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Design of a Powered Hand Orthosis

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Design of a Powered Hand Orthosis

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

Current hand orthoses act as a brace or support for controlling the posture of the hand and wrist. These types of orthoses often prevent the use of the hand for various activities of daily living (ADLs). The goal of this project was to design and manufacture a fully functional powered hand orthosis, which could be controlled and operated by the contralateral hand, and be used by people with diminished hand functions. The design reduces the twenty seven degrees of freedom in a healthy human hand to six and replicates the motions needed to perform the most common grips including the cylindrical (power), pinch, and key grips. Linear actuators are used to create the motion of the fingers. The actuators drive the motion around two different finger joints through a six-bar linkage. An additional degree of freedom results from the circumduction of the thumb from the side of the palm to in front of the palm. The device was designed to provide the user with the average strength of a sixty to sixty five year old person, and enable them to grasp and pick up common objects encountered when performing ADLs. The device could successfully perform the three main grips desired. Six degrees of freedom were incorporated into the device, making it possible for the user to grasp a variety of different objects. In addition, results showed that a single finger could exert a force of 50 Newtons. This correlates to an approximate hand strength of 200 Newtons, which was felt to be sufficient for most ADL’s. Several improvements can be made to the device including refining the anthropometrics and control system. Overall, this orthotic device increases the strength and functionality of the hand for people with diminished hand functions and could result in a higher quality of living.
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Introduction

Mobilization or dynamic orthoses are “designed to increase range of motion (stretch soft tissue contractures) and assist muscle weakness or spasticity to improve function” (Cooper 2006). The four fingers in each hand have four joints: the metacarpophalangeal joint (MP), the proximal interphalangeal joint (PIP), the distal interphalangeal joint (DIP), and the carpometacarpal joint (CMC). The thumb in each hand has three joints: the metacarpophalangeal joint, interphalangeal joint, and carpometacarpal joint (ASSH, 2009). The various joints of the human hand can be seen labeled in Figure 1.

![Figure 1: Joints of Fingers (Institute for Quality and Efficiency in Health Care, 2012)](image)

This project seeks to develop a powered dynamic hand orthosis that not only satisfies the criteria of an orthosis outlined above, but also seeks to replicate the function, not anatomy, associated with hand. This orthosis is intended to assist persons with a loss of function in one hand, which can come as a result of stroke, spinal cord injury (more specifically in the C4-C7 vertebrae), or a number of other factors which may cause hemiparesis. Hemiparesis is defined as the condition of having loss of strength or function in one side of the body. The orthosis is geared primarily toward persons affected by stroke, as it is the most common cause of hemiparesis. It will be designed for users who have diminished strength and sensory capabilities in one hand. The device will be operated by the user’s
contralateral, fully functional hand. Such a device will enable the user to move their fingers into the most common positions and grips that are used for a majority of daily living activities. These grips include the cylindrical power grip, the pinch grip, and the key grip. The power (cylindrical) grip is most commonly used and its grip force is the highest. It consists of the fingers curling towards the palm creating a fist formation. An example of when this grip would be used is to pick up a water bottle or other cylindrical shaped objects. The pinch (precision) grip is commonly used when picking up smaller, lighter objects. The two main fingers are the pointer and middle finger while the thumb is helping to hold the object on the other side. Examples of objects that can be held by the power and pinch grip can be seen in Figure 2. The last grip the orthosis will be used for is the key grip. This grip can help the user with common activities such as zipping a coat or even holding a pen to write with. This orthotic device will potentially allow for two separate degrees of freedom in the thumb, to accommodate these grips, as the thumb plays a pivotal role in most hand functions. In addition to aiding in the motion of the fingers and thumb, the device will allow the user to exert the amounts of force which need to be applied for the various grips.

Figure 2: Power and Pinch Grip (Britannica, Inc., 2004)
This orthotic device will primarily be used for rehabilitative purposes, but may be used as an assistive device if the proper user interface is utilized. As a rehabilitative device, the therapist will not have to physically place the patient's hand in various grips. Even more, the patient could be fully independent while performing rehabilitative exercises. With the control of the device on the contralateral hand, the function of that hand is severely diminished. A method for turning the control hand on and off will be beneficial in turning this into an assistive device as well. When the signal is cut off, the contralateral hand will be free to function while the orthotic maintains the desired grip. Such a control will allow the orthotic to be used as both a rehabilitative and assistive device.
Background

This section presents the definition of an orthosis, the target consumer for this orthotic, the largest cause of hemiparesis, the anatomy of the hand, and the most common types of grips the hand performs daily. In addition vital information from a physical therapist and an occupational therapist were obtained, as well as information regarding related patents, past projects, and innovative products available. All of these topics were explored in order to understand what types of similar products are already on the market in the area of assistive and rehabilitative hand devices. The goal is to fully comprehend the basic information of the hand and the users being targeted.

Orthoses

An orthosis is a device that, “provides functional stability to a joint or prevents, corrects, or compensates for a deformity or weakness” (Cooper, 2006). There are two types of orthotic devices. One type is known as static orthoses, which can be either a restrictive or immobilizing device. The other type of orthotic device is dynamic and therefore is mobilizing, and assists as well as improves the function of weak muscles. The purpose of an orthotic device can either be to help in the rehabilitation process of the patient and help increase their strength or it can be to assist the patient when performing Activities of Daily Living (ADL) by strength, stability, and support (Scarsella, 2007).

Hemiparesis

Hemiparesis is a condition that corresponds with weakness in one side of the body (hemi-meaning “one side” and paresis meaning “weakness”). Some common causes of hemiparesis are stroke and cerebral palsy, but can also include multiple sclerosis, brain tumors, and other injuries to the brain. Hemiparesis is not to be confused with hemiplegia, which is paralysis of one side of the human body. More generally, hemiparesis is caused by injury or disease (cancer) to the brain or spinal cord. However, “Stroke is the most common reason people develop hemiparesis” (Weiss, 2010).
Hemiparesis can cause common ADLs to be extremely difficult, making the easiest of functions impossible. The area of the weakness and the loss of abilities related to this condition are dependent on what area of the brain has been affected. If the right side of the brain is damaged, then the left side of the body will have these weaknesses (also, speaking and language difficulties). Vice versa, if the left side of the brain is damaged, then the right side of the body will experience weakness (also, learning processes, behavior, and non-verbal communication). “Pure Motor Hemiparesis” is self-explanatory in that it affects movement in the legs, arms, and face (Weiss, 2010).

There are many treatments for this condition. Concentrating on the motor control, the main two methods are sessions with Physical and Occupational Therapists. Physical Therapists’ main goals are to restore the function of the affected muscles back to full capability. This is achieved by various exercises. Occupational Therapists’ main goal is to have the patient regain the ability to complete ADL’s (Weiss, 2010). Further information regarding important information accumulated through interviews with physical and occupational therapists will be discussed later in this section of the paper.

**Stroke**

Stroke is more technically known as cerebrovascular disease. A 2005 study shows that 2.7% of men and 2.5% of women over the age of eighteen had a history of stroke. As men and women get older, the occurrences of transient ischemic attacks (a small stroke where symptoms last less than twenty-four hours) increase. It documented that approximately 800,000 people per year are diagnosed with having a stroke, whether it be a first or reiterated stroke. The American Heart Association (AHA) states that someone has a stroke every 40 seconds in the United States. This high stroke rate per year affects women more often than men, with 55,000 more women having a stroke than men. Stroke is also observed as a “leading cause of serious, long-term disability in the United States (AHA, 2009).”

A 2005 survey taken in 21 states and Washington D.C., found that 30.7% of stroke survivors received outpatient rehabilitation. Therapists around the country agree that increasing this percentage
could lead to better chances of regaining functional status, which would lead to a better “quality of life”.

“The length of time to recover from a stroke depends on its severity. Between 50% and 70% of stroke survivors regain functional independence, but 15% to 30% are permanently disabled, and 20% require institutional care at 3 months after onset (AHA 2009).”

There are many affects from stroke found in its survivors. A survey was taken from survivors over the age of 65 during the first six months after their stroke occurred. About half suffered from some form of hemiparesis. Also, a third of these survivors needed assistance when walking, which led to a quarter of the survivors being dependent in their ADL’s. Approximately a fifth of the victims were found to suffer from aphasia (impairment of speech). Due to these affects, 35% were found to have “depressive symptoms” and 26% were placed into a nursing home. Women were also found to have greater disability than men and also healed at a slower rate (AHA 2009).

While all of these affects are serious and need to be dealt with, our orthotic device will focus on improving functionality of the patients hand affected by hemiparesis. Hemiparesis is the most common side-effect of stroke, affecting hundreds of thousands of people a year.

**Anatomy**

Basic anatomy knowledge of the hand is needed to successfully design orthoses for the hand. In just the hand, there are twenty-seven bones overall. Fourteen are phalangeal bones, which are located in the fingers. Each finger contains three phalanges, with the exception of the thumb which only contains two. The phalange bones in the fingers are known as the distal (at the tip of the finger), middle, and proximal phalanges. The thumb only has the distal and proximal phalange (Freivalds, 2004). There are the five metacarpal bones in the palm, which from the thumb to the pinky are numbered one to five. Lastly there are eight carpal bones that lead to the wrist and these bones are arranged into two rows with most of the names of those bones coming from the shape of the bone. All the bones of the hand can be seen in Figure 3.
Each digit of the hand also contains four joints, except for the thumb which only contains three. The four joints are the two interphalangeal (IP) joints, one metacarpophalangeal (MCP) joint, and one carpometacarpal (CMC) joint. One of the IP joints is known as the distal IP (DIP) which is between the distal and middle phalange, while the other IP joint is known as the proximal IP (PIP) joint which is between the middle and proximal phalanges. The MCP joint is formed at the union of the metacarpal bones and the proximal phalanges (ASSH, 2011). The DIP, PIP, and MCP joints all have ligaments that provide stability (Center for Holistic Care, 2012). The CMC joint is where the metacarpal and carpal bones align together. This joint gives the palm and fingers motion which allows a person to curl their hand around and object. There are different flexion angles and ranges of motion for each digit. For example, the PIP joint has a larger flexion angle than the DIP joint. For metacarpal joints, as the flexion
angle of a finger increases the range of motion decreases. This shows why the small finger, which has the biggest flexion angle, has the smallest range of motion (Freivalds, 2004).

There are different types of muscles that are contained in the hand and wrist (Figure 4). One group is the extrinsic muscles which are big, long muscles that run from the forearm to the hand and provide strength. Two important and main extrinsic muscles are the flexor digitorum profundus (FDP) and the flexor digitorum superficialis (FDS). These are the important finger flexor muscles that are used in scenarios where repetitive work and additional strength is needed (Freivalds, 2004). Then, there are the small intrinsic muscles of the hand, which offer precise finger movement and allows for each finger to have its own independent movement. Intrinsic muscles are split into four separate groups of muscles. There are the thenar muscles, which act on the thumb, the hypothenar muscles, which act on the little finger, the lumbrical muscles that help the extension of the IP joints and the flexion of the MCP joints, and finally the interossei group of muscles, which allow for abduction and adduction in the fingers (Muscles and Tendons, 2012). Figure 5 shows where some of the muscles are located in the hand.

![Extrinsic vs. Intrinsic Muscles](image)

*Figure 4: Extrinsic vs. Intrinsic Muscles (Richards, 1997)*
Hand Grips

Examination of the types of grips in the human hand is very relevant to the development of a powered hand orthosis. As outlined in “Project Grip Typology”, types of grasp can be differentiated into two main categories: power grasps and precision grasps (Steinfeld, 1986). Power grasps utilize static stability of the hand after the fingers are moved to their desired position, and include cylindrical, spherical, and hook grips along with lateral prehension if the thumb is adducted away from the fingers. Precision grasps involve more precise movements and positions of the fingers that include palmar prehension, tip to tip, and lateral prehension with the thumb abducted, for a pad to pad or “key” grip.

Given the nature of the device being developed, not all of these grips will be able to be incorporated, however the main cylindrical power grasp as well as the palmar and lateral precision grips
will be made possible by the use of the device. Figure 6 demonstrates the most common grips performed by the human hand.

![Figure 6: Project Grip Typology (MacKenzie, 1994)](image)

Data for pinch and grip strength are presented in a relevant study from the Occupational Therapy Program at the University of Wisconsin. This study contains normative data for different types of grip strengths including: cylindrical grip strength, tip pinch strength, key pinch strength, and palmar pinch strength. These grip strengths are organized by age, sex, and hand dominance. From the study’s presented data, it can be gathered that most persons are naturally right handed, and that in both sexes, average strength decreases with age after age 40. The data also shows that women are typically weaker in grip and pinch strength than men. Of the subjects tested in the 60-64 age category, men had an average right hand grip strength of 399 Newtons, whereas women had an average grip strength of 245 Newtons. The pinch strength statistics are similar in that men’s average strength in the same age group was 70.3 Newtons which is greater than the average women’s strength of 44.9 Newtons. It can be concluded that the orthosis being developed will most likely be used on the right hand of a person older than 60 years of age, and that the orthosis may prove more useful for women with diminished grip strength than men. (Occupational Therapy Program, University of Wisconsin-Milwaukee)
These data along with other information about grip strength measurement and common grips used in most daily living activities will be used to develop design specifications for a powered hand orthosis. The grip strength that is necessary to be reproduced will be determined by real measurement of forces necessary in performing daily living activities. Data such as hand function is more important in the design than the actual physical structure.

**Physical Therapist Interview**

A physical therapist from Winthrop University Hospital in Mineola, New York was contacted for information (via email). In the email sent to her, she was asked multiple questions to get some expertise from her field. However, three main questions were emphasized. The first question was what kind of hand injuries she most commonly sees in her patients. The next was what the main causes of these injuries were. Lastly, “what are common exercises that physical therapists have the patients perform?”

She first said that a PT sees various kinds of hand injuries. She then went on to say the ones she sees the most are “post hand fractures, arthritis, and carpel tunnel syndrome”. Her priorities when a patient is checked into her services are as follows: 1. Decrease pain and swelling 2. Increase range of motion (ROM) 3. Increase strength in the hand. The main goal is to improve the patients “fine motor capabilities”. “The level of the spinal cord injury will determine how much ADL function the patient will achieve.” Some treatments include hot & cold packs, paraffin (hot wax), whirlpool, and massage. One type of exercise that is performed includes passively moving the hand and wrist (PROM). Passive range of motion is done by the therapist or done by the patient, with they’re good hand. This kind of exercise is critical for keeping the joints flexible during times of not being able to actively move the affected hand.

The next exercise is having the patient actively move their hand and wrist. An example of the motions of these exercises include touching each fingertip with the thumb, opening and closing the
hand, pinching/picking up an object with the fingers, and placing objects in a container and stacking them. Some exercises are also done to get them back to be independent which include zipping, buttoning, unbuttoning, and opening & closing lids. An advanced Active Range of Motion (AROM) exercise includes the therapist adding some resistance to the motions. These exercises are called Progressive Resistive Exercises (PRE’s). “PRE’s are done using ther-a-bands, putty, hand grips, squeezing a ball, or the therapist applying resistance to certain muscles.”

Some of the therapist’s final remarks were that for such an orthotic device to be effective, it is important to have a patient with a good amount of strength in their wrist and forearm. This will help stabilize the hand to make it function better. Also, “because the hand and fingers are vital for giving us input to our world, sensation is extremely important for function also”. She stressed how the anatomy of the hand is fairly complex, and it is critical that we understand the relationship between intrinsic muscles and extrinsic muscles.

**Occupational Therapist Interview**

An occupational therapist from Winthrop University Hospital in Mineola, New York was contacted. The purpose of the interview was to confirm a need for a hand orthosis and clarify what are the most important design specifications. She first started by saying that she had never worked with or seen any kind of powered hand orthosis. With this said, the therapist also stated that she believed a powered orthotic device would be effective in her line of work.

She started by talking about the possible uses of the device for rehabilitative purposes. When a patient of paralysis or weakness in the hand goes to therapy, the therapist works on their “Passive Range of Motion.” The way to work of passive range of motion is for the therapist to move the hand into various positions and grips. This type of exercise requires full assistance from the therapist because the patient neurological health is damaged. “Active Assistive Range of Motion” is exercised by half
assistance from the therapist and half movement from the patient. The final category is “Active Range of Motion.” These exercises belong solely to the patient. They are done when the patient is neurologically healed. The occupational therapist said our device could be used in the passive and active assistive exercises. These exercise are critical because if they are not done, than the hand will be practically useless when the active range of motion is regained.

Next, the therapist spoke about using the orthotic as an assistive device. The main point she stated was “No one cares about the movement of the hand if it is not functional.” She stressed concentration on being able to grasp common objects that include door knobs, toothbrushes, cell phones, and other objects the patient would come across during their ADL’s. Finally, the therapist said concentrate on the strength of the hand more than the number of different of functions the hand can perform. This was interpreted as the precision strength of a few functions trump a various number of weak functions.

Patents
Through research, multiple patents on the subject of hand orthotics and robotic gloves were accumulated. Even though most of the gloves found were completely robotic, their design would be altered and their mechanism could be used for a device which fits on a human hand. Images of a robotic linkage hand device can be seen in Figure 7 (US4834443).
Figure 7: Robotic Hand Patents (US4834443, US7296835)

The patent in Figure 8 uses a series of linkages, which may be incorporated into our design. One motor drives a linkage that is located at the metacarpal phalangeal. The rotation about the proximal interphalangeal is driven by a bar linkage with the rotation of the metacarpal phalangeal joint. Similarly, the rotation about the distal interphalangeal is driven by a bar linkage with the rotation of the proximal interphalangeal joint. These linkages lead to multiple moving parts with one driving mechanism. Although the idea of driving the linkages with a motor will be used in our final design, the concept of moving each individual joint in the finger will not be focused on in our orthotic device.

Figure 8: Linkage Hand Patent (US4834443)
The “Linkage Hand” Patent was the first powered hand orthotic viewed. The design consists of a pulley mechanism that drives the index and middle finger. The ring and small finger are free and are not assisted in any way. The thumb is immobilized by being strapped into the device and is not driven by any mechanism. A cable driven by a servo motor causes rotation around the metacarpal phalangeal, causing the fingers to close. In this design there is no rotation around the interphalangeal joint. An image of this patent can be seen in Figure 9 (US3967321).

During our research, this was the first patent to attempt to mobilize the hand orthotic. One problem is that this device allows only one degree of freedom which results in only the cylindrical grip. However, one component that could be useful is the elastic cable holding the hand open. The idea consists of a driving mechanism to close the fingers, and then passive motion to control the opening of the fingers via the elastic cable. This would be optimal in persons affected by hemiparesis who have a hard time opening their hand to grasp larger objects.

![Figure 9: Pulley Driven Orthotic (US3967321)](image)

The “Pulley Driven Orthotic” Patent is similar to the previous “Linkage Hand” Patent, in that it drives multiple fingers simultaneously. All four fingers are strapped into the device and rotate around an axis that goes through each metacarpophalangeal joint. The thumb again is strapped in but not driven.
The driving mechanism in this device is an air cylinder which is controlled using myoelectric sensors, as seen in Figure 10 (US3631542).

A significant characteristic from this patent is the aspect of the whole device being mounted to the body of the user. This makes it possible for the user to complete their ADL’s inside and outside their homes. The air cylinder also provides a simple solution for driving the movement of the fingers. When dealing with hemiparesis, the person usually has a difficult time opening their hand. This power orthotic also acts as a supportive brace by holding the fingers in the normal position. However, this device prohibits individual finger movement and has no driving mechanism to mobilize the thumb.

The final patent reviewed was the “Joint Actuator” Patent (Figure 11) (US5516249). It was the only design that gave the possibility of individually moving each finger, including the thumb. It consists of remote actuators located at each of the joints of the five digits. It is mounted to the hand through a glove that covers the palm and back of the hand.
Some interesting characteristics in this patent are the actuators located at each joint. Compared to other driving mechanisms, such as pistons and pneumatics, this driving mechanism allows the device to be smaller and lighter weight. This also allows for individual finger movement, which can lead to addition grips. One downside to the design is the amount of wires that it incorporates. This could be fixed by housing these wires to make them unseen.

Figure 11: Joint Actuator Patent (US5516249)

MQP, Design of a Human Hand Prosthesis

In 2012, Paul Ventimiglia completed a Major Qualifying Project (E-project-042612-145912, 2012) focusing on the design of a human hand prosthetic device. The prosthetic hand MQP sought to create a prosthesis capable of reproducing a wide array of functions that can be carried out by an unaffected hand. The prosthesis that was developed features 6 degrees of freedom for motion, finger pivot joints, a thumb joint gear box, and a system of motors and controllers that allow for the various motions required to carry out the multiple grasps. This prosthetic hand is able to perform the power grip, open-palm grasp, key grip, and precision pinch. This project had many of the same design goals and needed to produce many of the same varieties of movement as our orthotic device. One difference from this prosthetic device, though, is that our orthosis will be worn as an aid to motion in an existing semi-
functional hand of the user, rather than serve as a total replacement for a hand (Ventimiglia, 2012). An image of the final SolidWorks design of the prosthetic hand can be seen in Figure 12.

![Figure 12: SolidWorks model of the prosthetic hand positioned in a key grip (Ventimiglia, 2012)](image1)

NASA/GM Robo-Glove

In 2007, NASA and General Motors joined forces to design and build “Robonaut 2”, which is a “humanoid robot” currently on the International Space Station. They have since begun a new project of taking the technology in the hands on Robonaut and creating an assistive device for astronauts and GM factory workers. The revolutionary “K-Glove” has the capabilities of lessening the grip force needed to grasp a tool. This can be used in the factory for an employee working on a car or an astronaut working in space. It is said that a tool needing a grip force of 15-20 pounds can be lessened to a grip force of 5-10 pounds while using this device. The prototype of this device can be seen in Figure 13 (NASA, 2012).

![Figure 13: NASA’s and GM’s K-Glove (GM, 2012)](image2)
As a method of closing the fingers, NASA and GM tried to duplicate finger ligaments as close as possible. This provides a natural motion when closing your grip. All of the Robo-Glove components are mounted to the forearm, making transportation and movement fairly easy. The NASA/GM device operates by sensors picking up contact with an object, and closing the fingers to firmly grasp this object. This grasping is done through tightening of strips of material that try to mimic function of a finger’s ligaments.

The almost 100% portable design was examined and considered for the final design of the powered hand orthosis. Unlike this project’s goal, which is to improve the hand’s motion and function, the K-glove just increases the performance of a fully functional hand. When researching a need for our project, most of the target population has trouble moving their fingers. The new device needed to drive the motion of the fingers in the affected hand. The sensor technology can be used in the future to increase grip forces, but only after there is success in creating a method of initially driving the motion of each individual finger.

**Thumb Circumduction**

Thumb circumduction is the circular movement of the thumb. When there is not a significant angle that the thumb can rotate, the function of the hand is severely diminished. The angle that is measured in circumduction is shown as alpha (\(\alpha\)) in Figure 14.
An experiment published in the Journal of Orthopedic Research measured the angle alpha, with zero degrees being the thumb positioned parallel with the four other fingers (as shown in Figure 14). For testing, the wrist and four fingers were strapped down so that they did not interfere with the results (Figure 15).

<table>
<thead>
<tr>
<th>Angle</th>
<th>Standard deviation</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left hand</td>
<td>90.2</td>
<td></td>
</tr>
<tr>
<td>Right hand</td>
<td>90.9</td>
<td></td>
</tr>
<tr>
<td>Dominant hand</td>
<td>90.6</td>
<td></td>
</tr>
<tr>
<td>Non-dominant hand</td>
<td>90.5</td>
<td></td>
</tr>
<tr>
<td>Left-right hand</td>
<td>0.7</td>
<td>$p = 0.71$</td>
</tr>
<tr>
<td>Dominant-contralateral</td>
<td>0.1</td>
<td>$p = 0.97$</td>
</tr>
<tr>
<td>Largest angle male</td>
<td>110</td>
<td>Right dominant hand</td>
</tr>
<tr>
<td>Smallest angle male</td>
<td>74</td>
<td>Right dominant hand</td>
</tr>
<tr>
<td>Largest angle female</td>
<td>103</td>
<td>Left non-dominant hand</td>
</tr>
<tr>
<td>Smallest angle female</td>
<td>70</td>
<td>Left non-dominant hand</td>
</tr>
<tr>
<td>Largest angle</td>
<td>120</td>
<td>Dominant hand</td>
</tr>
<tr>
<td>Smallest angle</td>
<td>56</td>
<td>Non-dominant hand</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.7</td>
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<tr>
<td>Standard deviation</td>
<td>0.97</td>
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<td>Standard deviation</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>97</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>10</td>
<td></td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.5</td>
<td></td>
</tr>
</tbody>
</table>

Participants during this study were told to move their thumb as far as possible in order to achieve maximum circumduction. This meant the alpha values recorded were going to be maximum alpha values for each individual. The participants in this test were all healthy individuals. From the results, the largest angle of alpha for males and females was 110 degrees and 103 degrees, respectively.
In addition, the smallest male angle measured was 74 degrees and the smallest female angle for alpha was measured to be 70 degrees. Men were found to have a slightly higher range of motion than women (about 6 degrees).

Research was conducted to obtain a method for achieving six degrees of freedom in our device. When researching ways to drive the circumduction of the thumb, we came across a bionic hand called the “iLimb” which is seen in Figure 16. In this device, the user manually rotates the thumb using their healthy contralateral hand. Though this method was only viewed through a video, the device seemed to have multiple positions which the thumb could be set at.

Figure 16: iLimb Bionic Hand, Thumb Circumduction Idea (Touch Bionics, 2008)
Goal Statement
The goal of this project was to design and manufacture a fully functional powered hand orthosis, which could be controlled and operated by the contralateral hand, and be used by people with diminished hand functions.

Formulation of Design Specifications
There are two main problems that were addressed in this project. They were to find methods for enhancing the strength as well as function of a person’s hand that has been stricken by partial paralysis. The function criterion was developed by deciding which grips the device should perform. The grips chosen for this project were the cylindrical (power), pinch, and key grips. The cylindrical grip was chosen because it was found that it is the most commonly used grip. This grip allows a person to do many ADL’s, including driving a car, picking up a cup of coffee, or grasping the handle of a brief case. The pinch grip was chosen because of its capabilities of picking up smaller objects like coins or utensils. Finally, the key grip was chosen because not only can the user operate a key, but it was felt that this grip would be capable of holding a pen or pencil for writing. The strength criteria were worked on next. A strong design needed the right combination of motors and kinematic design.

The three grips chosen do not call for individual finger movement. However, the decision to have each finger move individually was made because it gives the device the capability of performing more grips. For rehabilitative purposes, the device can be used by patients in physical therapy. It may be used in the rehabilitative exercises without needing the help of therapists to position or stretch their hand. For using the device as assistive technology, the criterion was to not disable the healthy hand of the user while they were operating the orthosis.
Design Specifications

User Interface

1. The device shall be able to perform the power grip, the pinch grip, and the key grip.
   
   *These three grips were chosen because they are the grips that are most frequently used in Activities of Daily Living. These three grips are used in common activities like holding a cup, picking up a piece of paper, or turning a key in a lock of a door.*

2. The device shall be controlled with the contralateral hand.
   
   The contralateral hand will hit the switch to start the movement of the hand to perform the needed grip. Pressing the switch in the reverse direction will open up the users hand from the grip by contracting the linear actuator’s rod.

3. The device shall be turned on and off through DPDT momentary rocker switches which will be provided with the orthosis.
   
   Having the switches be DPDT momentary switches allows the user to just press the switch until the fingers curl to the desired position and then release the switch to shut off the motor. There will be no added motion needed by the user to then again flip the switch to the off position because this type of switch will perform that automatically.

4. The device shall have 5 or less control inputs.
   
   *Each finger and the thumb will be controlled by one input, allowing no more than a total of five control inputs.*

5. The device on the hand shall weigh no more than 0.5 kg (1.1 lbs.).
   
   *In order for this orthotic device to be completely portable, it shall not weigh more than 0.5 kg to ensure that the user will not be strained or have discomfort when carrying or using the device.*
6. The device on the hand shall not occupy a space larger than 178mm x 127mm (7inch x 5inch) in area and will be no thicker than 76mm (3 inches).

   The distance from the top of the middle finger to the wrist shall be no larger than 178mm (7 inches). The distance from the thumb to the small finger (horizontally across the fingers) shall be no larger than 127mm (5 inches). The thickness of the devices, being the direction of the palm to the back of the hand, shall be no thicker than 76mm (3 inches).

7. The device shall be completely portable.

   The device will be easy to carry around and will not be bulky to ensure that the user is able to carry around the orthosis and have it available to them wherever they need to use it. This includes having the battery pack, which powers the orthosis, located on the user as well.

8. The device shall have manufactured components that can be easily adjusted to accommodate for different hand sizes.

   Ease of manufacturability will be taken into consideration when creating this device in order to make sure that the orthosis can easily be made into different sizes. This will allow for a bigger target market to be able to use the product.

9. The device shall consist of modular, interchangeable parts.

   If any part of the orthosis breaks or is no longer working, easily interchangeable parts allows the user to easily have someone replace the part of their device and have it quickly work again.

10. The device shall cost a maximum of $500 to manufacture.

    In order for there to be a profit on this orthosis, the price to manufacture it must be lower than the cost a potential user would be willing to buy it for. This is why it is important to keep the manufacturing cost low and below the targeted $500.
Power
11. This device shall have a minimum grip force of 225 Newtons for the power grip.

   This value of grip force for the power grip was taken from a study that took average males between 60-64 years old and determined their range of grip strengths.

12. This device shall have a minimum grip force of 40 Newtons for the pinch grip.

   This value of grip force was derived from a study that took average males between 60-64 years old to determine their lowest grip strength needed for the pinch grip.

13. This device shall have a minimum grip force of 60 Newtons for the key grip.

   This value of grip force for the key grip was determined from the results of a study that calculated the lowest grip strength for the key grip from males between 60-64 years old.

14. The device shall have a rechargeable battery so no replacement battery is needed.

   In order to make the orthosis last longer, an easily rechargeable battery is needed so a new battery will not have to be bought by the user every time the battery’s charge wears off.

15. The device shall take no longer than 4.2 seconds to change from open palm grip to closed fist grip.

   This is important so the user will not be waiting for an extended period of time for the grip to be performed by the orthosis.

16. The device shall allow the user to move their fingers in accurate positions for the desired grip.

   This means that the speed of the linear actuator will be slow enough that the user can control the finger position precisely by the switches, while also being fast enough to allow the fingers to execute the necessary grip in a reasonable amount of time.

Kinematics
17. The device shall give the user the ability to individually position each finger.
In this design it was important to have each finger have its own movement so if the user wanted to perform the pinch grip, not all fingers would have to move the exact same distance simultaneously. This allows for a wider range of grips and uses for the orthosis. Having this design specification achieved, sets the device apart from most of the competitors’ products which only allow for all fingers to move in unison.

18. The device shall be able to grip an object with a diameter of 7.62 cm (3 in.).

This was chosen because the power grip is most commonly used to hold a cup or something of that shape and the average size of a cup is around 7.62 cm.

19. The device shall have six degrees of freedom.

The six degrees of freedom will include one degree of freedom for each of the 4 main digits allowing them curl towards and away from the palm and then two degrees of freedom for the thumb. The thumb will have two degrees of freedom since it is a very important finger that helps to hold on and grasp objects. Allowing two degrees of freedom for the thumb will let the thumb move up and down as if someone was spreading their fingers apart and will also have the motion of going towards and away from the palm.

20. The device will be designed to ensure that the user’s fingers will not reach an uncomfortable position when the fingers reach their maximum closed fist position and their maximum open palm position.

This is important so the user does not hurt their hand when using the orthosis. Safety is an important factor that must be taken into consideration when designing this mechanism.

Strength/Durability
21. The device shall last at least one year before maintenance.
Since the user will have invested their money into this orthosis, it is important to have all parts of the device last at least one year before necessary maintenance.

22. The device shall have the capability of working in different environments (rain, snow, etc.).

Since this will be a portable device the user should be able to use it wherever he or she would like to grasp an object. This makes it necessary for the orthosis to be able to last in non-perfect weather conditions where the user may need it. The device must have parts that do not rust easily so rain and snow will not affect it.
**Design Concepts**

Instead of creating full preliminary designs, the decision was made to break the ideas into concepts related to each of components. The plan was to combine the best conceptual components to optimize our final design.

**User Interface**

The first sub-section of the preliminary concepts is called “User Interface”. This sub-section describes what the user will do to activate the movement of the hand orthotic and how this action will be sent to the driving mechanism of the device. This control is accomplished using the contralateral hand. Throughout the design phase of the project, we tried to minimize the restrictions put on this hand while the device is in use. An electrically powered anthropometric design was critical so the user can easily control the device. All concepts consisted of an electrical component, which is able to send a signal to the driving mechanism of the fingers on the orthosis.

**Potentiometer**

Potentiometers were a viable solution for a way to control the orthotic device. One idea was to use a potentiometer which had a spring recall function. The control could have been a glove worn on the user’s healthy hand, which had the potentiometers mounted to the back and its strings connected to every fingertip. As the user curled their finger to the desired grip needed, the string potentiometer would measure the distance the finger displaces and a signal would be sent to the other glove, telling it how far to move the particular finger. Since there would be a potentiometer on every finger, this would allow for each individual digit to have its own individual movement.

Various potentiometers were found that included two that fit the need for the project. The first was a potentiometer from Precision Sales & Equipment Inc. (Figure 17). It had stroke length of 38 millimeters (1.5 inches) and the actual housing was only 19 millimeters (0.74 inches) in length and width.
The second option was a spring return linear potentiometer from A-Tech Instruments Ltd (Figure 18). It can measure the distance anywhere from 0-150 millimeters. The length of this potentiometer can be as small as 63 millimeters and can have a width as small as 18 millimeters depending on the series of specifications chosen (A-Tech Instruments Ltd, 2012).

Joysticks and Switches

Joysticks are an efficient and precise method of controlling motion, as they are highly adaptable and simple to use. They allow for a number of functions to be controlled by one device. Penny and Giles offer a variety of joysticks and switches for various applications (Figure 19). Notably, they offer small, finger operated joystick controllers that can be used in single or dual axis control. These were sufficient for any of the linear motion options that were being explored for the design of the orthosis.
Motor Controller

To be able to send the signal from the user interface to the driving mechanism various motor controllers were investigated. This motor controller could be hooked up to the user interface, like the potentiometer, and have the wires fed through the user’s sleeves and over to the driving mechanism on the disabled hand.

The Finger Tech tinyESC v2 design specifications showed that it could be a good motor controller for this project. It was very small and light weight so it could be easily placed on the user. The circuit board, seen in Figure 20, for this device is only 12.7x12.7x4.1 millimeters (0.5x0.5x0.16”) (FingerTech Robotics, 2012).
Power

The second sub-section of the preliminary concepts is described as “Power”. This power sub-section describes ideas for the driving force or mechanism behind the motion of the finger. This was a critical component because the power connects the user interface and kinematics of the device. The powered mechanism chosen would determine how much strength the user will be able to regain.

Linear Actuator

Linear actuators are an effective method for achieving small amounts of displacement. One of their key features is their compact geometry. Linear actuators can approximately range anywhere from between a half inch to five inches wide. However, decreasing the size of the actuator decreases its power. For this project, even the smallest actuators found contained the strength necessary for our design specifications.

The first linear actuator researched was the Finger Tech “Gold Spark” Gear Motor (Figure 21). The motor was 16mm in diameter, making it possible to mount four of them across the back of the hand (one for each finger). It uses a series of gears to displace the shaft in the desired direction (Finger Tech, 2012).


The next brand of linear actuators was Haydon Kerk. These actuators use a lead screw for displacement in the desired direction. The rotation of the screw moves the rod because of its threads. This design creates precision displacement. This seemed useful for our design, making the device less
bulky. The “21000 series” linear actuators have a thickness of approximately 20 mm. The family of Haydon Kerk actuators can be seen in Figure 22 (Haydon Kerk, 2012).

The last type of linear actuators researched was from Firgelli. Their “Micro Linear Actuator” line of motors was of high interest for our device (Figure 23). The rectangular bases would make for easy mounting to our device. At the end of each actuator, there is a cylindrical hole, which appeared to be a solution for connecting the driving mechanism to the finger. The actuators are only 15 mm thick, making it possible to line them up on the back of the hand, while optimizing space because of the rectangular cross section.

**Rotary Motors**

The next method of power investigated was rotary motors. The difficulty behind incorporating these types of motors into our design is fitting them on the back of the hand. If a prosthetic hand were
being designed, then these would be the primary idea for power because they could be aligned with the joints of the prosthetic fingers. However, with the hand in the way, the motors would have to be mounted to the back of the hand and then another gear mechanism would be needed to correlate the rotation of the motor to the rotation of the finger joints.

Motors from Haydon Kerk were revisited, concentrating on the rotary motors this time. Two different types of Haydon Kerk rotary motors can be seen in Figure 24.

![Haydon Kerk Rotary Motors](http://www.haydonkerk.com/Home/tabid/324/Default.aspx)

Since the motor’s shape is round, it would be difficult to mount these motor to the back of the hand. Ideas were brainstormed for incorporating the geometry of them to fit the device. One idea was to use the rotation of a cam shaft that lay across the knuckles of the hand. There would be one rotary motor on the side of the hand (next to the small finger). The cams would then push the top of the finger when it rotates (similar to how the linear actuators would work). The cams could be offset so that the small finger moves first, ring second, middle third, and index last. This would have provided the hand with a realistic motion. This was a strong idea because it only utilized one motor for the motion of the four fingers on the hand. However, another motor would be needed to drive the motion of the thumb. A 3D model of the cam shaft idea can be seen in Figure 25.
The last method of power that was researched was servo motors. There are servo motors available on the market that are inexpensive and easy to use. One example was a servo motor from Hobby Partz, (Figure 26). These motors are priced at approximately four dollars per device. These motors could have been mounted on the inside of the forearm and connected with cables connected to the servo. The other end of the cables would be attached to the tips of the fingers. When activated, the servo motors would reel in the cable, pulling the tips of the fingers and closing the hand. Passive motion would have to be incorporated to open the hand back up. This could be done through a pre-loaded spring in the finger design or the use of elastic material.
Kinematics

The third sub-section of the preliminary concepts is defined as “Kinematics”. This kinematic sub-section describes ideas for the motion of the fingers. This is a critical component because the kinematic motion is how the device will move the fingers to the desired positions. A more effective kinematic design will lead to using the power of each of the motors more efficiently.

Flexure Design

The first design concept was inspired by the modern auditorium chairs (Figure 27). The thought was that the finger would be like the seat that folds up and down. One difference is sheet metal would be used, creating a flexure design.

Figure 27: Ziba Auditorium Chairs (Ziba 2012)

When a force is applied to the top of the finger, the grooved cut outs would compress, forming the finger into its naturally round shape. This made for a relatively simple solution for creating the curl of a closed finger. Some variables for this concept were the number of grooves per finger and the method for applying the force to the tip of the finger. The more grooves, the more round the curl
becomes. However, increasing the number of grooves also increases the manufacturing cost and chance of fracture in the sheet metal.

The sheet metal could first be cut out into a full hand. Anywhere in-between 6 and 10 grooves will be cut into each finger to replicate its curl when closed. The resulting sheet metal would then be mounted to the back of the user’s hand. When the force is applied, the grooves will compress the finger to close. Ideas were brainstormed to put straight cuts into the back of the sheet metal finger, instead of the grooves on the front. In this case, when the force is applied, the slits will separate and the sheet metal will rotate around each crack. This ensures the user’s fingers will not get pinched in the process of using the device. A rough 3D Model of the sheet metal hand with the grooved cut outs can be seen in Figure 28.

Figure 28: Proposed Grooved Hand (SolidWorks)
**Four Bar Linkage Fingers**

The second design concept involved linear actuators and a four bar linkage system. The linear actuator is the driving force behind the motion of the fingers. An exoskeleton piece of plastic would surround the outside of the finger, one above and one below the interphalangeal joint. The actuator pushes the face of the proximal exoskeleton, causing the finger to rotate around the metacarpophalangeal joint. The rotation around the interphalangeal joint is driven by a four bar linkage design which pulls the bottom of the distal exoskeleton component as the finger rotates around the metacarpophalangeal. This combination of this rotation replicates the curl of the fingers. A rough 3D model of a single finger system can be seen in Figure 29.

![Figure 29: Motor Linkage Design (SolidWorks)](image)

Some design variables for this concept included the type of motor used. The stronger the motor, the higher grip force the device is capable of. However, in our research, as the strength of the motor increases, the size of the motor also increases as well as the weight. The placement and lengths of the four bar linkage would also be a critical factor in the design. This specification is important because it determines the relationship between the rotation around the metacarpophalangeal and interphalangeal...
joints. If the relationship is miscalculated, then the hand could either have a hard time grasping large objects or not be able to grasp smaller objects.

**Hand Mount**

The device needed a method of being attached to the hand. For solving this problem, a mounting structure was designed to go on the back of the hand (Figure 30). The finger mechanism was planned to be connected to this mount near the metacarpophalangeal joint. This mount would be connected to the hand through a strap of some sort wrapped around the palm.

![Figure 30: Hand Mount (SolidWorks)](image-url)
Design Selection

The final design selection for the orthosis was done by carefully deciding what the most effective, feasible, and compatible solutions were for the areas of the device’s user interface, power, and kinematics. We first found which design specifications were most important for the final design (Table 1). Using these critical specifications, the concepts were compared by using a decision matrix that ranked how each preliminary idea would perform for each category (Table 2).

<table>
<thead>
<tr>
<th>Number of Grips</th>
<th>Grip Force</th>
<th>Cost</th>
<th>Weight</th>
<th>Manufacturability</th>
<th>Bulkiness</th>
<th>Ease of Use</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Grips</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
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<td>1</td>
<td>0.5</td>
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<td>1</td>
</tr>
<tr>
<td>Bulkiness</td>
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<td>1.5</td>
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<tr>
<td>Ease of Use</td>
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<td>0.5</td>
<td>0.5</td>
<td>1</td>
<td></td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 1: Para-wise Comparison Decision Matrix

After ranking all the design specifications against each other, we found the top four specifications to be manufacturability, grip force, cost, and ease of use. Next, using these four specifications in an absolute ranking decision matrix, we found the best components from each section were the switch, linear actuator, and the linkage design. This matrix was beneficial because, as seen in Table 2, some concepts scored excellent in one category, but lower in the other three categories.

<table>
<thead>
<tr>
<th>User Interface</th>
<th>Grip Force</th>
<th>Manufacturability</th>
<th>Cost</th>
<th>Ease of Use</th>
</tr>
</thead>
<tbody>
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<td>Adequate</td>
<td>Poor</td>
<td>Excellent</td>
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<tr>
<td>Joystick</td>
<td>N/a</td>
<td>Excellent</td>
<td>Adequate</td>
<td>Poor</td>
</tr>
<tr>
<td>Switch</td>
<td>N/a</td>
<td>Excellent</td>
<td>Adequate</td>
<td>Adequate</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power</th>
<th>Grip Force</th>
<th>Manufacturability</th>
<th>Cost</th>
<th>Ease of Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Actuator</td>
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<td>Poor</td>
<td>N/a</td>
</tr>
<tr>
<td>Rotary Actuator</td>
<td>Adequate</td>
<td>Poor</td>
<td>Poor</td>
<td>N/a</td>
</tr>
<tr>
<td>Servo Motors</td>
<td>Poor</td>
<td>Excellent</td>
<td>Excellent</td>
<td>N/a</td>
</tr>
</tbody>
</table>

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## Final Design

Using the results from the decision matrices, the final components were chosen and designed for the hand orthosis. For the user interface, switches were chosen as the method to control and operate the linear actuators. There is one linear actuator per finger and each actuator is be operated by a separate switch. The linear actuator is located on a hand mount which is essentially the backbone of the device. The device is powered by a rechargeable battery pack that drives all of the linear actuators. The battery pack could be worn on the user’s belt and wired to the switches. The switches would be located on a docking station positioned somewhere on the lower forearm.

The kinematic system correlates the linear power from the actuators to the natural rotary motion of a curling finger. It consists of a linkage located between each finger component (explained in detail later). The linear actuator is the driving force that produces the curling movement of each finger through a slider pin joint (also explained later). As the stroke of the linear actuator increases, the fingers curl towards the palm causing the hand to close. As the linear actuator retracts, the hand opens back up. A mechanism for providing two degrees of freedom to the thumb was fully designed. The degree of freedom curling the thumb in towards the palm is still run by a linear actuator as well, the same way the other four fingers are driven.

### Control Selection

As mentioned, several available options were considered to control the device, but the most efficient and time effective solution became operating the orthosis by the use of simple switches. These switches allow the linear actuators to extend and retract along a straight plane. The switch chosen comes specifically with the type of linear actuator we are using. It is a Double Pole Double Throw

<table>
<thead>
<tr>
<th>Kinematics</th>
<th>Flexure Design</th>
<th>Adequate</th>
<th>Excellent</th>
<th>Excellent</th>
<th>N/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linkage Design</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Adequate</td>
<td>N/a</td>
<td></td>
</tr>
<tr>
<td>Slider Design</td>
<td>Adequate</td>
<td>Adequate</td>
<td>Excellent</td>
<td>N/a</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Absolute Ranking Decision Matrix
(DPDT) momentary switch. “Pole” stands for the number of switch contacts while “Throw” stands for the number of conducting positions. So this switch will have six contact pins. Momentary means it will be an on-off-on switch. This allows the switch to go back to the off position when the switch button is released. When the switch is activated the rod of the linear actuator will either move outward or retract back to the actuator’s case. A fuse also comes with every switch. This fuse will prevent the circuit from overloading and short circuiting. A picture of the switch that will be used in our final design is shown in Figure 31. The linear actuator also helps with the control because if the actuator rod becomes within 0.5mm of its full extension or retraction, the limit switch of the actuator will stop the power to the motor. This will prevent the actuator from being ruined while also preventing the user’s fingers from being overly extended in either direction.

![Firgelli Switch](http://www.firgelli.com/products.php)

**Figure 31: Firgelli Switch**

**Battery Selection**

A 6 volt rechargeable battery pack was chosen as the power for the orthosis. Other options were thought about, but this choice was the only one to satisfy all requirements needed. Another option that was looked at was using a 9 volt rechargeable battery to power the system. This would involve using a voltage divider circuit with either an op amp or a voltage regulator in order to drop down the voltage to the 6 volts needed to run the actuators. The 9 volt rechargeable battery, that met the most requirements needed, had a rating of 750mAh. Originally, this was thought to provide enough
current for all five actuators since each one only needs a current of 100mA to run. Unfortunately, their stall current is rated at 450mA, so if more than one actuator was started at the same time, the total stall current would be greater than what could be supplied by the 9 volt battery. A stall current occurs when the linear actuator is given full power from its rest position. This means that initially the actuator would take that 450mA to get started. Using a 9 volt battery for our device would eventually damage the linear actuator since not enough current is being supplied to power the motor.

The battery pack chosen for the final design was a 6 volt Tenergy NiMH rechargeable battery that has a rating of 3300mAh. This battery can supply the needed current for all five actuators and is relatively light weight, weighing only 10oz. The final Tenergy battery selected can be seen in Figure 32. This battery will be placed along the belt loop of the user’s body, on the same side that the orthosis is located.

![Tenergy 6 Volt Rechargeable Battery Pack](http://www.all-battery.com/6v3300mahnimhumpbatteryreceiverpackswithamiyajrconnector11109.aspx)

**Figure 32: Tenergy 6 Volt Rechargeable Battery Pack (Source at: http://www.all-battery.com/6v3300mahnimhumpbatteryreceiverpackswithamiyajrconnector11109.aspx)**

**Linear Actuator Selection and Design**

To correlate the linear motion of the motor and the rotary motion of the finger, a mechanism needed to be design. For this iteration, a slot mechanism was chosen. As the linear actuator is displaced, the finger would rotate towards the palm and the pin would slide up the slot. The opposite would happen when opening the hand. The motor and slot combination can be seen in Figure 33. The device was initially designed with an actuator with a stroke length of 30 millimeter. However, a 50 millimeter stroke actuator was chosen instead to achieve a greater finger closure. This was decided so
the device could grip objects with smaller diameters. The decision did not increase the cost of the device as the two actuators are the same price.

**Figure 33: Firgelli “Micro Linear Actuator” with Pin & Slot Connection**

**Kinematic Design**

After using the various decision matrices and weighing various design specifications, a final design iteration for the kinematics of the device was chosen. This iteration mainly concentrates on the kinematic sections of the project; however, it also correlates the power section (Figure 33) to the kinematics. These were the two components that needed to be designed, and not just bought. For the final design, the finger kinematics would be driven by a six-bar linkage design and would be powered by Firgelli micro-linear actuator motors. A 3-D cad model of a proposed design, with all its components labeled, can be seen in Figure 34. The yellow components are the casing over the fingers, the green and red components are the Firgelli motors, and the grey components are the hand and thumb mount. The Black component is a spring loaded pull pin that will be described in detail later.
The lengths of the fingers were calculated using the lengths of our group member’s finger. Calipers were used to get lengths to the nearest half millimeter. This procedure was also performed to get the thickness of each finger. The shape of the hand orthosis can be seen in Figure 35. All human finger sizes are different, but for the purposes of the project, arbitrary lengths were used to prove the device works. A future design goal is to create a design for the fingers that allows them to be adjustable in size so they can universally fit all human hands.
The movement of the fingers occurs as the linear actuator’s rod displaces out, or extends, a certain length. Through the linkage system, this causes the fingers to rotate around the metacarpophalangeal joint. When the motors are at their max displacement, the fingers have curled in all the way towards the palm, thereby placing the hand in a fist position (Figure 36). As previously stated, the actuators have a maximum displacement of 50 millimeters.

With each finger having its own linear actuator, the device is capable of moving each digit individually. This will be beneficial for gripping oddly shaped objects that could be encountered when using this as an assistive device. For rehabilitative purposes, this individual movement will help patients regain finger dexterity as well as comprehension of which finger they are moving. An example of the fingers in different positions can be seen in Figure 37.
As seen in Figure 38, the outer finger components, in yellow, have a slight bend in them. The idea behind this was created to account for the distal interphalangeal joint. Adding another rotating joint to the orthotic did not seem feasible, so the finger component was designed with the bend, which allows the grips to have a more cylindrical shape. This bend will obviously not change while the device goes to different positions, but the angle of the bend is set at an arbitrary intermediate position (approximately halfway between straight and the maximum angle the human distal phalangeal joint can rotate).

![Figure 38: Side View, Slight Bend in the Distal Finger Component](image)

**Linkage Design**

To solve the problem of needing rotation around two joints with only one motor source, a linkage was designed to rotate each of the fingers. The link was designed to connect the distal part of the finger to the hand mount. The linear actuator is connected to the finger through a slider pin joint. When the actuator displaces out, it pushes the vertical slot and rotates the proximal finger (closer to the palm). As the finger is rotating, the link pulls the distal part of the finger component in towards the palm, recreating the curl of human fingers. A linkage design was created in SolidWorks to make sure the design works and to calculate some initial lengths (Figure 39).
Figure 39: SolidWorks Linkage Assembly in Rest Position (left) and Maximum Displacement Position (right)

A linkage analysis was calculated to make sure the design could theoretically work, seen in Error! Reference source not found. Figure 40. Some confusion came up with the slider pin joint. Originally it was thought that this joint should be designated as a half joint. However, because the slider cannot move without the pin rotating, the decision was made to separate them in the calculation, and designate them as two full joints.

<table>
<thead>
<tr>
<th>Kutzbach Form Of Gruebler's Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>L := 6                               Number of Links</td>
</tr>
<tr>
<td>F1 := 7                              Full Joints</td>
</tr>
<tr>
<td>F2 := 0                              Half Joints</td>
</tr>
<tr>
<td>DOF := 3\times(L - 1) - 2\times F1 - F2 = 1 Number of DOF's</td>
</tr>
</tbody>
</table>

Figure 40: Kutzbach Equation

After the calculations were done and verified using the SolidWorks Assembly, the linkage was then designed as a CAD model in Creo. Some alterations were made because of pin holes being too close to edges and other reasons. The “six-bar finger mechanism” designed into the device can be seen in Figure 41.
The six-bar mechanism resulted in the nearly replicating the natural curling motion of the human hand. As the actuator displaced, the proximal finger rotated closer to the palm of the user’s hand (Figure 42).
Thumb Mechanism

We decided to use a manual method to obtain the thumb’s circumduction to achieve the sixth degree of freedom. The method is similar to the “iLimb” (mentioned in the background chapter). We have chosen to have a thumb rotation of 60 degrees across this cone-shaped plane that alpha was measured (Figure 14). This angle was chosen because not only does 60 degrees fit onto our orthosis, but it still allows the hand to be perfectly functional and not restrict the user in what they can grasp. Also, the orthotic device could not have a rotation that was too large for the disabled user because it could be unsafe. The team concluded that in the design, there should be three possible positions. From the sixty degree rotation angle previously talked about in the “Thumb Circumduction” section, the positions of the holes would be 30 degrees apart. The design for the thumb mount can be seen in Figure 43.

Figure 43: Thumb Mount

The hole highlighted in green, in Figure 43, will line up with the corresponding slit in the hand mount to stay in the desire position (explained more clearly later). To keep those two holes lined up, we purchased a spring loaded pull pin (black component in Figure 44). The user would simply pull the pins knob out and rotate the thumb mechanism into the desired position.
The location of the three adjustment holes with proximity to the rest of the hand mount can be seen in Figure 45. Also in Figure 45, the axis of rotation for the thumb mount can be seen circled in red.

The three possible hole positions for the plunger of the pull pin’s plunger can be seen in Figure 46. These holes are located on the back of the hand mount (Figure 45) and are each 30 degrees separated from the adjacent hole.
The thumb mount will be pinned to the hand mount at the axis of rotation circled in Figure 45. The user will pull the knob towards their body and rotate the thumb mount in the positive, counter clockwise direction to one of the two other angular positions. These different thumb positions will make the three grips (power, pinch, and key) stated in our design specifications possible.

The three angular positions that the thumb mount is capable of can be seen in Figure 47. The left most picture is what we are calling 0 degrees, the middle is 30 degrees, and the right most picture is the maximum limit of 60 degrees. One of the original design specifications was for the device to be able to grasp a cylindrical item that has a diameter of three inches. After performing some analysis in the Creo model, the maximum diameter possible was found to be a little over 3.5 inches. It was a “give and take” situation since the bigger the diameter designed for, the less the thumb would be a contributing factor when grabbing smaller objects. A decision 3.5 inches was made because at this diameter, smaller items could be grasped and other important grips could be performed, and also met our important design specification.
Force Analysis

There were a few reservations about this design at the time of conception. When a force is acting on the finger, the full force of each motor will be put on the slot mechanism. A big question was if the ABS plastic (which was the main contender for material for the manufactured components) was strong enough for the forces in its current dimensions. Similarly, a large stress is put on the linkage that rotates the upper finger. Due to this assumption, a decision was made to manufacture the link out of carbon steel. However, the goal was to minimize its thickness because of the lack of room between the fingers. Some force analyses were then performed to assure the actuator can handle the grip forces magnitude required in our design specifications.

FEA Analysis

An initial static FEA analysis in the CAD program was completed on one of the device’s fingers. The finger was positioned at maximum actuator displacement and all the components were connected at their pin locations using rigid mates. A fixed geometry may was put on the slot of the proximal finger component. The mate represented the force from the actuator, assuming that it did not back drive. A force of 50N was applied to the middle of the distal finger component, representing a grip force. The magnitudes from the results were not analyzed, but rather the locations of these high stresses were viewed. The reason for not looking at the magnitudes was because of the fingers complex motion. Rigid connections had to be made, which made the magnitudes unrealistic. However, through this analysis,
the areas of high stress were found to be at the distal joint and at the connection between the link and distal component, seen in red/green in Figure 48. Using this information, the hole was moved further from the edge so the force of the link does not tear the pin through the abs plastic material.

*Figure 48: High Stress Location at the Interphalangeal Joint from FEA*
Static Analysis with Free Body Diagrams

Static analysis was performed for the orthosis in order to find the forces acting on each component of the device. In order to execute this analysis, three different x-y coordinate systems were used on different Free Body Diagrams (FBD) so that there were enough equations to solve for all the unknown forces. In this report, the three possible coordinate systems that the FBDs could be drawn in are: x-y, x'-y', or x''-y''. With each FBD, there is an axis alongside of it that clearly illustrates which coordinate system was used for reference in that picture. For all coordinate systems, the x and y directions of the axis are pointing in the positive direction for a normal right-handed system.

Due to these three different coordinate systems, angles needed to be measured to get all the forces in their respective X & Y directions. **All the angles are measured in the positive (counter clockwise) direction from the closest axis.** For example if a force is 315 degrees from the positive x-axis, then Creo’s angle result was 45 degrees from the negative y-axis. Another example is if a force is 225 degrees from the positive x-axis, then creo’s angle result was 45 degrees from the negative x-axis. These examples can be visualized below in Figure 49.
The angles used in all the equations are described in Figure 50. $\Theta_1, \Theta_2,$ and $\Theta_3$ were all taken from measurements found from the program Creo. $\Theta_4$ was found through a simple derivation using the relationship between $\Theta_2$ and $\Theta_3$. $\Theta_1$ can be seen in Figure 58, $\Theta_2$ can be seen in Figure 51, and $\Theta_3$ and $\Theta_4$ can be seen in Figure 54.

$\Theta_1 = \text{Angle between normal force of pin on slot and motion axis of the actuator}$

$\Theta_2 = \text{Angle between distal finger component and "Link"}$

$\Theta_3 = \text{Angle between proximal and distal finger components}$

$\Theta_4 = \text{Angle between proximal finger component and "Link"}$

The first free body diagram drawn was that of the “distal” finger component. This is the component that is placed over the finger from the interphalangeal joint to the end of the finger. The forces drawn on this component are the grip force ($F_G$), the metal link ($F_I$), which is a two-force member, and the forces at pin B which split into $F_{BX}$ and $F_{BY}$. In this FBD, $\Theta_3$ was measured in the positive direction.
from the negative y-axis (Figure 51). Pin B is the location of where the two finger components are connected.

On this distal finger component (Figure 51), a x”-y” coordinate system was used. The axis cuts across pin B. The positive part of this x”-y” axis was facing right and up, respectively. It is a floating coordinate system that rotates with the distal finger component. So, for example, as this component rotates in towards the palm for a gripping position, the axis follows this counter clockwise motion of the distal component as well. However, since pin B is the connection between the two finger components, the forces $F_{Bx}$ and $F_{By}$ do not rotate with this coordinate system (since those forces lie on coordinate system $X'$-$Y'$). This results in four force components from pin B acting on this FBD (X&Y forces from both $F_{Bx}$ and $F_{By}$). A cropped picture of this distal component at an angle can be seen in Figure 52. The picture clearly shows the four force components from pin B (in the dotted lines) as well as the coordinate system that has rotated with the angle of the distal component.
After drawing this FBD, the three equilibrium equations were derived. These equations were the sum of forces in the x”-direction, the sum of forces in the y”-direction, and the moment around pin B (Figure 53). Delta (Δ) corresponds to the displacement of the actuator rod. A Delta (Δ) of zero would correspond to zero displacement, meaning the actuator has not extended from its original position.

<table>
<thead>
<tr>
<th>Distal Finger Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΣFₓ = −Fₓ₁(Δ) · cos(Θ₂(Δ)) − Fₓ₂(Δ) · sin(Θ₃(Δ)) + Fₓ₃(Δ) · sin(Θ₂(Δ)) = 0</td>
</tr>
<tr>
<td>ΣFᵧ = Fₓ₁(Δ) · sin(Θ₂(Δ)) − Fₓ₂(Δ) · cos(Θ₃(Δ)) − Fₓ₃(Δ) · cos(Θ₂(Δ)) + Fᵧ = 0</td>
</tr>
<tr>
<td>ΣM_B = −Fₓ₁ · c + Fₓ₂(Δ) · cos(Θ₂(Δ)) · b + Fₓ₃(Δ) · sin(Θ₂(Δ)) · a = 0</td>
</tr>
</tbody>
</table>

One concern with these calculations was if the “sign” of the force would change when it is appropriate. Using the FBD in Figure 51 and the equations in Figure 53, this concern was answered. For the sum of forces in the x-direction, Fₓ is positive for Θ₂ > 0 degrees. When Θ₂ equals zero degrees [sin(0)=0], Fₓ exerts no force in the x-direction. When Θ₂<0, the “sign” of the “sine” of theta turns negative, meaning Fₓ exerts a force in the negative x-direction, as it should. There are a couple other scenarios like this one which we have been looked at and validated.
There was one known variable in these equations, which was the grip force, \( F_G \) (Figure 54), and for our calculations we had \( F_G = 50 \) Newtons. Since the moment equation only involved two variables \( (F_G \) and \( F_L ) \), that equation could be rearranged and solved for \( F_L \).

The next step was to combine the two finger components and draw a new corresponding FBD (Figure 54). The two finger components involved were the distal and proximal finger components. The proximal part is the piece that is placed on top of the finger from the interphalangeal to metacarpophalangeal joint (the component with the slot mechanism). Note that components \( F_{Ax} \) and \( F_{Ay} \) are drawn in the direction of the positive axis.

![Figure 54: FBD Combined Finger Components](image)

This FBD of the combined finger components used the \( x'-y' \) coordinate system. The \( x' \)-axis is through pins A and B and the \( y' \)-axis is along the vertical line of the slot. This can also be seen by the \( x'-y' \) coordinate system drawn onto Figure 54. This FBD produced the equation for the sum of the forces in the \( x' \)-direction, as well as the sum of the forces in the \( y' \)-direction (Figure 55).
In order to have enough equations to solve for the additional unknowns, another FBD of a finger component had to be drawn. This resulted in the creation of a FBD for just the proximal finger component (Figure 56). For this drawing, the x'-y' coordinate system was used. This is the same one which we used for the combined finger component’s FBD. In this FBD, the $F_B$ components were drawn in the positive axis direction in order to take into account Newton’s Third Law.

The proximal component equations were found for the sum in the x'-direction, the sum in the y'-direction, and the moment around pin A (Figure 57). Pin A is where the proximal component is connected to the hand mount. $F_P$, which is shown on both of the last two FBDs, is the normal force of the actuator pin acting on the slot of the proximal finger component. Because of the low coefficient of friction between ABS plastic and stainless steel, and the ability of the pin in the slot to roll, we neglected
the frictional force in the \( y' \)-direction between the pin and the slot. We now had the right amount of equations to solve for all the unknown variables.

<table>
<thead>
<tr>
<th>Proximal Finger Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sum F_x = F_{bx}(\Delta) + F_{ax}(\Delta) - F_p(\Delta) = 0 )</td>
</tr>
<tr>
<td>( \sum F_y = F_{by}(\Delta) + F_{ay}(\Delta) = 0 )</td>
</tr>
<tr>
<td>( \sum M_A = F_p(\Delta) \cdot y(\Delta) - F_{by}(\Delta) \cdot z = 0 )</td>
</tr>
</tbody>
</table>

Figure 57- Finger Component 2 Equations

For the forces involved with the actuator, we drew a FBD and created equations that would help to solve for the forces of the \( F_{actx} \) and \( F_{acty} \). The axis used for the FBD was the \( x-y \) coordinate system which is the coordinate system of ground. The equations formulated were for the sum of the forces in the \( x \) and \( y \) directions as well as the moment around the actuator (\( M_{act} \)). A positive moment is in the counterclockwise direction. The FBD can be seen Figure 58 and the equations can be seen in Figure 59. \( F_p \) now has an \( x \) and \( y \) component when solving the equations because the \( x \)-axis for this FBD runs parallel with the length of the actuator rod. This means that \( F_p \) is no longer just along the \( x \)-axis of the FBD as it was in the two previous sets of diagrams.

Figure 58- Actuator Forces
After all equations were written and solved for, a final FBD of the entire system was drawn to show all the external forces (Figure 60). In addition, plots were created for all of the forces versus the actuator’s rod displacement. This created visuals to analyze and compare the forces at all positions of the actuator rod. When creating the graphs and solving the equations, \( F_G \) was still inputted as 50 Newtons and the actuator position was plotted in millimeters. The Appendix F contains the MathCad files with all these calculations and graphs.
Manufacturing

1\textsuperscript{st} and 2\textsuperscript{nd} Prototypes

The first actions that were taken towards the development of a final prototype were the manufacturing of two early prototypes. In order to demonstrate the motion of our six-bar linkage design, a single index finger mechanism was developed and manufactured (Figure 61). The initial prototype consisted of a rapid prototyped proximal and distal finger component, one two force member steel link, and several nail fasteners for the connections between the components.

![Figure 61: First Generation Prototype](image)

This first prototype was too small to be effective in moving an index finger, so a second one that was very similar was then created (Figure 62). It consisted of a steel mount that was cut and drilled accordingly, rapid prototyped proximal and distal finger components, and two steel two-force member links that were made by the same processes as the previously mentioned one. This prototype adequately demonstrated the desired open and close motion of the fingers. It was the first time the correlation between the linear motion of the actuator and the rotational motion of the joints was displayed. However, when the actuator was at its rest (zero displacement), the distal finger component was subject to a noticeable toggle. The need for the change in position of the link pin points was established and then incorporated into the design of the next prototype.
With the corrections from the previous prototype incorporated, a third prototype was designed and manufactured (Figure 64). This prototype included rapid prototyped thumb components, proximal and distal index finger components, and also a rapid prototyped hand mount. This prototype also included steel two-force member links manufactured by the same machining processes as previously mentioned, and steel shafts that serve as the pin between the actuators and the slots in the proximal finger components. These parts were assembled and the linear actuators for the index finger and thumb were mounted. The prototype demonstrated that a user could wear it, and that the device could assist in the motion of the index finger and thumb. This was the first prototype to incorporate the pull-pin design for thumb circumduction (Figure 63). The hand mount was a bit too large for the purpose of any member of our group testing it on their own hand, so dimensions were changed and it was redesigned to be somewhat smaller and conform to the hand more appropriately.
The geometry of the thumb mount was miscalculated and proved to be too big for any normal human hand. Advancing into the construction of the final prototype, the main area of concentration was to make this component more ergonomic for a human thumb.

Figure 64: Third Generation Prototype

**Final Prototype**

The final prototype is essentially a completed version of the third prototype (Figure 65). It included the revamped hand mount and rotating thumb components, the thumb finger component, and proximal and distal index finger components for all four fingers with their respective two-force member links and actuator contact shafts. When fully assembled, this prototype was able to fit on the hand of a user, and provide all of the motion that the device was designed for, including the opening and closing of each individual finger and thumb, and the circumduction of the thumb.

Figure 65: Final Prototype
Wiring

This powered hand orthosis was electrically powered by actuators so there are many components that had to be connected together and wired within a circuit. All five actuators were connected to the DPDT switch through its terminals. From the switches, the positive and negative wires were soldered onto an IC socket which was on a small, compact soldering board. The battery wires were then also wired onto this IC socket in order to power the switches. From there, the last part was to solder in a schottky diode that provided a 0.7 voltage drop going into the actuators (Figure 66). This diode would protect the battery from any damages due to increased current flow.

![Figure 66: Electrical Wiring Configuration: A.) Wires Soldered to Breadboard w/ Diode B.) DPDT Switches and Battery](image)

Planned Testing Procedures

With the detailed design, manufacturing, and assembly of the hand orthotic finished, the last item on the project agenda was to perform tests. A list of tests had been devised in order to confirm that the orthosis satisfies the goal of this project and meets the needs of the target population. Due to some difficulties with the connections of the device and lack of measurement resources, not all the following test were performed. However, the test procedures were documented for future groups to complete.
Developing a List of Tests

Developing a set of test protocols for the orthosis was fairly straightforward. Many of the original specifications are qualitative and have been proven to be sound through presentation of the design itself. One of the specifications that the device needed to be tested for are the forces that the orthosis will be able to exert in power, pinch, and key grips. Another critical specification that was calculated is the amount of time that the fingers take to go from being fully open and to fully close by the driving force of the actuator. Finally, we would test the orthosis to see how it handles different diameter objects when performing the power grip position. In the following pages, six critical specifications from the “Design Specifications” section are presented and are followed by the test protocol that would be used to determine if that specification was met. Appendix E contains a worksheet with three tables to assist with the documentation of the results.

1. **The device shall be able to perform the power grip, the pinch grip, and the key grip.**

   *These three grips were chosen because they are the grips that are most frequently used in Activities of Daily Living. These three grips are used in common activities like holding a cup, picking up a piece of paper, or turning a key in a lock of a door.*

   Since this is qualitative, we used the orthosis to perform certain activities of daily living. For the cylindrical (power) grip, we wanted to have the orthosis pick up and hold a cup with liquid in it. Another activity for this grip was to hold a hammer and/or screwdriver. To test the pinch grip, the plan was to have the user pinch and pick up a piece of paper, washer, or any other thin, light weight (less than 1 pound) item. For the key grip, the main test was to have the orthosis pinch, pick up, and turn a key in a door lock.

2. **This device shall have a minimum grip force of 225 Newtons for the power grip.**
This value of grip force for the power grip was taken from a study that took average males between 60-64 years old and determined their range of grip strengths.

Being one of the most important grips used in activities of daily living, the orthotic device must be able to aid the hand in performing the power grip. Using a grip force dynamometer to measure the grip strength, the orthosis was tested for the cylindrical or power grip. This measurement, if done completely, would confirm or prove false that the orthosis can produce a 225 Newton cylindrical grip force.

3. **This device shall have a minimum grip force of 40 Newtons for the pinch grip.**

   This value of grip force was derived from a study that took average males between 60-64 years old to determine their lowest grip strength needed for the pinch grip.

   Similar to the measurement of the force exerted in the power grip, the pinch grip was to be performed onto the measurement device so the hand dynamometer can give us a force reading that will either confirm or deny that the orthosis can aid a finger and thumb in applying a 40 Newton pinching force.

4. **This device shall have a minimum grip force of 60 Newtons for the key grip.**

   This value of grip force for the key grip was determined from the results of a study that calculated the lowest grip strength for the key grip from males between 60-64 years old.

   As in the measurements of power and pinch grip force, the thumb and index finger would apply a force to the force dynamometer, but this time in the form of a key grip. The measurement of the maximum force that can be applied, using the orthosis as the primary drive, will confirm whether or not the device is capable of applying 60 Newtons in a key grip.

5. **The device shall take no longer than 4.2 seconds to change from open palm grip to closed fist grip.**
This is important so the user will not be waiting for an extended period of time for the grip to be performed by the orthosis.

The swiftness that the orthosis can move is also an important factor in creating this type of device. The fingers were operated all at once and were tested with a stop watch to measure how long the finger components take to open and to close using just the motion provided by the actuators. The device was planned to be tested to see how long it takes the user to close all the fingers as well as manually rotate the thumb’s circumduction.

6. The device shall be able to grip an object with a diameter of 7.62 cm (3 in.).

This was chosen because the power grip is most commonly used to hold a cup or something of that shape and the average size of a cup is around 7.62 cm.

The original specification stated that the orthosis needed to be able to grip an object that was 3 inches in diameter. The orthosis was designed to be capable of grasping an object that has a diameter of 3.5 inches or below. Further tests were planned to see if the prototype could grasp these sized objects, which included dunkin’ donut cups and soda bottles.

Results of Modified Tests

Due to the time constraints of this project, the testing procedure previously mentioned was not followed when evaluating the final prototype. A variety of tests were completed that include measuring maximum force of a single orthosis finger, performing the specified grips, grasping objects encountered during ADL’s, and checking the device for general ease of use. To document the results of these tests, each design specification will be revisited. A description of what test was performed and the results from that test, both quantitative and qualitative, will be discussed. If no test was performed for a given specification, then a reason for the omission will be given.
Evaluation of Design Specifications

1. The device shall be able to perform the power grip, the pinch grip, and the key grip.
   - To test the ability to perform these three grips, a common object relating to each grip was picked up using the orthosis. The first object was a screwdriver, which the device successfully grasped, demonstrating its ability to perform the power grip. The second object was a quarter, which the device successfully picked up, demonstrating its ability to perform the pinch grip. Finally, the last object was a car key, which the device successfully held, demonstrating its ability to perform the key grip.

2. The device shall be controlled with the contralateral hand.
   - This specification was met without even doing any testing. The user wore the prototype on their right (disabled) hand and was able to operate the device with their left (healthy) hand.

3. The device shall be turned on and off through DPDT momentary rocker switches which will be provided with the orthosis.
   - In correlation with the previous design specification, the device was successfully operated (using the contralateral hand) through the Firgelli DPDT switches. These switches were taped together in a row, and rested on the right forearm of the user during the tests.

4. The device shall have 5 or less control inputs.
   - The device contained five linear actuators which were all individually operated using their own DPDT switch. However, to obtain the circumduction of the thumb, and sixth degree of freedom, a manual control input (Pull-pin) was designed into the device. The device has a total of 6 control inputs, with 5 of them being electrical. Even though the specification was not met, it was felt the sixth degree of freedom was necessary for the success of the project.

5. The device on the hand shall weigh no more than 0.5 kg (1.1 lbs.).
• The entire device (all hand components plus battery and switches) were weighed to be 0.725 kg (1.6lbs.). However, the battery would not be on the user’s hand, rather it would be in his/her pocket. Subtracting the weight of the battery from the previous total, the weight on the hand was found to be 0.45kg (0.97lbs.), which successfully met our design specification.

6. The device on the hand shall not occupy a space larger than 178mm x 127mm (7inch x 5inch) in area and will be no thicker than 76mm (3 inches).

• When looking at the device from the top (or looking at the back of the hand), the dimensions of the orthosis were measured at 192mm x 170mm (7.5inch x 6.7inch). This did exceeded our design specification’s limit. The reason for the large dimension of 170mm (side of hand to tip of thumb) was to fit the steel links between each of the fingers. The 192mm from tip of the middle finger to the wrist was necessary and would vary with the different hand sizes of different users. The thickness of the device (from the back of the user’s palm and up) was measured at 59mm (2.3inch) which met the design specification. This dimension was from the back of the hand to the top of the finger component slot. If another mechanism for rotation was devised, than the thickness of the hand would be reduced to 21mm (0.83inch) (back of the hand to top of the actuator).

7. The device shall be completely portable.

• This was obviously the first test performed after the final prototype was assembled. The user put the device on his hand, with the DPDT switches resting on his forearm, and had the Tenergy battery in his pocket. A Velcro strap was incorporated into the device to wrap around the users palm so the device did not slide off during operation.

8. The device shall have manufactured components that can be easily adjusted to accommodate for different hand sizes.
- After the device is done be manufactured, there is no way of adjusting the size of the device to accommodate for different hand sizes. However, using the CAD model, the dimensions could be easily altered to fit the user, and then be sent to the rapid prototyping machine for manufacturing.

9. The device shall consist of modular, interchangeable parts.

- Not counting the motors, switches, or connectors, the device consisted of 20 components:
  - 2 ABS plastic components for each finger (8)
  - 2 ABS plastic components for the thumb (2)
  - 1 ABS plastic component for the hand mount
  - 8 carbon steel links
  - 1 spring loaded pull-pin

- If any of these components were to break, the device could be disassembled, a new piece could be manufactured (purchased) to replace the broken component, and the device could be reassembled.

10. The device shall cost a maximum of $500 to manufacture.

- A final budget was not assembled; however, the device was estimated to cost approximately $600-$700. The bulk of this cost was $400 for the five linear actuators.

**Power**

11. This device shall have a minimum grip force of 225 Newtons for the power grip.

- A full hand grip force was not measured. However, a force measurement was performed on a single finger and that resulted in a maximum force of 50N. This correlated to a full hand maximum force of 200N, falling short of the design specification by 25N.

12. This device shall have a minimum grip force of 40 Newtons for the pinch grip.

- The specification was not tested due to the lack of time and necessary measurement resources.
13. This device shall have a minimum grip force of 60 Newtons for the key grip.

- The specification was not tested due to the lack of time and necessary measurement resources.

14. The device shall have a rechargeable battery so no replacement battery is needed.

- The Tenergy 6V battery chosen comes with a plug in the wall charger that is easily connected to the battery. The design specification was successfully met.

15. The device shall take no longer than 4.2 seconds to change from open palm grip to closed fist grip.

- The combination of the Firgelli linear actuators and six-bar linkage mechanism resulted in the device taking 4.17 second to change from open palm grip to closed fist grip. The design specification was successfully met.

16. The device shall allow the user to move their fingers in accurate positions for the desired grip.

- The device successfully met this specification. The success was clearly noticed when the orthosis could successfully squeeze a quarter using the precision pinch grips.

**Kinematics**

17. The device shall give the user the ability to individually position each finger.

- The five individual linear actuators allows for the user to individually position each finger. This design specification was met.

18. The device shall be able to grip an object with a diameter of 7.62 cm (3 in.).

- To test this specification, two different types of cups here grasped. The first was a soda bottle with a diameter of 2.5 inches. The orthosis easily grasped and picked up the bottle. Next was a Styrofoam coffee cup. This cup had a non-uniform diameter. However, the orthosis was able to grasp the cup near the bottom (smallest diameter). The diameter was measured to be 3 inches, which mean the device met this specification.

19. The device shall have six degrees of freedom.
• The hand orthosis was successfully designed with six degrees of freedom. These degrees of freedom included one in each finger, one in the thumb, and one for the circumduction of the thumb.

20. The device will be designed to ensure that the user’s fingers will not reach an uncomfortable position when the fingers reach their maximum closed fist position and their maximum open palm position.

• This specification was tested by operating each finger at every possible actuator position. At no point did any of the user’s fingers feel uncomfortable or hurt. This design specification was met.

Strength/Durability
21. The device shall last at least one year before maintenance.

• This specification could not be tested due to the time constraints of the project.

22. The device shall have the capability of working in different environments (rain, snow, etc.).

• This specification was not tested because it was assumed the device would, not only be unsafe, but also fail due to the fact that all of its electrical components are not protected.
Discussion

Performing the Three Grips

One test performed on the final prototype of the orthosis was a qualitative test that was intended to demonstrate the device’s ability to perform the power, pinch, and key grips. The CAD model showed these grips were possible theoretically. These tests were performed to verify the model (Figure 67).

The device needed to be able to assist the user in gripping a wide variety of items that ranged in size and shape. This means the device should be able to hold any round or flat object. The device was designed so a diameter of up to 3.5 in could be held. The 3.5 in diameter object was difficult to grasp, however, grasping the 3 in object was successful, meeting the design requirement. The final prototype was tested for its ability to achieve the three grips by having the user try and pick up and hold a screwdriver, a quarter, and a key. A picture of the device performing the power, pinch, and key grip can be seen in Figure 68. This test proved successful since each of the three grips was able to be used effectively and were adaptable enough to assist the user in an array of activities of daily living.
**Grip Force**

Another test performed on the prototype of the orthosis was to measure the amount of grip force that each finger could exert in each of the three grip configurations. In our original design specifications for the grip forces, it was stated that the device should be able to achieve 225 N grip force for the power grip, 40 N force for the pinch grip, and a 60 Newton force for the key grip. The power grip force was measured using a hand dynamometer. The index finger was tested to determine the maximum force it could produce. The hand dynamometer showed that this finger could produce a 50 N grip force. This measurement showed that the device can apply an acceptable amount of force in a power grip configuration. In addition, since this showed what one finger could exert for a force, the full four finger grip force was calculated by multiplying the result by four. This resulted in the device being able to produce a 200 N grip force, nearly matching our design specification. Unfortunately, because of the shape of the dynamometer, the pinch and key grip forces could not be tested. This means further testing should be done for these grips to calculate the force that can be exerted. To better evaluate the orthosis, all four fingers should be tested together with a force gauge to get a clear numerical result of how much force the device can be produced using the power grip.

**Operation Time**

The time it took to go from a finger fully opened to a fully closed position was evaluated during the brief tests. These tests verified that the device would be able to operate quickly and efficiently in order to be useful to its potential user. From the timed test, the time it took to close from the index finger being fully opened to close was 4.17 seconds. This is the same for all of the four main finger mechanisms. For the thumb, it takes the 0.83 seconds to drive the finger through its whole motion. With a result of 4.17 seconds, the design specification of under 4.2 seconds was successfully met.
**Miscellaneous Features**

First, having the power supply of the device be long lasting and rechargeable was important so the user would not have to buy new batteries every time the charge wore off or constantly charge the battery if it only lasted for an hour. To achieve this design specification a rechargeable 6 volt battery was used that had a long life cycle and a recharge time of only 1.5 hours. To allow the user to achieve accurate positions of each finger, momentary double pole, double throw switches were utilized. This allowed the user to have their healthy hand hold down the switch until the finger reached the desired position and with a release of their finger the actuator would automatically stop and keep its position.

In addition to the switches helping the user position each individual finger, every finger contained its own motor so each finger could have its own individual movement. This allowed for our orthotic device to be able to pick up a wider variety of objects and expand its capabilities. The thumb also had a second device attached to it which allowed it to have a second degree of freedom (and the sixth degree of freedom overall). The second part of the thumb was a pull-pin mechanism that allowed the user to move the thumb from the side of the hand to away from the palm. This would allow the user extra guidance and support when holding and grasping objects.

**Safety**

Since this device would be placed directly on a human, the device’s safety was another aspect which was important in the design specifications. Tests were performed to make sure the device would not over extend the user’s hand by either closing or opening up too much. This was achieve by selecting linear actuators that could not displace beyond the natural motion of a human finger. Also the actuators chosen had limit switches so the actuator would not move to a position less than 0.5mm from the end of the fully retracted or fully extended displacement. This would make sure the actuator was not displacing more than what we had originally calculated. As for the wiring, a diode was place on the
circuit board providing safety for the battery and preventing too much current from coming back to it through the wire.

**Durability**

One design specification that was not reached was that it would be able to be used in different types of weather environments. In the future this specification can definitely be taken into consideration, but for this prototype and with the time and budget given, this was not a priority or something that was focused on very much. Considerations for this should be taken in the future since it would add an extra benefit for the user and give them more chances to use the device. Also having the device be more portable is something to also look at in the future since there needs to be a better way developed to hold the switches and the battery on the user’s body.

Overall the majority of the design specifications written at the beginning of this project were accomplished. This prototype proved successful for its purpose and the goal of this project. Further testing and redesigns should be done in order to further this project and create a device that could be fully marketable.
Conclusions

For this project, a functional powered hand orthosis was designed, manufactured, tested, and evaluated. Testing was done to show that the device could not only execute the three most common grips (cylindrical grip, pinch grip, and key grip) in performing the common activities of living, but could also provide the user with enough force needed to successfully carry out these grips. Linear actuators drove the motion around the two finger joints through a six bar linkage in order to replicate the opening and closing movement of the fingers. The second degree of freedom for the thumb was created by a pull pin mechanism that allowed for 60 degrees of freedom in the circumduction motion of the thumb, which is from the side of the palm to in front of the palm. All degrees of freedom for the hand were controlled by the user’s healthy, contralateral hand. Overall, this design showed that an orthotic device could help people with hemiparesis perform the activities of daily living with their hand that had diminished strength. This project is a great starting point for another team to pick up and continue working on in the future to develop the design further.

Recommendations

Since this project was a first of its kind at WPI, there are several recommendations that could improve this device and further its progress.

1. **Create a powered mechanism for the 2nd degree of freedom of the thumb.**

Having the 2nd degree of freedom powered would allow the user to more easily move their thumb in a circumduction motion. Due to the lack of space on the hand mount, a sixth electrically driven motor did not seem feasible for the design of the orthosis. However, with more research, more compact actuators could be used to make this 6th powered DOF possible.

2. **Improve the methods that are used for the control section of the hand orthosis design.**

The DPDT switches were chosen because of the certainty that they would successfully drive the actuators. Now that the kinematic mechanism is fully design, the next part of the device to improve is
the control. This is the most important part, because it is how the user related to the device. More thought could be put into using the resistor strips explained in the Background of the report. The device could even follow the path of most prosthetics and harness myoelectric signals for signaling the movement of the orthosis.

3. Develop a way to configure the hand mount to better fit the shape and size of the user’s hand

The hand mount, which was created out of ABS Plastic, did not accurately fit on the user’s hand because it was hard to dimension the mount to the complex geometry of the human hand. Just as a Surveyor obtains the contours of a plot of land, the contours on the back of the hand could be acquired to meet this recommendation. Once these dimensions are known, the CAD model can be altered so the device can properly fit a user’s hand.

4. Perform life testing on the mechanism.

Life testing should be performed on the orthosis to figure out how each component of the orthosis will hold up over time. This could be done through continuous cycling of the fingers under no load and then under a maximum load.
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Appendix A

Questions to ask a Physical Therapist

1. How long have you been in the PT field?

2. Do you have a lot of patients who are trying to get strength back in their hand?

3. What joints do you think are the most important in the hand?

4. What hand functions do you think are most common in daily activities?

5. Out of the patients you have, what activities or movements are hardest for them? (if there is a common theme)

6. Have you seen any powered hand orthosis in use for either rehab or patient’s daily use?

7. If yes to #6:
   a. What was your overall view of the orthosis?
   b. What were the patients overall view of the orthosis?
   c. What problems were there with the device?
   d. What were some key parts or movements that were important in the orthosis?
Appendix B

Questions for Professor Fischer

1. Who was the target for this project?
2. What specific functions did you want to make sure you replicated?
3. What kind of preliminary designs did you have? How did you arrive at this final design?
4. If people tested the device, was it tested by the target customer or just by anyone?
5. What kind of market was this product intended for? Hospital, rehab, household use?
6. What were the major difficulties the group had when designing this device?
7. Do you know if there was anything the group wished they had known before hand?
8. What design specs were taken into consideration?
Appendix C

Physical Therapist Email

“First, a physical therapist treats all sorts of hand injuries in an out- pt setting. I would have to say that the most common ones are post hand fractures, arthritis, & carpe l tunnel syndrome. Basically, the therapist works to decrease pain & swelling and increase the ROM (range of motion) & then the strength in the hand. The aim is to improve the patient’s fine motor capabilities. Modalities like hot packs, cold packs, paraffin (hot wax), whirlpool (water), and massage are used. The therapist passively move the joints in the hand & wrist (PROM), has the patient move the joints (AROM), or adds some resistance to the AROM with progressive resistive exercises (PREs).

Examples of AROM- touching each fingertip with your thumb; open & close your hand; pinching some object or picking up an object with your fingers and placing them in a container or stacking them; zipping, buttoning, unbuttoning, opening or closing lids, etc.

PROM is done by the therapist or is taught to the patient using their good hand.

PREs are done using thera-band, putty, hand grips, squeezing a ball, or the therapist applying resistance to certain muscles.

Often it’s important to strengthen the wrist and forearm to help stabilize the hand to function better. Because the hand & fingers are vital for giving us input to our world, sensation is extremely important for function also.

The anatomy of the hand is pretty complex. It would be a good idea to look at a Grey’s Anatomy book. You need to understand the relationship between the intrinsic muscles, extrinsic muscles, ligaments, tendons, the motor nerves, the sensory nerves, and the fascia.

The level of the spinal cord injury will determine how much ADL function the patient will achieve. Like a stroke (CVA-cerebral vascular accident), location of the insult makes a big difference on the level of independence of the patient.”
Appendix D

Robotics Meeting

On October 4th, Steve and Bob met with Professor Fischer to discuss the similarities between the Assistive Glove MQP that he advised and our project. He brought us to his lab downstairs in Higgins Laboratories and showed us the device and gave us a very sound overview of the entire project.

Throughout this overview and explanation, it was explained to Professor Fischer what the primary objectives of our project are, and what research has been done so far. Professor Fischer brought up several issues that we have not addressed in the control of our device; he brought up the fact that the Assistive Glove was intended to control the amount of force exerted, and brought to light that we need to establish whether we will be controlling force or position of the fingers. He also gave several suggestions towards controlling and powering the device, including potentiometers, actuators, etc. He referred us to a researcher at Yale, Adam Dollar, who has done significant work in the area of grip assisting and recommended that we browse his work. He recommended the idea of experimenting with simple hobby servos to power our device.

While we were in the lab with Professor Fischer, Mike Delph arrived. Mike is currently a doctoral student working with Professor Fischer in the same area, and is one of the students who worked on the MQP. Mike has done significant research in the area of the exact need for assistive grasping devices, and encouraged us to contact him for a meeting where we will likely find more useful information relevant to our project, and discuss various control schemes and how these two projects could benefit from working together and perhaps integrating ideas.
Appendix E: Powered Hand Orthosis Test Worksheet

**Test 1: Gripping Everyday Items**

<table>
<thead>
<tr>
<th>Item</th>
<th>Can the orthosis enable the user to grab?</th>
<th>Yes</th>
<th>No</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cup (Diameter: ____)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hammer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Screwdriver</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paper</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paper Stack</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Key</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Washer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Test 1, Gripping Everyday Items

Tester:  
Date:  

**Tests 2, 3, and 4: Maximum Forces Applied**

<table>
<thead>
<tr>
<th>Grip</th>
<th>Grip Forces (N)</th>
<th>Grip Required</th>
<th>Maximum</th>
<th>(Required/Maximum)*100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td></td>
<td>240</td>
<td>Maximum</td>
<td></td>
</tr>
<tr>
<td>Pinch</td>
<td></td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Key</td>
<td></td>
<td>60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Test 2, Grip Forces

Tester:  
Date:  

**Test 5: Device Operation Times**

<table>
<thead>
<tr>
<th>Operation Time</th>
<th>Opening Time</th>
<th>Closing Time</th>
<th>Total Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pointer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ring</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pinkie</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Test 5, Operation Times

**All times should be equal to or less than 4.2 seconds, according to the original specification.**

Tester:  
Date:  


Appendix F: MathCad Calculations
\[ \begin{align*}
\theta_1(\Delta) & := 0.0000000040 \cdot \Delta^6 - 0.000006126 \cdot \Delta^5 + 0.0000303611 \cdot \Delta^4 + 0.0000349641 \cdot \Delta^3 \ldots \\
& \quad + -0.0671078511 \cdot \Delta^2 + 3.4001681169 \Delta - 3.4793828329 \\
\theta_2(\Delta) & := 0.0000000340 \cdot \Delta^6 - 0.0000059458 \cdot \Delta^5 + 0.004266871 \cdot \Delta^4 - 0.0166735631 \cdot \Delta^3 \ldots \\
& \quad + 0.4143157415 \cdot \Delta^2 - 7.7344904523 \Delta + 90.1970936451 \\
\theta_3(\Delta) & := -0.0000000427 \cdot \Delta^6 + 0.0000075078 \cdot \Delta^5 - 0.0005405028 \cdot \Delta^4 + 0.0209937924 \cdot \Delta^3 \ldots \\
& \quad + -0.5027975564 \cdot \Delta^2 + 8.4621636671 \Delta + 13.7538486464 \\
\theta_4(\Delta) & := (\theta_2(\Delta) + \theta_3(\Delta)) - 90
\end{align*} \]

\[ \begin{align*}
a & := .00225 \quad \text{F.g to the end} & \Delta & := 1, 1.01 \ldots 51 \\
b & := .00400 \quad \text{Link y component to base} & \text{F_g} & := 50 \quad \text{Newtons} \\
c & := .0225 \quad \text{Link x component to base} \\
y(\Delta) & := \left(0.000000007 \Delta^6 - 0.000001436 \Delta^5 + 0.0000123586 \Delta^4 - 0.00006081475 \Delta^3 \ldots \\
& \quad + 0.0195057584 \Delta^2 + 0.5538426499 \Delta + 17.2036523809\right) \times 10^{-3} \\
z & := 0.039 \quad \text{Distance from A to B} & \text{Y-comp distance of the pin to A} & \text{with respect to actuator distance}
\end{align*} \]

\[ \theta_1 = \text{Angle between normal force of pin on slot and motion axis of the actuator} \]
\[ \theta_2 = \text{Angle between distal finger component and "Link"} \]
\[ \theta_3 = \text{Angle between proximal and distal finger components} \]
\[ \theta_4 = \text{Angle between proximal finger component and "Link"} \]
Distal Finger Component
\[
\Sigma F_x = -F_{Bx}(\Delta) \cdot \cos(\theta_3(\Delta)) - F_{By}(\Delta) \cdot \sin(\theta_3(\Delta)) + F_L(\Delta) \cdot \sin(\theta_2(\Delta)) = 0 \quad \text{Sum in X}
\]
\[
\Sigma F_y = F_{Bx}(\Delta) \cdot \sin(\theta_3(\Delta)) - F_{By}(\Delta) \cdot \cos(\theta_3(\Delta)) - F_L(\Delta) \cdot \cos(\theta_2(\Delta)) + F_G = 0 \quad \text{Sum in Y}
\]
\[
\Sigma M_B = -F_G \cdot c + F_L(\Delta) \cdot \cos(\theta_2(\Delta)) \cdot b + F_L(\Delta) \cdot \sin(\theta_2(\Delta)) \cdot a = 0 \quad \text{Moment at B}
\]

Proximal Finger Component
\[
\Sigma F_x = F_{Bx}(\Delta) + F_{Ax}(\Delta) - F_p(\Delta) = 0 \quad \text{Sum in X}
\]
\[
\Sigma F_y = F_{By}(\Delta) + F_{Ay}(\Delta) = 0 \quad \text{Sum in Y}
\]
\[
\Sigma M_A = F_p(\Delta) \cdot y(\Delta) - F_{By}(\Delta) \cdot z = 0 \quad \text{Moment about A}
\]

Fingers Combined
\[
\Sigma F_x = F_G \cdot \cos(90 - \theta_3(\Delta)) + F_L(\Delta) \cdot \cos(\theta_4(\Delta)) + F_{Ax}(\Delta) - F_p(\Delta) = 0 \quad \text{Sum in X}
\]
\[
\Sigma F_y = F_L(\Delta) \cdot \sin(\theta_4(\Delta)) + F_G \cdot \sin(90 - \theta_3(\Delta)) + F_{Ay}(\Delta) = 0 \quad \text{Sum in Y}
\]

Actuator Component
\[
\Sigma F_x = F_p(\Delta) \cdot \cos(\theta_1(\Delta)\text{ deg}) + F_{Actx}(\Delta) = 0 \quad \text{Sum in X}
\]
\[
\Sigma F_y = F_p(\Delta) \cdot \sin(\theta_1(\Delta)\text{ deg}) + F_{Acty}(\Delta) = 0 \quad \text{Sum in Y}
\]
\[
\Sigma M_{Act} = M_{Act}(\Delta) - F_p(\Delta) \cdot \sin(\theta_1(\Delta)\text{ deg}) \cdot (\Delta) \cdot 10^{-3} = 0 \quad \text{Moment about Act}
\]

Solving
\[
F_L(\Delta) := \frac{F_G \cdot c}{\cos(\theta_2(\Delta)\text{ deg}) \cdot b + \sin(\theta_2(\Delta)\text{ deg}) \cdot a}
\]
\[
F_{Ay}(\Delta) := -\left[ F_L(\Delta) \cdot \sin(\theta_4(\Delta)\text{ deg}) + F_G \cdot \sin(90 - \theta_3(\Delta)\text{ deg}) \right]
\]
\[
F_{By}(\Delta) := -F_{Ay}(\Delta)
\]
\[
F_{Bx}(\Delta) := \frac{F_L(\Delta) \cdot \sin(\theta_2(\Delta)\text{ deg}) - F_{By}(\Delta) \cdot \sin(\theta_3(\Delta)\text{ deg})}{\cos(\theta_3(\Delta)\text{ deg})}
\]
\[
F_p(\Delta) := \frac{F_{By}(\Delta) \cdot z}{y(\Delta)}
\]
\[
F_{Ax}(\Delta) := -F_{Bx}(\Delta) + F_p(\Delta)
\]
\[
F_{Acty}(\Delta) := -F_p(\Delta) \cdot \sin(\theta_1(\Delta)\text{ deg})
\]
\[
F_{Actx}(\Delta) := -F_p(\Delta) \cdot \cos(\theta_1(\Delta)\text{ deg})
\]
Force exerted by the actuator in the x-direction in coordinate system X-Y.

Force exerted by the actuator in the Y-direction in coordinate system X-Y.
Moment exerted by the actuator in the counter clockwise direction in coordinate system X-Y.

Force exerted on the acuator in the x-direction in coordinate system X-Y.
Force exerted by the "Link" on the Distal Finger Component in coordinate system $X^{''}$-$Y^{''}$.

Force exerted on the proximal finger component at point B in the positive x-direction in coordinate system $X^{'}$-$Y^{'}$. 

*FL*(Δ) Newtons

*FBx*(Δ) Newtons
Force exerted on the proximal finger component at point B in the positive y-direction in coordinate system $X'-Y'$.

Force exerted on the proximal finger component at point A in the positive x-direction in coordinate system $X'-Y'$. 
Force exerted on the proximal finger component at point A in the positive y-direction in coordinate system X'-Y'.