib
Dim motor2dutycycle As New oNib
Dim motor3dutycycle As New oNib
Dim motor4dutycycle As New oNib

Dim MotorDelay1 As New oByte
Dim MotorDelay2 As New oByte
Dim MotorDelay3 As New oByte
Dim MotorDelay4 As New oByte

Dim Win As New oSpeaker


Sub Main()
  ooPIC.PullUp=1

'Set the duration of the motor vibration for each test.
'        Integer value between 0 and 255
  MotorDuration1 = 7
  MotorDuration2 = 7
  MotorDuration3 = 7
  MotorDuration4 = 7

'Set the delay between two vibrations for each test
'        Intger value between 0 and 255
  MotorDelay1 = 0
  MotorDelay2 = 0
  MotorDelay3 = 0
  MotorDelay4 = 0

'Set the dutycycle for each test.
'        Integer value between 0 and 15 (15 is max dutycycle, 0 is off)
  motor1dutycycle = 15
  motor2dutycycle = 15
```

```
 motor3dutycycle = 15
 motor4dutycycle = 15

'Set the motors to be run for each test.
'	See companion chart to see which motor corresponds to which part of which finger.
 Motor1a.IOLine = 3
 Motor1b.IOLine = 1
 Motor2a.IOLine = 2
 Motor2b.IOLine = 29
 Motor3a.IOLine = 28
 Motor3b.IOLine = 31
 Motor4a.IOLine = 30
 Motor4b.IOLine = 3

'Set the user input line for each test
'	See companion chart to see which input corresponds to the appropriate finger
'	Match the user input to the finger of the 'a' motor for each test
 UserInput1.IOLine = 10
 UserInput2.IOLine = 11
 UserInput3.IOLine = 9
 UserInput4.IOLine = 8

'-------------------------------------------------------------------------------------
'DO NOT CHANGE ANYTHING BELOW THIS LINE
 UserInput1.Direction = cvInput
 UserInput2.Direction = cvInput
 UserInput3.Direction = cvInput
 UserInput4.Direction = cvInput

 MotorInput1.IOLine = 12
 MotorInput1.Direction = cvInput
 MotorInput2.IOLine = 13
 MotorInput2.Direction = cvInput
 MotorInput3.IOLine = 14
 MotorInput3.Direction = cvInput
 MotorInput4.IOLine = 15
 MotorInput4.Direction = cvInput

 Wire1.Input.Link(MotorInput1)
 Wire1.Output.Link(RunMotor1.Operate)
 Wire2.Input.Link(MotorInput2)
 Wire2.Output.Link(RunMotor2.Operate)
 Wire3.Input.Link(MotorInput3)
 Wire3.Output.Link(RunMotor3.Operate)
 Wire4.Input.Link(MotorInput4)
 Wire4.Output.Link(RunMotor4.Operate)
```

```
  Wire1.InvertIn = cvTrue
  Wire1.Operate = cvTrue
  Wire2.InvertIn =cvTrue
  Wire2.Operate = cvTrue
  Wire3.InvertIn = cvTrue
  Wire3.Operate = cvTrue
  Wire4.InvertIn = cvTrue
  Wire4.Operate = cvTrue

End Sub


'-------------------------------------------------------------------------
'BUTTON 1


Sub RunMotor1_Code()

  Motor1a.Operate = 1
  Motor1a.DutyCycle = motor1dutycycle
  Delay = MotorDuration1
  Motor1a.Operate = 0

  Delay = MotorDelay1

  Motor1b.Operate = 1
  Motor1b.DutyCycle = motor1dutycycle
  Delay = MotorDuration1
  Motor1b.Operate = 0

  While UserInput1 = cvTrue And UserInput2 = cvTrue And UserInput3 = cvTrue And
UserInput4 = cvTrue
  Wend

  If UserInput1 = cvFalse Then
    Call Victors
  Else
    Call Buzz
  End If


End Sub


'-------------------------------------------------------------------------
```

```
'BUTTON 2

Sub RunMotor2_Code()

  Motor2a.Operate = 1
  Motor2a.DutyCycle = motor2dutycycle
  Delay = MotorDuration2
  Motor2a.Operate = 0

  Delay = MotorDelay2

  Motor2b.Operate = 1
  Motor2b.DutyCycle = motor2dutycycle
  Delay = MotorDuration2
  Motor2b.Operate = 0

  While UserInput1 = cvTrue And UserInput2 = cvTrue And UserInput3 = cvTrue And
UserInput4 = cvTrue
  Wend

  If UserInput2 = cvFalse Then
    Call Victors
  Else
    Call Buzz
  End If


End Sub


'------------------------------------------------------------------------
'BUTTON 3

Sub RunMotor3_Code()

  Motor3a.Operate = 1
  Motor3a.DutyCycle = motor3dutycycle
  Delay = MotorDuration3
  Motor3a.Operate = 0

  Delay = MotorDelay3

  Motor3b.Operate = 1
  Motor3b.DutyCycle = motor3dutycycle
  Delay = MotorDuration3
  Motor3b.Operate = 0
```

```
  While UserInput1 = cvTrue And UserInput2 = cvTrue And UserInput3 = cvTrue And
UserInput4 = cvTrue
  Wend

  If UserInput3 = cvFalse Then
    Call Victors
  Else
    Call Buzz
  End If

End Sub


'-----------------------------------------------------------------------
'BUTTON 4

Sub RunMotor4_Code()
  Motor4a.Operate = 1
  Motor4a.DutyCycle = motor4dutycycle
  Delay = MotorDuration4
  Motor4a.Operate = 0

  Delay = MotorDelay4

  Motor4b.Operate = 1
  Motor4b.DutyCycle = motor4dutycycle
  Delay = MotorDuration4
  Motor4b.Operate = 0

  While UserInput1 = cvTrue And UserInput2 = cvTrue And UserInput3 = cvTrue And
UserInput4 = cvTrue
  Wend

  If UserInput4 = cvFalse Then
    Call Victors
  Else
    Call Buzz
  End If

End Sub


Sub Victors()
        Do
                B :G :'A : halfB: G: A: halfB: C:
```

```
        Exit Do

                ooPIC.Delay = 1000
        Loop

End Sub

Sub B() ' Plays note 'B'
        Win.Beep(60473,80,0)
End Sub

Sub G() ' Plays note 'G'
        Win.Beep(59157,40,0)
End Sub

Sub A() ' Plays note 'A'
        Win.Beep(59853,40,0)
End Sub

Sub halfB() ' Plays note 'B'
        Win.Beep(60473,40,0)
End Sub

Sub C() 'Plays note 'C'
   Win.Beep(60757,80,0)
End Sub



Sub Buzz()
  Do
     Win.Beep(50000,50,0)
    Exit Do
  Loop

End Sub
```