MQP AHH 1302

Design of a Powered Hand Orthosis (2)

A Major Qualifying Project Report submitted to the Faculty of the
Worcester Polytechnic Institute in partial fulfillment of the requirements for the Degree
of Bachelor of Science.

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Abstract

Most hand orthotics are rigid and hold the hand in a fixed position. The goal of this project was to design and manufacture a powered hand orthosis to allow persons with dexterity and strength impairments to regain hand function necessary for independence by providing cylindrical and key grips. Based upon research into existing devices, three preliminary designs were developed with full analyses and were ranked according to our design specifications to select the final design. The prototype device uses cables to pull the fingers closed, a geared mechanism to raise and lower the thumb and a linear actuator to close it. Three degrees of freedom are controlled by two rocker switches for closure and a potentiometer for thumb rotation. These three switches are contained within a hand held enclosure that is worn on a belt. The device was found to function as expected and provided the motion necessary for the desired grips.

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Chapter 1: Introduction

The device designed by this project is intended to return the independence of the user by restoring the use of one hand through a powered orthosis. An orthosis is a device which, either statically or dynamically, attempts to compensate for a physical limitation of a user. The orthosis is intended to intended to provide a cylindrical or “power” grip and a pinch grip (Figure 1).

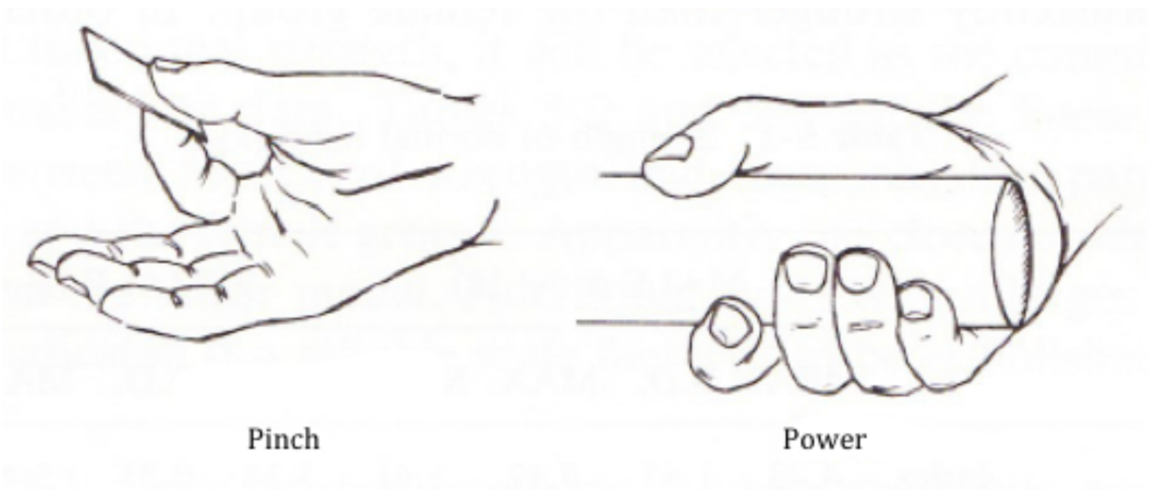

Pinch
Power

Figure 1 – Common Grips (Chao, 1989)

The two main targeted groups for the device are elderly and stroke patients. Though the main intention of the device is to provide function where there may be none, the device is also expected to provide therapy. Repeatedly moving limbs across constrained motion arcs has been found to restore muscle memory and function; therefore daily use of this device could result in restored function in the user. This effect would be most noticeable amongst stroke patients.

This device is also intended to be considerably less expensive than current, competing models. The single device currently on the market, detailed during the “Existing Products” section, has a retail value of approximately $2500 (Broadened Horizons). Other devices in development have equal or greater projected costs. With an ideal production cost of not more than $200, this device intends to fill a niche for a low-cost orthotic.

Chapter 2: Background

Importance of Biomechanics

The purpose of this project is to design an orthosis that will help the user regain independence and function through increased strength being applied to a grip. In order to provide a functioning product of this nature it is important that basic knowledge of the anatomy and biomechanics of the human hand is understood. This will allow for the design of a device that meets the functionality requirements while interacting properly with the user so that no injury will occur from the use of the orthotic.

Hand Anatomy

One of the defining traits of the human species is the ability to perform intricate hand motions involving precise placement of the fingers and thumb. This control is made possible by the complicated anatomy of the hand. The human hand is composed of 27 individual bones connected and pulled by a series of tendons and muscles. The bones can be broken down into three main groups: the phalanx, the metacarpals and the wrist bones (Gray, 2010). The phalanges are most critical to the type and quality of grips formed.

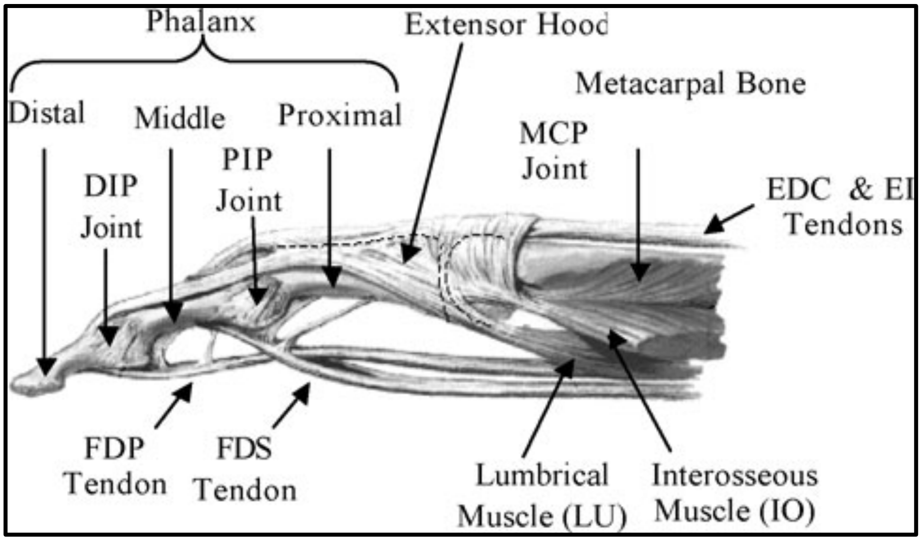


Figure 2 – Anatomy of finger (Balourdas, 2013)

Figure 2 shows the anatomy of the finger. Each finger is composed of a distal, middle, and proximal phalanx connected to the metacarpal bone. Between these bones are three joints: the distal interphalangeal joint (DIP), proximal interphalangeal joint (PIP), and the Metacarpal-phalangeal Joint (MCP) (Chao et al, 1989). Each joint serves identical function to a mechanical joint as detailed in the next section.

Tendons are responsible for actually opening and closing the hand while the muscle groups provide the force for the movement. The two main muscle groups that control hand movement are the intrinsic and extrinsic muscles (Chao et al, 1989). The extrinsic muscles are the large muscles located on the forearm responsible for controlling gross movement and provide strength. The intrinsic muscles are the smaller muscles located inside the hand which provide fine control (Gray, 2010).

Biomechanics of the Hand

The hand can be treated as a mechanism where the bones form links. The joints between the finger bones all have mechanical analogs, as shown in Table 1. It is worth noting that though the fingers and thumb have an identical layout of joints; the range of motion and control provided to the thumb is much larger (Chao et al, 1989). This is necessary to allow the hand to form a wide range of grips and positions.

Table 3 – Modified table of Finger Joint Mechanical Equivalents (Chao et al, 1989)

Hand Element	Joints	Mechanical Equivalent	Degrees of freedom
Finger	Distal Interphalangeal Joint	Hinge Joint	1
	Proximal Interphalangeal Joint	Hinge Joint	1
	Metacarpo- Phalangeal Joint	Universal Joint	2
Thumb	Interphalangeal Joint	Hinge Joint	1
	Metacarpo-phalangeal joint	Universal Joint	2
	Carpo-metacarpal	Universal Joint	2

While there are many ways that a human can orient their hand there are four specific grips that are commonly used. These include the cylindrical grip, pinch grip, lateral pinch, and palmar pinch shown in Figure 3.

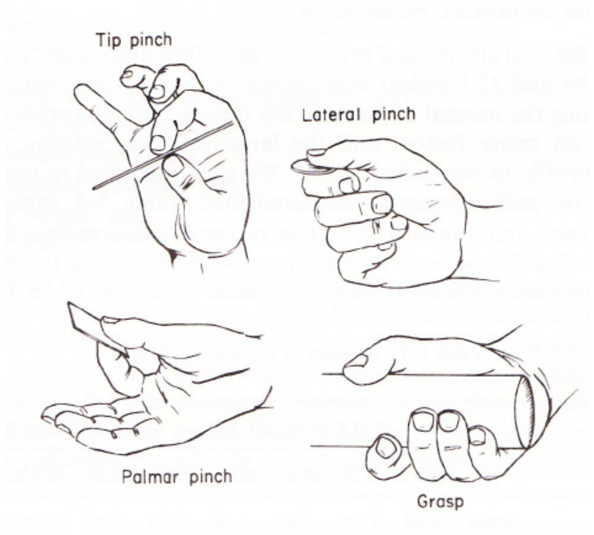


Figure 3 – Basic hand grips (Chao et al, 1989)

The lateral pinch is the grip one would use to hold a key. The cylindrical grip is commonly used for grasping objects which are either large or require significant strength to hold. This grip is made by closing all four fingers and wrapping the thumb around the closed fingers, much like making a fist. Some common uses of the power grip are for grabbing soda cans, cups, railings, and basic hand tools, such as a hammer. The pinch grip is used largely for picking up smaller objects and similar precise tasks. This grip employs the use of the thumb, the first finger, and occasionally second finger by pressing the digits together at the tip. Some common uses of the pinch grip may include manipulating zippers and picking up papers or other small objects. The palmar pinch is similar to the tip pinch, however the force comes much more from the thumb than the finger.

These grips can better be understood by observing the forces required in each grip. Table 2 shows the results of a study conducted by Chao et al (1989), which examined the amount of force provided by each finger in a variety of grips.

Table 2 – Summary of force provided by each finger in various grips (Chao et al, 1989)

		Male (n=18)				Female (n=22)			
		Mean [kg]	SD [kg]	Max. [kg]	Min [kg]	Mean [kg]	SD [kg]	Max. [kg]	Min. [kg]
Radial Lateral Movement at PIP	Index	4.43	1.45	7.12	1.61	3.34	0.85	5.45	1.67
	Long	4.43	1.76	8.18	1.82	2.89	0.79	4.73	1.78
	Ring	3.42	1.79	7.61	1.67	2.35	0.84	3.82	1.09
	Little	2.58	1.59	7.52	1.33	1.82	0.92	3.55	0.1
Ulnar Lateral Movement at PIP	Index	4.57	1.81	7.21	1.64	3.29	0.9	5.76	1.94
	Long	4.75	1.99	9.58	1.64	2.79	0.95	5.18	1.09
	Ring	3.63	1.83	9.2	1.48	2.35	0.94	4.36	1.24
	Little	2.66	0.93	5.15	1.45	2.11	0.76	3.70	1.03
Radial Pinch	Index	7.65	1.64	10.79	4.36	6.03	1.21	8.15	3.76
	Long	6.95	1.55	9.14	4.21	5.17	0.98	0.85	2.82
Tip Pinch	Index	6.43	1.01	9.7	5.33	4.82	1.08	6.94	2.48
	Long	6.46	1.94	10.2	3.97	4.66	1.24	7.33	2.79
Pulp Pinch	Index	6.58	1.35	8.45	4.45	4.55	0.92	6.97	3.06
	Long	6.36	1.48	8.61	3.06	4.57	0.92	7.00	3.30
	Grasp	37.51	8.69	58.48	23.20	22.3	6.28	36.70	11.97

Independent of the type of grip, the index finger provided the most force, followed by the middle or long, then ring and finally little finger. The study also found that the strongest grips are the two power grips, with the ulnar lateral movement grip being the strongest. This grip involves the fist bending down, away from the shoulder, such as when one might lift something. Radial lateral movement referred to the bending up towards the shoulder, as if one was curling a weight. The pinch grips listed are, in order, the fingers in the key grip position, fully extended (as one might hold a card) and in the pinch grip of Figure 3. Additionally, this study found the cylindrical grip, labeled grasp as in Table 2 and Figure 3, provided the most force (Chao et al, 1989).

Characteristics of the User

When it comes to the design of any rehabilitative product it is important to understand the characteristics and limitations of the intended user group. For the purpose of the design this orthotic characteristics of stroke patients were researched to gain a greater understanding of the functional needs and limitations for this particular demographic. Post stroke symptoms and the rehabilitation process are presented in detail.

Source of Impairment

The term impairment denotes a weakness or lack of fine control that makes normal tasks, such as holding or manipulating objects, difficult. While impairment may result from a variety of sources, the most common one is age. As one gets older, one's body loses the ability to repair damage to joints and muscles. This has a cumulative effect and leads to a significant drop in strength (Figure 4).

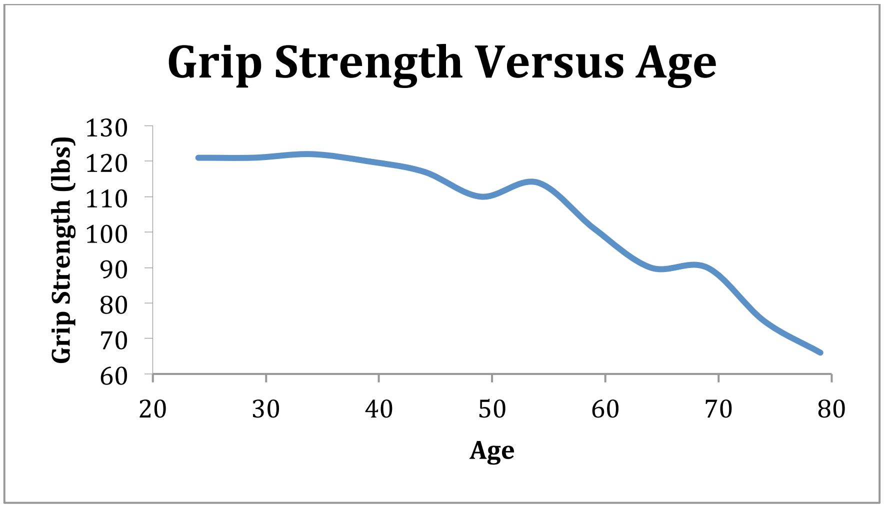


Figure 4 - Plot of Average Grip Strength Versus Age in Men (Mathiowetz, 1985)

The average man loses quarter of his grip strength by the age of 60 and half his grip strength by the time he reaches 80 years old, and the problem only worsens. Exercise can only do so much to mitigate the loss. The process is similar for women, though with lower overall numbers.

Although stroke can occur in people of all ages, stroke risk has a positive correlation with increased age. A stroke occurs when a blood vessel in the brain becomes clotted, damaging brain tissue. Between 30 to 40% of the patients that survive suffer from some manner of disability afterwards (Journal of Pakistan Medical Association, 2013). The degree and extent of the disability is dependent on where in the brain the lesion is located, but reduced motor function is most the common symptom (Journal of Pakistan Medical Association, 2013). Such impairments are generally only on one side of the body as a stroke is usually localized. Weakness on one side of the body is known as hemiplegia. Since some function is retained this is not true paralysis, however, function is not as strong or as controlled as before.

Symptoms of hemiplegia can also result from other causes. Neurological disorders such as cystic fibrosis can produce the same effect. Injuries of the hand can damage nerves and reduce function. The reason for reduced gripping ability can be divided into three categories: reduced strength, reduced fine control and reduced gross control.

Reduced strength in stroke patients is normally neurologically based. Muscles are not necessarily any weaker, but the nerves themselves cannot trigger the muscle as efficiently. Control is often lost amongst hemiparetic patients (Kamper, Rymer and Seo, 2010). Patients with hemiparesis have difficulty applying force to an object accurately. To hold an object, one must grip it and direct the force as normal to the grip surface as possible, thus maximizing the friction between the finger and the object. As noted in the study, however, “Due to the large deviation of the force direction from the normal … direction, the paretic digits slipped and moved more than 1 cm during 55% of all grasping trials” (Kamper, Rymer and Seo, 2010). In hemiparetic patients (Figure 5), the force from their fingers was directed much less accurately than that of healthy patients.

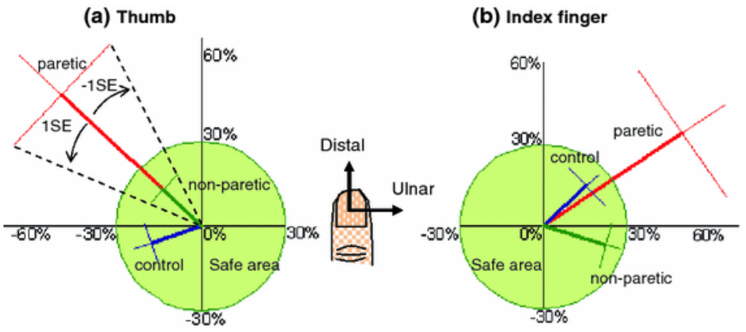


Figure 5 - Diagram of applied force when gripping an object. See text for explanation (Kamper, Rymer and Seo 2010)

The red lines mark the angle of force from a paretic hand measured between a flat plane and the angle between the surface of the finger tip, the green from a non-paretic hand on the same person. Blue indicates the control group, made of healthy patients. For the thumb, while the force was applied at roughly the same angle, there was much greater variation and thus less control than from a healthy hand as shown by the much longer red line. The trend was seen in the index finger as well, where the variation, while less than the thumb, was at a completely different angle than the non-paretic finger. It therefore follows that hemiparetic patients cannot grip as effectively for the same force as a healthy patient due to a misdirection of the force, with an implication that there is difficulty in directing force even in their nonparetic hand, as indicated by the difference the non-paretic and control hands The study also found that the maximum normal force a paretic patient could apply was 12N, whereas a healthy patient could apply 46N (Kamper, Rymer and Seo 2010). This number is from a pinch grip and is the normal force applied, not net force, henceforth why it differs significantly from Figure 5. This number is also more useful, as it is a measure of actual grip force, unlike in Figure 5, which is the maximum possible strength in the grip, neglecting direction.

A lack of gross control is typically a result of reduced feeling in the hand. The sense of touch is very important to grip, as it provides bio-feedback to regulate the force applied to prevent gripping too hard (Nowak, Hermsdörfer and Topka 2003). A study of acute stroke victims who had suffered a loss of feeling in their hands found that they could not accurately apply appropriate force to hold an object, applying as much as six times the necessary force (Nowak, Hermsdörfer and Topka 2003). The over-application of force was not found to be unique to stroke victims, as patients who had diminished feeling for other reasons exhibited the same issues. (Nowak, Hermsdörfer and Topka 2003). An effective orthosis must therefore provide direction for the force and be limited in how much force it can apply.

Rehabilitation Process

Despite how dramatic some of these impairments are, it is possible for one to recover function through rehabilitation. Rehabilitation can be divided into two distinct goals – restoration of physical function and alleviation of potential causes of depression. The former is the return of function of an impacted limb through exercise and repetitive motions. The latter can be effected with the return of quality of life by restoring the independence of the patient.

With strokes, there are a wide variety of methods used to rehabilitate patients. The exact method varies with the patient's physical characteristics and the location and severity of the stroke, but one of the most common and effective methods used is constraint-induced movement therapy (Langhorne & Berhnardt 2011), or CIMT. This method involves constraining the affected limb such that it can only move along one given path and then repeatedly moving the limb along that path, either with or without resistance. The goal is to retrain the limb to function in that manner and restore the "muscle memory" such that the action becomes automatic (Langhorne & Bernhardt 2011). This muscle memory may be created in the normal muscles for that motion or in different ones should the motion have to be created in a different manner.

Other forms of physical therapy rely on restoring muscle mass. There are two main ways of accomplishing this. The first is through resistance exercise – lifting a weight up and down. However, some muscles cannot be easily exercised this way, or the patient may not be able to make the motion. This issue can be resolved through the use of electrostimulation (Langhorne and Berhnhardt 2011). Electrostimulation involves applying electrical current to a muscle through electrode pads, forcing the muscle to expand and contract. This works the muscle without the person having to do so themselves.

The other aspect of rehabilitation comes in the form of mental and emotional support. Traumatic injuries, which result in permanent impairments, can remove one's independence. This can lead to depression (Newman 1972). Thus the goal of rehabilitation is also restore independence in some manner, thereby removing a potential cause for depression. Unfortunately, it is not always possible to rehabilitate someone fully in a short amount of time, if it is indeed possible at all. Therefore a powered orthosis can also be used in conjunction with rehabilitation exercises (Newman 1972). The orthosis can restore some function, increasing independence. Since the effectiveness of rehabilitation is dependent on the person themselves and their willingness to work at it, an improvement in their quality of life can effect a positive change in their recovery (Newman 1972). Ultimately, this means that successful rehabilitation must take into account the patients mental state as well as their physical.

Activities of Daily Living

Activities of daily living, ADLs, are tasks and actions that are performed repeatedly and constantly throughout the day and are critical to one's health and independence. These tasks are common between almost all people, independent of age. There are also numerous activities that do not meet the above definition of an ADL, but are still necessary to consider to restore independence. A list of the general categories for daily activities is listed below along with specific examples.

Table 3 – Common Daily Activities

Category	**Examples**
Personal Hygiene	Brushing teeth Washing hair
Dressing	Buttoning Zipping
Mobility	Holding railings Opening doors
Eating	Holding utensils, dishes
Cooking	Manipulating cooking implements Holding Pots and Pans
Using Hand tools	
Cleaning	Wiping wih cloth or sponge
Writing	
Driving	Opening doors Holding steering wheel
Passive Recreation	Reading a book
Active Recreation	Golf
Shopping	Holding a bag Examining products

Types of grips used daily

Table 4 shows the results of study conducted by Kilbreath (2005) on the frequency of hand use during in healthy elderly persons. The study shows that most activities are bimanual and the most common grip is the cylindrical grip. Therefore, it can be concluded that any orthotic must allow both hands to be used together in order to be useable in daily activities. Furthermore, it confirms that the orthotic must provide a cylindrical grip.

Table 4 – Grip and hand use in certain activities (Kilbreath, 2005)

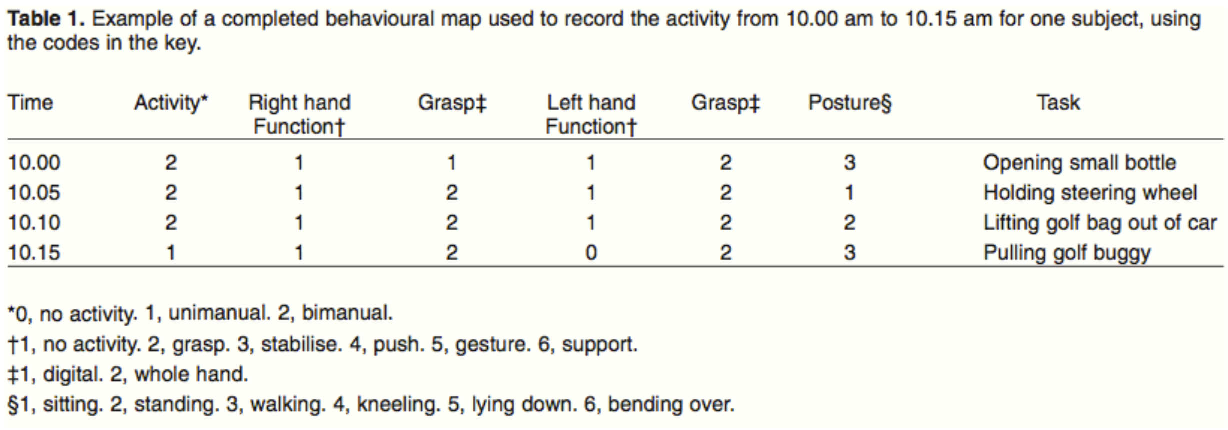


Table 1. Example of a completed behavioural map used to record the activity from 10.00 am to 10.15 am for one subject, using the codes in the key.

Time	Activity*	Right hand Function†	Grasp‡	Left hand Function†	Grasp‡	Posture§	Task
10.00	2	1	1	1	2	3	Opening small bottle
10.05	2	1	2	1	2	1	Holding steering wheel
10.10	2	1	2	1	2	2	Lifting golf bag out of car
10.15	1	1	2	0	2	3	Pulling golf buggy

*0, no activity. 1, unimanual. 2, bimanual.
†1, no activity. 2, grasp. 3, stabilise. 4, push. 5, gesture. 6, support.
‡1, digital. 2, whole hand.
§1, sitting. 2, standing. 3, walking. 4, kneeling. 5, lying down. 6, bending over.

Current technology

As with any new product, market research is an important step in the design process. Knowledge of current patents and products allows for a new device to be designed with the understanding of what technologies are effective and accepted by the users. Current patents and products for both passive and active orthotics are presented in this section.

Analysis of these patents and devices is necessary to develop an effective orthotic. Each accomplishes the task in a different manner and therefore provides potential designs to pursue. Furthermore, they provide a baseline for understanding where the developed device fits in market and what area is best to target.

Patents

A number of patents exist for hand orthotic devices and methods of powering existing orthotics. The oldest of the patents reviewed, US Patent 3,631,542, is dated January of 1972 and makes claims for a "Myoelectric Brace" that uses EMG signals from muscles near the brace, which are amplified by an electronic circuit. The amplified signal is then transformed into a control signal that activates a motor. The motor causes the hydraulic actuator mounted to the brace to extend or contract based on the signal received.

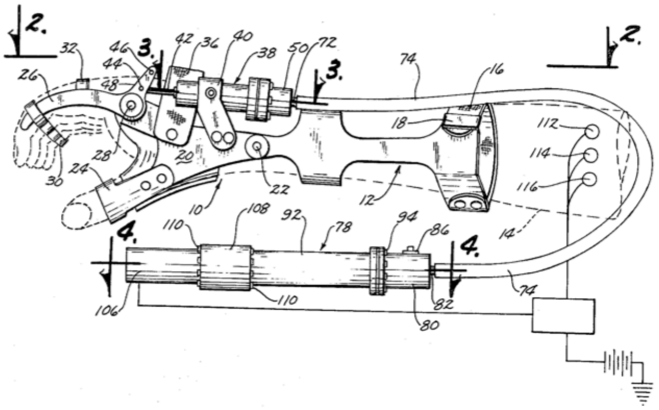


Figure 6 – US Patent 3,631,542. Myoelectric Brace.

The actuator rod, 42, is connected to a link, 26, which opens or closes the fingers that are attached to the brace (Potter, 1972). The patented device only allows the fingers one degree of freedom (DOF) and forms only one type of grip – the cylindrical grip. The thumb of the wearer is set in a fixed position. (Figure 6). This patented brace bears a striking resemblance to the Broadened Horizons PowerGrip orthotic device described in the next section.

Patented in 1988, US Patent 4,792,338 makes claims for an "Artificial Hand" which is a prosthetic rather than an ortotic. The patent drawings show a thumb and coupled first and middle finger that are operated by a system of linkages and gears in the plane of the first finger and thumb (Figure 7). The thumb and fingers pivot together to form a pinch type grip and are driven by an electric motor in the palm area of the artificial hand (Rennerfelt, 1988).

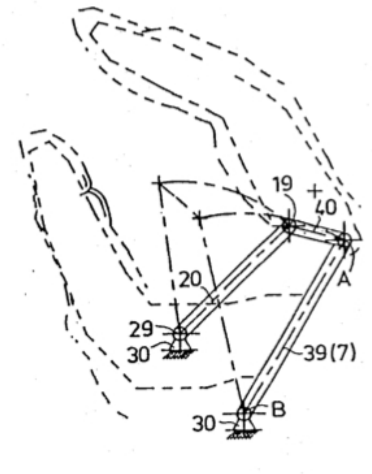


Figure 7 – Four Bar Linkage (US Patent 4,792,338)

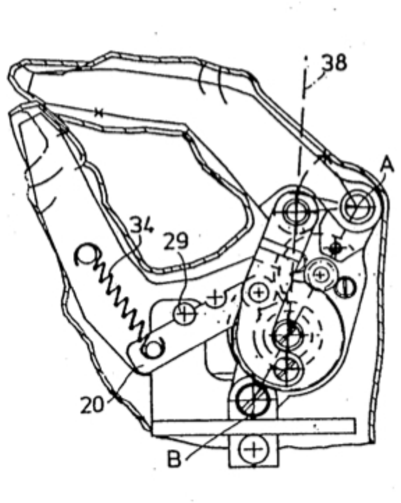


Figure 8 – Thumb Linkage (US Patent 4,792,338)

The most recent patent reviewed, US 8,235,928 B2, is dated in August of 2012. The patent makes claims for a "Low Profile Dynamic Extension Splint" that uses a flexible outrigger to keep the first and middle fingers in the extended position. Elastic material encasing the thumb is used to keep the thumb in an open position, but still allow the thumb to move to form a pinch type grip with the first two fingers. The device will allow the wearer to close their fingers normally to grasp an object and will assist in reopening the fingers once the wearer relaxes their muscles (Padova, 2012). The patent bears a similarity to, and references, the Saebo, Inc. Saeboflex orthotic, which will be described later in Figure 11.

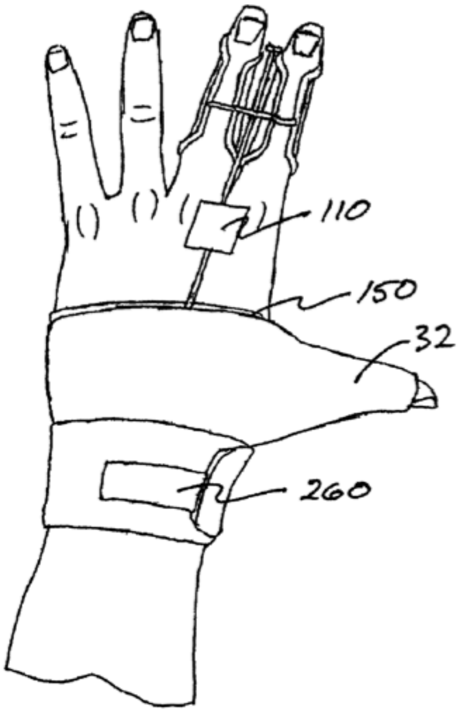


Figure 9 – US Patent 8,235,928 B2. Functional Low-Profile Dynamic Extension Splint and Methods for its use and Manufacture

Existing products

There are many existing hand orthotic devices on the market. These devices fall into two general categories: passive and active. A passive orthotic holds a fixed position or provides resistance to movement and is often used to facilitate the recovery from an injury. Conversely, an active orthotic is one that is designed to increase the abilities of the patient by actively controlling at least one joint. Passive devices are far more common than active and usually have a much lower price tag, generally around $100. Active type orthotics can cost over an order of magnitude more.

To best hold a fixed position, passive type orthotics are often shaped or fitted to the patient's hand. Their purpose is to adjust the hand's position so it rests in an orientation that cannot be otherwise achieved by the dexterity-impaired patient without assistance. The goal is that moving and holding the joints and fingers in these positions will eventually retrain the muscles and nerves, leading to increase dexterity and mobility similar to that of the original range of motion. One such passive device is the 'Restorative Hand', (Restorative Medical, Inc., 2009). A patient's hand is fitted to a molded, specifically-shaped piece of plastic, which is designed to hold the fingers in a fixed position, Figure 10.

Figure 10 – *Restorative Hand* A fixed passive orthotic by Restorative Medical, Inc

Another type of passive orthotic is one that uses springs and/or rubber bands to provide resistance to the fingers while in certain positions. These kinds of devices are often used as an exercise device for patients to aid in regaining strength and movement in their hands and fingers as the patient must overcome the restoring force. One example of such a product is the Saeboflex, made by Saebo, Inc. The company claims that their device "allows individuals suffering from neurological impairments, such as stroke, the ability to incorporate their hand functionally in therapy and at home by supporting the weakened wrist, hand, and fingers" (Saebo, Inc., 2013). The Saebo orthotic uses springs in order to provide resistance to the fingers in closing and to assist patients in opening their fingers once they have picked up an object, Figure 11.

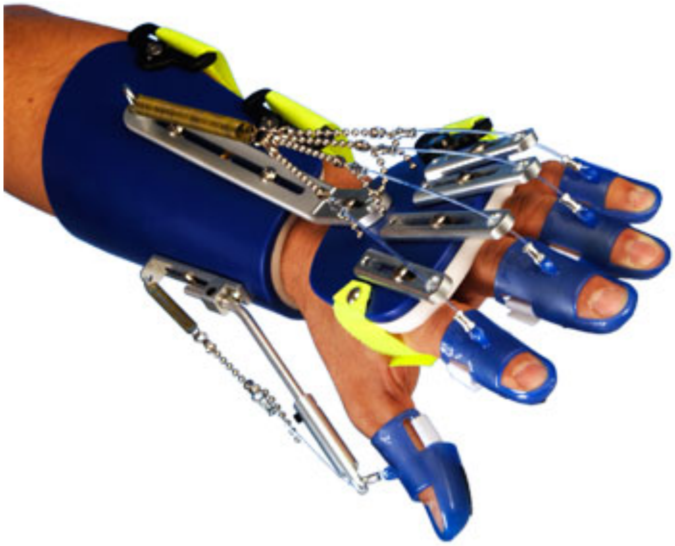


Figure 11 – Saeboflex by Saebo, Inc.

In contrast to passive type orthotics, active orthotics work by means of a powered component to move the fingers and joints. There are significantly fewer active hand orthotics on the market than passive ones. While conducting research, only one active orthotic available for sale. The orthotic, made by Broadened Horizons and called the 'PowerGrip', uses an electronically powered and controlled linear actuator to drive a single degree of freedom kinematic mechanism that would open and close the first two fingers of the wearer. The thumb and wrist of the user is held in a fixed position. The orthotic is powered by a battery pack and is controlled by a two-button controller. The website states that EMG muscle sensing switches may also be used with the orthotic, which would allow the user to use nerve input from the arm or elsewhere to close the hand. The device claims to allow the wearer to use both the power style grip and pinch grip (Broadened Horizons, 2013). There is no pricing available for the PowerGrip orthotic itself, but the adjustable training and evaluation device is priced at $2599.95.

Figure 12 – PowerGrip, an active orthotic by Broadened Horizons

Chapter 3: Problem and goal statement

Problem Statement

Patients who have suffered a stroke or similar impairment often have diminished strength and control over one side of the body. Specifically, they have may have limited use of one of their hands, impairing their day-to-day function.

Goal Statement

Develop a powered hand orthosis to provide cylindrical and pinch grip support for dexterity-impaired persons

Chapter 4: Design

Design Process

During the conducted research, it was observed that the motion of forming grips could be explained in two overall movements: the movement of the fingers and the movement of the thumb. Therefore, the design of the orthosis should be divided into the design of the thumb movement system and the design of the finger movement system.

Due to the physical location of the thumb and fingers with respect to the rest of the hand, the physical brace should be paired with the fingers and the thumb should be an attachment that could be fitted to the device regardless of the brace design. The design process, including design specifications and preliminary designs for each of the subsystems, is presented in the rest of this section.

Following the development of the design specifications and preliminary designs, a final design was selected. To do so, a weighted scoring system based on the design specifications was developed. Each design was then scored per this system, with the highest score being chosen as the final design.

Thumb Movement Subsystem Design

The thumb movement subassembly was designed to operate independent of the rest of the orthosis. Therefore, specific design specifications were developed for this subassembly. These specifications were used in the ultimate evaluation of the designs.

Thumb design specifications

The following design specifications were created to guide the design of the thumb movement subassembly. These specifications are intended to ensure that the design meets all of the functional and safety requirements for the system.

1. All degrees of freedom must be controlled by user.
2. Must have at least 1 powered degree of freedom
3. Motion paths must agree with natural motion of thumb.
    a. The MCP joint moves along a curved path. It should not be forced to a linear path.
4. Thumb must be able to be positioned in numerous positions to facilitate the gripping of objects.
5. Maximum force applied to thumb must not exceed 15 N in the normal direction and 35 N in the parallel direction of the bones of the thumb.
6. Movement system on thumb must not interfere with grip envelope.
7. Movement system on thumb must not interfere with the finger movement subsystem.
    a. It does not have to rely on the finger subsystem, but it can if optimal.
8. Thumb assembly must not bring total cost over $700.
9. Powered degree of freedom must be able to maintain the desired position.
10. Thumb assembly must not bring total weight over 1 kg.
11. Thumb must be able to be moved to a position which does not prevent closure of finger tips to within 2cm of the hand. tips.
12. Thumb must be controlled independently of the fingers.

13. Thumb control system must allow for other hand to be free whilst gripping.

14. Components of thumb system must not deflect under maximal loading such that it the device becomes inoperable.

15. Neutral position of thumb, i.e. no muscles extended or contracted, must be reachable and maintainable.

    a. Muscles should not be extended or contracted in this position.

16. Thumb movement system must not extend more than5cm from the user's wrist.

17. Apply a maximum of 10 N at the thumb tip.

Thumb preliminary designs

Three designs were developed for the thumb. These designs denoted A, B, and C, each would uses similar systems to the finger movement systems.

Design A (Figure 13)

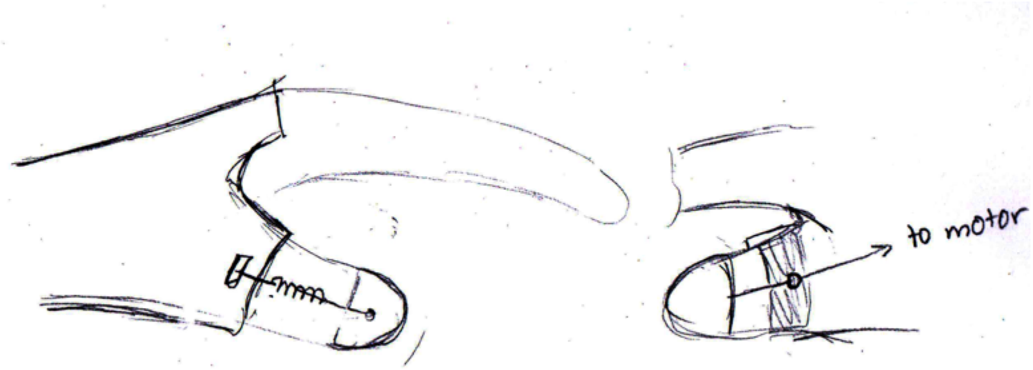


Figure 13 - Sketch of Thumb Design A

Design A, Figure 13, fixes the thumb such that it cannot move up and down. This provides the same support as if one was wearing a wrist brace. The thumb is then open and closed with a cable/spring system. In this case the cable would be routed on the underside of the hand and connected to a motor that would pull the cable in closing the thumb. The thumb would open by the force provided by a spring mounted on the back of the thumb. This is the simplest of the three designs as it involves the fewest components.

Design B (Figure 14)

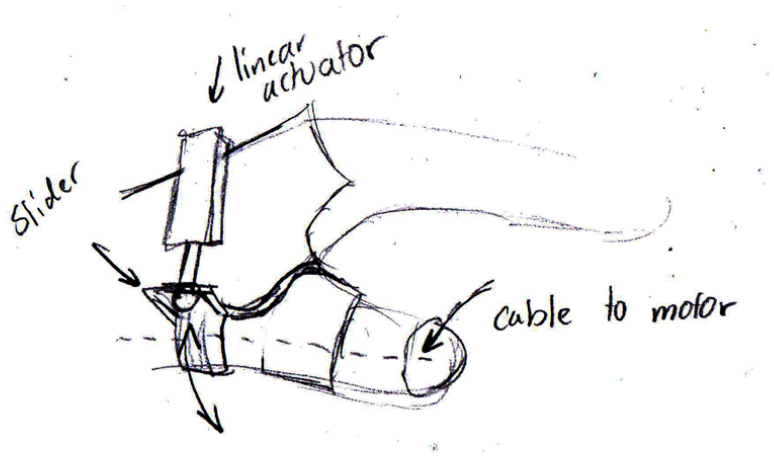


Figure 14 - Sketch of Design B

Design B (Figure 14) uses a similar cable/spring system to Design A to open and close the thumb. However, a linear actuator is used to control the side-to-side movement. The linear actuator is attached to a sliding link that pushes an arm along a track. The arm is connected to the thumb, thereby coupling the movement.

Design C (Figure 15)

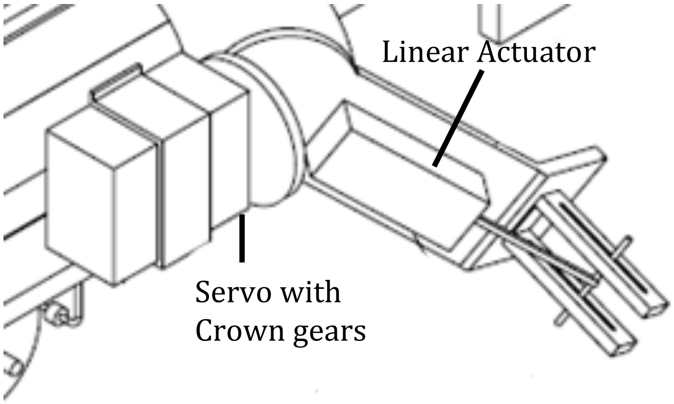


Figure 15 - Drawing of Design C

Design C (Figure 15) is based on the thumb design from the 2012-2013 MQP: Design of a Powered Hand Orthosis by Elyssa Dorenfeld, Robert Wolf, and Stephan Zeveska. It makes use of a linear actuator and sliding link instead of the cable to open/close the thumb. The linkage assembly is connected to a pivoting “shell” for the thumb, such that it pushes and pulls the thumb. To accomplish movement, a servo motor is mounted at an angle to the wrist. Two crown gears rotate the motion 90 degrees. Rotation then lifts and drops the thumb/actuator assembly. This servo needs to be placed in a location that does not create interference with the actuator.

Finger Movement Subsystem Design

The second system designed was the finger movement subassembly. As previously stated, this subsystem includes the method for opening and closing the fingers and the rigid brace that makes up the bulk of the orthotic. As with the thumb assembly, design specifications and preliminary designs for this system were created.

Design specifications

The following design specifications were developed to guide the design of the finger movement system and the brace to ensure that the created designs would meet the functional and safety requirements of the system.

Functional Considerations

- Provide powered user assistance in performing cylindrical and pinch grips.
- Attached subsystems must not rise more than 4 cm above the base attached to the wearer's hand
    - Should the movement mechanisms be too large, then this device will be severely limited in areas where it can be used as tall protrusions may interfere with small spaces.
- Provide an adjustable, power grip force of 10 N.
    - It is unnecessary for this device to provide the maximum strength of a male human, as this level of force is not necessary for most tasks and may cause injury in certain users.. This is a minimum force to hold objects, it is preferred that the device exceed this.

    - Hold vertically an object weighing 1kg and having a diameter of 9cm
        - This size and weight correspond to a filled 1L Nalgene bottle, which is the largest object expected to need to be held by the device.
    - Cylindrical grip diameter range of 2cm to 9cm.
        - The size of the cylindrical grip must vary in order to accommodate objects of various sizes. The minimum diameter corresponds to most hand tools.
    - First finger must be able to contact thumb.
        - In order to effectively form a pinch grip, the first finger must come in contact with the thumb. Otherwise, no useable grip is formed.

User Considerations

- Possesses a method of being fit to an individual user's hand.
    - An orthotic must fit the user's hand or else it can cause stress or injury.
- Be secured to the user's hand such that powered digits cannot move independently of the device.
    - If the user's hand can move freely, the device cannot increase their function.
- Thumb able to be held in a position suitable for gripping.
    - All grips require use of the thumb and fingers. It is possible to power only the fingers, assuming the thumb is locked in the position normally used for that grip.

- Surface between hand and device must have no protrusions or surfaces which can cause abrasive injury to the user's hand.
    - The device will contact at least the back of the hand. If there are moving parts or rough protrusions on the face of the device which makes this contact, the resulting pressure points and pinch hazards can cause injury.
- Must be able to be donned and doffed with unaugmented (i.e. healthy) hand only.
    - This is a device to increase independence. It cannot accomplish that if it requires another person to put it on and take it off the user.
- Operation must leave other hand free to use for gripping.
    - To make the device most useful, it must allow the use of two hands. Otherwise, it does not accomplish its goal of restoring two-handed function. This does not mean the opposite hand must be free at all times.
- Device must not weigh more than 500g.
    - If the device is to be used daily, the fatigue on the user must be minimized. Therefore, the weight must be kept to a minimum. Note, this is the weight on the hand only.
- Device must not require an outlet or other, fixed, power source.
    - To ensure portability, the device cannot be tethered to a wall outlet, otherwise, the device can only be used the cord's length from the outlet.
- Production price of not more than $500.

    - The only other competing device found had an estimated retail value of around $2600. The price a user has to pay is the result of a long chain of buyers and sellers, meaning the price will increase dramatically from the production cost. As patients have to pay out of pocket there is further incentive to keep the price as low as possible.
- Force on user's first two fingers should not exceed more than 10N normal and 30N parallel to the bone in all positions.
    - These are the maximum safe values which can be applied indefinitely to a person's fingers.
- Force used to open the hand must be adjustable to the individual user.
    - The amount of force required to open the hand varies with the user. Some users may have a permanently contracted hand, meaning that the force to open their hand would be higher than one who is capable of relaxing their hand fully. In the former case, the safety of this device would have to be assessed by the orthotist.

Power

- Must use commonly available, portable power source.
    - A user won't use this device if the power source is either difficult to replace or transport.
- Be able to run for 12 hours without requiring recharge.

    - This is for the convenience of the user. Twelve hours roughly corresponds to one day of use.
- Have a power source worn by the user.
    - The target group does not require the use of a wheelchair, therefore they have to carry the power source themselves. This weight is not included in the 500g limit above, as the power source is not expected to be attached directly to the device.
- Power source must weigh less than 250g..
    - A power source which weighs too much will not be willingly worn by the user. This would therefore prevent them from using the device in much of their daily lives.

Kinematics

- Minimize the number of moving parts.
    - Each moving part presents an increase in the level of complexity of the device, which in turn increases the chance of failure.
- Provide at least 1 DOF in the movement of the fingers.
    - This is the minimum amount of mobility for the device to function.
- Maximum grip width limited based on the user's hand size.
    - Hand sizes vary, and the same range of motion for a large hand is not safe for a small hand. Therefore, the device should limit the range of motion based on the user, not averages.

- Able to apply equal strength at a cylindrical grip diameter of 2cm and 9cm.
    - Objects vary in size and weight, meaning that for the device to be effective, it must be able to handle a variety of situations.
- Able to open and close full range of motion in a period greater than three and less than five seconds.
    - A maximum close time is required for convenience. Too long and a person won't want to use the device. However, it is possible to close too fast and remove the fine control of the user.
- Have fingers coupled in pairs
    - Two fingers provide more grip than one, but coupling more than two makes control difficult.
- All joints of the device must have centers of rotation in line with the natural anatomy of the hand.
    - Joints in the device not in line, and in the same direction, as the natural joints of the hand will, in the best case, not work. They are extremely likely to cause injury.
- All movement mechanisms must operate outside of the desired grip envelope.
    - Should parts used to move the device enter the grip envelope, e.g. a linkage arm between the thumb and first finger, the variety of graspable objects will be greatly reduced.

Durability

- Routine maintenance performable with hand tools by a certified orthotist.
    - Routine maintenance refers to adjusting and maintaining proper fit, tightening parts and similar tasks. These tasks may be harmful to the user or device if done improperly, therefore a certified orthotist can reasonably be expected to be doing such tasks. The user, on account of potentially only having one useful hand, is not expected to perform this maintenance.
- Be capable of surviving drops of at least 1.5m.
    - 1.5m is roughly shoulder height, it is unlikely that the device will be higher than this if not securely attached to the hand.
- Last 1,000,000 cycles before replacement of parts.
    - A device that's being used will wear. For the device to be marketable, it must have a reasonably long life. Assuming 1000 cycles per day, this is 2.5 years of use. It is unlikely that the device would go this long before servicing, but the number was chosen to provide a strong buffer.
- Individual components of the device must not make contact it such a way that there is repeated relative motion between the parts.
    - Friction causes wear and increases the force required to move the device. Therefore, moving contact surfaces should be minimized as much as possible.
- Components must not deflect under maximum loading in such a manner or to such a degree that the device is rendered inoperable.

- Device must be water resistant enough to handle splashes.

Not every situation this device will be in can be expected to be dry. Therefore, the device must not short out if exposed to water. It is reasonable to expect that it will not be submerged.

Chapter 5: Preliminary Designs

The following sections detail the three main designs developed during the design phase. While other designs were conceptualized, the following designs were found to be the strongest and therefore were fully developed. Each section provides an overall explanation of the function, the forces involved and the general component requirements and cost expectations. This was the data used to rank and choose the final design, as detailed in Chapter 6.

Cable Design

Description of design

This design uses cables attached to rings located at the tip of each finger that then run over the top of the hand and along the palm. Tension on the top or bottom cables opens or closes the hand, respectively. The cables can also be routed entirely along the top or bottom, though this would make for a more complicated device. A motor controlling a series of gears which wind and unwind the cables together is mounted on the bottom side of the wrist. The gears must wind together to ensure the fingers close together. It is important to note that the gear orientation provided in Figure 16 is not final and would likely need significant adjustment.

The hand is secured inside a glove mounted within a rigid frame. The hand and wrist are held in a fixed position. The fingers are articulated normally, though they cannot move independently of the device. The thumb is only allowed freedom, currently unpowered, at the distal joint, with the rest being fixed. Figure 16 shows a preliminary design for this system, including the rigid frame, cables and rods, motor, finger rings, mounting location for the thumb, and the flexible frame for finger movement.

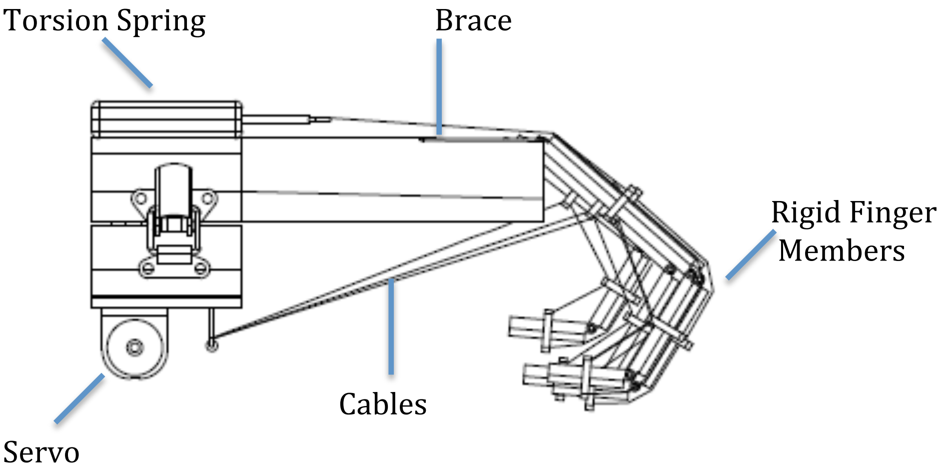


Figure 16 – Cable Design In Contracted Configuration

Force Analysis

For this design, the distance of cable contraction and the forces on the fingers at each bone were calculated. An overview of the calculations is provided below with detailed calculations located in Appendix B. These calculations were made using the assumption that that cable would be mounted on each of the phalanges at the middle of the bone. The angles of each phalanx were determined based on the angle of the preceding phalanx. Lengths were determined based on the relation of R'= R(1.4) and R''= R(2.5). R is equal to the length of the distal phalanx and R' and R'' are the lengths of the medial and proximal phalanges respectively (Buryanov, 2008).

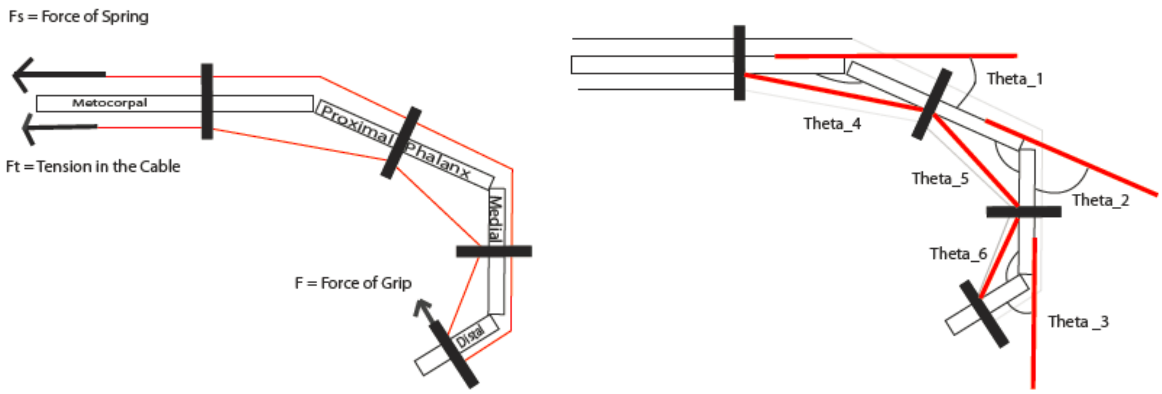


Figure 17 – Force Diagram of a single finger

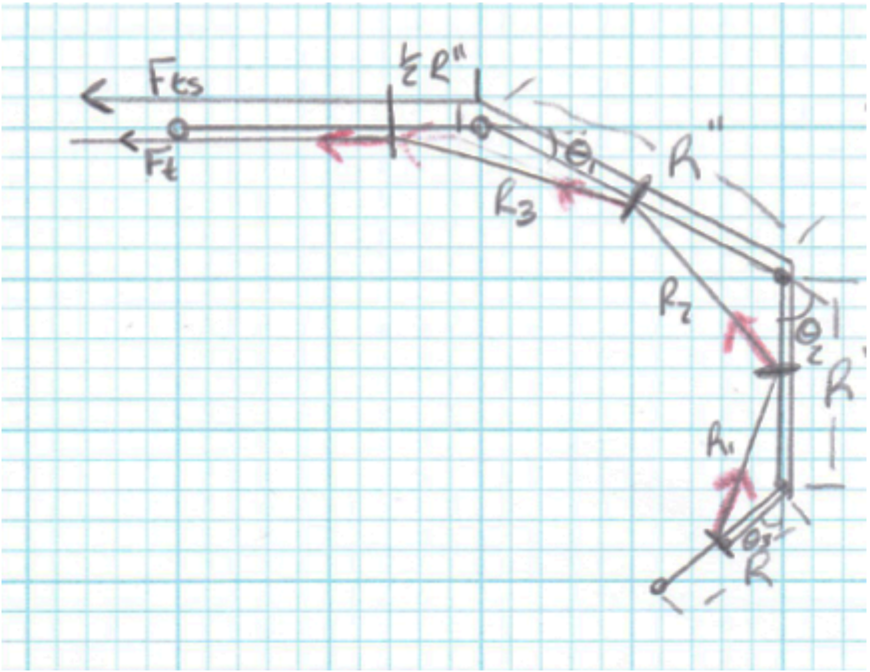


Figure 18 – Sketch of Referenced Dimensions

Length of Cable

To determine the length of the cable during the state of contraction, the following equations were derived based on the angle of each phalanx.

Equation1 $$R_1 = \sqrt{\left(\frac{1}{2} * R'\right)^2 + \left(\frac{1}{2} * R\right)^2 + 2 * R' * R * \cos\theta_4}$$

Equation 2 $$R_1 = \sqrt{R^2(0.74 + 2.8 * \cos(180 - \theta_3))}$$

Equation 3 $$R_2 = \sqrt{\left(\frac{1}{2} * R''\right)^2 + \left(\frac{1}{2} * R'\right)^2 + 2 * R' * R'' * \cos\theta_5}$$

Equation 4 $$R_2 = \sqrt{R^2(2.05 + 7 * \cos(180 - \theta_2))}$$

Equation 5 $$R_3 = \sqrt{\left(\frac{1}{2} * R''\right)^2 + \left(\frac{1}{2} * R''\right)^2 + 2 * R'' * R'' * \cos\theta_6}$$

Equation 6 $$R_3 = \sqrt{R^2(3.1 + 12.5 * \cos(180 - \theta_1))}$$

To determine the force on the fingers at each bone it was necessary to find the tension required in the cable; the torque needed by the motor; and the angle between the bone and cables. This was done using the following equations where phi is the angle between the cable on the underside of the hand and the finger at the point of connection.

Equation 7 $$\varphi_1 = \sin^{-1}\left(\frac{\sin\theta_4}{R_1} * 0.7R\right)$$

Equation 8 $$\varphi_2 = \sin^{-1}\left(\frac{\sin\theta_5}{R_2} * 1.4R\right)$$

Equation 9 $$\varphi_3 = \sin^{-1}\left(\frac{\sin\theta_6}{R_3} * 1.25R\right)$$

To determine the force, tension and torque required a summation of moments at each joint. This needed to balance. Figure 19 represents the forces of the medial phalanx where M is the moment, f is the force due to friction loss, the red arrow represents the force of the cable contracting the hand and the green arrow represents the force of the cable extending the hand.

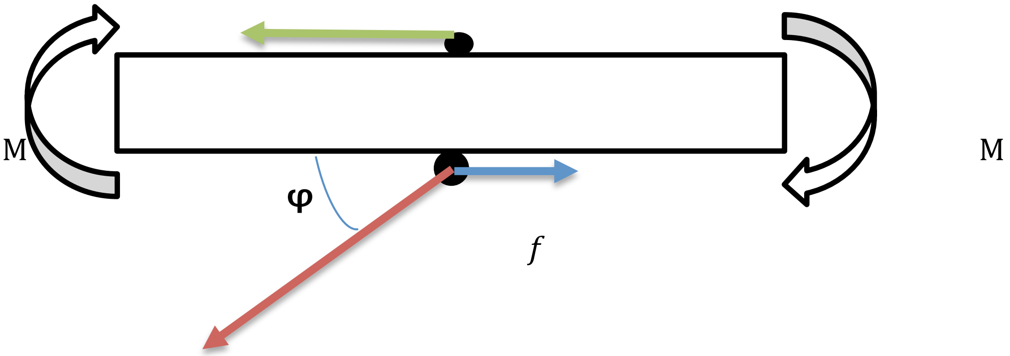


Figure 19 – Moment diagram for the medial phalanx

$$\sum M_2 = F_{ts}(\tfrac{1}{2}h) - F_t \sin(\varphi_2)(0.7R) + f_1(\tfrac{1}{2})h$$

These calculations were done for each of the bones. From this analysis the outputs were determined to be:

- Force perpendicular to fingertip = 10N
- Force from torsion spring = 6N
- Required tension in cables =12 N
- Torque = 0.144 N.m

Components and cost

To determine if the design would be able to be constructed within the project's time and budget restrictions all of the parts necessary to build the prototype were sourced and their prices were identified. Table 5 shows these parts and the total cost.

Table 5 – Cable Design Estimated Cost

Description	**Cost**	**Link**
Motor: 15 RPM 2 N*m Torque 1" diameter, 2.75" length, .15" shaft dia	$15	ebay
Small Spur Gear (.562" OD, 16 Teeth)	$21	Amazon Supply
Set Screw (Gear to Motor)	$1	McMaster
Motor to Frame Mount (Al Stock)	$24 (2"x2"x12" bar)	Onlinemetals
Cable With Fittings	$15	McMaster
Elastic Cord	$5	McMaster
Torsion Spring Retractor	$30	McMaster
Rod	$10	McMaster
Rod Mount	Custom	
Plastic Housing	$25	Amazon
Glove	$10	Amazon
Velcro Straps	$8.50	Amazon
Latch	$7	McMaster
Fasteners	$10	McMaster
TOTAL (Approximate)	**$200**	

Linkage Design

Description of design

This design uses a linkage system, driven forward by a linear actuator, to push/pull the fingers into the cylindrical grip and pinch grips. For the purposes of this design, the motions are the same, the thumb placement would change. It is designed to power just the first and second fingers, which are held tight to a frame and are therefore treated as part of the linkage.

Link 2 is driven forward. This pushes link 5 forward, in turn rotating both links 3 and 4, corresponding to the proximal and middle/distal phalanges respectively, about joint A. The fingers are secured to these components and cannot move separately. This continues through to position 2. At this point, as link 5 is past vertical, link 3 follows, but link 6 keeps rotating, thereby producing position 3. This allows for a range of grip shapes to be formed.

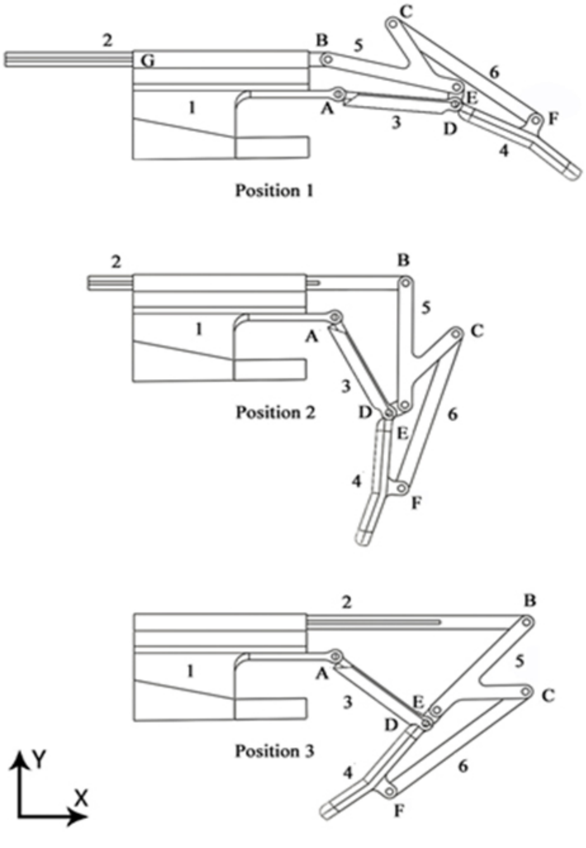


Figure 20 – Diagram of Motion Pattern and Positions for Linkage Design

Position 1 and Position 2 each correspond to a wider, flat grip. Position 3 is a more traditional cylindrical grip. The thumb in this design is held fixed and the gripping force is largely provided by the finger linkage.

To determine if this system can be controlled by just the linear actuator, a Grübler analysis is necessary. The system can be modeled as a planar mechanism. There are 6 total links, L, and 7 joints, J. Per the following equation N=1.

$$N = 3(L-1) - 2(J) = 3(6-1) - 2(7) = 1$$

Thus, this system has one degree of freedom, meaning the position of each joint can be defined simply by the location of the linear actuator.

Force Analysis

Static analysis was completed for Positions 1 and 3, as position 2 is very similar, mathematically, to position 1. The end result of this was the force at each joint. These calculations assumed a point force normal to the distal tip, centered in the middle, and pointing into the finger. The fingers were treated as rigid and fixed to the links. Table 6 lists the forces; Figure 21 shows the forces in pictorial form. Note, the force vectors shown are not precisely to scale.

Table 6 – Forces on Joints of Linkage Design

	Position 1		Position 3	
Force	X [N]	Y [N]	X [N]	Y[N]
A	0.002	.002	0.00	0.00
B	-0.642	-.768	-0.593	0.80
C	-2.39	2.15	2.54	2.00
D	-3.03	1.38	1.95	2.80
E	3.03	-1.38	-1.95	-2.80
F	2.39	-2.15	-2.54	-2.00
P	0.643	0.766	0.593	-0.80

Numbers above are factors applied to P, the applied force normal to finger tips.

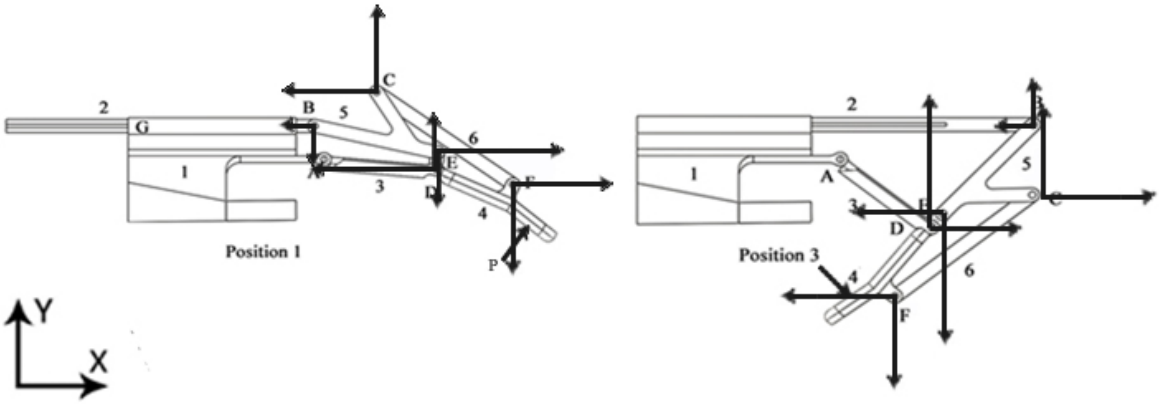


Figure 21 – Drawing of Forces on Joints of Linkage Design

Theoretically, links 3 and 4 could be replaced by the users fingers themselves. To check the feasibility, the forces at each finger joint were calculated and translated to such the components acting parallel to the finger bones and normal to the finger bones could be calculated. Table 7 shows these forces.

Forces on Fingers

Table 7 – Summary of Forces on Bones for Linkage Design

	Position 1		Position 3	
Location	Max (from normal)	Max (from parallel)	Max (from normal)	Max (from parallel)
Middle	63.9	7.64	9.2	6.77
Distal	13.5	350	12259	501

This design intends to have the first two fingers coupled. This means that that the maximum force is double what was calculated above, as the force would be shared between two joints. Therefore, if the fingers are used as the links only, the maximum safe force which can be exerted in 17.2 N.

Stress Analysis

A stress analysis was also done, using the previously derived forces. Using acrylic links, 12.7mm (0.5”) tall and 3.175mm (0.125”) thick, as would be appropriate for laser cutting, the stress levels are approximately 20 times lower than the ultimate tensile tress of acrylic, using. This is presuming a force of 27N directly applied along the link. Acrylic is also very stiff, meaning the deflection was negligible. It was therefore concluded the device would not fail under load. Further detail is located in Appendix C.

Components and cost

Parts Count

This count only includes the components specifically required as per the design. It does not include the actuator or any other fasteners or gearing that may be required, as they would be present in all designs making their inclusion here redundant

Table 8 – Linkage Design Parts Count

Name	QTY
Hand Frame	1
Acrylic Links	3
Acrylic Supports	2
Finger Sections	2
.125D x .25L Bolt	7
.125D x .375L Bolt	1
.125D Nuts	8
Total	24

Weight

Mass properties, assuming acrylic, on the model indicated a weight of 68g, neglecting fasteners, motor, and any gearing. It is very unlikely that this design will exceed 500g lb.

Cost

The following numbers are a rough estimate, given that this is not a final design.

Table 9 – Linkage Design Estimated Cost

Description	**Cost**	**Source**
Acrylic, 12x24"Sheet	7.90/ea	Amazon
Fasteners	$10	
Gears	$5/ea	McMaster-Carr
Actuator (linear/rotary)	$100-150	Amazon, McMaster-Carr
Velcro Straps	$8.50	
TOTAL (Approximate)	$150-200	*Cost depends on actuator*

Claw Design

Description of design

This design, shown in Figure 22, uses a rotary motor (2) with a gear (4) that is held in position by a motor mount (3) to drive the rigid frame (5) that rotates about a pin centered on the geared end. The frame is shaped in a curve to allow the wearer to grab objects of various shapes and sizes using both the power grip and the pinch grip while keeping the mechanism itself simple.

Attached to the rigid frame are two finger supports (6). These rigid components sit on top of the wearer's index and middle fingers and transfer the force necessary to close the hand. The wearer's fingers are held in place by Velcro straps that run underneath the fingers and attach to the finger supports (Not Shown).

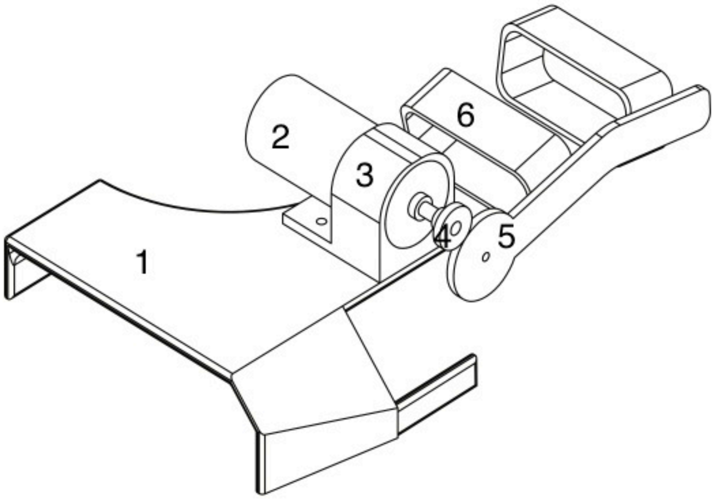


Figure 22 Original Claw Design

Revisions, Figure 23 and 24, allow the straps to be integrated into the supports and make the supports more ergonomic. A further potential refinement is to make the finger supports and frame three separate components instead of one. Each finger support would be attached to the finger frame by a short protrusion that would sit in a small 'track' cut out in the finger frame. The finger supports could then slide in these tracks as the mechanism moved, minimizing the potential for skin shear or similar injuries. It is worth nothing that such travel would be very small.

Figure 23 Front View of Finger Supports

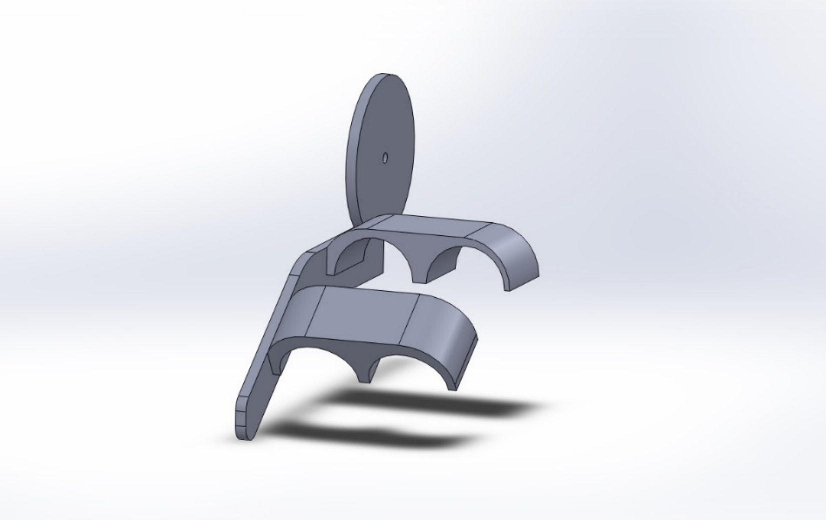


Figure 24 Isometric View of Finger Supports

Force Analysis

A basic two-dimensional force analysis was performed on the movement mechanism to determine the force that would be applied at the wearer's fingertips. A gearing ratio of 2:1

was chosen to limit the bulkiness of the mechanism. A motor, capable of providing 2 N*m of torque, T1, at a speed of 15 RPM was chosen. The distance, d, is the length from the tip of the wearer's fingers to the point of rotation, 2. F is the force applied perpendicular to the fingertips, and θ is the angle between the applied force at the fingertips and the axis of rotation. An assumption was made that theta decreases as the mechanism closes and the object being held becomes more perpendicular to the fingertips. The force applied at the fingertips was therefore given by:

$$F = (2*T1)/(d*\cos(\theta))$$

In the fully opened position, θ was assumed to be 45 degrees. This was the max value of θ. This gave an applied force of 21 N (4.75 lbf). In the fully closed position, the applied force was 39 N (8.75 lbf).

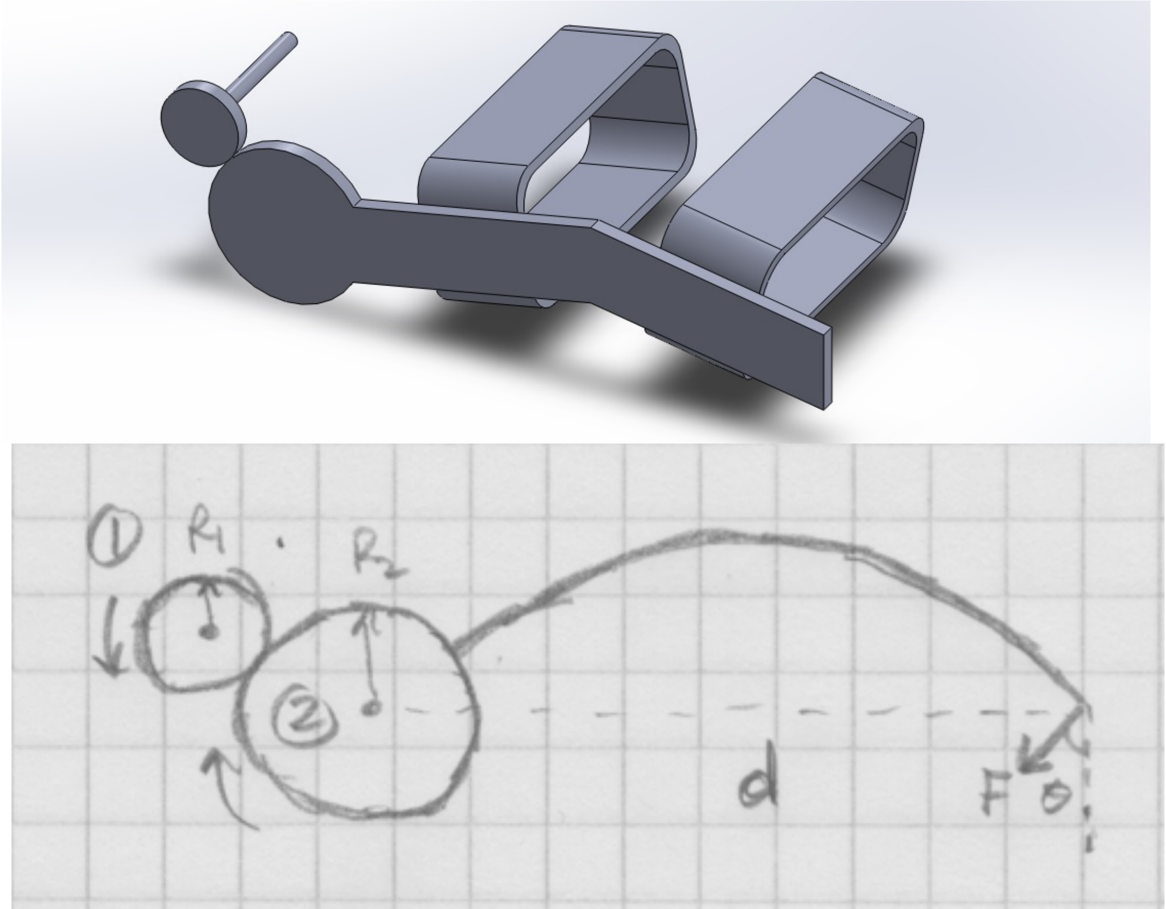


Figure 25 – Mathematical Overview of Claw Mechanism

With a gearing ratio of 2:1, the output speed of the mechanism was approximately 7.5 RPM (45 deg/s) under no load.

Stress Analysis

There are three major stress points in the movement mechanism for this design: the point of rotation for the finger frame, and the two points where the finger supports connect to the finger frame.

In an extreme case, the point of rotation for the finger frame would have to support the weight of the finger frame, both finger supports, the weight of the wearer's hand, and the weight of the object being held. The estimated weight of the heaviest object that could be held, a large bottle filled with water, is approximately 3.6 kg. An estimated weight for a human hand is 0.5 kg, and the weight of the movement mechanism is 0.02 kg. This would bring the total weight to 4.12 kg.

4.12 kg * 9.81 m/s^2 =~ 41 N

Area of pin =~ 2*10^-5 m^2

Giving a shear stress of approximately 2 MPa

Maximum shear stress and bending stress of aluminum: ~200 MPa (6061-T6 Alloy)

Grip Envelope

The grip envelope for this design would depend on the size of the wearer's hand and the method for moving (or not moving) the thumb. Measurements were taken assuming a fixed thumb position. Maximum grip envelope was approximately 10.2cm (4") and the minimum grip envelope was approximately 3.175cm (1.25"). The curved shape of the frame decreases the overall grip envelope.

Components and cost

Parts

The most recent design revision would include eight major components:

- Motor
- Motor Mount w/ two fasteners
- Input Gear (.5” diameter) w/ set screw
- Finger Frame w/ 1” diameter geared end
- Finger Frame Rotation Pin
- Proximal Finger Support
- Distal Finger Support
- Securing Straps (Velcro)

Approximate Cost

Table 10 – Claw Design Estimated Cost

Description	**Cost**
Motor: 15 RPM 2 N*m Torque 1" diameter, 2.75" length, .15" shaft dia	$15
Small Spur Gear (.562" OD, 16 Teeth)	$21
Set Screw (Gear to Motor)	$1
Motor to Frame Mount (Al Stock)	$24 (2"x2"x12" bar)
Movement Mechanism (Al Stock)	Custom Machined
Velcro Straps	$5
Pin/Bearing (Movement Mech. To Frame)	$10
TOTAL (Approximate)	**$76**

Chapter 6: Design Selection

Selection Process

For the thumb subassembly and the finger movement subassembly all designs were ranked on matrices under each heading with a score of 0 – 2, with the score based on how well the relevant design specification was met. The specific scoring criteria for the thumb and the finger movement systems can be found in Appendix A. An overall matrix was then created with the highest of each subheading receiving a score of 2, the next a 1, and finally a 0. This matrix was weighted and totaled to determine the final design. Numbers in parentheses reflect the relative weight of the category.

Scoring Weights

To determine how each score was going to be weighted overall, a pairwise comparison chart was developed for the overall design and the specific thumb designs. In this, a score of 1 means that row's parameter is more important than the column's, a score of 0.5 means they are equal and a 0 means the row's parameter is less important that the column's. The total was then taken for each row. The parameter's percentage contribution was then used to determine the parameter's weight, with a further break down to each specification in that parameter.

Table 11 – Thumb Scoring Weights

	Function	Safety	Physical Properties	Usability	Total
Function	X	0.5	0.5	1	2
Safety	0.5	X	1	0.5	2
Physical Properties	0.5	0	X	1	1.5
Usability	0	0.5	0	X	0.5

- Function (.3)
- Safety (.3)
- Physical Properties (.3)
- Usability (.1)

Table 4 – Overall System Scoring Weights

	Performance	Safety	Manufacturing	Maintenance	Cost	Ease of Use	Ease of Att.	Total
Performance	X	0.5	1	1	1	1	1	5.5
Safety	0.5	X	1	1	1	1	1	5.5
Manufacturing	0	0	X	1	1	1	1	4
Maintenance	0	0	0	X	0	0	1	1
Cost	0	0	0	1	X	1	0	2
Ease of Use	0	0	0	1	0	X	.5	1.5
Ease Of Att.	0	0	0	1	0	.5	X	1.5

- Performance (.24)
    - Force application (0.09)
    - Grip Envelope (0.045)
    - Grip Envelope Shape (0.045)
    - Deflection (0.045)
- Safety (.24)
    - Forces on Joints (0.045)
    - Stress on Fingers (0.045)
    - Pinch Hazards (0.045)
    - Slippage (0.027)
    - Feel (0.036)
    - Redundancy of joints (0.027)
- Manufacturing (0.2)
    - Degree of Custom Manufacture (0.036)
    - Complexity of Manufacture (0.054)
    - Time to Manufacture (0.09)
- Maintenance (0.05)
    - Availability of Components (0.01)

  - Ease of Replacement (0.018)
  - Frequency of Maintenance (0.018)
- Cost (0.09)
- Ease of Use (0.07)
  - Ergonomics (0.018)
  - Simplicity of Control (0.018)
  - Interference (0.01)
  - Weight (0.018)
- Ease of Attachment (0.016)
- Aesthetics (.01)
- Thumb Compatibility (0.1)
  - Thumb Compatibility with A (0.02)
  - Thumb Compatibility with B (0.03)
  - Thumb Compatibility with C (0.05)

Weighted Scores

Per the rubric developed, each design was given a raw score. Multiplying this score by the weighting factor produces a weighted score. The highest weighted score then became the design chosen. In the following tables, an asterisk denotes the weighted score.

Table 13 – Overall System Ranking

Specification	Weight	Cables	Linkage	Claw	Cables*	Linkage*	Claw*
Force Application	0.09	2	1	2	0.18	0.09	0.18
Grip Envelope	0.045	2	1	1	0.09	0.045	0.045
Grip Envelope Shape	0.045	2	1	0	0.09	0.045	0
Deflection	0.045	2	2	2	0.09	0.09	0.09
Normal Force	0.045	2	1	1	0.09	0.045	0.045
Parallel Force	0.045	2	2	1	0.09	0.09	0.045
Pinch	0.045	2	2	1	0.09	0.09	0.045
Slippage	0.027	2	2	2	0.054	0.054	0.054
Feel	0.036	1	2	2	0.036	0.072	0.072
Redundancy of joints	0.027	2	1	0	0.054	0.027	0
Custom Manufacture	0.036	1	0	1	0.036	0	0.036
Complexity	0.054	2	2	1	0.108	0.108	0.054
Time to Manufacture	0.09	2	2	1	0.18	0.18	0.09
Availability of Components	0.01	2	2	2	0.02	0.02	0.02
Ease of Replacement	0.018	1	2	2	0.018	0.036	0.036
Frequency of Maintenance	0.018	2	2	2	0.036	0.036	0.036
Cost	0.09	2	2	2	0.18	0.18	0.18
Ergonomics	0.018	2	2	2	0.036	0.036	0.036
Simplicity	0.018	2	2	2	0.036	0.036	0.036
Interference	0.01	1	2	1	0.01	0.02	0.01
Weight	0.018	2	2	1	0.036	0.036	0.018
Ease of Attachment	0.06	2	2	2	0.12	0.12	0.12
Aesthetics	0.01	2	0	1	0.02	0	0.01
Thumb Compatibility A	0.02	2	2	2	0.04	0.04	0.04
Thumb Compatibility B	0.03	2	2	1	0.06	0.06	0.03
Thumb Compatibility C	0.05	2	2	1	0.1	0.1	0.05
Total	**1.000**				**1.9**	**1.656**	**1.378**

Table 5 – Thumb System Ranking

	Weighted Amounts	A	B	C	A*	B*	V*
Function	0.3	7	8	8	2.1	2.4	2.4
Safety	0.3	6	7	8	1.8	2.1	2.4
Physical Properties	0.3	8	6	7	2.4	1.8	2.1
Usability	0.1	9	9	10	0.9	0.9	1
Total					**7.2**	**7.2**	**7.9**

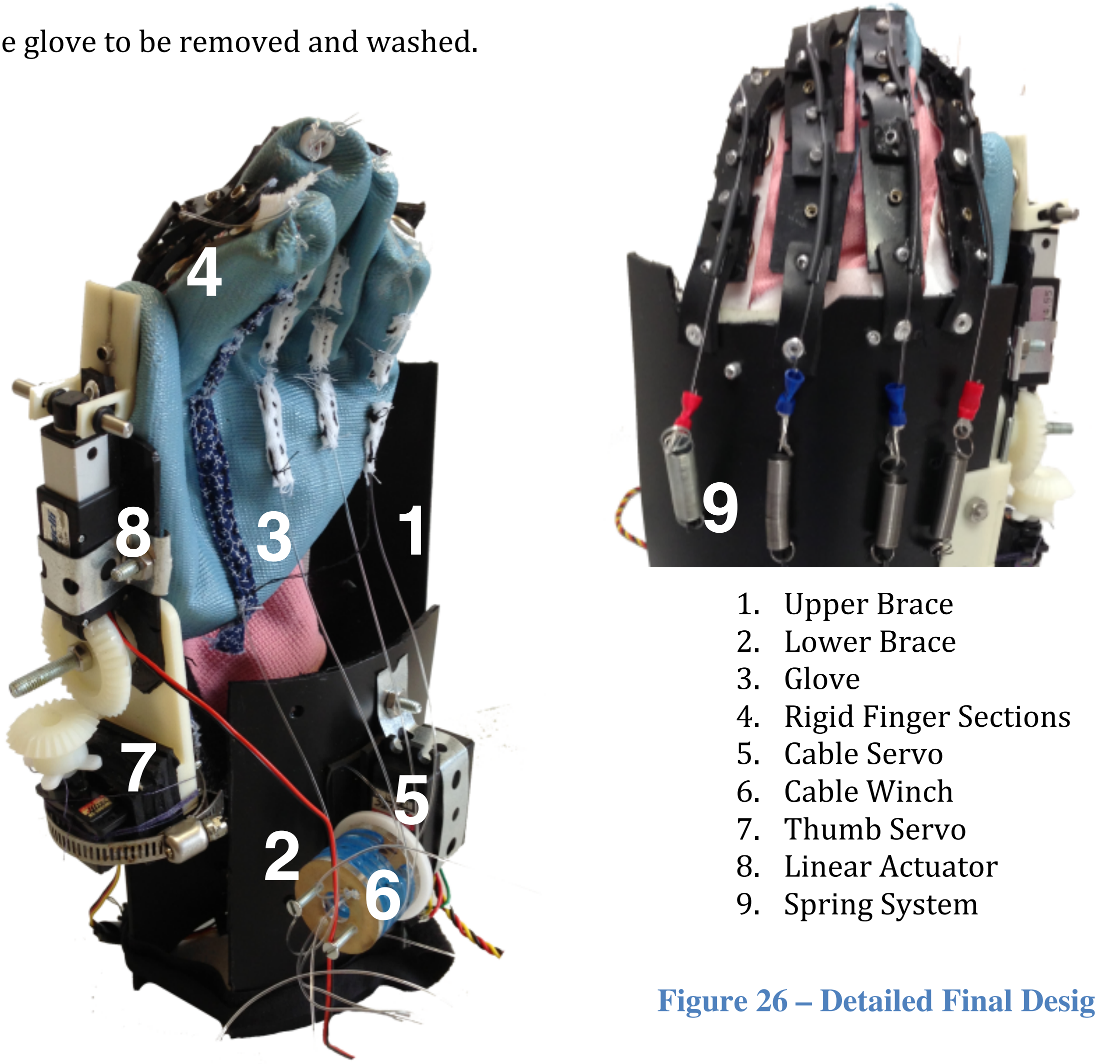
Using this ranking from the three thumb designs, compatibility of the thumb subassembly to the overall system was added to the weighted ranking for the three designs. This can be found on the table located on the next page. The cable design is the highest ranked and will therefore be used to fabricate the powered hand orthosis.

Chapter 7: Final Design

Description of Overall Mechanical Design

General Characteristics

Figure 26 displays the designed components with the major sections called out. The device consists of two main components – a frame (1-2) and a glove (3). The glove has been modified to have a slit up the side with the capability of adding a zipper for closure, allowing it to be easily taken on and off. Snaps have been mounted to the fingers and back of the hand, along with Velcro strips, to secure the glove to the frame. This system allows the glove to be removed and washed.



1. Upper Brace
2. Lower Brace
3. Glove
4. Rigid Finger Sections
5. Cable Servo
6. Cable Winch
7. Thumb Servo
8. Linear Actuator
9. Spring System

Figure 26 – Detailed Final Design

The frame also consists of two sections. The first is the “forearm” component (1), which is a hard plastic shell that extends from the wrist to partially up the forearm. This is meant to ensure stability of the device and to avoid putting the stress from the weight of held objects on the wrist. The underside of the forearm section (2) is hinged to allow the user to place their hand inside the frame instead of sliding. It is held closed by a Velcro strap. The servomotor used to close the fingers, in the same manner as described previously in the cable design chapter, is mounted to the underside.

The forearm section of the frame covers the hand and fingers. The movement subsystem is mounted to this section. The back of the hand is covered by a single piece of hard plastic. The fingers are covered by jointed sections of alternating plastic and rubber (4), which provide the support needed to move the fingers. The glove is connected to the finger supports via the snaps mentioned previously. The thumb assembly (7,8) is mounted to the frame, as well as four springs that provide force to open the fingers (9).

Movement:

Finger Closure System

All four of fingers are closed at the same time through cables running along the underside of the hand. The cables are secured at the fingertips and routed through channels in the glove attached to the finger and palms. The channels are spaced 1cm apart on the fingers to prevent the cable from binding or bunching. The channels are required to ensure the cable stays close to the fingers. The cables meet at a servomotor (5) mounted approximately at the wrist, on the underside of the frame. Each cable is wound up by the servo on a manufactured wheel of acrylic (6). This wheel is composed of five spaces and four individual disks. These disks are each a different diameter to account for the variation in necessary cable take-up for each finger. As the servo turns the cable is wound up onto this wheel causing the fingers to close.

Finger Opening System

The fingers are opened through springs mounted to the back of the fingers. The springs (9) provide a tensile force which "pulls" the fingers up and open when the servo is run opposite the direction of closing. The system therefore passive and requires no strength on the part of the user to open. The springs themselves are not directly connected to the fingers, but instead a cable runs between the spring and the fingertip along the top of the finger. The cable is guided through channels, similarly to the opening system.

Thumb Movement System

The design includes a base for the servo (7) to be mounted to and the plastic exoskeleton to revolve on. The linear actuator (8) and the thumb component are mounted as in the original design, with the linear actuator on top of the plastic member and the thumb section connected to the plastic member through a strip of rubber.

This entire assembly is attached via a hinge to the brace. This hinge can be moved to accommodate different thumb sizes. The hinge allows accounts for the angle of the brace and ensures the thumb is not forced into any uncomfortable or unnatural positions.

Electrical Design

Circuit

The backbone of the entire orthotic is the electrical system, which provides the power necessary for each of the servos and linear actuator to move. The electrical system also acts as the ‘brain’ of the orthotic, providing a way of interfacing with the wearer of the orthotic through two switches and a potentiometer. This capability is provided by an Atmel ATMega328 microcontroller. Supporting circuitry used for current monitoring, voltage regulation, and motor control is described in further detail in this section. An overview of the electrical system can be seen in the electrical schematic shown in Figure 26, and a larger version in Appendix E.

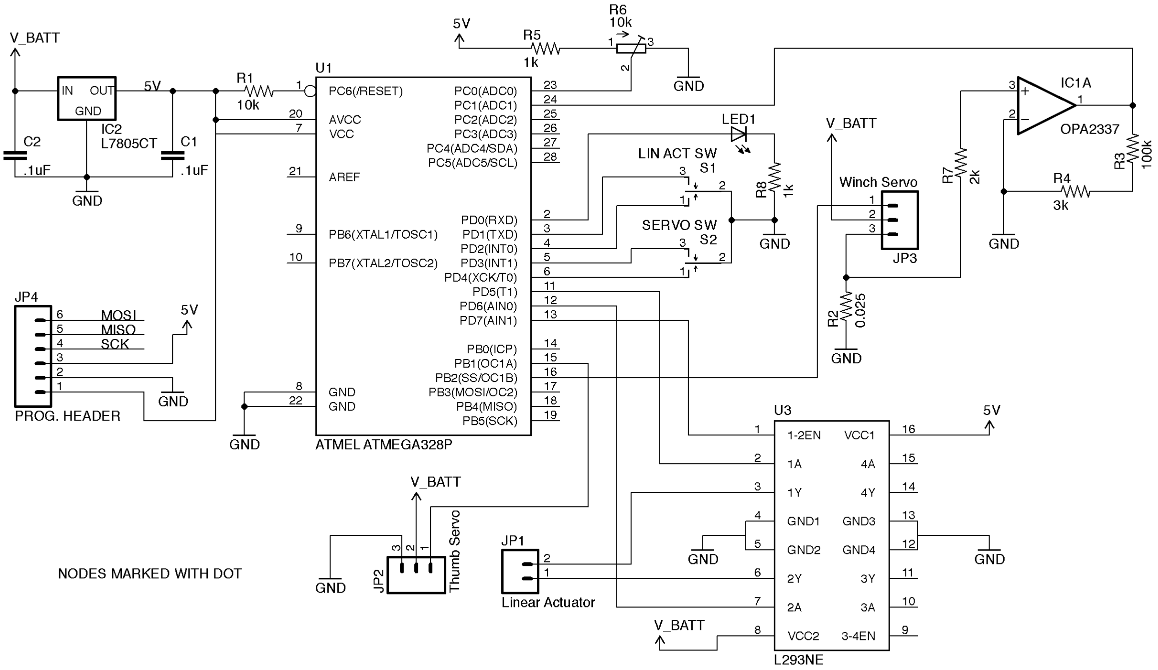


Figure 26 – Circuit Schematic

The correct voltage must be supplied to each of the drivetrain components - the two servos and linear actuator – and each of the supporting integrated circuits (ICs). A 5V voltage regulator (Figure 27) is used to ensure a stable voltage is provided for the microcontroller and other ICs, while the servos and linear actuator are powered directly from a 6V battery. The regulator used is a L7805, marked 'IC2' in the circuit schematic. The voltage regulator has two decoupling capacitors between the input-ground and output-ground nodes to reduce electrical noise. These are marked 'C1' and 'C2' in the circuit schematic (Figure 25).

Figure 27 – 5V Regulator

Placed between the servo and the connection to ground is a very small, precise resistor known as a shunt resistor. The shunt resistor, marked 'R2' in the schematic, is used to indirectly measure the current through the servo using the principle of Ohm's law: V = I*R. The resistance of the shunt is known to within 1% of the nominal value and the voltage is measured across the shunt resistor by using a simple amplifying subcircuit. The current can then be calculated by the controller to obtain the servo load. Further actions, such as stopping movement of the servo when it is being overloaded, can then be done based on the current measurement.

The amplifying subcircuit consists of a rail-to-rail op amp, two feedback resistors to control the gain of the op amp, and a capacitor to filter out any high frequency noise generated by the servos. The filtering capacitor is placed across the op amp inputs. The op amp is used to amplify the voltage across the shunt resistor with a gain of approximately 40. The op amp output is connected to an analog input in the microcontroller to be calculated into a current reading. The op amp is a small 8-pin IC made by Texas Instruments (Figure 28), marked 'IC1A' in the schematic

Figure 28 – Texas Instruments OPA2337 Op Amp

The other major component in the circuitry is the L293 IC (Figure 29). This is known as a quad half-h driver. It is often used as a motor driver integrated circuit. There are three digital logic inputs to the IC that determine the output to the linear actuator. Pin 1 is called the 'enable' pin. When this pin is pulled to logical high, 5V, it allows the linear actuator to be powered. When the 'enable' pin is pulled to logical low, 0V, power is cut from the linear actuator. Pins 2 and 7 are the two 'input' pins. When one pin is pulled 'high' and the other 'low' the linear actuator will move one direction. When the respective pins are pulled 'low' and 'high' the linear actuator will move in the opposite direction. If the pins are pulled high or low simultaneously the linear actuator will not move.

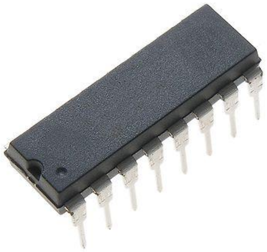


Figure 29 – Texas Instruments L293NE Integrated Circuit

Microcontroller and Code

The microcontroller chosen for prototyping this project was an open-source and very popular controller called the Arduino. It was chosen due to the relative ease of programming, low cost, vast capabilities, and expansive user base. The Arduino is programmed using a subset of the C programming language, an old and still popular programming language. Additionally, the Arduino provides an easy method to program standalone microcontrollers made by Atmel (Figure 30).

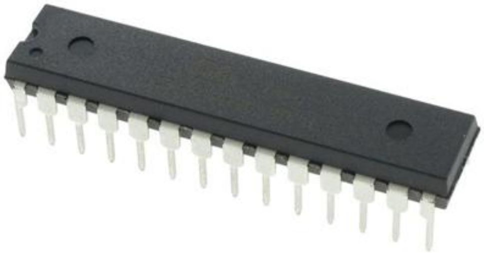


Figure 30 – Atmel ATMega328P Microcontroller

The software is best described when broken down into each 'function'. The beginning of the code defines the different variables that will be used in the program as well as the code libraries. The next part of the code is the 'setup' function. This is the function run at the very beginning of the program and is only run once. It is where many of the initial variables are set. The final function is the 'loop' function. This is the function in the program repeated infinitely so long as the microcontroller is powered on. Inside this ‘loop’ function are four different subsections: one to calculate the running average of the current through the shunt resistor, one to take the inputs from the potentiometer and determine the output for the thumb servo, one to take the inputs from the buttons to determine the output for the linear actuator, and a final one to take the inputs from the buttons to determine the output to the winch servo.

The basic functionality of the programming was completed relatively easily. Programming was done in sections, with each input and respective drive component combination done separately, starting with the thumb servo, then the linear actuator, and ending with the winch servo. The current sensing and limiting were the most difficult to implement. When a stall or over current condition is detected, the servo will stop and hold the current position as long as the user is still holding down a button. Once the button is released the user can then continue to use the inputs normally. This serves to limit the force applied by the device.

The software code can be found in Appendix D of the report and a basic logic flow chart for the programming (Figure 31).

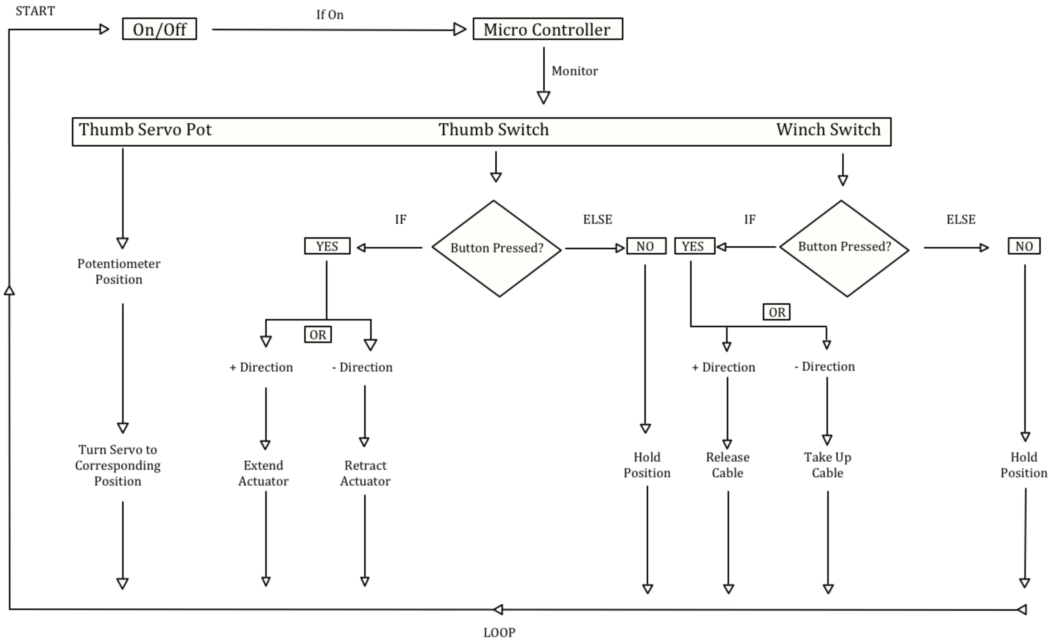


Figure 31 – Microcontroller Logic Diagram

Power System

The entire electrical circuit is powered by a 6V 3300 mAh battery pack. At idle, the current used by the circuitry is around 300 mA, giving a battery life of approximately 11 hours. As the servos and linear actuator are working the current usage will increase depending on the load applied. The average battery life has not been tested.

Chapter 8: Manufacturing

Manufacturing Process

Using the final CAD model created for the cable design as reference, the device was constructed by hand. With the exception of the thumb assembly which was largely printed using a rapid prototyping machine, the device was constructed using hand tools. Attempts were made to create the components as closely to the CAD drawings as possible. The original model of the brace, rigid finger members, and thumb assembly can be seen in figure 32.

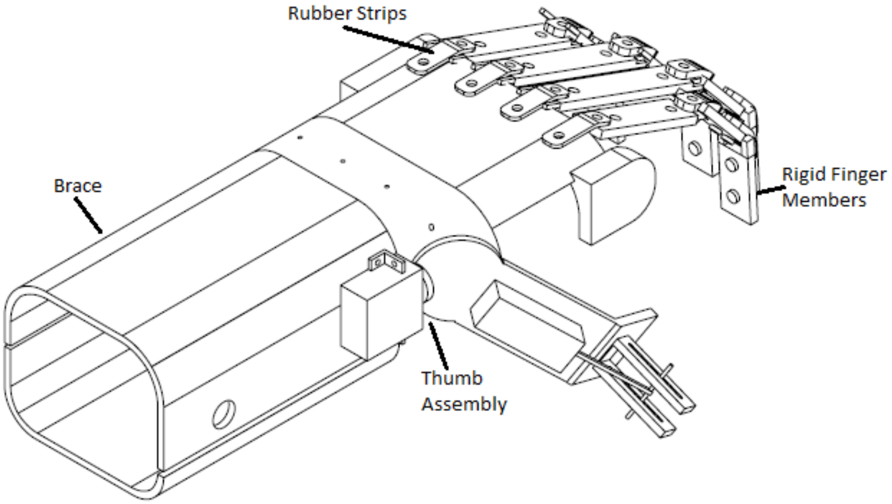


Figure 32 – Original CAD Model of the Exoskeleton of the device

Selection of components

Using the part sourcing completed for the preliminary cable design, components were selected based on size, price, and availability. The size constraint of the hand proved finding appropriate parts to be occasionally difficult. The gears for the thumb assembly were limited in available sizes, meaning that to ensure functionality, much larger gears than originally desired had to be used.. For this prototype McMaster, ServoCity, and Plastics Unlimited were used to acquire most of the required parts.

Build of Mechanical System

Brace

Process

The brace was cut from a sheet of High Density Polyethylene (HDPE), a readily available thermoplastic. This was formed over a mold with a heat gun. To facilitate safe shaping, a cast of a hand was created to avoid potential burns. Components were attached with either rivets or screws.

Outcomes

A full sized brace, Figure 33, with hinged under-support and capability of accepting all mounts was created. Anchors for the springs and holes for the servos were added. The remaining components were then added.. The ultimate shape of the brace was not as originally designed, for reasons outlined below.

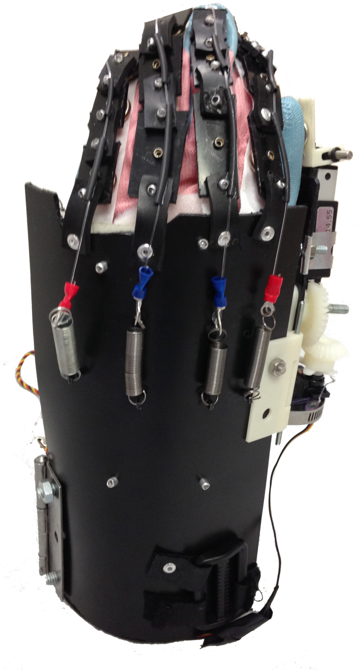


Figure 33 – Top View of Built Brace

Difficulties

The main difficulty encountered in creating the brace lay in shaping. Originally, the brace was to be made from 0.125” thick HDPE, but this proved to be too rigid and therefore difficult to form. This was then switched to 0.083” thick HDPE. This was found to be easier to shape, but still would not hold the form desired. It was found that simply bending, and even over-bending, the plastic was not enough to get the shape required. Therefore, a “mold” was created and the brace left in the mold to better take a shape.

Originally, the plastic was only heated in sections. This left residual stresses that meant that the brace wanted to “spring back” to its original form. Furthermore, the brace was not heated sufficiently. Once these issues were accounted for, the brace was much easier to shape.

The first brace attempt, made from the 0.125” thick HDPE, was cut precisely as drawn, or as near too as could be done with a Dremel Tool. HDPE cannot be laser cut, as it has a propensity to melt and requires excessive power regardless. Unfortunately, this first brace could not be easily bent to the specifications of the drawing.

To account for this, the second brace attempt, was oversized and but from 0.083” thick material. The overall form, once finished, was not found to fit properly. This could not be easily corrected; therefore this became a “test” brace, meaning it was used to determine how to mount components.

A third brace was then created. The blank for this had little shaping beyond gross dimensions. The excess was cut away after shaping. To get a more precise fit, the plastic was heated and then attached to a group members protected arm with rubber bands and left until cooled. A shape closer to the designed brace was then reached. This is the brace that was ultimately used in the final prototype.

Glove

Process

A low cost gardening glove was purchased for the base of the glove. This glove was chosen because the cloth of the top of the glove allow for the skin to breath while the rubber coating on the bottom of the glove protect the hand from the cables. The glove was cut up the side of the thumb so a zipper could be sewn in to allow the user to get the device on more easily. For the glove prototypes, Velcro was used for ease of sewing as, for the purpose of the prototype, this was more critical than the ease of use of the user.

For attachment to the device a Velcro patch was placed on the back of the hand and fabric snaps installed onto the back of the first finger. On the bottom of the hand channels were sewn into the glove to guide the position and force distribution of the cables.

Outcomes

Two preliminary gloves were produced, though only one glove was had all channels, snaps and rivets installed. This was the original glove used. Reinforcement was necessary to the back of the glove to ensure the snaps did not tear out.

Difficulties

The first difficulty encountered with the glove was sewing the channels into the glove. Having the glove constructed while sewing the channels gave little room to sew on the inside of the glove. An attempt to solve this involved cutting a glove in half with the intention of resewing once the channels were installed. This was not found to be effective. The second difficulty encountered was the fabric on the back of the glove was too fragile for the snaps to connect to the exoskeleton. The first glove was ripped heavily during initital testing. It was originally abandoned and a second glove made, but size issues with the second glove prevented reliable use of the device. Thus the first glove was reinforced heavily before final assembly.

Finger Movement System

Finger Movement

Process

The springs were mounted to the back of the brace with anchors screwed into place. The springs were then "threaded" through holes on the top of the anchors. The servos were mounted using 3D Printed brackets. Finally, the thumb was actuated through a 3D printed slider.

Outcomes

A functional first finger with securely mounted systems was created.

Difficulties

The difficulty with the finger itself largely came from the springs, which were originally set to have a constant of 2 lbf/in. This was found to be too high, so weaker springs were used instead, with constants around 0.4 lbf/in.

3D printing the brackets resulted in holes that were not solidly reinforced, meaning that the screws used to attach them to the bracket had little to bite into for the threads. This resulted in loose servos. This was corrected by not using 3d printed brackets, but rather metal brackets bent and reshaped to hold the servos. Stacks of rubber strips were used to align the servos.

Rigid Finger Sections

Process

The sections were cut from HDPE. Rubber strips were riveted between them, then riveted to the glove. Fabric snaps were then riveted to the sections, with their opposites to the glove. Eyelets were also secured to each section to facilitate the flow of the cable.

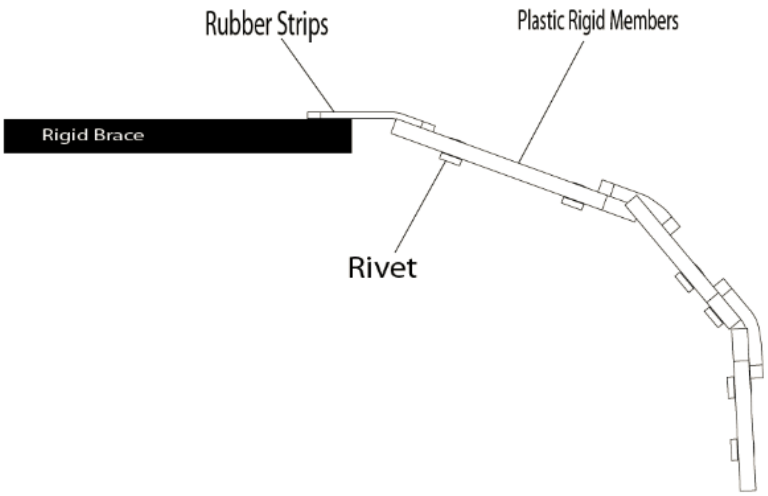


Figure 34 – Single Rigid Finger Section

Outcomes

All four fingers were created and proved to be fully functional. These were attached to all relevant components.

Difficulties

Originally, each section was to be cut from acrylic. However, despite trying two thicknesses, the acrylic shattered each time. Therefore, HDPE was used instead, though it was not heat formed. This allowed for the rivets to be used without breaking. Additionally, this offered some manner of "flex" in the finger sections, making the finger section conform better to the finger beneath.

Thumb Movement System

Process

Using the redesigned thumb assembly, CAD drawings were created for the modular thumb design. The two components of the hinge design were printed using a rapid prototyping machine and were held together using a M4 threaded rod. The servo was attached to the bottom section of the hinge assembly using cotter pins, rubber strips, and a metal hose clamp. While these components were not ideal for the application they did allow for adjustment with the location of the servo with the respect to the crown gear. The linear actuator and crown gear for the thumb were mounted onto a piece of HDPE that was cut to the appropriate size of the thumb, Figure 35. The linear actuator was attached using steel ribbon. The HDPE system was attached to the thumb hinge using a blot that runs through the hinge and the crown gear.

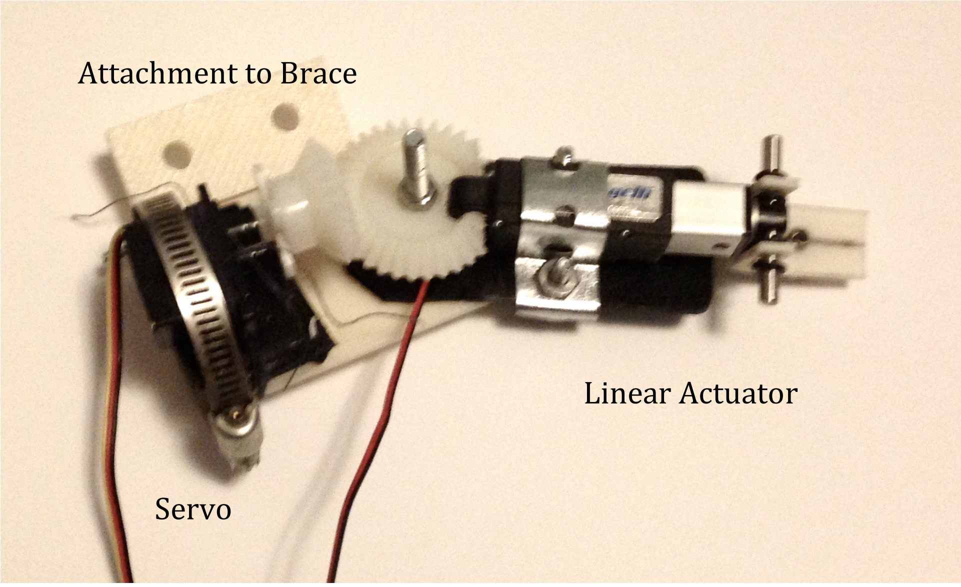


Figure 35 – Thumb Assembly

Outcomes

The thumb system proved to be operational by rotating and closing the thumb.

Difficulties

One problem that was encountered in the build of this system was keeping the linear actuator system tight against the hinge system. When the system would rotate the nut that would keep the system in place would “walk” up the bolt. This was addressed be adding in a locking washer, though this method was not perfect.

Build of Electrical System

Circuit

Initial circuit

For early prototypes the circuitry was done on a solderless breadboard. This allowed for each of the servos and linear actuator programming to be completed and tested for proper function separately before the three were combined into one product.

All programming was initially done with an Arduino board because it allowed for fast changes to be made to the circuitry. Programming the final stand-alone microcontroller required a much more time consuming process.

The electrical circuit also evolved over the course of the early prototype stages. The early circuits were much larger in component count and board space. For example, the Arduino needs a power source of 8-12 Volts, while the servos could operate on a power source of 5-6 Volts. Multiple voltage regulators were needed in order to meet all needs of the individual components. Initially a 9V battery pack was chosen to power the circuit and components, though this was replaced by a 6V battery pack in the final build.

Final Circuit

The final circuit was trimmed down significantly from the early prototype stages. A solderable breadboard was used so components could be placed closer together to minimize volume. Additionally, a standalone microcontroller was used which allowed the entire circuit to operate on a lower voltage. Reducing the voltage required also had the benefit of reducing power needed to operate the circuit. In the final iteration the microcontroller and all other ICs operated off of a 5V source that was created using a single 5V regulator. All of the servos and linear actuator were powered directly from a 6V battery.

Switches

The switches chosen for the electrical system were three position momentary switches. The benefit of the momentary switches is that they return to a neutral position if they are not actively being pressed. This meant that the servos would not be powered if the wearer accidentally tripped or fell and dropped the switch box.

Control Housing

The housing for the controls was created using laser cut acrylic. The use of acrylic was chosen because it was cheap to buy, easy to cut into the desired shape, and simple to construct. It is also a fairly robust material that can take a lot of physical abuse.

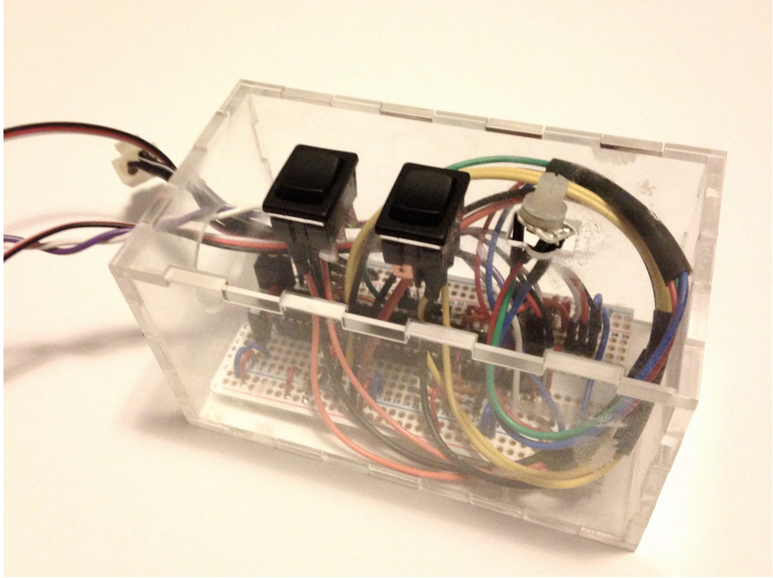


Figure 36 – Control Housing

Chapter 9: Testing

Fully detailed testing protocols are included in Appendix F. Below is a summary of what was done and what was found.

Safety Procedure

Safety was ensured through manual activation of the mechanical systems. The test started with only a single finger attached to the brace. This finger was opened and closed using the tester's muscles. The thumb assembly was then added. This was also articulated manually. During both of these phases, the tester was feeling for pinch points, abrasion or other sources of discomfort and potential injury. Any sources of discomfort found were corrected immediately. Once no more sources of discomfort were found, the actuators were added. The test was then repeated, slowly, using the powered actuators. A second tester was on hand to immediately disconnect the power should anything have gone wrong.

The remaining three fingers were then added to the orthotic. These were also actuated manually before powered testing was completed.

Safety Results

During testing a few areas of discomfort were found when wearing the orthotic: The position of the eyelets on the finger tips allowed the tips of the wearer's fingers to come in contact with the eyelets, and a pinch point was discovered when the lower portion of the brace was closed and secured. Padding was added to the pinch point to reduce contact with the wearer's skin and the eyelets were repositioned so they wouldn't make contact with the wearer.

Functionality Procedure

Once the orthotic was determined to be safe to operate it was tested for functionality. The primary concern was the force generated by the cylindrical and pinch grips.

A preliminary force measurement was taken once it was verified that a single finger was safe. This was intended to verify that the device actually generated force using a hand dynamometer. A hand dynamometer, in this case a Baseline Digital Smedley Spring, consists of three main components: a gripping surface, a method of generating resistance, and an output gauge. A hand presses on the surface, increasing the resistance which is measured by the gauge, thereby showing the force exerted by the hand. In this case, the resistance is generated by a spring. The tester donned the device and it used to grip a hand dynamometer (Figure 37). The finger was then closed and the dynamometer's reading was recorded. This was repeated multiple times to ensure consistency and repeatability

.

Figure 37 – Using Dynamometer with Device

This process was repeated with all of the fingers attached using two servos of different torque ratings. The thumb could not be measured in this way, as the minimum force to trigger than dynamometer was more than the thumb could apply. Pinch grip maximum force was measured by testing a single finger in the same manner.

Donning and doffing times were recorded by repeatedly putting on and taking off the device and measuring the time required to complete the actions. The average of the recorded times was taken.

The next step was to determine what size objects the orthotic could hold. An assortment of test objects that fell within the related design specification's range were used. A "pass" was given if the object could be held for 10 seconds without noticeable slipping.

More informal testing, without dedicated protocol, occurred during Project Presentation Day, where the device was donned and doffed repeatedly, actuated in various stages and used in a manner to actual daily use. This revealed some issues which are detailed in the Analysis section.

Functionality Results

Table 6 – Summary of Grip Force for a Given Servo

Hitec HSR 1425-CR Servo [.3 N*m of Torque]	Force
Cylindrical Grip	13 N*
Pinch Grip	12 N*

Hitec HS-645MG Servo [.9 N*m of Torque]	Force
Cylindrical Grip	20N**
Pinch Grip	19N**

Mean Donning/Doffing Time : 10 Seconds

Largest Object Held – 9cm Diameter Full Nalgene Bottle, Weighing 1KG

Smallest Object Held – 2cm Diameter Screw Driver

A disposable water bottle was also held without crushing.

*Due to the issue with the motor back driving, the peak force held is listed here.

**This was the maximum force before discomfort encountered. Because theoretically the device could go higher, but was not tested higher, this is the peak “safe force,” and is a measure of the maximum measured not the average

Evaluation of Physical Properties

Physical properties such as size and weight were also measured. Dedicated protocol was not required.

Physical Properties

Weight: 490 g
Size: No components protruding more than 3cm away from any surface.

Analysis

Testing showed the device was functional and proved the design concept worked, though there were some issues. These issues are addressed after comparing the prototype to the design specifications set for it.

Satisfaction of Design Specifications

A prototype must be assessed against its design specifications to determine its success. The following two sections detail if design specifications were met and if not, why.

Satisfied Thumb Design Specifications

- All degrees of freedom must be controlled by user.
    - Controls were provided through a switch and potentiometer.
- Must have at least 1 powered degree of freedom
    - This was exceeded. Two degrees of freedom were provided.
- Motion paths must agree with natural motion of thumb.
    - The thumb did not move in unnatural manners.
- Thumb must be able to be positioned in numerous positions to facilitate the gripping of objects.
    - The thumb could be raised and lowered to accommodate various object sizes.
- Movement system on thumb must not interfere with grip envelope.
    - All components for moving the thumb were external to the grip envelope.
- Movement system on thumb must not interfere with the finger movement subsystem.

  - All components for moving the thumb were separate and located away from the finger movement system.
- Thumb assembly must not bring total cost over $700.
  - In the prototype a recycled actuator was used, but the actuator would not have brought the cost over $700 even if bought new. The thumb assembly cost approximately $50 not including the cost of the 3D printed parts.
- Powered degree of freedom must be able to maintain the desired position.
  - Back driving the linear actuator and servo was not found to be possible.
- Thumb assembly must not bring total weight over 500 g.
  - The thumb assembly weighs 126g but the overall weight is 490g.
- Thumb must be able to be moved to a position, which does not prevent closure of fingertips to within 2cm of the hand.
  - The thumb could be moved to either avoid or create interference with fingers.
- Thumb must be controlled independently of the fingers.
  - Two separate control surfaces were provided for thumb and a third was provided for the fingers.
- Thumb control system must allow for other hand to be free whilst gripping.
  - Though the switch must be depressed to move the thumb, it did not have to remain depressed for the thumb to hold the position, thus freeing the contralateral hand.
- Components of thumb system must not deflect under maximal loading such that it the device becomes inoperable.

    - Under maximum tested loaded, no problematic deflection was encountered.
- Neutral position of thumb, i.e. no muscles extended or contracted, must be reachable and maintainable.
    - Due to the fine movement control of the thumb, this could be reached.
- Thumb movement system must not extend more than 4cm from the user’s wrist.
    - The thumb assembly protruded less than 3 cm.

Not Satisfied Thumb Design Specifications

- Apply a maximum of 10 N at the thumb tip.
    - This was not met. The thumb could not provide this force. This was due to the linear actuator not being strong enough. However, it was found that this specification was not critical to actually holding either the screwdriver or the Nalgene bottle. It is possible that if a user desired to hold and object with just the thumb, this would present an issue.

Note Tested Thumb Design Specifications

- Maximum force applied to thumb must not exceed 15 N in the normal direction and 35 N in the parallel direction to the bones of the thumb.
    - This was not tested as a test could not be developed to do so..

Satisfied Device Design Specifications

Functional Considerations

- Provide powered user assistance in performing cylindrical and pinch grips.
  - The device provided a strong cylindrical grip and was capable of forming a pinch grip.
- Attached subsystems must not rise more than 4 cm above the base attached to the wearer's hand
  - No components protruded more than 3 cm above the base.
- Provide an adjustable, cylindrical grip force of 10 N.
  - The device provided a cylindrical grip force of 20 N.
- Hold vertically an object weighing 1kg and having a diameter of 9 cm
  - The device was capable of doing so.
- Cylindrical grip diameter range of 2cm to 9cm.
  - The device held a screw driver with a 2 cm diameter handle as well as the 9 cm diameter bottle.
- First finger must be able to contact thumb.
  - The device could perform this action.

User Considerations

- Possesses a method of being fit to an individual user's hand.
    - The prototype was designed to fit a certain hand size, but potential for adjustment exists.
- Be secured to the user's hand such that powered digits cannot move independently of the device.
    - A glove, snapped to the device, ensured that unintended movement was not possible.
- Thumb able to be held in a position suitable for gripping.
    - The powered, mobile thumb ensured this.
- Surface between hand and device must have no protrusions or surfaces which can cause abrasive injury to the user's hand.
    - Some discomfort still exists, but without potential to cause injury.
- Must be able to be donned and doffed with unaugmented, (i.e. healthy), hand only.
    - This was found to be possible.
- Operation must leave other hand free to use for gripping.
    - Controls had to be pressed by the contralateral hand to induce movement, but not to hold position.
- Device must not weigh more than 500g.

    - Neglecting the battery pack and controls, which were not mounted to the device itself, the device weighed 490g.
- Device must not require an outlet or other, fixed, power source.
    - The device was battery powered.
- Production price of not more than $500.
    - The device cost $195.
- Force used to open the hand must be adjustable to the individual user.
    - Different springs can be substituted for the ones on the prototype, thus this is possible.

Power

- Must use commonly available, portable power source.
    - A 6V RC vehicle battery was used.
- Have a power source worn by the user.
    - Due to restrictions presented from the length of wires that were available for the prototype the battery was not mounted on the user. This was also done for testing purposes so that if something went wrong the battery could be quickly disconnected. However, the control box is physically capable of being adjusted for a user to wear with the battery.

Kinematics

- Minimize the number of moving parts.
    - All moving parts were critical to function and could not be removed.
- Provide at least 1 DOF in the movement of the fingers.
    - All fingers moved together in opening and closing, thus this was all that was provided.
- Maximum grip width limited based on the user's hand size.
    - The design meant that exceeding this was not possible.
- Able to open and close full range of motion in a period greater than three and less than five seconds.
    - The device completed desired motion in a period of approximately 3-4 seconds.
- All joints of the device must have centers of rotation in line with the natural anatomy of the hand.
    - All joints were provided by the hand, not the device, thus it was not possible to fail this design specification.

Durability

- Routine maintenance performable with hand tools by a certified orthotist.

    - Though no orthotists were consulted on their ability to maintain the device, it was assembled using only hand tools and thus maintenance is expected to only require hand tools.
- Individual components of the device must not make contact it such a way that there is repeated relative motion between the parts.
    - No wear surfaces, which caused undesired issues, were seen on the prototype.
- Components must not deflect under maximum loading in such a manner or to such a degree that the device is rendered inoperable.
    - Under maximum tested load, significant deflection was not encountered.

Not Satisfied Device Design Specifications

- Have fingers coupled in pairs
    - Fingers were coupled fully together, not pairs. Function was not impeded.
- All movement mechanisms must operate outside of the desired grip envelope.
    - Strictly speaking, thus was not met, as cables ran through the grip area. Function was not impeded.
- Battery must weigh less than 250g.
    - The battery weighs 276g. In future iterations a slimmer battery could easily be obtained.

Not Tested Device Design Specifications

- Force on user's first two fingers should not exceed more than 10N normal and 30N parallel to the bone in all positions.
    - No test was developed, but mathematically this property was from the calculations that were completed for the cable preliminary design.
- Be able to run for 12 hours without requiring recharge.
    - Due to the age and battery life of the battery that was utilized for this prototype would not last 12 hours without requiring to be recharged.
- Able to apply equal strength at a cylindrical grip diameter of 2cm and 9cm.
    - This could not be tested as the dynamometer was not capable of accommodating such difference in grip size.

- Be capable of surviving drops of at least 1.5m.
    - This was not tested as failure may have been catastrophic to the project. Furthermore, this would not be a reasonable expectation of such a prototype.
- Last 1,000,000 cycles before replacement of parts.
    - This was not practical to test. Furthermore, this would not be a reasonable expectation of such a prototype.
- Device must be water resistant enough to handle splashes.
    - This would not be a reasonable expectation of such a prototype.

Discussion of Test Results

The 20 N maximum grip strength found was not the physical limit of the device, but rather the safe limits that the device could be used. Exceeding this force was found to cause strong discomfort to the tester. It is possible for the device to have a stronger grip, but not reasonable. It would not be possible to use the weaker servo, as this would back drive should the 13 N force on the fingertips be exceeded, meaning that it would drop heavier objects. The stronger servo did not have this issue.

A different issue was encountered between the thumb servo and the microcontroller. The microcontroller was capable of reading very fine resolution changes in the resistance provided by the potentiometer. When this data was sent to the servo, which had a much more coarse resolution, the differences resulted in the servo “twitching” because it was bouncing back and forth between different potentiometer input data points. These twitches were largely deadened by the weight of the hand in the device, but not enough to be ignored. This issue could be better addressed by using the microcontroller to average the signal to the servo so output better matches the resolution of the servo. An additional capacitor could also have been used to filter out some of the electrical noise in the signal.

Reliability problems also existed with the thumb servo and assembly. The two miter gears used did not reliably mesh. This was the result of two issues – imperfect servo mounting and a mounting nut that kept backing out. The latter issue could be corrected with either Loc-Tite or multiple nuts stacked on each other. Ensuring that the nut was more than finger tight reduced the problem for a while, but was not a permanent fix for the problem. The former issue is a direct result of using all manual manufacturing to attach and shape components.

The brace served to locate all attached components. However, those attachment points were all drilled or otherwise created by hand onto surfaces that did not agree with the original drawing. The result was significant hand fitting of components, including using stacks of rubber to more accurately space components. Where this issue was most noticed was in the thumb servo area, as noted previously. The thumb servo, while tight, still had some freedom to move and shake, both horizontally and vertically. This meant that under the load of the hand, the servo's gear could lift off and no longer mate with the gear on the thumb. This would cause problems accurately controlling the motion of the thumb.

Other issues with the fit of the brace included securing the brace to the wrist comfortably. The brace was not shaped to properly enclose the wrist, despite numerous attempts. This allowed some travel of the brace in regards to the back of the hand.

During the less formal testing during demonstration on Project Presentation Day, other issues were found. The cables running to the winch wheel were not kept under sufficient tension. The cables would unwind from the wheel and then become tangled together, impeding function. This issue could be avoided by always keeping the cables under tension or by enclosing the winch wheel.

Also noticed during Project Presentation Day was that, despite a lack of fine control provided for controlling the grip force, fine control was still possible. One of the objects held by the device was a disposable plastic water bottle. These bottles have very thin walls, meaning they crush easily. The device was capable of holding the bottle without crushing it, a process that was repeated at least three times. It is worth noting that such an action was done during demonstration, so no dedicated protocols were written.

Chapter 10: Conclusions

The device works and would make a viable orthotic, with some revisions. The cable design was found to produce a very organic movement and requires little effort to scale to the hand sizes of different users.

As this is the second iteration of this project, it is worth examining the previous project's conclusions and recommendation and to determine if progress has been made. The previous iteration's first recommendation was to create a powered mechanism for the thumb's second degree of freedom (Dorenfeld, Wolf, & Zeveska 2013). This project accomplished that with the geared servo design. The second recommendation was to improve the control mechanism (Dorenfeld, Wolf, & Zeveska 2013). By pairing the fingers, much of the complexity of controlling the previous year's device was removed. The current iteration only uses three independent controls versus the previous project's five, with more intuitive controls. The third recommendation was to configure the hand mount such that it better fit the size and shape of the users hand (Dorenfeld, Wolf, & Zeveska 2013). In the case of this iteration, though there were fit issues with the brace, the cable design was much more conducive to different hand shapes and the glove/brace interface much more comfortable. The last recommendation was to perform life cycle testing on the device ((Dorenfeld, Wolf, & Zeveska 2013)). This was not performed, as this iteration of the device is still not refined enough to warrant such testing.

Chapter 11: Recommendations

Although the orthotic was successful in meeting the majority of the design specifications and functioning properly, there is a lot of room for improvement. Outlined below are recommendations for future work involving this project:

(1)

Due to the hand built nature of the device it was not as reliable or as comfortable as desired. The first recommendation for future work is:

Use 3D printed or otherwise computer-controlled manufacturing to create the brace and attachment points.

Computer-controlled manufacturing is more accurate than hand manufacturing, so the issues mentioned above would likely be removed. It is possible that, should the brace still be handmade, that a mold, baked in an oven, would be sufficient, assuming the mold was created accurately. The attachment points could then be created more accurately, as surfaces would in their expected locations.

(2)

No force limits were present in the design. There was a method of preventing the servo from continuously running at stall torque, but no other regulation was included. The second recommendation is:

Provide for an adjustable, maximum force limit and provide feedback on the force applied.

This would allow the user to adjust the force the device exerts, which means that the user would not have to rely on their own sense of touch to know when limits have been reached. Obvious feedback, such as a scale of lights, would also allow the user to understand the force they are applying before the limit.

(3)

Lastly, numerous issues stemmed from the quality of actuators and servos used. Hobby grade actuators, intended for lower cost robots, RC vehicles, and similar applications, lack the required precision for this device. The last recommendation is:

Improve the quality of actuators and servos so they are capable of accepting and outputting finer control.

This would remove the cause of the issue and would potentially allow for finer overall control, allowing the previously mentioned force limits and feedback to be better implemented. Ideally, finer control over the actuators could mean that a less coarse control system would be possible as well.

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Appendix

Appendix A: Selection Guidelines

Each device was ranked on matrices under each heading with a score of 0 – 2, with the score based on how well the relevant design specification was met as detailed below. An overall matrix was then created with the highest of each subheading receiving a score of 2, the next a 1, and finally a 0. This matrix was weighted and totaled to determine the final design. Numbers in parentheses reflect the relative weight of the category.

Finger Movement

Performance

Force application

The force applied at critical points as defined in the design specifications.

Score of 0 – Does not provide 6 lbs. of force at finger tips.

Score of 1 – Provides 6 lbs. of force at fingertips, but either with difficulty or in limited circumstances.

Score of 2 – Provides 6 lbs. of force at fingertips in all normal circumstances.

Grip Envelope

The grip envelope minimum and maximum as defined in the design specifications.

Score of 0 – Envelope cannot be adjusted between .5 and 5.5 inches, assuming an adult male sized hand.

Score of 1 – Envelope can be adjusted between .5 and 5.5 inches, assuming an adult male sized hand, but either with difficulty or in limited circumstances.

Score of 2 – Envelope can be adjusted between .5 and 5.5 inches, assuming an adult male sized hand, in all normal circumstances.

Grip Envelope Shape

The grip envelope shape is defined as the overall motion pattern and its ability to conform to objects of various shapes and sizes.

Score of 0 – Device can only hold one shape, or cannot effectively hold objects in entire grip envelope.

Score of 1 – Device can hold multiple shapes, but cannot effectively hold all objects in entire grip envelope.

Score of 2 – Device can hold multiple shapes and can effectively hold all objects in entire grip envelope.

An effective grip is one where the object is held between multiple points of contact around its body. Holding a cube at two corners, while this does mean there are multiple points of contact, is not secure enough to meet this definition. A strong grip pattern would ideally articulate both the proximal and middle joints (the distal being effectively coupled to the middle), and hold them in multiple positions.

Deflection

A measure of the overall expected deflection in links and components, and what interference this would cause.

Score of 0 – Deflection, under maximum force at finger tips, would prevent movement of components or would move joints more than .125" out of line of the joints of the hand.

Score of 1 – Deflection, under maximum force at finger tips, while not preventing movement of components, would move joints more than .125" out of line of the joints of the hand.

Score of 2 – Deflection, under maximum force at finger tips, would neither prevent movement of components nor would move joints more than .125" out of line of the joints of the hand.

"Out of line" is simply the magnitude, independent of direction, of the displacement.

Safety

Force Normal to Fingers

Score of 0 – Force normal to fingers exceeds 10N, with max force at finger tips.

Score of 1 – Force normal to fingers is less than or equal to 10N, with max force at finger tips, but in limited positions.

Score of 2 – Force normal to fingers is less than or equal to 10N, with max force at finger tips, in all positions.

Force Parallel to fingers

Score of 0 – Force parallel to fingers exceeds 30N, with max force at finger tips.

Score of 1 – Force parallel to fingers is less than or equal to 30N, with max force at finger tips, but in limited positions.

Score of 2 – Force parallel to fingers is less than or equal to 30N, with max force at finger tips, in all positions.

Pinch Hazards

Score of 0 – Pinch hazards are present and unavoidable.

Score of 1 – Pinch hazards exist in certain configurations, but are not always present.

Score of 2 – No pinch hazards exist, regardless of configuration.

Slippage

Score of 0 – Device cannot be secured in such a way to prevent more than .25" of travel when a force of 5 lbs. is applied parallel to the back of the hand.

Score of 1 – Device can be secured to prevent .25" of travel when a force of 5 lbs. is applied parallel to the hand, but doing so would bring discomfort to the user, or in limited positions.

Score of 2 – Device can be secured to prevent .25" of travel when a force of 5 lbs. is applied parallel to the hand, without discomfort to the user and in all positions.

Feel

Score of 0 – Device does not allow users hand and fingers to come in contact with held device in a manner, which allows for the sense of touch to be transferred.

Score of 1 – Device does allow users hand and fingers to come in contact with held device, but feeling is not transmitted along entire hand.

Score of 2 – Device allows feeling to be transferred everywhere on users hand and fingers.

A device which scores a 0, but uses a touch sensor to "feel" for the user, circumvents the issue of force feedback, but would still score a 0 on this metric as it is not as timely or accurate as the user himself.

Redundancy of joints

A measure of the necessity of certain joints on the device and if they can be replaced simply by the joints of the hand.

Score of 0 – Joints on the device which correspond to joints on the hand cannot be replaced entirely by the joints on the hand.

Score of 1 – Joints on the device which correspond to joints on the hand can be replaced, but doing so would violate other safety requirements by inducing a lower score.

Score of 2 – Joints on the device which correspond to joints on the hand can be replaced without impacting safety.

Manufacturing

Degree of Custom Manufacture

A measure of the percentage of parts requiring custom manufacture.

Score of 0 – 66% or more of parts must be custom manufactured, neglecting parts common to all designs.

Score of 1 – 33% - 65% of parts must be custom manufactured, neglecting parts common to all designs.

Score of 2 – Less than 32% of parts must be custom manufactured, neglecting parts common to all designs.

Complexity of Manufacture

A measure of complexity of manufacture.

Score of 0 – Manufacture processes are required to be manual and cannot be automated or standardized.

Score of 1 – Manufacture processes can be automated or standardized, but not fully.

Score of 2 – Manufacture processes can readily automated or standardized.

Time to Manufacture

A measure of the length of time required to fully manufacture the device, neglecting lead times on components.

Score of 0 – Device takes more than 3 weeks to manufacture.

Score of 1 – Device takes between 2 and 3 weeks to manufacture.

Score of 2 – Device takes less than 2 weeks to manufacture.

Maintenance

Availability of Components

The ease which replacement parts can be obtained.

Score of 0 – 66% or more of all parts are unique to a particular user's device.

Score of 1 – 33-65% of all parts are unique to a particular user's device.

Score of 2 – Less than 33% of all parts are unique to a particular user's device.

Ease of Replacement

The degree of difficulty of replacing individual parts.

Score of 0 – Device must be fully disassembled for most replacements.

Score of 1 – Device must be partially disassembled for most replacements.

Score of 2 – Parts may be replaced with minimal disassembly required.

Frequency of Maintenance

A measure of how often maintenance on the device is expected, based on the number of components which may wear, loosen or otherwise impact function, and the degree to which this may cause issues.

Score of 0 – Device must have routine maintenance performed between weekly and monthly.

Score of 1 – Device must have routine maintenance performed between monthly and biannually.

Score of 2 – Device must have routine maintenance performed no more frequently than biannually.

Routine Maintenance is defined as tightening fasteners, light lubrication of joints, replacement of Velcro straps (if designed as such), and similar tasks.

Cost

A measure of the cost to manufacture, measured in component cost for prototype, as the expected retail cost is dependent on this number.

Score of 0 – Device components cost over $700 to manufacture.

Score of 1 – Device costs between $300 and $700 to manufacture.

Score of 2 – Device costs less than $300 to manufacture.

Ease of Use

Ergonomics

The comfort and safety of the user.

A measure of the safety and projected comfort of the user.

Score of 0 – Device is unsafe due to unnatural paths of motion, poor fit or related issues.

Score of 1 – Device has the potential for unnatural paths of motion, poor fit or related issues.

Score of 2 – Device cannot be rendered unsafe without breaking.

Unnatural paths of motion include fingers being driven above the back of the hand more than X degrees, being driven parallel to the axis of the knuckles, especially at middle joint, or to other biomechanically impossible positions. Similarly, a failure arise when moments are applied which would bend the finger at locations other than joints. "The potential" is defined as the device can be adjusted to produce these unsafe conditions, either accidentally or willfully, without being broken.

Simplicity of Control

A measure of the required number of inputs and what fine control is necessary for them. This is the minimum amount of control.

Score of 0 – Requires more than two inputs from user, or requires significant fine control from user, meaning normal grips require force regulation or precise timing on the part of the user.

Score of 1 – Requires two inputs from user, but either with difficulty or in limited circumstances, or requires some fine control from user, meaning normal grips

Score of 2 – Requires one or two inputs from user, in all normal circumstances and requires little or no fine control from user.

A normal grip is defined as one which falls into a category of an ADL, as detailed in the "Beginning of Design" section, and does not account for more complicated actions, such as attempting to tie string or other dexterity-intensive actions.

Interference

The potential for interference of the movement subsystem with the grip envelope.

Score of 0 – Movement subsystem decreases effective grip envelope by more than an inch, always.

Score of 1 – Movement subsystem decreases effective grip envelope by not more than an inch.

Score of 2 – Movement subsystem does not impact the grip envelope.

Weight

The weight of the device on the hand, assuming power is mounted elsewhere.

Score of 0 – Device weighs more than 1.25 lbs.

Score of 1 – Devices weighs between .75 and 1.25 lbs.

Score of 2 – Device weights less than .75 lbs.

Ease of Attachment

The ease with which the device can be donned with one hand.

Assessed base on the shape of the hand frame and how easily the hand can be put inside the device, then secured. This is assuming the user has practice.

Score of 0 – The device cannot be donned by the user with the only opposite hand, or doing so takes more than 2 minutes.

Score of 1 – The device can be donned with only the opposite hand, but doing so takes between 30 seconds and 2 minutes.

Score of 2 – The device can be donned with only the opposite hand in under 30 seconds.

Aesthetics

Only an issue between two very similarly ranked designs (less than 5%) difference in scores. Otherwise, this is fairly independent of design, as all designs can be made to be aesthetically pleasing, to an extent.

As this is between two designs, and no more, a scoring system is unnecessary.

Thumb System

All scoring for the thumb subsystem is based on the following scoring system.

Scoring: 0 – Fails, 1 – Meets, 2 – Exceeds

Function

1. Must have at least 1 powered degree of freedom
2. Movement system on thumb must not interfere with the finger movement subsystem.
3. Thumb must be controlled independently of the fingers.
4. Apply a maximum of 6lbs. at the thumb tip.

Safety

1. Motion paths must agree with natural motion of thumb.
2. Powered degree of freedom must be able to maintain the desired position.
3. Neutral position of thumb, i.e. no muscles extended or contracted, must be reachable and maintainable.

Physical Properties

1. Thumb assembly must not bring total cost over $700.
2. Thumb assembly must not bring total weight over 1 lb.
3. Components of thumb system must not deflect under 5lbs of load such that the device becomes inoperable.
4. Thumb movement system must not extend more than 2” from the user’s wrist.

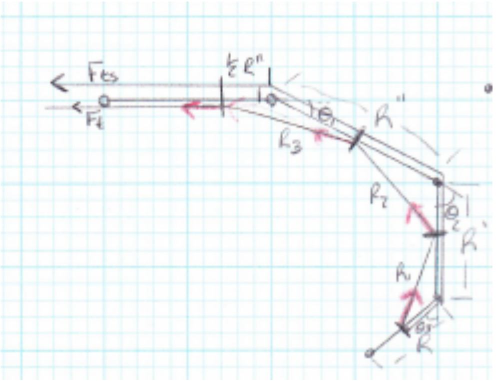
Usability

1. All DoF must be controlled by user.
2. Thumb must be able to position in numerous positions to facilitate the gripping of objects.
3. Movement system on thumb must not interfere with grip envelope.
4. Thumb must be able to be moved to a position which does not prevent full closure of fingers.
5. Thumb control system must allow for other hand to be free whilst gripping.

Appendix B: Cable Force Analysis and MatLab Code

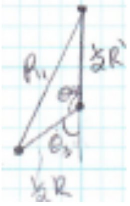
The following are the calculations for the cable design. These calculations determine the change in length for each finger, the moment at each joint of the finger and the force throughout the finger as the cable is being pulled.

Change in cable length



- F_s = Force of Spring
- F_t = Tension in Cable
- Angles of all phalange bones are in relation to the preceding bone.
- For the index finger
  - R' = 1.4R
  - R" = 2.5R
- Tie down locations located at the middle point of each phalax
- h = height of joint

Solving for R_1

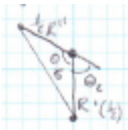


$$\theta_6 = 180 - \theta_3$$

$$R_1 = \sqrt{\left(\tfrac{1}{2} * R'\right)^2 + \left(\tfrac{1}{2} * R\right)^2 + 2 * R' * R * \cos\theta_6}$$

$$R_1 = \sqrt{R^2(0.74 + 2.8 * \cos(180 - \theta_3))}$$

Solving for R_2



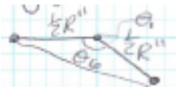
$$\theta_5 = 180 - \theta_2$$

$$R_2 = \sqrt{\left(\frac{1}{2} * R''\right)^2 + \left(\frac{1}{2} * R'\right)^2 + 2 * R' * R'' * \cos\theta_5}$$

$$R_2 = \sqrt{R^2(2.05 + 7 * \cos(180 - \theta_2))}$$

Solving for R_3

$$\theta_4 = 180 - \theta_1$$



$$R_3 = \sqrt{\left(\frac{1}{2} * R''\right)^2 + \left(\frac{1}{2} * R''\right)^2 + 2 * R'' * R'' * \cos\theta_4}$$

$$R_3 = \sqrt{R^2(3.1 + 12.5 * \cos(180 - \theta_1))}$$

Change in cable length

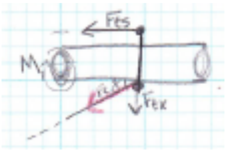
$l_{BC} = R_1 + R_2 + R_3$

Solving for the force at the finger tips through moment calculations

Looking for the force applied at fingertip in equilibrium

Distal Phalanx

$$\varphi_1 = \sin^{-1}\left(\frac{\sin\theta_6}{R_1} * 0.7R\right)$$

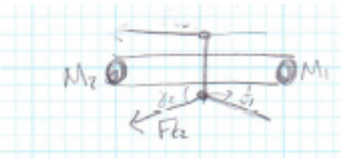


$$M_{top} = F_s(\tfrac{1}{2}h)$$

$$M_{bottom} = F_t \sin(\varphi_1)\tfrac{1}{2}R$$

$$F_{t1}\frac{F_s(\tfrac{1}{2}h)}{\sin(\varphi_1)\tfrac{1}{2}R\cos(\varphi_1)}$$

Medial Phalanx

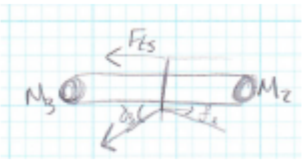


$$\varphi_2 = \sin^{-1}\left(\frac{\sin\theta_5}{R_2} * 1.4R\right)$$

$$\sum M_1 = F_s(\tfrac{1}{2}h) - F_{t2}\sin(\varphi_2)(0.7R) + \tfrac{1}{2}fh$$

$$F_{t2} = \frac{(F_s - f_1)(\tfrac{1}{2}h)}{\sin(\varphi_2)(0.7R)\cos(\varphi_2)}$$

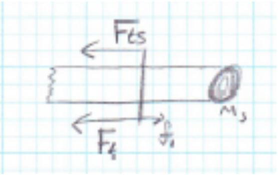
Proximal Phalanx



$$\sum M_2 = F_s(\tfrac{1}{2}h) - F_{t3}\sin(\varphi_3)(1.25R) + \tfrac{1}{2}fh$$

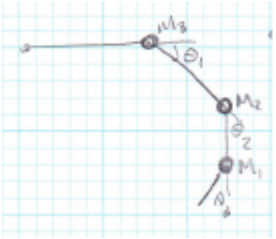
$$F_{t3} = \frac{(F_s - f_1)(\tfrac{1}{2}h)}{\sin(\varphi_3)(1.25R)\cos(\varphi_3)}$$

Metacarpal bone



$$\sum M_3 = (F_s + f - F_t)h$$

Solving for force at fingertip:



$$\sum M_3 = \tfrac{1}{2} fh - F_s(\tfrac{1}{2}h) - F_{t3}(\sin(\varphi_3)\tfrac{1}{2}R + \cos(\varphi_3)\tfrac{1}{2}h)$$

$$F_{t3} = \frac{-(f_2 + f_3 + F_t)(\tfrac{1}{2}h)}{\sin(\varphi_3)(1.25R)\cos(\varphi_3)}$$

$$\sum M_2 = \tfrac{1}{2} f_1 h - F_{t2}\sin(\varphi_2)(0.7R) = \tfrac{1}{2} f_2 h + F_{t3}\sin(\varphi_3)\tfrac{1}{2}R - F_{t3}\cos(\varphi_3)\tfrac{1}{2}h$$

$$F_{t2} = \tfrac{1}{2} f_1 h - \tfrac{1}{2} f_2 h + F_{t3}(\sin(\varphi_3)\tfrac{1}{2}R + \cos(\varphi_3)\tfrac{1}{2}h)$$

$$\sum M_1 = F_s(\tfrac{1}{2}h) - F_{t1}\sin(\varphi_1)\tfrac{1}{2}R + F_{t1}\cos(\varphi_1)\tfrac{1}{2}h$$

$$= \tfrac{1}{2} fh + F_{t2}(\sin(\varphi_2)\tfrac{1}{2}R + F_{t2}\cos(\varphi_2)\tfrac{1}{2}h)$$

$$F_{t1} = \frac{(F_s - f_1 + F_{t2})\tfrac{1}{2}h + F_{t2}\tfrac{1}{2}R\sin(\varphi_2)}{\sin(\varphi_1)\tfrac{1}{2}R - \cos(\varphi_1)\tfrac{1}{2}h}$$

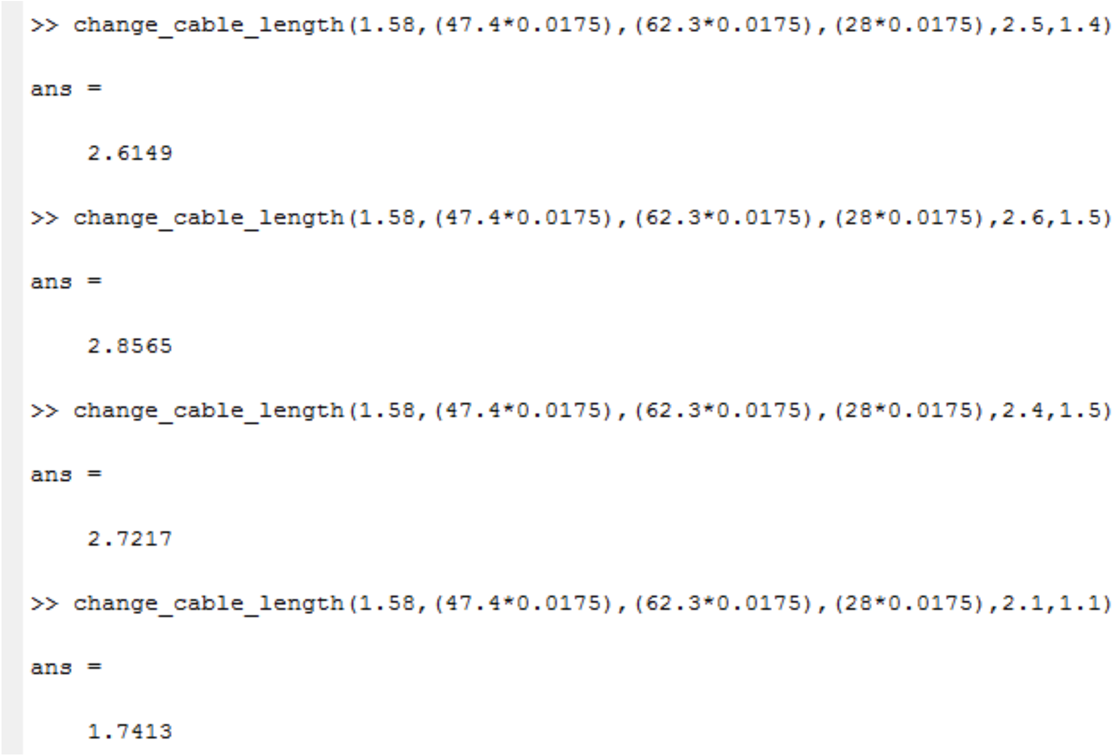
To accommodate for the calculations that needed to be performed on each finger a script was written in MatLab that could be applied to each finger. Using the math worked out on the following pages the first MatLab scrip was created to calculate the change in cable length. This was then adapted into the second code to include the cable tension required for each of the four fingers to provide a force of 7.175N at each fingertip. The calculations are based off of those just detailed out where the force at each bone is calculated through the moment at each joint. The calculations were completed using the spring constant of 2 lb/ft.

```
function [DL] = change_in_cable_length_three(R, T1, T2, T3)

T4=180-(T3*180/pi);

T5=180-(T2*180/pi);

T6=180-(T1*180/pi);
```

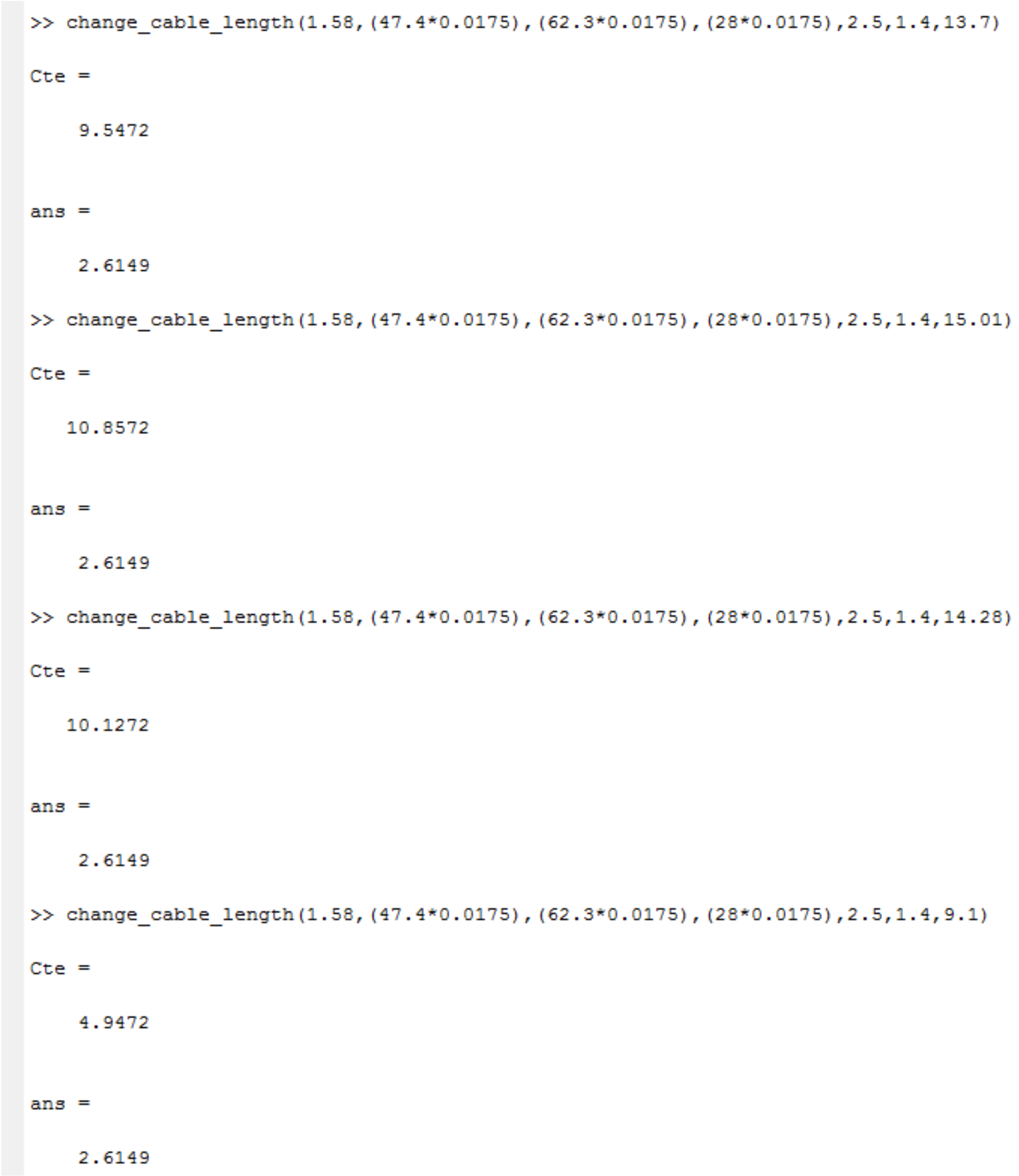
```
R4=1.4*R;

R5=2.5*R;

R1=sqrt(((0.5*R4)^2)+((0.5*R)^2)+(2*R4*R*cos(T4))*-1);

R2=sqrt(((0.5*(R5))^2)+((0.5*R4)^2)+(2*R5*R4*cos(T5)));

R3=sqrt(((0.5*(R5))^2)+((0.5*R'')^2)+(2*R5*R5*cos(T6))*-1);

DL=R1+R2+R3-R-R4-R5;

end
```

```
function [Ft] = cable_tension(R, T1, T2, T3, c, h, Fts)

T4=(180-T3)*(pi/180);

T5=(180-T2)*(pi/180);

T6=(180-T1)*(pi/180);

R4=1.4*R;

R5=2.5*R;

R1=sqrt(((0.5*R4)*(0.5*R4))+((0.5*R)*(0.5*R))+(2*R4*R*cos(T4))*-1);

R2=sqrt(((0.5*R5)^2)+((0.5*R4)^2)+(2*R5*R4*cos(T5)));

R3=sqrt(((0.5*R5)^2)+((0.5*R5)^2)+(2*R5*R5*cos(T6))*-1);

P1=asin(R1*0.4*R/sin(T4));

P2=asin((R2*1.4*R/sin(T5)));

P3=asin((R3*1.25*R/sin(T6)));

Ft=(Fts*0.5*h)/((0.5*R*sin(P3)*(1-(c*sin(P3))-(c*c*sin(P3))*sin(P2)))+(1-
(c*sin(P3))-(c*c*sin(P3)*sin(P2))*cos(P1)*0.5*h)-(0.5*R4*sin(P2)*(1-
(c*sin(P3)))));

Ft1=Ft*(1-cos(P3)-(c*c*sin(P3)*sin(P2)));

Ft1x=cos(P1)*Ft1;

Ft1y=sin(P1)*Ft1;
```

```
Ft2=Ft*(1-(c*sin(P3)));

Ft2x=cos(P2)*Ft2;

Ft2y=sin(P2)*Ft2;

end
```



```
>> change_cable_length(1.58,(47.4*0.0175),(62.3*0.0175),(28*0.0175),2.5,1.4)

ans =

    2.6149

>> change_cable_length(1.58,(47.4*0.0175),(62.3*0.0175),(28*0.0175),2.6,1.5)

ans =

    2.8565

>> change_cable_length(1.58,(47.4*0.0175),(62.3*0.0175),(28*0.0175),2.4,1.5)

ans =

    2.7217

>> change_cable_length(1.58,(47.4*0.0175),(62.3*0.0175),(28*0.0175),2.1,1.1)

ans =

    1.7413
```



```
>> change_cable_length(1.58,(47.4*0.0175),(62.3*0.0175),(28*0.0175),2.5,1.4,13.7)

Cte =

    9.5472


ans =

    2.6149

>> change_cable_length(1.58,(47.4*0.0175),(62.3*0.0175),(28*0.0175),2.5,1.4,15.01)

Cte =

   10.8572


ans =

    2.6149

>> change_cable_length(1.58,(47.4*0.0175),(62.3*0.0175),(28*0.0175),2.5,1.4,14.28)

Cte =

   10.1272


ans =

    2.6149

>> change_cable_length(1.58,(47.4*0.0175),(62.3*0.0175),(28*0.0175),2.5,1.4,9.1)

Cte =

    4.9472


ans =

    2.6149
```

Finger	Change In Cable Length (cm)	Force required (N)
2	2.61	11.94
3	2.86	13.00
4	2.72	12.41
5	1.74	8.72

Appendix C: Linkage Design Force and Stress Analysis

A force analysis was conducted to determine the loadings on each linkage in the design. This was completed for positions 1 and 3, as position 2 was found to be mostly identical to position 1, only rotated 90 degrees.

The two positions, with points labeled, are shown in Figure 37. They are identical to the positions from the function section.

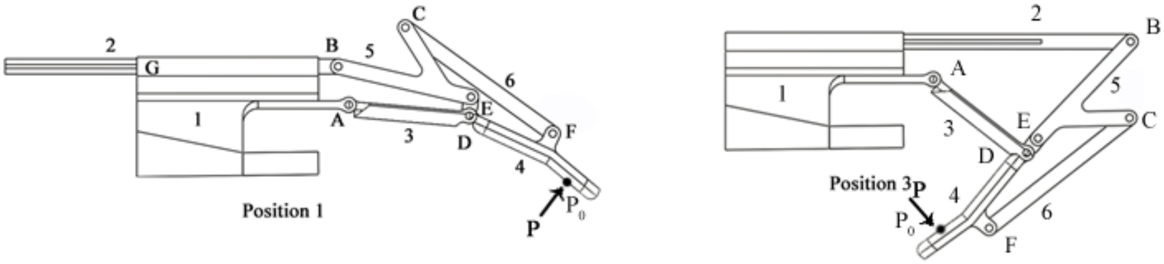


Figure 37 - Diagram of Positions with Points

Point	Coordinates – Position 1 (inches)	Coordinates – Position 3 (inches)
A	(0.00,0.00)	(0.00,0.00)
B	(0.10,0.63)	(3.31,0.57)
C	(0.84,1.27)	(3.38,-0.59)
D	(1.89,-0.42)	(1.60,-1.20)
E	(2.10,-0.13)	(1.76,-0.94)
F	(3.29,-0.89)	(0.94,-2.45)
P_0 (Application point of P)	(3.36,-1.64)	(0.19,-2.43)

$|\mathbf{F}| = F$, $\mathbf{F} = X\,\hat{\imath} + Y\,\hat{\jmath}$

P is left as a variable such that this is solved for any force normal to the finger tips.

Position 1 – Link 4 (Figure 37)

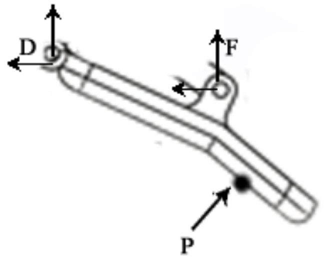


Figure 37 - FBD of Link 4, Pos 1

$$\mathbf{P} = .643P\,\hat{\imath} + .766P\,\hat{\jmath}$$

Link 6 is a two force member at 138 degrees.

$$\mathbf{F} = -.736F\,\hat{\imath} + .677F\,\hat{\jmath}$$

$$\sum X = P_x + D_x - F_x = .643P + D_x - .736F \rightarrow .643P = .736F - D_x$$

$$\sum Y = P_y + D_y + F_y = .766P + D_y + .677F \rightarrow .766P = -(.677F + D_y)$$

$$\sum M_d = -.46(.736F) + 1.4(F_y) + 1.22(P_x) + 1.47(P_y) = -.46(.736F) + 1.4(.677F) + 1.22(.643P) + 1.47(.766P)$$

$$0 = .595F + 1.91P$$

$$\mathbf{F} = -3.21\mathbf{P} = 2.39P\,\hat{\imath} - 2.15P\,\hat{\jmath}$$

$$\therefore \mathbf{D} = -3.03P\,\hat{\imath} + 1.38P\,\hat{\jmath}$$

Position 1 – Rest of System (Figure 38)

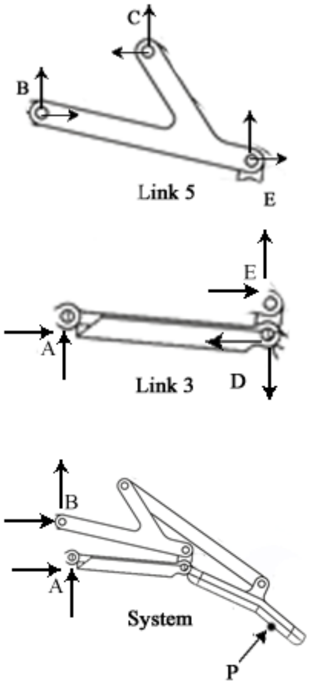


Figure 38 - FBD of Remainder of System, Pos 1

Link 5

$$\mathbf{C} = -\mathbf{F}$$

$$\sum X = C_x + B_x + E_x = -2.39P + B_x + E_x \rightarrow 2.39P = B_x + E_x$$

$$\sum Y = C_y + B_y + E_y = 2.15P + B_y + E_y \rightarrow 2.15P = -(B_y + E_y)$$

Link 3

$$\sum X = D_x + E_x + A_x = -3.03P + E_x + A_x \rightarrow 3.03P = E_x + A_x$$

$$\sum Y = D_y + E_y + A_y = 1.38P + E_y + A_y \rightarrow 1.38P = -(E_y + A_y)$$

System

$$\sum X = P_x + B_x + A_x = .643P + B_x + A_x \rightarrow .643P = -(B_x + A_x)$$

$$\sum Y = P_y + B_y + A_y = .766P + B_y + A_y \rightarrow .766P = -(B_y + A_y)$$

Matrix Representation

$$\begin{vmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 2.390 \\ 0 & -1 & 0 & -1 & 0 & 0 & 2.150 \\ 1 & 0 & 0 & 0 & 1 & 0 & 3.030 \\ 0 & -1 & 0 & 0 & 0 & -1 & 1.380 \\ 0 & 0 & -1 & 0 & -1 & 0 & 0.643 \\ 0 & 0 & 0 & -1 & 0 & -1 & 0.766 \end{vmatrix}$$

Solving this matrix via WolframAlpha, an online math utility, yielded a reduced echelon form matrix containing the unknown forces. Combined with the previously found solutions resulted in the force in each linkage, shown in the following table as a coefficient of P, i.e. 3.03 means 3.03P.

	A	**B**	**C**	**D**	**E**	**F**	**P**
X	0.002	-0.642	-2.39	-3.03	3.03	2.39	0.643
Y	0.002	-0.768	2.15	1.38	-1.38	-2.15	0.766

Position 3 – Link 4 (Figure 39)

An identical procedure was followed for Position 3, with different coordinates used.

$\mathbf{P} = .593P\,\hat{\imath} + -.800P\,\hat{\jmath}$

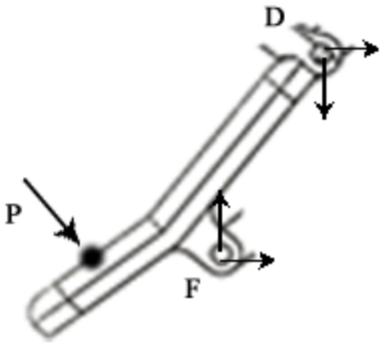


Figure 39 - FBD of Link 4, Pos 3

Link 6 is a two force member at 38.25 degrees.

$\mathbf{F} = .619F\,\hat{\imath} + .785F\,\hat{\jmath}$

$\sum X = P_x + F_x - D_x = .593P + .785F - D_x \rightarrow .593P = .785F + D_x$

$\sum Y = -P_y + F_y + D_y = -.800P + .619F + D_y \rightarrow .800P = .619F + D_y$

$\sum M_d = -.660F_y + 1.25F_x + 1.41P_y + 1.23P_x = -.660(.619F) + 1.25(.785)F + 1.41(.800P) + 1.23(.593)P$

$0 = 1.858P - .572F$

$\mathbf{F} = 2.54P\,\hat{\imath} - 2.00P\,\hat{\jmath}$

$\therefore \mathbf{D} = 1.95P\,\hat{\imath} + 2.80P\,\hat{\jmath}$

Position 3 – Rest of System (Figure 40)

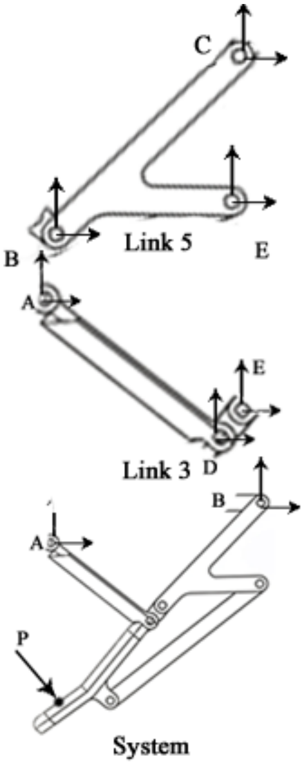


Figure 406 - FBD of Remainder of System, Pos 3

Link 5

C = -F

$\sum X = C_x + B_x + E_x = 2.54P + B_x + E_x \rightarrow 2.54P = -(B_x + E_x)$

$\sum Y = C_y + B_y + E_y = 2.00P + B_y + E_y \rightarrow 2.00P = -(B_y + E_y)$

Link 3

$\sum X = D_x + E_x + A_x = 1.95P + E_x + A_x \rightarrow 1.95P = -(E_x + A_x)$

$\sum Y = D_y + E_y + A_y = 2.80P + E_y + A_y \rightarrow 2.80P = -(E_y + A_y)$

System

$\Sigma X = P_x + B_x + A_x = .593P + B_x + A_x \rightarrow .593P = -(B_x + A_x)$

$\Sigma Y = P_y + B_y + A_y = -0.80P + B_y + A_y \rightarrow 0.80P = B_y + A_y$

Again, these equations were combined into a matrix.

$$\left|\begin{array}{ccccccc} -1 & 0 & -1 & 0 & 0 & 0 & 0.593 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0.800 \\ -1 & 0 & 0 & 0 & -1 & 0 & 1.950 \\ 0 & -1 & 0 & 0 & 0 & -1 & 2.800 \\ 0 & 0 & -1 & 0 & -1 & 0 & 2.540 \\ 0 & 0 & 0 & 1 & 0 & 1 & 2.000 \end{array}\right|$$

With the following result:

	A	B	C	D	E	F	P
X	0.00	-.593	2.54	1.95	-1.95	-2.54	.593
Y	0.00	0.80	2.00	2.80	-2.80	-2.00	-.800

Analysis of Finger Loads

To assess the potential of redesigning the device such that fingers could be used as links without support on the outside, the forces acting along and normal to links 3 and 4 were found. Links 3 and 4, theoretically, would become the user's fingers.

The force parallel was calculated by the following equation:

$$\mathbf{F} \cdot \boldsymbol{v} = F_{\text{parallel}}$$

$\mathbf{F}$ = force vector, $\boldsymbol{v}$ = unit direction vector of the link, $\mathbf{V}$ = direction vector of link

$$\boldsymbol{v} = \mathbf{V}/|\mathbf{V}|$$

The force normal was then found by using the Pythagorean Theorem.

$$A^2 + B^2 = C^2 \, , \; C^2 - A^2 = B^2$$

$$A = F_{\text{parallel}} \, , \; C = F, \; B = F_{\text{normal}}$$

For link 3, the Force vector was simply **A**. This corresponds to the proximal phalange However, since **A** is zero in both cases, it is omitted. As link 4 covers the middle and distal portion, two different sections must be taken. The middle phalange's force vector is **D** and the proximal is **P**. As these values were dependent on P, the next step was to determine the maximum value of P which did not exceed safety criteria found via research.

$$P_{\text{para}} = 30P/F_{\text{parallel}}$$

$$P_{norm} = 10P/F_{normal}$$

P is required in the expression to cancel it in F. Equation is in Newtons.

The dot product was taken with WolframAlpha. Microsoft Excel was used to then calculate the remaining quantities. It is worth noting that for position 1, the proximal phalange was not calculated as **A** has a very small magnitude.

	V	***v***	$F_{parallel}$	F_{normal}	P_{para}	P_{norm}
Middle 1	0.940	-0.610	3.3	0.03	9.09	339
	0.840	-0.544				
Middle 3	-0.720	-0.795	-3.25	1	9.2	10
	-0.550	-0.607				
Distal 1	0.643	-0.667	0.995	0.01	30.2	1960
	0.690	0.720				
Distal 3	-0.560	-0.490	0.060	0.00	501	12259
	0.753	0.658				

This calculation finds that the middle phalange in position 3 cannot handle a P of more than 9.2N, or 2.07 lbs. Distributed over two fingers, as this design would theoretically do, this is a maximum P of 4.14 lbs., without any support whatsoever. Support could easily be provided to increase this number.

Stress Analysis

The two locations with the highest potential for failure are both link 4, before the distal bend, as the forces present are the highest. Position 1 could potentially produce failure in tension and position 3 in shear. These links are expected to be made of acrylic, which is brittle and fails at 70 MPa and has a Young's Modulus of 3.2 GPa (Engineering Toolbox). In Imperial, the failure stress is 10,153 PSI and modulus is 464,000 PSI.

$$\sigma = P / A$$

$$\tau = P / A$$

$$\varepsilon = \sigma / E$$

Tensile Stress

P = 3.3 * 6 lbs. = 19.8 lbs.

Dimensions are of links 5 and 6, which is the theoretical smallest value that link 4 would be modified to.

A = .125" * .25" = .03125 in^2

σ = 19.8 lbs. / .03125 = 633.6 PSI

ε = 633.6 / 464,000 = .0013

This leads to a deflection of approximately .002"

Failure is not likely in pure tension, as the ultimate tensile strength is approximately 20 times higher.

Shear

P = 1 * 6 lbs. = 6 lbs.

A is same as above.

τ = 6 lbs / .03125 in^2 = 192 PSI

Deflection requires ν, or poisson's ratio, with value .35 (Laird Plastics).

G = Shear Modulus = E/(2(1+ ν) = 494000 PSI / (2(1+.35)) = 182963 PSI

γ = shear strain = τ/G = 192 PSI / 182963 = .001. This is also well within the bounds of safety.

Even accounting for a lower strength in shear, failure is not likely to occur.

Though this calculation was done with the data from links 3 and 4, it is reasonable to assume that all links will be safe. The next tension in link 6 is less than the value used here. In link 5, the only other link not accounted for, the magnitude of the forces at each point is approximately the same, if not less. Therefore it can be assumed that the device is not likely to fail.

Appendix D: Microcontroller Code

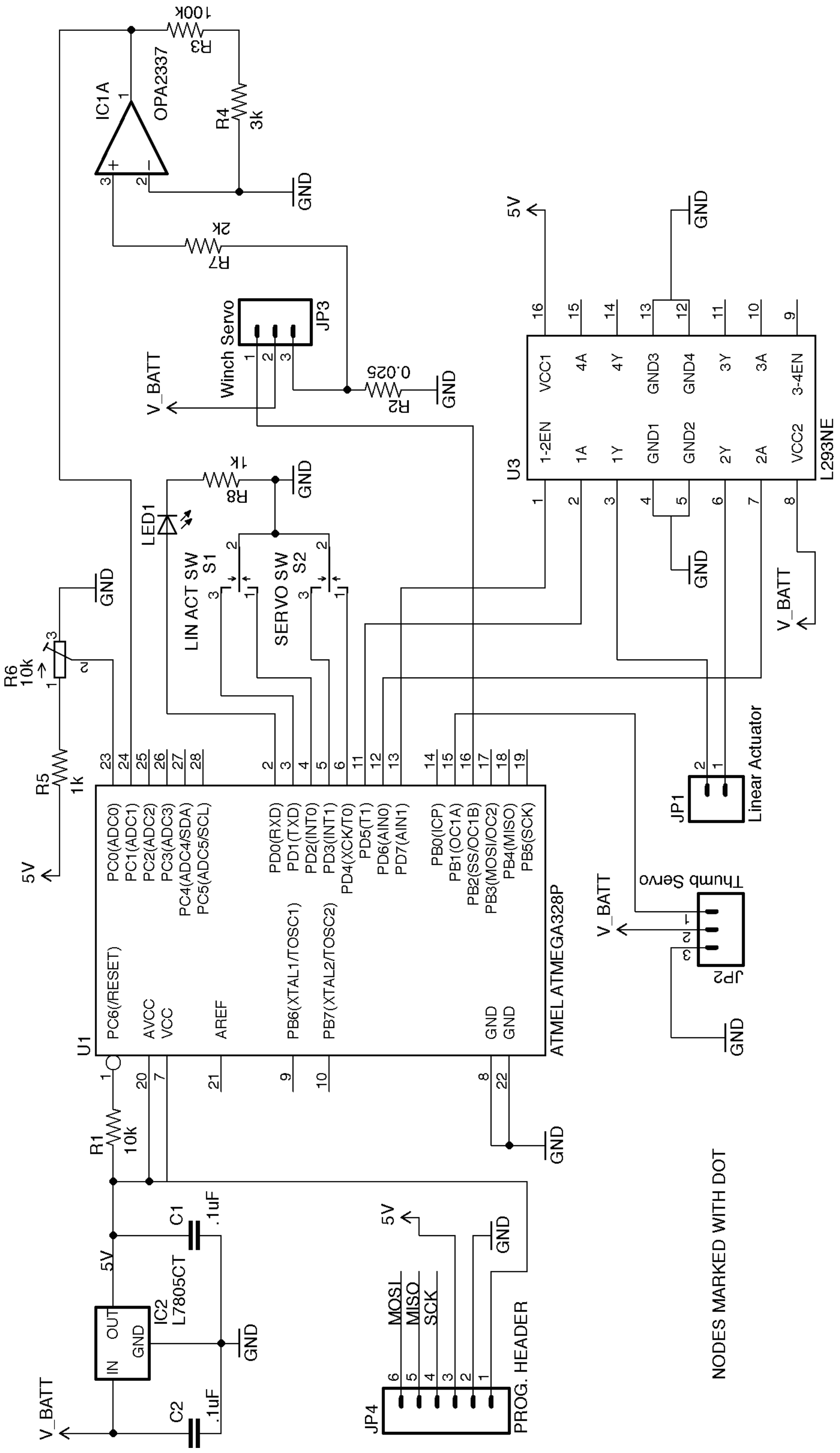
```
// Reed Hebert, Ian Crowe, Brittany Nichols
// 04/05/2014
// MQP Powered Hand

#include <Servo.h>;
Servo thumbServo;
Servo winchServo;

const int numReadings = 300;

int readings[numReadings];
// the readings from the analog input
int index = 0;          // the index of the current reading
long total = 0;         // the running total
long average = 0;       // the average
int winchStall;

void setup(){

 //Serial.begin(9600);   // Open Serial Port for Debug
 pinMode(0, OUTPUT);
 pinMode(1, INPUT_PULLUP);      // Switch 1 LIN -
 pinMode(2, INPUT_PULLUP);      // Switch 2 LIN +
 pinMode(3, INPUT_PULLUP);      // Switch 3 Winch Servo
 pinMode(4, INPUT_PULLUP);      // Switch 4 Winch Servo
 pinMode(5, OUTPUT);      // Output 1, Digital Pin 5
 pinMode(6, OUTPUT);      // Output 2, Digital Pin 6
 pinMode(7, OUTPUT);      // Output 3, Digital Pin 7
 thumbServo.attach(9,1050,1950); // Attach servo Pin 9
 winchServo.attach(10,1000,2000); // Attach servo Pin 10
 winchStall = 0;

 for (int thisReading = 0; thisReading < numReadings; thisReading++) {
  readings[thisReading] = 0;
 }

}

void startUpLED() {
 digitalWrite(0,HIGH);
}

void loop(){
```

```
 startUpLED();
 const int potPin = A0;  // Potentiometer read pin
 const int winchServoRead = A1;  // Read Op-Amp Output
 float winchVOut;
 float winchCurrent;
 int thumbPos;    // Variable to store position value
 int buttonOne = digitalRead(1);     //  Digital In 1
 int buttonTwo = digitalRead(2);     //  Digital In 2
 int buttonThree = digitalRead(3);  //  Digital In 3
 int buttonFour = digitalRead(4);   //  Digital In 4
 const int LinIn1 = 5;      //  In1 = Pin 5 Digital
 const int LinIn2 = 6;      //  In2 = Pin 6 Digital
 const int LinEnable = 7;   //  Enable Pin = Pin 7 Digital

 //RUNNING AVERAGE
 total= total - readings[index];
 readings[index] = analogRead(winchServoRead);
 total= total + readings[index];
 index = index + 1;
 if (index >= numReadings)  {
  index = 0;
 }
 winchVOut = total / numReadings;
 winchVOut = (winchVOut*.0049)/45; // Op Amp Output
 winchCurrent = (winchVOut/.025); // Current
 //END RUNNING AVERAGE

// Thumb Servo Code Below:
 thumbPos = analogRead(potPin);
 thumbPos = map(thumbPos, 0, 920, 1050, 1950);
// Scale to use with 90 deg servo (in uS)
 thumbServo.writeMicroseconds(thumbPos);
 delayMicroseconds(1);

// Winch Servo Code Below:
 if (winchCurrent > .500) {
  winchStall = HIGH;
 }
 else {
  winchStall = LOW;
 }

 if (buttonThree == LOW) {
  winchServo.writeMicroseconds(1000);  // Turn Servo Left
  if (winchStall == HIGH){
```

```
//  If stall is detected
     while (buttonThree == LOW){
//  And Button is still held
     winchServo.write(1500);
//  Stop servo rotation
     }
    }

    delayMicroseconds(1);
  }

  if (buttonFour == LOW)  {
    winchServo.writeMicroseconds(2000);  //Turn Servo right
    if (winchStall == HIGH){
//  If stall is detected
     while (buttonFour == LOW){
//  And Button is still held
     winchServo.write(1500);
//  Stop servo rotation
     }
    }

    delayMicroseconds(1);
  }

  if (buttonThree && buttonFour == HIGH) {
// Button not pressed
    winchServo.writeMicroseconds(1500);
    delayMicroseconds(1);
  }

// Linear Actuator Code Below:
  digitalWrite(LinEnable, HIGH);
// Enable Linear Actuator Driver

  if (buttonOne && buttonTwo == HIGH) {
// If NO button is pressed
    analogWrite(LinIn1, 0);  // Linear Act. NO MOVEMENT
    analogWrite(LinIn2, 0);
    delayMicroseconds(1);
  }
  if (buttonOne == LOW) {  // If button1 IS pressed
    analogWrite(LinIn1, 255);  // MOVE - DIR
    analogWrite(LinIn2, 0);
    delayMicroseconds(1);
  }
```

```
  if (buttonTwo == LOW) {    // If button2 IS pressed
    analogWrite(LinIn1, 0);  // MOVE + DIR
    analogWrite(LinIn2, 255);
    delayMicroseconds(1);
 }

}
```

Appendix E: Electronic Subsystem Schematic



Appendix F: Testing Protocols

Testing Protocols for Partial Device

Safety

Purpose

To determine any potential wear, pinch or pressure hazards existing in the fingers of the device

Materials

- Orthotic: Cables should be routed through the device but not initially connected to anything including the springs and servo
- Temporary torsion spring: Attached to underside of brace to keep cables in line

Method

Device in open, neutral position

1. Don the orthotic
2. Close and open finger slowly using only the force provided by the user's movement
    a. Do not pull or otherwise force the motion
3. Note feelings of discomfort
    a. See "Fixing Hazards"
4. Affix springs to back of device
5. Close finger slowly, using only the force provided by the user's movement
    a. Do not pull on cable or otherwise force the motion
6. Open finger slowly, relying on springs to do work
    a. Note that some muscular control will be required to control rate of opening
7. Note feelings of discomfort
    a. See "Fixing Hazards"
8. Affix cable from finger to torsion spring
    a. This is to allow the cable to be taken up and out of the way
9. Close finger slowly, using the torsion spring
    a. Pull spring away, such that it is forced to unreel
    b. Pull cable to replicate motor

        c. Allow for cable take-up by torsion spring
10. Open finger slowly, allowing the springs on back of device to do as much work as possible
11. Note feelings of discomfort
    a. See “Fixing Hazards”

Function

Purpose

To verify all systems related to the fingers are functioning as intended and motion path is as expected

Materials

- Orthotic: First finger should have the cable routed and connected to the servo and the spring

Method

Device in open, neutral position and all previously found sources of discomfort removed

1. Don the orthotic
2. Close finger slowly using servo, with reduced power to servo
    a. Hand should be passive allowing the servo to do the work
    b. Note the path and ensure it is as expected
3. Open finger slowly by unreeling servo with reduced power to servo
    a. Allow springs to provide opening force
    b. Keep hand passive
4. Note signs of discomfort
    a. See “Fixing Hazards”
5. Repeat 2 – 4 until sure of function
6. Increase power to servo
7. Repeat 2 – 4 at full power

Force

Purpose

To determine the baseline grip force output of the device through a single finger.

Materials

- Orthotic: Device with functional first finger and thumb
- Hand Dynamometer

Set Up

While wearing the orthotic, hold the dynamometer with it, with the grip surface beneath the finger. The finger will most likely be lightly resting against this surface. The dynamometer should be held with enough support so that it does don't move through the test. Should this not be able to be accomplished by the device alone, an assistant should carefully apply the necessary force to support the dynamometer.

Method

Device in open, neutral position

1. With the orthotic donned, grip Dynamometer with thumb around frame, ensuring thumb does not interfere with grip surface.
    a. "Grip surface" referring to the moving surface used to read force
2. Ensure Dynamometer is stable in grip
3. If Dynamometer is not stable, support with offhand
    a. Ensure offhand does not interfere with sensor surface
4. Ensure remaining unaugmented fingers do not assist in gripping
5. Close finger fully, note highest reading on dynamometer
6. Open finger fully
7. Repeat process at least 3 times
8. Record peak force for each step

Testing Protocols: Thumb

Safety

Purpose

To determine any potential wear, pinch or pressure hazards existing in the thumb section of the device

Materials

- Orthotic: All powered methods of movement should be disconnected

Method

1. Don the orthotic
2. Raise thumb using only the force provided by the user's movement
    a. Do not otherwise force the motion
3. Lower thumb, using only the force provided by the user's movement
    a. Do not otherwise force the motion
4. Note signs of discomfort
    a. See "Fixing Hazards"
5. Close and open thumb, using only the force provided by the user's movement
    a. Do not otherwise force the motion
6. Note signs of discomfort
    a. See "Fixing Hazards"
7. Repeat steps 3-6, but use opposite hand or have an assistance "force the motion"
    a. i.e. Replicate the electronic actuators without using them

Function

Purpose

To verify all systems related to the thumb are functioning as intended and motion path is as expected

Materials

- Orthotic

Method

Device in open, neutral position and all previously found sources of discomfort removed

1. Don the orthotic
2. Raise thumb slowly, with reduced power to servo
    a. Hand should be passive allowing the servo to do the work
    b. Note path, ensure it is as expected
3. Lower thumb slowly, with reduced power to servo
    a. Hand should be passive allowing the servo to do the work
    b. Note path, ensure it is as expected
4. Note signs of discomfort
    a. See "Fixing Hazards"
5. Repeat 2 – 4 until sure of function
6. Increase power to servo
7. Repeat 2 – 4 at full power
8. Close thumb slowly, with reduced power to linear actuator
    a. Keep hand passive, allow actuator to do work
    b. Note path, ensure it is as expected
9. Open thumb slowly, with reduced power to linear actuator
    a. Keep hand passive, allow actuator to do work
    b. Note path, ensure it is as expected
10. Note signs of discomfort
    a. See "Fixing Hazards"

Force

Purpose

To determine the baseline grip force output of the device through the thumb.

Materials

- Orthotic: Device with functional first finger and thumb
- Hand Dynamometer

Set Up

The dynamometer must be supported, likely by an assistant. Hold the dynamometer such that the thumb can press against the grip surface.

Method

Device in open, neutral position

1. With the orthotic donned, grip Dynamometer with thumb as above.
2. Ensure Dynamometer is stable in grip
3. If Dynamometer is not stable, support with offhand
    a. Ensure offhand does not interfere with sensor surface
4. Ensure remaining unaugmented fingers do not assist in gripping
5. Close finger fully, note highest reading on dynamometer
6. Open finger fully
7. Repeat process at least 3 times
8. Record peak force for each step

Testing Protocols: Remaining Fingers

Safety

Purpose

To determine any potential wear, pinch or pressure hazards existing in the fingers of the device

Materials

- Orthotic: Device with cable run, but not attached to servo, springs unattached for remaining 3 fingers
- Torsion spring with cable

Method

Device in open, neutral position

9. Don the orthotic
10. Close and open fingers slowly using only the force provided by the user's movement
    a. Do not pull on cable or otherwise force the motion
11. Note feelings of discomfort
    a. See "Fixing Hazards"
12. Affix springs to back of device
13. Close and open fingers slowly using only the force provided by the user's movement
    a. Do not pull on cable or otherwise force the motion
    b. Note that some muscular control will be required to control rate of opening
14. Note feelings of discomfort
    a. See "Fixing Hazards"
15. Affix cable from finger to torsion spring
    a. This is to allow the cable to be taken up and out of the way
16. Close fingers slowly, using the torsion spring
    a. Pull spring away, such that it is forced to unreel
    b. Pull cable to replicate motor
    c. Allow for cable take-up by torsion spring
17. Open fingers slowly, allowing the springs on back of device to do as much work as possible

18. Note feelings of discomfort
    a. See “Fixing Hazards”

Function

Purpose

To verify all systems related to the fingers are functioning as intended and motion path is as expected

Materials

- Orthotic

Method

Device in open, neutral position and all previously found sources of discomfort removed

1. Don the orthotic
2. Close fingers slowly with the movement being powered by the servo with a reduced power
    a. Hand should be passive allowing the servo to do the work
    b. Note the path and ensure it is as expected
3. Open fingers slowly by allowing the servo to back drive
    a. Hand should be passive allowing the springs to do the work
4. Note signs of discomfort
    a. See “Fixing Hazards”
5. Repeat 2 – 4 until sure of function
6. Increase power to servo
7. Repeat 2 – 4 at full power

Testing Protocols: Full Device

Force

Purpose

To determine the baseline grip force output of the device through all fingers.

Materials

- Orthotic: Device with functional first finger and thumb
- Hand Dynamometer

Set Up

While wearing the orthotic, hold the dynamometer with it, with the grip surface beneath the finger. The finger will most likely be lightly resting against this surface. The dynamometer should be held with enough support so that it does don't move through the test. Should this not be able to be accomplished by the device alone, an assistant should carefully apply the necessary force to support the dynamometer.

Method

Device in open, neutral position

1. With the orthotic donned, grip Dynamometer with thumb around frame, ensuring thumb does not interfere with grip surface.
    a. "Grip surface" referring to the moving surface used to read force
2. Ensure Dynamometer is stable in grip
3. If Dynamometer is not stable, support with offhand
    a. Ensure offhand does not interfere with sensor surface
4. Ensure remaining unaugmented fingers do not assist in gripping
5. Close finger fully, note highest reading on dynamometer
6. Open finger fully
7. Repeat process at least 3 times
8. Record peak force for each step

Donning/Doffing Device

Purpose

To assess the ease with which the device can be donned and doff and to determine the need for repeated practice or instruction.

Materials

- Orthotic
- Stop watch

Method

Device in open, neutral position

1. Start timer
2. Don device
3. Stop timer
4. Note elapsed time and reset timer.
5. Start timer
6. Doff device
7. Stop timer
8. Note elapsed time and reset timer.

Usability

Purpose

To determine the effectiveness of the device in its intended function and to determine any problems with the design.

Materials

- Orthosis
- Screw driver with handle 2cm in diameter, Filled Nalgene bottle with diameter 9cm, various objects between these two sizes
- Stop watch

Method

Setup

Layout objects in ascending order of size. Ensure each is vertical or otherwise can easily be picked up.

Process

1. Don device
2. Pick up first object (screw driver) using device power only
3. Hold for 10 seconds
    a. Ensure object does not slip more than 1cm during this time
4. Note if slippage occurred
5. Place first object using device power only
6. Repeat 2 through 5 for all objects
7. For each object which slipped, but the slippage could be assigned to tester error, repeat 2 – 5 for that object.