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Assistive Device to Augment Strength in the Weak Hand of a Stroke Patient

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Title: Assistive device to augment strength in the weak hand of a stroke patient

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Background: More than 700,000 Americans suffer strokes annually. Stroke is the third leading cause of death in the country. And stroke causes more serious long-term disabilities than any other disease (ScienceDaily).

A stroke can be very debilitating to its victims. The amount of damage done to the brain varies among stroke victims and consequently the physical debilities do as well. Patients can experience effects ranging from complete inability to move muscles to a mild deficit in mobility of muscles. Commonly, stroke patients incur damage to one hemisphere of their brain. This damage leaves them physically impaired on the opposite side of their body.

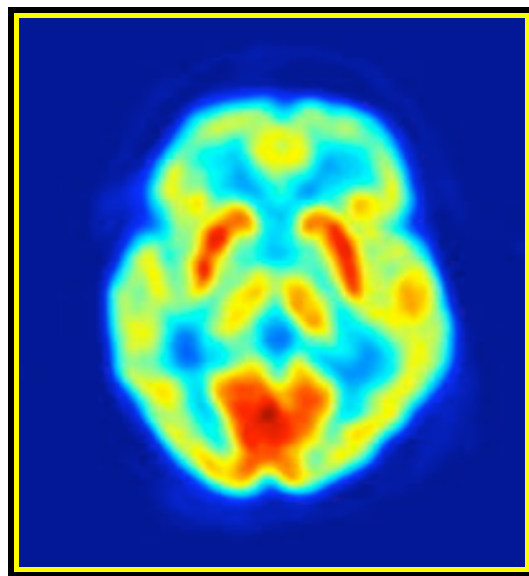


Figure 1, PET scan of the human brain

Studies have found that the brain is capable of many degrees of recovery to trauma. Scans, such as the PET and MRI, have been developed to detect the flow of blood in certain areas of the brain, see above Fig 1.

Researchers have found that when a person completes a physical task, blood flow increases in the local of the brain responsible for that task. Using this technology it has been found that one ability of the brain is to transfer the responsibility of a function from the trauma hemisphere to the healthy hemisphere. The brain will undergo re-wiring rather than re-growth. This is like the brain using a “spare tire” to make up for the loss of function, as the function is never completely regained. The majority of improvement in function occurs within the first three months after stroke (ScienceDaily). Patient therapy during this post-stroke time could be extremely valuable.

The goal of our design project is to augment the movement of the patient’s hand, allowing for a “smooth” process of brain repair to the region of the brain responsible for various hand movements. We would like our design to be capable of assisting a patient up to the average normal human hand grip strength, ~ 279 N (Oh and Radwin).

A key characteristic of post-stroke hand mobility is that the majority of patients require more effort extending rather than gripping. Also, studies have shown that grip force and extension force are variable, depending upon the openness of the hand (Oh and Radwin). These trends in hand strength add complexity to hand therapy and will consequently be important components to the development of our device.

Design Problem: After stroke some patients regain no movement of the affected body part, but most regain movement but not full strength. There are groups working on robotic devices that sense and augment movement. This helps the movement itself, and is hypothesized to improve recovery of strength and or dexterity. The device should be a glove or mitten design that could sense and augment finger movements in stroke patients.

Client Requirements: Our client, Dr. Matt Jensen would like our team to develop a glove or mitten that is able to augment finger movements in stroke patients. This device should include the following items:

- Sense when the patient is opening or closing their hand and augment this movement based on pressure
- Able to be removed from hand with little to no work involved
- A safety feature so the patients fingers are not broken
- Be affordable and convenient for all stroke patients
- Can include electric, hydraulic, or various other mechanical approaches



Figure 2, The HOWARD therapeutic device

Similar Products: Researchers and therapists alike have been working hard for many years to accomplish a therapeutic device not only for the hand, but for other “hinged” ligaments

such as knees and arms. Although there are not many products on the market today that mimic our proposed design, there is one in particular that seems to work towards the same goal. This product is named the HOWARD device (Hand-Wrist Assisting Robotic Device). The HOWARD is a robotic device that attaches to the hand using Velcro straps and augments the movement of the patient's hand. The device only helps that patient move if the hand is initially moved at least (1/10) of an inch. The HOWARD device strives to significantly improve grasping and releasing ability, manual dexterity, and range of hand and wrist motion (Phend).

Product Uniqueness: Our device will be very similar but will deviate from the HOWARD by allowing patients not only to use it for therapy, but also for everyday use, which the HOWARD is not currently capable of doing. This way, patients will get practice accomplishing day-to-day tasks they may not do in therapy.

Design Alternatives: On the most basic level, amplifying a stroke patient's grip force is about transfer of energy. Given a relatively small exertion of power from the user, the device must use an outside power source to add to the power generated by the user to increase the total grip force he or she can produce. There are three fundamental systems of transmitting energy in this manner from one place to another: mechanical, electrical, and hydraulic systems. Each of these three systems was considered as a candidate for the energy transmission system upon which the device would be based.

Since safety, both of the user and of the people whom the user would interact with in everyday life, was of paramount concern in designing this amplification device, precision of control was the major evaluative criteria in consideration of each of these systems. The system must be able to deliver a precise amount of power for any given power input, without fail, so as

to avoid generation of dangerous levels of force. Size and weight of the system was also considered as a major criterion for the most viable candidate. Because the device's ability to be used in everyday life is the central point of difference between this device and similar apparatus already on the market, it must be small and light. If it is too heavy or unwieldy, it will be discourage patients from using the device in regular activity. Also, if heavy, repeated use could cause other musculo-skeletal debilities due to the abnormal load at the hand, especially in an already weakened stroke patient. By the same token, ease of use was also considered carefully in selection. Ease of use includes both functions during use and while idle, as well as the level and frequency of maintenance required for the system.

Factors that were considered, but on a more minor scale were the level of augmentation each system could supply, the aesthetic appeal each system would allow, and the overall cost. On average, human grip strength is around 327 N. Each system, given the correct selection of elements, is able to output this amount of force, albeit with different numbers and sizes of constitutive elements. As such, making the force output of the system most efficient was a consideration which was not deemed to be the priority at this stage of the design process. Similarly in the case of aesthetic appeal, this attribute is secondary to the actual functioning of the device at this stage of the project, but must be considered in the future in order to encourage users to wear the device. The cost of the device was also secondary to the ultimate functionality of the device, but will obviously be minimized as the design process proceeds.

Hydraulic Systems: Hydraulic systems function based on a few basic properties of liquids: shapelessness, incompressibility, and transmission of force (“Hydraulic systems”). These properties lead to the application of Pascal’s Law which states that pressure in a fluid acts

equally in all directions. Hydraulic systems harness the consequences of this law to generate large amounts of force via controlled transmission of liquid through a network of hoses and reservoirs to pistons of varying sizes. Of the three power transfer systems, this one can generate the greatest amount of power. It also generates very smooth motion, which is very desirable in order to minimize vibrational harm the device inflicts on a user.

Unfortunately, this system tends to require a large number of constituent parts. At minimum, it requires reservoir to store the fluid. It requires a pressure source like a pump, as well as a pressure user which generates either linear or rotary motion. In order to control flow, it requires a large network of valves, filters, and hoses to generate the correct outputs for given inputs. Finally, of course, the system requires a transmission fluid. This causes further problems compounding that of the system's already excessive size. The fluid can leak, meaning the system may require regular maintenance.

Mechanical Systems: Mechanical systems use gear ratios to transfer power via tradeoffs between speed of rotation and torque generated. Ultimately, these systems are the most intuitive to understand as they consist of a number of “real” mechanical elements such as gears, levers, belts, springs, and other elements which allow you to see the flow of energy. Unfortunately, because of these elements, mechanical systems tend to be large. Furthermore, in our particular case, the control logic will be particularly complex because grip strength varies with the degree of openness of the hand. As such, a mechanical system would require the ability to switch between multiple gear ratios to provide the desired amplification. This will add to the size of this type of system, as well as decreasing the level of control that designers have overall. The need to shift gear ratios will also interfere with the system's ability to operate smoothly on the scale of

the hand, and may introduce undue stress upon the user's musculo-skeletal system. The speed of system response will also be hindered due to this need necessity in the control logic.

Electrical Systems: Electrical systems provide a number of control and size advantages over either purely hydraulic or mechanical systems. As shown in figure 3 below, a complex system of springs and pistons and masses can be replaced by an equivalent network of sources, resistors, inductors, and capacitors.

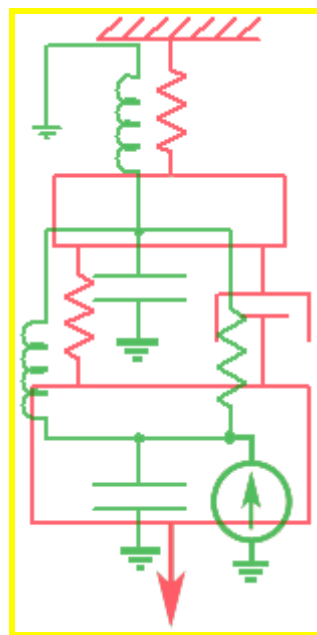


Figure 3, Equivalent mechanical (red) and electrical systems (green). The mechanical system will most likely consist of elements much larger than those of the electrical system, especially when dealing with the controlling and output force ranges encountered by this device.

This network of electrical elements can be shrunk down and printed onto a very small chip if necessary. This size reduction allows for very complicated logical controls to be applied in a very small amount of space and mass. Furthermore, the ability to use a microprocessor to seamlessly switch between different sets of logic (the equivalent to shifting gear ratios) will reduce the excess vibrational stress introduced to the user and decrease the reaction time of the

system. If contained properly, this type of system would also require little maintenance, as moving parts are minimized reducing the need for regular oiling and care. Finally, using this type of system as a basis for control will allow incorporation of mechanical and hydraulic components (e.g. actuators and rotational motors) as may be necessary to generate forces of the required magnitudes. Table 1 below summarizes the evaluations that were made for each system and demonstrates the major reasons for our selection of an electrically based system.

Design Criteria (Points out of 100)	Electronic	Mechanical	Hydraulic
Accuracy and Precision (30)	30	10	10
Size/Weight (20)	20	15	10
Ease of Use (20)	15	15	10
Augmentation Factor (15)	10	10	15
Aesthetics (10)	10	10	5
Cost (5)	5	5	0
Total	90	65	50

Table 1, Design matrix for selection of a basic control system for the device.

Stepper Motor: Stepper motors are common types of motors used in a wide array of settings such as in floppy disc drives, scanners, and printers as well as other industrial applications. They are mass produced and relatively small, cheap, and quiet compared with other

types of motors. They have excellent response to acceleration and deceleration commands and operate in an open loop system with no positive feedback required (Images).

A stepper motor is a type of electric motor that partitions the rotation into multiple steps. It contains a permanent magnetic rotating shaft, called the rotor, and electromagnets on the fixed portion that surrounds the motor, called the stator (Fraser). The rotor is surrounded by a gear-like device that can align with one of the electromagnets. When one of the electromagnets is activated, usually by an external control circuit such as a microcontroller, the gear aligns with the first one and is slightly offset from the second electromagnet. Then to move it one step, the first electromagnet is turned off and the second one is powered on. The gear then aligns with the second electromagnet and moves slightly (Images). The more electromagnets the motor has the more precise each step can be. The process is repeated until the motor runs a complete 360 degrees, and it can then be repeated infinitely until power is removed. Frequent movements like these allow the motor to precisely “step” to a new angle. The angle that the motor achieves can vary widely by application. Typical motors run at an angle from about 1 to 5 degrees per step (Shinano). The process can then be reversed with the second electromagnet shutting off and the first one being powered on. This results in a movement in the opposite direction. A mechanism for this movement is shown in the figure below (Figure 4).

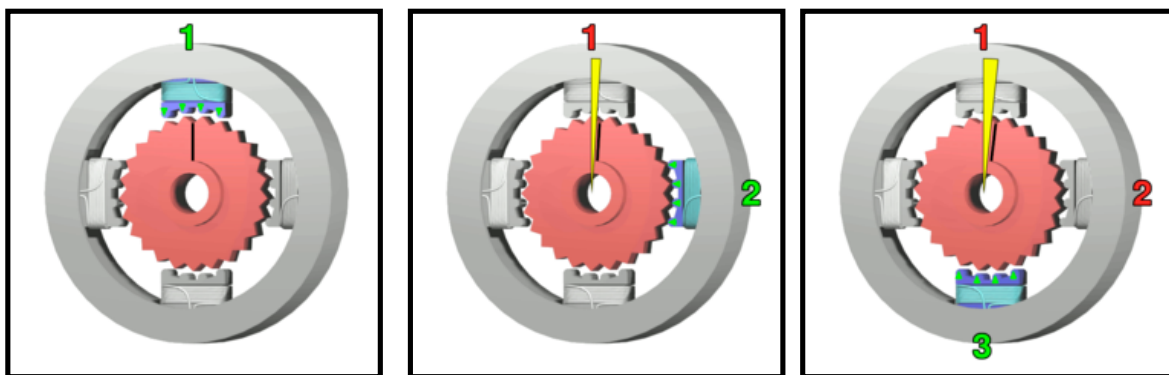


Figure 4. The first electromagnet (labeled 1) is activated first. Then, to move one step, the first one is deactivated and the second electromagnet is activated, which aligns the gear with the second one to move one step. To move another step the process is repeated with the next electromagnet.

There is also the notion of half-stepping which can increase the precision of the device. This can be controlled by the programming of the microcontroller to have two of the electromagnets activated at one time. The rotor will then move to a position in between each active electromagnet. This can be followed by one of the electromagnets turning off and the gear moving to a normal step position (Shinano). This process can then be repeated for each half step or full step in the process. Stepper motors operate with an open loop system with no positive feedback required. This means that the controller has no feedback on where the rotor actually is. This generally means the motors have to be over-engineered so that the motor does not lose any steps in the process (Images). This leads to an increase in the size of the motor and therefore an increase in the device as a whole.

The motor that we are considering for the project has very precise control over movement angle at approximately 1.8° per step, which equates to 200 rotor teeth in the gear. It can be easily controlled with a microcontroller and a simple circuit. It can also be powered by a small battery or other power source.

Advantages: Stepper motors are generally low cost, efficient motors that continuously provide precise angles with each step (Shinano). The BME lab has plenty of motors that can be borrowed at no cost. Stepper motors also have high reliability. They perpetually create exact angle measures without need for recalibration (Shinano). When implementing this design on our device, the fact that there can be precise angles directly associated with it is a major advantage

because it allows the user's hand to move to the exact position he or she wishes. Also, they are very durable and can work in most environments. At a low speed, which is the condition our device will be operating under, it provides a high torque ratio and therefore enough rotation for a human hand (Images).

Disadvantages: Although the design offers promise in several areas, there are also a few obstacles to its implementation. Stepper motors in general produce a vibration called resonance that is more vigorous than other types of motors. This is caused by the rapid movement of the gear clicking from one position to the other because the motor has to accelerate and decelerate in a short period of time (Images). This could lead to an uncomfortable sensation to the user unless proper casing is applied. Also, they experience decreasing torque at increasing speeds. However, this is a minor issue because our device will mainly be operating at low speeds as the patient moves his or her hand. Stepper motors are also more complicated than typical DC motors because they need the precise amount of electricity to the precise places at the precise time and usually have many wires integrated in the circuit (Images). Fortunately, with the correct microcontroller this integration can be easily solved.

Microcontroller: Microcontrollers are essentially small computers used in a variety of applications such as remote controls, automobiles, and cell phones. They are specific purpose computers designed to do one task , which means they can come in a variety of forms. They are a single integrated circuit with many features in common with normal computers.

Microcontrollers usually include a small central processing unit (CPU) to control the signals and execute the program, serial inputs and outputs, RAM and ROM for data and operating storage and in-circuit programming. They consume very low power, usually 50 milliwatts or less, are

usually small and inexpensive (Brain). They operate at low speeds, usually only a few MHz, but this is adequate for many typical applications. Many have the ability to convert to a low power mode called “sleep mode” until a button press returns it to normal. This is ideal for low power and long lasting battery life. They can work in many types of environments and can be implanted or embedded into many types of devices. Because they are imbedded they do not have a typical human interface of normal computers. This means they must be connected to an external source that will provide directions for it. In many cases this external source is a typical computer connected via a USB cable. (Brain)

When used in conjunction with the stepper motor, the microcontroller is also called the indexer and is the pulse source for the motor. This can be programmed to produce the steps of the motor by providing the power to energize specific electromagnets which move the rotor. The number and rate of pulses determines the speed, direction of rotation and the amount of rotation of the motor output shaft. The input of these variables can be controlled by an external analog sensor, which for our project will be the amount of force the user will supply with his or her hand (Maxim).

The microcontroller we are using for our project is called the BASIC Stamp Discovery Kit (BS2-IC) provided by parallax. It is called a “stamp” because it is about the size of a postage stamp. It includes a BASIC program to get started and only requires a 9V power source (Parallax). Since the program only runs on the BASIC programming language, there will be some limitation in the usage of the device. However, for our purposes, a simple program will be enough to move the device the desired amount. It can be connected to a computer via a USB cable so a program can be created to send the desired number of pulses to the stepper motor

(Parallax). Even though these are generally considered to be low cost devices, this will be the major expense in the production of our prototype.

Sensor: For our prototype we will need a noninvasive sensor that will output analog signals to be processed by the microcontroller. One type of sensor that will work with our design is a liquid pressure sensor similar to a blood pressure sensor. These are regularly used in hospitals and clinics all around the world for accurate measuring of arterial pressure. For our project, we will not need the arterial pressure, but the same basic concept can be used to measure the amount of force and movement exerted by the user of our prototype, which is then translated into movement by our device.

Blood pressure sensors operate by inflatable cuffs placed around the upper arm of the patient. This cuff is then attached to a manometer which accurately measures arterial pressure without need for calibration. When vibrations or pressure is sensed on the cuff the signal is transferred into a transducer in the monitor that converts the measurements into electrical signals. These electrical signals are then transferred into systolic and diastolic arterial pressure (Danfoss). An amplifier will also be needed to increase the signals from the sensor to the microcontroller.

For our device, we will wrap the cuff of the sensor around the patient's hand so that it fits comfortably, yet securely. This cuff could be custom designed to fit around a person's fingers so it doesn't occupy the palm of the hand. This will allow the user to be able to grasp objects with his or her hand. When the user wishes to move his or her hand, he or she will put slight pressure on the cuff with his or her fingers. This will translate to the manometer which will give an electrical output signal. Instead of giving readings in systolic and diastolic pressure, however, these signals will be transferred to the microcontroller which will then further process it.

Advantages: The blood pressure sensor is a noninvasive sensor that provides quick and simple oscillometric measurements which can easily be converted to output signals with our microcontroller (Danfoss). They are easy to use and affix to the hand and are very reliable with virtually no complications. Also, there is little discomfort or pain to the user. Blood pressure sensors are fairly common devices found in many places and are relatively inexpensive (Vernier). The BME lab has extra blood pressure sensors that we can borrow for our experiment at no cost.

Disadvantages: The blood pressure sensor has many advantages; however, there are some hindrances in its design as well. This type of sensor may provide less accurate readings than other more precise sensors (Vernier). Also, since the design uses an inflatable cuff, this may obtrude the palm and the user will have difficulty picking up objects. When objects are picked up and grasped in the palm, there may be some pressure on the cuff, which will cause the device to continue closing the hand. This is a major problem and will be corrected in the future with a more advanced sensor.

Prototype Design: The current prototype design combines the stepper motor, microcontroller and liquid pressure sensor into one device. The cuff of the blood pressure sensor will be attached to the user's hand and can sense the amount of pressure the person applies to it. When pressure is sensed, this signal is sent to the manometer which reads it and outputs an electrical signal to the microcontroller. The microcontroller will then be programmed to process the signal and send a new signal to the stepper motor instructing it to move in the appropriate way. It can be programmed for different speeds and different angles depending on how much the user inputs. Since there is also a sensor on the back of the hand, this process can be reversed to move in the opposite direction and open the user's hand.

Future Work: The complexity and scope of stroke rehabilitation design project have posed a substantial challenge. In the future we will enhance many aspects of our device. We will work in steps to enhance the features of our device. We will look into improved mobility and mechanics, improved sensory input and output, and a more compact size.

Our current design is limiting to the hands range of motion in the future we will enhance our design to better match the mechanics of the human hand. To do this we will increase the number of joints and mechanical complexity of the device to account for all the different movements a patient may want to make with there hand. For example our current focus is on the movement of the four fingers simultaneously; in the future we will focus on allowing each finger to move individually via its own mechanism. This improved mobility will allow for a more effective rehabilitation.

The sensitivity of input and output of our device is crucial to its function. In the future we will incorporate sensors that accept input in a way that can easily be detected and translated into the proper mechanical movement. Currently we are looking into using a blood pressure sensor for the purpose of setting up a reasonable system of pressure input and mechanical output. In the future electrical sensors will be incorporated that are sensitive and easy to calibrate. These sensors will be incorporated with the hope of increasing the ease of use to the patient. As far as mechanical output, we will implement a motor and gear system that allows for a smooth and rapid response to input.

Finally, we will re-create our design with smaller and more efficient/practical components. One of the main purposes of this device is to be user friendly and portable. To accomplish this we will integrate a smaller controller unit, battery, and mechanism. Although

the design proposal represents a significant challenge, success with such a device would be well worth the effort as a rehabilitation device to the many people who are victims to strokes.

Appendix

Product Design Specifications

PRODUCT DESIGN SPECIFICATIONS

February 3, 2008

Title: Assistive device to augment strength in the weak hand of a stroke patient

Team:

Tom Fleming-Team Leader
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Mark Reagan-Communicator

Function: After stroke some patients suffer complete loss of mobility in the affected body part; however, most regain a certain degree of their original mobility and strength. There are groups working on robotic devices that sense and augment movement - this helps patient mobility, and is hypothesized to improve recovery of strength and or dexterity. The device

should be glove or mitten design that could sense and augment finger movements in stroke patients.

Client requirements: Our client, Dr. Matt Jensen, would like our team to develop a glove or mitten that is able to augment finger movements in stroke patients. This device should be able to sense when a patient is opening or closing his/her hand and augment their movement based on the pressure being applied on the glove. The device should also be able to be removed from the hand with little work involved. Important areas of focus include efficiency of the design, safety regarding glove movements, and the ability to be affordable and convenient for all stroke patients. This project may involve electric, hydraulic, and various other mechanical approaches.

Design Requirements:

1. Physical and Operational Characteristics

a. Performance Requirements

The product should be able to improve the mobility of a stroke patient's hand while being comfortable and safe for the patient. It should be unobtrusive and be able to be worn only when the user wishes. The device must be portable and capable of being attached and worn by a patient in a home setting. It should have a significant battery life so the user can wear it for long periods of time. To add to its practicality, the device should be able to achieve average hand strength assistance, approximately 279 N.

a. Safety

If electrical power is used, electrical safety is the main concern and the device should have proper guidelines on use. Electrical components should be encased in a protective material to reduce the risk of electrical shock. If other power sources are used, proper safety should be taken and proper instruction on use of the device should be given. Device should be tested to ensure its efficiency over time. Minimal user training should be required.

b. Accuracy and Reliability

The device should be able to withstand prolonged use and be readily available whenever the user would like to use it. It should have lengthened battery life for continual use. It should accurately sense the amount of force the user wishes to exert and assist in the sought movement.

c. Life In Service

The product would ideally have a power source that would last all day, approximately 6-12 hours. Additionally, it will be capable of recharging during night, approximately 6-12 hours. The product itself should last the lifetime of the user to reduce costs for patients.

d. *Shelf Life*

If batteries or another degradable power source is used, proper storage should be noted and labeled on the device. Electrical wires and other mechanics should have proper encasing so they don't degrade over time. It should be able to be stored in a home environment so it can be near the patient.

e. *Operating Environment*

The device will have to be robust enough to function in a number of different environments. Wearers may use it in a number of different temperature and humidity environments, including the possibility of total liquid immersion (as in the case of the user spilling a glass of water on the device). The device will most likely be subject to dirty and dusty conditions. The device must withstand shock loads, as objects could be dropped on the device during daily use. Electrical interference may be encountered due to the variety of household appliances, which radiate electromagnetically.

f. *Ergonomics*

Since the product will be worn on the user's hand and potentially be used in interaction with other humans, force restrictions must be established to protect both the user and other parties who might interact with the user. In the case that the user was to shake another party's hand, for example, the device must have a force feedback mechanism in order to avoid crushing the hand. Range of motion must also be restricted to avoid hyperextension or hyper-flexion of the fingers. Also, the fingers have no ability to rotate about the long axis, so torsion forces must be minimized or eliminated. Furthermore, the device must be comfortable enough to wear for extended periods of time.

g. *Size*

The device will be worn on the hand and must not be excessively large so as to be unwieldy in daily use.

h. *Weight*

The device must not add significant weight to the user's arm. Such excessive weighting could cause stress injuries to the user over extended periods of use. Ideally the device will weigh less than 1 lb.

i. *Materials*

Materials which will come in direct contact with the skin (i.e. the glove material itself) must be non-allergenic, and also non-irritating. Mechanical materials must be strong enough to withstand shock loading. Electrical components must be protected from liquid, dirt, and dust via some protective material.

j. *Aesthetics, Appearance, and Finish*

The device must mimic the shape of the human hand. It must be stylish and aesthetically pleasing so that the user is not discouraged from using the device in public.

2. Production Characteristics

a. *Quantity*

One prototype is needed at the current time, however product be designed for possible mass production in the future.

b. *Target Product Cost*

The price for production of the prototype must not exceed \$1000. The mass produced final design should be affordable to all stroke patients.

3. Miscellaneous

a. *Standards and Specifications*

FDA approval will be necessary. IRB approval will be necessary before any testing is done. Product must be able to be easily translated into mass production. Product must be proved beneficial to the recovery of stroke patients.

b. *Customer*

Stroke patients with loss of mobility in the hand. The range of patient mobility can vary from low to high, as long as some mobility is present.

c. *Patient-related concerns*

The product will have to undergo rigorous testing to ensure that it is safe for all patients under all circumstances. It must not have the potential to cause injury to the hand.

d. *Competition*

The concept of assistive movement stroke recovery therapy is new but widely known. Other devices for a wide array of body parts have been designed to assist the movement of stroke patients. To our knowledge and to the knowledge of our client no other “removable” devices have been made for the hand.

References

- “BASIC Stamp Discovery Kit." Parallax. 2007. 3 Mar. 2008
<<http://www.parallax.com/Store/Microcontrollers/BASICStampProgrammingKits/tabid/136/ProductID/297/List/1/Default.aspx?SortField=ProductName,ProductName>>.
- “Blood Pressure Sensor." Vernier. 2008. 3 Mar. 2008 <<http://www.vernier.com/probes/bps-bta.html>>.
- Brain, Marshall. "How Microcontrollers Work." Howstuffworks.Com. 3 Mar. 2008
<<http://electronics.howstuffworks.com/microcontroller1.htm>>.
- Cheever, Eric. Analogous Electrical and Mechanical Systems. Department of Engineering. Swarthmore College. 2005.
<<http://www.swarthmore.edu/NatSci/echeeve1/Ref/Analog/ElectricalMechanicalAnalog.html>>.
- Dr. Matt Jensen, UW Department of Neurology, Client

Fraser, Neil. "Electronic Control of a Stepper Motor." 19 July 1999. 23 Feb. 2008
 <<http://neil.fraser.name/hardware/stepper/ttl.html>>.

"How Sensors Work - Pressure Mapping Systems." Danfoss Limited (1998). 3 Mar. 2008
 <<http://www.sensorland.com/HowPage036.html>>.

"How Stepper Motors Work." Images Scientific Instruments. 2007. 22 Feb. 2008
 <<http://www.imagesco.com/articles/picstepper/02.html>>.

"Hydraulic Systems." Department of Naval Science. University of California at Berkley. 2006.
 16 Feb. 2008 <<http://navsci.berkeley.edu/ns10/index.htm>>.

Lovelace, Jeff. Out With Electrical, In With Mechanical. *Penton Media Inc.*, 2008.
 <http://www.motionsystemdesign.com/Issue/Article/66298/Out_with_mechanical_in_with_electrical_.aspx>.

"Micro Tutorial 1: Understanding DC Electrical Characteristics of Microcontrollers." Maxim. 3
 June 2002. Dallas Semiconductor. 3 Mar. 2008 <http://www.maxim-ic.com/appnotes.cfm?appnote_number=1087&CMP=WP-15>.

Oh, S. and R. G. Radwin. Pistol grip power tool handle and trigger size effects on grip exertions
 and operator preference, *Human Factors*, 35(3), 551-569, 1993. 25 Feb. 2008

Roberts, Colin T. Comparison of linear actuators with pneumatics and Hydraulics [Electronic
 Version]. *SKF Group Technical Press*, 2007.
 <<http://www.abrasivesmagazine.com/mtext/product/Comparison.pdf>>.

Robotic Device Helps Stroke Patients Regain Hand Use." American Stroke Association Meeting
 (2007). 9 Feb. 2007 <<http://www.medpagetoday.com/MeetingCoverage/ASAMeeting/tb/5023>>.

"Robotic Therapy Helps Restore Hand Use After Stroke." ScienceDaily. 13 Feb. 2007. 24 Feb.
 2008 <<http://www.sciencedaily.com/releases/2007/02/070208131535.htm>>

"Stepper Motor Operation and Theory." Shinano Kenshi Corporation. 5 Mar. 2008
 <<http://www.shinano.com/xampp/docs/Stepper%20Motor%20Operation%20&%20Theory.pdf>>.

Trinkel, Bud. Fluid Power Basics: Practical Knowledge about Hydraulic and Pneumatic
 Component Systems [Electronic Version]. *Penton Media Inc.*, 2007.
 <<http://www.hydraulicspneumatics.com/200/eBooks/>>.