Project ID:

Novel Adaptive Gripping Device for Tasks Requiring Fine Motor Control

A Major Qualifying Project Report submitted to the faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the degree of Bachelor of Science

April 27, 2017

Prepared by:

Sarah Bucknam (BME)

Caitlin Grow (ME)

Presented to:

Professor Pradeep Radhakrishnan, Advisor
Department of Mechanical Engineering

Professor Kwonmoo Lee, Ph.D., Advisor
Department of Biomedical Engineering

Abstract

Fine motor control is essential for a student's success in school, and beneficial for their independence and overall quality of life. A C6 spinal cord injury left our client with a severe lack of fine motor control in both hands and complete paralysis below his shoulders. The goal of this project was to design and produce a novel device that would aid the user in performing tasks requiring fine motor control in order to increase his independence. There are no current devices on the market that fit our client's specific need: lightweight, portable, easy to use, and purely mechanical. The final design incorporates a body powered voluntary opening pivoting prehensor and one fixed prehensor. This device was manufactured and tested by the client and demonstrated proper functionality. It allowed the client to complete tasks requiring fine motor control more quickly and efficiently than before, increasing his independence.

Acknowledgements

The authors would like to thank all volunteers who contributed to the development of this device: Jared Grier for being a knowledgeable resource (WPI mechanical engineering student), Christopher Nycz for his help with the motion capture (WPI graduate student), John Bylund, Austin McCalmont and Nicole Alves for their help in machining the metal components (WPI mechanical engineering students), Erica Stults for 3D printing the gripping component, and Professors Pradeep Radhakrishnan and Kwonmoo Lee (WPI Advisors on the project).

Executive Summary

Introduction and Background

A C6 spinal cord injury leaves a patient with minimal wrist and arm control, and little to no sensation in the fingers and below the nipple line. This kind of traumatic injury drastically impacts the patient's life, reducing or eliminating their independence. Accidents during sports, car collisions and falls are common causes of spinal cord injuries (SCIs), particularly in children and young adults. When students return to an educational setting after an SCI, they have shown adequate or above average participation compared to peers in the classroom. A gripping device would be considered an accommodation that would increase the performance level of students with an SCI for tasks that they previously could not perform. The aim of this project was to synthesize a planar artificial hand to aid the user in the pick and place of small objects that require fine motor control. The adaptive device was created based on the requirements of a client with a C6 spinal cord injury.

Need and Current Adaptive Devices

The client's injury completely eliminated sensation in his hands and fingers. Because of this, he is unable to perform tasks such as placing resistors, a requirement to be an independent student. Additionally, he struggles to perform tasks such as sorting pills or swiping a card, that are necessary for maintaining his independence in his daily life. There are many adaptive devices available on the market meant to help those with an injury or impairment regain some of their independence by aiding the user perform various tasks. Most notably, a company called *Quadtools* produces a tool called “The Cripper” that is designed to help patients with disabilities such as quadriplegia to reach and grab items that are further away. The client currently has one of the *Quadtools* devices that he uses frequently, but because of its long length it is not portable or useful in a classroom environment. Additionally, this and similar devices are extremely expensive and can be difficult to acquire when considered along with all the other necessary medical expenses endured after experiencing an SCI. Due to this situation, there is a need for an adaptive device that is lightweight, portable, inexpensive, and, most importantly, gives the user increased fine motor control.

Design and Manufacturing

A list of design specifications were created from the client statement and the project goal. The list was comprised of: portable, easy to use, lightweight, safe and repeatable. From the design specifications two preliminary designs were created. Both incorporated an attachment made of an aluminum bar and rings secured with Velcro. Both designs also used a body powered voluntary open technique with a fixed and pivoting prehensor. That is, the device is closed in a resting state and a force that is provided by the user is used to open the device.

The first preliminary design is situated on the dorsal side of the arm with a handle-styled actuator attached to the pivoting prehensor. The second is situated on the palmar side of the arm and is actuated through a linkage system. Kinematic outlines were drawn of the entire system as well as of each link individually. Equations were derived from force body diagrams to find the forces necessary to maintain the grip of an object as well as to actuate the device. According to a decision matrix composed of design requirements the second design was proven to be a better design and a prototype was constructed.

The prototype was constructed in two components: the prehensors and the attachment. The prehensors were designed in Solidworks and 3D printed on the WPI campus using ABS plastic. The attachment was made of an aluminum bar and Velcro. The aluminum was machined in the machine shop where the rings were molded based on measurements of the client's wrist and arm. The Velcro straps were sewn to fit the client's arm exactly and loops were created for ease of use so the client can attach and remove the device on his own without any assistance.

Testing and Results

The device was tested using a fine motor skills assessment commonly used for teaching preschool children. The testing plan involved timing the user while sorting 12 colored candies into different receptacles. The test was performed five times in three different situations: first, by a control, second, by the client without the device, and third, by the client with the adaptive device. The client's sorting time without the device was nearly six times the average of the control. With the use of the prototype the time was reduced to approximately double that of the control. These results depict a dramatic reduction in time with the use of the device.

Statistical analysis was performed on the results, showing that despite a larger standard deviation for the client performing the trials without the assistive device, the data is acceptable and shows a statistically significant difference between the three comparisons.

Discussion and Conclusion

Prior to the development of this design the client could not sort his pills. The task was too time consuming and tiring so he would most likely ask someone else to do it for him. With the device the client is now able to accurately and quickly sort his pills into the pill organizer.

While the device did aid in the pick and place of small objects and the time needed to do so, there are some areas of improvement in the design aspects of the device. Since the gripping component of the design is 3D printed and attached with screws it is possible to produce different types of prehensors in different shapes and sizes for specific applications. Also, the band that provides the default-closed state could be replaced by a spring that is more durable and aesthetically pleasing. Finally, the aluminum bands and Velcro closure system could be improved to be more ergonomic.

Table of Contents

List of Figures

List of Tables

Keywords

Exoskeleton: a rigid external covering for the body in some invertebrate animals, especially arthropods, providing both support and protection

Prosthetic: denoting an artificial body part, such as a limb

End Effector: the device at the end of a robotic arm, designed to interact with the environment. The exact nature of this device depends on the application of the robot

Degree of Freedom: each of a number of independently variable factors affecting the range of states in which a system may exist; a direction in which independent motion can occur

Range of Motion: the full movement potential of a joint, usually its range of flexion and extension

Soft robotics: a new direction of technological development and a novel approach to robotics, unhinging its fundamentals, with the potential to produce a new generation of robots, in the support of humans in our natural environments

Actuator: a component of a machine that is responsible for moving or controlling a mechanism or system; requires a control signal and a source of energy, the control signal is low energy and may be electric voltage or human power

Fine Motor Control: the coordination of muscles, bones, and nerves to produce small, exact movements

Bowden cable: a type of flexible cable used to transmit mechanical force or energy by the movement of an inner cable relative to a hollow outer cable housing

Voluntary Opening (VO): the user actively opens the prehensor and a passive spring restores the default closed state

Voluntary closing (VC): the user actively closes the device and some passive element such as a spring, returns the prehensor to the default open state

Prehensor: a part that grasps (fingers)

Chapter 1. Introduction

Fine motor control is essential for a student's success in school, and beneficial for their independence and overall quality of life. A C6 spinal cord injury left our client with a severe lack of fine motor control in both hands and complete paralysis below his shoulders. This kind of traumatic injury drastically impacts a patient's life, reducing or eliminating their independence. While the client has used adaptive device currently on the market, he has found them to be difficult to transport as well as challenging to use in a classroom setting. The goal of this project was to design and produce a novel device that would aid the user in the pick and place of tasks that require fine motor control in order to increase his independence.

From a client statement and the project goal design specifications of portable, easy to use and lightweight were generated. Two preliminary designs were established and a final design was chosen based on a decision matrix. From this final design a prototype was constructed of aluminum and 3D printed ABS plastic. When completed the prototype was tested and found to reduce the time necessary for the client to complete tasks requiring fine motor control. The prototype was determined to be a success. The client is now able to perform tasks such as sorting his pills, that he was unable to do prior to the development of this device, therefore, increasing his independence in daily life.

The MQP team was made up of Sarah Bucknam, Biomedical Engineering with a concentration in Biomechanics, and Caitlin Grow, Mechanical Engineering with a concentration in Biomechanical Engineering.

Chapter 2. Background

Paralysis

Spinal cord injuries can severely impact a person's life. Depending on the location and severity of the injury, a patient could lose some or all motor control and ability to send messages between the brain and the rest of the body. This can have an enormous impact on the patient's daily life, often causing them to require daily assistance in order to complete simple tasks such as making food, cleaning their living space, or doing laundry. Spinal cord injuries can be caused by traumatic injuries such as sports, car accidents, or falls, and are known to occur more frequently in young adults between the ages of 16 and 30 [1]. It is possible for a person to "break their neck" without sustaining a spinal cord injury if they simply fracture a vertebra, but paralysis occurs when the spinal cord itself is injured.

Spinal cord injuries are categorized into different levels based on the location of the injury [1]. The top part of the spinal cord is referred to as the Cervical (C) Nerves. C1-C4 are the highest vertebrae that are closest to the top of the spinal column. So if these are injured, the patient has the likelihood of complete paralysis and will require 24-hour assistive care. C5-C8 injuries can vary depending on the severity, but the patient is also going to

Figure 1 – The Spinal Column [1]

experience a large loss in mobility. The lower half of the spinal cord is categorized as Thoracic (T) Nerves. Injuries of the T1-T5 are likely to impact the patient from the chest down, frequently leading to paraplegia. T6-T12 injuries usually also result in paraplegia, but the patient will have normal upper body movement. The last two sections of the spine, Lumbar and Sacral Nerves, are less traumatic injuries but still can affect the person's ability to maintain their previous way of life, depending on the severity of the injury.

Figure 1 (previous page) shows the complete spinal column with C1-8 highlighted. The specific injury addressed by this project was a C6 injury. Injuries at this level can impact the nerves in the hands, trunk, legs, and arms. The person should be able to have some wrist and arm control but very little sensation in the fingers and anything below the nipple line [1]. Injuries anywhere above C5 nearly always result in death, as it would impact the nerves that control the heart and lungs as well as the rest of the body. C5 and C6 injuries have the largest impact on a patient's life since they cause the greatest possible reduction in independence while still leaving the potential for the person to try and live a life as close as possible to before their injury.

Quadriplegics in Schools

Accidents during sports, car collisions and falls are common causes of SCIs, particularly in children and young adults. When students with a SCI return to the educational setting, they have shown adequate or above average participation and performance compared to peers in the classroom [2]. These students are eager to learn and are engaged in classroom activities. Research also suggests that there are no significant differences between the education that students with SCI and other students receive in general education classrooms. The classrooms provide adequate educational settings for all students [3]. Customized accommodations for individual student needs are provided by schools under Section 504 of the Vocational Rehabilitation Act of 1973 [2]. The purpose of that section is to eradicate discrimination based on handicap. An assistive gripping device for fine motor control could be an accommodation that increases the performance level and independence of students with a SCI.

Employment rates of students with SCI increased upon the completion of graduation [2]. Seventy-one percent of college graduates were employed compared to zero percent of those who had never enrolled. The level of injury was not related to the rate of employment [2]. Therefore keeping young persons in school is imperative to employment success. The aim of this project was to aid in the performance of young persons in their everyday lives, including their hands on learning in school activities to ensure the completion of high school and college graduation.

Fine Motor Control in Daily Life

Motor skills refer to the movements and actions of the muscles, these are categorized into two groups: gross and fine. Fine motor skills refers to the ability of the user to use the small muscles to operate the arms, hands and fingers and their movements are fine motor skills [4]. The smaller muscles of the fine motor system work along with the larger muscles of the gross motor system to provide movement and stability of the body. Figure 2 shows the muscles of the forearm and hand in the posterior superficial view. The muscles of the arm, such as the Flexor Carpi Ulnaris and the Triceps brachii, work to provide gross motor movement of the arm. The muscles of the hand work with the tendons to provide the fine motor movement of the hand.

Fine motor skills develop in children when engaging in tasks that require the use of their fingers. This development is important because it provides them with the foundation necessary to succeed throughout life, in education and for independence performing self-care tasks. Fine motor skills provide the ability to write, manipulate objects such as fold and tie, feed and wash oneself, brush hair and teeth, etc. [5]. Fine motor movements are those that enable humans to grasp, reach and release. The movements of the hand require hand strength, flexibility, dexterity and coordination. When these abilities of the hand are lost, such as after a SCI, the fine motor skills are affected.

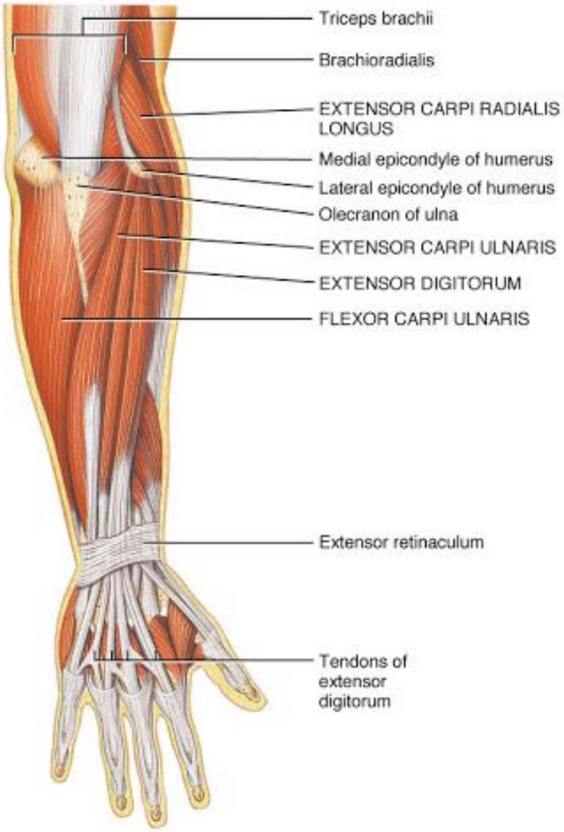


Figure 2 – Muscles of the lower arm and hand [6]

Chapter 3. Development of Need

Client's Injury

In May 2015, our client fell from a tree and landed on his back, fracturing his C6 vertebrae and paralyzing him from the chest down. This left him with no ability to move around on his own without a wheelchair, and very limited motion in his shoulders and arms. He spent two years recovering, and with the help of rehabilitation and various adaptive devices (discussed in chapter 4), he is now capable of living mostly independently on campus and has returned as a student. Over the course of his first year of recovery, his injury improved from being classified as C6 to C7. This means he has increased sensation in his arms and fingers. He still has very limited fine motor control. He is unable to fully grasp or manipulate anything in his hands or fingers, which greatly reduces his ability to perform some tasks he used to complete with ease. He needs to use his hands, wrists, and forearms in order to gain enough leverage to simply open a water bottle.

The greatest impact from this injury is the reduction in independence. Tasks such as sorting pills necessary to maintain his health on a daily basis became a daunting task that could take hours if one of the smaller pills dropped out of his organizer. At WPI, he is planning on taking ECE classes that require him to be able to manipulate small resistors. In his current state, he does not have the fine motor control necessary to complete these tasks, and he has not found an adaptive device currently on the market that can work for him; this is the need that this project addressed.

Current Motor Control

Tracking software, as well as videos and observations were used to assess the client's current motor control. The tracking software consisted of six cameras and six reflective markers. The markers were placed in six different positions on the client's hand and forearm to create two planes. He was asked to move his wrist in different motions and the software was used to measure the changing positions of the markers. From this data we were able to determine the maximum angle his wrist is able to extend off the table as well as the velocity of his wrist. The client's data was compared to that of a person without an SCI. The figure below shows the system set up including the six cameras and the motion capture software on the computer.

Figure 3 - Motion capture setup

Videos and observations were used to assess the client's current condition and to verify the need for an adaptive gripping device. He was asked to perform a series of tasks that included: write his name on a piece of paper in pencil, erase it, and then place a paper clip on the paper. Observations were made to determine the client's strengths as well as his limitations. His strengths include his adaptability and his wrist strength, control and range of motion. He was able to successfully perform all three tasks, however, they were time consuming and difficult to do with one hand. The most prevalent limitation was that of fine motor control.

The client performed the tasks differently than that of a person without an SCI. This adaptability has increased his independence in many ways. While an able bodied person may hold an eraser between his/ her fingertips, he must hold the eraser between two fingers, shown in Figure 4 below. This limits the motion and amount of pressure of the eraser.

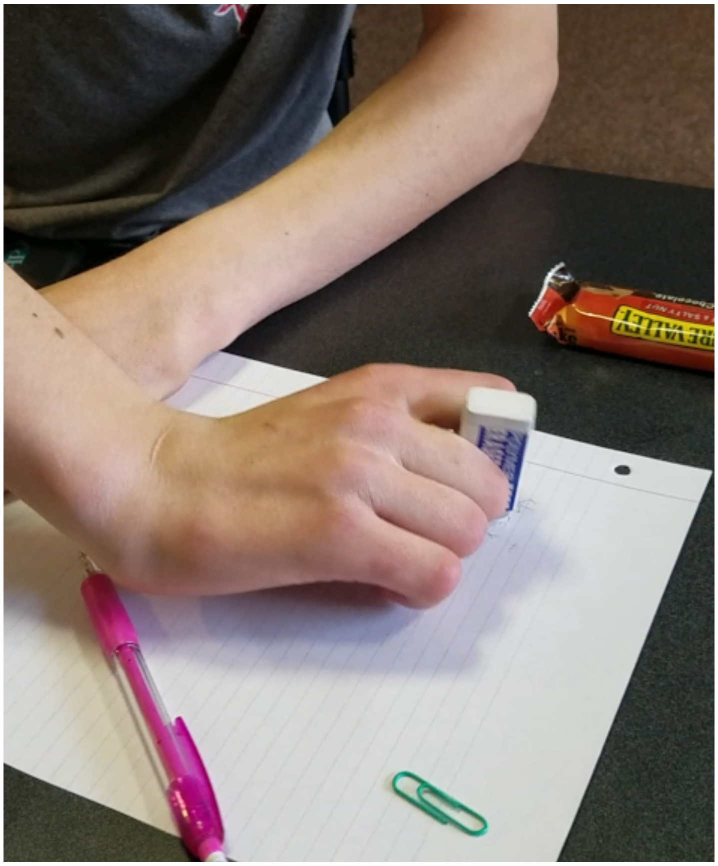


Figure 4 - Observation of client performing various tasks requiring fine motor control

The goal of an adaptive gripping device is to aid in the pick and place of small objects such as resistors and pills. The observations made during this exercise show a need for this kind of device due to the client’s limited fine motor skills. Depending on the adaptability of the device, it could be used to hold an eraser or pencil as well as resistors and pills.

Chapter 4: Existing Adaptive Technologies

This section contains analysis of many current adaptive devices and technologies that are available on the market. Many are much too complex and do not fit the project's specific need. Advantages and disadvantages of each design are listed and aided in the design of this project. The current technologies are examples of the different devices that are available to help patients in different situations requiring assistance with fine motor control. There is also a discussion of industrial standards and the process that we would have to go through to get this device to be commercially available.

Full Hand Exoskeletons

1. Design of a low cost multi degree of freedom hand exoskeleton [7]

This design of a five-fingered hand exoskeleton contains three degrees of freedom (DOF) in each link. A motor is used for actuation. There are 4 connecting rods, as shown in Figure 5, that serve as the joints of each finger as well as join each middle and distal phalange together. The mechanism of the thumb acts similarly however it contains an additional DOF and linkage that in turn also connects the four-finger links respectively. The wrist joint is connected to a solid base that bears the majority of the weight of the exoskeleton. The advantages of this design include the many degrees of freedom similar to that of the natural kinematics of the human fingers. While there are many advantages to this design, there are also many challenges. The disadvantages include the need for a motor actuation system. While this project requires a simulation of the motion of the hand, a motor actuation system is not desired.

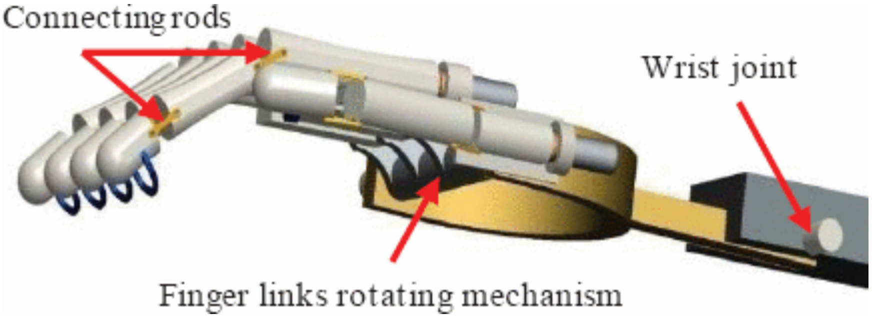


Figure 5 - Design of a low cost multi-degree of freedom hand [7]

2. A soft exoskeleton for hand assistive rehabilitation application using pneumatic actuators with variable stiffness [8]

The “ExoGlove” design, shown in Figure 6, is a soft wearable robotic device for assistive and rehabilitation purposes to improve hand function and mobility. The main body is made of a glove with Velcro straps as well as customizable pneumatic actuators with variable stiffness. Different hand motions are achieved through adjustments in stiffness of the actuator in different localities. The localities with lowest stiffness correspond to the joints and those with higher stiffness to the finger segments. The actuators are attached on the dorsal side of the glove and connector tubing is plugged in from an air source. Upon pressurization bending occurs where the stiffness is lowest and there is a change in the relative joint angles. The advantages of the design include the variation of therapy exercises that can be achieved. The disadvantages include the actuation system as well as the feedback system.

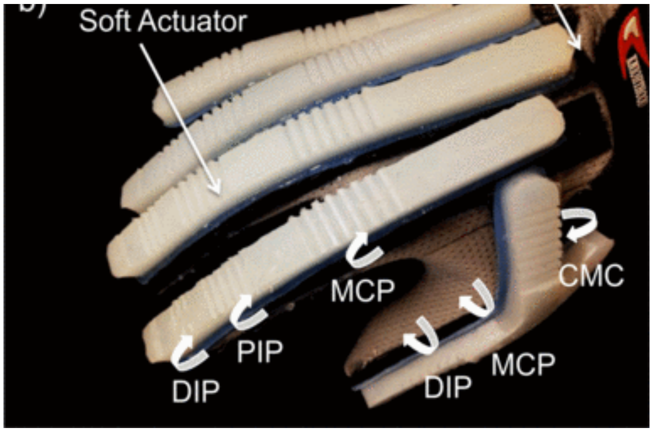


Figure 6 - A soft exoskeleton for hand assistive rehabilitation [8]

3. Design and development of the wearable hand exoskeleton system for rehabilitation of hand impaired patients [9]

This exoskeleton system is portable and lightweight integrated with mechanical structures and actuator units. The main goal of this design was to achieve the DOF for finger flexion and extension with non-complexity mechanical structure. The requirements for this design included: bidirectional movements of each exoskeleton finger; decoupled motion of the finger joints; safety through mechanical structure; lightweight, low cost and easy equipped for the human hand. The four components of this system, shown in Figure 7 below, include: the mechanical structure, actuator unit, control unit, and sensor unit. The fingers of the exoskeleton are connected through cable wires to the actuating motors controlled by the control unit. Cable guides adjust the entering and exiting angles of the cable. Motors controlled by an Arduino board easily and precisely control the rotating angle. The disadvantages of this system include the weight and complexity of the actuator unit.

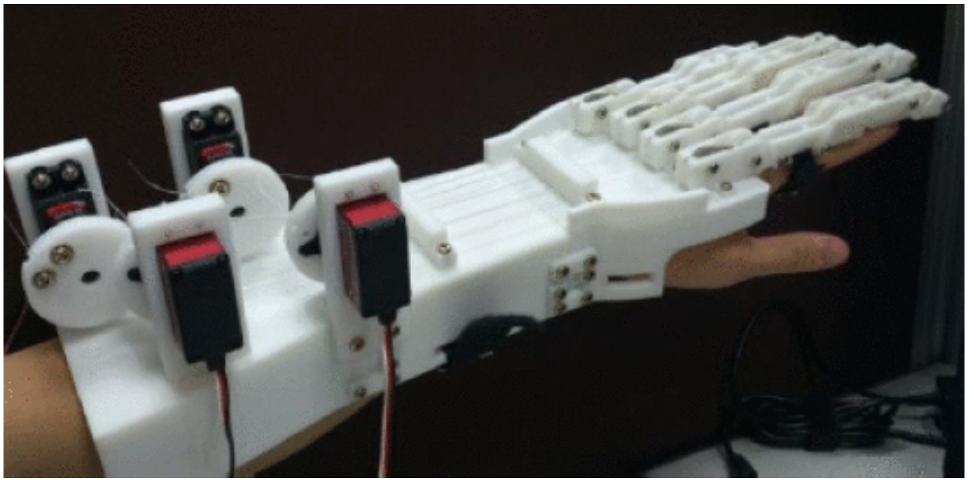


Figure 7 - Wearable hand exoskeleton system for rehabilitation [9]

4. Mechantronic Design and Characterization of the Index Finger Module of a Hand Exoskeleton for Post-Stroke Rehabilitation [10]

The HANDEXOS design, shown in Figure 8, is focused on the issue of misaligned joint axes whose complex anatomy makes alignment during extension and flexion difficult. This novel device has a shell like structure for links fastened together with Velcro straps on both the dorsal and palmar side of the hand. A remote underactuation system with Bowden cables transmission reduces the inertia of the moving parts. Each finger has an independent module and is made of three links connected by means of three active and three passive degrees of freedoms. The active DOFs assist in the extension and flexion of the joints while the passive DOFs assist in rotation and translation of the joints. Neoprene foam layers the inner surface of the dorsal shell for comfort and adjustment between the device and the human hand. The weight and complexity of this design are a few disadvantages.

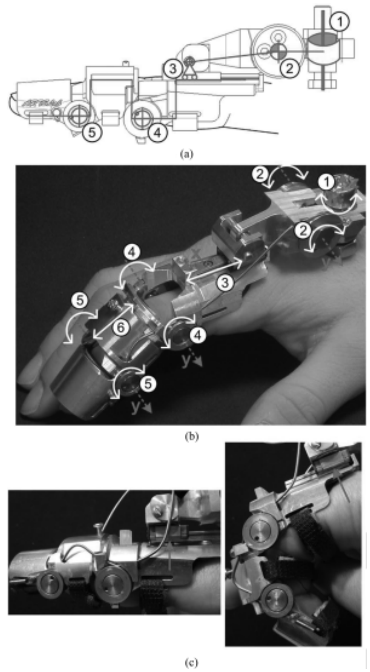


Figure 8 - HANDEXOS [10]

5. A new hand exoskeleon device for rehabilitation using a three-layered sliding spring mechanism [11]

   This design effectively incorporates a new multi-layered compliant mechanism into a robotic hand rehabilitation device. The advantages of compliant mechanisms include no backlash, no lubrication required, no machine noise, no abrasion powder as well as the compact and lightweight design due to the monolithic structure. This mechanism, shown in Figure 9 below, distributes one DOF actuated linear motion into three rotational motions of the joints to simulate a natural finger flexion / extension motion. Each finger require three DOF motions however the thumb is fixed for the sake of robust grasping. This mechanical setup is an under-actuated system (with fewer control inputs than the mechanisms DOF). The four fingers are actuated by a single actuator, this provides simplicity to the system however this limits the performable motion of the fingers. The primary application of this design is to provide robotic support as an assistive / therapeutic device of activities of daily life.

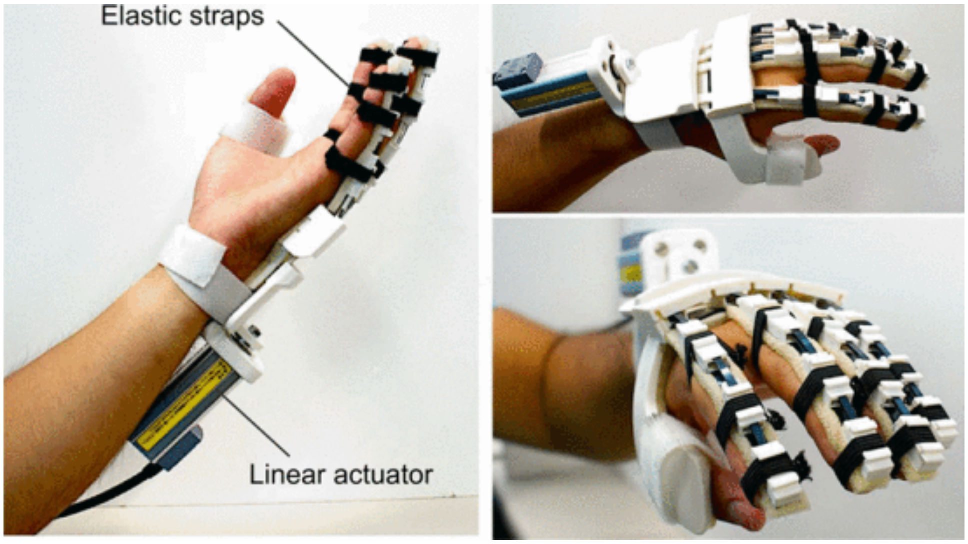


Figure 9 - Hand exoskeleton device for rehabilitation using a three-layered sliding spring mechanism [11]

6. "Mechanical Hand" Patent [12]

This is a patent for a mechanical hand device designed to restore the use in the hand of a quadriplegic patient. This device is simple, lightweight, and is inexpensive. This patent pertains to this project specifically in materials used and the method of attaching the device to the client as shown in the Figure 10. This patent discusses different stages in the development of this gripping device, that accomplishes a similar task but in a very different way to that of the goal of this project.

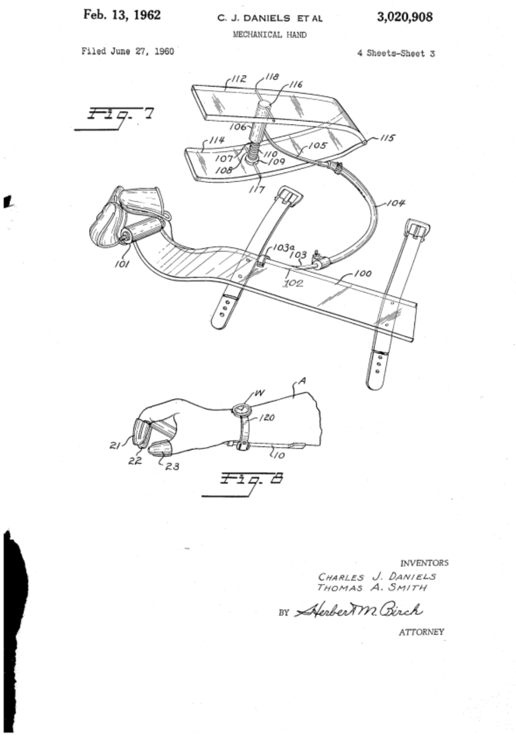


Figure 10 - Patent of "Mechanical Hand" [12]

Voluntary opening Prehensors

1. Sierra 2-load VO hook [13]

This voluntary opening design requires the user to actively open the prehensors, or gripping fingers, while a passive spring restores to the default closed state. The design, shown in Figure 11, employs two torsion springs: one that is engaged at all times and the other only when the high-grip force setting is activated. This allows for two grip force settings: 3 ½ and 7 lbs. The prehensors are lined with nitrile rubber to increase grip force.

Figure 11 - Sierra 2-load VO hook [14]

2. The Vector Prehensor device [13]

This split hook prehensor design is similar to the Sierra 2-load VO hook but had a band default closing system instead of a spring. The grip force applied to the prehensor is proportional to the torque applied to the band about the pivot. The torque varies based on the band force. This design may be used as a purely mechanical solution to the project goal.

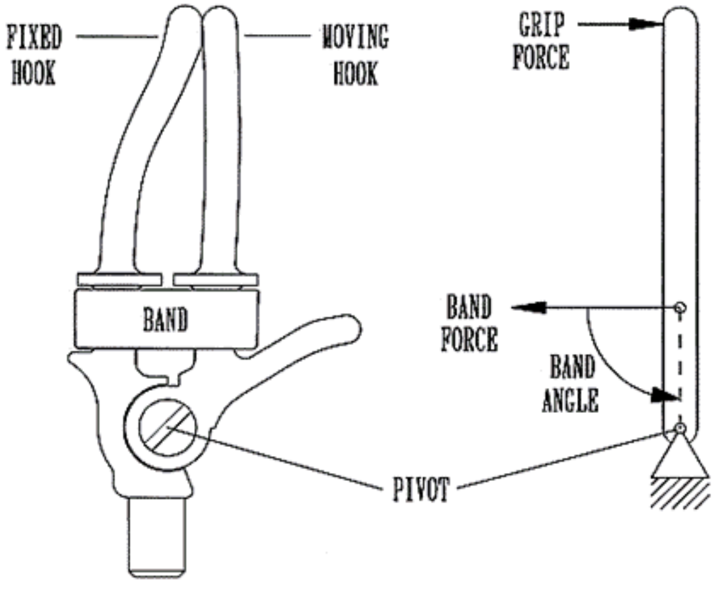


Figure 12 - The Vector Prehensor device [13]

Arm attachment concepts

Quadtools is a company that has developed a variety of “reacher” devices that allow quadriplegics to reach and grab different items that they previously could not. Many of their devices have attachments at the end that allow the person to perform tasks such as trimming plants (figure 13). The device that is the closest to what we will be developing is called “the Cripper”. It is similar to an arm extension that allows the person to pick up small items that are about two feet away. There is also an extended version that allows the person to reach up to three feet away (figure 14). The client currently owns a device similar to the "Cripper" and can use it to assist him is grabbing larger objects from far away such as an item that has fallen on the floor. It is not useful for detailed tasks requiring fine motor control, such as sorting pills, because it requires the client to be seated about 2 feet away from the pills he is trying to sort which is extremely inconvenient and reduces the precision of the motion.

Quadtools Garden Shears $199.00
Weight: 18 oz. Length: 30" overall Reach: 20"

- Fruit, floral, and garden shears
- Stainless Steel
- No grip necessary
- Two-handed operation

Figure 13 - Quadtools Garden Shears [15]

The Original Lightweight Cripper $189.00
Weight: 12 oz. Length: 29" overall Reach: 17"

The Original Heavy Duty Cripper $199.00
Weight: 14.5 oz. Length: 29" overall Reach: 17"

- The Original Lightweight Cripper will pick up to 3 pounds, the Heavy Duty will pick up to 10 pounds
- Precise enough to pick up a needle or a dime
- Inner pincers for increased leverage
- Stainless steel jaws and hardware

The 36" Cripper $229.00
Weight: 18 oz. Length: 36" overall Reach: 24"

- Lift capacity 3 lb.
- Precise enough to pick up a needle or a dime
- Inner pincers for increased leverage
- Stainless steel jaws and hardware

Figure 14 - Quadtools "Cripper" [15]

Industry Standards

There are currently a variety of different products similar to this available on the market, but all are specially made for each individual purpose. There is not a lot of information available regarding current best practices in creating a custom adaptive device for an individual client as it is still a new and developing market. Many devices, such as the ones pictured in figure 14, did not go through the FDA (U.S Food and Drug Administration) at all since they are merely considered a tool, similar to a hammer or a set of pliers. The FDA has produced documentation on the regulation of some medical devices, and we will be adhering to those standards in this project.

If we were planning on sending this device to the market, we would have to adhere strictly to the regulations set out by the FDA since we are considering this device to be an adaptive medical device. The design we have created actually avoids many of the problems discussed by the FDA as potential issues for medical devices. It is classified as a Class I device, which could go to market in about 60-90 days without the need for human or clinical trials. A 510k could be required for marketing, but there are no premarket approval applications necessary [16].

The most important factor that avoids much of the FDA regulatory checks is that our device is purely mechanical. This means that all regulations involving electricity, power sources, or output do not apply to this device. Additionally, there is no concern involving a “hackable” device. Since there are no components connected to software or programming in any way, the device cannot be controlled from an outside source. If the device were to be altered to include an electronic component, it would be reclassified as a Class II device. This means that it would have to go through many more safety checks and more forms would have to be submitted before the device could go to market. Specifically, all details regarding the wiring of be device would have to be shown to be completely protected and safe and removed from possible contact with the user’s arm in order to prevent electrocution. The charging or power mechanism must be clearly defined and shown to work well and safely [16].

The most important things to report in order to send the device to market is that results from trials. They must be reported in such a way to limit human error or bias and include sound statistical analysis. All materials used in the device must be shown to be completely safe; they should be non-toxic, non-abrasive, and must not release any radiation. Finally, the way in which the device is advertised is strictly regulated in order to avoid misrepresentation [16].

Chapter 5: Design

Design Process

The project followed the design process and its components learned in classes at WPI. First, background research was performed to understand paralysis from an injury and associated fine motor skills. This research aided in the understanding of the client's injury as well as his current motor control. Next, benchmarking of current adaptive technologies including materials and industry standards were completed to assess existing designs as well as look for areas in need of improvement and how this applies to the client's case. Two mind maps were created to better understand the pick and place process for the client and what was required by this kind of device. This study led to the creation of design specifications and then preliminary designs were generated. Detailed analysis was carried out followed by a selection of the final design. A prototype was manufactured and tested. Finally, the project was discussed and conclusions were drawn. A Gantt chart that displays the timeline of this process is in Appendix A.

Client Statement

In his current state, the client has good muscle control of his shoulders, arms, and wrists, but very little functional control of his fingers. The need this project addressed was that of fine motor skills, specifically the pick and place of small objects. The specific example task the client wanted to accomplish was the ability to hold small resistors (used in ECE classes) and place them in specific locations on a breadboard. Additionally, the device would allow the client to pick up and accurately place pills of varying sizes into a pill organizer. The user has the ability to control large motions but very minimal fine motor skills, needed for these types of tasks. The requirements by the client of an adaptive device were as follows: a device that was small, lightweight, portable, easy to attach and easy to use.

There are many different gripping devices currently on the market, but most are very large and inconvenient to carry around, or they are expensive. Additionally, there are very few that have the level of control required for the specific tasks the client wanted to accomplish. After meeting with the client and discussing his specific needs, he confirmed that there is not currently a device available that would fulfill this specific need.

Mind Mapping

Two mind maps were created to understand the pick and place of an object, specifically for the client. Both are shown in Appendix B. The first discusses the manipulation of an object, starting from the pick, through the placement and other things to consider with a student that is paralyzed. There are many ways an object can be picked up and where an object can be picked up from. Different objects require different forces necessary to pick and then maintain a grip on the object. While maintaining the grip on an object the user may be required to change the object somehow. For example, when placing a resistor in a breadboard the user must bend each end of the resistor prior to placement. The hand has many degrees of freedom that allow for accuracy when placing the object in the desired location. The number of degrees of freedom however can make a design more complex. Time is a factor for accurately placing an object especially for small objects. Other factors to consider when working with this client are the aid from others he may receive to assist with the task versus the independence the client wants to have in his everyday life.

The second mind map considers the manipulation of an object with the use of a current adaptive device used by the client. The device is similar to that of the "Cripper" by Quadtools discussed previously in Chapter 4 (figure 14). The device is used for reaching for an object that is several feet away from the body, most often above the head or below a desk or bed. The discussion of the mind map begins with the attachment of the device and continues through the reach, grip and placement of the object as well as a few other things concerning the strengths and limitations of the current design. From this mind map specifications for the design of this project were developed. Both mind maps can be found in Appendix B.

Design Specifications

Functional Requirements:

Pick up object ~ 1 gram (resistor/ pill)

Maintain grip of object

Aid user to manipulate and place the object

Body powered voluntary open prehensor (one fixed and one powered)

Design Specifications:

Geometry

Weight: Less than 5 1bs +/- 1 lb.

Size: Less than 12 in. by 3 in. by 4 in.

Cost

No more than $250 to produce

Kinematics

Force: provide X amount of grip force to hold objects of ~ 1g

Force required by the user to open prehensor: X lbs.

Grip Range: 0 in. to 2 in.

Provide at least 1 DOF

Operation

Durability: lifetime of 1 thousand cycles

Safety: No sharp edges. Easy to attach and hold in place. Lightweight.

Attachable to the right wrist and arm

Portable

Purely mechanical device – provide simplicity – minimize the number of moving parts

Repeatable

Provide Fine Control – space between contact points on a breadboard are ~0.1 in.

Preliminary Designs

Design 1

The first preliminary design consists of a body powered voluntary open prehensor that is situated on the dorsal side of the wrist. In a resting state the device is closed. A force provided by the user actuates the device. This is important because during the pick and place of the object the device will maintain the grip of the object without a force needed by the user. A handle is attached to a pivoting prehensor that is powered by the user to open the device. The pivoting prehensor is attached to a fixed prehensor that is connected to the attachment component of the device. The attachment is made of Velcro and metal to secure the device to the arm and wrist. The attachment is explained further in the following section. Preliminary design one is shown in Figure 15 below.

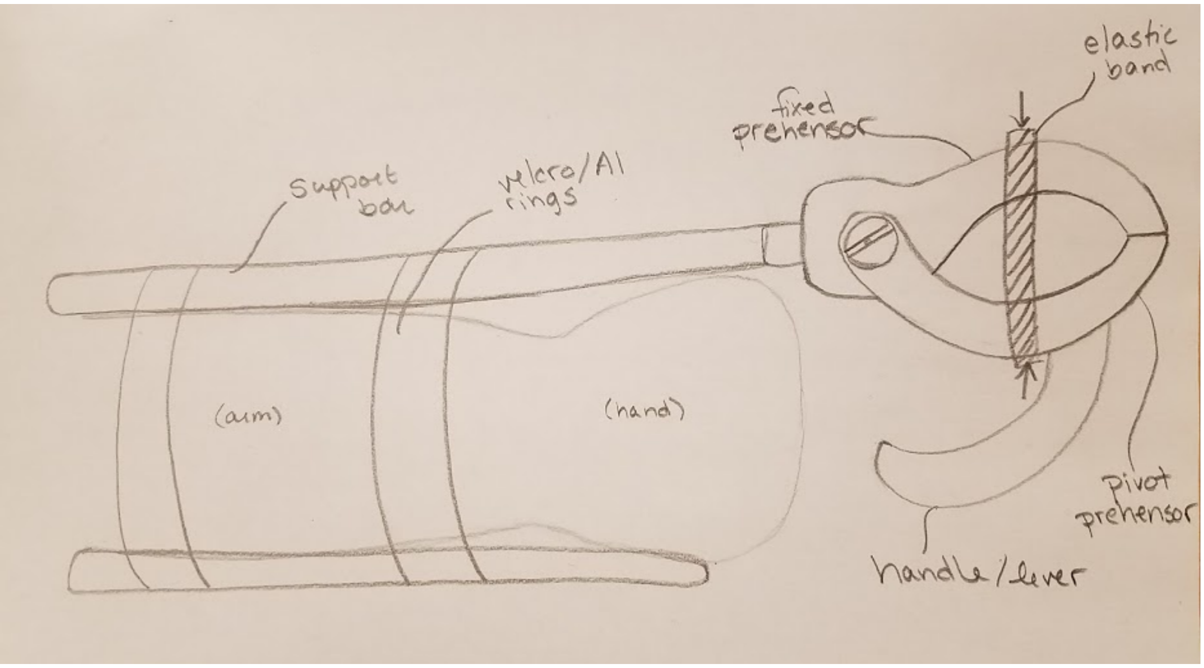


Figure 15 - Preliminary Design 1

Design 2

The second preliminary design is also a body powered voluntary open prehensor, however, it is secured to the arm on the palmar side of the wrist /arm. This allows for the shoulder to relax during the pick and place of the object. Aluminum O and C rings secure the device to the wrist and arm of the user. The wrist attachment is the lever arm that will actuate the linkage system of the device. An upward motion of the wrist by the user will open the prehensors or gripping parts of the device. Similar to the first design, one prehensor is fixed while the other pivots and an elastic band will provide the force necessary for a default closed state. The user may relax after the object has been picked up and the device will continue to hold the object. Then the user may use the natural motion of the hand to place the object in its desired location. Preliminary design two is shown in Figure 16 below.

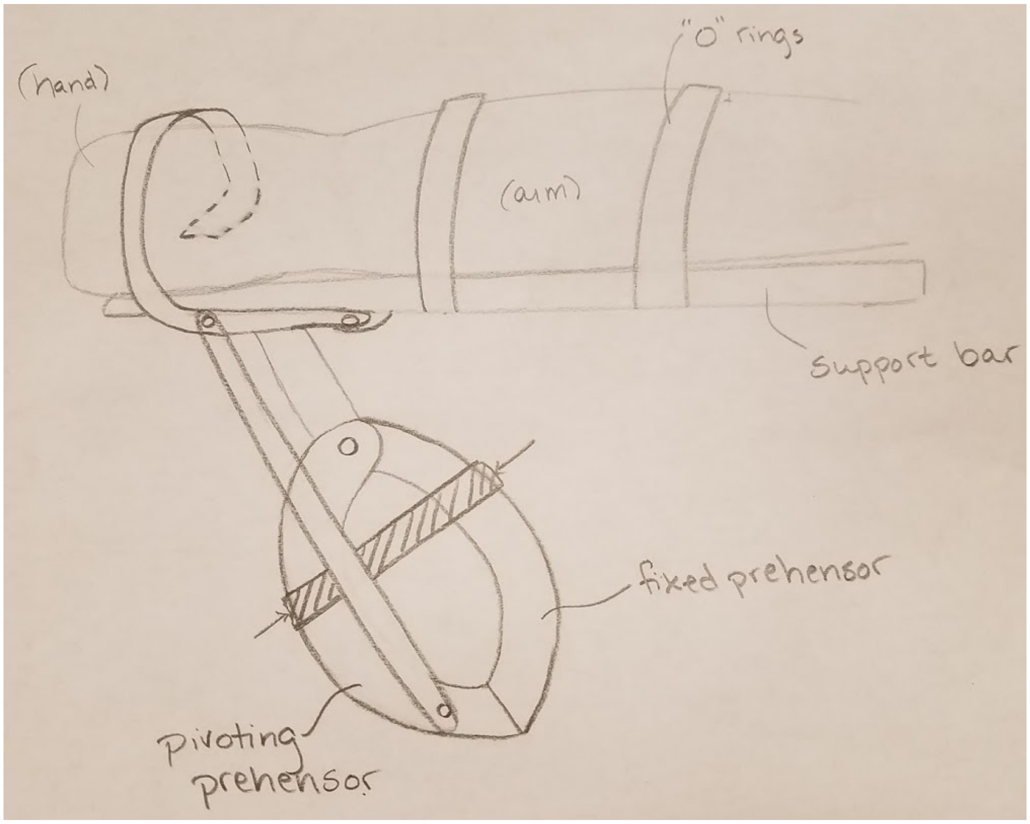


Figure 16 - Preliminary Design 2

Attachment of Design

Both preliminary designs feature the same attachment design. The following drawing depicts the general idea of how to attach the device to the client's arm. After meeting with the client and observing how he used his current gripping device, it was determined that there were areas of improvement on the method of attachment used in most devices currently available on the market. By adding the Velcro straps and changing the locations of the openings in the aluminum bands to be more ergonomic, our arm attachment is simpler and more comfortable for the client than his current device.

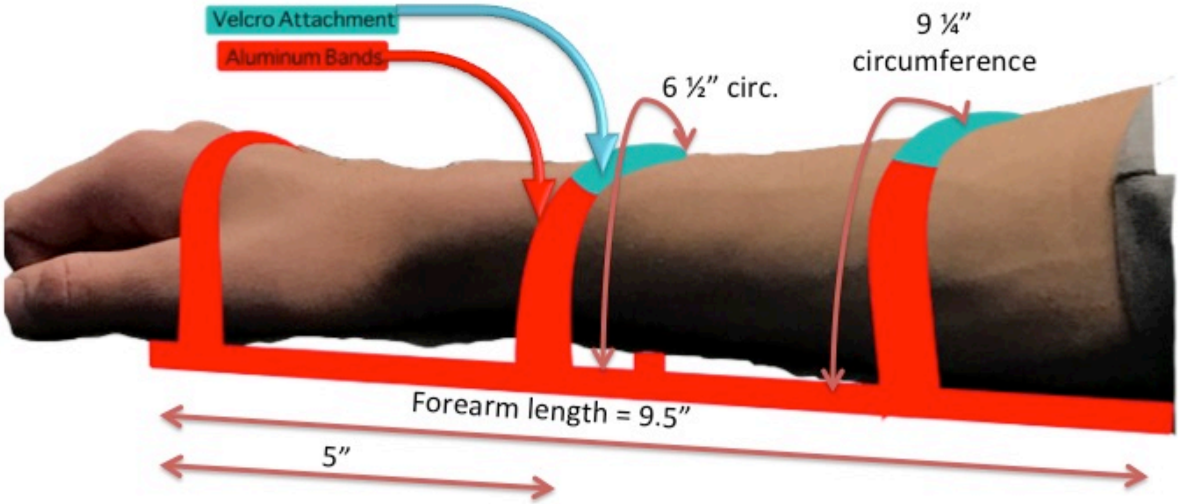


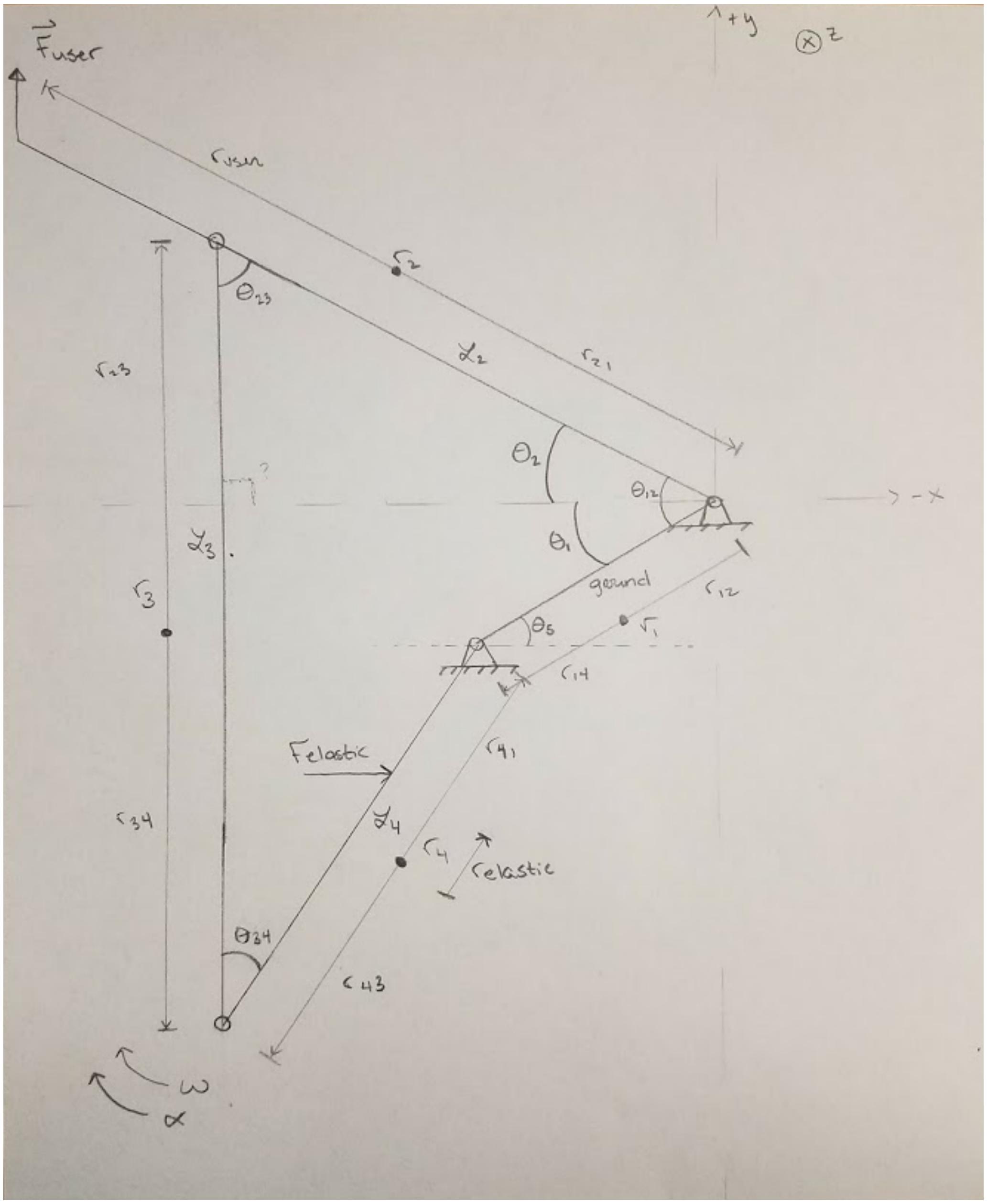
Figure 17 - Attachment Design

Chapter 6: Analysis and Selection of Final Design

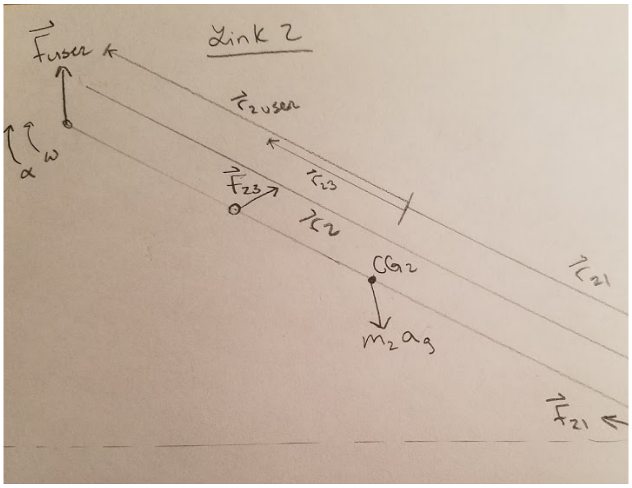
Kinematic Analysis

Prelim Design 2:
Analysis of Gripping Force

Kinematic Drawing of Final Design



Link 2



Force Balance Equations for Link 2:

$\sum \mathbf{F} = \mathbf{F}_{user} + \mathbf{F}_{21} + \mathbf{F}_{23} = m_2\, \mathbf{g}_2$

$\sum \mathbf{T} = \mathbf{T}_{21} + (\mathbf{R}_{user} \times \mathbf{F}_{user}) + (\mathbf{R}_{21} \times \mathbf{F}_{21}) + (\mathbf{R}_{23} \times \mathbf{F}_{23}) = I_G \boldsymbol{\alpha}_2$

From these equations we get 3 equations:

$F_x = F_{user\,x} - F_{21\,x} - F_{23\,x} = m_2\, g_{2\,x}$

$F_y = F_{user\,y} + F_{21\,y} + F_{23\,y} = m_2\, g_{2\,y}$

$T = T_2 + (R_{user\,x} F_{user\,y} - R_{user\,y} F_{user\,x}) + (R_{21\,x} F_{21\,y} - R_{21\,y} F_{21\,x}) + (R_{23\,x} F_{23\,y} - R_{23\,y} F_{23\,x}) = I_G \alpha_2$

In a default state where F user = 0:

Knowns:

m2 = 0.006lb / g = 0.006 lb / 384 in/s2

gx = 0

gy = 32 ft/s2 = 384 in/s2

$\alpha_2 = 0$ rad/s

$R_{21\,x} = 0.5$ in

$R_{21\,y} = 0$

$R_{23\,x} = 0.5$ in

$R_{23\,y} = 0$

Unknowns:

$F_{21\,x}$, $F_{21\,y}$, $F_{23\,x}$, $F_{23\,y}$, T_2

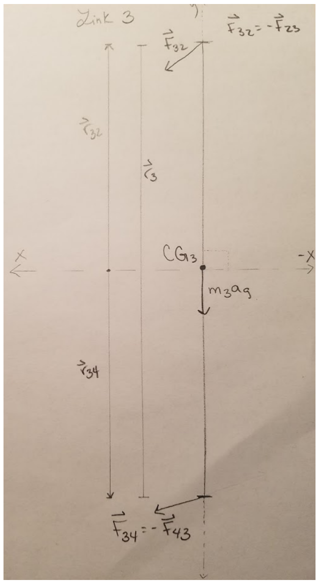
Plug known values into the three equations:

$F_x = (-)F_{21\,x} - F_{23\,x} = 0$

$F_y = F_{21\,y} + F_{23\,y} = 0.006$ lb

$T = T_2 + 0.5\text{in}\,(F_{21\,y}) + 0.5\text{in}\,(F_{23\,y})$

Link 3



Force Balance Equations for Link 3:

$\sum \mathbf{F} = -\mathbf{F}_{32} + \mathbf{F}_{34} = m_3\, \mathbf{g}_3$

$\sum \mathbf{T} = (\mathbf{R}_{32} \times \mathbf{F}_{32}) + (\mathbf{R}_{34} \times \mathbf{F}_{34}) = I_G \boldsymbol{\alpha}_3$

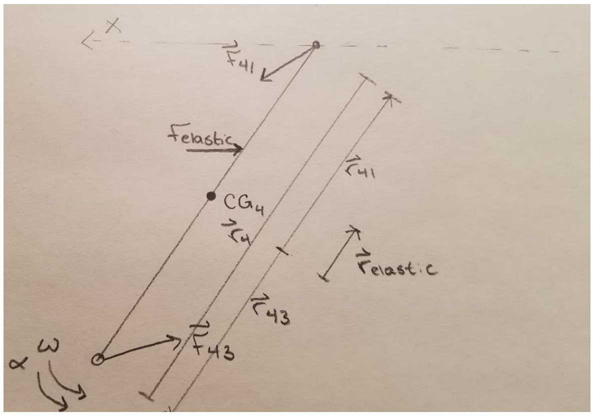
From these equations we get the following 3 equations:

$F_x = -F_{32\,x} + F_{34\,x} = m_3\, g_{3\,x}$

$F_y = -F_{32\,y} + F_{34\,y} = m_3\, g_{3\,y}$

$T = (R_{32\,x} F_{32\,y} - R_{32\,y} F_{32\,x}) + (R_{34x} F_{34\,y} - R_{34\,y} F_{34\,x}) = I_G \alpha_3$

Link 4



Force Balance Equations for Link 4:

$\sum \mathbf{F} = \mathbf{F}_{43} + \mathbf{F}_{41} + \mathbf{F}_{elastic} = m_4\, \mathbf{g}_4$

$\sum \mathbf{T} = \mathbf{T}_{41} + (\mathbf{R}_{43} \times \mathbf{F}_{43}) + (\mathbf{R}_{41} \times \mathbf{F}_{41}) + (\mathbf{R}_{elastic} \times \mathbf{F}_{elastic}) = I_G \boldsymbol{\alpha}_4$

From these equations we get the following 3 equations:

$F_x = F_{43\,x} + F_{41\,x} + F_{elastic\,x} = m_4\, g_{4\,x}$

$F_y = F_{43\,y} + F_{41\,y} + F_{elastic\,y} = m_4\, g_{4\,y}$

$T = T_4 + (R_{43\,x}\, F_{43\,y} - R_{43\,y}\, F_{43\,x}) + (R_{41\,x}\, F_{41\,y} - R_{41\,y}\, F_{41\,x}) + (R_{elastic\,x}\, F_{elastic\,y} - R_{elastic\,y}\, F_{elastic\,x}) = I_G \alpha_4$

List of the 9 equations:

$F_x = F_{user\,x} + F_{21\,x} + F_{23\,x} = m_2\, g_{2\,x}$

$F_y = F_{user\,y} + F_{21\,y} + F_{23\,y} = m_2\, g_{2\,y}$

$T = T_2 + (R_{user\,x}\, F_{user\,y} - R_{user\,y}\, F_{user\,x}) + (R_{21\,x}\, F_{21\,y} - R_{21\,y}\, F_{21\,x}) + (R_{23\,x}\, F_{23\,y} - R_{23\,y}\, F_{23\,x}) = I_G \alpha_2$

$F_x = - F_{32\,x} + F_{34\,x} = m_3\, g_{3\,x}$

$F_y = - F_{32\,y} + F_{34\,y} = m_3\, g_{3\,y}$

$T = (R_{32\,x}\, F_{32\,y} - R_{32\,y}\, F_{32\,x}) + (R_{34x}\, F_{34\,y} - R_{34\,y}\, F_{34\,x}) = I_G \alpha_3$

$F_x = F_{43\,x} + F_{41\,x} + F_{elastic\,x} = m_4\, g_{4\,x}$

$F_y = F_{43\,y} + F_{41\,y} + F_{elastic\,y} = m_4\, g_{4\,y}$

$T = T_4 + (R_{43\,x}\, F_{43\,y} - R_{43\,y}\, F_{43\,x}) + (R_{41\,x}\, F_{41\,y} - R_{41\,y}\, F_{41\,x}) + (R_{elastic\,x}\, F_{elastic\,y} - R_{elastic\,y}\, F_{elastic\,x}) = I_G \alpha_4$

These equations can now be used to customize the device based on the force the user can produce as well as the force the band should produce to return the device to the closed state.

Weighted Decision Matrix

The two preliminary designs were compared using a weighted decision matrix. From the design specifications, five major requirements were chosen as the most prevalent for this design. These five requirements were given definitions as they pertain to the project as well as relative weights based on which requirements were considered the most important. The five requirements and their definitions and weights are shown in Table 1 below.

Table 1

Requirement	Weighting Factor	Relative Weight	Definition
Portability	20%	0.20	How easily the product can be carried around, how well the client can move around with the product
Ease of Use	25%	0.25	How easy the product is to operate, how easily the device can be set up
Lightweight	10%	0.10	Product weighs less than 5 lbs

Safety	25%	0.25	How secure the product is attached
Repeatability	20%	0.20	Product is able to withstand many cycles and able to grip different shaped and sized objects

Values were assigned to each preliminary design for each requirement on a scale of one through five where one signifies a design that is considered insufficient, and five, a design that is excellent. The values were determined by comparing the products to each other. As depicted in Table 2 preliminary design 2 was chosen and a prototype was constructed.

Table 2

Requirement	**Weight**	**Prelim Design 1**	**Prelim Design 2**
Portability	0.20	3	4
Ease of Use	0.25	1	4
Lightweight	0.10	4	4
Safety	0.25	4	4
Repeatability	0.20	3	5
	Rank Score	**2.85**	**4.2**

Selection of Materials

The gripping component of the device was 3D printed and ABS plastic was chosen as the material. ABS plastic is an industrial thermoplastic that is commonly used in industry. The tensile strength of this material is 37 MPa. This material can be printed in low or high density. High density was chosen to ensure the parts could withstand the forces necessary to actuate and maintain the grip of an object.

Aluminum was selected because it is a metal commonly used to create other adaptive devices based on its lightweight and consistent reliable strength [17]. It also was beneficial for this project because it was inexpensive and simple to machine into the necessary parts.

The Velcro straps were selected because they can easily be secured and detached with very minimal force, to ensure the client could attach and use the device on his own.

Chapter 7: Manufacture and Testing of Prototype

Manufacture of Prototype

Gripping Component:

The gripping component of the device was 3D printed using high density ABS plastic. The computer aided design was created using Solidworks. The gripping component was made up of three parts: the fixed prehensor, the pivoting prehensor, and the link. The fixed prehensor was design at an angle to allow for comfort for the user when operating the device. It was assumed that the user would be sitting while using the device as the client for this project is confined to a wheelchair since his injury. The two holes at the top of the prehensor fixed the prehensor to the aluminum attachment component using screws. The large hole in the center of the prehensor is where the pivoting prehensor was situated and allowed to move when actuated by the user.

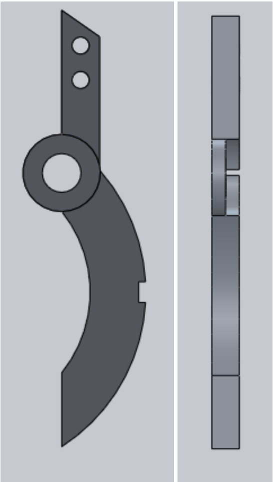


Figure 18 - Fixed prehensor front and side views

Each prehensor incorporated an indent where the elastic band was placed around both prehensors. The indents prevented the elastic band from sliding on the prehensors when the device was actuated. The pivoting prehensor contained a hole below the indent where the link attaches. The link was also connected to the wrist attachment that actuated the device.

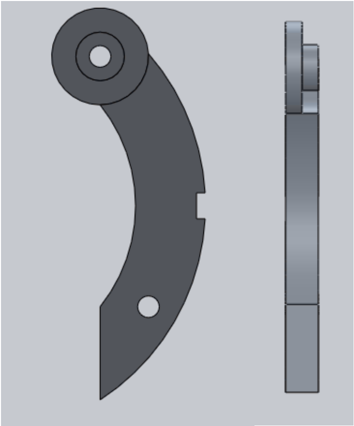


Figure 19 - Pivoting prehensor front and side views

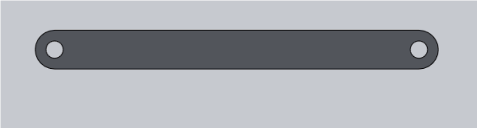


Figure 20 - Link front view

Below is a figure of the CAD assembly design of the device. This image clearly shows the set up of the gripping component of the device. The pivoting prehensor was situated in the fixed prehensor and the link was positioned on top of the pivoting prehensor. The left hand side of Figure 25 shows the front view of the assembly while the right hand side shows a side view.

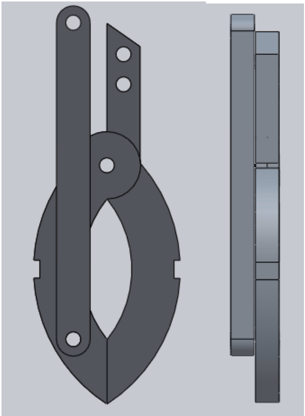


Figure 21 - Assembly front and side views

Attachment:

The arm attachment component of the design was first sketched on paper using measurements of the clients arm. This design was transferred onto the aluminum bar, which was then cut into segments and holes were drilled in pre-specified locations in the machine shop. The edges of each segment were beveled and cleaned up to ensure they would not be sharp and cause harm to the client. The bands were then bent using vice grips and a metal shaper to fit the client's arm exactly, and Velcro straps were sewn to fit exactly into the device.

Prototype:

These designs were finalized individually and then attached with screws to create the final prototype.

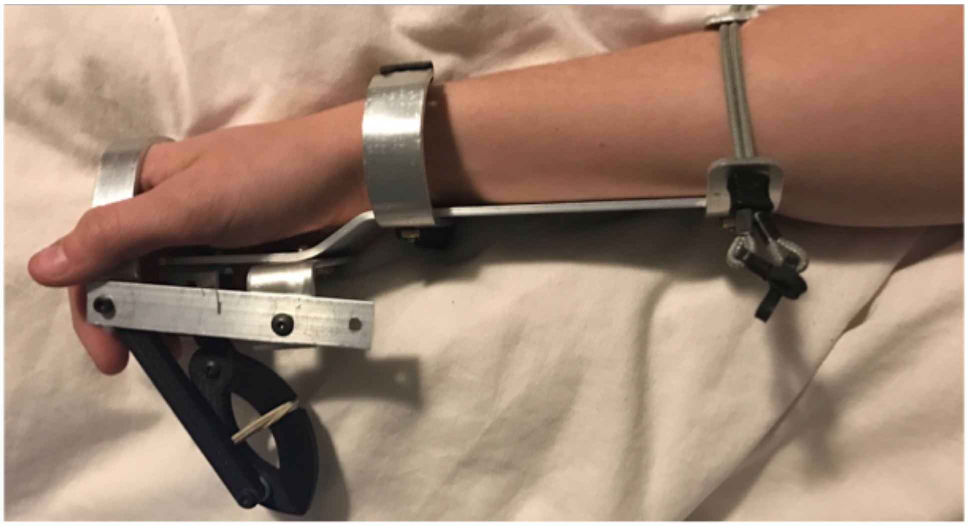


Figure 22 - Final prototype

Testing

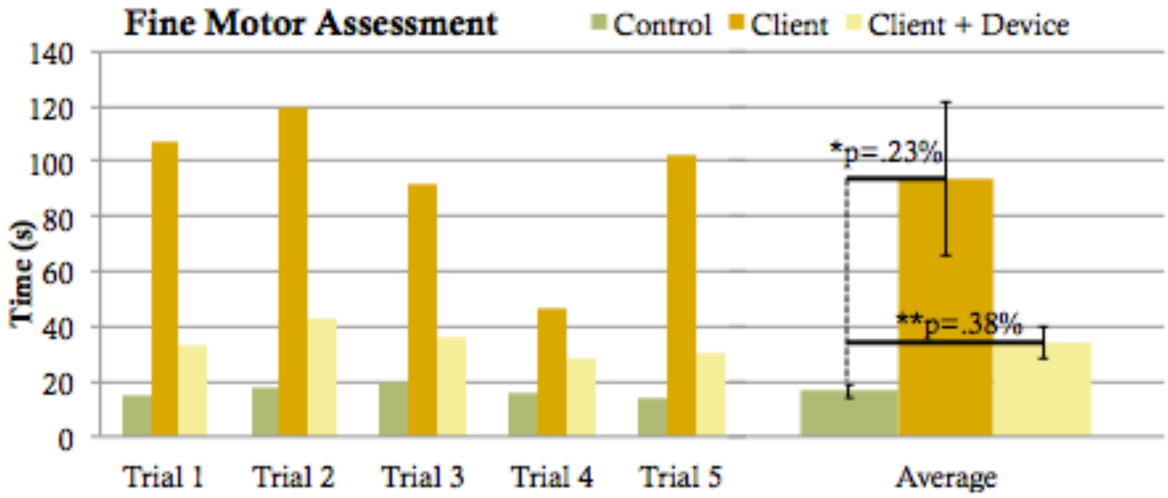
The device was tested using a fine motor skills assessment commonly used for teaching preschool children [18]. The testing plan involved timing the user while sorting twelve colored candies from the table top into different receptacles, set up as shown in Figure 19. This test was used to simulate the client sorting pills into an organizer.

Figure 19 - Testing set up

The test was performed in five trials, first, by a control (someone with average fine motor skills), second, by the client without the device, and third, by the client with the adaptive device. The control was asked to sort the candies as she normally would, with the natural ability fine motor control. The time it took her to sort the twelve candies from start to finish was recorded five separate times. This data was then averaged. The client was then asked to sort the pills without the device. He was asked to perform this task without the device to determine if he was even able to complete the task and so show his limited fine motor control. He performed the test five times however it was very tiring and time consuming for him. The same data was recorded and averaged. Finally, the client was asked to perform the test again with the device. He was able to quickly and accurately sort the candies. The same data was recorded and averaged. The average trial time taken by each group was compared in order to determine the impact the device had on the client.

Results and Statistical Analysis

Results from the testing of the prototype are shown in the figure 20 below. Five trials were performed and that data is shown on the left of the chart below. The larger bars on the right side of the chart show the average time taken for the five trials. The control is shown in green, the client without the device is shown in gold and the client with the device is shown in yellow. When compared to the control, the client's sorting time without the device was nearly six times the average. With the use of the prototype the time was reduced to approximately double the control time.



	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average
Control	14.95	17.92	19.32	16.34	13.49	16.404
Client	107.59	119.67	91.79	46.68	102.02	93.55
Client + Device	32.71	43.17	36.4	27.96	30.39	34.126

Figure 23 - Results

A KS test was performed in Matlab on the data from the 5 trials and the data was all found to be statistically significant. Since the P values were both less than 5%, as shown in figure 20, the results from the study can be accepted.

Chapter 8: Discussion

Evaluation of Design

The device dramatically improved the client's pick and place for tasks requiring fine motor ability. As shown by the testing results above, his time to sort candies improved from six times that of the control to only 18 seconds different. This device was able to close the gap between the client’s abilities with an SCI and the natural abilities of the control. However, the real success was in that of the client's newfound ability to sort his own pills. A task that he was previously unable to perform on his own in a reasonable amount of time. Prior to the development of this design the client found this task too time consuming and tiring so he would most likely ask someone else to do it for him. With the device the client is now able to accurately and quickly sort his pills into the pill organizer. As a result his independence has increased with the help of this device.

Future Recommendations

While the device did aid in the pick and place of small objects and the time needed to do so, there are some areas of improvement in the design aspects of the device. This would be especially important if the device were to be mass produced for a commercial market. First, the kinematic analysis allows for the device to be extremely customizable for different purposes. Since it is possible to solve the equations relating to different forces, the closing system can be adjusted for specific applications and/ or users. Also, the band that provides the default closed system could be replaced by a spring that is more durable and aesthetically pleasing. Second, as the gripping component of the design is 3D printed and attached with screws it is possible to produce different types of prehensors in different shapes and sizes for specific applications. The prehensors can be designed in different ways similar to that of different pliers used in various activities. Finally, the aluminum bands and Velcro attachment system could be improved to be more ergonomic and could possibly be made out of a high density plastic in order to cut down on production time.

Chapter 9: Conclusions

In the end, this project was a success. The team was able to design and produce a prototype device that assisted the client with tasks requiring fine motor control. The device was created from 3D printed and aluminum machined components and was lightweight and easy to use by the client's standards. Additionally, it was safe and the motion was repeatable with no signs of wear or breakdown. The device was tested and improved the client's ability to pick and place small objects by 300% in the test. The client was also able to sort pills that were previously too small for him to manipulate on his own.

References

[1] Sheperd Center and KPKinteractive, "Understanding Spinal Cord Injury - What you should know about spinal cord injury and recovery." Sheperd Center, 16-Jan-2017.

[2] Dudgeon et al., Educational performance and vocational participation after spinal cord injury in childhood, *Archives of Physical Medicine and Rehabilitation* **77** Issue 10 (1996) 995-999

[3] Logan, K. et al., *The Association for Persons with Severe Handicaps* **22** (1997) 16-27

[4] My VMC, "Fine Motor Skills," *Parenthub*, 04-Nov-2014. [Online]. Available: https://www.parenthub.com.au/education/fine-motor-skills/. [Accessed: 16-Jan-2017].

[5] Lashno, M., Activities of Daily Living and Fine Motor Abilities, Children's Project, First Edition, Chapter 12

[6] "The muscles of the arm and hand," *Anatomy Medicine*, 16-Jan-2017. [Online]. Available: http://anatomy-medicine.com/musculoskeletal-system/87-the-muscles-of-the-arm-and-hand.html. [Accessed: 16-Jan-2017].

[7] Talha Shahid and Umar S. Khan, "Design of a low cost multi degree of freedom hand exoskeleton," *Conference on Robotics and Emerging Allied Technologies in Engineering (iCreate)*, pp. 312–316, Apr. 2014.

[8] Hong Kai. Yap, Jeong Hoon. Lim, Fatima. Nasrallah, James C.H. Goh, and Raye C.H. Yeow, "A soft exoskeleton for hand assistive and rehabilitation application using pneumatic actuators with variable stiffness," *IEEE*, pp. 4967–4972, May 2015.

[9] Shu-Wei Pu, Sung-Yu Tsai, and Jen-Yuan Chang, "Design and development of the wearable hand exoskeleton system for rehabilitation of hand impaired patients," *IEEE*, pp. 996–1001, Aug. 2014.

[10] Azzurra Chiri, Nicola Vitiello, Francesco Giovacchini, Stefano Roccella, Fabrizio Vecchi, and Maria Chiara Carrozza, "Mechantronic Design and Characterization of the Index Finger Module of a Hand Exoskeleton for Post-Stroke Rehabilitation," *IEEE*, vol. 17, no. 5, pp. 884–894, Oct. 2012.

[11] Jumpei Arata, Keiichi Ohmoto, Roger Gassert, Oliver Lambercy, Hideo Fujimoto, and Ikuo Wada, "A new hand exoskeleton device for rehabilitation using a three-layered sliding spring mechanism," *IEEE*, pp. 3902–3907, May 2013.

[12] Charles J Daniels and Thomas A Smith, "Mechanical Hand," US3020908A.

[13] Daniel D. Frey MS, Lawrence E. Carlson DENG, and Vidya Ramaswamy MS, "Voluntary-Opening Prehensos with Adjustable Grip Force," *JPO*, vol. 7, no. 4, pp. 124–131, Fall 1995.

[14] “Sierra 2-load Voluntary Opening Hook,” *The O&P*, 02-Feb-2017. .

[15] Quadventure Quadtools, “Quadtools,” *Quadtools*, 02-Feb-2017. [Online]. Available: http://www.quadtools.com/. [Accessed: 02-Feb-2017].

[16] U.S. Food & Drug Administration, “How to Study and Market Your Device,” *FDA*, 16-Sep-2015. [Online]. Available: https://www.fda.gov/MedicalDevices/DeviceRegulationandGuidance/HowtoMarketYourDevice/default.htm. [Accessed: 02-Feb-2017].

[17] Jenkins, M. L., and M. Jenkins. *Materials in Sports Equipment, Volume 1*. N.p.: Woodhead, 2003. Print.

[18] Bilodeau, Edward A. And Ina Bilodeau, “Motor-skills learning.” *Motor-Skills Learning | Annual Review of Psychology* [Online].

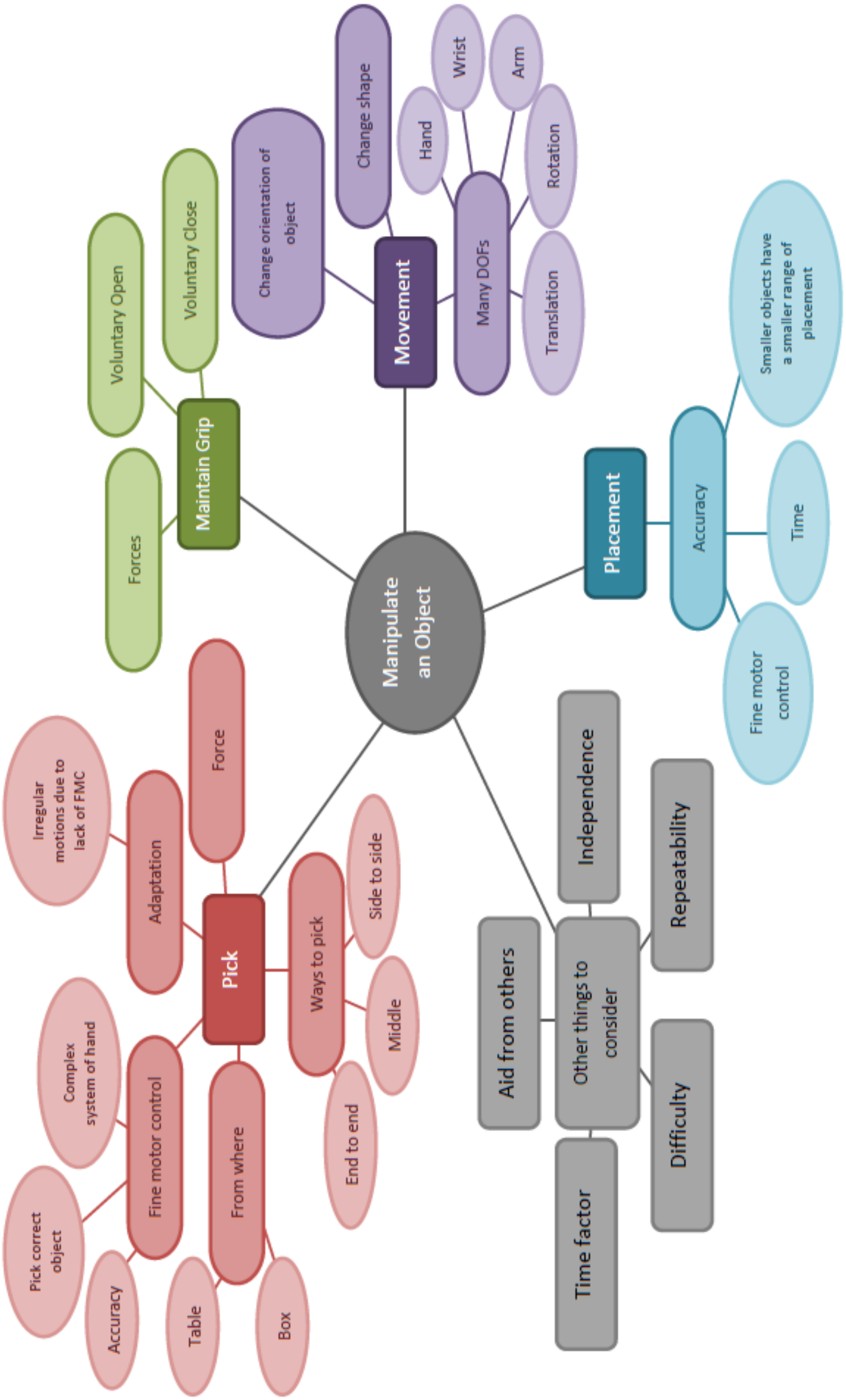
Appendices

Appendix A: Gantt chart

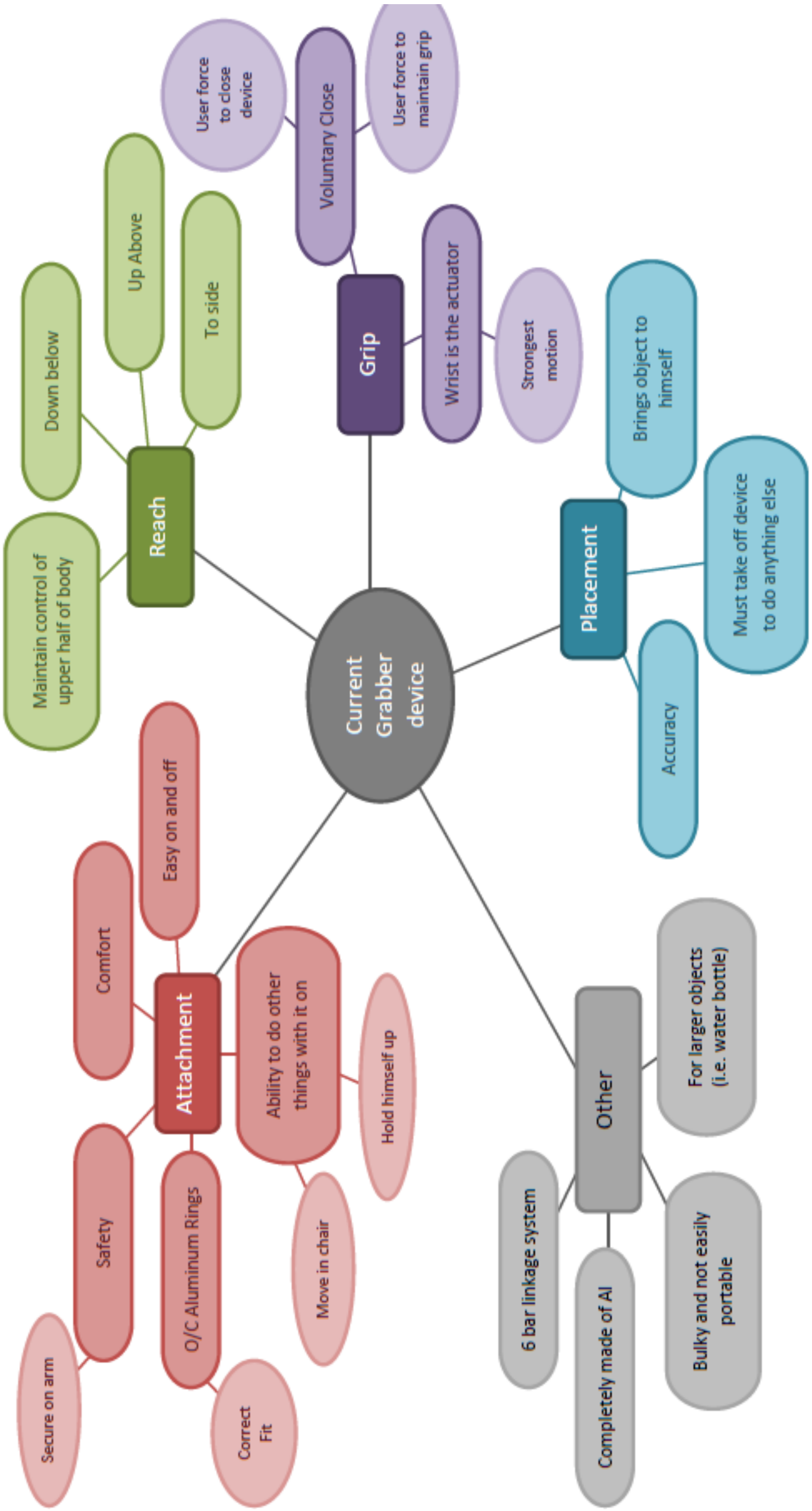
░ Sarah	B term	C Term							D term						
█ & Caitlin	Oct-Jan	Jan. 15-21	Jan. 22-28	Jan. 29-4	Feb. 5-11	Feb. 12-18	Feb. 19-25	Feb. 26-5	Mar. 12-18	Mar. 19-25	Mar. 26-1	Apr. 2-8	Apr. 9-15	Apr. 16-22	Apr. 23-28
Development Activity	Week 1-7	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14
Project development	░	█	█	█											
Background Research	░	░	█	█	█										
Existing Technologies	░	░	█	█	█										
Development of Need	░	░	░	█	█										
Design Specifications	░	░	░	█	█	█									
Preliminary Designs						█	█	█							
Selection of Final Design								█	█						
Kinematic and Force Analysis									█	█	█	█	█	█	
Manufacture of Prototype												█	█	█	
Testing of Prototype													█	█	
Final Presentation														█	
Final Report	░	░	█	█	█	█	█	█	█	█	█	█	█	█	█

Appendix B: Mind Maps

Mind map 1



Mind map 2



Current Grabber device
Reach
Maintain control of upper half of body
Down below
Up Above
To side
Grip
Voluntary Close
User force to close device
User force to maintain grip
Wrist is the actuator
Strongest motion
Placement
Brings object to himself
Must take off device to do anything else
Accuracy
Attachment
Easy on and off
Comfort
Safety
Secure on arm
O/C Aluminum Rings
Correct Fit
Ability to do other things with it on
Hold himself up
Move in chair
Other
6 bar linkage system
Completely made of Al
Bulky and not easily portable
For larger objects (i.e. water bottle)