Design of a Hand Orthosis

A Major Qualifying Project Report
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Abstract

Persons with reduced hand strength and dexterity have difficulty completing daily tasks, especially those requiring two hands. Reduced strength can be caused by stroke, arthritis, injury, and advanced age. Orthoses which assist the individual in achieving useful hand postures and force levels are generally limited to use in a physical therapist's office. The goal of this project is to design and fabricate an affordable hand orthosis for persons with reduced grip strength. The orthosis is a wrist-activated device with non-powered kinematic motion suitable for home use. The orthosis provides a 13N grip force and enables the user to carry out the cylindrical power grip and the pincer precision grip. These are the most commonly used grips and can be used to carry out tasks normally completed with a lesser used grip. The device was manufactured mainly out of plastic to keep weight and cost low. All portions of the orthosis in contact with the user were lined with foam for comfort. Test results showed that the pincer grip configuration enables the user to hold objects from 7.5mm to 45mm and the power grip can hold objects 30m to 80mm.

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1 Introduction

Persons with reduced hand function often are unable to grasp and hold items, making activities of daily living (ADLs) and instrumental ADLs (IADLs) difficult to impossible. An orthosis can aid the user in maintaining the correct hand and finger positioning for securely gripping items and assist in performing the corresponding necessary finger motion.

Commercial orthoses are often unwieldy, and in the case of powered devices, usually prohibitively heavy for everyday use. Specialized products requiring less grip strength, such as hair brushes with enlarged handles, are limited to improving a single task and difficult to transport due to their large size. This project goal is to design and fabricate an active device with non-powered kinematic motion suitable for everyday home use that allows a user with reduced hand functionality to securely grasp items by supporting the wrist and assisting with finger flexion.

Functionality can typically be classified into two types: basic activities of daily living (ADLs) and instrumental activities of daily living (IADLs). In 1969, Doctor Sidney Katz sought the need to assess functional ability of the elderly. By measuring the abilities of his patients, he could provide them with more individualized treatment. Ultimately, Katz created the Index of Independence in Activities of Daily Living, often referred to as the Katz ADL Index. The Katz ADL Index consists of six categories: bathing, dressing, toileting, walking, continence and feeding (Fisher, 2008).

The second type of functional classification, Instrumental Activities of Daily Living (IADLs), were studied by Lawton and Brody while assessing the elderly in 1969. IADLs are considered to be more complex than ADLs, but their measurement is still a strong indication of functionality. The Lawton-Brody IADL Scale consists of eight categories: ability to use the telephone, shopping, food preparation, housekeeping, laundry, mode of transportation, responsibility for own medication and ability to handle finances. Both the Katz ADL index and the Lawton-Brody IADL Scale are capable of assessing a person's level of independence (Fisher, 2008).

Hand grips are typically divided into two categories: power and precision grips. Power grips, cylindrical, spherical and hook, use the entire hand, while precision grips, pinch, pincer and key, only use the tips of the fingers and thumb. The combination of one power and one precision grip allows individuals to function independently in most situations. Specifically, a cylindrical grip and pincer grip (Figure 1) are the most important versions of power and precision grips due to their versatility in replacing other grips and performing tasks (Sancetta, 2014).

Figure 1: Important Grips (Sancetta, 2014)

The target demographic for a product of this type primarily consists of individuals with arthritis and stroke survivors. A device capable of improving the hand strength of these two grips would significantly increase a person's ability to accomplish daily tasks and live independently.

2 Background

In order to identify the primary functions and specifications of our hand orthotic device, it is first necessary to identify both the target consumer as well as the target functionality. This background defines orthoses devices, the biomechanics of hand orthosis devices, the therapy obtained from using devices, the users of the devices, and finally the current technology including what devices are on the market. This research is the basis for developing a product that improves on current devices.

2.1 Orthoses

Orthoses devices can control biomedical alignment, correct deformity, protect from injury, reduce pain, increase mobility, or increase independence (Australian Orthotic Prosthetic Association, 2016). While there are many different types of devices, we are specifically interested in two categories: devices that are used for rehabilitation and devices that are used to increase function. Rehabilitation devices are commonly used in coordination with a therapist in an attempt to regain lost function or improve muscle functionality over time. The primary goal of these devices is to regain unassisted functionality over time or to at some point regain all function that was previously lost. A functional orthosis device seeks to improve the ability to complete tasks in everyday life. While it may assist with the improvement of long term independent function, the device is targeted at making activities of daily living (ADLs) easier for the user (Scarsella, 2007).

Within both of these areas, there are two subtypes of devices: active and passive. Active devices rely on input from the user, most commonly responding to a user’s movements. These devices provide assistance with particular movements, but are reliant on the movements of the user. As a result, active devices are heavily dependent on the user’s range of motion and strength. Passive devices move the body without requiring muscle movement of the body part(s) to be moved. One example of a passive device is a brace which holds the arm in a particular position. Often times, passive devices are used by users who are unable to fully utilize active devices due to movement restrictions.

2.2 Anatomy, Biomechanics, and Grips

2.2.1 Hand Anatomy

In order to successfully design a hand orthosis, one must understand the basic anatomy of the human hand. The hand has twenty-seven bones, which are connected and pulled by a series of tendons and muscles. These twenty-seven bones are broken down into three main groups: the phalanges, the metacarpals, and the wrist bones (Gray, 2010). Each finger has three phalange bones, while the thumb has only two. The phalange bones can be further categorized as distal, middle or medial, and proximal phalanges (Freivalds, 2004). The metacarpals are located in the palm and are numbered, one to five, starting from the thumb and ending at the pinky finger (Figure 2). There are also eight carpal bones, arranged in two rows that comprise the wrist.

Figure 2: Bones in the Hand (Human Anatomy Body, 2015)

In each digit of the hand, except the thumb, there are four joints between the carpals, metacarpals, and phalanges. These are known as the carpometacarpal (CMC), metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP)joints (Mora et al, 2012). The thumb has only three joints as it lacks a middle phalange. Figure 3 shows a depiction of the joints in the hand.

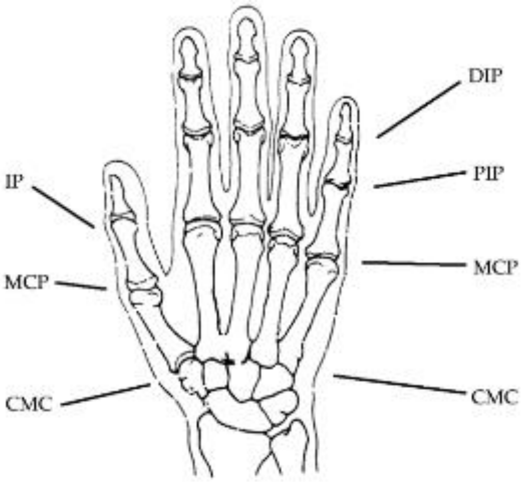


Figure 3: Joints in the Hand (Mora et al, 2012)

The MCP joint connects the metacarpal and proximal phalanges. Ligaments also provide stability in the MCP, DIP, and PIP joints. The CMC joint connects the metacarpal and carpal bones and allows the palm and fingers to move. These joints, along with tendons, allow a person to curl their fingers around an object.

Muscles provide the forces required for the hand to move. Two groups of muscles are responsible for hand and wrist movements: extrinsic and intrinsic muscles (Figure 4).

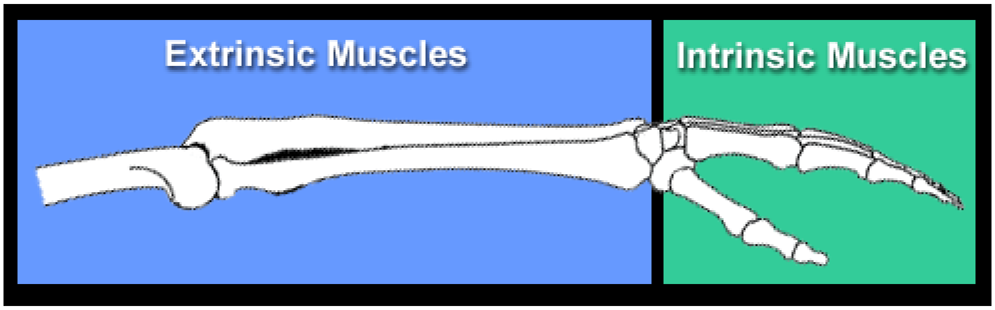


Figure 4: Extrinsic vs. Intrinsic Muscles (Richards, 1997)

Extrinsic muscles, located on the forearm, allow for gross movement, provide strength, and are important for repetitive finger flexion and situations requiring additional strength (Freivalds, 2004). Intrinsic muscles, located inside the hand, provide control and allow each finger to have its own independent movement (Gray, 2010). Intrinsic muscles are generally separated into four groups: thenar muscles which act on the thumb, hypothenar muscles which act on the pinky finger, lumbrical muscles which assist in the extension of IP joints and flexion of MCP joints, and interossei muscles which allow for abduction and adduction of the fingers (Gray, 2010). The lumbrical and interossei muscles are both located in the palmar region of the hand.

2.2.2 Biomechanics of the Hand

Kinematics is the study of motion without regard to the forces that cause the motion (Gustus et al, 2012). Kinematic study of the hand refers to a set of possible motions that a hand can perform, and specifically the positions and orientations of the hand during these motions. Movement of the hand can be viewed as a kinematic mechanism with bones as rigid links. The kinematic state of the hand is described by the position and orientation of each bone. A combination of a position and orientation is called a posture. The hand is capable of numerous postures; however, in most situations only a subset of postures is used. Constraints, or joints, also limit the number of postures of the hand.

The joints in the hand all have mechanical equivalents as either universal joints, which have two degrees of freedom (DOF), or hinge joints, which have one DOF. The number of DOF is related to the possible motions of rigid bodies, or bones. Table 1 lists the hand joints and their mechanically equivalent joints.

Table 1: Modified Table of Mechanical Equivalent Joints in the Hand (Chao et al, 1989)

Hand Element	Joints	Mechanical Equivalent	DOF
Fingers	Distal Interphalangeal Joint (DIP)	Hinge Joint	1
	Proximal Interphalangeal Joint (PIP)	Hinge Joint	1
	Metacarpophalangeal Joint (MCP)	Universal	2
Thumb	Interphalangeal Joint (IP)	Hinge	1
	Metacarpophalangeal Joint (MCP)	Universal	2
	Carpometacarpal Joint (CMC)	Universal	2

The hand has a total of twenty-one DOF. Each finger has four, three for extension and flexion and one for adduction and abduction. The thumb, which is more complicated, has five DOF. These include one DOF at the IP joint and two DOF at each the MCP and CMC joints. Figure 5 shows a hand and the DOF at each joint. Single DOF joints are represented by red arrows, while two DOF joints have a second axis shown in green, which represents the additional DOF.

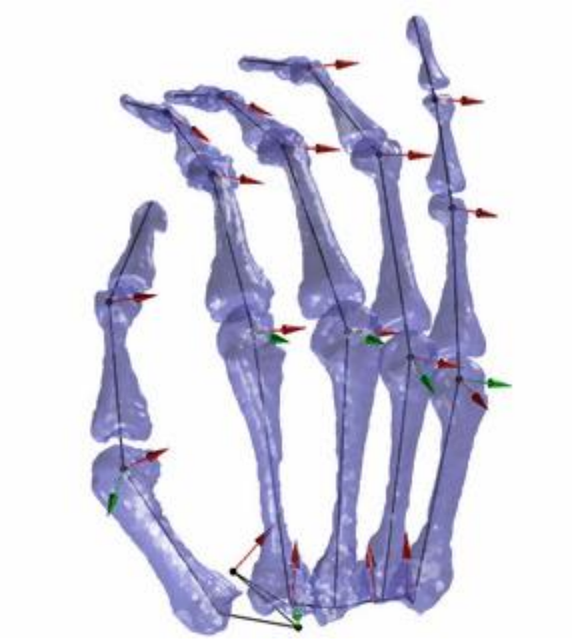


Figure 5: Kinematic Model of Hand (Gustus et al, 2012)

As noted, the thumb has one more DOF than each finger. This means that the range of motion and control of the thumb is also larger, which allows the hand to form a wide range of grips and positions.

2.2.3 Hand Grips

Hand grips are generally categorized into two groups: power and precision (Napier, 1956). Power grips use the entire hand, while precision grips only use the tips of the fingers and thumb. There are numerous types of grips such as the pinch, pincer, power, and key (Figure 6).

Figure 6: Various Hand Grips (Sancetta, 2014)

A pinch grip uses the tips of the index finger and thumb to grip small objects. The pincer grip is very similar to a pinch grip. The only difference is that the pincer grip also uses the middle finger, which provides more stability. A power, or cylindrical, grip is used to grip larger objects. In this grip, each phalange as well as the palm contacts the object. Two other types of power grips exist but are less commonly used. They are the spherical and hook grips. The spherical grip is similar to the cylindrical grip except the phalanges are spread apart such as when unscrewing a jar lid. The hook grip is commonly used to carry groceries and toolboxes. Finally, a key grip is used to hold any object between the tip of the thumb and middle phalange of the index finger. While these four grips are commonly used, people can perform most tasks with just two main grips. A power grip and a precision grip, specifically the pincer grip, allow individuals to perform most daily tasks (Sancetta, 2014). The pincer grip is slightly more important than the pinch grip due to the increased stability while gripping similar objects. The pincer grip can also be used to hold a key and replace the key grip. The power grip, or cylindrical grip, is also essential and versatile as it can be used for tasks such as opening bottles, holding cups, or opening doors. The pincer and the power grips also have some important similarities (Figure 7). Fingers typically follow the same path when forming these two grips. The major difference is that the thumb closes slightly so that it intersects the index and middle fingers in the pincer grip.

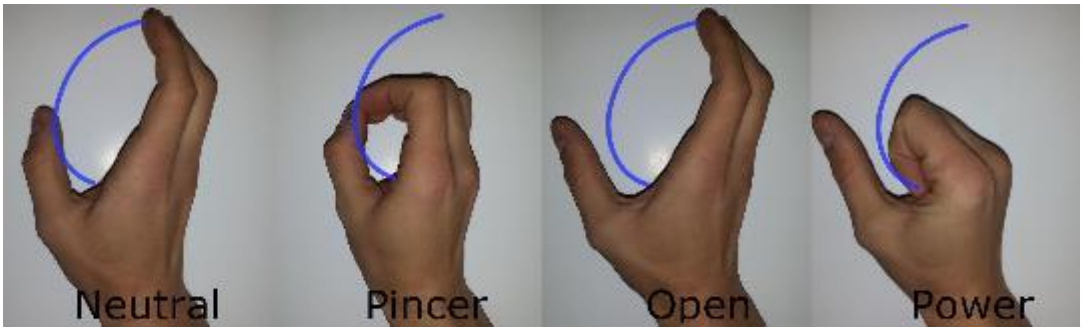


Figure 7: Finger Motions in Pincer and Power Grips (Sancetta, 2014)

It is also important to note that only the phalanges on the thumb move during these grips, unless the object is very large. Therefore, when designing a hand orthosis to assist in performing these grips, the thumb metacarpal can remain stationary. This removes two DOF and simplifies the overall movement of the system (Sancetta, 2014).

2.2.4 Kinematics of Hand Grips

When designing a device to assist with specific grips, such as the cylindrical and pincer grips, it is also important to understand the kinematics required to create these postures in the hand. Recall that a hand posture is defined as a combination of positions and orientations of the bones in the hand and phalanges. When gripping a cylindrical object, the distal, middle, and proximal phalanges must form specific angles with one another based on the size of the object and the contact points. Contact points are defined as the various points where the object touches the phalanges. Since there can be a very large number of potential contact points, one must make various assumptions to model the posture required to form a cylindrical grip. Assuming that the first contact point lies in the center of the distal phalange, one can determine the angle required by the DIP joint, or Ɵ'1, by trigonometry (Figure 8).

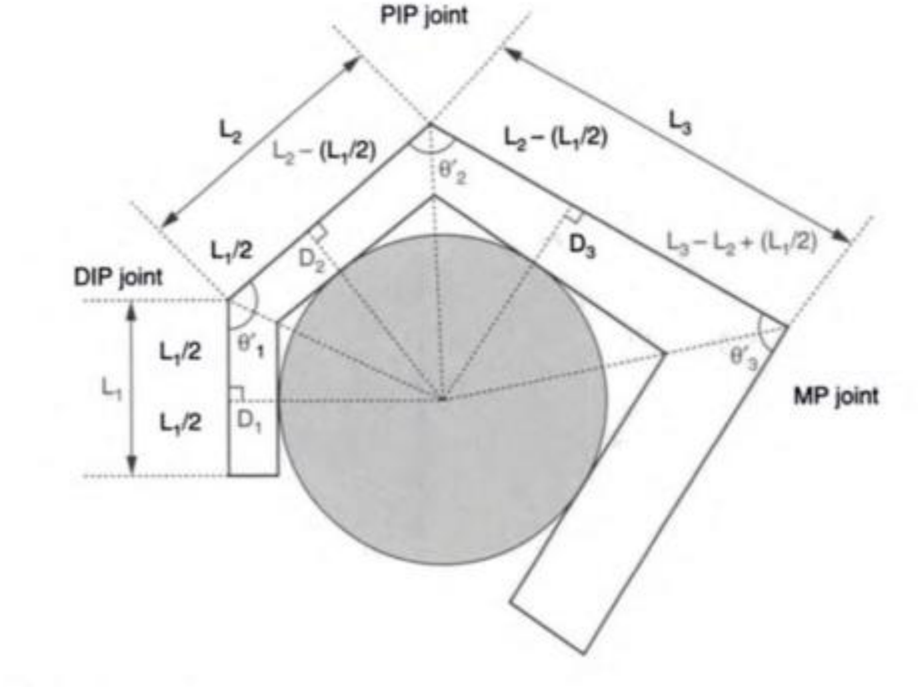


Figure 8: Joint angles during a cylindrical grip (Freivalds, 2004)

The DIP joint angle is equal to:

$$\theta'_1 = 2tan^{-1}\left[\frac{2(R + D_1)}{L_1}\right]$$

where D1 is thickness of the distal phalange at the contact point, R is the radius of the cylindrical object, and L1 is the length of the distal phalange. The second contact point falls off center with the middle phalange. Trigonometry can also be used to calculate the required PIP joint angle to be:

$$\theta'_2 = 2tan^{-1}\frac{2(R + D_2)}{2L_2 - L_1}$$

where D2 is the thickness of the middle phalange at the contact point and L2 is the length of the middle phalange. The third contact point also lies off center with the proximal phalange. Trigonometry can also be used to calculate the required MP, or MCP, joint angle to be:

$$\theta'_3 = 2tan^{-1}\frac{2(R + D_3)}{2L_3 - 2L_2 + L_1}$$

where D3 is the thickness of the proximal phalange at the contact point and L3 is the length of the proximal phalange. These joint angles are critical when designing a device to assist with a cylindrical grip. An orthotic device would need to assist in creating these correct angles, based on various contact points and cylindrical object sizes. The model presented above assumes one contact point and calculates the angles of the joints based on that assumption (Freivalds, 2004). However, it is difficult to always achieve the same contact point when grasping objects. Therefore, this model should be viewed as an approximation. The same type of trigonometric calculations can result in similar, but slightly different, joint angles based on various contact points.

As noted in the previous section, the fingers follow the same path when forming a pincer grip as they do when forming a cylindrical grip. The main difference is that the path of the thumb intersects the index and middle fingers. Therefore, a similar approximation can be made when determining the required joint angles of the fingers. The main difference is that in the pincer grip, the object does not contact the phalanges at three various positions as described in the previous model because the object is grasped with just the tips of the fingers (distal phalanges) rather than the distal, middle, and proximal phalanges. In the pincer grip, the object typically contacts the distal phalanges of the index finger, middle finger, and thumb (Figure 6). A similar approximation can be made to determine the required joint angles of the fingers based on the size of the object. It is also important to note that only the phalanges on the thumb need to move to intersect the index and middle fingers (Figure 7). Therefore, by approximating the joint angles of the fingers in a similar way presented for a cylindrical grip and calculating the necessary movement of the distal and proximal phalanges of the thumb, one can create the hand posture required to form a pincer grip.

To further simplify the movement of the thumb during a pincer grip and reduce the number of variables, the thumb can be fixed in a position with specific values for IP and MCP joint angles. The movement and the joint angles of the fingers, then, are only dependent on the thickness of the object. For example, a user or device grasping a pencil with a pincer grip would simply need to move the distal and proximal phalanges of the thumb into a fixed position and place the fingers in a position where the pencil is in contact with the distal phalange of the thumb. Then the fingers would follow a path as if they were forming around a cylindrical object, such as a ball. Eventually, the fingers would intersect the thumb with the pencil in between (Figure 9).

Figure 9: Cylindrical and Pincer Grip Similarity

These assumptions, similarities, and simplifications of the movements required by a cylindrical and pincer grip allow for the creation of a single device to assist in forming and strengthening both grips. In addition to kinematics and positions of the fingers and thumb, an analysis of moments and forces generated in the fingers is important for a hand orthosis device.

2.3 Users

There are a variety of conditions that lead to weakened hand, wrist, and grip strength. The most common conditions result from injury or wear and tear. Both of these conditions can lead to arthritis which is the leading cause of diminished hand strength; the two most common types are osteoarthritis and rheumatoid arthritis. Both osteoarthritis and rheumatoid arthritis are common in advanced age (usually in those above the age of 60), and bring about stiff joints, particularly in the wrists, hands and fingers. rheumatoid arthritis is an autoimmune disease while osteoarthritis is typically the result of the wear and tear of joints. Injuries occurring in early adulthood and in some cases even childhood have the potential to progress into osteoarthritis (Scherer, 2012). Injuries to the hand and wrist, in particular, are likely to cause trouble later in life due to the high concentration of scar tissue in weakened areas such as the joints. Arthritis can be treated with prescription medications as well as physical therapy. While there is no cure for arthritis, continuing to use the affected joints greatly reduces the long-lasting effects.

Likewise, strokes can cause a number of physical disabilities, including paralysis and problems controlling movements. These motor control issues can lead to difficulty with everyday activities including walking and grasping objects. The severity of these effects can be treated with rehabilitation. The rehabilitation process begins as soon as possible following a stroke, often within 48 hours of the stroke itself (Barrett, 2013). Statistics show that 65% of stroke survivors suffer from long term effects and rehabilitation improves the function of a stroke survivor to the point where they can be as independent as possible. Unfortunately, many of the devices used in rehabilitation facilities are expensive, and their use is limited to time spent in the facility. Joel Stein, MD, director of the rehabilitation medicine service and physiatrist-in-chief at New York-Presbyterian Hospital, suggests that devices intended to supplement standard therapy and provide everyday function would result in “a better shot at improving outcomes” (Stuart, 2015). A user who continues rehabilitation exercises at home has an increased chance of gaining additional function compared to those who are limited to the standard treatment.

A study performed by Virgil Mathiowetz in collaboration with University of Wisconsin-Milwaukee’s Occupational Therapy Program examined normal hand strength in adults. During this study, 310 male and 328 female subjects were tested using a calibrated Jamar dynamometer, and it was found that the average grip for healthy women was 58.4 lb and for healthy men was 98.7 lb (Mathiowetz, 1985). A study done by the neurological rehabilitation unit of Frenchay Hospital in Bristol, UK determined that stroke survivors, on average, have 18% of their normal power grip strength (Sunderland, 1989). This means that for stroke victims, the average woman has a power grip strength of about 10.5 lb, while an average man has a power grip strength of about 17.8 lb. While many stroke victims have the hand strength required to accomplish daily tasks, their inability to control the movement of their hand makes some of these tasks near impossible.

Decreasing grip strength and hand function is not limited to medical conditions or injury. Figure 10 demonstrates the deterioration of grip strength with age for men. Advancing age can cause diminished grip strength without any additional ailments.

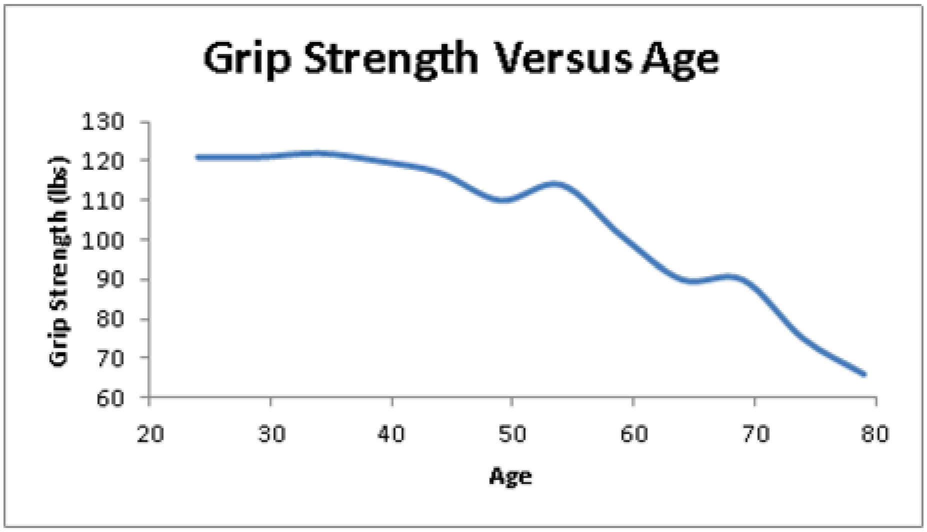


Figure 10: Normal Deterioration of Power Grip Strength vs. Age for Men (Mathiowetz, 1985)

Both those who suffer strokes and those who have arthritis are affected daily by weakened hand strength. Weakened hand functions suggest the need for a device to restore hand strength to patients which returns a sense of independence to their everyday lives. Degradation of grip strength, whether caused by arthritis or stroke, can negatively affect a person’s ability to accomplish tasks in their daily lives.

2.3.1 Physical Therapy

The stroke rehabilitation process begins as soon as the patient is able to participate. Typically, rehabilitation exercises involve passive movements to restore muscle memory in the affected area. As treatment progresses, the individual may be able to actively control the affected area with his/her own muscles while using an assistive device. In the case of hand impairment in stroke survivors, common activities include stretching, moving balls and blocks, placing objects into precise locations, and grip strength exercises. A patient may initially rely upon passive exercises if there is little or no ability to move the fingers independently. A therapist or the individual's unaffected hand moves the fingers of the impaired hand. This aids in restoring muscle memory as well as reducing the chances of long term shortening or elongating of the muscles and tendons. A patient with minimal to low hand functionality might use a combination of passive stretching exercises and active exercises such as grasping a ball and lifting it. For moderate to high functionality, therapy can also focus on finer motor control. The patient may be asked to sort blocks into baskets based on shape or color. Likewise, a person undergoing physical therapy for arthritis would typically undergo exercises focused on providing pain-free movement to joints through repetitive motion.

Where in the past it was believed that a person recovering from a stroke would reach a plateau after which no additional function could be regained, more recent studies have shown there is no time limit restricting benefits of continued therapy even years after a stroke has occurred (Barrett, 2013). This increases the need for low cost assistive devices for survivors of strokes intended for home use. While insurance may not cover rehabilitation with a physical therapist indefinitely, a properly fitted orthosis can be worn by the patient outside of the doctor's office after the covered treatment has ended. Continued use of an orthosis as a therapy device is likely to aid the user in regaining function that would have been lost if the patient was to end treatment altogether.

2.4 Daily Tasks

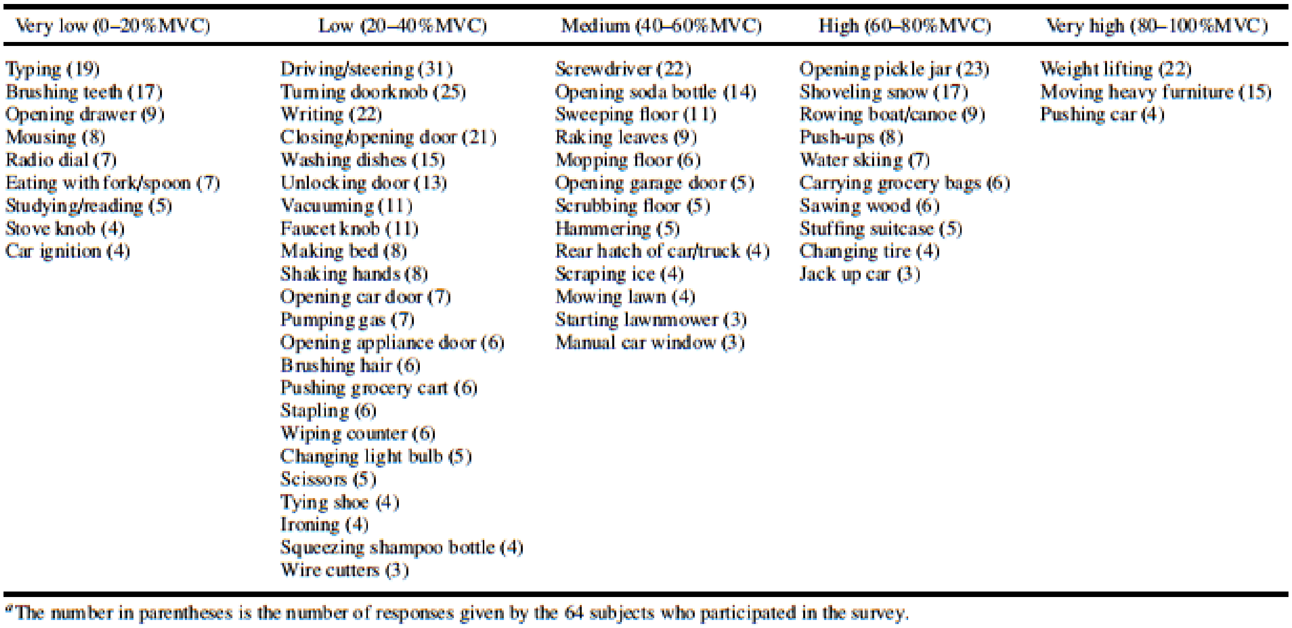
The ability to perform daily tasks independently is crucial to an individual's ability to be self-sufficient. Daily tasks include a number of activities that, at times, can require a significant amount of grip strength and precision. Often referred to as activities of daily living (ADLs), these tasks are vital to a person's independence and include moving and caring for one's body, such as eating and dressing. More specific and measurable activities are deemed instrumental activities of daily living (IADLs) and can be broken down into several categories, including using the telephone, shopping, preparing food, housekeeping, having the responsibility to take own medication, using transportation, and the ability to handle finances (Lawton, 1969). These activities reflect a person's level of independence, and their ability to accomplish these tasks would be important to consider when assessing a product design. These IADLs can be separated into more specific tasks. For example, shopping would include carrying different sized bags and holding many different shaped items. Preparing food would include the ability to hold utensils, as well as open boxes or cans. Housekeeping could be generalized to include the ability to do laundry, use the telephone and maintain one's hygiene (i.e. bathe and brush teeth). Transportation would include the ability to grip a steering wheel or handrails.

For the purpose of evaluating our orthotic device, the following tasks were considered: brushing teeth, writing, opening a door and eating. The forces and grips associated with these activities can be seen in Table 2. While these tasks were not assessed individually, the force values would serve as the target output force of the orthosis when testing the device.

Table 2: Tasks of Daily Living and Associated Forces

Task	Force Required	Grip Type
Brushing Teeth	4 lb	Power
Writing	8 lb	Pinch
Opening Door	20 lb	Power
Eating	4 lb	Pinch

These values were retrieved from an article in the Journal of Occupational Rehabilitation where estimated forces were compared to the forces found when completing a task on a work simulator. The article did not give specific forces for any of the activities listed, but instead separated the activities into difficulty categories calculated using the percentage of a subject's maximum voluntary contraction or %MVC. Figure 11 shows which activities fell into each category.



Very low (0–20%MVC)	Low (20–40%MVC)	Medium (40–60%MVC)	High (60–80%MVC)	Very high (80–100%MVC)
Typing (19)	Driving/steering (31)	Screwdriver (22)	Opening pickle jar (23)	Weight lifting (22)
Brushing teeth (17)	Turning doorknob (25)	Opening soda bottle (14)	Shoveling snow (17)	Moving heavy furniture (15)
Opening drawer (9)	Writing (22)	Sweeping floor (11)	Rowing boat/canoe (9)	Pushing car (4)
Mousing (8)	Closing/opening door (21)	Raking leaves (9)	Push-ups (8)	
Radio dial (7)	Washing dishes (15)	Mopping floor (6)	Water skiing (7)	
Eating with fork/spoon (7)	Unlocking door (13)	Opening garage door (5)	Carrying grocery bags (6)	
Studying/reading (5)	Vacuuming (11)	Scrubbing floor (5)	Sawing wood (6)	
Stove knob (4)	Faucet knob (11)	Hammering (5)	Stuffing suitcase (5)	
Car ignition (4)	Making bed (8)	Rear hatch of car/truck (4)	Changing tire (4)	
	Shaking hands (8)	Scraping ice (4)	Jack up car (3)	
	Opening car door (7)	Mowing lawn (4)		
	Pumping gas (7)	Starting lawnmower (3)		
	Opening appliance door (6)	Manual car window (3)		
	Brushing hair (6)			
	Pushing grocery cart (6)			
	Stapling (6)			
	Wiping counter (6)			
	Changing light bulb (5)			
	Scissors (5)			
	Tying shoe (4)			
	Ironing (4)			
	Squeezing shampoo bottle (4)			
	Wire cutters (3)			

[a] The number in parentheses is the number of responses given by the 64 subjects who participated in the survey.

Figure 11: Summary of the Average Force Classification for Activities (Marshall & Armstrong, 2004).

While the chosen activities do not encompass all activities of daily living, they are a practical representation of the tasks that the user of an orthotic device may need to carry out. A hand orthosis for activities of daily living would be able to accomplish most tasks at 20-40%

MVC. Personal care and feeding tasks appear almost exclusively in the very low and low categories with the exception of opening bottles and jars.

2.5 Current Technology

There are several devices requiring no power or batteries designed to improve the gripping ability of many types of users, some of which assist the user in maintaining proper wrist position as well. Most require the user to have a minimal amount of preexisting flexion and extension in the fingers. Fingers are not required to exert any force, either in flexion or extension, to utilize devices which secure tools or similar items to the hand in a fixed position. Devices which provide force to assist finger motion, without using an externally powered motor or actuator to drive the motion, do require the user to have existing hand strength. A person utilizing a device to assist finger extension must provide sufficient flexion force to oppose the device's force and close the fingers and vice versa for assisted finger flexion. Examples of this are the Saebo orthoses described later in this section.

The Gripeeze and Active Hands products (Figure 12) are two similar gloves which enable a user to maintain a grip on a tool or handle.

Figure 12: Gripeeze (left) and Active Hands (right) (gripeeze.com, 2010; activehands.com, n.d.)

A Velcro strap holds the palm closed after the tool is properly positioned against the palm. Both brands enable a person lacking the ability to maintain a tight cylindrical grip but with sufficient gross motor control to use small hand tools and upper body exercise machines. Neither assists the movement of the hand, wrist or arm. They can be used on one hand, with the user placing the tool in one hand and securing it in place with the other, or on both hands with assistance to secure the second hand.

Similarly, Eazyhold enables the user to hold objects of varying diameters, ranging from silverware to children’s sippy cups. The elastic cuffs (Figure 13 left) have two holes on either end designed to fit around the object and secure the object to the palm by wrapping around the back of the hand (Figure 13 right). A user with one affected hand can use the opposite hand to secure the cuff and position the item in the desired position.

Figure 13: Eazyhold Gripping Cuff (left), Eazyhold in use (right) (eazyhold.com, 2016)

Saebo is a company focused on designing products specifically for stroke patients. They offer two wearable devices designed to both align the hand and wrist in a position suitable for grasping objects and assist with finger extension. Users of the SaeboGlove and SaeboFlex have fingers that are significantly flexed in the neutral position and they have difficulty extending the fingers. The devices apply force to pull the fingers into an extended position resulting in an open resting position. Users must have some existing finger flexion to utilize either device. The SaeboGlove (Figure 14) is a low-profile device offering moderate support to the wrist and fingers. As the name implies, the user wears the device like a glove and a wrist strap provides additional stability. Elastic tensioners on each phalanx apply the force needed to assist the patient in opening his/her hand to increase the size of the grip envelope.

Figure 14: SaeboGlove Low Profile Assistive Hand Flexion Device (saebo.com, 2016)

The SaeboFlex (Figure 15) provides the same assistance to open the hand, but utilizes springs rather than elastic tensioners which results in a greater force applied. This is a high profile device which attaches with a strap around the palm, a wrist brace, and plastic enclosures for each finger. Both Saebo devices are used in therapy centers as well as independently in the home outside of formal sessions with a physical therapist.

Figure 15: SaeboFlex High Profile Assistive Hand Flexion Device (saebo.com, 2016)

The Phoenix Hand by Enable is a prosthetic device that uses wrist flexion with a series of strings and elastic bands to close the fingers and grasp objects (Figure 16).

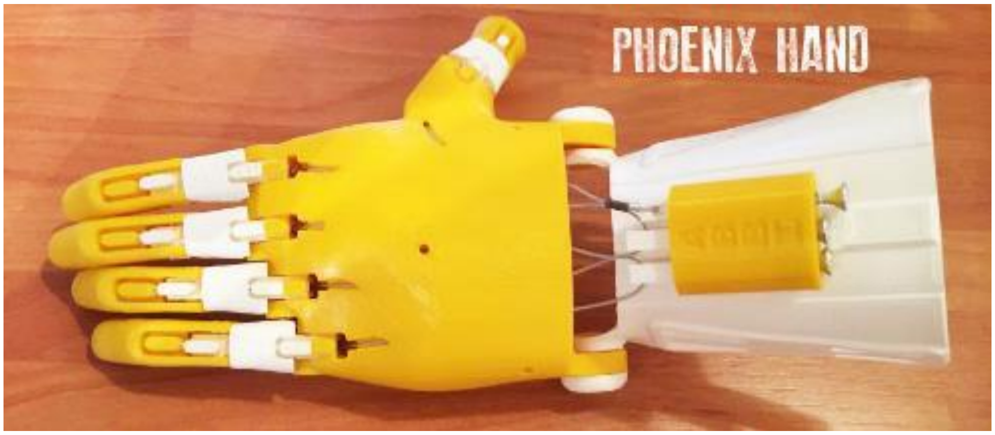


Figure 16: Phoenix Hand (Enable, 2016)

The Phoenix Hand also utilizes a whippletree mechanism to evenly distribute the force and tension through the fingers of the prosthetic. Although this is a prosthetic device, the concept of a whippletree could be used in the design of a hand orthosis seeking to increase grip strength. The whippletree mechanism is discussed in more detail in Section Whippletree Concept5.2.6.

A multitude of products for personal hygiene, dressing, and daily activities also exist for persons with arthritis. However, most are task specific and simply provide a larger or extended handle for an easier grip surface. Such specialized assistive devices are tailored to make household tasks simpler, but have limited use outside of the house. Rather, they are designed to remain at home; the hairbrush stays in the bathroom, cutlery in the kitchen, faucet and doorknob grips attach semi-permanently to the respective handles, etc. The same large grip that enables individuals to use the devices makes them more cumbersome to transport. Compression gloves are also marketed toward those with arthritis to improve circulation and decrease swelling thus reducing pain. The effectiveness and mechanism by which compression gloves work to increase functionality and reduce pain is still not known (Nasir, 2014).

2.6 Patents

When examining existing devices, there are numerous methods that have been used to achieve the desired hand movement. Many devices use a system of linkages forced into motion, either by an actuator or by tension in a cable, to contort the hand in a practical manner.

US Patent 3967321 for an Electrically Driven Hand Orthosis Device for Providing Finger Prehension (Figure 17) enables a person with no active hand function to grasp objects. The mechanism includes a trough which holds the index and middle finger and is controlled by buttons or sensors mounted to the arm of the user's wheelchair on the same side as the hand using the orthosis. For a user who wears the device on the right hand, activation of the device is achieved by pressing buttons on the right arm of a wheelchair using the right forearm or elbow. One button activates a motor which causes the fingers to move toward the thumb and another button reverses the motor which pushes the fingers away from the thumb. Between the press of either button and the start of motion, a time delay gives the user time to align the hand with the target object. An arm splint holds the forearm and thumb in a stationary position with respect to the upper arm while the fingers pivot about a joint. Each phalanx remains stationary relative to the other phalanges within the finger trough. An improvement of this device over previous devices noted by the authors is the ability of the affected hand and arm to activate the device for that hand. In this way, it is possible for a user to utilize a device on each hand.

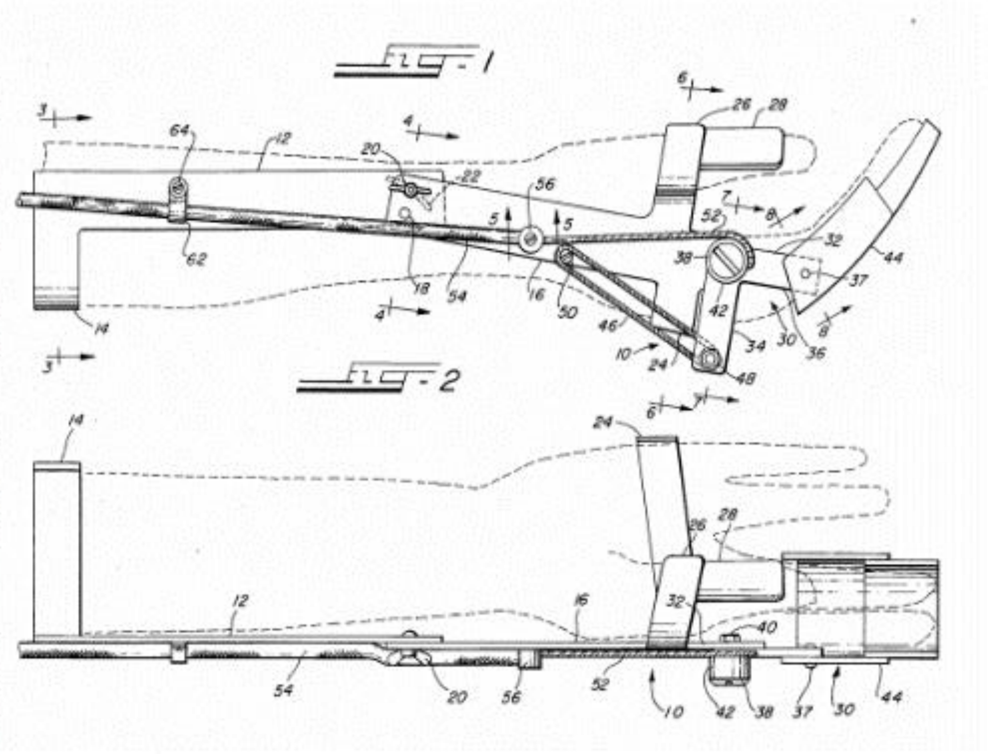


Figure 17: US Patent 3769321 for an Electrically Driven Hand Orthosis Device for Providing Finger Prehension (Ryan et. al., 1975)

The orthosis has two joints, identifiable by part labels 20 and 38, allowing two degrees of freedom. The two joints allow extension and flexion of the wrist where arm splint 12 is connected by a pin and nut to hand trough 16, and extension and flexion of the fingers where hand trough 16, is connected with a screw and bolt to finger trough assembly L bracket 32. Finger trough 44 is rigidly connected to the finger trough assembly L bracket with rivet 17, and is not free to rotate at that point.

The motion is driven by cable 52 wound around a pulley by a motor in a separate control box mounted to the user's wheelchair. The cable is attached to the pulley at one end and annular member 42 at the other. Winding the cable rotates the finger trough assembly counterclockwise, flexing the fingers. Spring 46 is used to maintain a normally open finger position by biasing the finger trough assembly clockwise. Since the motor winds the cable around a pulley, it holds the hand closed maintaining the grip force until the reverse button is pushed. The device is capable of producing only one grip which is either the pinch or pincer grip dependent upon the relative positioning of thumb and fingers; recall that in the pinch grip the thumb contacts the index finger while in the pincer grip the thumb contacts the index and middle fingers. It is not possible to determine which grip is achieved based on the patent documentation (Ryan et al., 1976). This device is of interest because it uses a cable to drive rotational motion of the device.

US Patent 20050273027, for a Dynamic Hand Splint, uses a system of pin and slider joints, manipulated by tensioned strings and springs, to bend the fingers (Figure 18). The patent is owned by Saebo, a company mentioned in section 2.5. Fingertip caps 18 at each fingertip are connected to finger tensioner 24 with finger tensioning leads 22. A separate thumb tensioner 26 connects the thumb tip cap 20 to thumb tensioner 28. Finger tensioner 24 is mounted to hand support 14 while thumb tensioner 26 is mounted to forearm support 12. The tensioners pull the fingers toward an extended position and away from the gripping position. Guides on the hand support align the parts and run the wire behind the fingers outside the grip envelope.

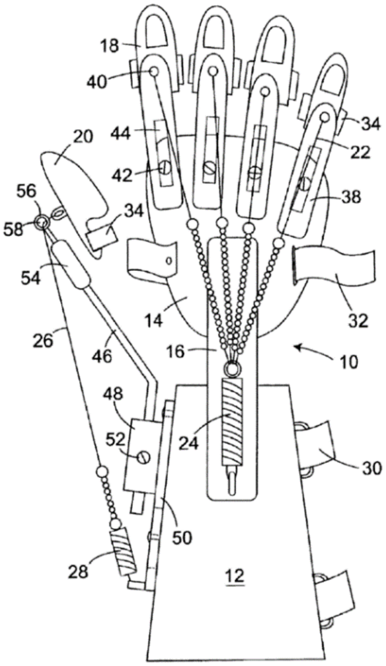


Figure 18: US Patent 20050273027 for a Dynamic Hand Splint (Farrell & Hoffman, 2005)

Though the device aids in finger extension, not flexion, the fingertip cap method of attachment and relative location of each of the key components as well as the methods used for routing cabling are potentially of use to this project. The fingertip cap design does not allow flexion of the DIP joint keeping the distal and medial phalanges linearly aligned. This signifies that objects can be grasped without utilizing this degree of freedom. Additionally, rather than using a wrist brace as a wrist support, the product uses a wide cuff, 12, connected to hand support 14 with support connector 16. A similar fastener configuration with a channel in the hand support for the support connector attachment point would allow the device to rotate in one orientation only limiting the wrist DOF from three to one and would restrict the range of motion to allowable levels. This design is a currently available commercial product used in rehabilitation and therapy facilities.

Patent JP2009022577A is for active gripping equipment (Figure 19). It is a non-powered device where the thumb is held stationary and the fingers are moved based on wrist motion. The thumb is attached to member 6 with band 11. The index and middle fingers are attached to one another and to member 5 with band 12 near the DIP joint. Member 6 holding the thumb is fixed to the palm by auxiliary portions encompassing both sides of the hand. Member 5 attached to the fingers is free to rotate about shaft 17 which is located at the PIP joint. Two springs or other elastic components, members 7 and 8, connect free member 5 to fixed section 6. Bending of fingers is linked to dorsiflexion of the wrist; grip force is variable depending upon how far backward the wrist is positioned. The two springs must have different elastic constants in order to bias the device toward an open or closed hand in the neutral wrist position. Changing which member has the larger spring constant biases the device in the opposite direction (2009).

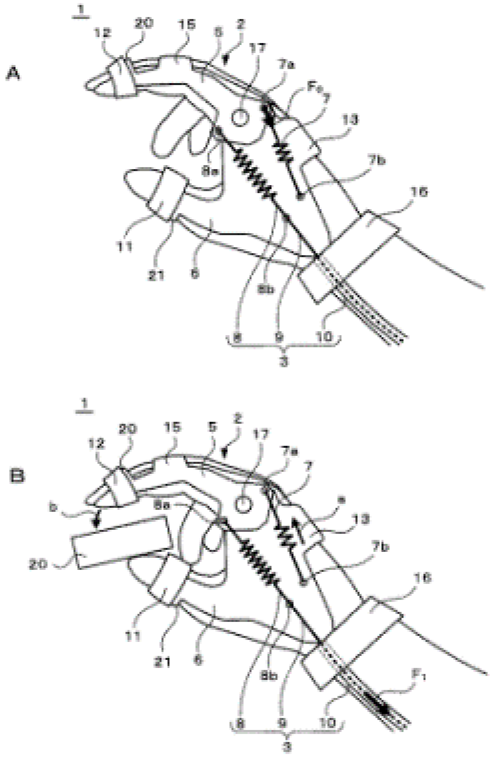


Figure 19: Patent JP2009022577A Active Gripping Equipment (Shunji, 2009)

While it is not strictly necessary for the device to contain two elastic members, member 8 can be removed and wire 9 can be directly attached to member 5 without causing the device to fail, utilizing an elastic component allows greater applied force while requiring a narrower range of wrist flexion and extension. This device is interesting because it uses linear springs to directly cause rotational motion. One potential area for improvement upon this design is modifying member 5 such that it does not interfere with the grip envelope in any hand position.

US Patent 8255079, for a Human Grasp Assist Device, accomplishes movement using a series of rings to manipulate the hand and fingers. These rings move as the result of a Tendon Drive System (TDS), which is essentially a system of wires, acted upon by an actuator to recreate the functions of human tendons. The rings, parts D, M and P, and TDS 16 are shown in Figure 20.

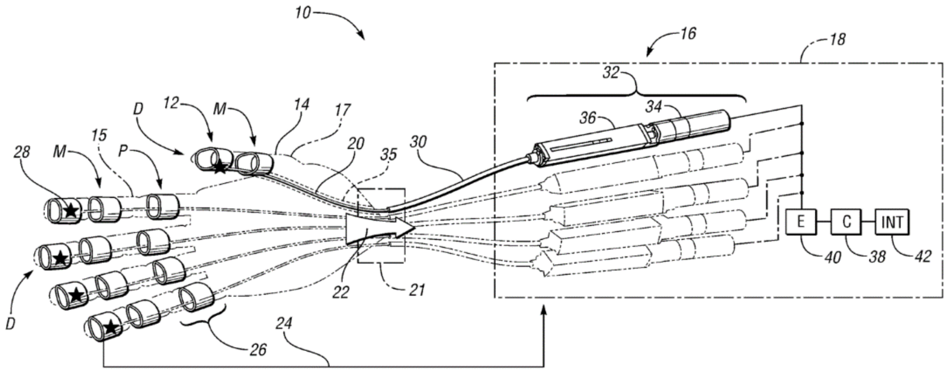


Figure 20: US Patent 8255079 for a Human Grasp Assist Device (Linn, Ihrke, & Diftler, 2012)

A ring 26 is positioned on the medial and distal phalanges of each finger connecting the tendons 20 to the user’s fingers, possibly through a wearable glove. At least one sensor 28 on the distal phalange of each finger and thumb, provides a measure of grasping force sending feedback to the microcontroller 38 driving the tendons 20. The device can then apply a force using actuators 32 that pulls on the tendons 20 causing the distance between the phalange rings 26 to decrease. This augments the user's grip force with the controller calculating the necessary applied force to attain the desired total grasping force.

This device is different from the previous devices in this section because it can apply force to more than one joint or tarsal per finger. The three bands, or two for the thumb, all serve as points where tendons can apply force to flex the finger. In cases where the path of each finger is important, control over each tarsal is highly beneficial. Another even more important benefit is that the total force is applied over a greater area. This reduces the likelihood of injury in a properly fitted device and increases the stability of the power grip where all tarsals are in contact with the item.

US Patent 20140243721, for a Myoelectric Hand Orthosis (Figure 21) uses Shape Memory Alloys (SMA) to alter the position and orientation of the fingers. SMA wire, often including Nitinol, achieves a desired shape when heated to a certain temperature. It then returns to its original shape when cooled. As seen in Figure 21, the SMA wire 110 connects to rings 160 on each finger, and when heated, the SMA wire bends, causing the fingers to bend as well. The system of wires and rings is held in place by a flexible membrane 150. The device is activated through sensors picking up electrical impulses from the muscles in the hand. A pressure sensor monitors the applied force and sends feedback to a microcontroller. Forearm and hand supports are used to hold the SMA wire, power supply, circuitry, sensors and processor in place. The device is operated externally either from a controller or iPad, where pushing buttons triggers the micro-processors in the glove.

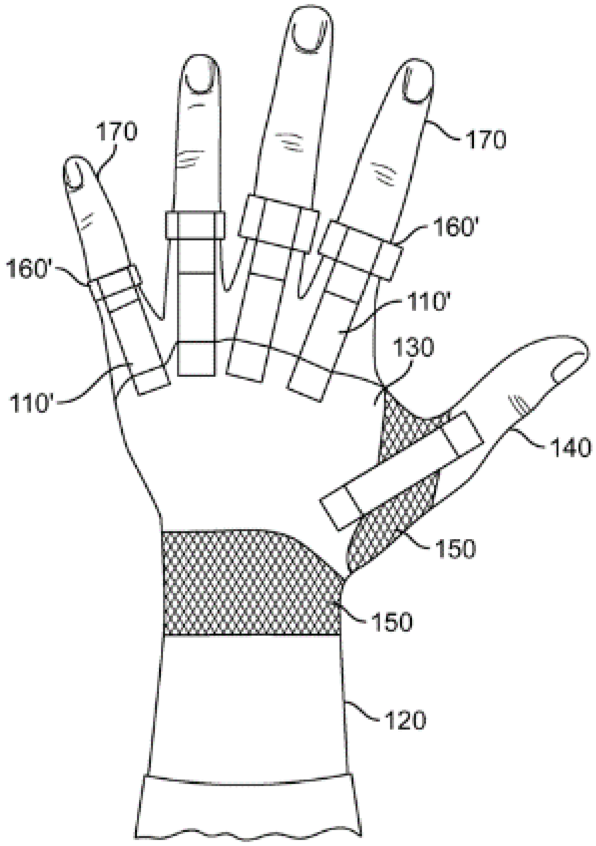


Figure 21: US Patent 20140243721 for a Myoelectric Hand Orthosis (Bryant, 2014)

According to the patent, the number and configuration of the SMA wires can vary from one per finger to one at each joint of the fingers, thumb, and wrist.

3 Goal Statement

Develop a user-activated, non-powered hand orthosis device capable of assisting individuals with reduced grip strength with the cylindrical and pincer grip positions to enhance their ability to accomplish activities of daily living (ADLs) and instrumental ADLs (IADLs), independently. This product will provide a low budget, low maintenance, and aesthetically pleasing device to individuals who have trouble closing their hands with enough force to perform ADLs and IADLs.

4 Device Capabilities

4.1 Functional Requirements

1. Device must be able to position the fingers and thumb to form the power and pincer grips.
    a. These grips are the most common and are most frequently used to accomplish activities of daily living.
2. Pincer grip must allow user to grasp items down to 7.5 mm (diameter of a pen) and up to 45 mm (average large egg size).
    a. The device must assist the user in completing activities of daily living that require this range of sizes.
3. Must apply 20 N of force in a pincer grip.
    a. This corresponds to a large enough force to make the pincer grip useful (Nycz, 2016).
4. Power grip must allow user to grasp items down to 30 mm (to hold a railing) and up to 90 mm (average cup size).
    a. The device must assist the user in completing activities of daily living and common household tasks based on the tasks listed in Table 2.
    b. Smaller items tend to be lighter and are more suited to the pincer grip and it is not always necessary for a user to hold them using a power grip.
    c. Products which increase the diameter of handles already exist for common items such as toothbrushes and pens. Users have the option of purchasing such a product to widen the handle for the power grip if he or she does not wish to adapt to utilizing the pincer grip for the specific task.

5. Must be able to apply 20 N of force, normal to the distal phalange, in the power grip
    a. This corresponds opening a door handle which is the daily task requiring the greatest power grip strength
6. Should meet all ISO safety standards for orthotic devices
    a. Namely ISO 22523:2006 for External limb prostheses and external orthoses - Requirements and test methods
7. Should operate independently of other hand while the user performs a task.
    a. The opposite hand may be used for setup and adjustment, but should be free to work independently while the device is active.
8. Must give the user control over when the hand opens and closes.
    a. The device must use input from the user to activate motion
9. Must allow the user to don and doff independently
    a. The functionality of the device is diminished if the user cannot initiate or terminate its use without assistance from another person. The user may be unwilling to wear the device outside of the home if it cannot be easily removed.
10. Should be comfortable when worn continuously for 8 hours
    a. Users' skin should not be irritated after wearing device
    b. Users should have no pain or injury due to wearing device

4.2 User Requirements

1. User must be able to passively flex fingers enough to close one's hand to hold an object, using a cylindrical grip, as small as 30 mm in diameter (to hold a railing).
2. User must be able to passively flex fingers enough to close one's hand to hold an object, using a pincer grip, as small as 7.5 mm in diameter (diameter of a pen).

3. User must be able to extend his/her own fingers with sufficient force to overcome the force applied by the finger flexion mechanism if applicable.
    a. In devices that use voluntary closing, there is no force to overcome. In devices that use voluntary opening, the user must be able to overcome the force to open the hand
        i. In voluntary opening, the user must provide the difference between the flexion force applied and the assisting extension force.
    b. In devices that use voluntary opening, there is no minimum amount of extension required to utilize the device; however, the amount of extension limits the maximum object size the user is able to grasp

4.3 Design Specifications

1. Any contact surface where parts move in relation to each other must not directly contact the user's hand or arm
    a. Moving parts have the potential to pinch anything near the joint or irritate the skin; thus the user's body should not be in a position which allows contact with a joint.
2. The device must be capable of accommodating varying hand sizes
    a. The device should fit small, medium, and large sized hands. The design should be based around five specific hand measurements (hand length, hand breadth, 3rd finger length, dorsum length, and thumb length) which drive sizing (Linnane, 2015). A single device does not need to fit all hand sizes.
3. The weight of the device should not exceed 200g
    a. A user must not be unduly fatigued by wearing and operating of the device.

   b. Users will have limited hand and arm strength so the device must be as light as possible; 200g is an achievable target that would allow many patients to be able to use the device (Nycz, 2016)
   c. Other finger or wrist flexion/extension splints weigh ~500g (dynasplint)
4. Maintenance and adjustments must require only hand tools
   a. No special tools should be required for providing routine maintenance to or for fitting the device.
5. Manufacturing of all prototypes by the WPI team must cost under $1,000
   a. This is the allotted budget for this project.
6. Cost to manufacture final prototype should be under $200 to maintain affordability.
   a. $200 in creation costs given a 3x markup for retail sale results in a $600 cost to the consumer
   b. Consumer cost should be comparable to devices which offer similar assistive functionality
7. Must be able to be cleaned with common household cleaners
   a. Materials should be chosen such that the device can be regularly sanitized. The material should not degrade or react with approved cleaners.
8. Must be water resistant
   a. The product is intended to be worn daily and should withstand rain and occasional splashes of water.
9. Must remain functional after a drop of 1.5 meters.
10. Should have no protrusions larger than 3 cm that could catch on clothing or other items.

5 Designs

5.1 Finger Motion Functional Decomposition

A hand orthosis which drives finger motion must include a means by which to generate force and a method of transferring that force to the fingers of the user. These two actions can be broken down further into four categories of components in the hand orthosis. Activation type refers to the motion produced by the user which generates the force. This motion can be any movement which is not the motion being driven by the orthosis. Transmission of movement from activation site to the mechanism is how the force generated by the user is applied from a distant site to the finger motion mechanism. The mechanism causing the finger/hand movement is the portion of the device which moves the fingers by guiding them along a set path during flexion and/or extension. Finally, attachment to user encompasses the means by which the mechanism is secured to the hands and fingers. The attachment method affects force distribution and fit of the device. The components being considered for this project are described by category in the following sections. A full chart of the different components can be found in Appendix D: Finger and Thumb Functional Decomposition.

5.1.1 Type of Activation Movement

The first component of a hand orthosis is the activation movement. In order to activate the device, the user undertakes some non-hand motion such as flexing or extending their wrist, abducting or adducting their wrist, flexing their elbow, or moving their shoulder. This activation movement is then transmitted from the activation location to the hand mechanism which causes finger movement. Many upper limb prosthetic devices use similar activation movements. An activation movement could also come from the contralateral hand. When selecting the activation type, it is important to consider the user's range of motion in these areas. For example, if a stroke patient has little to no movement or control of their wrist, the wrist activation types would not be acceptable. Another factor when selecting the activation type is the position of the user's hand when the device is activated. If the activation movement constantly causes the user to be in an uncomfortable position and unable perform ADLs, the activation type would be unsuitable. A passive hand orthosis could also have no activation. If the device is always assisting in closing regardless of the motion and body position of the user, the device would require no active movement from the user to initiate the closing force.

Finger Extension

Energy used to open the hand from a closed fist can be stored and then used to close the hand. However, is unusual for a person with diminished finger flexion force to have significant finger extension force. Therefore, there is a limited number of people who would benefit from a device using a finger extension activation mechanism.

Wrist Motion (Flexion/Extension)

Wrist flexion and extension is one way to activate the orthosis. By flexing or extending the wrist, cables, springs, or a combination of the two would be lengthened or shortened causing the fingers to open or close. As mentioned previously, the user must have enough range of motion in the flexion and extension directions to use this method of activation. The wrist activation should also not put the user in uncomfortable positions and therefore it would be ideal to have the fingers close when the wrist is oriented close to zero degrees as grip strength is the highest in this position (Kattel et al, 1996). Zero degrees refers to the wrist being in the neutral position with no flexion or extension.

Wrist Motion (Abduction/Adduction)

Wrist abduction and adduction is similar to flexion and extension. However, movement in the radial and ulnar directions is typically more difficult and people have much less range of motion compared to in the flexion and extension directions. Therefore, it could be difficult for the user to activate the device as well as control the variance in finger movement due to the smaller range of motion. If the user does have adequate range of motion and control of the wrist, the wrist activation in the extension and flexion directions would be preferred over activation from movement in the radial and ulnar directions.

Elbow Motion

Elbow motion activation is another way to activate the orthosis. In a similar way to wrist flexion and extension, the user would flex or extend their elbow causing cables, springs, or a combination of the two to become shorter or longer. This would then cause the fingers to be opened or closed through some mechanism. Using the elbow as an activation movement does not require the user to have significant wrist control. Another benefit of using the elbow as an activation movement is that people typically have a much greater range of motion in the flexion direction of their elbow than in their wrist allowing for more variance and control over finger movement. However, using the elbow as an activation site may lead to other issues concerning the user's position and ability to perform ADLs. For example, flexing the elbow to a certain degree to grasp a cup or utensil and then keeping the elbow flexed in that same position while bring the cup or utensil towards one's mouth could be difficult and uncomfortable for the user.

Shoulder Motion

Shoulder movement is another way to activate the hand orthosis. This concept was inspired by an upper limb prosthetic hook (Figure 22).

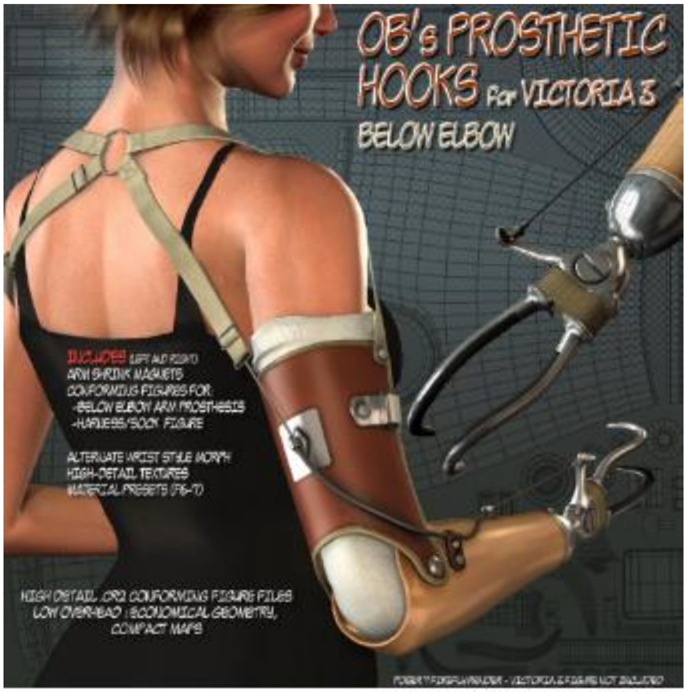


Figure 22: Shoulder Activated Prosthetic Hook: OB's Prosthetic Hooks (2015)

This purely mechanical prosthetic uses shoulder movement to activate the hook by pulling a lever causing the hook to open. Rubber bands around the hook resist the opening and cause the hook to return closed around an object. Using the shoulder to activate an orthosis in a similar way would avoid the issues of the wrist and elbow activations putting the user in an uncomfortable position. However, a shoulder activated orthosis would be much larger and visible as it would run all the way up the arm and onto the back. Such a large device may be undesirable to many users.

Wrist, elbow, and shoulder activation movements are all possible ways to activate the orthosis. Each movement has its advantages and disadvantages depending for the user. Therefore, when this device is marketed it may be beneficial to have multiple attachments available where the user could choose which activation type works best for them. For this project, we will select one activation type to simplify the manufacturing phase, but any of the four activation types could be best for a certain user.

5.1.2 Transmission of Movement from Activation to Mechanism

After the user activates the hand orthosis device, the activation movement must be transmitted to a mechanism. The transmission of this activation movement can be accomplished through cables, springs, a combination of cables and springs, or a linkage. For this project, cables are defined as both strings and bands. The transmission of activation movement is key to creating movement in the fingers through some other mechanism. When selecting an option for the transfer of movement, it is important to consider whether the option is capable of producing an adequate amount of force when combined with various functional components.

Cables

Cables routed from the activation location to the finger mechanism location can be shortened or lengthened when the device is activated to cause movement of the fingers. Pulling the fingers open and closed using cables is commonly seen in prosthetic hand devices such as the Phoenix Hand by Enable (See Whippletree Concept). The problem with using just cables to pull the fingers open or closed is that they will not naturally return to the neutral position. Therefore, a band or spring that opposes the motion would be required to ensure the fingers could return to the neutral position. Depending on the mechanism, cables could be used to either pull the fingers open or closed.

Springs

Linear springs routed from the activation location to the finger mechanism location could be compressed or stretched when the device is activated to cause movement of the fingers. Springs are able to apply significant forces even when the change in length is small. Springs would be beneficial to use when small displacement of the activation method would otherwise limit the capabilities of the device. Although the springs themselves could provide the necessary resistance to return the fingers to their neutral positions, using just springs to transfer movement could raise other issues. Springs can be prone to buckling in compression when the deflection becomes too large. Also, large springs of customizable lengths may be difficult to find without manufacturing them internally and could potentially add unnecessary bulk to the device.

Torsional springs using the change in angle rather than change in length can also be used. Buckling is not a concern for torsional springs and small displacements can be used to store a large amount of energy. However, torsional spring dimensions that are compatible with the human body requires custom fabricated springs which has a significant cost.

Cables and Springs

The combination of cables and springs, as mentioned previously, would solve the problem of providing resistance for the fingers to return to neutral position. By combining cables with springs, the forces provided to the fingers could be increased as well. If springs are used in compression, the concern for buckling would still require consideration. This combination could also be used to either pull the fingers open or closed.

Adjustable forearm mounting

An additional component could be an adjustable mounting location. For example, when using the wrist activation type (extension/flexion) moving the mounting location up the forearm could tighten the cables, springs, or combination of the two eventually resulting in a greater force. This variance in mounting location could be accomplished using the contralateral hand. Although an adjustable forearm mounting location component is not itself a component for transmission of movement, it could be a way for users to increase the forces provided to the fingers from the activation movement.

Cables, springs, or a combination of cables and springs are all potential ways to transfer the activation movement to the mechanism location. As mentioned, careful analysis of the forces each option could provide when coupled with other functional components, as well as addressing areas for concern, is necessary for the design of this hand orthosis.

5.1.3 Mechanism Causing Finger/Hand Movement

The third component of a hand orthosis device is the mechanism that causes the fingers to move. After the device has been activated and the activation movement has been transferred, the mechanism provides the movement of the fingers. This movement can be accomplished through more cables, finger linkages, springs, or even shape memory alloys. When selecting an option for the mechanism, it is important to consider how the mechanism moves the fingers. A poor device would produce forces on the fingers in a way that causes discomfort to the user or causes the fingers to flex or extend in an unnatural manner.

Cables

Cables running along the fingers, either on the sides, tops, or bottoms could provide the necessary mechanism to flex and extend the fingers. A benefit of using cables is that they can be very low profile and lightweight. A difficulty in using cables is determining where to attach them along the fingers and whether they should run along the top, side, or bottom so that the fingers will properly flex and extend.

Finger Linkages

Finger linkages are another mechanism to move the fingers. A kinematic linkage could assist in flexing and extending the fingers along the correct path. A benefit to using a linkage is that the linkage would ensure the fingers always follow the same path. A disadvantage to a linkage type mechanism is that it could potentially increase the weight of the device significantly as well as increase the overall bulk. Different linkage designs would be required depending on whether the device attempted to pull the fingers closed or open. A full kinematic analysis, along with how the linkage interacts with the hand as one system, would be required for the incorporation of a linkage in this orthosis design

Torsional Springs

Torsional springs aligned at the joints of the fingers could provide the mechanism for flexing and extending the fingers. As the torsional springs provide their own force and resistance, a design with torsional springs may not need one of the activation types or transmission of movement types described previously. Instead, the act of opening the hand loads the springs and activates the mechanism. The springs always act to close the fingers with the fist as the neutral position. However, it may be difficult to align the springs with each joint.

Cables, finger linkages, and torsional springs are all possible mechanisms for moving the fingers. As mentioned, a careful kinematic analysis of the mechanism and the hand as a whole system is required. The next important, and possibly more important, component is how to attach these mechanisms to the fingers. The mechanism must be attached to the hand in order for the force to be transferred.

5.1.4 Attachment to user

The final section of the complete orthosis is the component or components which connect all other portions of the orthosis to the user’s body. The attachment must secure to the user’s hand or fingers as well as connect to the mechanism driving the hand motion. A proper fit is crucial as an orthosis that does not properly transmit force through the hand produces significant potential for injury. When choosing a method of attaching the mechanism to the fingers, the requirements of the mechanism driving finger motion must be taken into account to ensure proper force distribution. Therefore, each attachment method is not suitable to be paired with all mechanisms. In addition, the method of attachment is highly related to comfort and can be a deciding factor in whether the user chooses to wear the device or not. A device can function perfectly but be a poor device if the user is not willing to utilize it.

Glove

Perhaps the most intuitive of all attachment methods is a glove. Gloves are readily available in many materials and thicknesses. However, if the glove material is too thin it could tear easily and more durable gloves tend to be bulkier. The typical sizing of small, medium and large fits most hands and elastic wristbands on some glove types prevent them from falling off. Gloves are also completely flexible which does not restrict finger motion but is not compatible with other components which need to be mounted rigidly to the hand. In this case, a glove could be paired with another attachment type.

Finger Sleeves

Finger sleeves are similar to the finger portion of gloves but they do not cover the back of the hand or the palm. For this project, a finger sleeve is taken to be a flexible membrane which slides over the finger and may or may not include a strap or other fastener to hold the membrane around the finger. It may cover multiple phalanges of the same fingers or multiple phalanges of multiple fingers if the finger motions are to be coupled. Two examples of finger sleeves are finger cots (Figure 23) and Lee Tippi Fingertip Grips (Figure 24).

Figure 23: Example of a Finger Cot (Currell, 2009)

Figure 24: Lee Tippi Fingertip Grips (leeproducts.com, 2010)

For a finger sleeve which covers the fingertip, materials such as rubber or silicone provide grip surfaces with a high coefficient of friction which can be higher than that of the uncovered finger thereby allowing reduced force required to grasp objects. Since they cover less of the hand than gloves, finger sleeves can be made of a thicker material without being as obtrusive. Care must be taken during the donning and doffing processes as each sleeve must be donned of doffed individually with special attention taken to prevent tangling or snagging the sleeves on the mechanism. Like gloves, the flexibility of finger sleeves makes them unsuitable as a rigid mounting point.

Rings

A ring is a closed loop that wraps around one phalanx of a finger. They can be made of rigid or soft materials such as aluminum or silicone respectively (Figure 25).

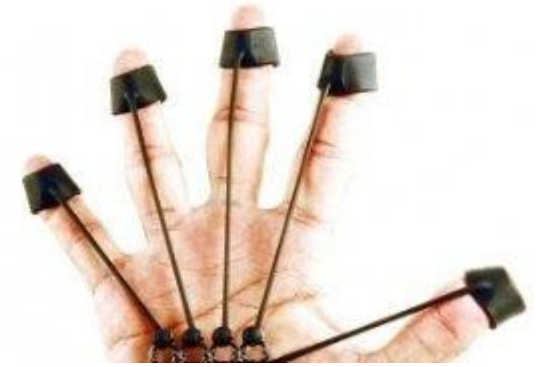


Figure 25: Flexible Finger Rings Attached to Distal Phalanges (amazon.com, 2016)

Rings are very versatile attachment points as the location of the rings can be varied to suit the needs of the mechanism; multiple rings, and therefore multiple contact points, per phalange are possible. Unlike gloves and finger sleeves, designated attachment points, not simply a hole, for connecting to the mechanism can be built into the rings. To prevent the fingers slipping past each other and crossing, rings should not be used as a standalone method of coupling the fingers. While the ring must be secure enough to remain in place, it cannot be too snug and restrict blood flow. Like the finger sleeves, each ring must be donned and doffed individually which can be time consuming.

Rigid Finger Channels

This project defines a rigid finger channel (Figure 26) as a solid piece or pieces which encompass the top and sides of the finger with a strap on the palm side to hold it snugly against the finger. The channel may fit over one or multiple phalanges. In the case of multiple phalanges, it may hold them fixed in relation to each other or contain joints in the device to allow DIP and/or PIP rotation.

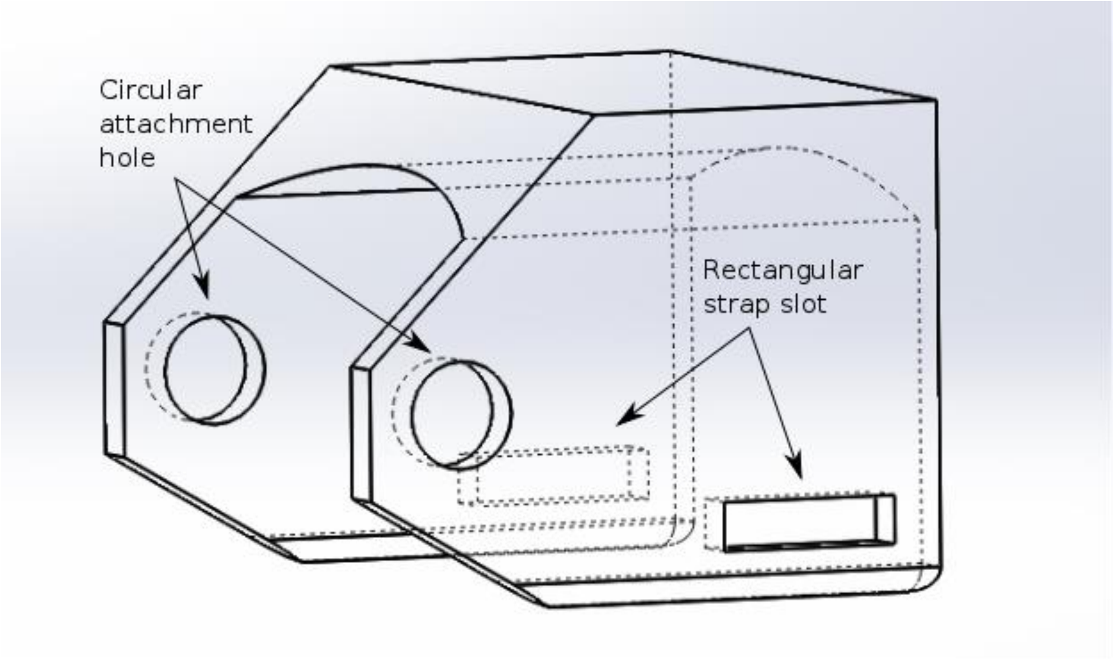


Figure 26: Rigid finger channel with a circular hole for attachment to other sections and rectangular slot for attachment strap

As with the rings, designated attachment points can be built into the finger channels. The rigid finger channel is a very stable attachment point allowing hardware such as screws to be used. The channels do not have rotational symmetry along the bone direction resulting in a low probability that the channels, and mechanism, will rotate around the fingers during use. However, as the name implies, the channels are rigid which may be a source of discomfort after long periods of use. Additionally, they have the potential of forcing the user's fingers apart from one another into an outstretched star shape due to their width.

Braces

Regardless of the method of attachment, a wrist or thumb brace may be needed to keep the hand aligned properly and provide resistance to the forces applied by the finger motion mechanism. In a person with weakened grip strength, support for the wrist may be necessary to attain a hand orientation suitable for gripping, an example is the air cast seen in Figure 27. In addition to supporting the user's hand and arm, a brace can serve as a mounting point for the device or its components. It can be fully rigid and prohibit all wrist/thumb movement or it can be slightly elastic to gently resist motion away from a defined neutral. There are several wrist braces available commercially which serve the function listed above.

Figure 27: Air cast wrist brace with no thumb support (betterbraces.com, 2016)

Some wrist braces, such as the Comfortform shown in Figure 28, incorporate thumb supports into their design. Unlike the Comfortform brace, many thumb supports do not extend over the IP joint. This is significant because the power and precision grips utilize the thumb tip as the point of contact between the thumb and fingers or thumb and the object. Without active flexion of the IP joint countering the force applied by the fingers, the IP joint can be forced into a hyperextended position causing pain or injury.

Figure 28: Comfortform wrist brace with thumb support (mvmsinc.com, 2016)

The various attachment methods described above vary in where they are positioned on the hand and how they are secured. In certain cases, two methods can be paired together such as rigid finger channels utilized with finger sleeves for greater comfort or a glove with integrated rings to make donning and doffing simpler. The mechanism and attachment to fingers should be designed such that the connection between the two uses space efficiently and maintains any mechanical advantage gained by the mechanism.

5.2 Components for Finger Motion

5.2.1 Design 1: Internal Band System

Activation Type: Wrist Motion (Flexion/Extension)
Transmission of Movement: Cable
Mechanism Causing Finger Movement: Cables for Flexion
Attachment to User: Glove or Finger Sleeves and Ring

This concept focuses on providing grip force by pulling the hand closed with cables controlled by the orientation of the wrist. The device will look and feel like a brace with very few external signs that it is an assistive device. On the inside, there will be cable running from each individual finger to the primary hub located on the forearm. This hub will be adjustable for each user, allowing the mounting point of the cables to be altered at will. The cables will run across the center of the palm and attach to individual sleeves, similar to the fingers of a glove that span the first link of the proximal joint. The thumb will also have cable running to the sleeve, but would have to be adjusted based on which grip the user would use.

The user will control the device by changing the orientation of his/her wrist. When the user extends his/her wrist, the cable will resist the movement and pull the hand towards a closed position. While an item is being gripped, the cable will be held in tension and resist the forces of the gripped object. When the user rotates his/her wrist inward, the cable will slacken and allow the hand to more easily open. An existing version of this design can be seen in Figure 29.

Figure 29: Example of Internal Band System (King, 2007)

In order to determine if this design is attainable, it is necessary to look at the fundamental analysis of the system. Since the forces acting on the hand depend heavily on the position of the wrist, we selected the maximum open and closed positions of the wrist to analyze the forces acting on the system.

Figure 30 shows the general concept for the device. The fingers are shown as rectangular links with dots showing the location of the connecting joints. The blue line shows the cable, running on the inner side of the hand and the blue dots are the points connecting the cable to the hand. The mounting points allow the cable to slide, changing the relative length of cables in between each of the individual mounting points when the hand is closed. The cable is connected to a slider joint located on the forearm.

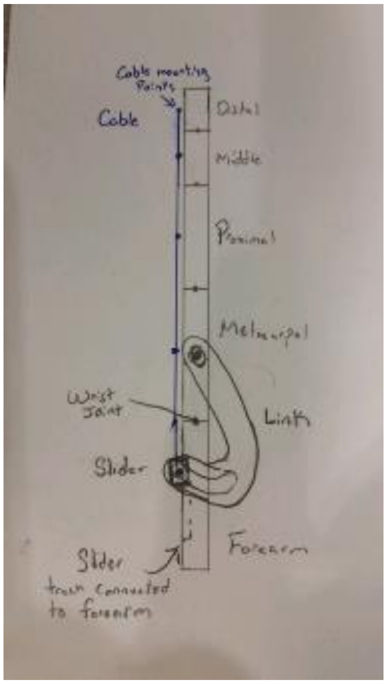


Figure 30: Internal band system with open hand

The slider has a track running down the length of the forearm. The slider is connected to the back of the metacarpals as an extension of the linkage (i.e. it is a joint with 0 DOF). The linkage has a slot which connects to the slide with a pin joint, transferring the angled movement of the wrist to a vertical movement along the forearm. This linkage acts similar to a cam follower. The purpose of the slot is to control the magnitude of the force on the slider with respect to the angle of the wrist.

Using the Gruebler mobility equation based on a 2 dimensional representation of the mechanism, the mobility (M) is related to the number of Links (L) less the number of full joints(J) and half joints (H) shown in Equation 1. This equation shows that the linkage has 1 DOF, meaning that the single motion provided by the wrist would be sufficient to completely define the motion of the system.

Equation 1: Gruebler/ Kutzbach Mobility Equation

$$M = 3(L - 1) - 2J - H$$

$$L = 3$$

$$J = 2$$

$$H = 1$$

The device works by rotating the wrist in extension which both closes the hand and keeps the inner cable in tension. When the hand closes around an object, the wrist is used to apply a force to resist the force applied by the gripped object. The force of the wrist keeps the cable in tension via the single linkage. The tension on the cable keeps the fingers from opening. The amount of force that is applied by the wrist must be sufficient to keep the slider from moving. This should allow users to hold objects with increased grip force.

Figure 31 shows the hand with wrist extension. The metacarpals are at angle α relative to the vertical alignment of the hand. In this orientation, the slider is at position 2, or the furthest away from the hand. The distance that the slider moves is equal to the amount of excess cable generated by closing the hand. Using the law of cosines and assuming the cable is connected at the center of each finger joint, the total cable difference from the center of the metacarpals to the center of the distal is 0.45 inches. These calculations appear in Appendix E: Cable Length Calculations.

$F_{extension}$ is equal to the amount of force generated by extending the wrist which is dependent on angle α. A study was conducted which shows that the maximum force a wrist in extension can generate is 29N at 45 degrees at the center of the metacarpals (Jung, 2002). This number is derived in the report by testing the point force at the center of the metacarpal produced by the moment of the wrist. While the wrist can generate a higher force at lesser angles, the force at 45 degrees will be the limiting factor. In order for this design to be viable, we must be able to generate the 20N of output force outlined in our design specifications at the maximum wrist angle. The cable (T_{cable}) is equal to the force of the linkage in the Y direction (F_y) which is equal to the product of the force of extension multiplied by the sin of the angle of the applied force (θ). As designed, the linkage can generate a force of 29N * Sin(45) = 20.5 N in the cable.

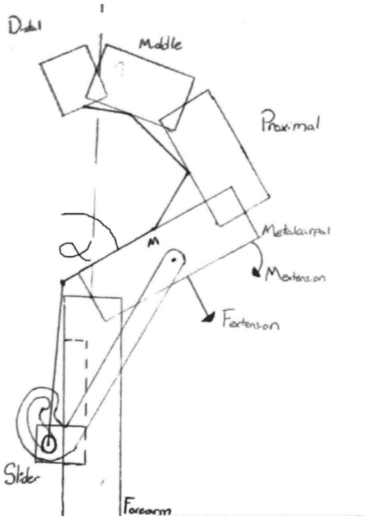


Figure 31: Internal band system with closed hand

This model of the maximum change in cable shows the cable is mounted to the center of each finger segment and that the cable is not hampered by the hand or objects being contacted. In the proposed model, the cable actively interferes with the cylindrical grip; however, modeling the mounting points of the cable at the center of each finger generates the largest change in cable length. While further testing may prove that running the cable across each joint would be more efficient, it is important to prove that the concept would be viable with the largest change in cable length.

From our initial testing, we found that the amount of variation in the length of the cable in extension will be able to compensate for about 3.9in of change (Appendix B: Change in String Length Experiment). Since the cable may need to move further than the contour of the wrist facilitates, the movement of the link may be necessary to keep the cable in tension. The mounting point of the link is moving $\frac{1}{2}M*\sin(\alpha)$, assuming that it is mounted near the center of the metacarpal joint, where M is the length of the Metacarpal joint and α is the angle of the wrist. Using the average metacarpal length of 3in (Linnane, 2015), the base of the link moves 0.75in which would be more than sufficient to maintain cable tension.

After establishing the amount of tension on the cable, it is important to look at how much force of the cable is acting on the individual fingers. The finger is being acted upon by the force of the gripped object perpendicular to the surface. The finger is also being pulled by the tension in the cable. Finally, the digit is acted upon by the middle digit. In this setup, the finger joints are used as part of the mechanism. Another limitation of this arrangement is that the cable occupies space within the grip envelope, potentially interfering with the gripping of an object. Even approximating this angle as 30 degrees, the resulting grip force is about 10.25 Newtons with an input force of 29N.

With a desired force of 20N, it would be necessary to augment this design with a feature to provide a mechanical advantage of at least 2. This could be accomplished with two pulleys or several other types of mechanical devices.

This design allows for a very streamlined device with lightweight components. This setup also allows for control over the movement of the thumb independently of the rest of the device. Finally, the design is very adaptable to individuals, meaning that the tension and the forces can be adjusted based on the individual user.

The primary challenge of this design is that the setup requires cables across the user's palm. This means that it may be uncomfortable to use and may interfere with the grip envelope. In addition, the maximum amount of applicable force is a function of the angle of the wrist. This could prove too inconsistent and potentially risky when carrying heavy objects. Table 3 shows an estimated total cost for the components of this design.

Table 3: Internal Band Estimated System Cost

Item Name	Item Cost ($)	Item Amount	Total Item Cost ($)
3-D Printed Links	35 per in^3	2 in^3	70
Base Glove/ Material	20 per glove	1	20
Fasteners	15		15
Cable	10 per yard	1 yard	10
Padding	10 per roll	1 roll	10
CAM follower	20	1	20
Approximate Total Cost ($)		$145	

5.2.2 Design 2: External Band System

Activation Type: Wrist Motion (Flexion/Extension)
Transmission of Movement: Cable
Mechanism Causing Finger Movement: Finger Linkage (Open to Closed)
Attachment to User: Coupled Fingers/ rigid finger channels

This design focuses on using tensioned strings to move the user's fingers into the desired positions. The strings would be tensioned while the hand is at a resting, open position, and the movement of fingers would be driven by wrist movement. The tensioned strings would be mounted on the back of the metacarpal and wrist. As the palm of the hand is moved toward the inner arm, the fingers would be closed, forming the desired grip. Different thumb position would result in the power and pincer grips. The index and middle finger would be treated as one while the ring and pinky would be treated as one. Each set of fingers would be held in place by an external linkage system and the tensioned strings would exist alongside these links shown in Figure 32. The device would have a wrist cuff, or gauntlet, where the tensioned strings would meet.

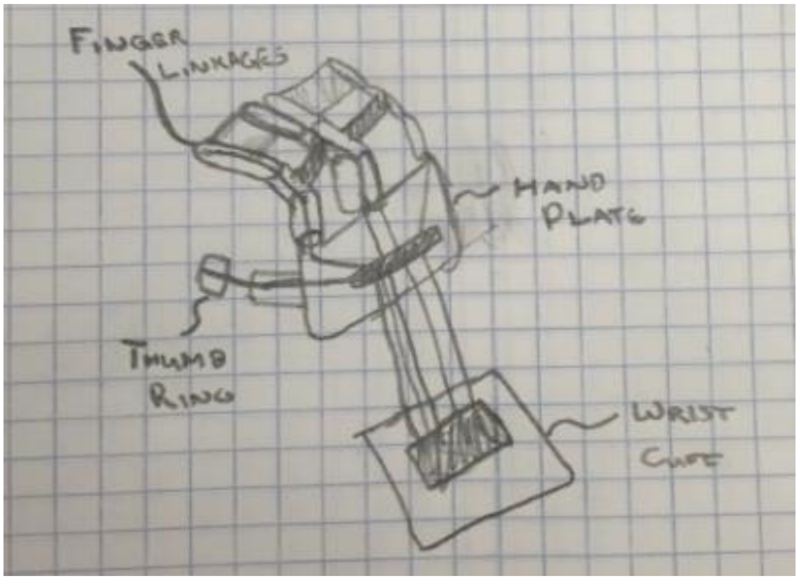
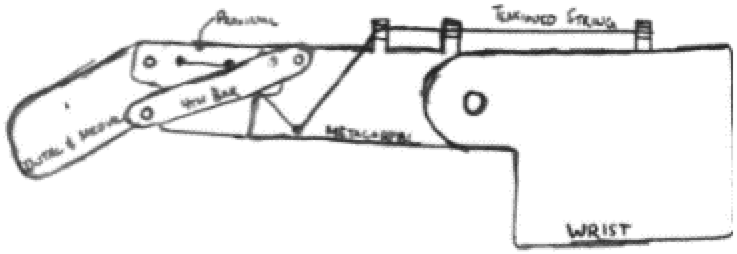


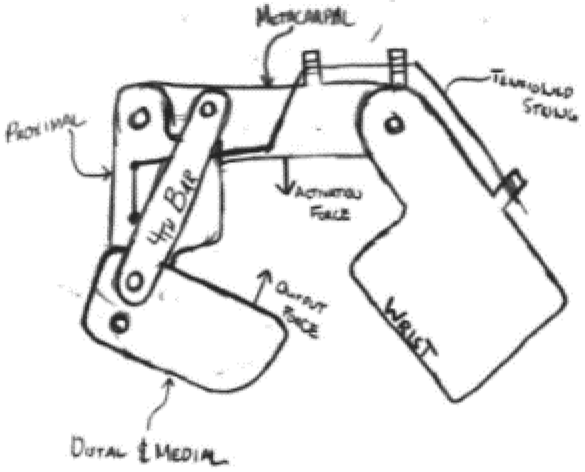
Figure 32: External Tension Concept Sketch

Many components of this design, including the links, would need to be solid pieces instead of fabric. This could lead to some discomfort if the solid pieces are not the correct size for the users. However, this design would leave the user’s palm free, allowing the user to feel the items they grasp. This device would require very little existing hand strength, but relies heavily on a user’s wrist motion. Also, this device’s activation type could be moved up the arm to the elbow for user’s who struggle with wrist movement.

By bending the wrist inward (flexion), the hand plate would distance itself from the wrist cuff, causing the strings to pull taut, and ultimately causing the fingers to bend inward toward the user’s palm. To assure that the forces are evenly distributed across all linkages, a whippletree mechanism could be used. However, the thumb would need to operate differently than the fingers. A crucial difference between the pincer and power grip is the position of the thumb, shown in Figure 7. Being able to lock the thumb in different positions would allow the user to make different grips. Figure 33 shows an example of the external finger linkages, in the open and closed positions and Figure 34 shows the forces acting on each link in the external band system design.



At Rest



After Activation

Figure 33: Four Bar Finger Linkage, Open and Closed with Tension

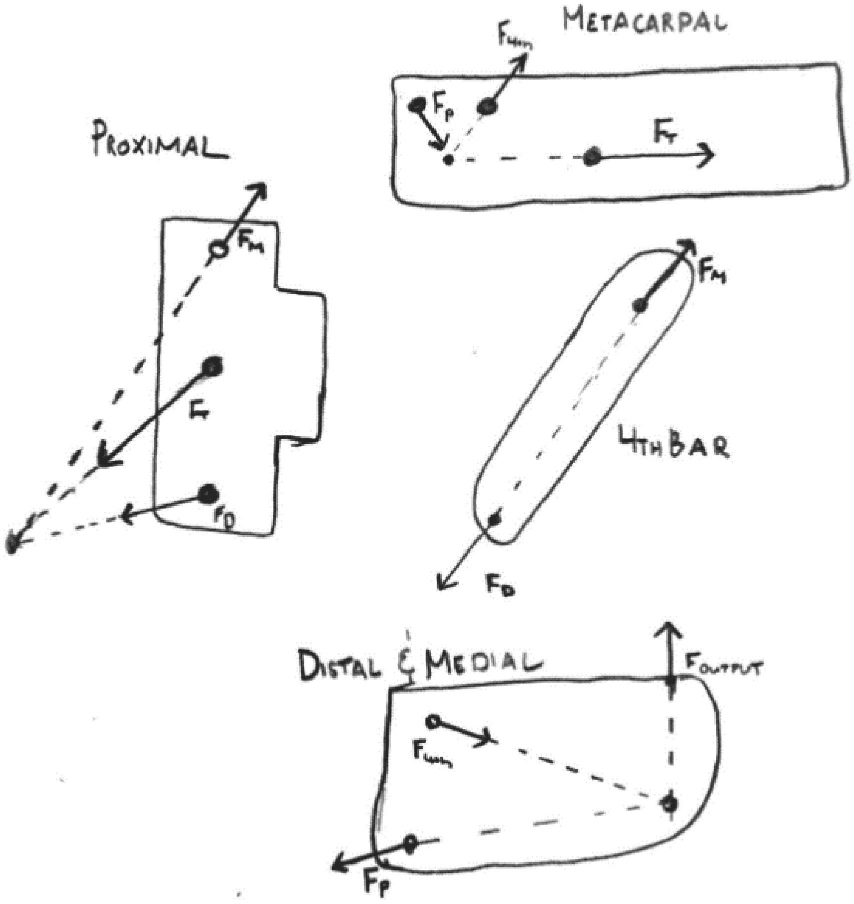


Figure 34: Forces Acting on Links of External Band System Design

This design, under ideal conditions, will have an output force of roughly 11 Newtons. The calculations to find the output force are located in Appendix G: Design 2 Calculations. Table 4 shows an estimated total cost for the components of this design.

Table 4: External Band System Estimated Cost

Item Name	**Item Cost**	**Item Amount**	**Total Item Cost**
3-D Printed Links	~\$35 per in^3	~3 in^3	~\$105
Velcro Straps	~\$10 per package	1 package	~\$10
Fasteners	~\$15		~\$15
Cable	~\$10 per yard	~1 yard	~\$10
Padding	~\$10 per roll	1 roll	~\$10
Total Cost			~\$150

5.2.3 Design 3: Compression Spring Driven Linkage

Activation Type: Wrist Motion (Flexion/Extension)
Transmission of Movement: Cable and Spring
Mechanism Causing Finger Movement: Finger Linkage (Closed to Open)
Attachment to User: Rigid finger channel

Closed to Open Finger Linkage

A similar linkage to the linkage in Design 2 could also assist in pulling the fingers from closed to open (Figure 35). The main difference in the linkage design is simply that the cable is attached at a different location. The closed to open finger linkage also includes a spring attached to a slider. The primary goal of this design is to maintain alignment of the hand and forearm while the fingers are in the closed position as this orientation allows for the greatest grip strength.

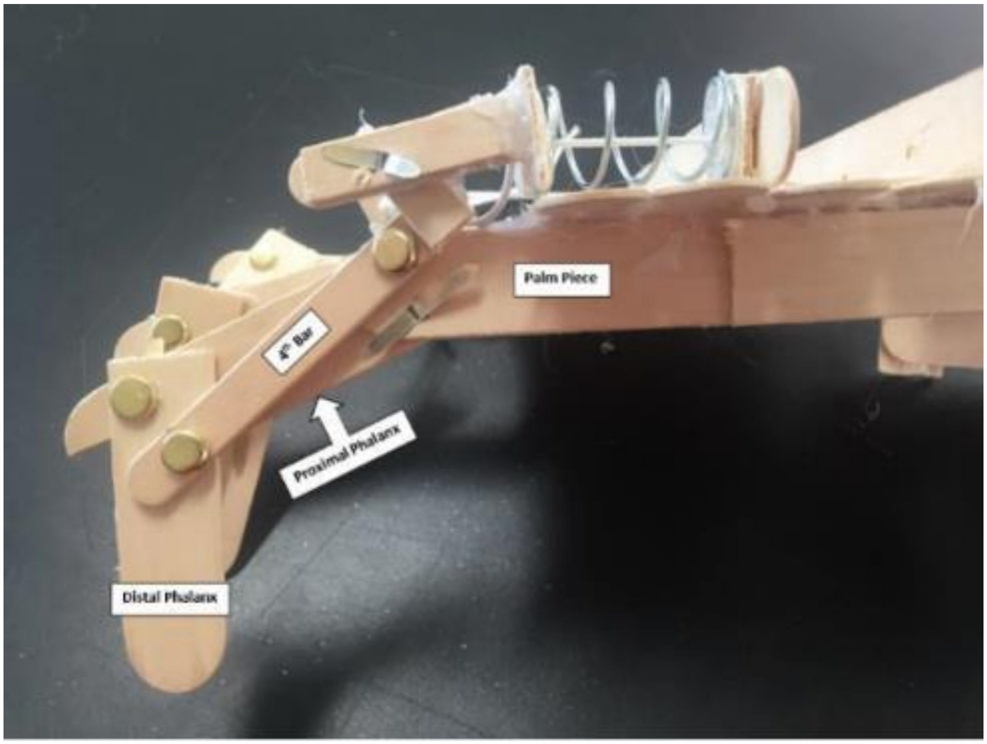


Figure 35: Basic Frame Closed to Open Linkage Device

Similar to the open to closed linkage system design, the fingers are attached to a mechanical linkage system positioned either on top of or beside the fingers (Figure 36). It is important to note that the distal phalanx portion of this linkage covers both the middle and distal phalanges. These linkages would be connected to compression springs along the back of the hand and would control the movement of the fingers. These linkages would have a range of motion from fully closed to fully open.

The linkages would also be connected to a cabling system grounded on the forearm. When the user rotates the wrist in flexion, the cables pull on the linkage mechanism causing it to open the fingers and compress the spring. As the cable pulls towards the right, the slider also moves toward the right, compressing the spring and moving the linkage in way that opens the fingers.

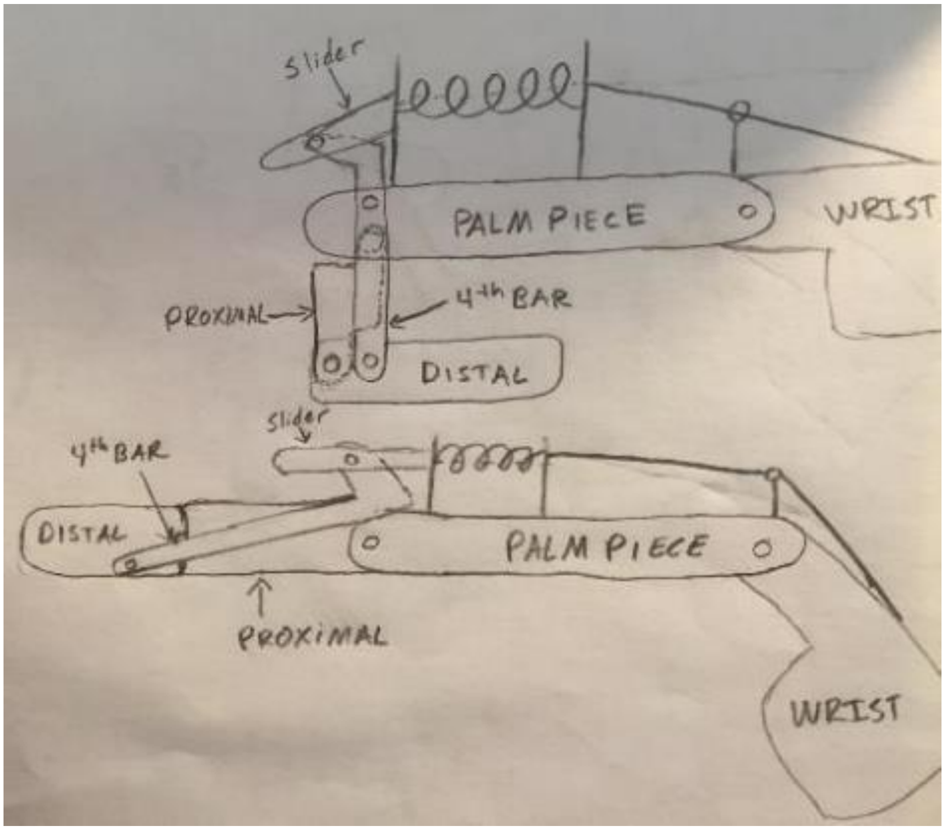


Figure 36: Closed to Open Positions (Top – Neutral, Fingers Closed, Bottom – Wrist Flexed, Fingers Extended)

Once the desired object is within the grip envelope of the user, the wrist is extended to the normal position. Moving the wrist back towards the neutral position would cause the spring to decompress and the slider to move back towards its starting position, resulting in the fingers closing. The linear compression springs provide resistance to opening by forcing the fingers back closed. Therefore, in this design, the springs control the grip force. Since the springs will be compressed the most when the fingers are open the furthest, the force will be greatest at this position. As the fingers return to closed and the springs decompress, the force decreases. This concept is ideal because larger objects are typically heavier and require a larger grip force, whereas smaller and lighter objects require a smaller grip force. Also, the springs do not necessarily need to be preloaded in the neutral closed position because the user requires no force assistance in this position as they would not be able to hold any object anyway. The smallest opening of the fingers would result in the smallest force, whereas the greatest opening of the fingers would result in the greatest force. Also, the maximum grip force would be designed into the device and therefore not directly controlled by the user.

The linear compression springs in both designs may be prone to buckling. Below a certain length, which is called the critical buckling length, springs can begin to bend laterally instead of continuing to decrease in length (Spring Design, 2016). The compression springs should be dimensioned so that they will not buckle by using springs with lengths less than the critical buckling length, which is a function of the geometry and the type of end fixations of the springs.

Though the linkages in both designs described above (Design 2 and Design 3) do not currently include a mechanism to assist movement of the thumb, the linkage designs could be extended to the thumb as well. A single point of contact at the proximal phalanx would allow the necessary movement to the power and pincer grip positions.

A working zeroth order prototype was created for each linkage system to ensure they worked correctly. In the first linkage design, pulling the cable causes the fingers to close, while in the second linkage design, pulling the cable causes the fingers to open. Another distinct difference is that in the open to closed design, the user controls the grip force. In the closed to open design, however, the springs that resist opening control the grip force. The benefit of using the linkage system design where the fingers are open in the neutral position is that the device would most likely be easier to don and doff than the linkage system where the fingers are closed in the neutral position. However, when the cables pull the fingers closed in the first linkage design, the compression springs simply act to resist the closing motion and return the fingers back to their neutral positions. In contrast, in the linkage system design which starts closed (Figure 35), the linear compression springs provide force in the closing direction to return the fingers to neutral. This allows the designer to control that force with a selection of springs with various spring constants. Also, a spring driven linkage design which starts closed allows for position force variance where larger grips have larger forces and smaller grips have smaller forces.

It is also important to understand how the forces will act in this design. A free body diagram is helpful to understand these forces (Figure 37). The free body diagram shows the forces in the linkage when the device is in a partially open position where the wrist has activated the device to some degree.

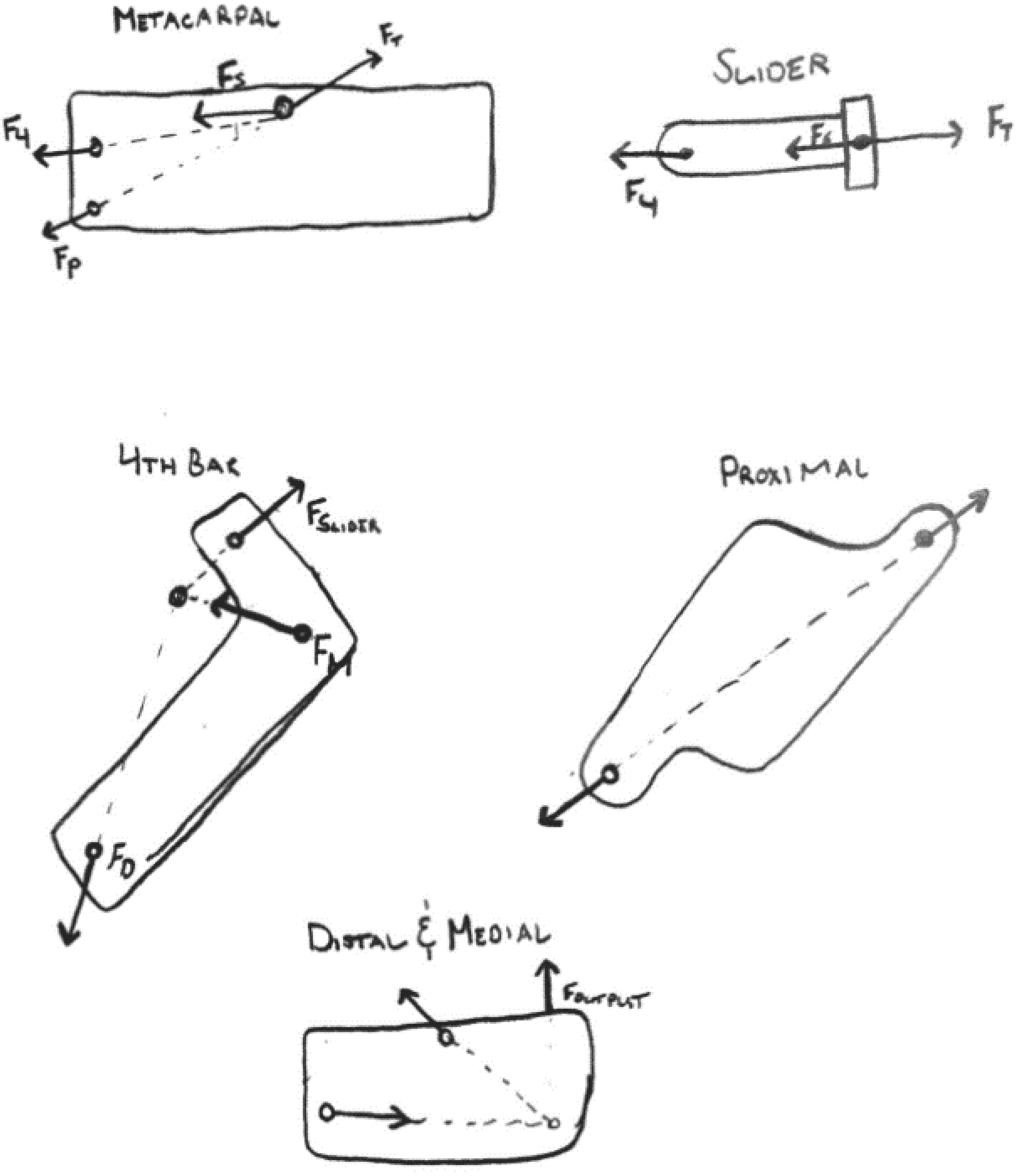


Figure 37: Closed to Open Design FBD

After creating several zeroth order prototypes and conducting initial analysis, these preliminary designs could both work as a hand orthosis device. Particularly, the linkage design that pulls the fingers open while the spring provides resistance and forces the fingers back closed seems superior because the springs control the grip force. By having the springs control the grip force, the device could potentially generate greater grip strength through the selection of various springs. However, fine tuning of the best spring would be necessary for users to hold objects such as an egg without cracking it. Design 3 would be able to produce a maximum of approximately 20 N of grip force (Appendix H: Design 3 Calculations). However, if Design 3 were to be chosen, further analysis would need to be conducted to show the relationship between force and position. Table 5 shows an estimated total cost for the components of this design.

Table 5: Compression Spring Driven Linkage Estimated Cost

Item Name	Item Cost	Item Amount	Total Item Cost
3-D Printed Links	~\$35 per in^3	~3 in^3	~\$105
Velcro Straps	~\$10 per package	1 package	~\$10
Fasteners	~\$15		~\$15
Cable	~\$10 per yard	~1 yard	~\$10
Padding	~\$10 per roll	1 roll	~\$10
Compression Springs	~\$15	18-20 springs	~\$15
Total Cost			~\$165

5.2.4 Design 4: Torsional Spring

Activation Type: Finger Extension
Transmission of Movement: N/A
Mechanism Causing Finger Movement: Torsional Springs
Attachment to User: Rigid finger channel

To minimize bulk on top of the fingers, torsional springs can be utilized alongside each finger, or finger pair as the fingers can be coupled in this design. To activate this device, the user extends his or her fingers and the device immediately resists. Therefore, the hand is continuously pushed into a fist as the resting position. Torsional springs are available in diameters of less than ¼ inch allowing them to form a device with a lower profile than one utilizing compression springs. The springs would be aligned with the DIP, PIP and MCP joints, pushing the fingers toward a closed fist (Figure 38). Linear plastic links (red) alongside each phalange hold the springs in place and align each spring (blue) with the user's knuckles. The plastic links run along the side of the fingers and soft straps (not shown) attach them to the fingers. A glove or partial finger sleeves can be used in lieu of straps to facilitate donning the device and ensuring the user's fingers do not get caught between links. A precise fit is critical for this design as improper spring position would put unnecessary and potentially harmful force on the user's fingers.

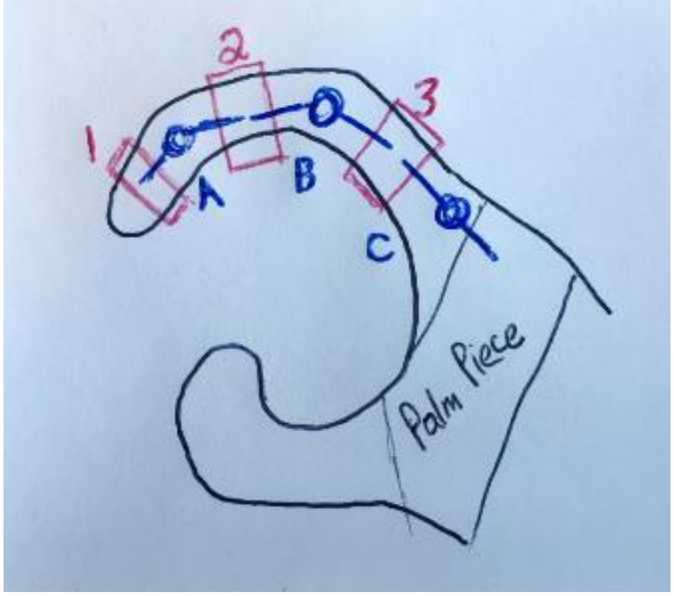


Figure 38: Torsion spring design; rigid finger channels (red), torsion springs (blue), palm support (black)

Springs in this design hold the fist fully closed in the neutral position. The torsional springs do not continually apply significant force past the fully closed position which avoids unnecessary stress on the fingers and joints. The maximum allowable rotation driven by the spring was determined by using the median range of motion of each joint. The median ROM at each finger joint is as follows: MCP is 79-97°, PIP is 87-90°, DIP is 52-68° (Bauknecht et al, 2011). The fully closed position of the fist should not require the joints to rotate past these positions. Using the median ROM of hand joints as a guide, the springs corresponding to the PIP and the MCP joints should have angles of 270° in the neutral position, and springs corresponding to the DIP joint should have angles of 210° in the neutral position (Figure 38). Therefore, the resulting range of motion assisted by the spring is 30° for the DIP joint and 90° for the PIP and MCP joints (Figure 39). Though the springs used for the PIP and MCP joint produce a rotation corresponding to the upper range given by the median, the rotation angle was chosen from stock spring rotation values.

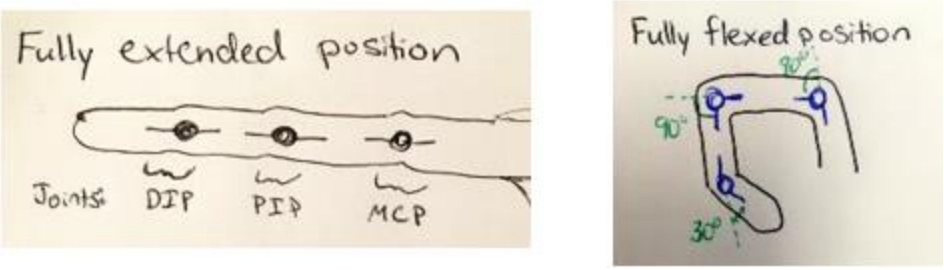


Figure 39: Torsion Spring Sizes and Positions

One consideration to be made is that a user with reduced finger flexion strength may also have reduced finger extension strength. The torsional spring design can be modified to incorporate a cabling system which assists with finger extension (Figure 40). The torsion springs hold the hand in a closed fist position while a cabling system on the back of the hand activated by wrist flexion assists the user in opening his or her hand to grasp objects. Flexing the wrist causes cables to pull the plastic links toward the back of the hand causing the fingers to extend. When the wrist is returned to neutral which is a slightly flexed position, the cables do not exert a force on the fingers and the hand returns to a closed fist.

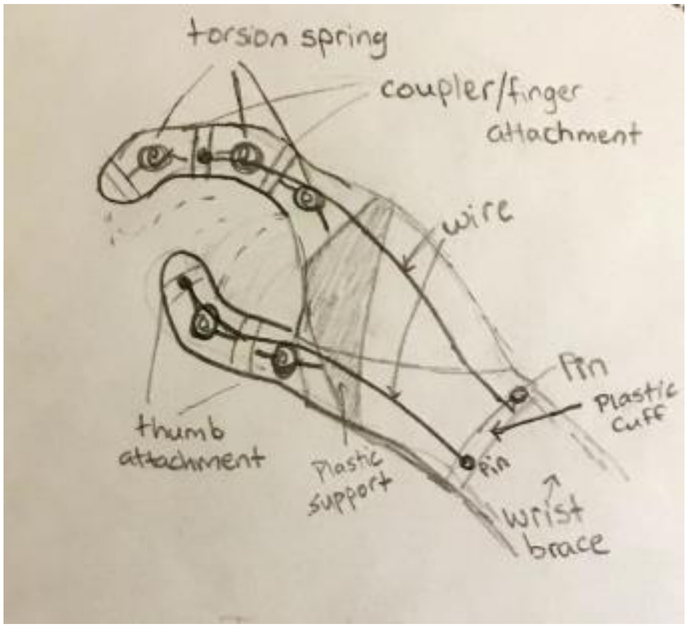


Figure 40: Torsion spring design with wrist flexion assisting finger extension

A preliminary analysis of the force produced by available springs in comparison with the 20 N target applied force yielded the result that torsional springs sized small enough to fit alongside the finger are not capable of producing the required forces. The springs considered were only those with an outer diameter of 3/8" or less as the spring should not extend below the finger or it will interfere with the grip. The leg length was taken to be a maximum of ½" to be shorter than the length of the phalange while still allowing the maximum moment arm (Figure 41). The location of the resultant force was taken to be ½ the total leg length as the output location as the force needs to be evenly distributed over the phalange.

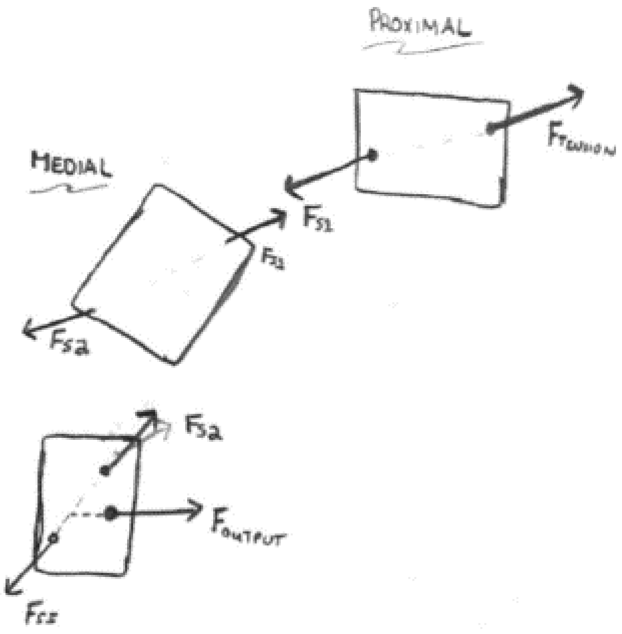


Figure 41: Free body diagrams of each finger channel for the pincer and power grips

The deflection angle was calculated by determining the difference between the neutral position of the spring and a linear, straight finger with legs 180° apart.

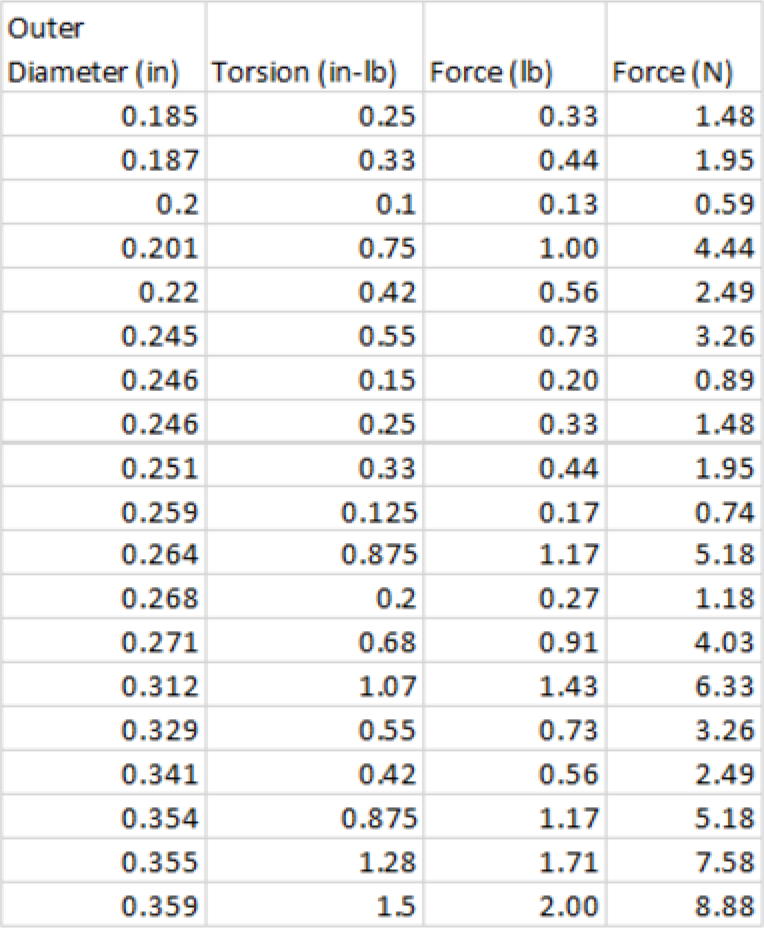
Equation 2: Formula for calculating force produced by a torsion spring with given torque

$$F = \frac{\tau}{L} * \frac{d}{D}$$

L= length of the moment arm
d= spring deflection
D= maximum spring deflection

Table 6 is a list of 270° springs offered by leespring.com, the corresponding torsion values and the calculated force each would be able to produce with the finger extended to 180°. From this list of available springs, the maximum force which can be produced is 8.88 N at the PIP joint.

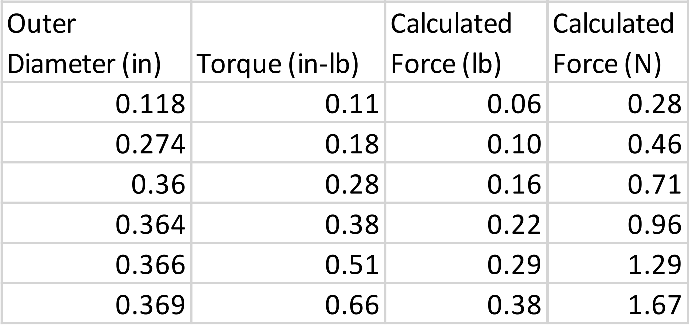
Table 6: Available 270° Springs and calculated force output (LeeSpring, 2016)



Outer Diameter (in)	Torsion (in-lb)	Force (lb)	Force (N)
0.185	0.25	0.33	1.48
0.187	0.33	0.44	1.95
0.2	0.1	0.13	0.59
0.201	0.75	1.00	4.44
0.22	0.42	0.56	2.49
0.245	0.55	0.73	3.26
0.246	0.15	0.20	0.89
0.246	0.25	0.33	1.48
0.251	0.33	0.44	1.95
0.259	0.125	0.17	0.74
0.264	0.875	1.17	5.18
0.268	0.2	0.27	1.18
0.271	0.68	0.91	4.03
0.312	1.07	1.43	6.33
0.329	0.55	0.73	3.26
0.341	0.42	0.56	2.49
0.354	0.875	1.17	5.18
0.355	1.28	1.71	7.58
0.359	1.5	2.00	8.88

There are significantly fewer 210° torsional springs available. Leespring.com was one of the few web retailers which offered springs of this type. Available 210° springs are listed in Table 7 below alongside the corresponding torsion values and the calculated force each would be able to produce with the finger extended to 180°. The maximum force produced was calculated to be 1.67 N.

Table 7: Available 210° Springs and calculated force output (LeeSpring, 2016)



Outer Diameter (in)	Torque (in-lb)	Calculated Force (lb)	Calculated Force (N)
0.118	0.11	0.06	0.28
0.274	0.18	0.10	0.46
0.36	0.28	0.16	0.71
0.364	0.38	0.22	0.96
0.366	0.51	0.29	1.29
0.369	0.66	0.38	1.67

It is important to note that not all springs on the market are represented in Table 6 and Table 7, though a wide range of suppliers were considered and leespring.com had the widest selection. Additionally, many companies can fabricate custom springs allowing the customer to select the angle, diameter, material and many other specifications. However, the cost of custom springs is expected to be significantly higher than stock varieties. It was not feasible for this preliminary analysis to obtain specifications for custom springs.

Due to the nature of this design, the maximum grip force produced will be the equal to the force applied by the weakest of the springs, not the sum. This is because each spring acts independently of the other two. When a force is applied to the medial or distal phalange, the spring on the joint to the palm side of the phalange is the spring applying force on the object. All subsequent springs provide a reaction force to balance the forces in subsequent phalanges. Therefore, even though 8N can be applied at the medial phalange from the PIP spring, this is not the grip force.

A benefit of torsional springs is that maximum grip force applied can be increased by using springs with different properties while not increasing the forces on the resting hand. This can be achieved because torsional springs can have leg lengths at varying angles corresponding to the angle of the knuckles in a closed fist. Once the hand reaches the closed position, the springs are in their neutral position and cannot push the fingers further into a fist. By utilizing a normally closed hand position, the user is able to maintain a comfortable wrist angle with the wrist and forearm linearly aligned while holding an object rather than having the wrist unnaturally bent. Lifting heavy objects in a power grip especially benefits from this setup due to better support from the wrist and forearm in this position. However, proper fitting torsional springs are costly. They take up space in between the fingers where there is usually free space. Table 8 shows an estimated total cost for the components of this design.

Table 8: Torsional Spring Design Estimated Cost

Item Name	Item Cost	Item Amount	Total Item Cost
Springs	~$7 each (stock)	5	~$35
3D printed Spring Supports	$35 per in^3	2 in^3	$70
Base Spring Support	$15	1	$10
Straps	$6.50 per 100	2	$0.13
Hardware + Misc	$20		$20
Total Cost			~$135

5.2.5 Design 5: Cable Driven Rotation

Activation Type: Wrist motion (flexion/extension)
Transmission of Movement: Cable
Mechanism Causing Finger Movement: Cable and rotational pin
Attachment to User: Rigid finger channels

Patent 3967321 (Figure 17) demonstrates that a cable pulled in a linear fashion can directly cause rotational motion. A cable connected to a free cylindrical member in such a way that pulling unwinds the cable enabling rotational motion from a linear pull without pulleys or gears. Cable driven extension uses wrist flexion to activate the flexing of fingers. A cable over the back of the hand transmits the wrist motion to the fingers. The cable is split into multiple smaller cables before it reaches the fingers. The small cables are wound around cylindrical pegs on both sides of rigid finger channels (Figure 42). Only the PIP joint is rotated in this design. The hand is in an open (fingers extended) resting position.

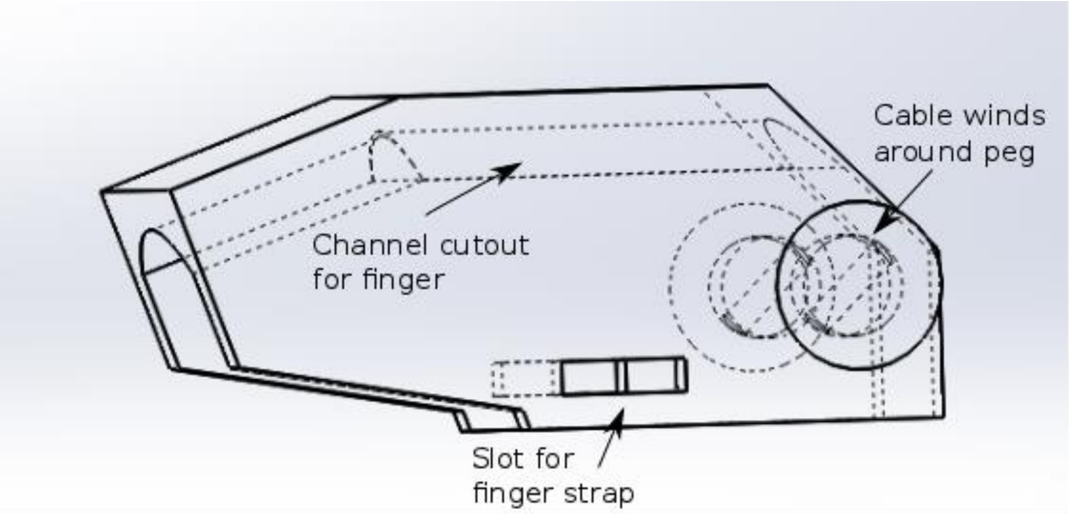


Figure 42: Finger channel covering distal and medial phalange with peg for cable driven rotation

As seen in Figure 42 and Figure 43, the cable or wire is wound such that its free end extends on the bottom side of the peg. The top of the finger channel is curved to match the curvature of the finger and keep the finger centered within the channel. The wide slot at the bottom of the piece allows a strap which holds the finger securely within the channel. The strap must be adjustable and can use hook and loop closures or a buckle to do so.

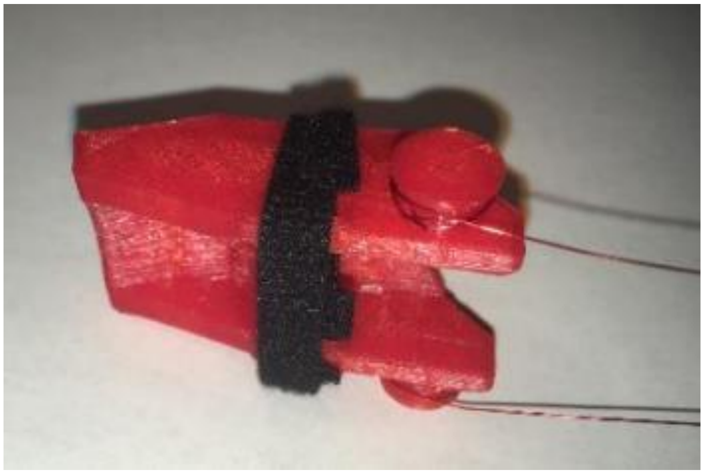


Figure 43: Finger channel with strap and cable attached

The amount of motion produced by the device is dependent upon the diameter of the peg and the change in cable length during wrist flexion while the amount of force produced by the device is dependent upon the diameter of the peg and activation force of the user. There is a limited length increase in the distance along the back of the hand from the PIP joint to the forearm. Increasing the angle of wrist flexion increases this increase in length but requires a larger ROM. Appendix B: Change in String Length ExperimentAppendix B: Change in String Length Experiment details an experiment carried out by the team to determine the change in cable length along the back of the hand during wrist flexion. In the experiment, change in length was measured at 30° and 45° of wrist flexion. A change of 10mm was determined to be the maximum value that can be transferred to the device as this was the smallest change produced at 45°. The length increase of the cable correlates to the amount of rotation as the cable must unwind from the peg. The maximum desired rotation of the PIP joint, and, thus the peg, is 90° and the necessary change in length can be calculated using $\Delta l = \frac{\pi D}{4}$ where D is the diameter of the peg. The diameter also affects the applied torque. From basic statics, it is known that τ=F*l or force multiplied by distance. Keeping cable tension constant, increasing the radius of the peg results in a greater applied torque. The forces acting on the rigid finger piece can be seen in Figure 44.

Figure 44: Free Body Diagram for Cable Driven Rotation

The peg must be closely aligned with the PIP joint to produce the ideal force output. A method of positioning the finger channel properly should be incorporated into the part. In future iterations of the design, the cables running alongside the fingers should be covered to reduce the profile and tangling of wires.

This device must be custom sized to the user's fingers to ensure a snug fit. It does not require any large components to be mounted on the back of the hand, only cable routing, resulting in a thin profile. However, the pegs take up significant space between the fingers and thus it would be advantageous to couple the fingers in this design. Table 9 shows an estimated total cost for the components of this design.

Table 9: Cable Driven Rotation Estimated Cost

Item Name	Item Cost	Item Amount	Total Item Cost
3D printed finger channels	$35 per in^3	4.5 in^3	$158
Cable for channel attachment	$10 per yard	½ yard	$5
Bike Cable	$4 set of cable ad tubing	1 set	$4
Wrist support/mounting	$20	1	$5
Finger Straps	$6.50 100 pack	2	$0.13
Hardware	$5		$5
Total Cost			~$187

5.2.6 Whippletree Concept

A whippletree is a mechanism that allows forces to be evenly distributed between linkages. Whippletrees were first used to evenly distribute the forces provided by horses with different gaits that pulled the same carriage. Whippletree mechanisms have also been used in prosthetic devices such as the Phoenix Hand by Enable. The concept of a whippletree could also be used when designing a hand orthosis to control the phalanges and distribute forces.

When grasping a non-uniform object, such as a wine glass, the fingers gripping the stem part of the glass need to close more than the phalanges gripping the upper part of the glass provided that the kinematics of the device are designed to allow it. A whippletree mechanism would assist the "stem" fingers to continue to close even after the "upper glass" fingers contact the glass. A whippletree mechanism (Figure 45) connected to the wrist and a linkage system assisting the fingers would allow a hand orthosis device to assist in gripping non-uniform objects by evenly distributing the forces.

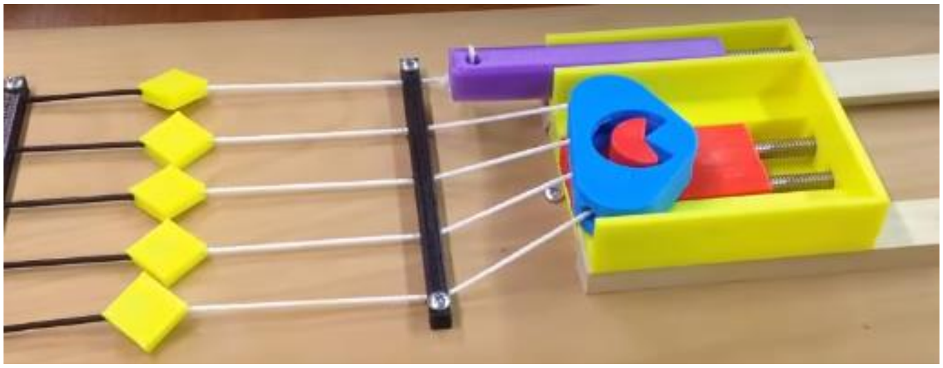


Figure 45: Whippletree Mechanism Model (Enable, 2016)

The yellow diamonds represent the fingers and the top diamond, connected to the purple rectangular block, represents the thumb. The yellow box represents the portion of the device that would be attached to the user's wrist. The white strings represent cables connecting the wrist portion of the device to linkage system for the fingers, while the black elastic strings provide tension to assist in closing the hand. These black elastics could also potentially be replaced with springs to increase the amount of force. The blue piece is the whippletree, which distributes the force and tension through the fingers when the wrist is flexed by rotating along the red piece. The white string attached to the second and third diamonds from the top (index and middle finger) is connected and wraps through the blue whippletree. The bottom two diamonds (fourth and fifth fingers) are also connected with one white string going through the blue whippletree. When the wrist bends, or the yellow box is slid to the right in the model, the four fingers and thumb would be provided with forces to close the same amount (Figure 46).

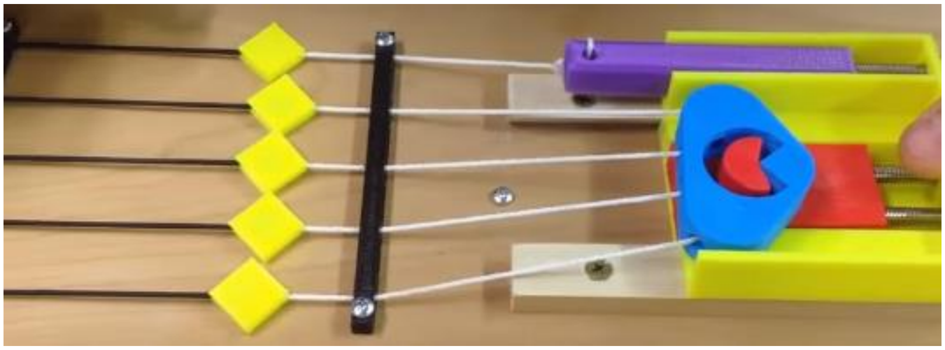


Figure 46: Whippletree Model Simulating Wrist Bending (Enable, 2016)

However, if one finger is obstructed, or comes into contact with an object before the others, the other fingers will continue to close as the whippletree pivots and distributes the force through them (Figure 47). If all of the fingers instead were connected to tensioning blocks like the thumb (purple block) is in the model, the fingers would stop closing when one was obstructed. This type of motion is undesirable when gripping non-uniform objects, such as in the wine glass example, because more phalange contact with an object will lead to a more reliable grip.

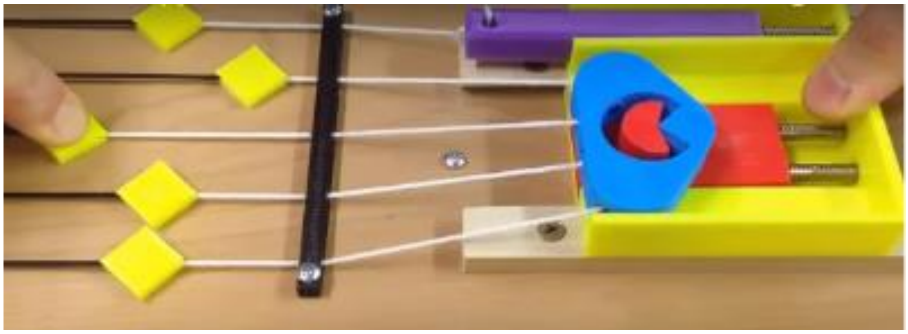


Figure 47: Whippletree Model Simulating Wrist Bending and Obstruction (Enable, 2016)

5.2.7 Elevated cable routing bar

One method for standardizing change in cable length and cable take-up is by routing the cable over an elevated bar positioned laterally across the wrist. The bar serves to align the cable with the other components as well as ensure it does not rub against the hand or arm. Different orientations of the bar produce varying amounts and rates of cable take-up.

The illustrations and equations in this section detail the possible configurations and the change in cable length each is capable of providing. An overview of the calculations is explained in this section with full calculations for each bar configuration located in Appendix C: Elevated Bar Calculations. Measurements for the location of the bar and height of the bar were bounded using best judgment so that the device would not interfere with motion of the hand or arm. The maximum length along the metacarpals from the wrist to the mounting point of one cable end was limited to 80mm and the maximum length from the wrist extending along the forearm toward the elbow was limited to 100mm. The maximum height of the bar should be less than 30mm above the arm when the fingers are in the open position. Where the bar is angled, the angle between the bar and forearm was limited to be less than 90°. For practicality sake, the wrist angle studied was between 0-45° of flexion. This range of motion corresponds to the motion used to activate the device (Figure 48).

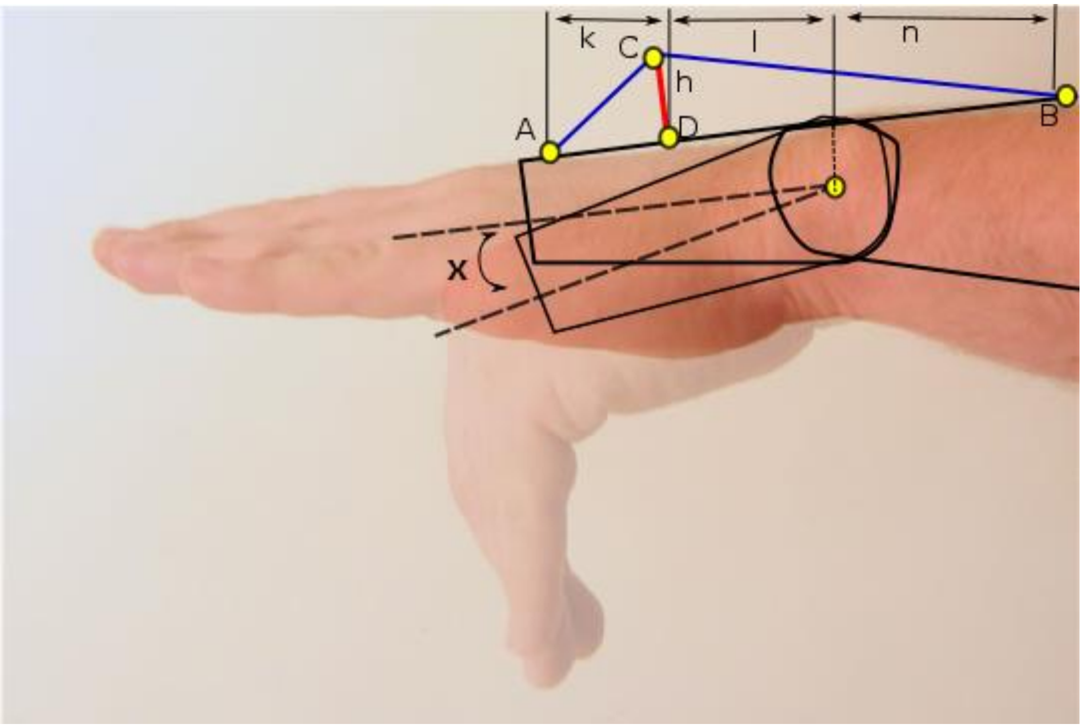


Figure 48 Elevated bar diagram with labelled variables

Basic geometry was used to determine the initial and final positions of point A on the metacarpals, point B on the forearm, and point C representing the location of the bar. The location of each of these points with respect to the wrist pivot as the origin was defined using variables for lengths and angles and input into MathCAD. The variables used in each configuration can be seen in the diagrams for each configuration. Variables k, l, m, and n denote distances along the forearm, h and r dictate the location of the bar, and β represented the angle between the bar and forearm. Variable x was used to represent the angle of wrist flexion. The unit used for distance was millimeters and the unit for angle was radians. The locations between A and C and between B and C were calculated in MathCAD using the formula for distance between two points P1 and P2 in 2D space using their horizontal and vertical components x and y.

Equation 3: Formula for distance between two points

$$distance = \sqrt{(P_{2_x} - P_{1_x})^2 + (P_{2_y} - P_{1_y})^2}$$

The total cable length is the sum of the distances between A and C and between B and C. The distance calculation was carried out for the initial and final position. The difference in length between the final and initial position is the total change in length, Δl.

Recall that the formula for Δl was written in terms of variables for lengths and angles. The Maximize command in MathCAD was used to find the value of each variable which would yield the maximum Δl. Maximize takes an input function, the variables within the function, a guess for the value of each variable, and optional maximum and minimum bounds for each variable to determine a maximum value of the function within the given bounds. The output of Maximize is a column matrix of the values for each input variable corresponding to the maximum value. From these individual values, the maximum value of the input function can be calculated. The same best judgement limits given in the beginning of this section were defined in MathCAD for each configuration. Graphs of Δl vs wrist angle x were created to guide the guess values for each variable. A separate graph was created for each variable other than x. For each graph, values of one variable were changed while the other variables were held constant at the guess values. The value producing the maximum Δl for each variable was input as the new guess value and the constants of the other graphs were updated accordingly. Several iterations ensured that accurate maximum values were being used. Since the change in length function for each configuration was dependent upon several variables, it was possible that there were several possible local maximums within the allowed bounds. Therefore, it was imperative that the guesses were revised multiple times based changes of the graphs occurring during each iteration.

Five configurations of the elevated bar were studied to determine where the bar should be located to produce the required length change within the specified bounds. In Figure *49* to Figure *53* depicting each configuration, distances are represented by lowercase letters, individual points by lowercase letters, and x and β are angles. The solid black lines over the forearm and metacarpals represents the interface between the user and the bar to provide support and mounting points. Dashed lines are for reference only. Solid colored lines show the initial (resting, fingers open) position and semi-transparent colored lines show the positions of components at some degree of flexion. The large yellow circle represents the wrist pivot for flexion and extension.

Configuration 1: Vertical Bar over metacarpals

The first configuration (Figure *49*) utilizes a bar mounted over the metacarpals perpendicular to the metacarpal piece. The bar is horizontal length l away from the wrist and vertical distance h above the hand. At point A, horizontal distance k+l from the wrist, the cable is routed back down to the metacarpals. On the forearm, point B located length n from the wrist is where the other end of the cable terminates. Wrist angle is represented by x.

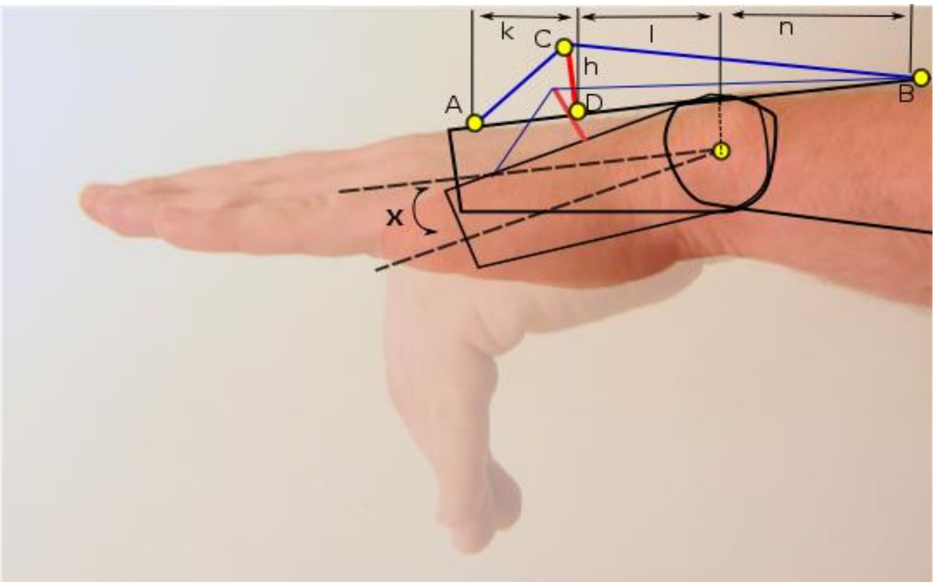


Figure 49: Blue cable routed over a red vertical bar over metacarpals

Configuration 2: Angled Bar, palm mount

Configuration 2 (Figure *50*) utilizes an angled bar mounted on the back of the metacarpal piece. The bar is angled toward the forearm and the length r and angle β are chosen such that the bar, point C, is directly over the wrist when the wrist is extended to align with the forearm. Therefore, length l is derived from r and β with the relationship $l=r*\cos(\beta)$. One end of the cable routes to point A on the metacarpals length k+l from the wrist and the other end routes to point B length n from the wrist.

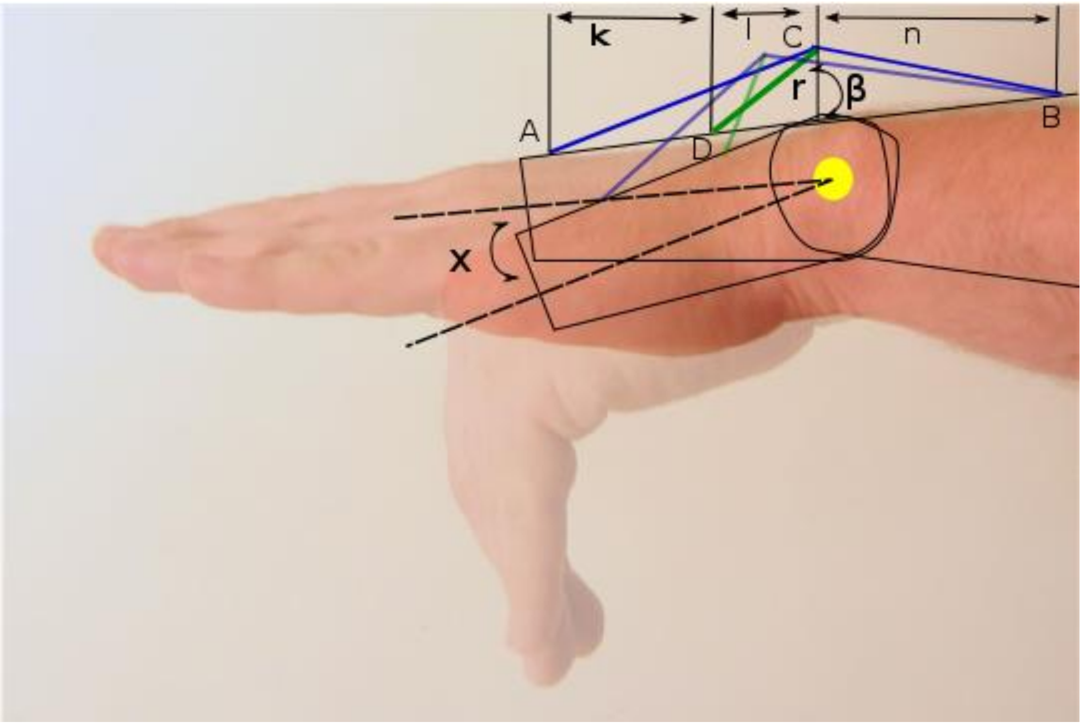


Figure 50*: Blue cable over green bar attached to metacarpals angled over the wrist*

Configuration 3: Angled bar toward forearm, rotating wrist mount

The bar in configuration 3 (Figure 51) is mounted to the metacarpal piece from the wrist angled toward the forearm. Since the bar is mounted to the metacarpals, it rotates as the wrist rotates at the same angle as the wrist. The bar is r mm from the wrist and makes angle β with the forearm in the resting position. One end of the cable is routed to point A on the metacarpals length m from the wrist and the other end routes to point B length n from the wrist.

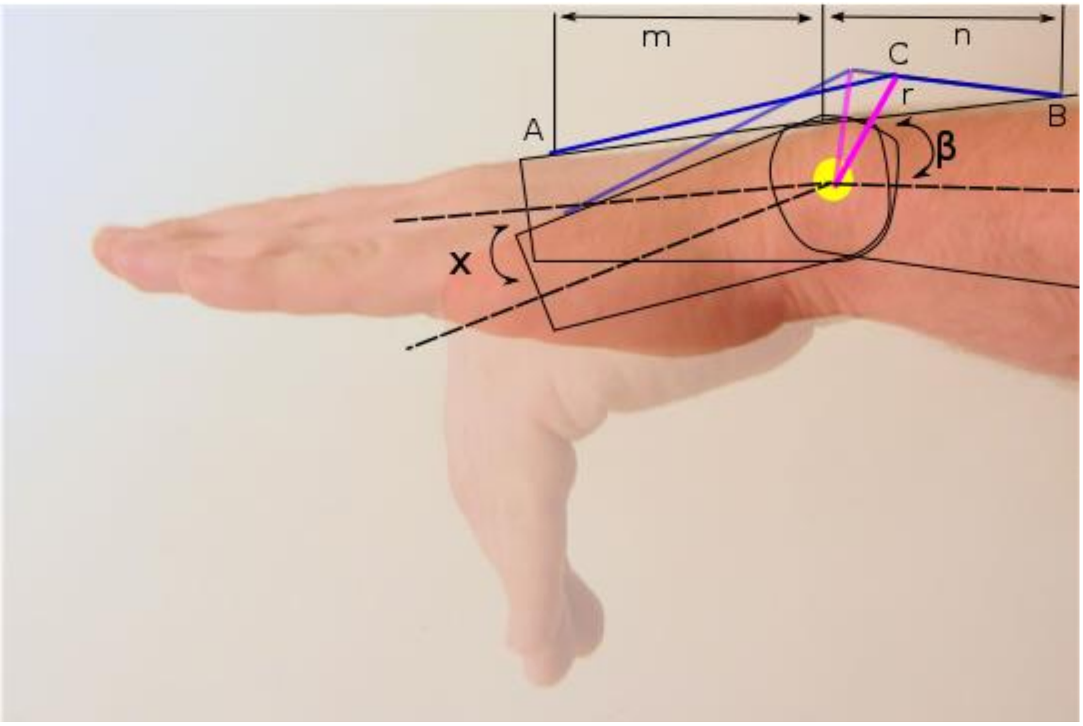


Figure 51: Blue cable over pink bar attached to metacarpals at the wrist angled toward the forearm

Configuration 4: Angled bar toward palm, fixed wrist mount

The angled bar in configuration 4 (Figure 52) is mounted to the forearm piece at the wrist angled toward the metacarpals and thus does not rotate. The location of the bar is r mm from the wrist at angle β with respect to the metacarpals in the resting position. As with previous configurations, the cable is routed from point A length m from the wrist to point n on the forearm.

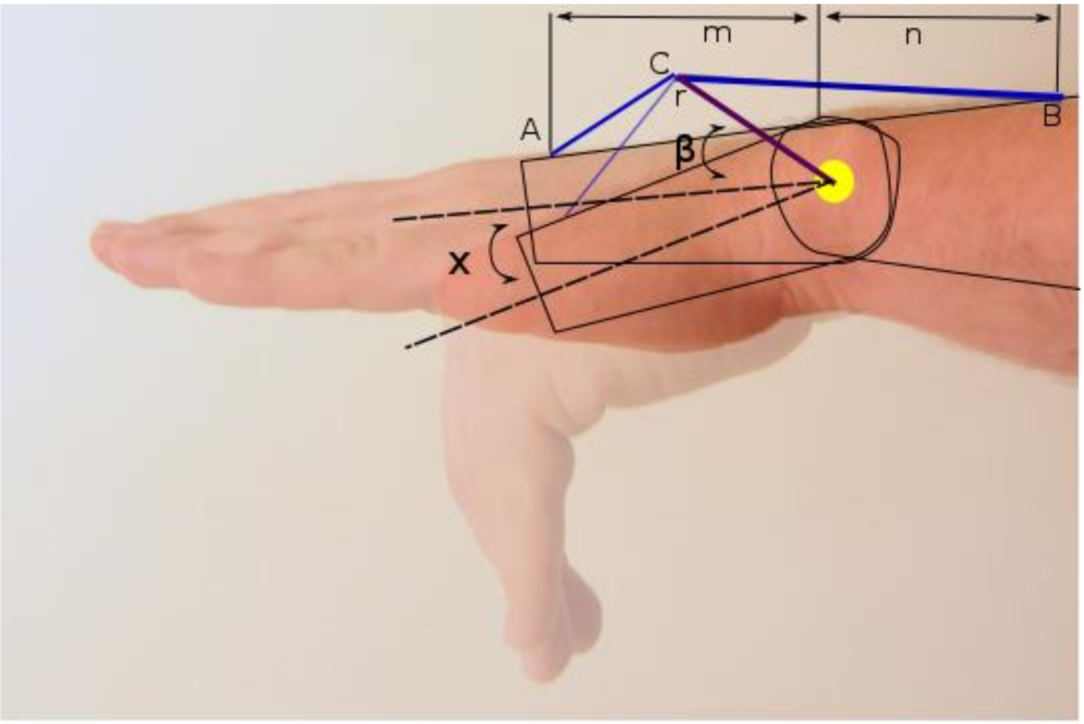


Figure 52: Blue cable over purple bar attached to forearm at the wrist angled toward metacarpals

Configuration 5: Angled bar toward palm, rotating wrist mount

Configuration 5 (Figure *53*) consists of a bar angled toward the palm mounted to the metacarpal piece at the wrist which rotates as the wrist rotates. The bar makes angle β with the metacarpals and it is located length r from the wrist. One end of the cable is routed to the metacarpals at point A length m from the wrist and the other end is routed to the forearm at point B length n from the wrist.

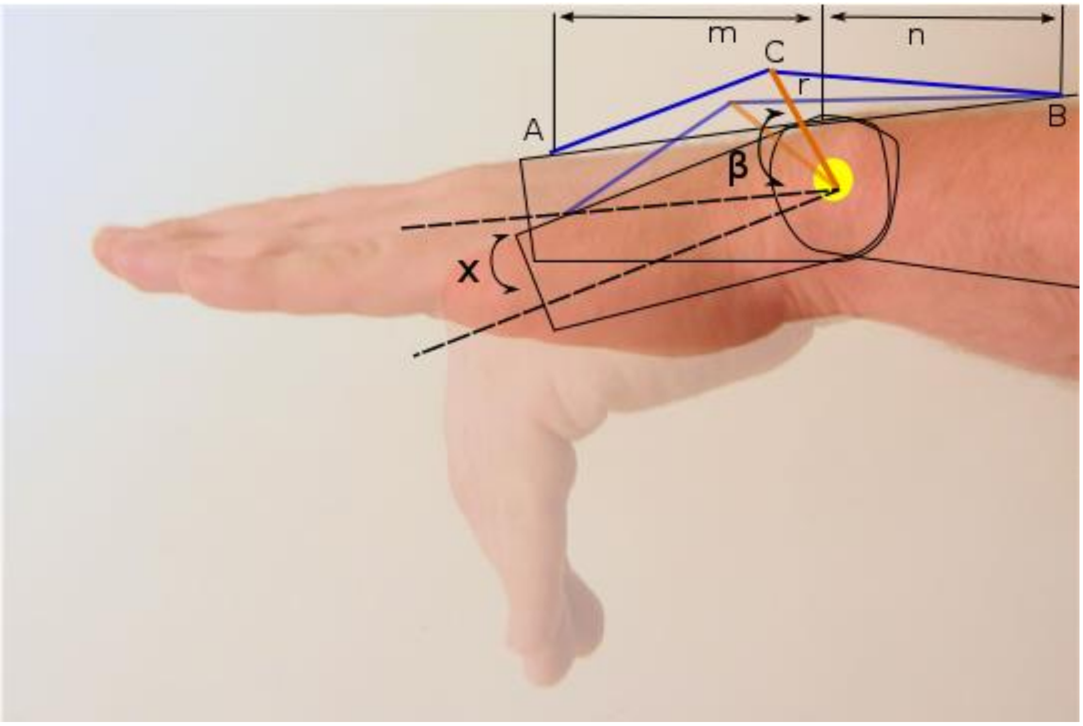


Figure 53: Blue cable over orange bar attached to metacarpals at the wrist angled towards metacarpals

Results

Table 10 displays the results of the change in length calculations from each elevated bar configuration and the experimental result from the change in length experiment detailed in Appendix B: Change in String Length Experiment. All but one configuration is capable of producing a change in length greater than that of the bare wrist. See Appendix C: Elevated Bar Calculations for detailed calculations.

Table 10: Change in cable length produced by each studied configuration

Bar configuration	**Maximum change in length**
Bare wrist (experimental value)	10 mm
Vertical Bar over metacarpals Figure *49*	4 mm
Angled Bar toward forearm, palm mount Figure *50*	19 mm
Angled bar toward forearm, rotating wrist mount Figure 51	23 mm
Angled bar toward palm, fixed wrist mount Figure 52	23 mm
Angled bar toward palm, rotating wrist mount Figure 53	22 mm

Using the elevated bar in all configurations except the first gives a significantly higher change in length compared to routing the cable over the wrist alone. In addition, it greatly reduces the dependence of the change in cable length on the size of the user's hand and wrist. When the cable was routed over the wrist alone, wrist and hand size determined the change in length generated. A bar not only prevents the cable from rubbing across the user's wrist, it also standardizes the distance change without much regard to hand size. An elevated bar allows users with small hands to achieve the same change as a user with large hands.

5.3 Introduction to Thumb Functional Decomposition

Similar to the fingers, the thumb requires an activation movement, a translation of activation movement, a mechanism to move the thumb, and a way to attach the components to the thumb. However, there are four main options for motion of the thumb. The thumb could move with continuous motion, coupled or uncoupled to the fingers, move with incremental motion, meaning it could be fixed at various locations, or remain completely fixed in one position. The following sections will describe the various sub-options in each of these four main options. A full chart of all the different options appears in Appendix D: Finger and Thumb Functional Decomposition.

5.3.1 Description of thumb components

Continuous Motion Coupled to Fingers

Continuous motion coupled to the fingers means that the thumb would be activated and move at the same time as the fingers. Therefore, all of the same options available for the fingers for activation type, translation of movement, mechanism causing movement, and attachment to hand could also be used for the thumb. However, coupling the thumb to the fingers makes it difficult to achieve both the power and the pincer grips because the thumb needs to be in a different position for each grip.

Continuous Motion Uncoupled from Fingers

Uncoupling the thumb from the fingers allows the device to potentially achieve both grips. In the pincer grip the thumb intersects the index and middle fingers, whereas in the power grip it does not necessarily need to move, as long as it does not obstruct the fingers and is adequately supported. This motion could be activated by the contralateral hand or one of the activation movements (wrist, elbow, shoulder, etc.) which is different than what is used for the hand. However, using two separate activation movements could make the device very difficult for the user to control and would undoubtedly put their hand or arm in awkward positions when performing many tasks. The mechanism causing the motion of the thumb could be in the form of a linear slide, a gear system, or a pulley system. The components could be attached to the thumb in a similar way to the fingers with a glove, a ring, a sleeve, or a rigid finger channel.

Incremental Motion Uncoupled from Fingers

Gear systems, ratchet systems, and locking mechanisms similar to that used in a beach chair could be used for the mechanism component. A glove, ring, sleeve, or rigid finger channel could also be used to attach the components to the thumb in this option.

Completely Fixed

A final option is to keep the thumb completely fixed. This would simplify the thumb component of the device tremendously, but would make it very difficult to achieve both the pincer and power grips as the fingers would therefore need to travel along two different paths for each grip. Because of this, a fixed thumb would most likely not be suitable for this hand orthosis device.

5.4 Components for Thumb Motion

This section outlines some the designs created from the initial functional decomposition of the thumb. The following sections include designs related to Incremental Motion Uncoupled from the Fingers (Beach Chair, Zip Tie, and Distal Phalanx), Continuous Motion Uncoupled from the Fingers (Torsional Spring), and a Fixed Thumb.

5.4.1 Beach Chair Incremental Motion Thumb Design

This design uses incremental motion to move the thumb from one position to another to achieve both the pincer and power grips. The thumb will be braced so that the distal phalanx of the thumb is slightly flexed. A linkage with a slider and locking mechanism similar to a beach chair will drive the movement of the thumb. Starting from position 1 (Figure 54), the user would user their contralateral hand to push the pin, which is shown by an X, and slide link 1 to position 2 where the pin would lock into the second hole. The movement of link 1 would move link 2 which would move the thumb about the CMC joint towards the palm. In position 2 (Figure 55), the thumb would be in position to intersect the fingers to form the pincer grip.

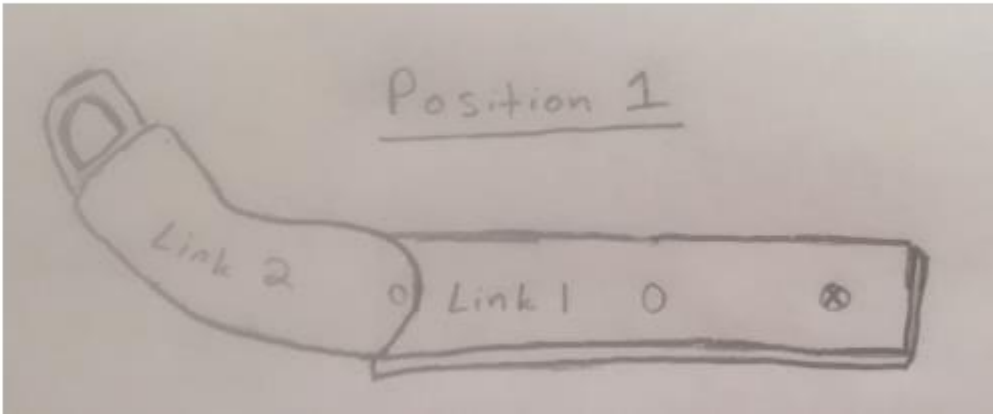


Figure 54: Beach Chair Incremental Motion Thumb Design - Position 1

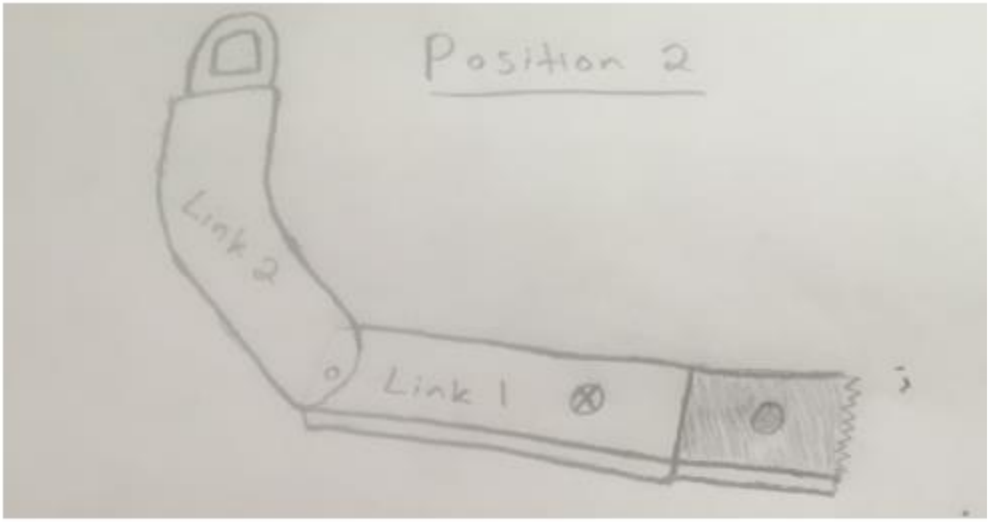


Figure 55: Beach Chair Incremental Motion Thumb Design - Position 2

An important consideration is the forces in the thumb and through the thumb device. A free body diagram helps show the forces in the device when the thumb is in contact with an object (Figure 56).

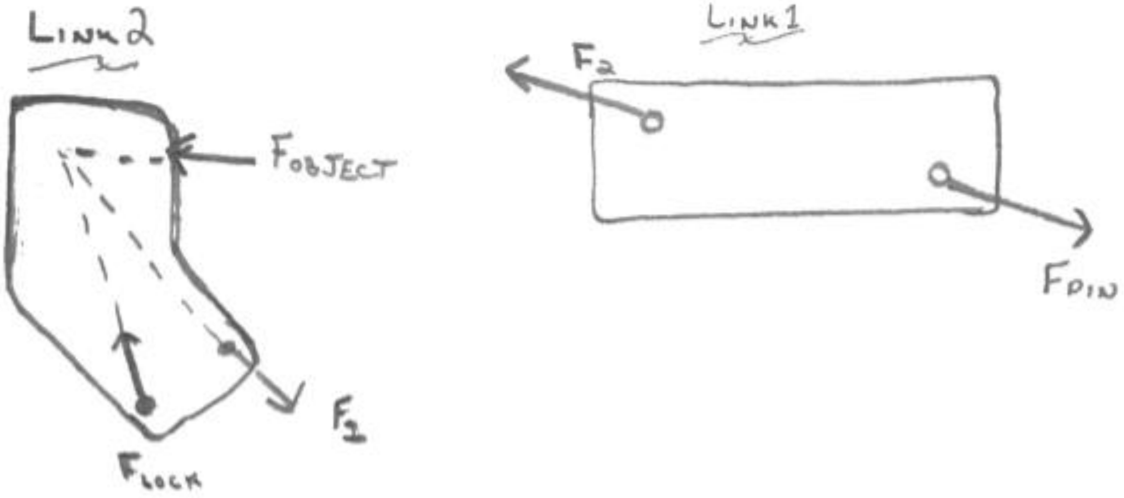


Figure 56: Beach Chair Incremental Motion Design - FBD

The device needs to be able to hold the thumb in a fixed position while gripping an object. Since the finger design aims to produce 20 N of force in the power grip and 10 N of force in the pincer grip, the device must be able to withstand 20 N of force applied at the thumb tip. This value of 20 N will drive the design and material selection for components in this design.

5.4.2 Zip Tie Incremental Motion Uncoupled from Fingers

This design would fix all joints in the thumb except for the CMC joint and would utilize a Zip Tie based system to generate incremental motion. The brace would only have one degree of freedom to move between two locations (both the pincer grip and power grip positions). The Zip Tie acts similar to a ratchet, allowing for movement of the thumb in one direction along the single DOF while resisting movement in the opposite direction. Figure 57 shows the basic layout of the thumb support.

Figure 57: Zip Tie Based Hand Thumb Positioning Device

Starting from the open position, the user would be able to move the thumb from the power grip to the pincer grip at will. In order to return to the power grip, the user would use his/her alternate hand to press on the release mechanism and simply move the thumb back to position. The thumb would move at the CMC joint only, and the brace itself would prevent motion that would deviate from the path.

The forces applied to the device tie can be seen in Figure 58. The maximum force that can be applied to the end of the thumb is equal to the maximum amount of force generated by the fingers (20N). A majority of zip ties have a bundle strength much greater than the 5 pounds of force generated by the primary device.

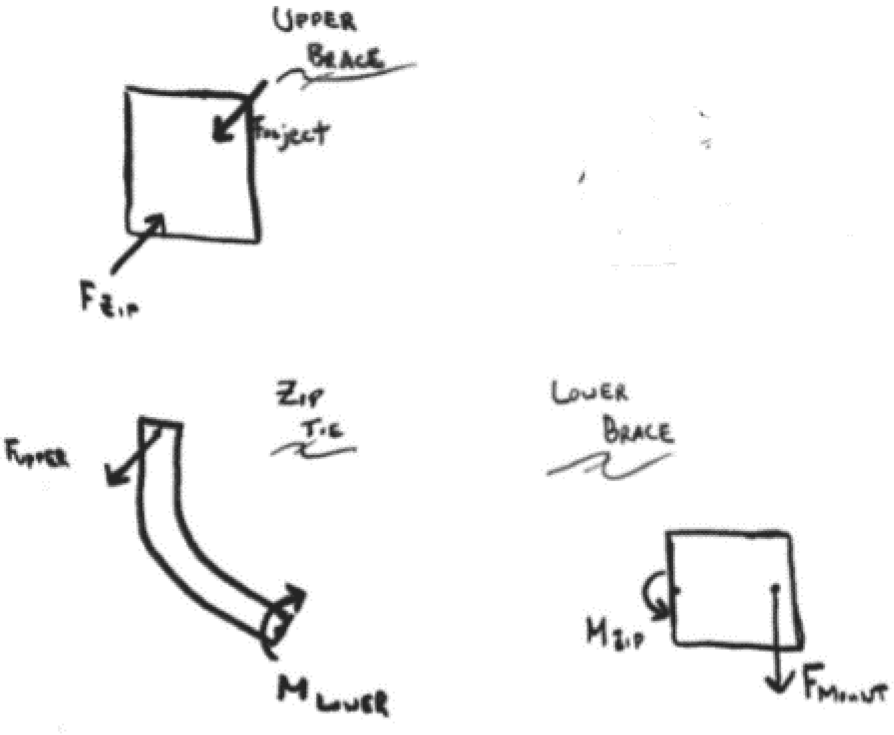


Figure 58: Zip Tie Thumb Part FBDs

This device would have the added benefit of allowing users with different sized hands to control the location of the thumb in the pincer grip. The multiple teeth of the Zip Tie allow for a finer control over thumb position.

5.4.3 Torsional Spring Thumb Design

Torsional springs placed alongside the joints in the thumb allow continuous motion of the thumb (Figure 59**Error! Reference source not found.**). Four springs would be used, two on each side of the IP joint and two on each side of the MCP joint. The symmetry of the springs along the bone axis reduces the shear forces across the finger. The user would need sufficient strength to extend his/her thumb away from the resting closed position. All spring angles would be 210° which corresponds to a deflection of 30° from a linear alignment of the phalanges and palm. Due to symmetry, the spring pairs can be approximated as one spring with two times the spring constant acting on the bone axis of the finger.

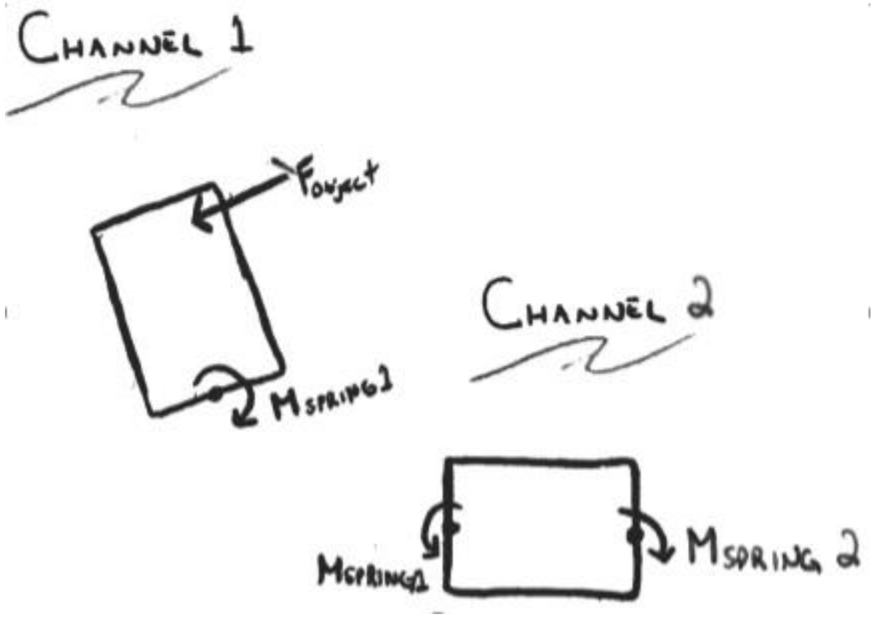


Figure 59: Torsion springs actuating thumb motion using rigid finger channels; FBD of both channels shown, for simplicity, single springs are shown in place of spring pairs

As shown in Figure 59, the moment of spring 1 opposes the applied force from the finger and the two spring moments act in opposite directions on channel 2. The force of spring 1 is applied at the center point of channel 1 and the force applied by the finger is distributed across the entire contact area of the finger. Therefore, it can be estimated to be a point force applied at the center point with a magnitude equal to the integral of the force curve. The location of each force is equidistant from the center point of the channel. Thus, both forces must be equal for equilibrium to be satisfied.

5.4.4 Fixed Thumb Design

This thumb design positions the thumb and does not allow it to move. While the thumb position is a significant factor in distinguishing between the power and pincer grips (Figure 7), the thumb can remain stationary and the two grips can be made in some form. The ultimate drawback of this design is that a stationary thumb would limit the minimum circumference of an object capable of being held in the power grip. The difference in the grips is seen in Figure 60. The rigid thumb channel would be fixed to the solid piece covering the metacarpal at the desired angle. Figure 61 shows the forces acting on the fixed thumb in all positions.

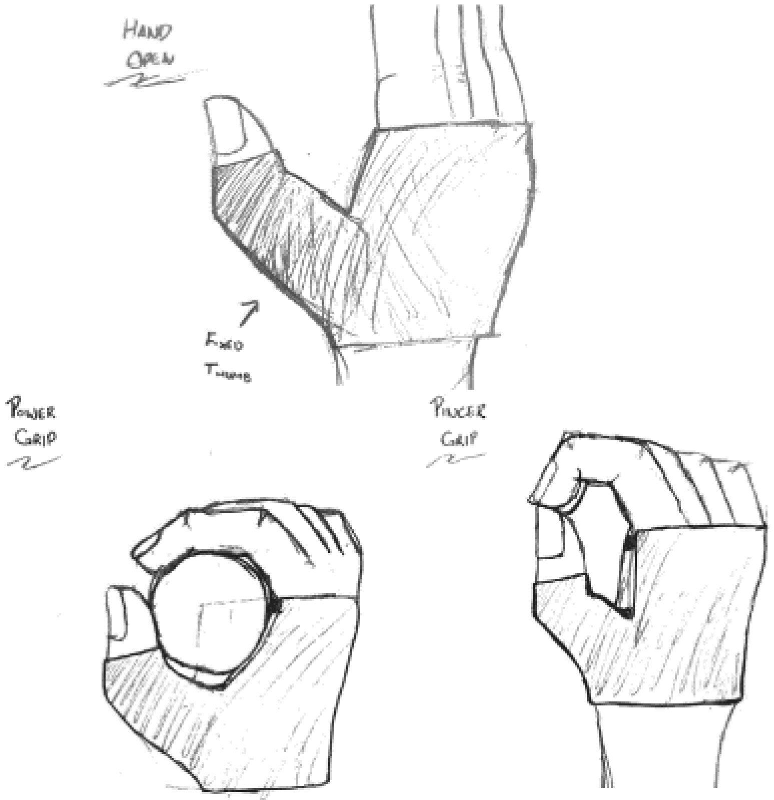


Figure 60: Fixed Thumb Design Hand Positions

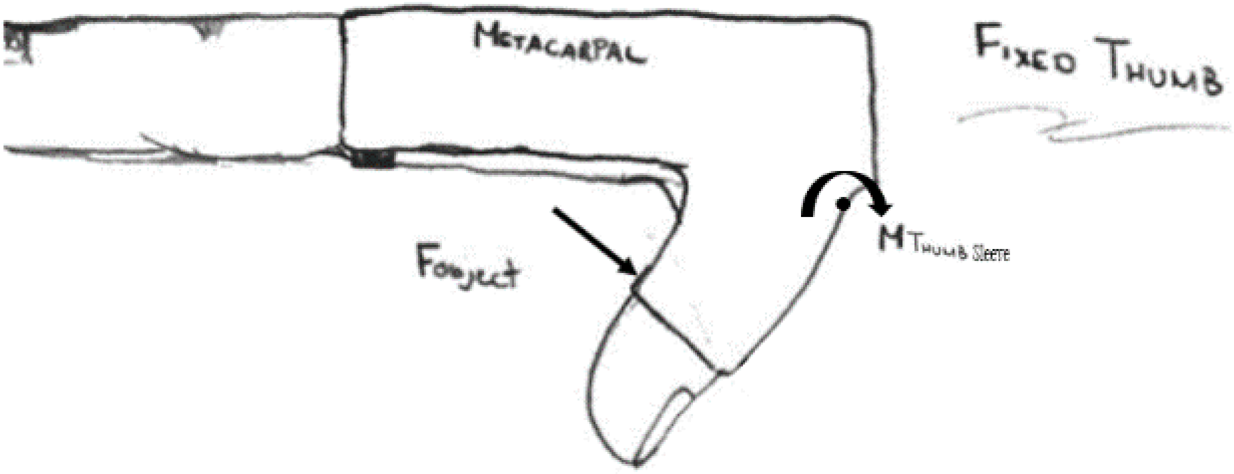


Figure 61: Forces and Moments Acting on Fixed Thumb

5.4.5 Thumb Distal Phalanx Incremental Motion

As mentioned in Section 2.2.3, the pincer and power grips feature near identical finger movements and are differentiated by the thumb movement. This design, featuring incremental motion of the thumb's distal joint, utilizes very little movement to distinguish between the power and pincer grips. Essentially, the thumb's metacarpal and proximal phalanx remain fixed, only allowing the distal phalanx to move. The distal phalanx will be locked into the desired position using the contralateral hand. When locked into the first position, the thumb would not interfere with the motion of the fingers allowing the user to perform the power grip. When locked in the second position, the thumb would interfere with the index and middle fingers' motion, allowing the user to perform the pincer grip. The position of the distal phalanx would be locked using a peg system or possibly a mechanism similar to a beach chair's locking system. The design can be seen in both positions in Figure 62.

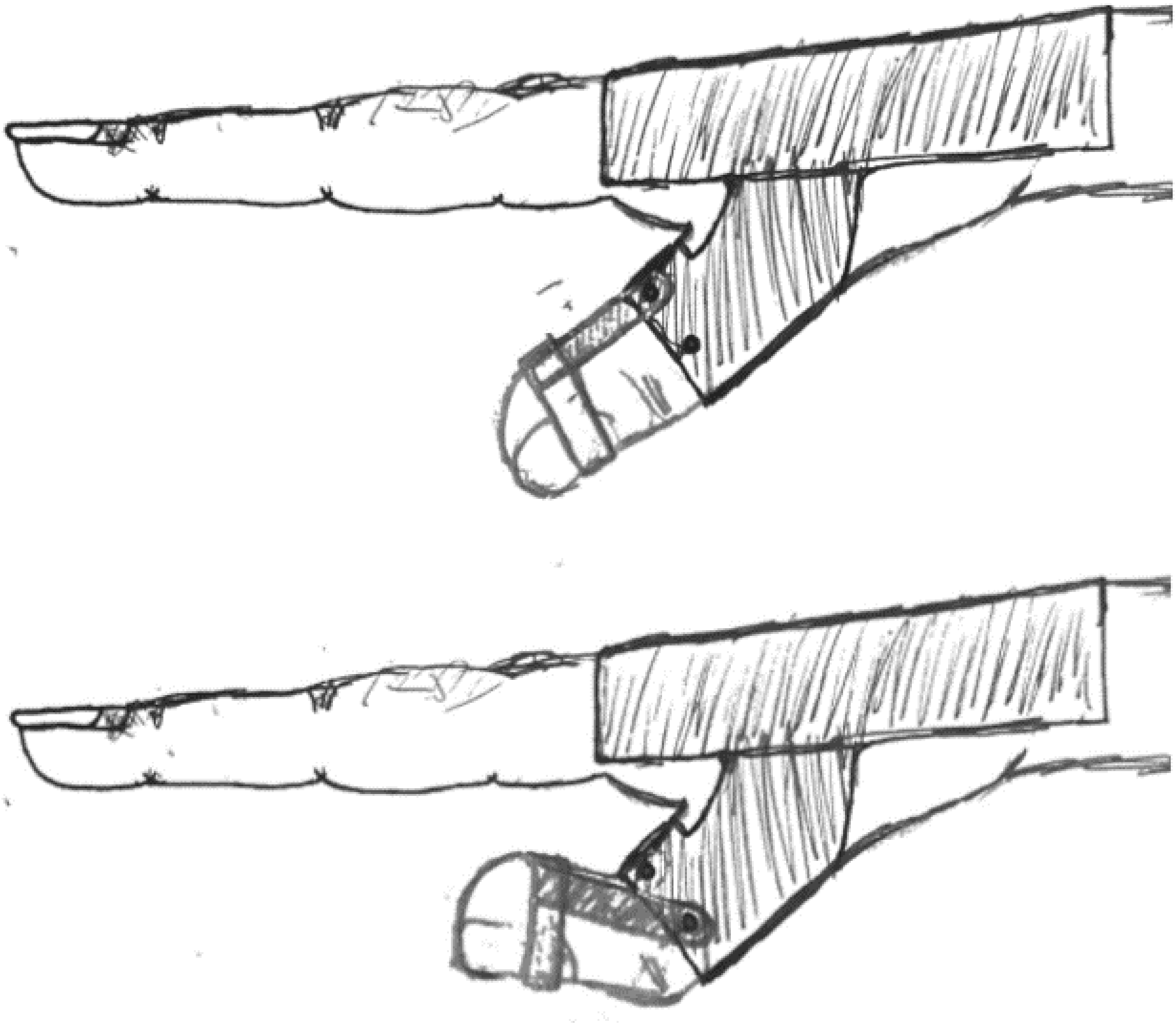


Figure 62: Distal Phalanx Power (Top) and Pincer (Bottom) Grip Positions

The thumb's metacarpal bone and proximal phalanx would be fixed to the hand's metacarpal plate, preventing them from moving. The distal phalanx of the thumb would have a ring on it, connected to the rigid thumb sleeve at the proximal phalanx using a solid bar. This bar would not be able to pivot about any point on the thumb ring, so when pinned to the rigid thumb sleeve, the thumb's distal joint will be locked into position.

6 Design Selection

As the design process is an iterative process, different components of the hand orthosis device were evaluated at different times. The structure of this chapter follows the timeline of that iterative process. First, the finger designs concepts were developed and rated. A hybrid finger design was then created by combining the best components of the finger designs. Next, thumb designs were created and rated with the hybrid finger design. Finally, mechanical advantage design concepts were created and rated to establish a final design made up of the best finger, thumb, and mechanical advantage components.

Each time a set of designs was evaluated, it was rated when combined with the previously determined best components. For example, the thumb designs were first combined with the hybrid finger design and then rated. Also, when the mechanical advantage designs were compared, they were combined with the hybrid finger and thumb design and then rated. By rating the components in this manner, the selection process could account for how the components interacted with each other. Also, it was determined that the finger motion was the primary focus of the design since it was both more complex and more important which is why the finger designs were rated first. Ideally, numerous full designs with all the various combinations of components would have been created and compared to determine the final design. However, due to the number of possible combinations and time it would take to produce numerous full designs, the components of the device were evaluated as outlined in the following sections.

6.1 Pairwise Comparison

Using the specifications outlined in 4.1 Functional Requirements we first established a set of quantifiable and measurable categories and sub-categories to compare our designs. The definitions of each of these categories are further explained in Section 6.2.

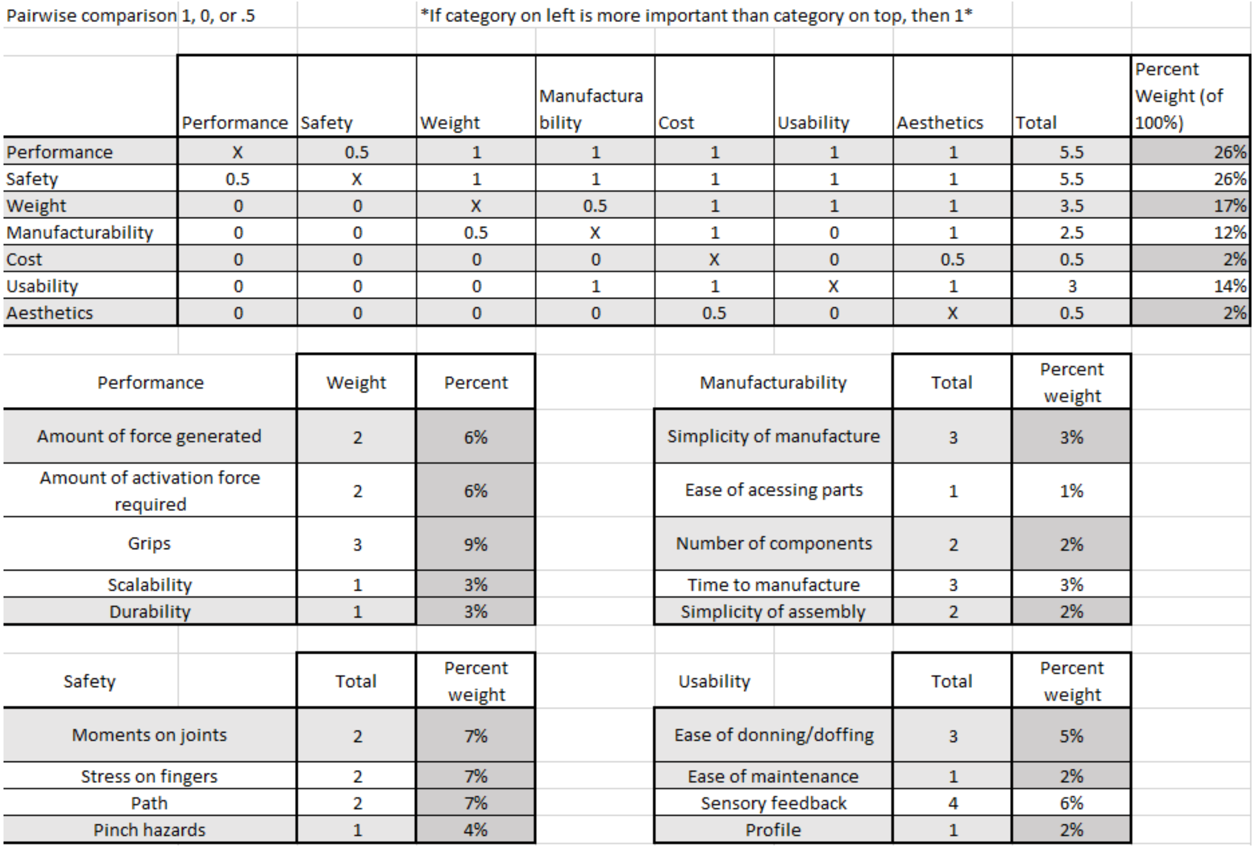
- Performance
    - Amount of Force Generated
    - Amounted of Activation Force Required
    - Grips
    - Scalability
    - Durability
- Safety
    - Moments on Joints
    - Forces and Stress on Fingers
    - Path
    - Pinch Hazards
- Weight
- Manufacturability
    - Simplicity of In-House Manufacturing
    - Ease of Accessing Parts
    - Number of Components
    - Time to Manufacture
    - Simplicity of Assembly
- Cost

- Usability
    - Ease of Donning/Doffing
    - Ease of Maintenance
    - Sensory Feedback
    - Profile
- Aesthetics

A pairwise comparison method was used to identify which main categories were more important and therefore deserved more weight when comparing designs. A pairwise comparison works by matching each category head-to-head against one another. This can be done in the form of a table with every category listed in each row and column. One can then compare each category individually against the rest of the categories using a 0, ½, 1 scale. A value of 1 is assigned if the category in the row is of more importance than the category in the column. Similarly, a value of 0 is assigned if the category is of less importance than the category in the column. A value of ½ is assigned if the categories are of equal importance.

Pairwise comparisons were completed for all the main categories. The final score was the average of the four individual assigned scores. A discussion was held when the average was an intermediate value such as 0.75 and the team agreed upon the appropriate final score. Values were assigned for percentages for the categories and sub-categories with guidance from the pairwise comparison results. These weighted percentages helped identify the best design or best parts of each finger design. The results made performance and safety the two most important categories, with weight, manufacturability, and usability slightly less important. Finally, cost and aesthetics both accounted for 2% of the rankings (Table 11).

Table 11: Results from Pairwise Comparison



Pairwise comparison 1, 0, or .5

If category on left is more important than category on top, then 1

	Performance	Safety	Weight	Manufacturability	Cost	Usability	Aesthetics	Total	Percent Weight (of 100%)
Performance	X	0.5	1	1	1	1	1	5.5	26%
Safety	0.5	X	1	1	1	1	1	5.5	26%
Weight	0	0	X	0.5	1	1	1	3.5	17%
Manufacturability	0	0	0.5	X	1	0	1	2.5	12%
Cost	0	0	0	0	X	0	0.5	0.5	2%
Usability	0	0	0	1	1	X	1	3	14%
Aesthetics	0	0	0	0	0.5	0	X	0.5	2%

Performance	Weight	Percent
Amount of force generated	2	6%
Amount of activation force required	2	6%
Grips	3	9%
Scalability	1	3%
Durability	1	3%

Manufacturability	Total	Percent weight
Simplicity of manufacture	3	3%
Ease of acessing parts	1	1%
Number of components	2	2%
Time to manufacture	3	3%
Simplicity of assembly	2	2%

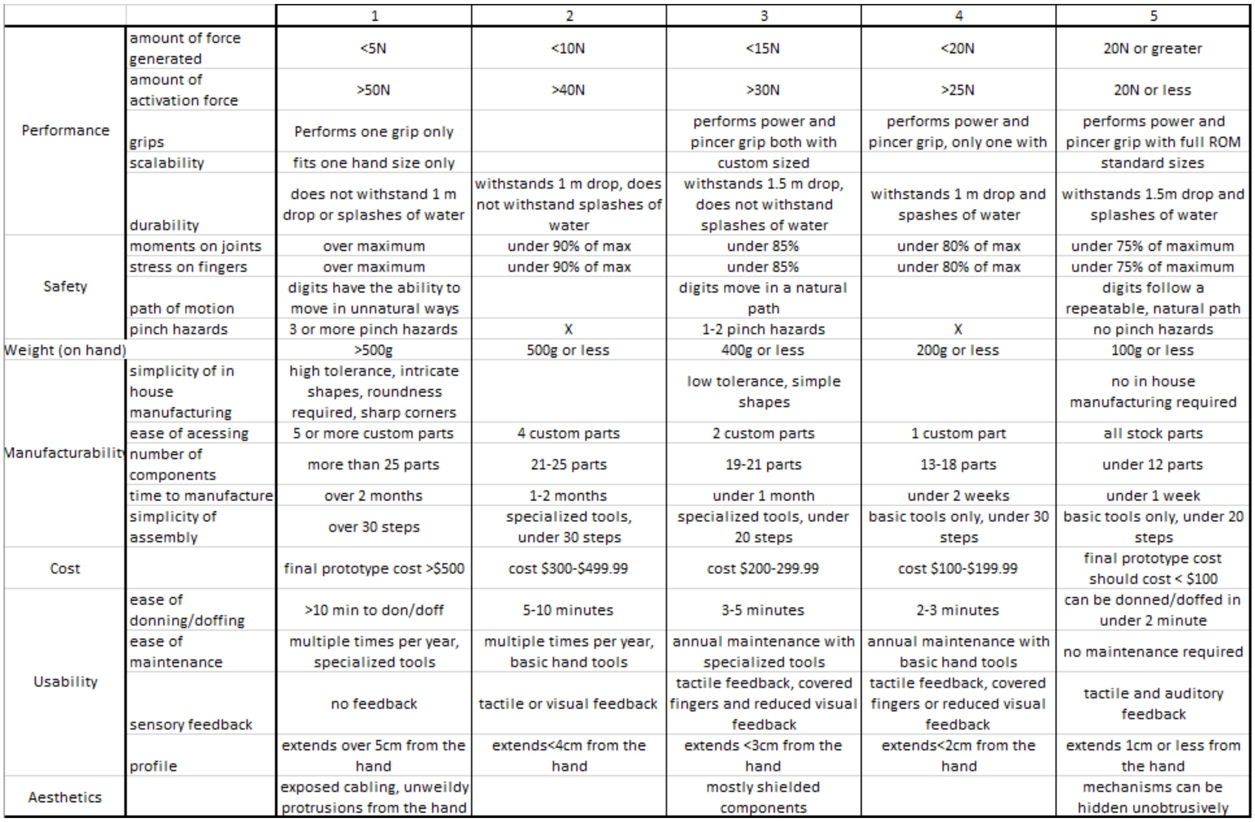
Safety	Total	Percent weight
Moments on joints	2	7%
Stress on fingers	2	7%
Path	2	7%
Pinch hazards	1	4%

Usability	Total	Percent weight
Ease of donning/doffing	3	5%
Ease of maintenance	1	2%
Sensory feedback	4	6%
Profile	1	2%

6.2 Finger Design Comparison

As mentioned, the finger design concepts were rated first. A five-point scale was used to assess each finger design with respect to the categories and sub-categories previously outlined. A value of 1 represents unacceptable performance of the device within the category while a five represents exemplary performance in a certain area (Table 12).

Table 12: Scoring Rubric for Finger Design Comparison

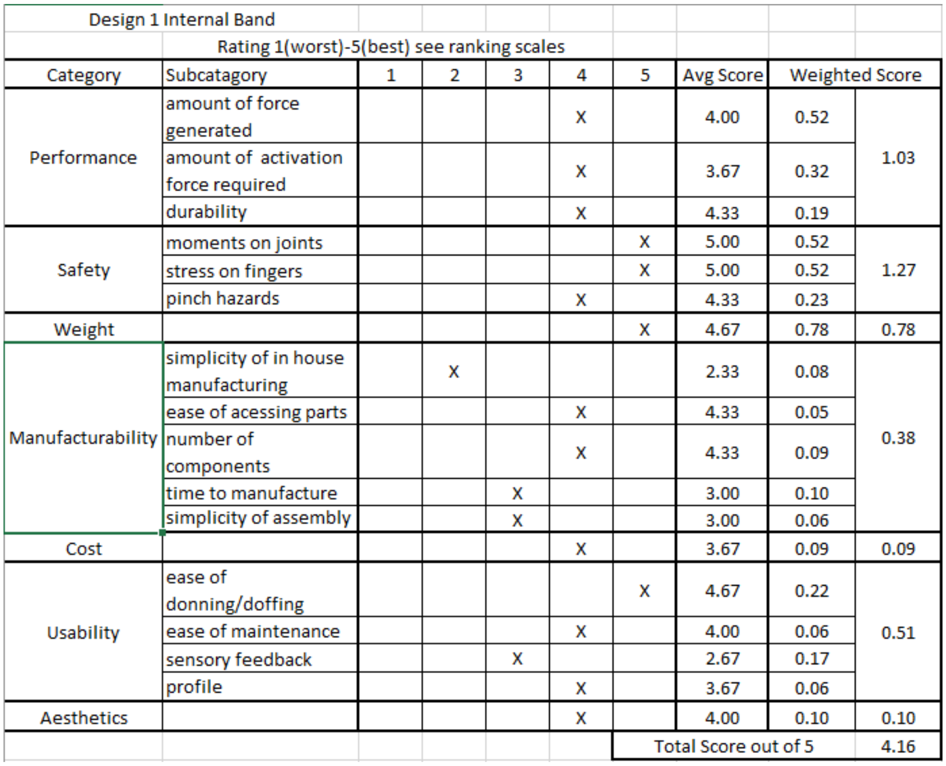


		1	2	3	4	5
Performance	amount of force generated	<5N	<10N	<15N	<20N	20N or greater
	amount of activation force	>50N	>40N	>30N	>25N	20N or less
	grips	Performs one grip only		performs power and pincer grip both with	performs power and pincer grip, only one with	performs power and pincer grip with full ROM
	scalability	fits one hand size only		custom sized		standard sizes
	durability	does not withstand 1 m drop or splashes of water	withstands 1 m drop, does not withstand splashes of water	withstands 1.5 m drop, does not withstand splashes of water	withstands 1 m drop and spashes of water	withstands 1.5m drop and splashes of water
Safety	moments on joints	over maximum	under 90% of max	under 85%	under 80% of max	under 75% of maximum
	stress on fingers	over maximum	under 90% of max	under 85%	under 80% of max	under 75% of maximum
	path of motion	digits have the ability to move in unnatural ways		digits move in a natural path		digits follow a repeatable, natural path
	pinch hazards	3 or more pinch hazards	X	1-2 pinch hazards	X	no pinch hazards
Weight (on hand)		>500g	500g or less	400g or less	200g or less	100g or less
Manufacturabilit	simplicity of in house manufacturing	high tolerance, intricate shapes, roundness required, sharp corners		low tolerance, simple shapes		no in house manufacturing required
	ease of acessing	5 or more custom parts	4 custom parts	2 custom parts	1 custom part	all stock parts
	number of components	more than 25 parts	21-25 parts	19-21 parts	13-18 parts	under 12 parts
	time to manufacture	over 2 months	1-2 months	under 1 month	under 2 weeks	under 1 week
	simplicity of assembly	over 30 steps	specialized tools, under 30 steps	specialized tools, under 20 steps	basic tools only, under 30 steps	basic tools only, under 20 steps
Cost		final prototype cost >$500	cost $300-$499.99	cost $200-299.99	cost $100-$199.99	final prototype cost should cost < $100
Usability	ease of donning/doffing	>10 min to don/doff	5-10 minutes	3-5 minutes	2-3 minutes	can be donned/doffed in under 2 minute
	ease of maintenance	multiple times per year, specialized tools	multiple times per year, basic hand tools	annual maintenance with specialized tools	annual maintenance with basic hand tools	no maintenance required
	sensory feedback	no feedback	tactile or visual feedback	tactile feedback, covered fingers and reduced visual feedback	tactile feedback, covered fingers or reduced visual feedback	tactile and auditory feedback
	profile	extends over 5cm from the hand	extends<4cm from the hand	extends <3cm from the hand	extends<2cm from the hand	extends 1cm or less from the hand
Aesthetics		exposed cabling, unweildy protrusions from the hand		mostly shielded components		mechanisms can be hidden unobtrusively

After the finger designs were fully rated, the scores were multiplied by the weights established in the pairwise comparison (Table 13 through Table 17). The first finger design 5.2.1 Design 1: Internal Band System consists of finger sleeves and cables running on the inside of the palm. Shortening or pulling on the cables causes the fingers to flex. The second finger design 5.2.2 Design 2: External Band System uses a cable driven linkage. The cable is routed over the back of the metacarpals and causes the fingers to flex when shortened or pulled. The third finger design 5.2.3 Design 3: Compression Spring Driven Linkage uses linear springs and a linkage to hold the fist in a resting closed position. Cabling routed over the back of the metacarpals can be used to oppose the closing force and allow the user to more easily extend the fingers. The fourth finger design 5.2.4 Design 4: Torsional Spring uses torsional springs on the right and left of the DIP, PIP and MCP joints. The springs hold the hand in a resting closed position. The fifth design

5.2.5 Design 5: Cable Driven Rotation attaches rigid finger channels around the fingers with a round peg on either side. A cable wound around the peg rotates the channels when pulled and causes the fingers to flex.

Table 13: Finger Design 1 Rating

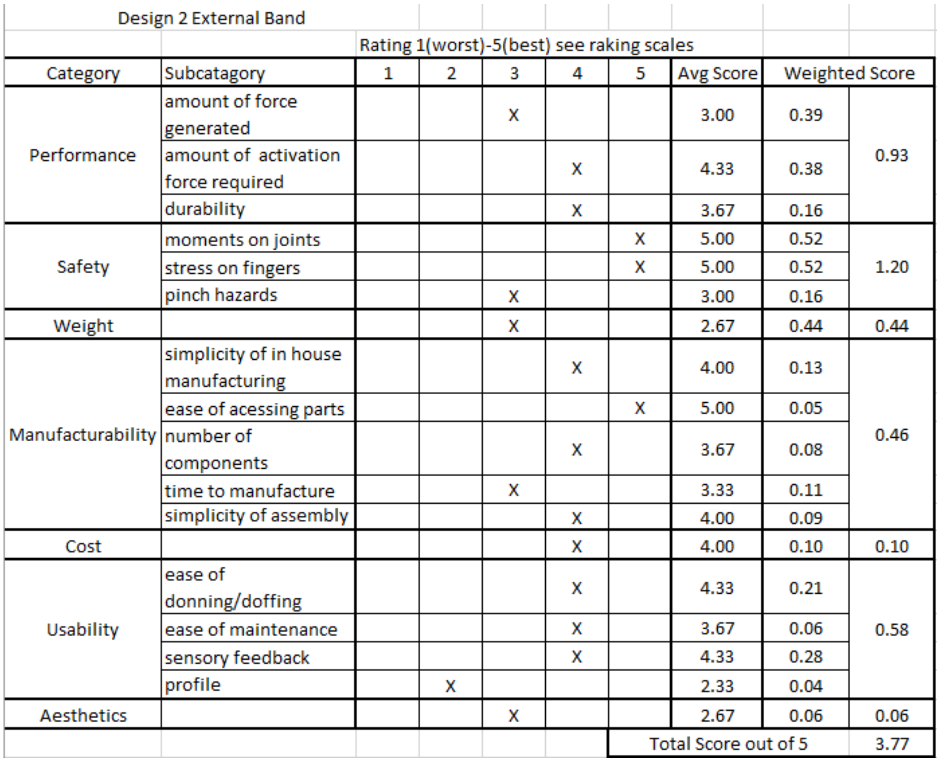


Design 1 Internal Band

Rating 1(worst)-5(best) see ranking scales

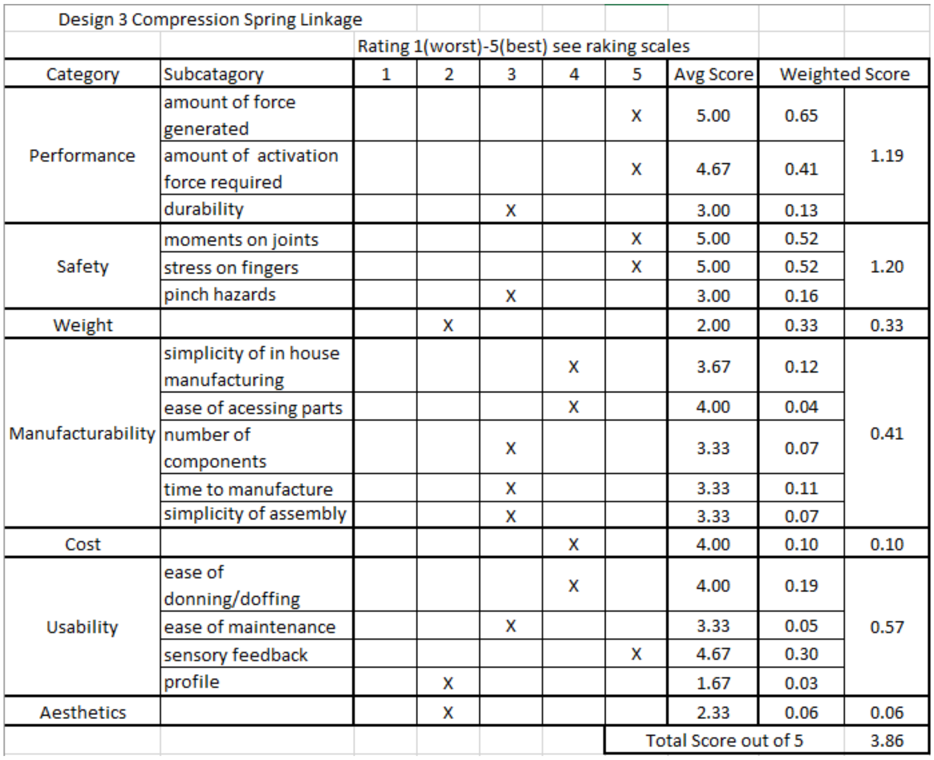
Category	Subcatagory	1	2	3	4	5	Avg Score	Weighted Score	
Performance	amount of force generated				X		4.00	0.52	1.03
	amount of activation force required				X		3.67	0.32	
	durability				X		4.33	0.19	
Safety	moments on joints					X	5.00	0.52	1.27
	stress on fingers					X	5.00	0.52	
	pinch hazards				X		4.33	0.23	
Weight						X	4.67	0.78	0.78
Manufacturability	simplicity of in house manufacturing		X				2.33	0.08	0.38
	ease of acessing parts				X		4.33	0.05	
	number of components				X		4.33	0.09	
	time to manufacture			X			3.00	0.10	
	simplicity of assembly			X			3.00	0.06	
Cost					X		3.67	0.09	0.09
Usability	ease of donning/doffing					X	4.67	0.22	0.51
	ease of maintenance				X		4.00	0.06	
	sensory feedback			X			2.67	0.17	
	profile				X		3.67	0.06	
Aesthetics					X		4.00	0.10	0.10
						Total Score out of 5			4.16

Table 14: Finger Design 2 Rating



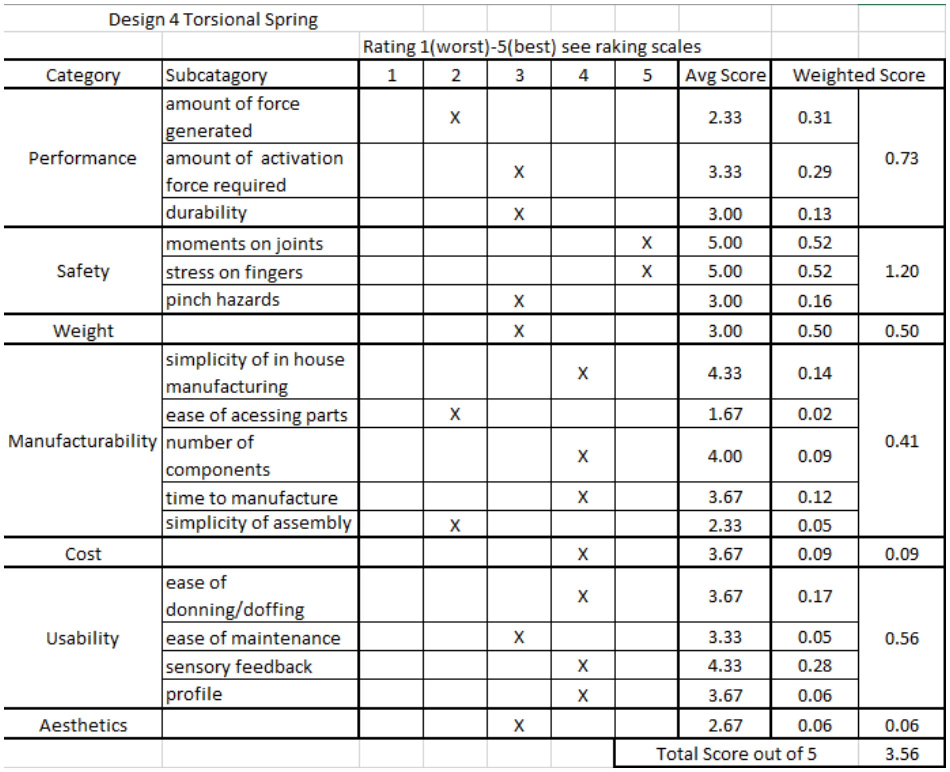
Design 2 External Band									
		Rating 1(worst)-5(best) see raking scales							
Category	Subcatagory	1	2	3	4	5	Avg Score	Weighted Score	
Performance	amount of force generated			X			3.00	0.39	0.93
	amount of activation force required				X		4.33	0.38	
	durability				X		3.67	0.16	
Safety	moments on joints					X	5.00	0.52	1.20
	stress on fingers					X	5.00	0.52	
	pinch hazards			X			3.00	0.16	
Weight				X			2.67	0.44	0.44
Manufacturability	simplicity of in house manufacturing				X		4.00	0.13	0.46
	ease of acessing parts					X	5.00	0.05	
	number of components				X		3.67	0.08	
	time to manufacture			X			3.33	0.11	
	simplicity of assembly				X		4.00	0.09	
Cost					X		4.00	0.10	0.10
Usability	ease of donning/doffing				X		4.33	0.21	0.58
	ease of maintenance				X		3.67	0.06	
	sensory feedback				X		4.33	0.28	
	profile		X				2.33	0.04	
Aesthetics				X			2.67	0.06	0.06
						Total Score out of 5			3.77

Table 15: Finger Design 3 Rating



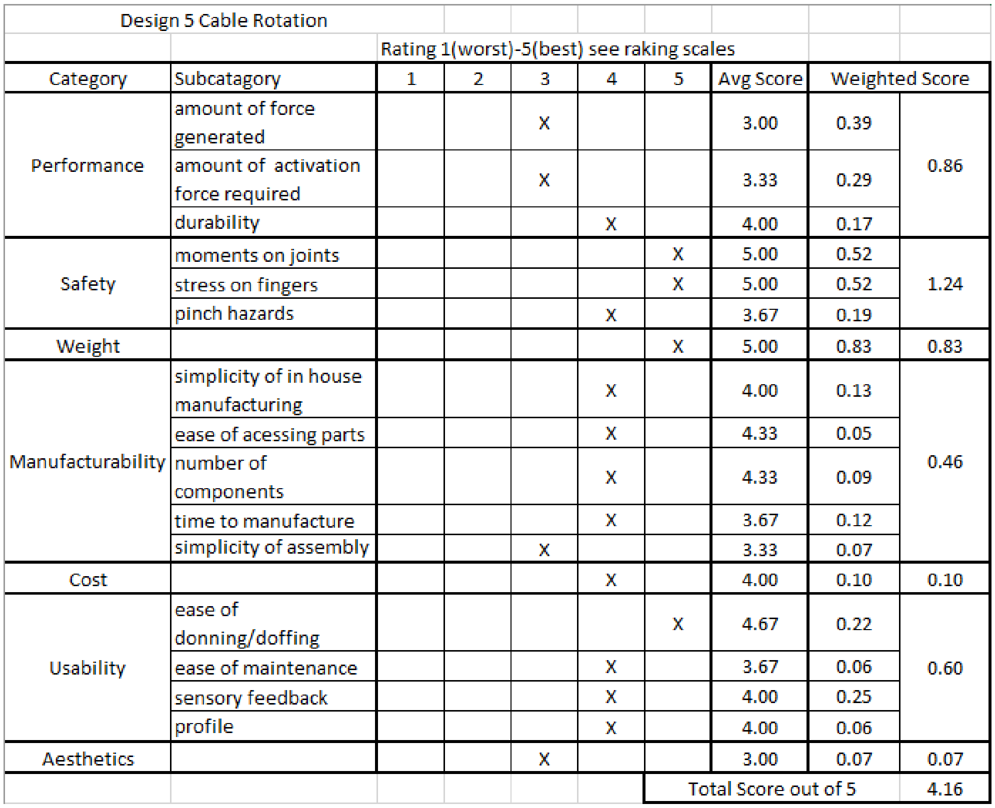
Design 3 Compression Spring Linkage									
		Rating 1(worst)-5(best) see raking scales							
Category	Subcatagory	1	2	3	4	5	Avg Score	Weighted Score	
Performance	amount of force generated					X	5.00	0.65	1.19
	amount of activation force required					X	4.67	0.41	
	durability			X			3.00	0.13	
Safety	moments on joints					X	5.00	0.52	1.20
	stress on fingers					X	5.00	0.52	
	pinch hazards			X			3.00	0.16	
Weight			X				2.00	0.33	0.33
Manufacturability	simplicity of in house manufacturing				X		3.67	0.12	0.41
	ease of acessing parts				X		4.00	0.04	
	number of components			X			3.33	0.07	
	time to manufacture			X			3.33	0.11	
	simplicity of assembly			X			3.33	0.07	
Cost					X		4.00	0.10	0.10
Usability	ease of donning/doffing				X		4.00	0.19	0.57
	ease of maintenance			X			3.33	0.05	
	sensory feedback					X	4.67	0.30	
	profile		X				1.67	0.03	
Aesthetics			X				2.33	0.06	0.06
						Total Score out of 5			3.86

Table 16: Finger Design 4 Rating



Design 4 Torsional Spring									
		Rating 1(worst)-5(best) see raking scales							
Category	Subcatagory	1	2	3	4	5	Avg Score	Weighted Score	
Performance	amount of force generated		X				2.33	0.31	0.73
	amount of activation force required			X			3.33	0.29	
	durability			X			3.00	0.13	
Safety	moments on joints					X	5.00	0.52	1.20
	stress on fingers					X	5.00	0.52	
	pinch hazards			X			3.00	0.16	
Weight				X			3.00	0.50	0.50
Manufacturability	simplicity of in house manufacturing				X		4.33	0.14	0.41
	ease of acessing parts		X				1.67	0.02	
	number of components				X		4.00	0.09	
	time to manufacture				X		3.67	0.12	
	simplicity of assembly		X				2.33	0.05	
Cost					X		3.67	0.09	0.09
Usability	ease of donning/doffing				X		3.67	0.17	0.56
	ease of maintenance			X			3.33	0.05	
	sensory feedback				X		4.33	0.28	
	profile				X		3.67	0.06	
Aesthetics				X			2.67	0.06	0.06
						Total Score out of 5			3.56

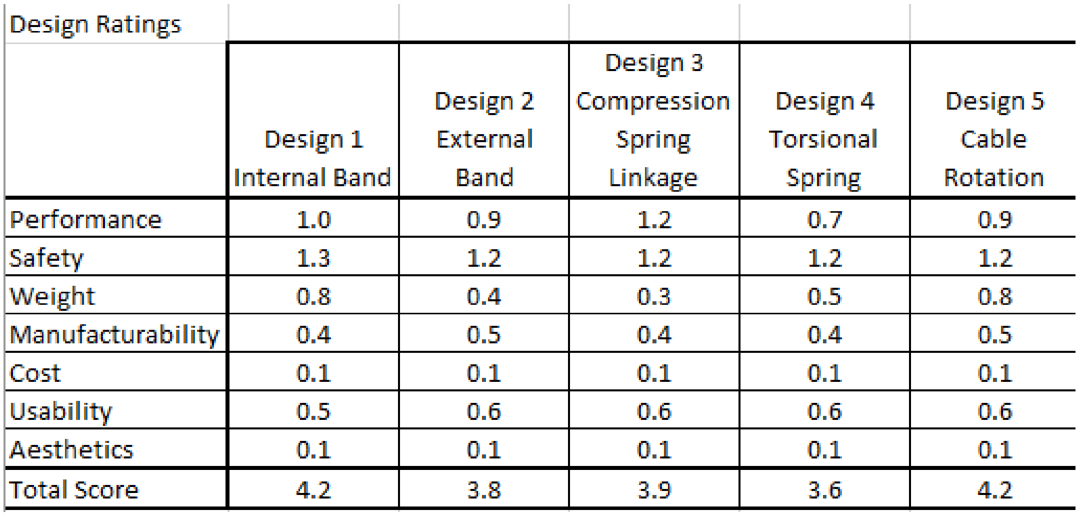
Table 17: Finger Design 5 Rating



Design 5 Cable Rotation									
		Rating 1(worst)-5(best) see raking scales							
Category	Subcatagory	1	2	3	4	5	Avg Score	Weighted Score	
Performance	amount of force generated			X			3.00	0.39	0.86
	amount of activation force required			X			3.33	0.29	
	durability				X		4.00	0.17	
Safety	moments on joints					X	5.00	0.52	1.24
	stress on fingers					X	5.00	0.52	
	pinch hazards				X		3.67	0.19	
Weight						X	5.00	0.83	0.83
Manufacturability	simplicity of in house manufacturing				X		4.00	0.13	0.46
	ease of acessing parts				X		4.33	0.05	
	number of components				X		4.33	0.09	
	time to manufacture				X		3.67	0.12	
	simplicity of assembly			X			3.33	0.07	
Cost					X		4.00	0.10	0.10
Usability	ease of donning/doffing					X	4.67	0.22	0.60
	ease of maintenance				X		3.67	0.06	
	sensory feedback				X		4.00	0.25	
	profile				X		4.00	0.06	
Aesthetics				X			3.00	0.07	0.07
						Total Score out of 5			4.16

As seen, Finger Design 1 and Finger Design 5 scored the highest. The weighted scores for each design category were also compared for each finger design to understand areas of strength and weakness within these finger designs (Table 18).

Table 18: Category Score Comparison to Determine Design Strengths and Weaknesses



Design Ratings					
	Design 1 Internal Band	Design 2 External Band	Design 3 Compression Spring Linkage	Design 4 Torsional Spring	Design 5 Cable Rotation
Performance	1.0	0.9	1.2	0.7	0.9
Safety	1.3	1.2	1.2	1.2	1.2
Weight	0.8	0.4	0.3	0.5	0.8
Manufacturability	0.4	0.5	0.4	0.4	0.5
Cost	0.1	0.1	0.1	0.1	0.1
Usability	0.5	0.6	0.6	0.6	0.6
Aesthetics	0.1	0.1	0.1	0.1	0.1
Total Score	4.2	3.8	3.9	3.6	4.2

This comparison helped develop a hybrid finger design combining the best components of Design 1 and Design 5.

6.3 Hybrid Finger Design

Next, a hybrid finger design was developed from the ratings of the finger design concepts. The scores indicated that Design 1 Internal Band (Section 5.2.1) and Design 5 Cable Driven Rotation (Section 5.2.5) would both perform acceptably. By combining individual components from both designs, a hybrid design was created to optimize the performance of the device. Rigid finger channels from Design 5 and the mechanical advantage produced by the cable tensioning mechanism from Design 1 were combined to increase the maximum force that could be applied by the device while reducing the wrist moment necessary to activate the device.

Figure 63 shows the layout of the hybrid design. The device is broken into several sections, labeled 1 through 6, including: distal and middle phalange channel (1), proximal phalange channel (2), metacarpal base (3), wrist cable routing bar (4), forearm brace (5), and pulley system (6) (Figure 64).

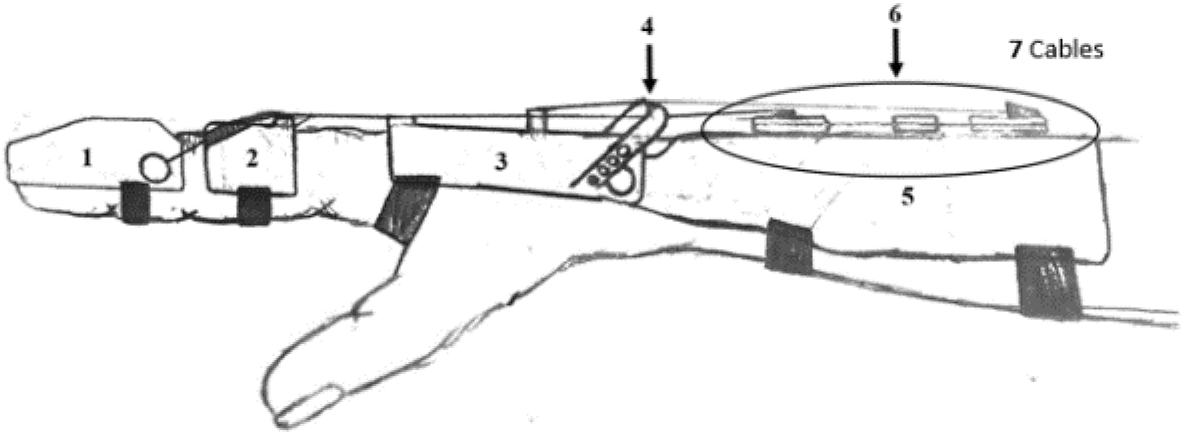


Figure 63: Hybrid Design with Labeled Parts

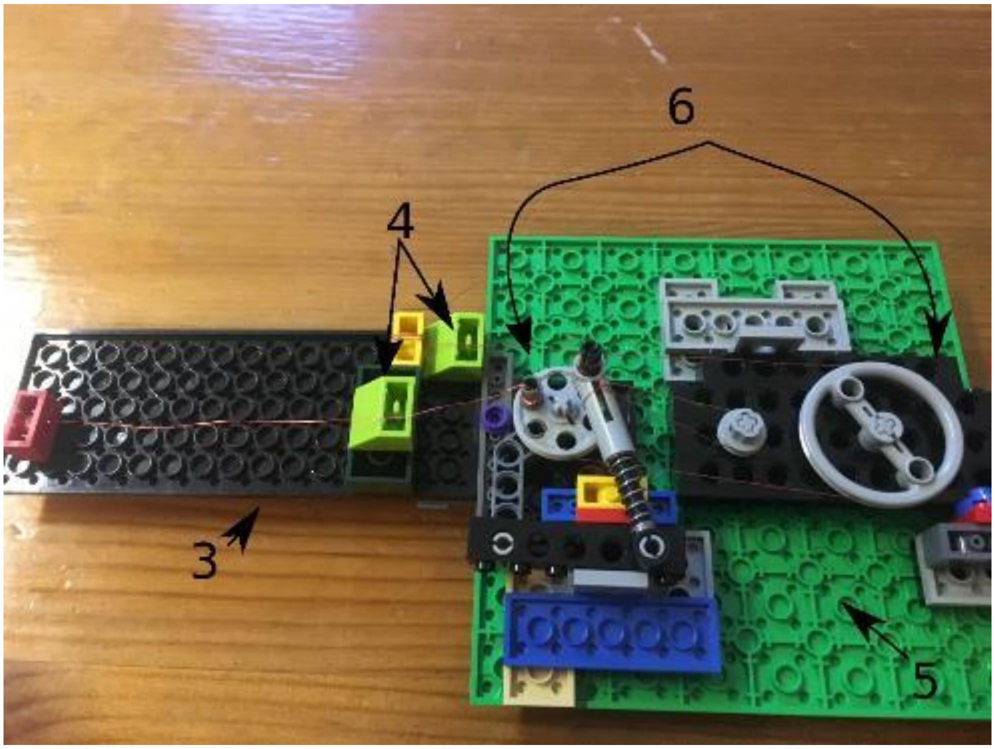


Figure 64: Zeroth Order Prototype of Hybrid Design

1. Distal and Middle Phalange Channel

The attachment to the user is similar to the cable driven rotation design (Finger Design 5). The mechanism is the same; a cable wound around the peg is pulled toward the palm causing the entire channel to rotate which closes the fingers. In this iteration (Figure 65) rather than moving each finger separately, the fingers are coupled into two pairs. The index and middle fingers are coupled by one channel and the ring and pinky fingers are coupled by a second channel which reduces the amount of cabling and added bulk. The new design has more rounded edges and the overall dimensions were decreased.

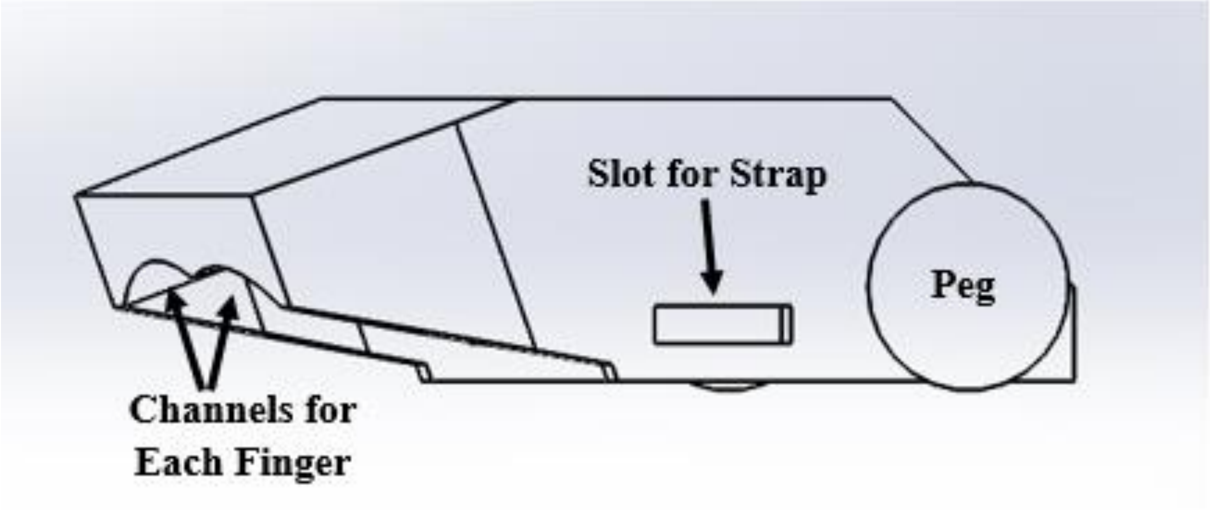


Figure 65: Rigid finger channel coupling two fingers covering the distal and medial phalange

2. Proximal phalange channel

Also, based on the cable driven rotation design, a second finger channel (Figure 66) rests on the proximal phalanges of the coupled fingers. The peg in this section is located between the fingers so as not to interfere with the external peg of the distal/medial finger channel.

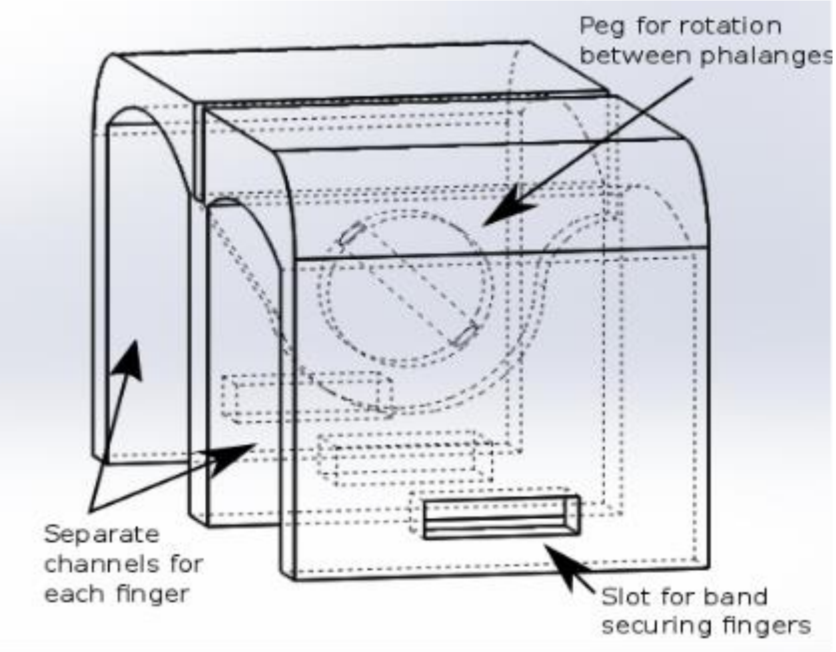


Figure 66: Proximal phalange channel coupling index and middle fingers

The proximal phalange channel will incorporate a cable routing system on the exterior of the part for the cable to run from the distal/proximal phalange channel to the back of the hand with reduced tangling.

3. Metacarpal Base

The Metacarpal Base is a rigid piece of material covering the back of the user's hand. It will allow for the routing of cables from the fingers to the pulley system as well as provide a base for the cable providing the tension to the pulley system. The base will provide a system through which the finger cables can be routed without tangling. The metacarpal base will connect to the forearm piece at a pin joint. This will allow the user to bend their wrist in flexion thus tensioning the cable and driving the device.

4. Wrist Cable Routing Bar

The wrist cable routing bar at the base of the wrist is an important part of this design. The C shaped bar is rigidly connected to the metacarpal base at an angle of roughly 45 degrees facing toward the wrist. One cable is attached to the top of the bar and connects to the mechanical advantage component. When the wrist is bent in flexion, the bar presses upward on the cable and pulls the cable forward on the arm. This creates a greater change in cable length than the wrist alone can provide, allowing for a greater mechanical advantage through a mechanism which uses an increased change in length to increase output force.

One of the benefits of this design is the amount of scalability that the bar offers. The bar can have several locking positions along its length in order to facilitate different users. For users with smaller hands and wrists, the height of the bar can be changed to facilitate the greater change in string length to generate the desired amount of cable displacement. This adjustability means that users with smaller hands, thus less natural wrist deflection, can create a change in length similar to those with larger hands.

5. Forearm Brace

The forearm brace is grounded to the user's forearm by straps and serves as the mounting point for the pulley system. Pulleys A and B are rigidly mounted to the forearm while pulley C moves parallel to the forearm (Figure 67). The brace attaches to the metacarpal base with a simple pin joint aligned with the pivot point of the wrist.

6. Pulley System

Section 6 is the pulley system shown in detail in Figure 67. This system of three pulleys generates a mechanical advantage of 3, meaning that the cable to the fingers will have three times the tension as the cable to the metacarpals. The amount of force generated by the wrist in flexion is 45N about the center of the metacarpals (Jung, 2002). Based on the expected loss from the activation motion to both finger pairs, a mechanical advantage component is necessary to achieve the desired 20N grip force. The tradeoff is that the cable to the metacarpals will need to move three times the distance compared to the cable to the fingers. Section 3 ensures the correct change in distance is accomplished mechanically.

Pulley C is mounted on a slider that moves horizontally along the length of the forearm. There is also a routing tunnel located on the surface of the forearm in order to prevent a force in the direction out of the page (Figure 67) from affecting the pulley.

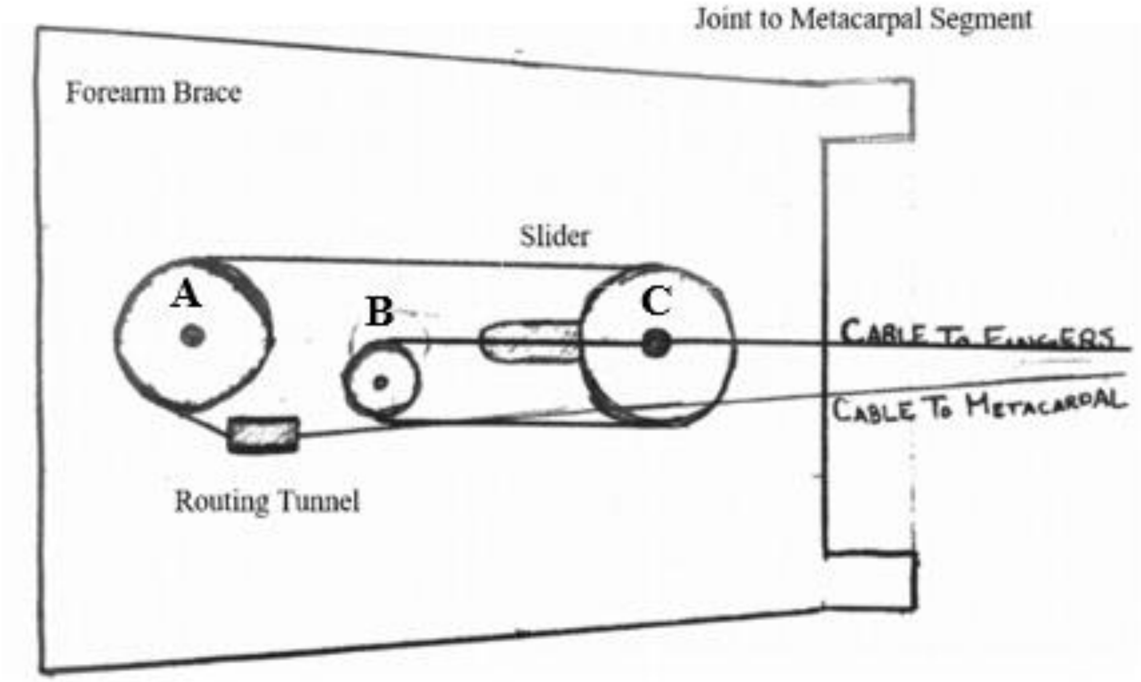
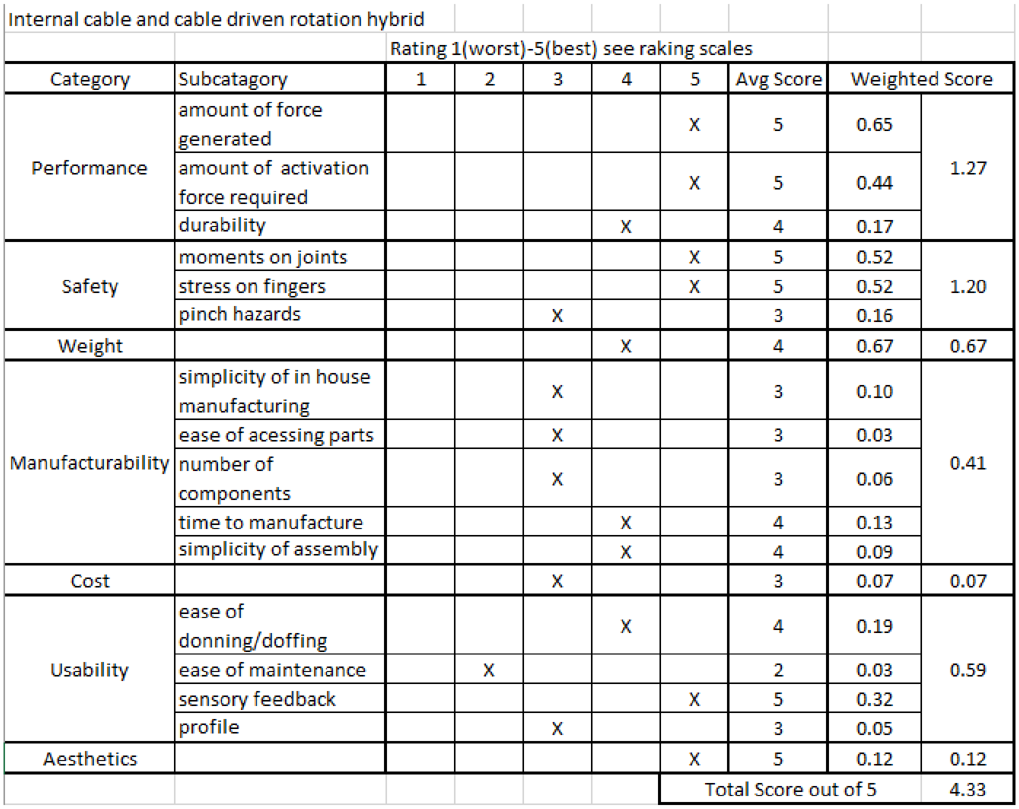


Figure 67: Pulley System on Forearm

This overall design takes the better aspects of designs 1 and 5 and adds a pulley system produce the mechanical advantage to guarantee the requisite 20 N of grip force at the fingers. A pulley system is one way to create a mechanical advantage. More mechanical advantage designs are discussed in Section 6.6.

Table 19 shows that the design improved to 4.33 which is higher than any of the individual finger designs.

Table 19: Hybrid Finger Design Rating Results

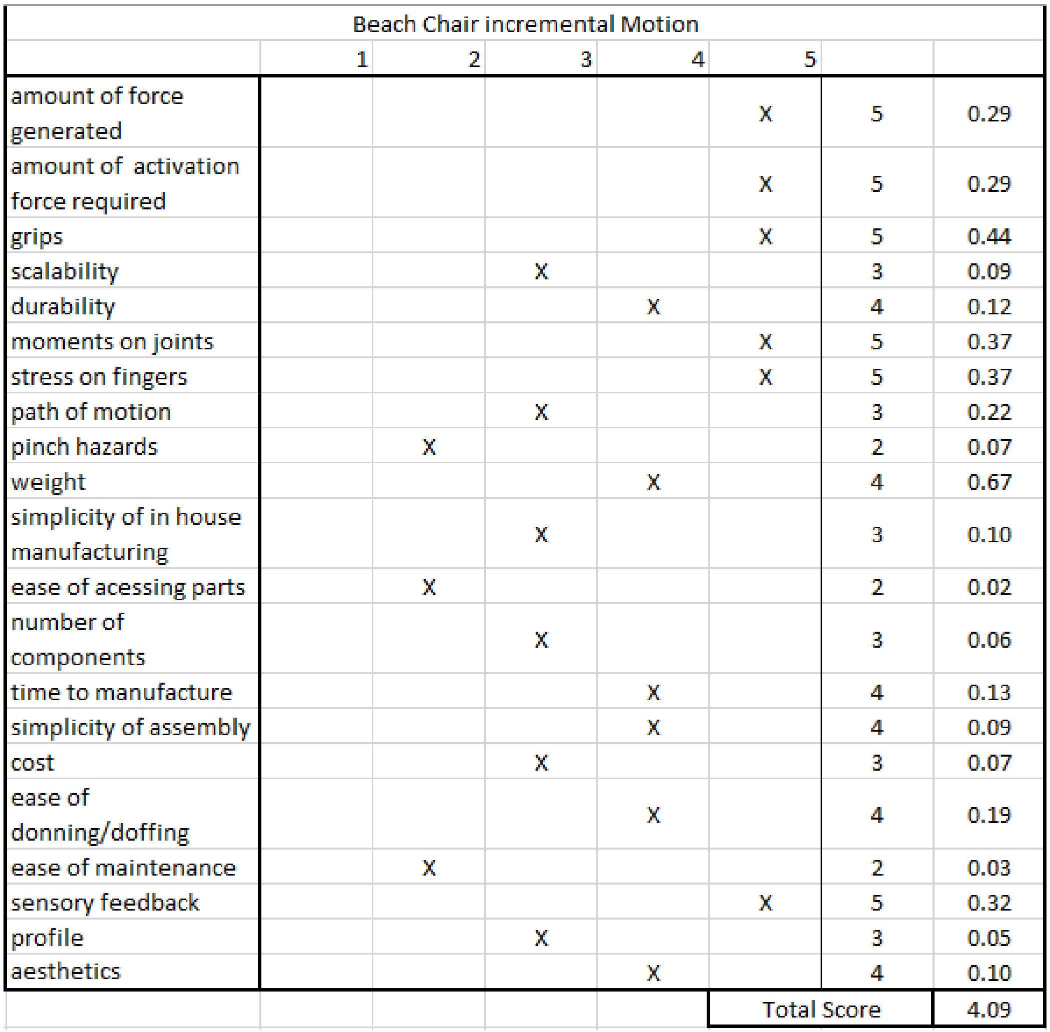


Internal cable and cable driven rotation hybrid									
		Rating 1(worst)-5(best) see raking scales							
Category	Subcatagory	1	2	3	4	5	Avg Score	Weighted Score	
Performance	amount of force generated					X	5	0.65	1.27
	amount of activation force required					X	5	0.44	
	durability				X		4	0.17	
Safety	moments on joints					X	5	0.52	1.20
	stress on fingers					X	5	0.52	
	pinch hazards			X			3	0.16	
Weight					X		4	0.67	0.67
Manufacturability	simplicity of in house manufacturing			X			3	0.10	0.41
	ease of acessing parts			X			3	0.03	
	number of components			X			3	0.06	
	time to manufacture				X		4	0.13	
	simplicity of assembly				X		4	0.09	
Cost				X			3	0.07	0.07
Usability	ease of donning/doffing				X		4	0.19	0.59
	ease of maintenance		X				2	0.03	
	sensory feedback					X	5	0.32	
	profile			X			3	0.05	
Aesthetics						X	5	0.12	0.12
						Total Score out of 5			4.33

6.4 Comparison of Hybrid Finger with Five Thumb Designs

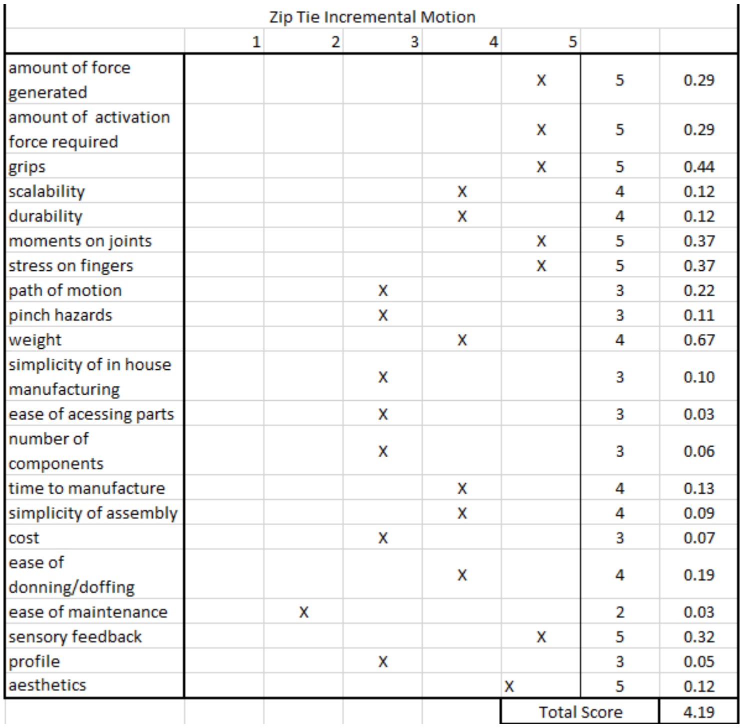
Next, the five thumb designs (Section 5.4) were combined with the hybrid finger design and rated to determine the best overall combination (Table 20: Hybrid Finger Design with Beach Chair Incremental Motion Thumb Design Rating-Table 24: Hybrid Finger Design with Distal Phalanx Incremental Motion Thumb Design Rating). As mentioned, the thumb designs were rated while combined with the hybrid finger design to account for how the thumb designs interacted with the best finger design. Since it was determined that the finger motion was more critical and more difficult to achieve, it was important to select a finger design first and then select the thumb design that worked the best with that hybrid finger design.

Table 20: Hybrid Finger Design with Beach Chair Incremental Motion Thumb Design Rating



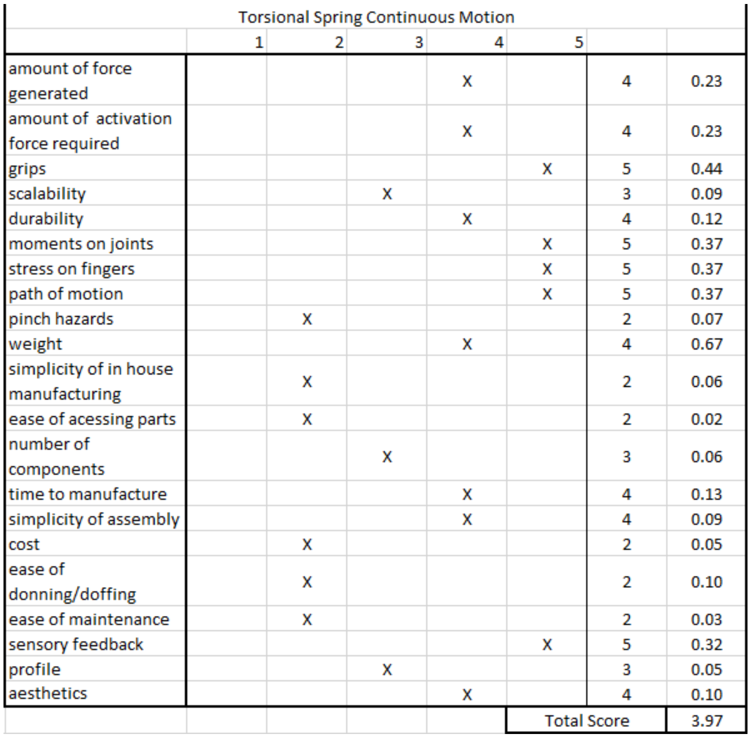
Beach Chair incremental Motion							
	1	2	3	4	5		
amount of force generated					X	5	0.29
amount of activation force required					X	5	0.29
grips					X	5	0.44
scalability			X			3	0.09
durability				X		4	0.12
moments on joints					X	5	0.37
stress on fingers					X	5	0.37
path of motion			X			3	0.22
pinch hazards		X				2	0.07
weight				X		4	0.67
simplicity of in house manufacturing			X			3	0.10
ease of acessing parts		X				2	0.02
number of components			X			3	0.06
time to manufacture				X		4	0.13
simplicity of assembly				X		4	0.09
cost			X			3	0.07
ease of donning/doffing				X		4	0.19
ease of maintenance		X				2	0.03
sensory feedback					X	5	0.32
profile			X			3	0.05
aesthetics				X		4	0.10
					Total Score		4.09

Table 21: Hybrid Finger Design with Zip Tie Incremental Motion Thumb Design Rating



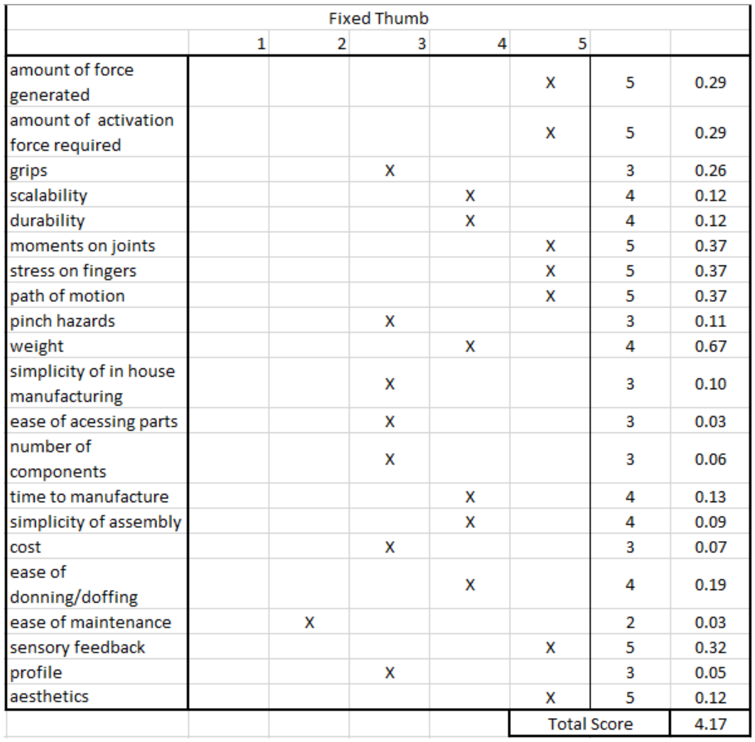
	Zip Tie Incremental Motion						
	1	2	3	4	5		
amount of force generated					X	5	0.29
amount of activation force required					X	5	0.29
grips					X	5	0.44
scalability				X		4	0.12
durability				X		4	0.12
moments on joints					X	5	0.37
stress on fingers					X	5	0.37
path of motion			X			3	0.22
pinch hazards			X			3	0.11
weight				X		4	0.67
simplicity of in house manufacturing			X			3	0.10
ease of acessing parts			X			3	0.03
number of components			X			3	0.06
time to manufacture				X		4	0.13
simplicity of assembly				X		4	0.09
cost			X			3	0.07
ease of donning/doffing				X		4	0.19
ease of maintenance		X				2	0.03
sensory feedback					X	5	0.32
profile			X			3	0.05
aesthetics					X	5	0.12
					Total Score		4.19

Table 22: Hybrid Finger Design with Torsional Spring Continuous Motion Design Rating



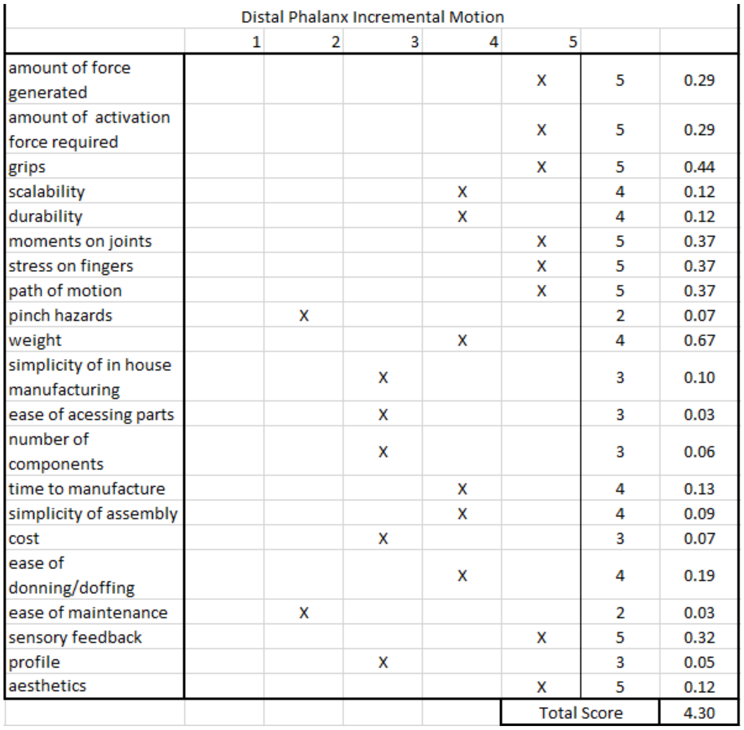
	Torsional Spring Continuous Motion						
	1	2	3	4	5		
amount of force generated				X		4	0.23
amount of activation force required				X		4	0.23
grips					X	5	0.44
scalability			X			3	0.09
durability				X		4	0.12
moments on joints					X	5	0.37
stress on fingers					X	5	0.37
path of motion					X	5	0.37
pinch hazards		X				2	0.07
weight				X		4	0.67
simplicity of in house manufacturing		X				2	0.06
ease of acessing parts		X				2	0.02
number of components			X			3	0.06
time to manufacture				X		4	0.13
simplicity of assembly				X		4	0.09
cost		X				2	0.05
ease of donning/doffing		X				2	0.10
ease of maintenance		X				2	0.03
sensory feedback					X	5	0.32
profile			X			3	0.05
aesthetics				X		4	0.10
					Total Score		3.97

Table 23: Hybrid Finger Design with Fixed Thumb Design Rating



			Fixed Thumb				
	1	2	3	4	5		
amount of force generated					X	5	0.29
amount of activation force required					X	5	0.29
grips			X			3	0.26
scalability				X		4	0.12
durability				X		4	0.12
moments on joints					X	5	0.37
stress on fingers					X	5	0.37
path of motion					X	5	0.37
pinch hazards			X			3	0.11
weight				X		4	0.67
simplicity of in house manufacturing			X			3	0.10
ease of acessing parts			X			3	0.03
number of components			X			3	0.06
time to manufacture				X		4	0.13
simplicity of assembly				X		4	0.09
cost			X			3	0.07
ease of donning/doffing				X		4	0.19
ease of maintenance		X				2	0.03
sensory feedback					X	5	0.32
profile			X			3	0.05
aesthetics					X	5	0.12
					Total Score		4.17

Table 24: Hybrid Finger Design with Distal Phalanx Incremental Motion Thumb Design Rating



	Distal Phalanx Incremental Motion						
	1	2	3	4	5		
amount of force generated					X	5	0.29
amount of activation force required					X	5	0.29
grips					X	5	0.44
scalability				X		4	0.12
durability				X		4	0.12
moments on joints					X	5	0.37
stress on fingers					X	5	0.37
path of motion					X	5	0.37
pinch hazards		X				2	0.07
weight				X		4	0.67
simplicity of in house manufacturing			X			3	0.10
ease of acessing parts			X			3	0.03
number of components			X			3	0.06
time to manufacture				X		4	0.13
simplicity of assembly				X		4	0.09
cost			X			3	0.07
ease of donning/doffing				X		4	0.19
ease of maintenance		X				2	0.03
sensory feedback					X	5	0.32
profile			X			3	0.05
aesthetics					X	5	0.12
						Total Score	4.30

The combination of the hybrid finger design with the Thumb Distal Phalanx Incremental Motion Design (Section 5.4.5) proved to be the best combination. The hybrid finger design paired with the zip tie incremental motion thumb design received the second highest score. The hybrid finger design with the fixed thumb surprisingly received the third highest score due to the simplicity of the design. However, the design with the fixed thumb does not allow the fingers to have a full range of motion and limits the size of the power grip radius, which is why it received a slightly lower score.

6.5 Mechanical Advantage Design Concepts

After examining the hybrid finger design combined with the thumb distal phalanx incremental motion thumb design, it was determined that additional mechanical advantage designs needed to be investigated. The initial hybrid finger design used a pulley system to produce the required mechanical advantage (Section 6.3). This section outlines various mechanical advantages concepts that could be used in place of the pulley system. After developing these mechanical advantage design concepts, the full hybrid design with the thumb was rated with the various mechanical advantage concepts.

6.5.1 Straight Line Linkage

Another way to increase the force with which the fingers close is by using a linkage system. A linkage can increase the mechanical advantage of the system as the pulley, lever and gear systems do. A linkage system similar to Hoeken's Straight Line Linkage (Figure 68) helps pull the fingers closed as the wrist flexes. A prototype was created by creating a design of this linkage and having the coupler rock back and forth along the straight portion of the curve as the wrist flexes and extends.

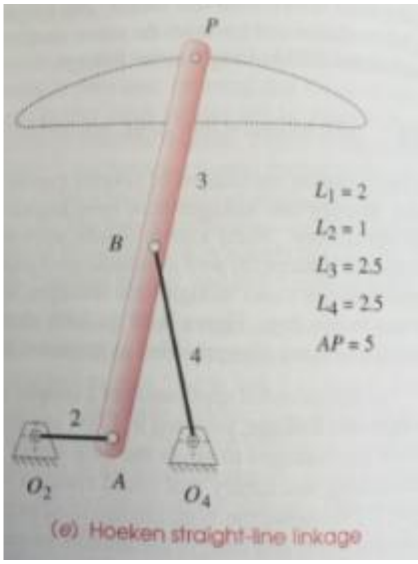


Figure 68: Hoeken Straight Line Linkage (Norton, 2012)

In the prototype (Figure 69), link 2 is connected to the metacarpal piece (link 1). Link 4 is fixed and a part of the forearm piece while connected to link 3. In this depiction, link 4 which is fixed to the forearm piece is defined as ground. The coupler point of link 3 hangs slightly above the hand and is connected to the finger pieces by a cable. A Gruebler Analysis shows that this 4 bar linkage is in fact a 1 DOF system.

DOF=3(n-1)-2J_1-J_2

DOF=3(4-1)-2(4)=1

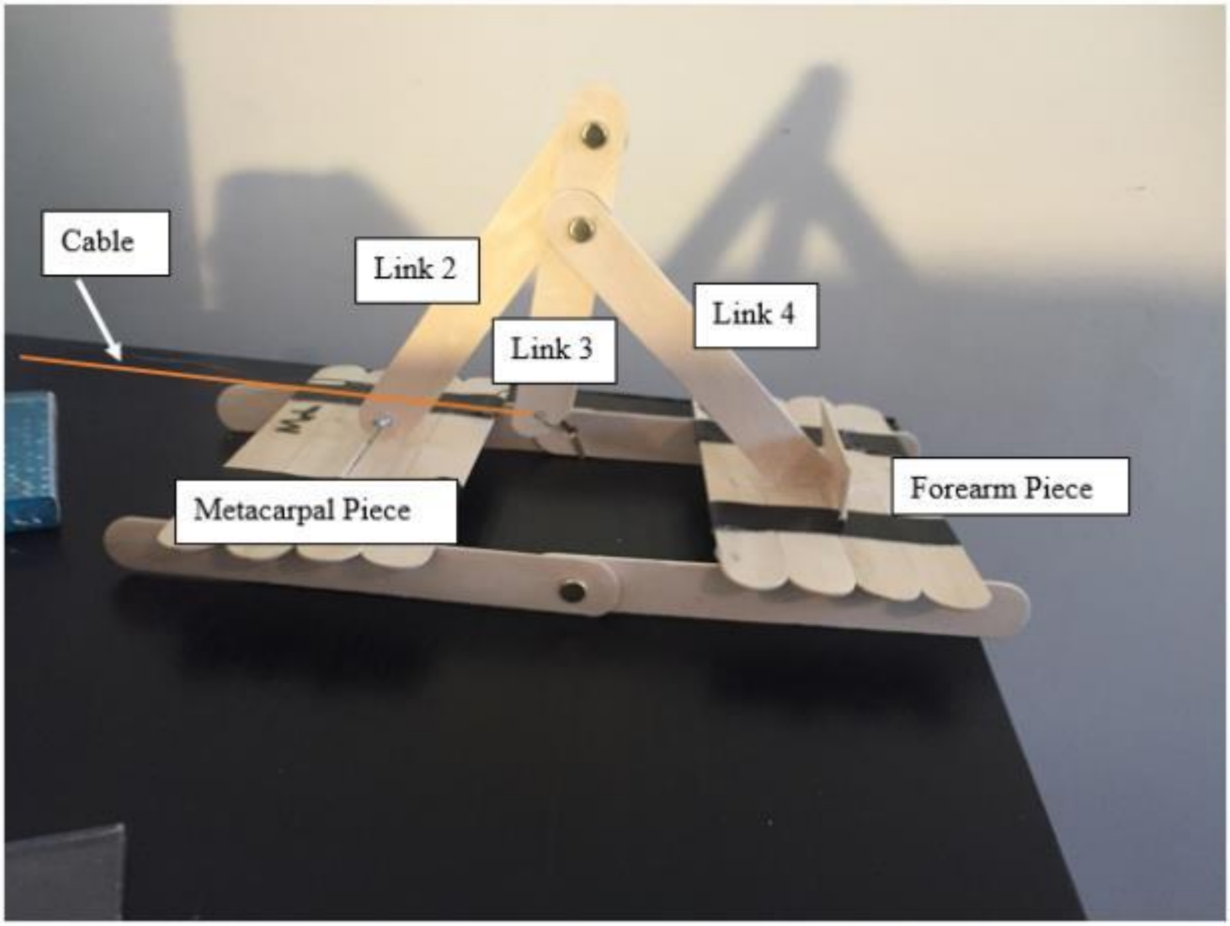


Figure 69: Linkage with Wrist in Neutral Position

As the wrist flexes (Figure 70), link 3 moves to the right pulling the fingers closed. It is important to note that the cable connecting link 3 to the fingers remains approximately parallel to the metacarpal piece when the wrist flexes because the linkage is a version of Hoeken’s Straight Line Mechanism. If the linkage were not an approximate straight line linkage, the cable could potentially be pulled at an angle which would reduce the output force and effectiveness of the device.

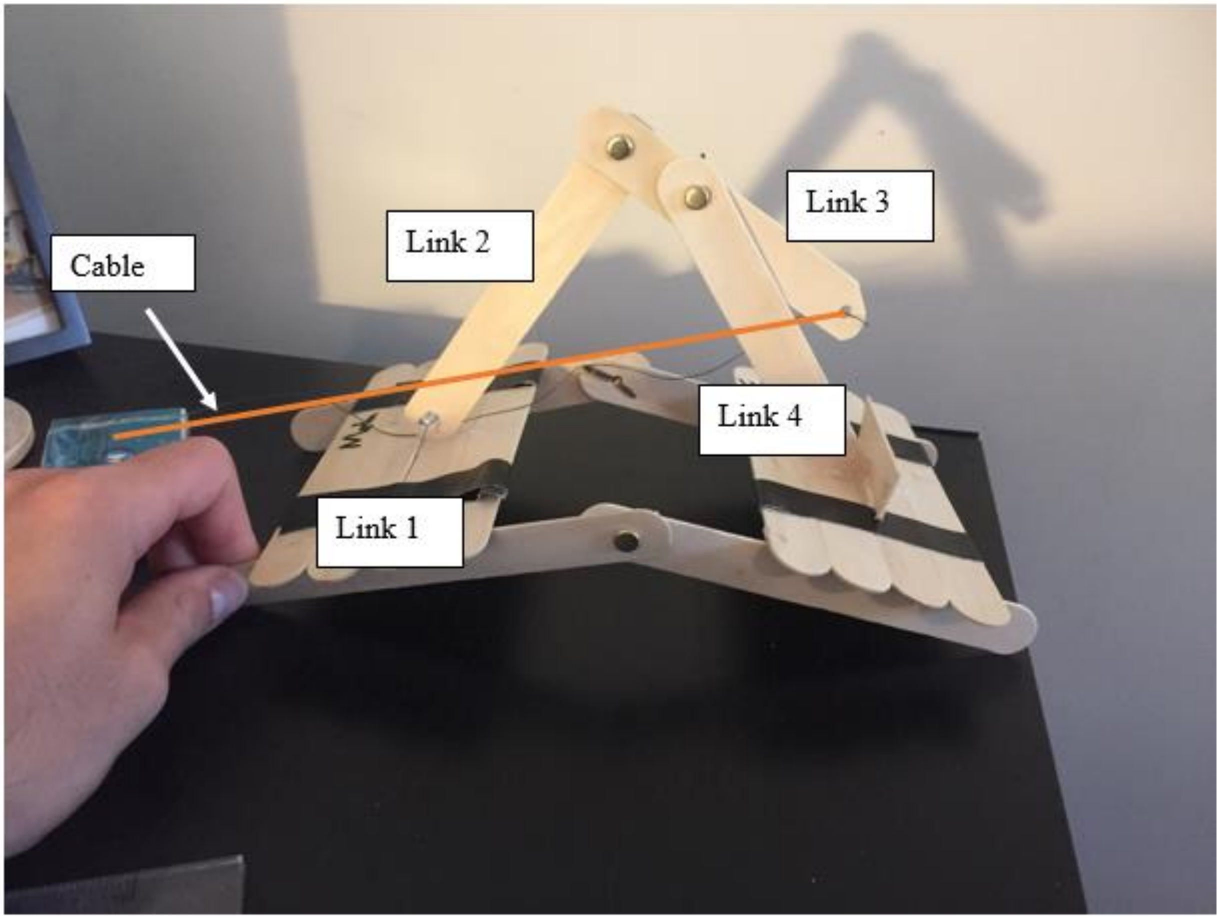


Figure 70: Linkage with Wrist Flexed and Cable Pulling Fingers Closed

Other linkages, such as the Peaucellier–Lipkin Linkage (Figure 71), are capable of producing perfect straight-line output motion. However, these linkages typically require more links (8 in Peaucellier-Lipkin case) which would increase the bulk of the device. An inversion of the Hoeken Linkage, which only produces approximate straight line motion but is less bulky, should be adequate as the motion of the coupler link is small. Other approximate straight line linkages such as the Roberts, Evans, or Chebyschev linkages could work for this type of design.

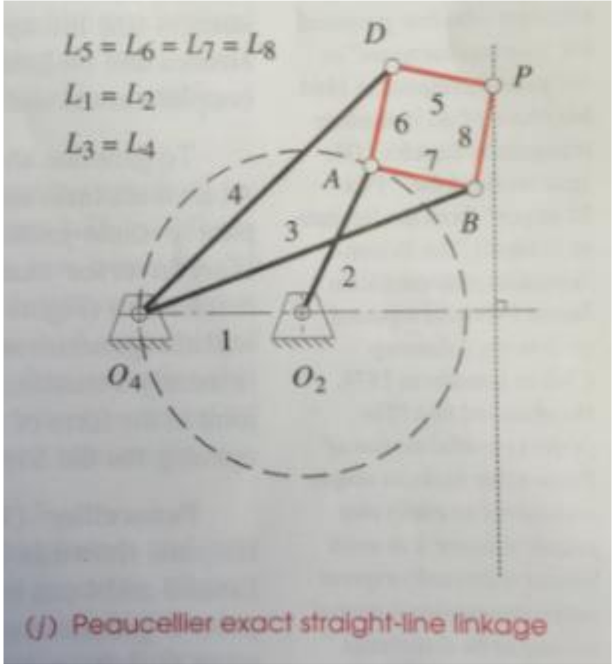


Figure 71: Peaucellier–Lipkin Linkage (Norton, 2012)

To further reduce the size of the linkage prototype design, it is important to understand the mechanical advantage of the linkage system shown in the prototype, or how much the input force is amplified. The mechanical advantage is given by:

Equation 4: Mechanical Advantage Formula

$$MA = \frac{F_{out}}{F_{in}}$$

Assuming an input force of approximately 45 N (average value for force produced from wrist flexion measured from middle of metacarpal), and a known F_{out} (based on peg diameter) value required to meet the specifications of the device (produce 20 N of grip force), one can estimate the approximate mechanical advantage necessary (Jung, 2002). Next, the lengths of the links can be calculated using the following equation, where L is the link length, u and v are the angles at which the output and input forces act, respectively, and r is the distance at which the force acts.

Equation 5: Link Length Calculation Formula

$$MA = \left(\frac{L_{out} * sinu}{L_{in} * sinv}\right)\left(\frac{r_{in}}{r_{out}}\right)$$

An optimization of straight-line motion and link lengths would be required to further this design. A more accurate straight line motion can be produced with more links. The approximate straight-line motion and correct link lengths will be required to produce the appropriate output force. The length of the coupler link also determines how much the cable will change in length or move as the wrist flexes to a certain degree. However, it will also be important to limit the height of the linkage above the device for usability and aesthetic purposes.

6.5.2 Forearm Levers

This design features levers on the forearm to generate mechanical advantage throughout the entire device (Figure 72). The metacarpal bar serves to increase the change in string length as a result of wrist flexion (Figure 73). There are two cables connected to the metacarpal bar that each connect to a lever. These levers rotate about a fixed pivot. At the opposite end of the lever, a string connects from the lever to the fingers. As the wrist flexes, the cable from the metacarpal bar pulls on one end of the lever, causing a rotation about the fixed pivot. The cable at the opposite end of the lever then pulls on the fingers, causing them to close. When the wrist stops acting in flexion, the spring forces the lever back into its starting position, re-tensioning the cable from lever to metacarpal bar.

The mechanical advantage of this device can be determined by dividing the length of the lever’s activation side (with cable from metacarpal bar) by the length of the reacting side (with cable to fingers). Similar to a pulley system, a greater change in length would need to be generated to create the desired finger motion with desired force.

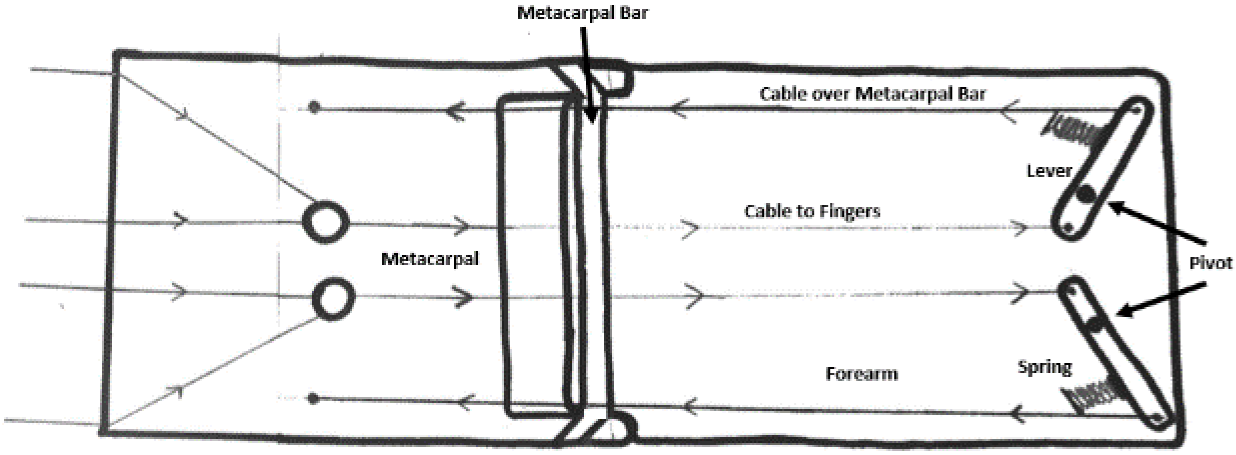


Figure 72: Forearm Lever Design Top View

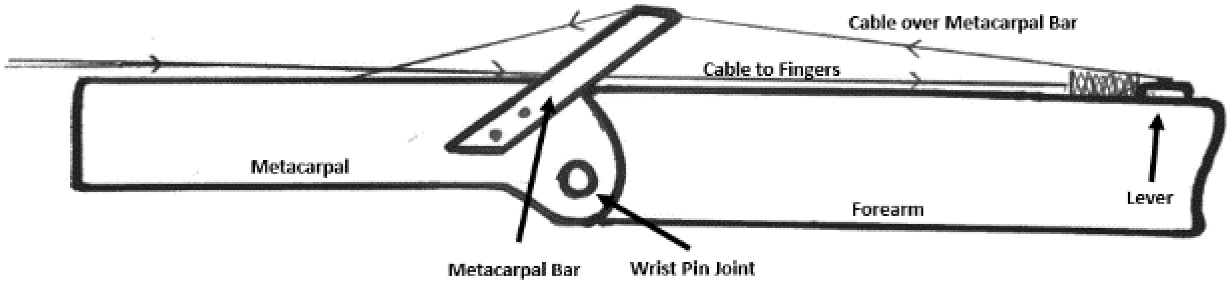


Figure 73: Forearm Lever Design Side View

6.5.3 Gears

Bevel Gear System

The first gear design utilizes a bevel gear mounted on the wrist joint in order to produce the desired mechanical advantage. The bevel gear mechanism is shown in Figure 74. The bevel gear [1] would be connected to and rotate with the metacarpal piece. When the user rotates his/her wrist, the bevel gear would spin, rotating the small spur gear [2]. This gear would be in alignment with a much larger gear [3] positioned on the forearm. Gear 3 would then connect to the finger mechanisms via cable. This gear ratio increases the total amount of output torque. The necessary gear ratio can be found by using the relationship between the radii of the gears (r) and the torque (t).

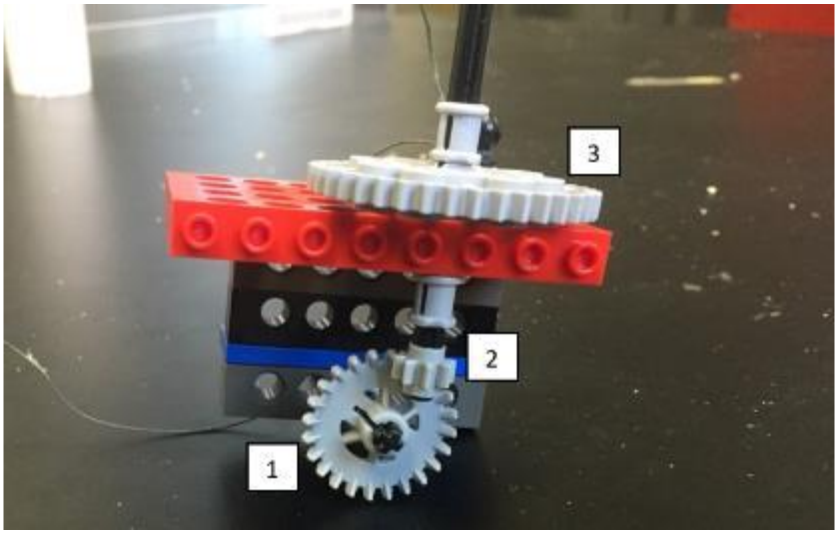


Figure 74: Bevel Gear System

Equation 6: Gear Ratio Formula

$$Gear\ Ratio = \frac{r2}{r1} * \frac{r3}{r2} = \frac{Tout}{Tin}$$

For this application, 100 N of tension in the cable connected to the fingers is desired. The amount of torque the wrist can generate from the center of the metacarpals in an average person is about 45 Newtons (Jung, 2002). Here, a necessary assumption must be made about how much torque drives the bevel gear attached to the wrist. For this value, assume that the average distance from the wrist to the center of the metacarpal is 0.05m. With this assumption, the total input torque from the wrist motion is 2.25Nm.

Equation 7: Wrist Input-Torque Calculation Formula

$$Twrist = Fwrist * Length = 45Nm * .05m = 2.25Nm$$

$$TorqueBevelGear = 2.25Nm$$

In order to find the gear ratio, the necessary amount of torque output going to the fingers needs to be estimated. This can be determined by using an estimated gear size of 0.025 m and the estimated required output force of 100N to the fingers.

$$Required\ Final\ Torque = 100N * .025m = 5Nm$$

Looking at the ratio of the torque output to the torque input, a gear ratio of 2.22 is produced. This means that the gear train between the bevel gear and the output gear would need to produce a gear ratio larger than the minimum of 2.22.

$$Gear\ Ratio = \frac{5Nm}{2.25Nm} = 2.22$$

This design can easily generate the required amount of output torque by increasing the gear ratio. While it meets the force requirements of the design specifications, it does not meet the size constraints. Not only does the initial bevel gear have to hang outside of the forearm, but the larger gear [3] would also extend beyond the arm (Figure 74). While this design produces the force, it is does not fulfill the size requirements for the mechanical advantage device.

Spur Gear System

The spur gear design uses two spur gears in order to generate 100N of tension in the cable going to the fingers. This design (Figure 75) uses two gears mounted on the top of the forearm. Cabling extends from the center of the metacarpals to gear 1. When the wrist is flexed, gear 1 to rotates clockwise. The driven gear (gear 2) rotates counterclockwise pulling the cable attached to the finger device. All of the calculations for the bevel gear design also apply to this design since they are based on the same gear ratios without the use of an idler. Assuming the same ratio for the torques in the bevel gear section, a gear ratio of 2.22 is necessary.

$$Gear\ Ratio = \frac{Tout}{Tin} = \frac{5Nm}{2.25Nm} = 2.22$$

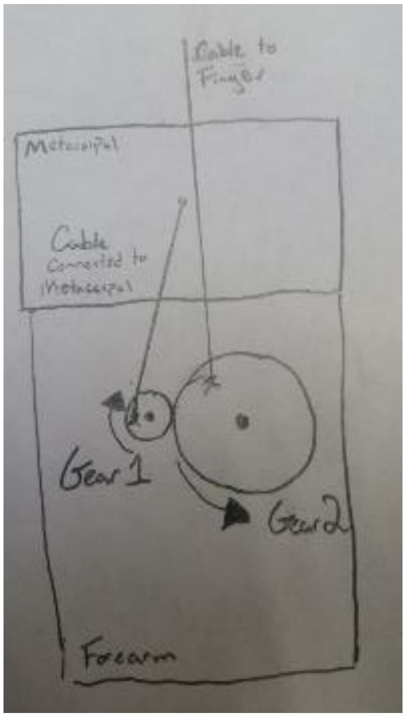


Figure 75: Spur Gear System

This design concept utilizes the change in gear size to generate mechanical advantage. While it can easily generate the requisite amount of force, this gear design is limited once again by the overall diameter of the larger gear. The plain spur gear design however, does not extend beyond the width of the forearm envelope, so it is preferable to the bevel gear design.

6.6 Rating Mechanical Advantage Design Concepts

Lastly, the mechanical advantage design concepts were rated when combined with the previously selected hybrid finger and thumb concepts. A set of criteria was developed and defined to rate the mechanical advantage designs. Since these mechanical advantage concepts were designed to each produce the required mechanical advantage of 3, they were not rated on force production or amplification. The designs were rated based on height, width, assembly, part availability, safety, and durability. A pairwise comparison was used to help determine the weights of each category, Table 25. The final weights were determined based on best judgment from the team guided by the results in the Score column from the pairwise comparison.

Table 25: Pairwise comparison and weights of each mechanical advantage evaluation criteria

	Height	Width	Assembly	Parts	Safety	Durability		Final Weight
Height	X	0	1	1	0	1	3	18%
Width	1	X	1	1	0	1	4	25%
Assembly	0	0	X	1	0	0	1	10%
Parts	0	0	0	X	0	0	0	5%
Safety	1	1	1	1	X	1	5	30%
Durability	0	0	1	1	0	X	2	12%

The rating table (Table 26) assigns a score of 1, 3 or 5 to each design in each category. A score of 1 represents poor, 3 represents acceptable, and 5 represents excellent. The score was then multiplied by the previously determined category weights. The weighted scores for each design is the total score out of 5 possible points.

Table 26: Scores for each mechanical advantage design by category with weighted final score

	Pulley	Lever	Linkage	Bevel Gear	Spur Gear
Height	0.5	0.5	0	0.5	0.5
Width	1	1	1	0	1
Assembly	0	0.5	0.5	0	0.5
Parts	0.5	1	1	0.5	0.5
Safety	0.5	1	1	0.5	1
Durability	0	1	1	0	0.5
Total 100 max	51.5	86	77	26.5	77.5

The lever design scored highest with a score of 4.4/5. The linkage and spur gear designs had the second highest score with 4.1/5. The lever design was selected because a lever is more easily sourced or manufactured and more durable than spur gears and results is a slimmer profile than the linkage design.

6.7 Final Design

The final design is a combination of the selected concepts from the finger, thumb, and mechanical advantage comparisons. This final design combines the hybrid finger design, the thumb distal phalanx incremental motion design, and the lever mechanical advantage design (Figure 76 and Figure 77). The numbers in the figures refer to the various components that make up the device, finger channels [1], metacarpal base [2], sliding rails for cable routing bar [3], cable routing bar [4], cable re-direct [5], change in length bar [6], thumb component [7], forearm gauntlet [8], and lever [9].

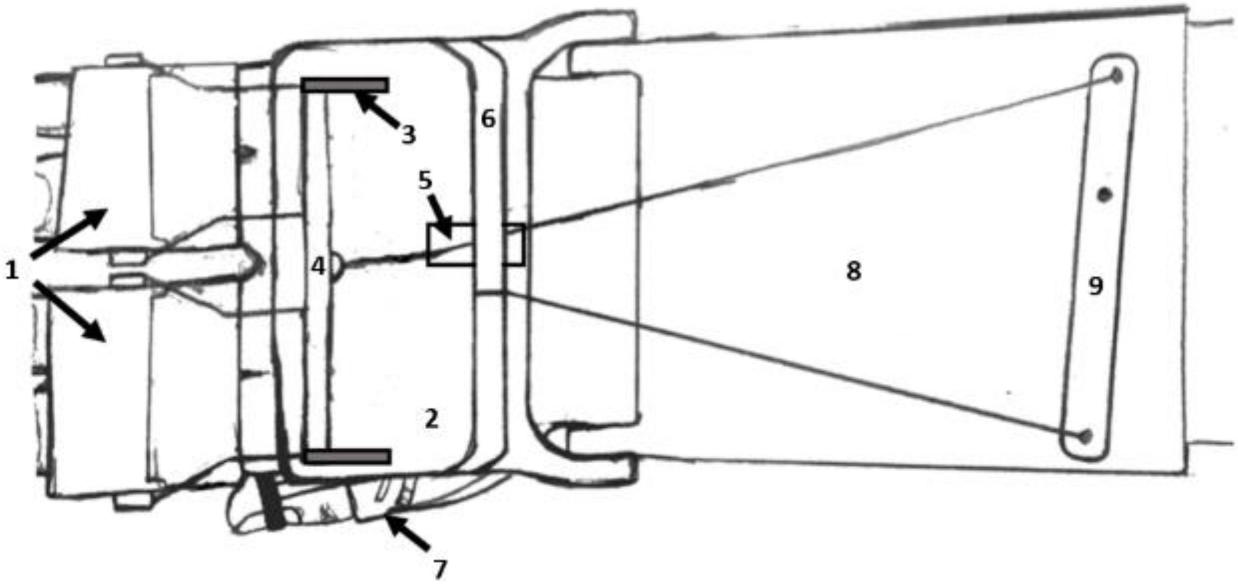


Figure 76: Final Design Top View

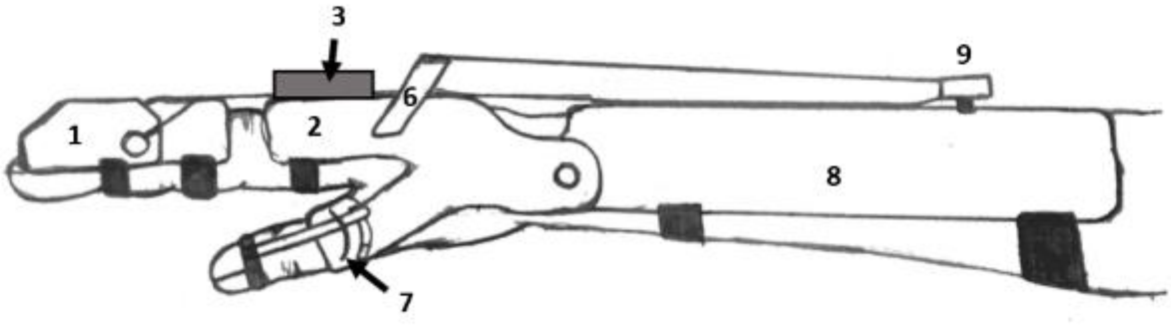


Figure 77: Final Design Side View

1. Finger Channels

The finger channels consist of two sections, one for the distal and medial phalanges and the other for the proximal phalanges. Fingers are coupled in pairs by the finger channels and each channel is driven by separate cables. Pegs on the left and right sides of the distal/medial channel hold a cable which unwinds and rotates the distal and medial phalanges up to 90° in flexion at the PIP joint when the cable is pulled. A single cable from the proximal channel connects in the center of the piece between the index and middle fingers and causes a rotation of 75° at the MCP joint. Additional details can be found in Section 5.2.5 and Section 6.3. Each cable from the channels connects to the cable routing bar [4].

2. Metacarpal Base

The metacarpal base attaches to the top of the hand. This piece will be 3D printed and will have slots for Velcro straps to attach to the user's hand. There will be sliding rails [3] for the cable routing bar [4] designed into the top of the metacarpal base. The metacarpal base also extends to the thumb and connects to the thumb component [7]. In addition, the change in cable length bar attaches to the metacarpal base. The orientation of this bar will be discussed in [7].

Finally, the metacarpal base has holes that will line up with the holes of the forearm gauntlet [8] to be pinned at the wrist.

3. Sliding Rails for Cable Routing Bar

The sliding rails will be designed into the metacarpal base and will allow the cable routing bar [4] to slide back and forth as the wrist flexes. The rails will be approximately 1.5 cm long so that the cable routing bar can slide enough to pull the fingers fully closed. These rails must be designed so that the cable routing bar only slides back and forth and cannot rotate as rotation of the bar could cause unwanted torque on the fingers.

4. Cable Routing Bar

The cable routing bar is attached to the metacarpal base through the sliding rails. It is free to move toward the forearm as the wrist flexes and the cable pulls on the bar. As the bar slides closer to the forearm, it pulls the cables connected to the finger pieces, causing them to close. The cable routing bar should pull each of the finger cables directly perpendicular to the length across the hand and not at an angle. If it were to pull at an angle and therefore pull one of the finger cables more than another, an unwanted torque would be acting on the fingers. Therefore, the cable routing bar extends almost fully across the metacarpal base and attaches to each of the four finger cables.

5. Cable Re-direct

The cable re-direct sits atop the metacarpal base and ensures that the cable running from the small side of the lever pulls the cable routing bar directly towards the forearm. As the cable attachment point on the lever [9] is not in line with the center of the cable routing bar, the cable would be pulling at an angle. This could potentially cause the cable routing bar to be pulled off the sliding rails causing the device to fail. By re-directing the cable through a tubing or ring, the cable routing bar will be pulled in a direction parallel to the sliding rails. Friction reduces the tension in the cable, but should not be significant enough as the mechanical advantage from the lever can overcome this loss.

6. Change in Length Bar

As calculated in Section 5.2.7, four out of five studied configurations produced a significant change in cable length. To attain a mechanical advantage of 3, the final design uses a cable pulling 3 times the target distance to create a force amplification of 3. Therefore, the change in cable length produced by the bar must provide a change in length which is 3 times the required input to the finger channels, or $3 * \frac{\pi * 8}{4} = 19$ mm. All four configurations meet this requirement. As a result, the configuration of the elevated bar was chosen based on the mounting positions of the associated components. A shorter distance along the metacarpals was favored to leave room for the cable routing bar components [3] and [5]. The distance from the wrist to the lever determined the necessary size of the forearm gauntlet [8] which should be minimized to reduce overall weight and bulk. The metacarpal-mounted angled bar towards the forearm (Figure 51) was the best choice given these criteria.

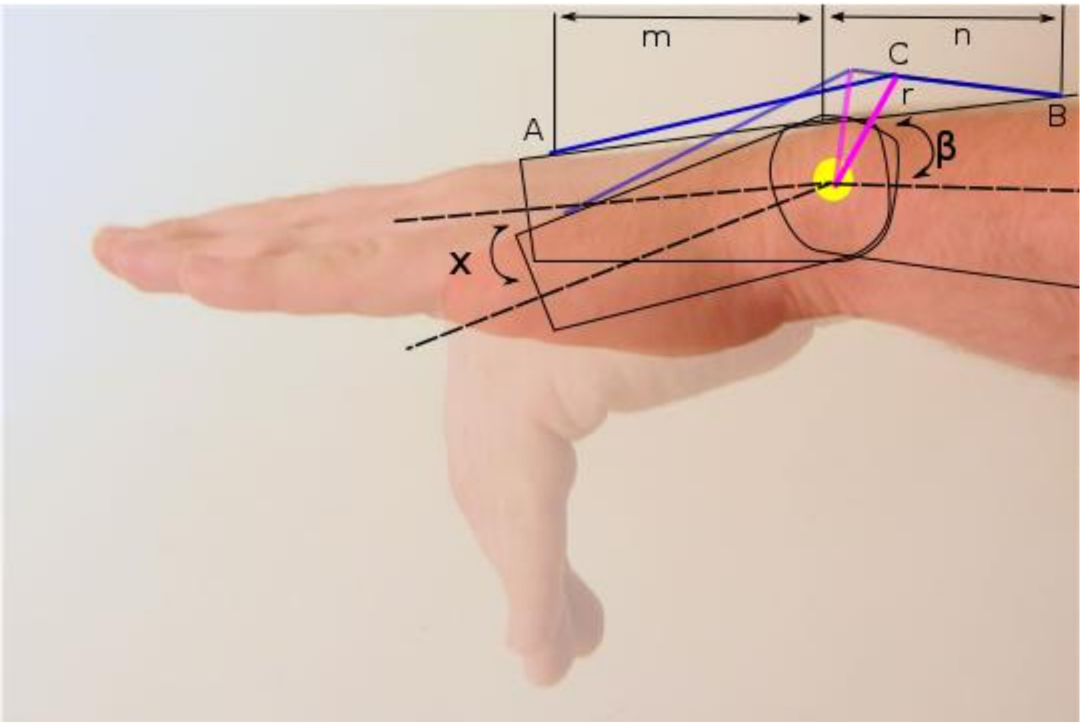


Figure 51 (repeated): Blue cable over pink bar attached to metacarpals at the wrist angled toward the forearm

The bar is angled at β=30° with the forearm in the resting position and r=30mm. Distances m and n are 20 mm and 50 mm respectively. The maximum change in length produced from these dimensions is 23 mm.

7. Thumb Component

The final thumb design is an improvement upon the Thumb Distal Phalanx Incremental Motion Design in Section 5.4.5. While the general concept of this thumb design has remained largely the same, efforts have been made to assure it is more effective in creating the two different grips. A crucial difference between the power and pincer grips is the location of the thumb. This refined design rigidly locks the user’s proximal phalanx in relation to the metacarpal plate. By doing this, the position of the thumb metacarpal remains fixed as well. The thumb’s distal phalanx would be able to move between two positions, activated by the contralateral hand. The distal phalanx would lock into two positions using the system seen in Figure 78. The overall functionality of the system would remain the same as the original Distal Phalanx Incremental Motion design, but the improved locking mechanism would increase usability.

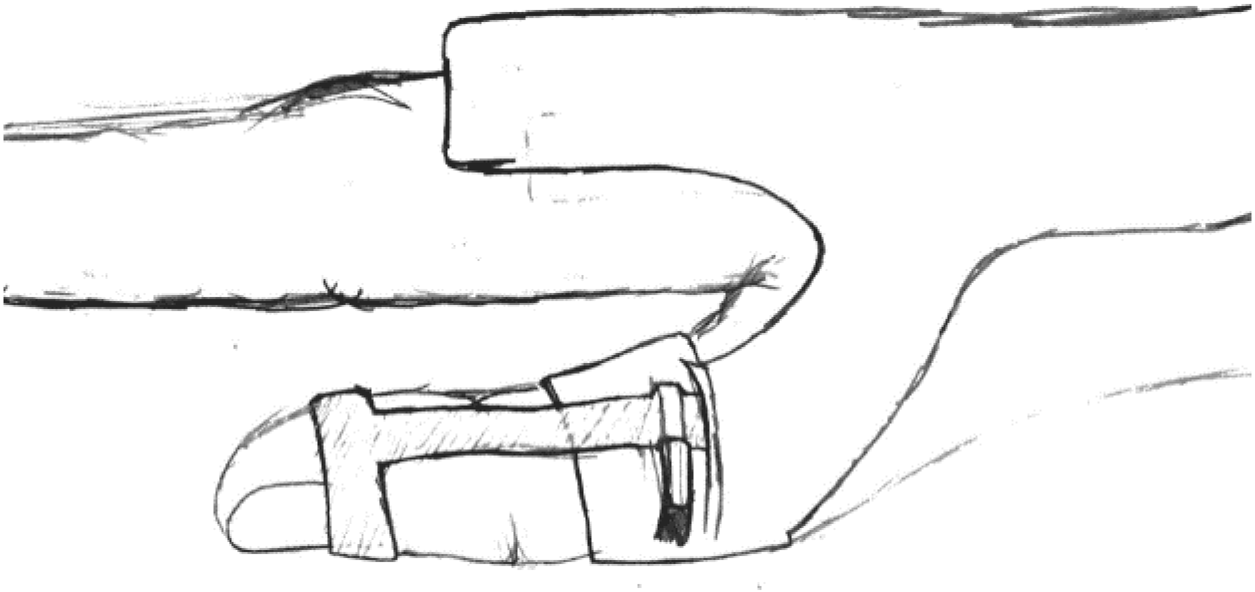


Figure 78: Thumb Distal Joint Incremental Motion Final Design

A crucial aspect of this design is the location of the proximal thumb ring relative to the metacarpal plate. If the ring is not located correctly, the user could experience discomfort and it may not allow for the user to make two unique grips. It is also important to note that different hand sizes would provide different angular values, so the values provided indicate an ideal set that should accommodate various hand sizes. If these values are imperfect, they will still allow the user to make the power and pincer grip, but when forming the pincer grip, more or less of the thumb may intersect the index finger.

The proximal phalanx of the thumb should be locked relative to the metacarpal plate at an angle of approximately 45 degrees in abduction. This would allow for some variance in hand size because the thumb’s metacarpal could flex at any reasonable angle allowing the proximal phalanx to remain at 45 degrees. Ultimately, if the distal phalanx of the thumb is allowed roughly

60 degrees of rotation, coupled with the angle of the proximal phalanx (Figure 79) the user will be able to make both the pincer and power grips.

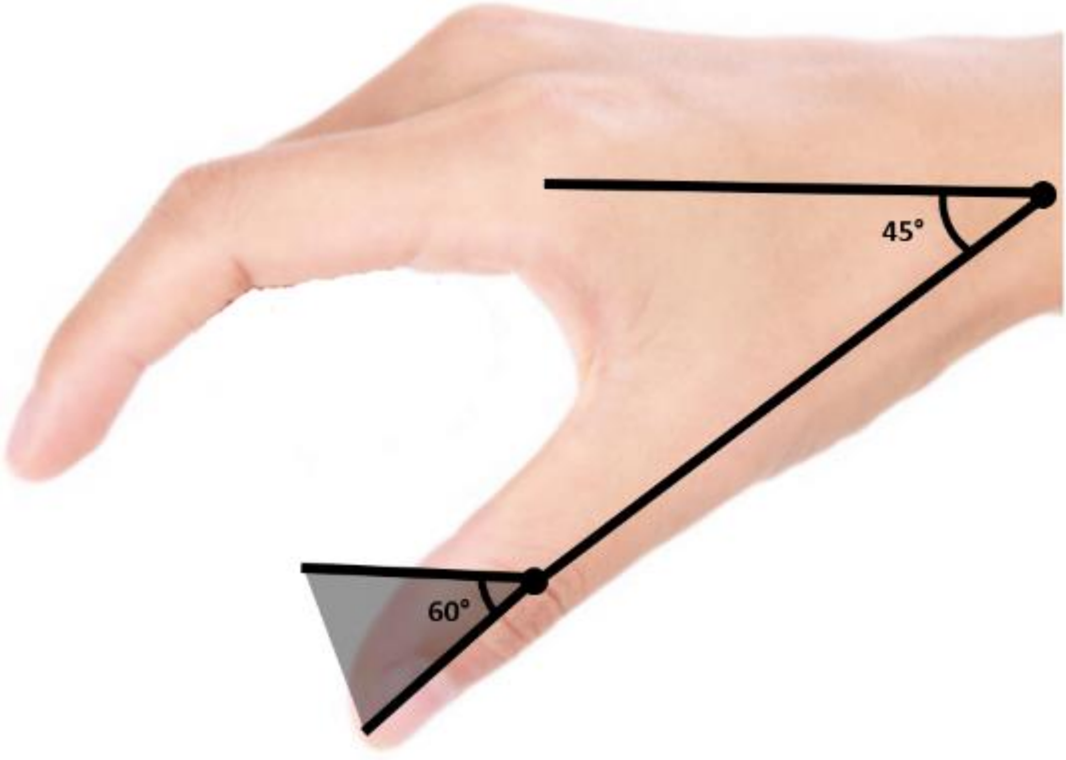


Figure 79: Desired Angles of Thumb

The new positional locking system (Figure 80, Figure 81) will allow the user to lock the distal phalanx in the two positions. The user will place their distal phalanx into the distal ring, and the connecting rod will keep it in position with the proximal ring. The alignment slot will fit over the alignment bar, forcing any movement of the connecting bar to follow that path. The alignment bar will have height differences at each end that lock the thumb into position for either the pincer or power grips. The positional bar serves to keep the connecting rod in an orientation such that the alignment slot and bar remain in a functional position. To switch between the power and pincer grip, the user would pull the lift tab and slide the connecting rod until it locked into the desired position.

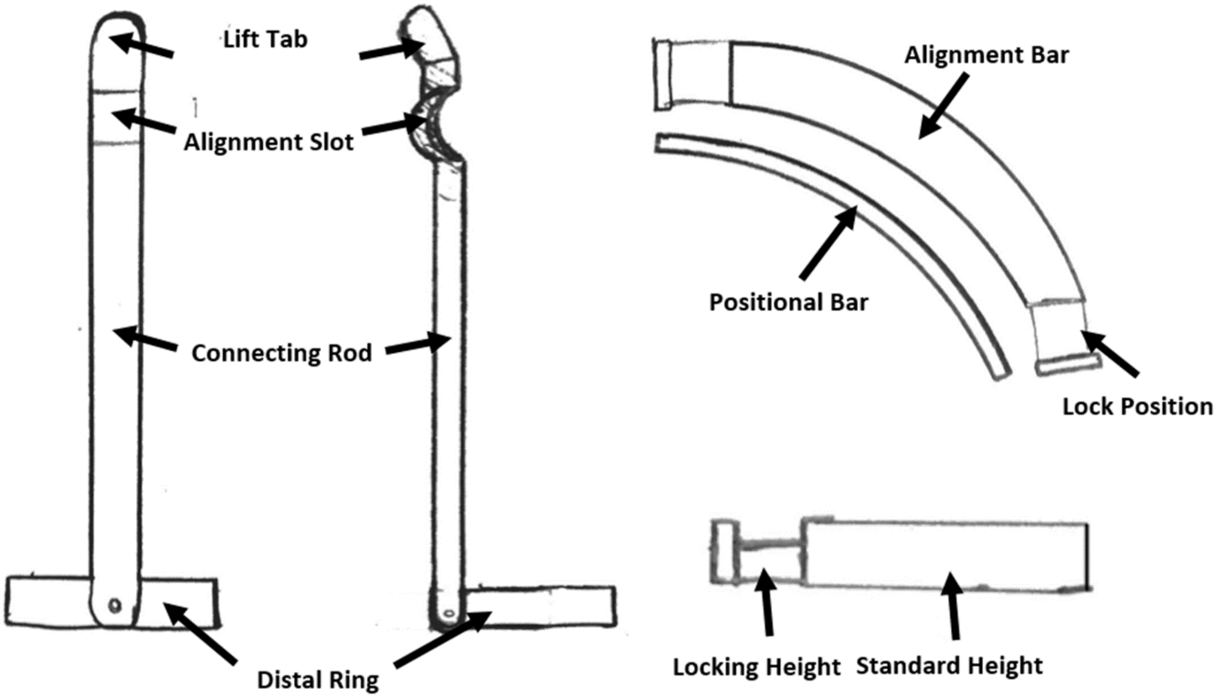


Figure 80: Components of Thumb Locking Mechanism

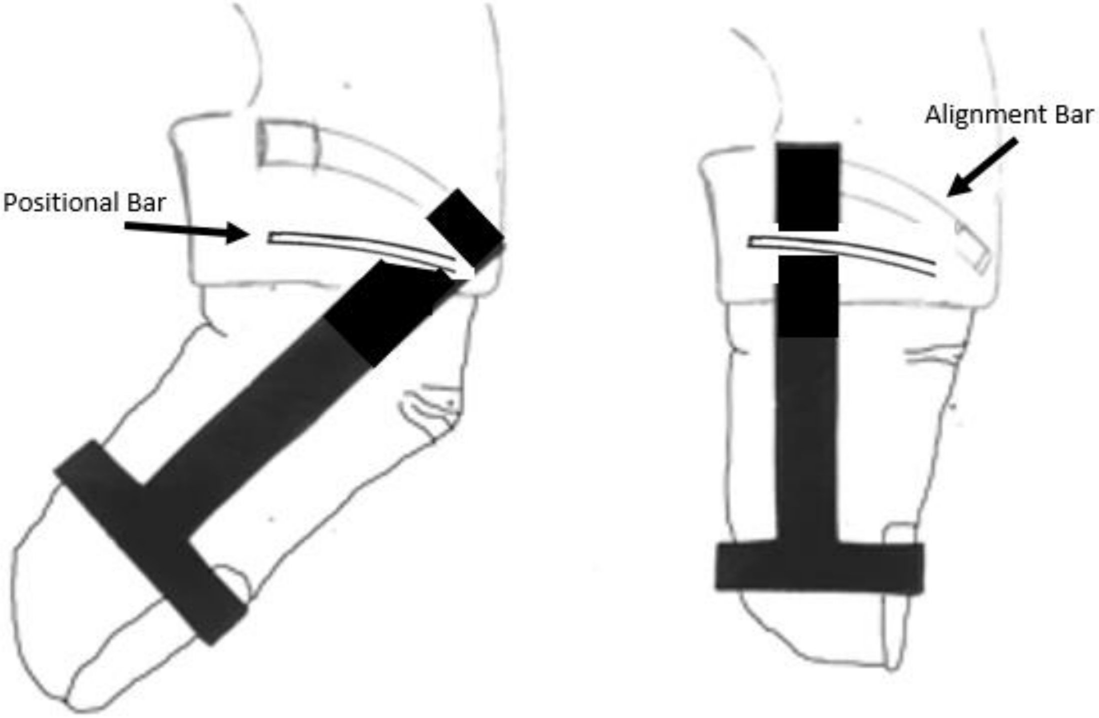


Figure 81: Thumb Positions

8. Forearm Gauntlet

The forearm gauntlet will be 3D printed using polylactic acid (PLA) so that it can be thermoformed to fit the user. The gauntlet will use a similar design to that of E-nable’s prosthetic hands. The part is first printed as a flat part (Figure 82).

Figure 82: Forearm Gauntlet before Thermoforming

The orange dot signifies an additional hole that will need to be designed into the part or drilled out to attach the lever. PLA has a glass transition temperature of approximately 60-65 degrees Celsius, which means that the material will become soft and rubbery as the temperature approaches this value. Therefore, PLA can be thermoformed in boiling water. Thermoforming will allow for a much better fit on individual users (Figure 83).

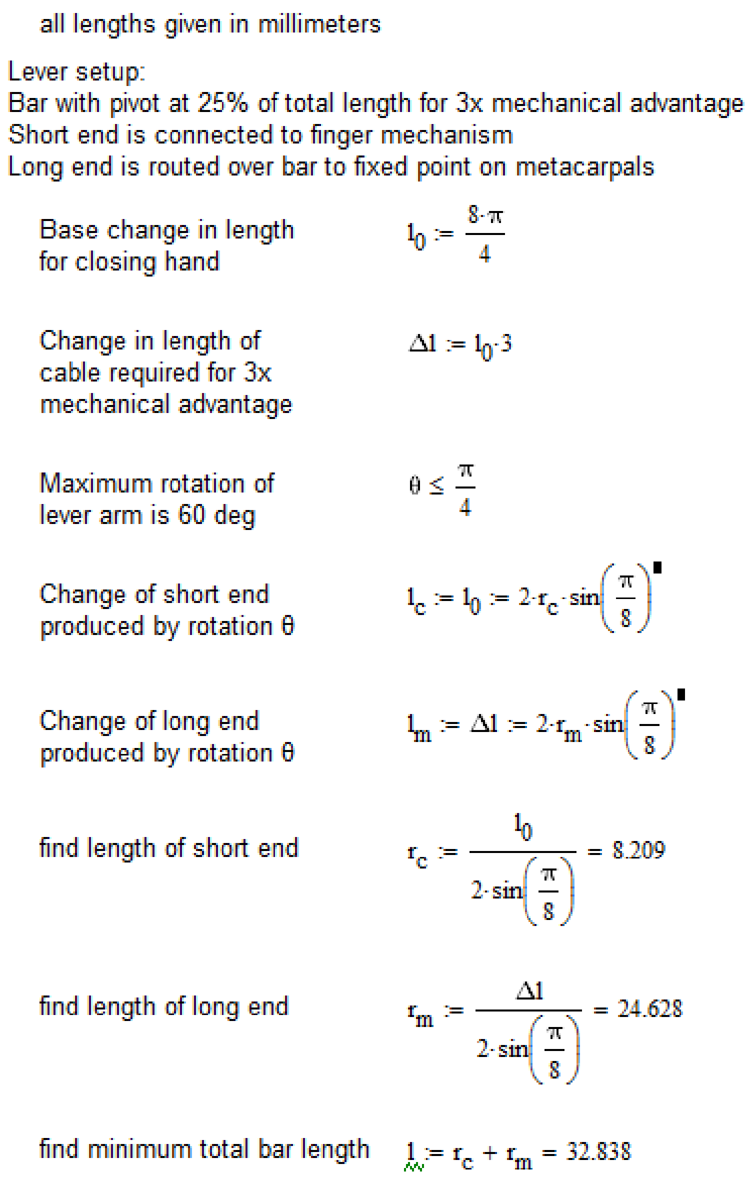
Figure 83: Forearm Gauntlet after Thermoforming

The forearm gauntlet will also have slots in the side for Velcro straps to secure the gauntlet to the forearm. Finally, the gauntlet will have pin holes so that it can connect to the metacarpal base piece [2] (Figure 76, Figure 77) at the wrist.

9. Lever

The lever mechanical advantage design is based on Section 6.5.2. After building a zeroth order prototype, it was realized that using two levers side by side would make the device far too large, extending a significant distance to the left and right of the forearm. Therefore, a design using one lever was created which can easily be scaled to fit within the width of the forearm. The lever creates the required mechanical advantage of three by using a 3:1 lever arm ratio. One cable connects the long side of the lever to the change in length bar [6]. The second cable is connected to the short side of the lever. This second cable travels under the change in length bar [6], through a redirect [5], and connects to the center of the cable routing bar [4]. As the wrist flexes, the change in length bar [6] pulls the cable to the left, rotating the lever in the clockwise direction and pulling the fingers closed. The tension force in the cable connected to the short end of the lever is amplified by a factor of 3 due the lever ratio. Using one lever also makes it easy to alter this mechanical advantage ratio if necessary by simply moving the pin location.

The lever is attached to the forearm gauntlet [8] by a pin which allows the lever to rotate smoothly. This pin will most likely be in the form of a metal bolt which is strong enough to withstand the forces it will experience from the tension from the cables. As the lever could potentially spin 360 degrees or more when the device is off the user and therefore cause the cable to become tangled, stops will most likely be implemented so the lever is only allowed to move the necessary amount to close the fingers. A 60° rotation was determined to be the maximum desirable rotation of the lever. Using this limit, the calculations in Figure 84 show the necessary length of the lever to achieve a 3:1 ratio and provide sufficient cable take up to rotate the fingers fully.



all lengths given in millimeters

Lever setup:
Bar with pivot at 25% of total length for 3x mechanical advantage
Short end is connected to finger mechanism
Long end is routed over bar to fixed point on metacarpals

Base change in length for closing hand

$$l_0 := \frac{8 \cdot \pi}{4}$$

Change in length of cable required for 3x mechanical advantage

$$\Delta l := l_0 \cdot 3$$

Maximum rotation of lever arm is 60 deg

$$\theta \leq \frac{\pi}{4}$$

Change of short end produced by rotation θ

$$l_c := l_0 := 2 \cdot r_c \cdot \sin\left(\frac{\pi}{8}\right)$$

Change of long end produced by rotation θ

$$l_m := \Delta l := 2 \cdot r_m \cdot \sin\left(\frac{\pi}{8}\right)$$

find length of short end

$$r_c := \frac{l_0}{2 \cdot \sin\left(\frac{\pi}{8}\right)} = 8.209$$

find length of long end

$$r_m := \frac{\Delta l}{2 \cdot \sin\left(\frac{\pi}{8}\right)} = 24.628$$

find minimum total bar length

$$l := r_c + r_m = 32.838$$

Figure 84: Calculations to determine lever length for 3x mechanical advantage

7 Analysis

7.1 Position Analysis

In order to meet the desired functional requirements for the orthosis device, the device needs to be able to support both the power and pincer grips. The position analysis section looks at using the kinematics of the orthosis device and hand to show that the range of motion satisfies these design specifications.

Figure 85 shows the modified 2D schematic diagram of the thumb and index figure (Chen, 2008). Based on this diagram, it is possible to solve for the forward kinematic equations for the thumb. Figure 86 shows the equations derived to produce the location of the tip of the thumb in 2D space based on the angle of the joints (θ1, θ2) and the lengths of the fingers (l1,l2). The full process and assumptions are located in Appendix K: 2D Position Analysis.

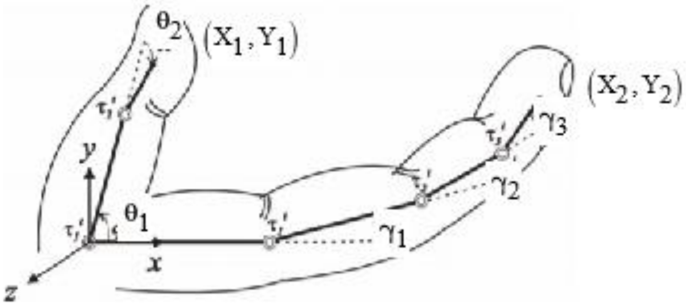


Figure 85: Hand Coordinate System

$$X_1 = l_1 \cdot \cos(\theta_1) + l_2 \cdot \cos(\theta_1 + \theta_2)$$

$$Y_1 = l_1 \cdot \sin(\theta_1) + l_2 \cdot \sin(\theta_1 + \theta_2)$$

Figure 86: Thumb Forward Kinematic Equations

A similar method was used in order to develop the kinematics of the fingers. The resulting kinematic equations can be seen in Equation 8. Of note, d in Equation 8 is the length of the metacarpal joint. Each person has not only differently sized hands, but widely varying proportions of the joints themselves. The orthoses device's range of motion is highly dependent on the range of motion of the individual hand sizes.

Equation 8 Fingers Forward Kinematic Equations

$$X(\gamma_2) := d + l_1 \cdot \cos(\gamma_1) + (l_2) \cdot \cos(\gamma_2 + \gamma_1) + (l_3) \cdot \cos(\gamma_3 + \gamma_2 + \gamma_1)$$
$$Y(\gamma_2) := l_1 \cdot \sin(\gamma_1) + (l_2) \cdot \sin(\gamma_2 + \gamma_1) + (l_3) \cdot \sin(\gamma_3 + \gamma_2 + \gamma_1)$$

In order to verify that it was possible to create the pincer grip, both the thumb and the fingers location in the X and Y direction were plotted (Figure 87). The two different lines show the path of the fingers when rotated 90 degrees from the base position. The results show that there is a configuration that can successfully generate a pincer grip where the finger tips will effectively touch. Further detail can be found in Appendix K: 2D Position Analysis.

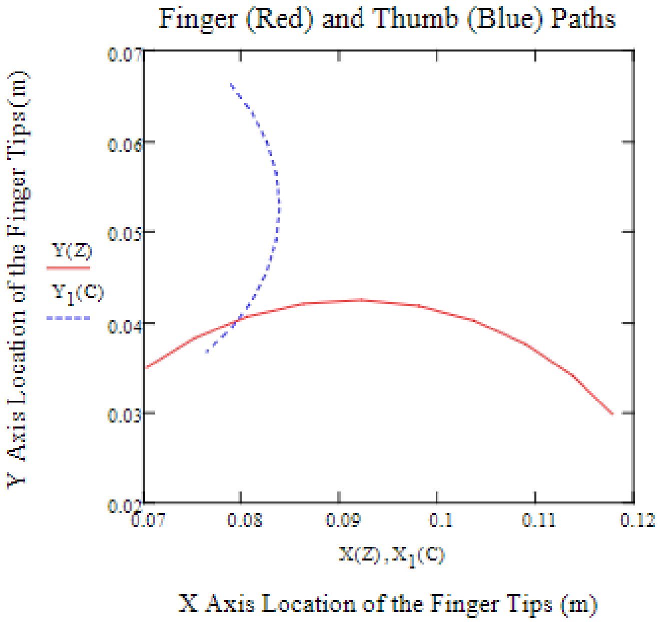


Figure 87: Finger & Thumb Location Graph

7.2 Material Analysis

To determine if PCL plastic will have sufficient strength for the hand orthosis, a three point bending test was carried out on samples of the material. A rectangle 2.5” x 1” x varying thickness was placed across a 2” span and a force gauge was used to apply a force at the center using a tip with diameter 0.25” (Figure 88). The dimensions of the sample were chosen to represent approximately half of the span over the back of the hand.

Figure 88: Flat sample three point bend test setup

Table 27 gives the testing results for three thicknesses of a flat PCL bar. All three samples were able to support the maximum force measured by the force gauge which was 25 lb.

Table 27: Flat PCL bar three point bend test results

Thickness	Force	Stress	Result
½ in	25 lb	300 lb/in^2	No visible deformation
¼ in	25 lb	1200 lb/in^2	< 0.5 cm deformation
1/8 in	25 lb	4800 lb/in^2	< 2cm deformation

A second three point bending test on curved samples of PCL was used to evaluate the effects of curvature on the material's strength because the component must be slightly curved to conform to the hand and forearm (Figure 89).

Figure 89: Curved sample three point bend test setup

The material was formed in the same manner as the flat sample but was left to cool on a round surface. The curved samples were able to support the maximum load as well (Table 28). Stress was not calculated for the curved samples as the equation for stress in a three point bending test is not valid for a curved sample.

Table 28: Curved PCL sample three point bend test results

Thickness	Force	Result
½ in	25 lb	No visible deformation
¼ in	25 lb	<1cm deformation
1/8 in	19 lb	Bent until flat

In all tests of PCL except the 1/8 inch curved sample, the force gauge reached the maximum measurement without cracking or plastically deforming the sample. The 1/8 inch curved sample was forced flat at a 19 lb force and returned to the bent shape when the force was removed. Thinner samples were not tested because the PCL cannot be reliably formed thinner than 1/8 inch. The results indicate that the material is robust enough to form the main structural components of the orthosis as long as the minimum part thickness is 1/8 inch. However, the flexibility of the plastic has the potential to allow significant bending of the orthosis under high loading.

The 0.25" force gauge tip was used to apply force to the finger channels in varying orientations. The channel was placed with the cutout facing up and the cutout facing down. In the cutout facing up position, force was applied in the center of each channel and to the channel divider. In the channel facing down orientation, force was applied to the right and left sides, the center of each channel, and the center of the part. Then, the part was held steady and force was applied to the side at the peg, middle, and far side (Figure 90).

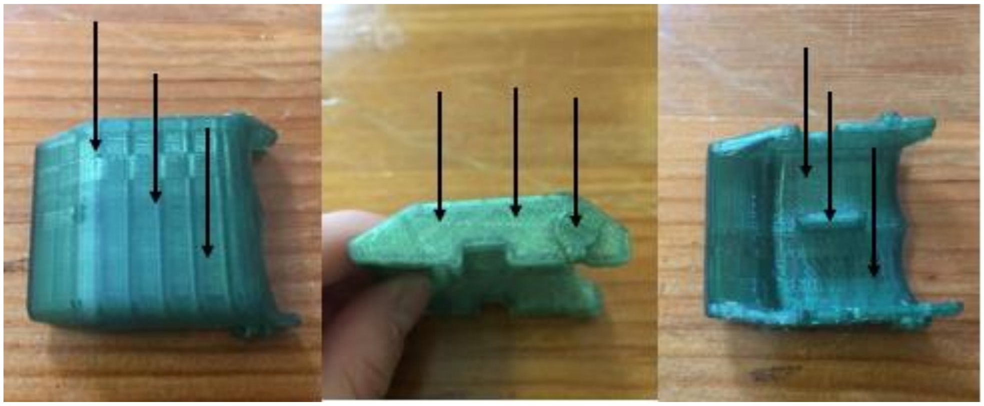


Figure 90: Finger channel force application locations

Due to the variability in 3D printed parts and each printing cycle, not each part behaved the same way under testing conditions. All parts deformed elastically when tested on the side. However, in the first cycle of tests, cracking was heard during some tests and less than 0.5 cm elastic deformation occurred when testing with the channel facing down during some tests. A second round of tests was deemed necessary and the infill percentage of the part was raised to 30% for greater structural stability. There was no cracking heard during testing of the parts with 30% infill and the amount of defection decreased as well.

8 Manufacturing

8.1 Proof-of-Concept Prototypes

The first actions taken towards creating a functional final prototype was to create several proof-of-concept prototypes. The intent of this exercise was to find a design that could move the fingers between open and closed, independent of activation. These designs included finger linkages, sleeves, and 3D printed pieces, activated in various ways. By creating the proof-of-concept prototypes, it was determined that the 3D printed pieces (Figure 91) activated by tensioned cables were the best design to use moving forward.

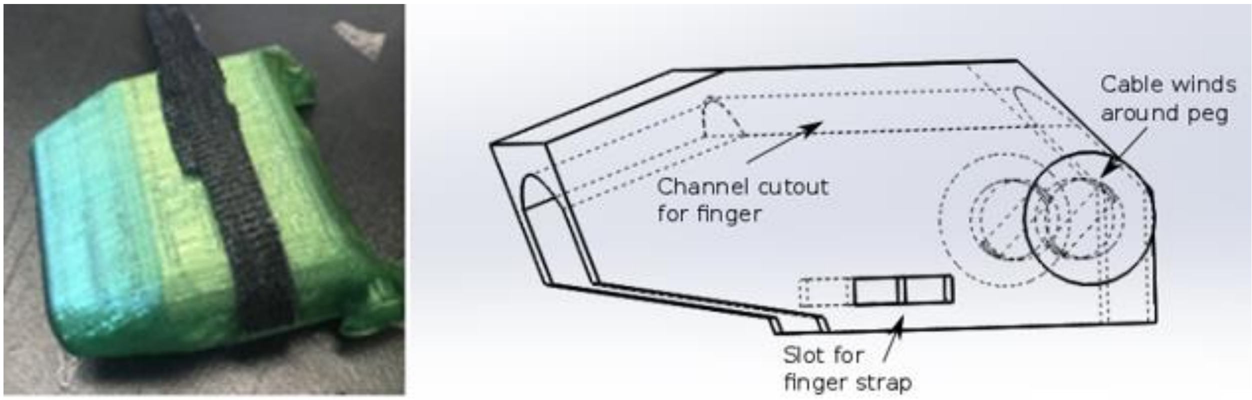


Figure 91: Finger Sleeve Design, Printed (Left) and CAD Model (Right)

8.2 Zeroth Order Prototypes

After establishing a functional finger design, zeroth order prototypes were created in an effort to assure an entirely functional orthosis. When building the zeroth order prototype, it had been established that the orthosis was to be activated by wrist flexion. However, the force output, determined by calculation, by the fingers when utilizing wrist activation was deemed unacceptable. The zeroth order prototypes were created in an attempt to identify a method of mechanical advantage capable of increasing the force output through the fingers.

Several options were tested including a system of pulleys (Figure 92), levers (Figure 93), linkages (Figure 94) and gears (Figure 95). Each method of mechanical advantage was evaluated to determine the most viable method to utilize in the final design. It was determined that the lever design was most successful, both in usability and manufacturability.

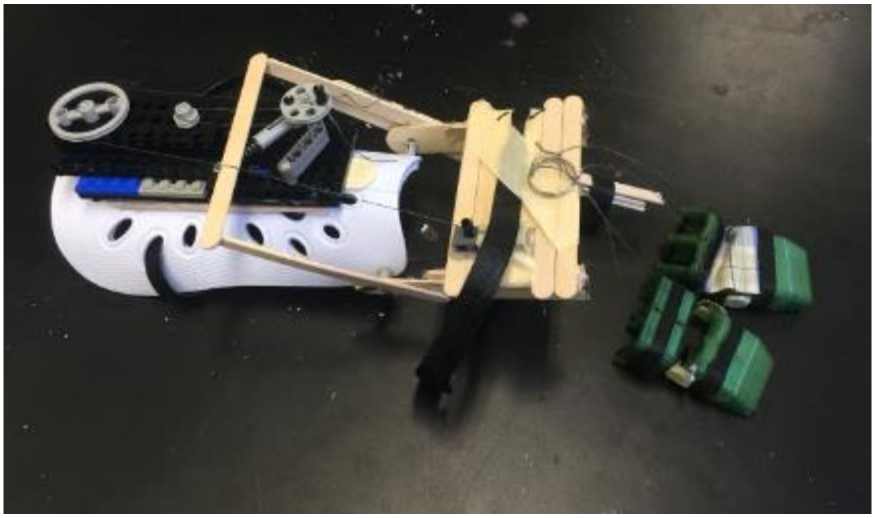


Figure 92: Pulley Mechanical Advantage Design, Described in Section 6.3

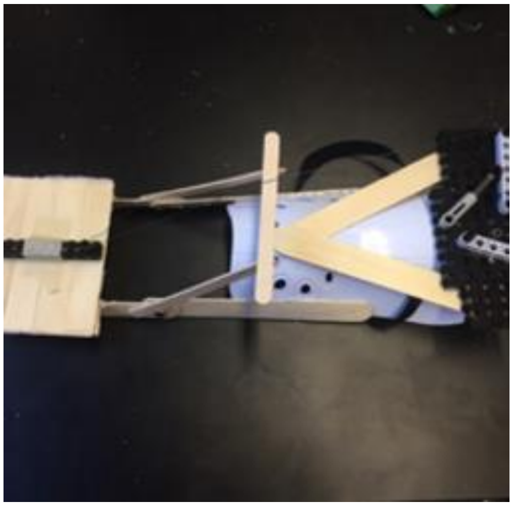


Figure 93: Initial Lever Mechanical Advantage Design, Described in Section 6.5.2

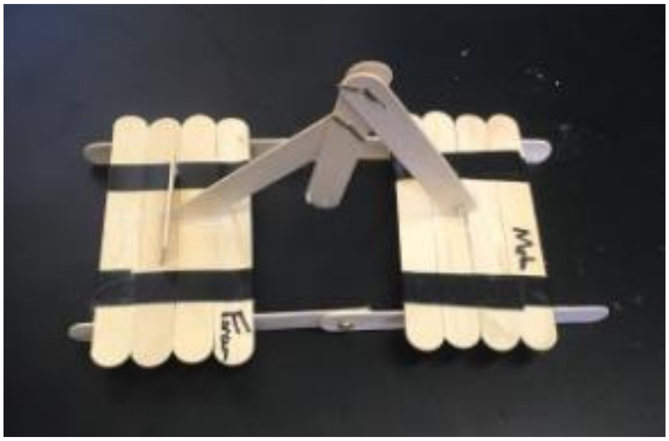


Figure 94: Linkage Mechanical Advantage Design, Described in Section 6.5.1

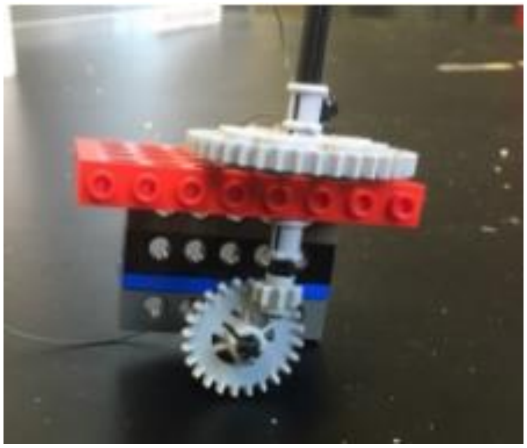


Figure 95: Gear Mechanical Advantage Design, Described in Section 6.5.3

8.3 First Order Prototype

Using the knowledge from the proof-of-concept and zeroth order prototypes, a first order prototype was built (Figure 96). The intent of the first order prototype was to create a fully functional device and identify overall weaknesses in the design. The first order prototype utilized the 3D printed fingers identified in the proof-of-concept design as well as the lever identified in the zeroth order prototype. The first order prototype was the first to utilize materials that could potentially be used in the final design. These materials included the Velcro wrist and finger straps, high density polyethylene (HDPE) for the cable routing slider and lever, and

ThermoMorph for the forearm gauntlet and metacarpal plate. This prototype also featured an extended bar over the metacarpal used to create an additional change in cable length and tension in the cables. Regarding materials, this prototype showed that the ThermoMorph was successful in providing the user with custom, comfortable, forearm and metacarpal pieces, while the thin piece of HDPE would not work for the lever. In addition, the extended metacarpal bar was determined to be unnecessary and, therefore, something that should not be used in the final prototype.

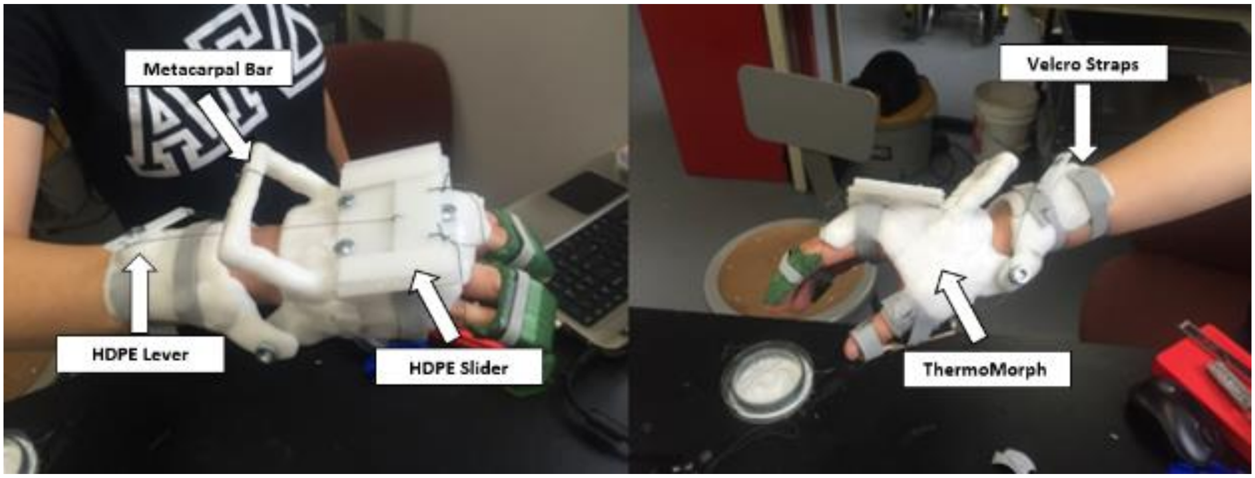


Figure 96: First Order Prototype, Labeled

8.4 Final Prototype

For the final prototype (Figure 98) a complete wrist-driven hand orthosis was manufactured. The user's finger size was taken to determine the size of the 3D printed finger pieces. ThermoMorph plastic was used to construct the forearm gauntlet and metacarpal plate. These pieces are custom fit, assuring a comfortable device. After shaping the forearm and metacarpal pieces, the two were connected using a 3D printed piece. Connecting the metacarpal and forearm using a link and two pin joints rather than simply one pin joint, allows for more freedom in the user's wrist movement. The slider, in the final prototype, was 3D printed. This slider helps to route the cable from the fingers to the lever. The lever was also built using ThermoMorph and fastened to the forearm gauntlet using a pin, allowing it to rotate. One cable was tied to the metacarpal plate and the other end was attached to a screw that was attached to the lever. As this screw is tightened, the tensioning of the cable can be adjusted (much like the tensioning of guitar strings). At the other end of the lever is the same cable/screw system with the other end of the cable connected to the slider. The fingers were attached to the slider as well using cable. The 3D printed fingers were lined with thin foam padding to provide the user with a more comfortable fit. The user is to put on the device using Velcro straps. These straps allow a user to put the device on using their contralateral hand.

Upon construction of the device, the team determined that the selected thumb design could not be constructed with the technology and resources available to the team. The selected design consisted of a thumb ring connected to the metacarpal piece with a connecting rod. The connecting rod would be able to move relative to the metacarpal piece by sliding in an alignment slot. There was not enough space surrounding the thumb in the prototype to incorporate an alignment slot. The team was unable to utilize stock components such as sliders, hinges, or bolts in lieu of creating a slot without interfering with the grip envelope or adding significant weight and protrusions. Furthermore, the team did not have a method of locking the thumb in place within the given size constraints. To accomplish a precision and power grip, the team developed a new component, a removable thumb ring (Figure 97). The ring is to be used for the precision grip of items smaller than 30 mm. Rather than move the distal phalanx of the thumb to decrease the distance between the thumb tip and fingertips, the thumb ring has an elevated portion which extends perpendicular to the thumb tip toward the fingertips.

Figure 97 Thumb ring with extended tip to achieve the pincer grip without thumb movement

The ring consists of an oval piece of PCL formed around the thumb. The oval shape provides a snug fit which does not rotate as easily as a cylinder would. The side of the ring over the thumb tip is built up and covered in a Tippi gel fingertip grip for more secure grip. Since the part is removable, it has a Velcro strip along the side with a corresponding Velcro strap on the metacarpal piece. The thumb ring is permanently attached to the metacarpal piece with a cable to minimize the chances of the part being lost.

This final prototype was used in testing to assess the overall design and device.

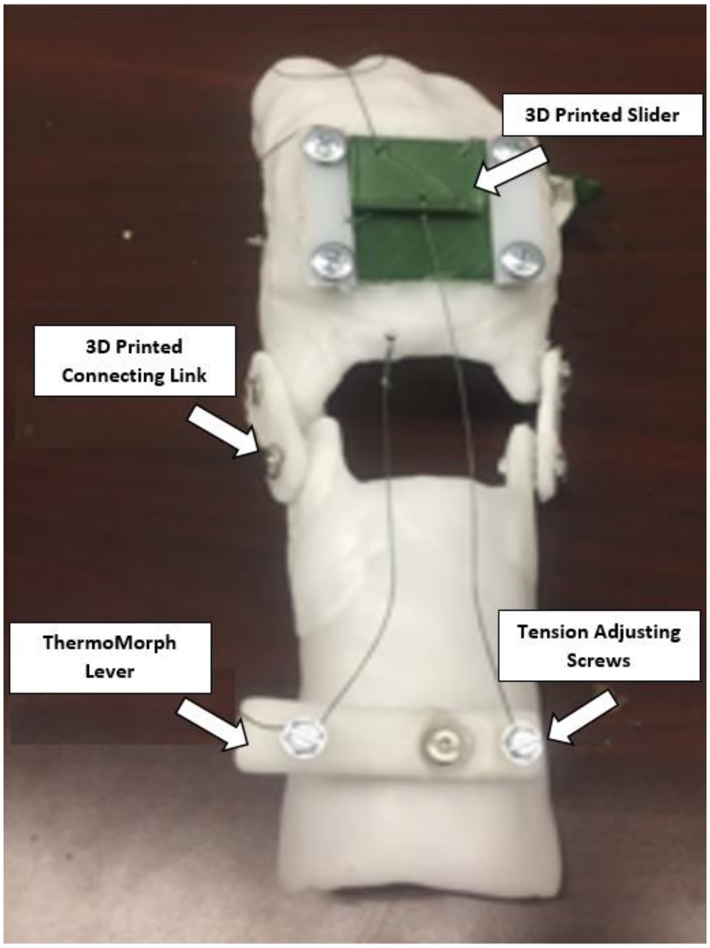


Figure 98: Final Prototype, Labeled

9 Testing and Results

The Functional Requirements and Design Specifications for this hand orthosis device were evaluated independently. The detailed testing protocol, including a short explanation and description of what the test hoped to accomplish, which specification(s) the test evaluated, step by step instructions, and how the test was evaluated, can be found in Appendix J: Testing Protocol. Tests were evaluated with a user survey or interview, through observation, through measurement (such as timing), or other means (See Appendix J: Testing Results for detailed results). Chapter 10 summarizes and provides an analysis of these testing results.

Functional Requirement Testing Results

Power Grip Envelope Test Results:

In the power grip envelope test, the user, while seated, was instructed to attempt to form a power grip around two objects. The first object was a tapered cup with the smallest diameter being 70 mm and the largest diameter was 90 mm. The second object was a roll of tape approximately 30 mm in diameter (Figure 99).

Figure 99: Power Grip Test Objects

These two objects simulate the ideal grip range the user can achieve with the power grip as outlined in Section 4.1. The user was instructed to attempt to form a power grip around each object, placed on a tabletop, while wearing the device. The user successfully formed a grip around both objects, lifting them off the tabletop. Initial tests showed that the user had difficulty picking up the 30 mm roll of tape from the tabletop as the finger pieces interfered and contacted the table first. However, when the roll of tape was elevated on a box with some of it hanging over the edges or the roll of tape was moved to the edge of the table, the user was successfully able to form a power grip and pick up the tape (Figure 100).

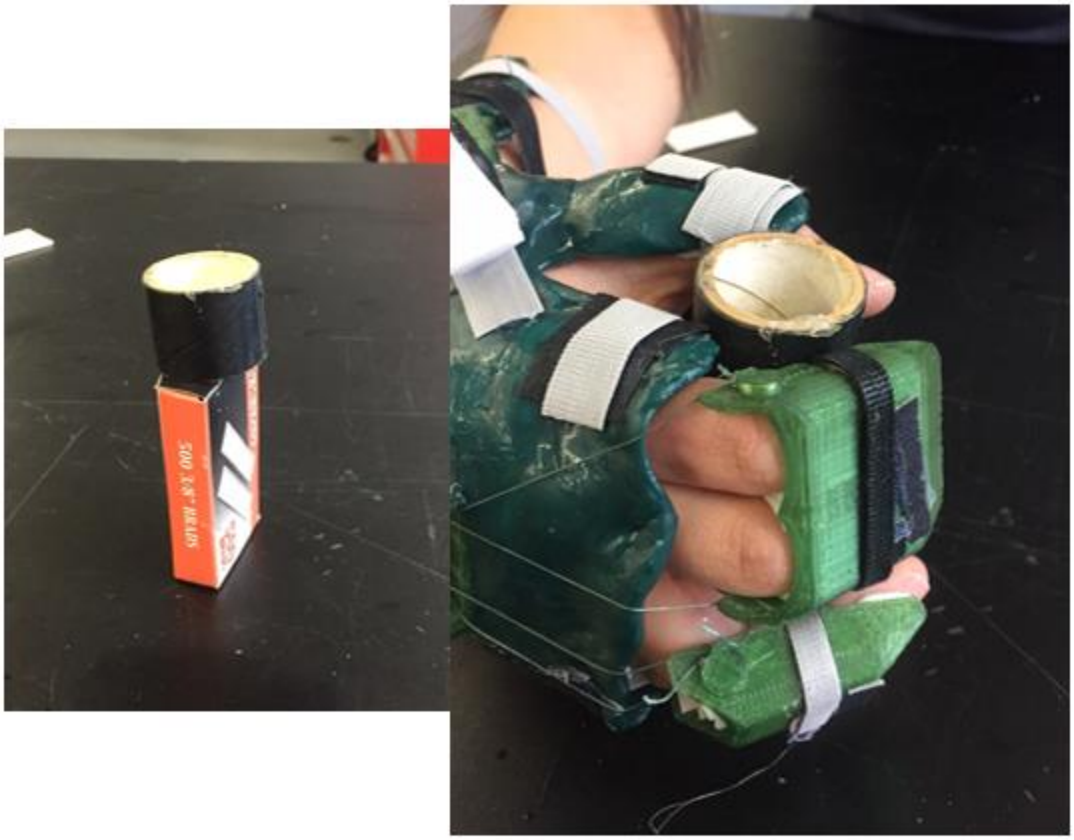


Figure 100: Modified Setup and Completion of Roll of Tape Power Grip Test

The user was also able to form a power grip around the cup at a maximum diameter of approximately 80 mm after attempts at various diameters on the cup (Figure 101).

Figure 101: Successful Power Grip around Cup

Pincer Grip Envelope Test Results:

The pincer grip envelope test was completed using a roll of tape approximately 45 mm in diameter and a pencil of approximately 7.5 mm in diameter (Figure 102).

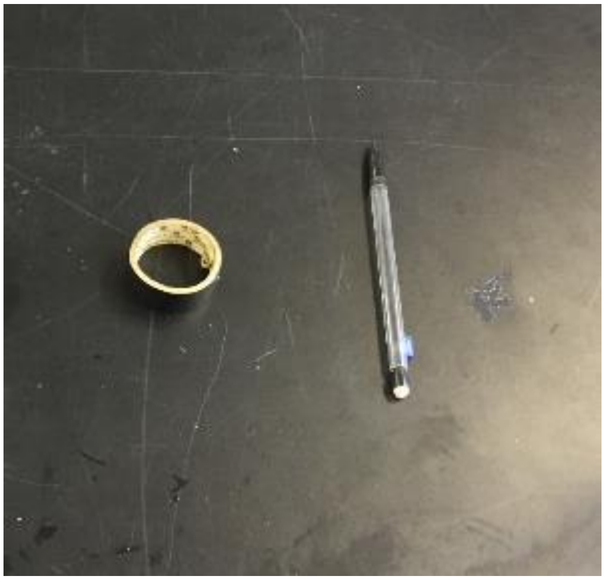


Figure 102: Pincer Grip Test Objects

These two objects simulate the ideal grip range the user can achieve with the pincer grip as outlined in Section 4.1. With the device on, the user was first instructed to detach the thumb component and put it on their thumb so that they could form the pincer grip around smaller objects. The user was then instructed to form a pincer grip around each object, placed on a tabletop. The user successfully formed a pincer grip around the roll of tape (Figure 103).

Figure 103: Successful Pincer Grip around 45 mm Roll of Tape

The user initially struggled when attempting to pick the pencil up from the table. However, when the pencil was elevated or moved to the edge of the tabletop, the user was able to easily for a pincer grip and pick up the pencil (Figure 104). This result was similar to the power grip envelope test when the user attempted to pick up the 30 mm roll of tape.

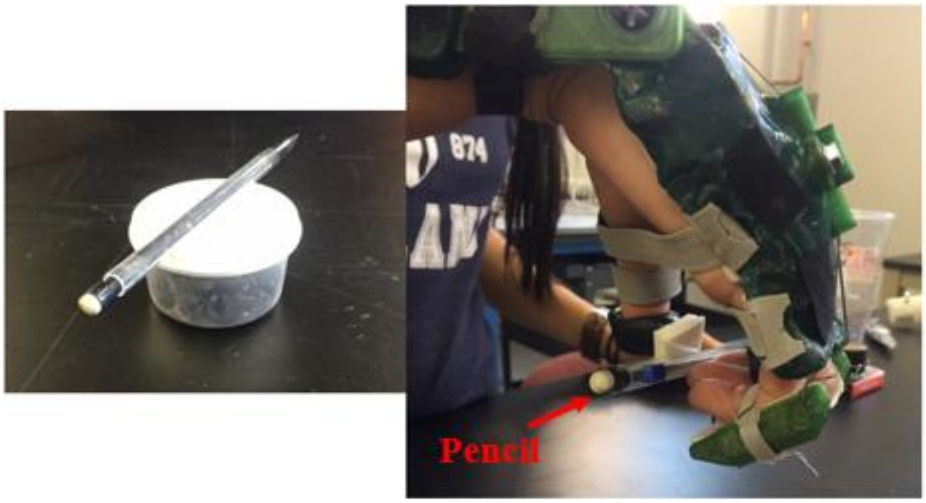


Figure 104: Modified Setup and Successful Pincer Grip around Pencil

Grip Force Test Results:

The grip force test was completed using a hand-held force dynamometer. The force was measured in three ways: with the hook around the finger (A), with the hook connected to the back of the finger piece (B), and with the finger pushing on the force gauge (C, Figure 105). The user was then instructed to flex their wrist causing the fingers to close and push or pull on the force gauge. To make sure the force gauge remained stationary during the tests, setups A and B were done with the force dynamometer lightly secured in a bench vice and setup C was done on top of a table against the wall.

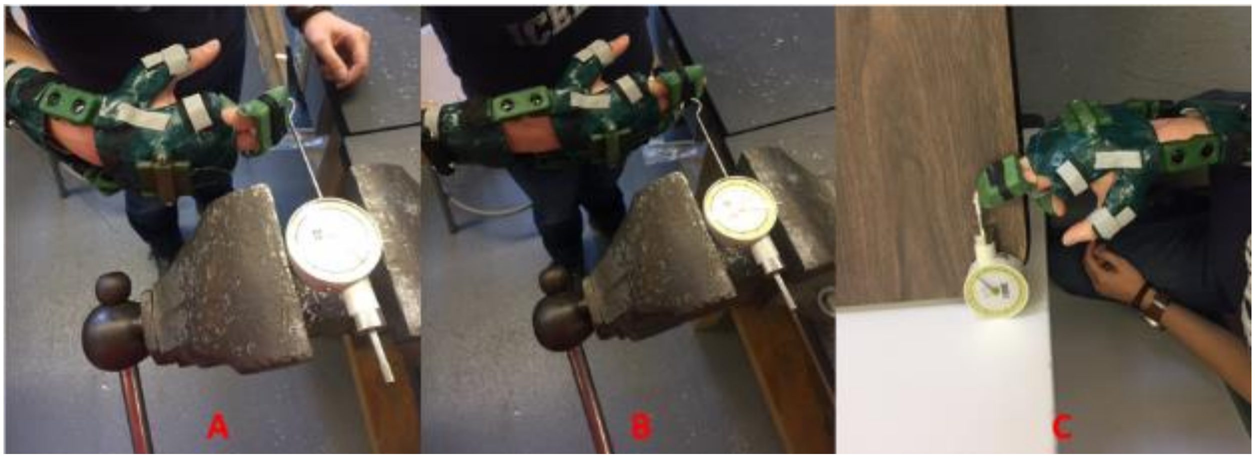


Figure 105: Force Test Setups (A: Attached to Finger Sleeve, B: Attached to Velcro Strap, C: Pushed by Finger)

The force values registered from each of these three setups are shown in Table 29. Setups A and B resulted in similar force values of approximately 3 lbf. However, Setup B resulted in a lower force value most likely because when the hook was attached to the back of the finger piece, the force gauge measured only a component of the normal grip force due to the angle with which the finger was pulling the force gauge.

Table 29: Force Test Results

	Setup A	**Setup B**	**Setup C**
Force (lbf)	3.0	2.2	3.1
Force (N)	13.3	9.8	13.8

<u>Ease of Don/Doff Test Results:</u>

The group conducted the Don/Doff test 5 times with one group member (Table 30). In this test, the user was allowed to practice donning and doffing the device up to five times before the actual test. The user was then instructed to don the device, at which time the timer would start. When the user had completely donned the device, the timer was stopped and the time was recorded. Similarly, the timer was started when the user began to doff the device, and stopped when the device had been completely removed. Finally, the doff time was recorded. Please Appendix J: Testing Results for detailed results regarding this test.

Table 30: Don/Doff Test - Results from 5 Tests with 1 Group Member (Summarized)

	Mean (s)	**Standard Deviation (s)**
Donning	38	5
Doffing	22	1

Extended Use Test Results:

One team member wore the device for four consecutive hours to evaluate comfort and determine how the device would affect daily activities such as eating, drinking, and household tasks. More examples of activities of daily living are given in Section 2.4. This test was meant to be open ended as the user was simply instructed to wear the device and attempt to do as many of their normal daily activities while wearing it as possible rather than give the user a list of tasks to perform. By leaving the extended use test open ended, it was hoped that the group could receive results that might not have been anticipated.

One source of major discomfort was due to over-tightening of the Velcro straps on the forearm piece and the fingers. The palm piece did not cause any discomfort. There was no rubbing between the device and the user nor were there moving parts in contact with the hand. The user was unable to don a sweatshirt or jacket while wearing the device. However, a sweatshirt sleeve could be pulled down over the device after the device was donned with the sleeve rolled up. After about 1 hour of use, the user reported sweat began to accumulate on the palm due to the device trapping heat. After approximately two hours, the forearm piece became uncomfortable at the end furthest from the wrist due to the tight fit. At the conclusion of the test, there was no significant fatigue due to the weight of the device.

Design Specification Testing Results:

The device was weighed using a scale that reported the mass in kg to two decimal places (Table 31). The device was weighed twice: once with the entire device and once with just the pieces that would be located on the hand (hand gauntlet and finger pieces).

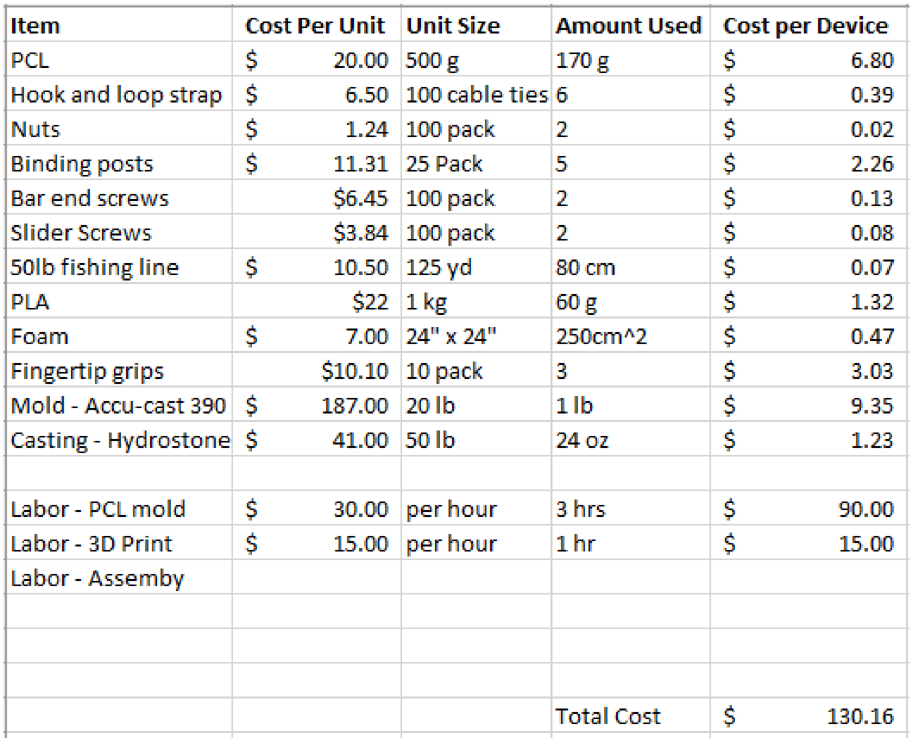
Table 31: Device Weight Test – Results

	Entire Device	**Hand Pieces**
Mass (kg)	0.22	0.14
Weight (lb)	0.49	0.31

Cost to Construct Results:

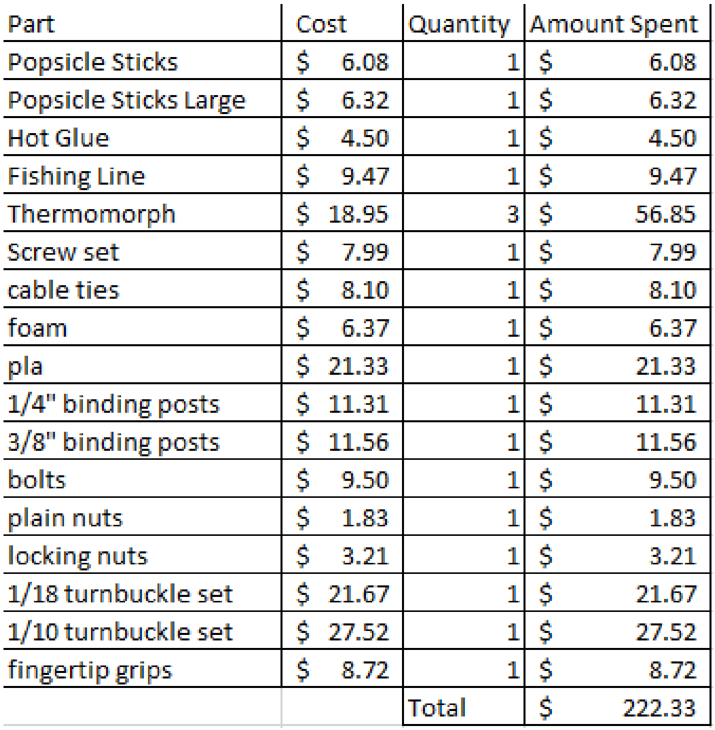
The cost to produce the final prototype, which includes labor estimates, as well as the cost spent on the entire project is tabulated in Table 48 and Table 49.

Table 32: Cost to Produce Final Prototype – Results



Item	Cost Per Unit	Unit Size	Amount Used	Cost per Device
PCL	$ 20.00	500 g	170 g	$ 6.80
Hook and loop strap	$ 6.50	100 cable ties	6	$ 0.39
Nuts	$ 1.24	100 pack	2	$ 0.02
Binding posts	$ 11.31	25 Pack	5	$ 2.26
Bar end screws	$6.45	100 pack	2	$ 0.13
Slider Screws	$3.84	100 pack	2	$ 0.08
50lb fishing line	$ 10.50	125 yd	80 cm	$ 0.07
PLA	$22	1 kg	60 g	$ 1.32
Foam	$ 7.00	24" x 24"	250cm^2	$ 0.47
Fingertip grips	$10.10	10 pack	3	$ 3.03
Mold - Accu-cast 390	$ 187.00	20 lb	1 lb	$ 9.35
Casting - Hydrostone	$ 41.00	50 lb	24 oz	$ 1.23
Labor - PCL mold	$ 30.00	per hour	3 hrs	$ 90.00
Labor - 3D Print	$ 15.00	per hour	1 hr	$ 15.00
Labor - Assemby				
			Total Cost	$ 130.16

Table 33: Total Cost of All Materials Purchased



Part	Cost	Quantity	Amount Spent
Popsicle Sticks	$ 6.08	1	$ 6.08
Popsicle Sticks Large	$ 6.32	1	$ 6.32
Hot Glue	$ 4.50	1	$ 4.50
Fishing Line	$ 9.47	1	$ 9.47
Thermomorph	$ 18.95	3	$ 56.85
Screw set	$ 7.99	1	$ 7.99
cable ties	$ 8.10	1	$ 8.10
foam	$ 6.37	1	$ 6.37
pla	$ 21.33	1	$ 21.33
1/4" binding posts	$ 11.31	1	$ 11.31
3/8" binding posts	$ 11.56	1	$ 11.56
bolts	$ 9.50	1	$ 9.50
plain nuts	$ 1.83	1	$ 1.83
locking nuts	$ 3.21	1	$ 3.21
1/18 turnbuckle set	$ 21.67	1	$ 21.67
1/10 turnbuckle set	$ 27.52	1	$ 27.52
fingertip grips	$ 8.72	1	$ 8.72
		Total	$ 222.33

Drop Test Results:

The device was dropped onto a concrete floor from a height of 1.5 m at various angles (Figure 106). The device was dropped with the top of the hand piece facing vertically upwards (A), with the device turned on its side so that the thumb faced the floor (B), with the device held vertically and fingers facing down (C), with the device held vertically and fingers facing up (D), and with the hand piece facing vertically downwards (E). Each drop angle was performed once. The device was examined during and after each drop for any broken pieces, cracks, or other damage. These tests resulted in no visible damage to the device.

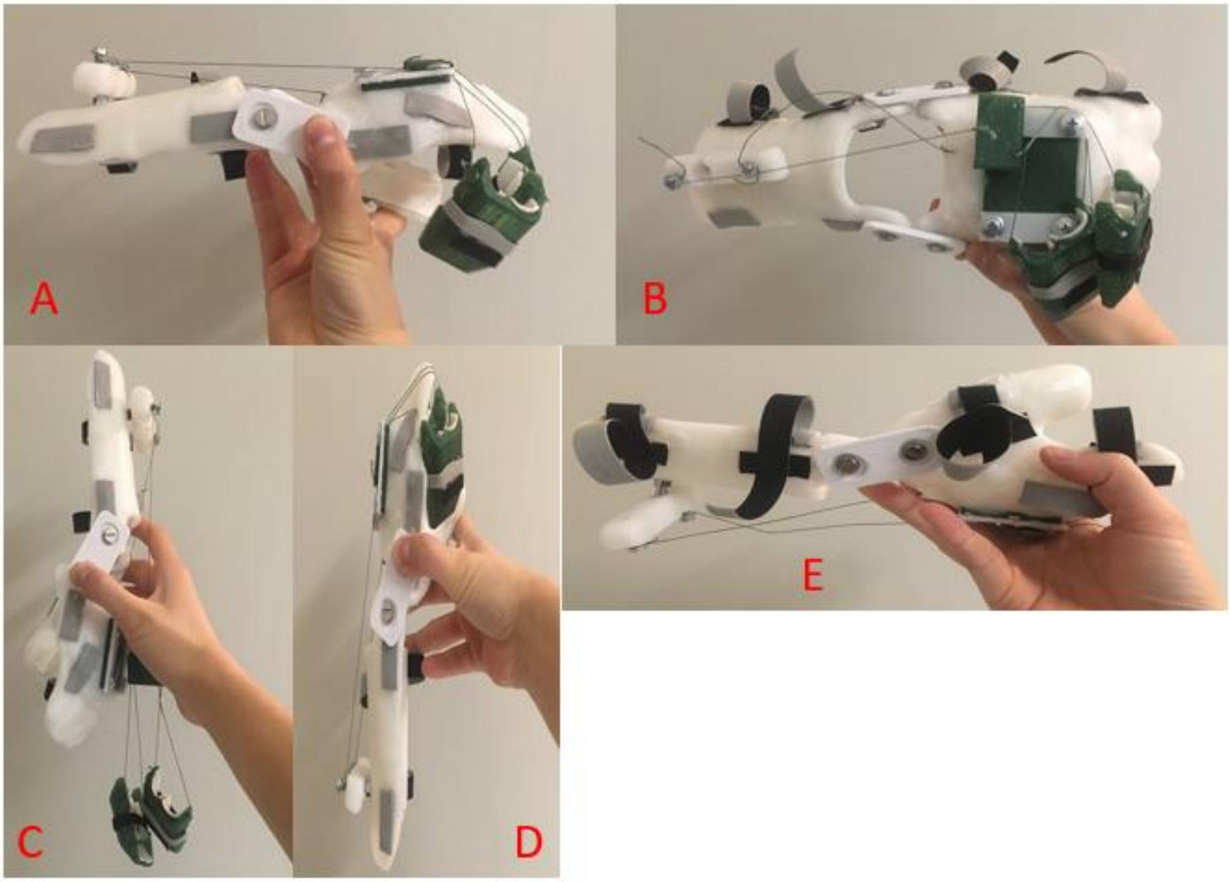


Figure 106: Various Drop Test Starting Positions (A: Flat/Upright, B: Side, C: Vertical/Fingers Down, D: Vertical/Fingers Up E: Flat/Inverted)

Protrusion Measurement Results:

The group measured the protrusions on the device using a set of calipers. The protrusions that were measured include: the lever extending in the direction vertically above the forearm, the lever extending in the longitudinal direction outside the forearm, the finger pieces extending in the direction vertically above the fingers, the finger pieces extending in the longitudinal direction outside the hand, and the links connecting the hand and forearm piece (Figure 107, Figure 108).

Table 34: Protrusion Measurement Results

	Protrusion 1	**Protrusion 2**	**Protrusion 3**	**Protrusion 4**	**Protrusion 5**
Description/Location	Lever extending above forearm	Lever extending in longitudinal direction	Finger piece extending above finger	Finger piece extending outside hand	Pieces connecting hand gauntlet and forearm piece
Length (cm)	2.6	1.0	0.7	0.5	0.6

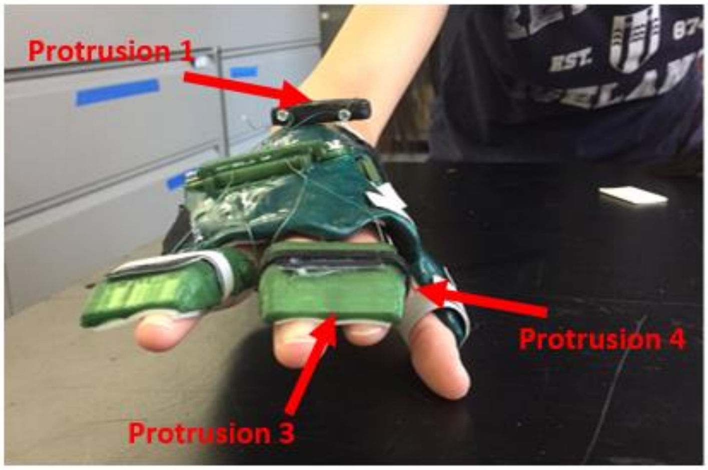


Figure 107: Protrusion 1, 3, & 4

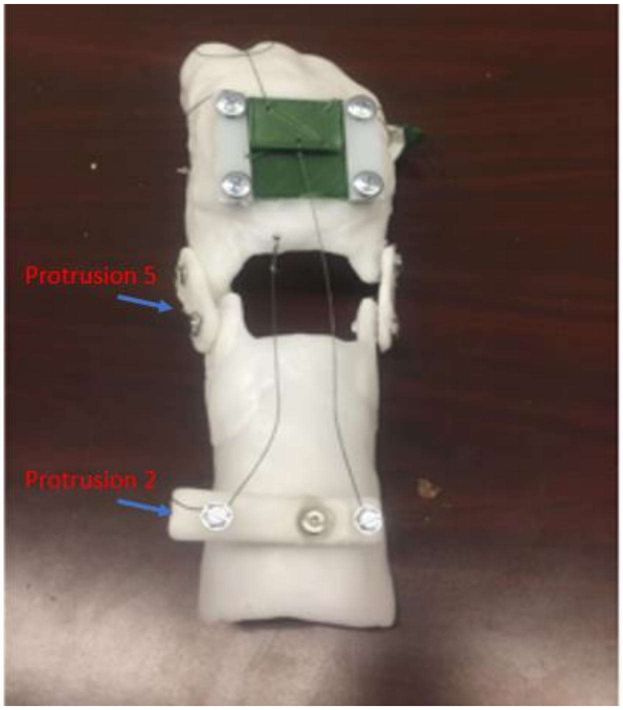


Figure 108: Protrusions 2 & 5

ISO 22523:2006 Standards

The group was unable to test whether the device met the ISO Standards (22523:2006) for external limb prostheses and external orthoses (Functional Requirement 6, Section 4.1) as Worcester Polytechnic Institute (WPI) did not have access to these expensive standards.

10 Analysis of Results

The results can be divided into six main categories: performing grips, grip force, usability, safety, durability, and cost. The results from the tests presented in Chapter 9 are discussed in the following sections.

10.1 Performing Grips

Based on the results from the power and pincer grip envelope tests, users are able to successfully form a power grip around objects with diameters ranging from 30-80 mm and a pincer grip around objects with diameters ranging from 7.5-45 mm. The range of the power grip envelope is slightly below the ideal range of 30-90 mm outlined in the Functional Requirements. However, the user was only able to achieve a secure grip on a cup up to 80 mm in diameter due to their smaller hand size. Therefore, the limitation on the maximum grip envelope is primarily a function of the user's hand size and not limited by the device. The ranges achieved, along with the forces produced, by the device allow the user to perform many tasks such as lifting a cup, holding a railing, picking up a pen, or holding a utensil.

10.2 Grip Force

The power grip force tests resulted in a force value of approximately 13-14 N. The second setup for the force test, which measured the force with a force gauge connected to the back of the finger piece with a hook, registered a slightly lower force value (~10 N). However, this is most likely due to the angle with which the force gauge was pulled. In other words, the second setup resulted in the force gauge measuring only a component of the grip force and therefore its value was lower. The values of 13-14 N obtained are still slightly below the ideal 20 N of grip force outlined in the Functional Requirements. To accommodate for this slightly lower grip force produced by the device, the group decided to add fingertip grips to the fingers of the device (Figure 109). These fingertip grips increase the friction between the user and the objects, allowing users to securely hold heavier objects with a slightly lower grip force.

Figure 109: Fingertip Grips Used to Increase Friction Between User and Objects

10.3 Usability

The total weight of the device (220 g) was measured slightly higher than the allowed 200 g from the specification. However, the weight of only the hand components was below 200 g, making it comparable to other hand orthosis devices. In general, users are able to hold more weight on their forearm than their hand, making it more important to reduce the weight on the hand. Also, reducing the weight on the hand makes it easier for the user to control the device through wrist flexion.

The one specification the device is far from meeting is Design Specification 2, which states that the device must be capable of accommodating varying hand sizes. The device is not suited to fit multiple hand sizes as most of the device was made from a thermoplastic and thermoformed to fit an individual hand. Manufacturing the device using the thermoplastic does not easily allow for small, medium, and large sizes but allows for a much better individual fit.

During the grip envelope tests, it was observed that the user had difficulty picking up smaller objects from the tabletop unless these objects were elevated so that part of the object was hanging in free space or the object was moved to the edge of the table. This difficulty comes from the small protrusions on the finger pieces as they interfere and contact the table first, making it difficult for the user to grab the object. Although not ideal, users may have to learn to do things a slightly different way while wearing the hand orthosis device, such as sliding a pen to the edge of the desk before picking it up.

During the extended use test, tasks involving gross movement such as pulling open a cabinet door with a large handle were completed without difficulty. In general, using the device to grip items around a vertical axis, such as when lifting a cup, was easier than gripping an object lying flat, as in grasping a pan handle. For tasks requiring more dexterity such as putting away spice containers, the user had a strong preference for using the contralateral hand. Despite the contralateral hand being the non-dominant hand, the user chose to complete the majority of tasks with this hand which did not affect the user’s ability to complete the tasks or increase the time it took to accomplish the tasks compared to using the dominant hand. When the user attempted to complete tasks requiring fine movements with the hand using the device, the time to complete the task was increased and the user preferred to use the contralateral hand for subsequent tasks. As mentioned previously, users may need to learn to do certain tasks a new way while wearing the hand orthosis. However, persons with little to no grip strength in one hand will benefit significantly from a hand orthosis device enabling a second hand.

10.4 Safety

The protrusion test showed that the device had no protrusions greater than the 3-cm maximum described in the specification. The final device is much sleeker than initial prototypes as it does not feature an elevated bar and therefore, users will be less apt to catch protrusions of the final device on clothing or other objects.

Design specifications 1, 2, and 4 were tested by examining the device. The device does not have any points where the joints on the device contact the user's skin, which could result in potential pinches. The inside of the device was also padded with foam so that the user is more comfortable while wearing the device.

As shown in the extended use test, there were two sources of discomfort. One comes from over tightening of the Velcro straps. This can be addressed by using markers on the strap to visually depict how tight the strap should be. The other is from the forearm piece being too tight against the arm. Using a cast hand model to mold the orthosis would give the manufacturer the ability to form the pieces around a mold that is larger than the user's actual dimensions by adding a spacer between the casting and plastic to account for the thickness of the foam and therefore make a more comfortable forearm piece.

10.5 Durability

The device withstood the drop tests and showed no signs of damage after falling multiple times at various angles on a concrete floor. Therefore, the hand orthosis device should withstand occasional drops from the user without breaking. Also, the device should withstand splashes of water without damage as the device is made of primarily plastic.

10.6 Cost

The cost to manufacture the final device (\$130.16) and the total cost (\$222.33) for the entire project were both significantly less than the specification allowed (\$200 and \$1000 respectively). The cost to manufacture the final device, which includes labor estimates, should make a hand orthosis device such as this very affordable compared to other hand orthosis devices.

11 Conclusions

The intent of this project was to design an orthotic device capable of assisting a physically impaired individual in completing daily tasks. To accomplish this, a wrist-powered hand orthosis was designed, manufactured and evaluated through testing. While many hand orthoses exist for the purpose of rehabilitation, there is a need for a user-activated device intended for daily wear.

The designed wrist-driven hand orthosis features custom-fit ThermoMorph forearm gauntlets and metacarpal plates. Custom-fit pieces assure a comfortable and well-fitting device. As the user moves their wrist in flexion, the forearm gauntlet and metacarpal plate move some distance away from each other dependent on the user's hand size. This change in distance causes the 3D printed finger sleeves to rotate, forcing the user's hand to close. By rotating the device's thumb ring, the user can achieve a power and pincer grip, allowing them to manipulate different sized objects.

The user's hand begins in an open position, and through the activation process is closed. As the user bends their wrist in flexion, pre-tensioned cables are used to pull finger sleeves, and as a result, the user's fingers, closed. The cable is routed from the device's metacarpal plate over the back of the user's wrist, and is attached to a lever on the forearm gauntlet. The lever, in its current form, is made of Polycaprolactone (PCL) plastic, and as a result, was difficult to manufacture. While it functions, it is not a smooth, well-made piece. Another cable is also attached to the lever, across the wrist, and is connected to a slider on the back of the metacarpal. The slider serves to route the cable in such a way that the cables pulling the fingers closed are pulled linearly. Because of the cable routing system, the fingers are pulled closed in the same way every time the user moves their wrist in flexion.

The reproducible finger motion allows for the thumb, singularly, to distinguish between the pincer and power grips. The thumb does not necessarily need to move, but instead must serve as a support for the item being held. In the pincer grip, the object being held is supported in a different thumb position than it is when held in a power grip. The thumb ring implemented in the design allows, simply for an object to be supported in multiple positions, and therefore, a single pattern of finger motion can be used to create two distinct grips.

The device was successfully tested. User’s wearing the device demonstrated the ability to grip objects within the range of roughly 30 to 80 mm in diameter in the power grip, and roughly 7.5 to 45 mm in the pincer grip. The orthosis also generated an output force of about 3 lbf (about 13 N), which, while below proposed specifications, provides a user with the ability to accomplish many daily tasks. The proposed addition of gel fingertip grips will allow for increased friction between the orthosis and object being held. The orthosis was also considered fairly user friendly, in that its overall weight was comparable to other hand orthoses, and the time necessary to don and doff the device took less than a minute. The device was capable of withstanding drops and was capable of handling exposure to water. Ultimately, this device functions and would make an excellent orthotic for daily use with a few revisions.

12 Recommendations

While the wrist powered hand orthosis currently functions, several alterations could be made to improve the functionality of the device. The recommendations for improvements were made after evaluating and discussing the results of testing.

12.1 Sizes/Fit

Future iterations of the design should look more carefully at the scalability and fit of the device. Based on the limitations of the current design, the device does not easily scale in term of both hand sizes and fit. While finding people to test the device, it was clear that not only did the hand have to be a similar size, but every person moves in a slightly different way. To mitigate this, further research should go into finding a way to adapt the device to better fit vastly varying users.

While the work around to this issue is custom sized components, the device design could be greatly improved by generating a sizing standard. This change would lead to the device being mass producible as opposed to having to create one for each individual user.

12.2 Lower Profile

A large challenge in the project was to minimize the number of protrusions on the device. While the device itself is fairly discrete, the positioning of the thumb prevents the device from being put on under a long sleeve shirt. Further development in the thumb arrangement could yield a configuration for which the thumb does not protrude as much. This would be useful in optimizing the device for public consumption with the express goal of lowering the profile.

12.3 Thumb Design

The thumb ring allows the user to grip small items down to the size of a pencil with reduced tactile feedback. To attain a more natural feel while using the device, future improvements should examine methods for moving the thumb itself rather than creating a protrusion from the thumb tip. Constricting or machining a channel for the thumb from a material that can be formed into more precise shapes than Polycaprolactone (PCL) plastic may help achieve a functional two position locking thumb mechanism. Additionally, the thumb ring is a detachable component and can potentially be lost by the user. An integrated component, such as a mechanism for thumb movement like the design suggested in Section 5.4.5, would improve the ease of use of the device.

12.4 Manufacturing and Materials

One challenge faced by the project team was the shaping of the PCL plastic metacarpal and forearm pieces. If this material is to be used in commercial orthoses, it is recommended that the orthotist create a mold of the patient's hand and corresponding model for the forming of the PCL plastic pieces. This would reduce the amount of time the patient must spend in the therapist's office, eliminates the risk of the melted PCL plastic injuring or sticking to the patient during the forming process, and gives the person fabricating the parts a solid model that can be rotated and temperature controlled as necessary. Protrusions can be attached to the model for the straps and attachment points to reduce the amount of final machining and to ensure a more comfortable fit.

It is suggested to explore 3D printing for the metacarpal and forearm pieces. To reduce the challenges caused by forming large sections of PCL plastic, a 3D printed base or entirely 3D printed part can be used for the metacarpal and forearm pieces. It is known that polylactide (PLA) plastic and some other plastics used in 3D printing can be thermoformed by placing the part in hot water or using a heat source. The team was unable to explore this option due to size constraints on the 3D printers available for use. Perhaps in an environment more suited for mass manufacturing, where large scale 3D printers are more readily available, the ability to 3D print the forearm and metacarpal pieces may be possible.

A material that can be easily machined or formed should be selected for the lever. The low melting point of PCL plastic led to sections of the part melting during cutting and drilling. This was undesirable as it created jagged edges and non-uniform cuts as the melted zone was not consistent.

12.5 Activation Methods

Various activation methods, or ways for the user to activate the device, were examined towards the beginning of the project including: wrist, elbow, and shoulder. Although it was decided that the wrist would be used for activation in this hand orthosis device, users with future revisions of the device could potentially activate it by other means such as the elbow or shoulder. Making the device capable of being activated by other movements with a few slight adjustments, such as extending the cable and connecting to an elbow or shoulder piece, could potentially allow more people to benefit from this type of hand orthosis device. For example, some users may not be able to actively flex their wrist enough to use this device but may have better mobility in their elbow or shoulder.

12.6 Whippletree

The whippletree concept (discussed in Section 5.2.6) was, also, thoroughly examined while developing this hand orthosis device. The addition of a whippletree in a prosthetic or hand orthosis device allows for individualized movement of fingers, therefore allowing user to grab objects of more complex geometries. Ultimately, this hand orthosis device did not include a whippletree (Figure 110). However, future revisions of this device would greatly benefit from a whippletree mechanism, which would pull individual fingers more closed than others based on the shape of the object the user was gripping, instead of the slider piece that pulls all of the fingers closed at the same time.

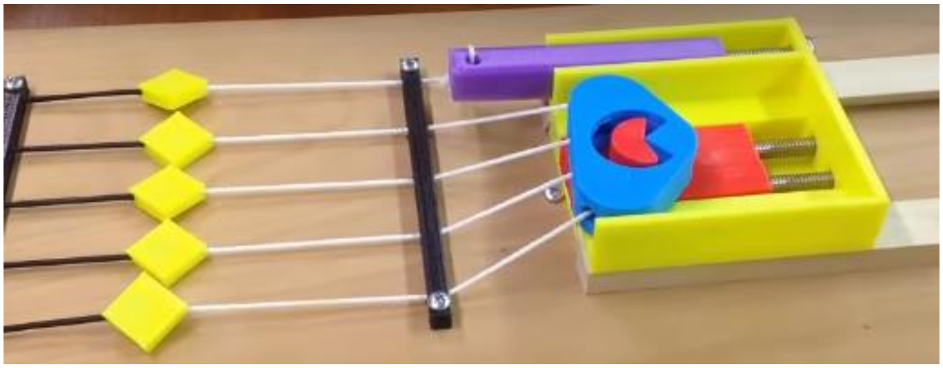


Figure 110: Whippletree Mechanism (Figure 45 Repeated)

References

"About Orthoses and Prostheses." - The Australian Orthotic Prosthetic Association Ltd. (AOPA). Association Online, n.d. Web. 10 Apr. 2016.

Barrett, 2013, NIP- Neurology in Practice: Stroke (1)

Bryant, M. F. (2014). U.S. Patent No. US 20140243721. Washington, DC: U.S. Patent and Trademark Office.

Chai, Huei-Ming. "Kinesiology, NTUPT." Kinesiology, NTUPT. N.p., 5 Nov. 2004. Web. 21 Sept. 2016.

Chao, E.Y., 1989, "Biomechanics of the hand: a basic research study," World Scientific,Teaneck Teaneck, N.J.

Chen, C. H., et al. "Fusion of hard and soft control techniques for prosthetic hand." Proceedings of the International Association of Science and Technology for Development (IASTED) International Conference on Intelligent Systems and Control (ISC 2008), Orlando, Florida, USA. 2008.

Clauser, 1969, WEIGHT, VOLUME, AND CENTER OF MASS OF SEGMENTS OF THEHUMAN HUMAN BODY

Crosby, C. A., & Wehbe, M. A. (1994). Hand strength: Normative values. Journal of HandSurgery Surgery, 19(4), 665-670. doi:10.1016/0363-5023(94)90280-1

Crowe, I., Hebert, R., Nichols, B. (2014). Design of a Powered Hand Orthosis (2). (MajorQualifying Qualifying Project No. AHH-1302). Worcester Polytechnic Institute.

Dorenfeld, E., Wolf, R., & Zeveska, S. (2013). Design of a powered hand orthosis. (MajorQualifying Qualifying Project No. AHH-1233). Worcester Polytechnic Institute.

El Koura, G., & Singh, K. (2003, July). Handrix: animating the human hand. In Proceedings ofthe on Computer animation (pp. 110119). Eurographics Association. 119). Eurographics Association.

Enable. (2015). Phoenix hand. Retrieved August 29, 2016, from http://enablingthefuture.org/phoenix-hand/

Farrell, J., & Hoffman, H. (2005). U.S. Patent No. US 20050273027 A1. Washington, DC: U.S. Patent and Trademark Office.

Fisher, T. (2008). Assessing Function in the Elderly: Katz ADL and Lawton IADL (Unpublished master's thesis). Dalhousie University. Retrieved April 28, 2016, from https://dalspace.library.dal.ca/bitstream/handle/10222/14829/Fisher-Appendix3.pdf?sequence=4

Freivalds, A. Biomechanics of the Upper Limbs: Mechanics Modeling, and MusculoskeletalInjuries Injuries, CRC Press, Boca Raton, Florida, 2004.

Gray, H. H.V.C., 2010, "Gray's Anatomy," Sterling, pp. 1280.

Gustus, A., Stillfried, G., Visser, J., Jörntell, H., & van der Smagt, P. (2012). Human hand Biological cybernetics, 106(11-12), 741755. 755.

Human Anatomy Body. (2015). Hand Anatomy. Retrieved 2016, from http://humananatomybody.info/hand-anatomy-human-body/

Jung, Myung-Chul, and M. Susan Hallbeck. "The effect of wrist position, angular velocity, and exertion direction on simultaneous maximal grip force and wrist torque under the isokinetic conditions." International Journal of Industrial Ergonomics 29.3 (2002): 133-143.

Kattel, B. P., Fredericks, T. K., Fernandez, J. E., & Lee, D. C. (1996). The effect of upper-extremity posture on maximum grip strength. International Journal of Industrial Ergonomics, 18(5), 423-429.

King, Marcus. "An Improved Lateral Key-Pinch Grip Orthosis For Tetraplegics With Wrist Extension." An Improved Lateral Key-Pinch Grip Orthosis For Tetraplegics With Wrist Extension. N.p., n.d. Web. 24 Apr. 2016.

Linn, D. M., Ihrke, C. A., & Diftler, M. A. (2012). U.S. Patent No. US 8255079 B2. Washington, DC: U.S. Patent and Trademark Office.

Mathiowetz, V., Kashman, N., Volland, G., Weber, K., Dowe, M., & Rogers, S. (1985). Grip andpinch Arch Phys Med Rehabil, 66(2), 69-74.(2), 69-74.

Mora, M. C., Sancho-Bru, J. L., & Pérez-González, A. (2012). Hand posture prediction usingneural International Journal of AdvancedRobotic Systems Robotic Systems

MIT. (n.d.). Normal Ranges of Joint Motion. Retrieved April 24, 2016, from http://web.mit.edu/tkd/stretch/stretching_8.html

Napier, J. "The Prehensile Movements of the Human Hand." Journal of Bone and Joint Surgery. 38B (1956): 902-13. 38B (1956): 902-13.

Nasir, S. H., Troynikov, O., & Massy-Westropp, N. (2014). Therapy gloves for patients withrheumatoid Therapeutic advances in musculoskeletal disease, 6(6),226-237. 226-237.

Richards, L., Loudon, J., Muscle Arrangement, University of Kansas Medical Center, 1997.http://classes.kumc

http://classes.kumc.edu/sah/resources/handkines/muscles/musclemain.htm

Ryan, John et. al. (1975). U.S. Patent No. US 3767321. Washington, DC: U.S.

Patent and Trademark Office.

Sancetta, B. (2014). Powered Hand Orthosis Research Project. Worcester Polytechnic Institute.

Scarsella, M., Electromechanical System Integration for a Powered Upper Extremity Orthosis, Polytechnic Institute, 2007. http://www.wpi.edu/Pubs/ETD/Available/etd041707-131108/unrestricted/Scarsella.pdf 041707-131108/unrestricted/Scarsella.pdf

Scherer, E. (2012). Arthritis in the Fingers. Retrieved March 26, 2015, from fingers.htm

fingers.htm

Shunji, 2009, Active gripping equipment

Stuart, A. (2015). Arm and Hand Exercises for Stroke Rehab. Retrieved April 10, 2016, from

http://www.webmd.com/stroke/features/arm-and-hand-exercises-for-stroke-rehab

Sunderland, A., Tinson, D., Bradley, L., & Hewer, R. L. (1989). Arm function after stroke. Anevaluation Journalof Neurology, Neurosurgery & Psychiatry 52(11), 1267-1272.52(11), 1267-1272.

Spring Design. (2016). Retrieved September 05, 2016, from http://www.meca.insa toulouse.fr/~paredes/Springs2K/index.php?ide=Cbuckling

Xue, Y. 2004, Finger joint orthopedic instrument

Appendices

Appendix A: Meeting with Christopher Nycz

Meeting with Christopher Nycz – Hand Orthosis
Date: 9/19/16

Date of Meeting: 9/14/16 5-6 pm
Location: 85 Prescott St. (RBE Conference Room 2nd Floor)
Attendees: Christopher Nycz, Connor Kurtz, John Mulready, Steven Murphy, Tyler Tao

We met with one of Professor Fischer's PhD students, Christopher Nycz (WPI Doctoral Candidate), to discuss the types of robotic hand orthosis' they are currently working on in the Automation and Interventional Medicine (AIM) Robotics Research Lab.

From this meeting we learned that the target weight for a device on the hand is 200 grams with a maximum of no more than 400 grams. We also learned that an orthotic device should be able to produce in the range of 10-20 N of force to perform most ADLs. Christopher mentioned that this force range was something he has gathered over time and that he is currently putting load cells into common objects such as door knobs and toothbrushes to determine the required forces of everyday tasks. He said his tests should be complete in approximately a month and that he could share his results with our group at that time.

One thing that stood out to us was that Christopher was more concerned with being able to do a few tasks very well rather than a large number of tasks. Because of this, Christopher's research focuses on developing robotic hand orthosis to aid in forming just the pincer and the key grips, not the cylindrical or power grip.

Christopher also showed us a purely mechanical shoulder activated hook prosthetic device that he had seen which has led us to consider shoulder movement as an activation movement for our orthosis. At the end of the meeting, we were able to go into the lab to see two devices that hand been previously developed. One was a glove with string running along both the inside and outside of each finger. A gearbox located in a backpack caused these strings to be pulled to flex and extend the fingers. The second robotic device was worked on in collaboration with three countries. This device used a springy plastic material for the fingers and curled as fingers would when activated.

Appendix B: Change in String Length Experiment

We completed the change in string length experiment on 10/26/16 in the MQP Laboratory. In this experiment, we first taped a protractor to the wall. Then, each group member taped a piece of string to their wrist with the string running over the back of the hand. A mark was made on the string and the back of the hand for reference. Each member then flexed their wrist to 30 and 45 degrees where a second and third mark were made on the string. We then measured the distance between the reference mark and the 30 degree mark, as well as the distance between the reference mark and the 40 degree mark. Finally, we repeated the process above for each group member extending their wrist to 30 and 45 degrees with the string taped to the inner part of the wrist the and running along the inside of the hand. Table 27 below shows our results from this experiment.

Table 35: Results from Change in String Length Experiment

Reults from Change in String Length Experiment

		Flexion (deg.)		Extension (deg.)	
		30	45	30	45
Change in Length (cm)	Tyler	0.5	1.0	0.8	1.2
	Connor	1.1	1.7	1.2	1.5
	John	1.0	1.5	0.9	1.3
	Steven	1.3	1.8	1.5	2.0
	Average	1.0	1.5	1.1	1.5
	SD	0.3	0.3	0.3	0.3

This experiment proves that we can use wrist flexion or extension to move the fingers for a hand orthosis device because the string does change length when the wrist is flexed or extended. Due to the small change in length and the need to accommodate persons with smaller hands (and therefore would produce a smaller change in length), however, we believe additional components such as a slider or gear system would be required to further increase the change in length of the cables.

Appendix C: Elevated Bar Calculations

Configuration 1: Vertical Bar over metacarpals

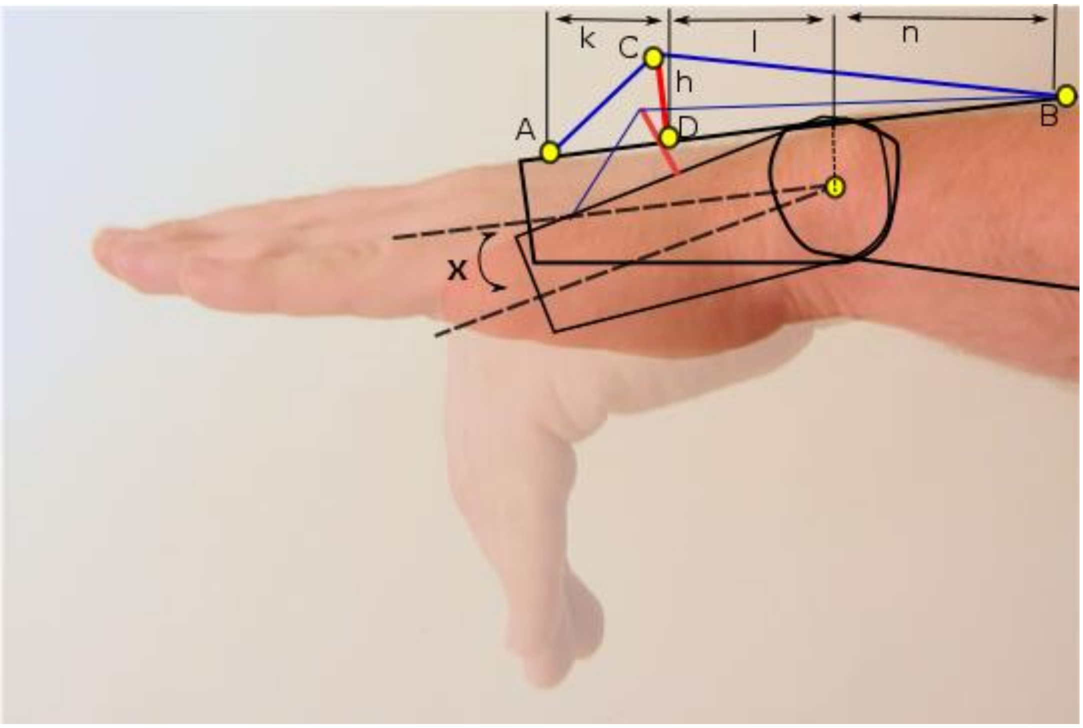


Figure 49 (repeated): Blue cable routed over a red vertical bar over metacarpals

Figure 111shows the derivation of the change in length formula for the vertical bar mounted over the metacarpals. Point A is defined by lengths k and l and is dependent on wrist angle x. Point B is defined by length n. Point C is defined by lengths l and h and is dependent on x.

$$A_1(k,l) := \begin{bmatrix} -(k+l) \\ 0 \end{bmatrix} \qquad A_2(k,l,x) := \begin{bmatrix} -(k+l)\cdot\cos(x) \\ -(k+l)\cdot\sin(x) \end{bmatrix} \qquad D_1(l) := \begin{pmatrix} -l \\ 0 \end{pmatrix} \qquad D_2(l,x) := \begin{pmatrix} -l\cdot\cos(x) \\ -l\cdot\sin(x) \end{pmatrix}$$

$$B_1(n) := \begin{pmatrix} n \\ 0 \end{pmatrix} \qquad B_2(n) := \begin{pmatrix} n \\ 0 \end{pmatrix} \qquad C_1(l,h,x) := \begin{pmatrix} D_1(l)_0 \\ D_1(l)_1 + h \end{pmatrix} \qquad C_2(l,h,x) := \begin{pmatrix} D_2(l,x)_0 + h\cdot\sin(x) \\ D_2(l,x)_1 + h\cdot\cos(x) \end{pmatrix}$$

$$AC_1(k,l,h,x) := \sqrt{\left(C_1(l,h,x)_0 - A_1(k,l)_0\right)^2 + \left(C_1(l,h,x)_1 - A_1(k,l)_1\right)^2} \qquad AC_2(k,l,h,x) := \sqrt{\left(C_2(l,h,x)_0 - A_2(k,l,x)_0\right)^2 + \left(C_2(l,h,x)_1 - A_2(k,l,x)_1\right)^2}$$

$$CB_1(l,h,x,n) := \sqrt{\left(B_1(n)_0 - C_1(l,h,x)_0\right)^2 + \left(B_1(n)_1 - C_1(l,h,x)_1\right)^2} \qquad CB_2(l,h,x,n) := \sqrt{\left(B_2(n)_0 - C_2(l,h,x)_0\right)^2 + \left(B_2(n)_1 - C_2(l,h,x)_1\right)^2}$$

$$x_1(k,l,h,x,n) := AC_1(k,l,h,x) + CB_1(l,h,x,n) \qquad x_2(k,l,h,x,n) := AC_2(k,l,h,x) + CB_2(l,h,x,n) \qquad \Delta l(k,l,h,x,n) := x_2(k,l,h,x,n) - x_1(k,l,h,x,n)$$

Figure 111: Derivation of equation to determine change in cable length of vertical bar over metacarpals configuration

Figure 112 depicts graphs showing the effects of changing k, l, h, and n on the change in length. The optimal guess values are as follows: k=40, l=10, h=30, and n=10.

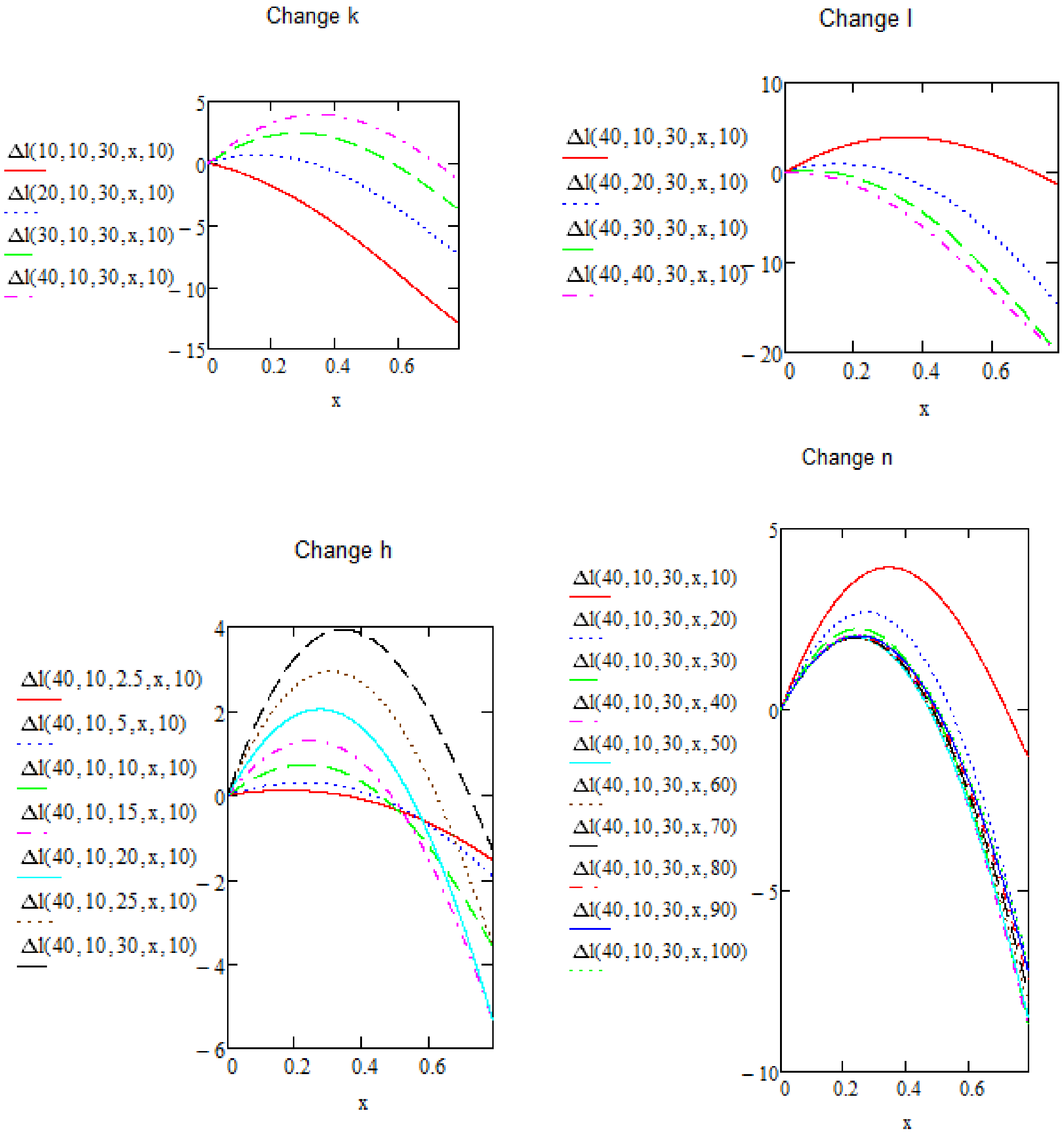
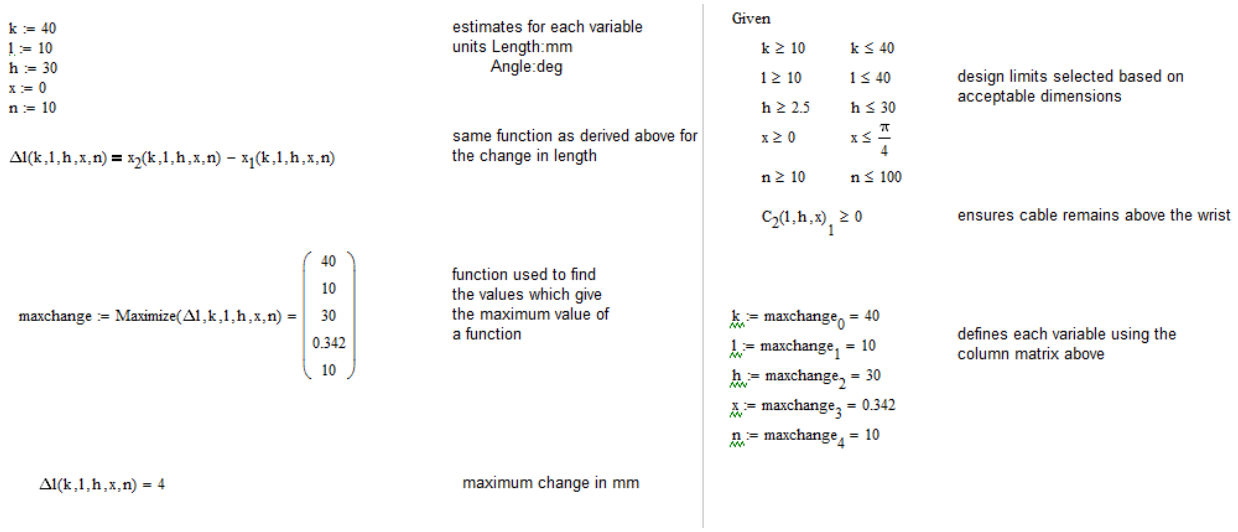


Figure 112: Graphs showing the effect of single variable changes on change in cable length as a function of wrist angle for configuration 1

The calculations and definitions required for the maximum function is seen in Figure 113. The previously stated optimal guesses were input first, seen in the left column. Then the function was re-stated, for clarity only. In the right column, the bounds for each variable are denoted using the Given command. An additional consideration was given to the vertical height of the bar limiting it to above the forearm so that it does not contact the wrist. The Maximize command seen in the left column was used to find the configuration that yields the maximum change in length. In the right column, each input variable is re-defined from the guess to its respective output from Maximum. Finally, the value for Δl was calculated and can be seen as the last item in the left column.



$k := 40$
$l := 10$
$h := 30$
$x := 0$
$n := 10$

estimates for each variable
units Length:mm
Angle:deg

$\Delta l(k,l,h,x,n) = x_2(k,l,h,x,n) - x_1(k,l,h,x,n)$

same function as derived above for the change in length

$$\text{maxchange} := \text{Maximize}(\Delta l,k,l,h,x,n) = \begin{pmatrix} 40 \\ 10 \\ 30 \\ 0.342 \\ 10 \end{pmatrix}$$

function used to find the values which give the maximum value of a function

$\Delta l(k,l,h,x,n) = 4$

maximum change in mm

Given

$k \geq 10$ $\quad k \leq 40$
$l \geq 10$ $\quad l \leq 40$
$h \geq 2.5$ $\quad h \leq 30$
$x \geq 0$ $\quad x \leq \frac{\pi}{4}$
$n \geq 10$ $\quad n \leq 100$

design limits selected based on acceptable dimensions

$C_2(l,h,x)_1 \geq 0$

ensures cable remains above the wrist

$k := \text{maxchange}_0 = 40$
$l := \text{maxchange}_1 = 10$
$h := \text{maxchange}_2 = 30$
$x := \text{maxchange}_3 = 0.342$
$n := \text{maxchange}_4 = 10$

defines each variable using the column matrix above

Figure 113: MathCAD calculation determining the maximum change in cable length and the corresponding value for each variable for configuration 1

Configuration 2: Angled Bar, palm mount

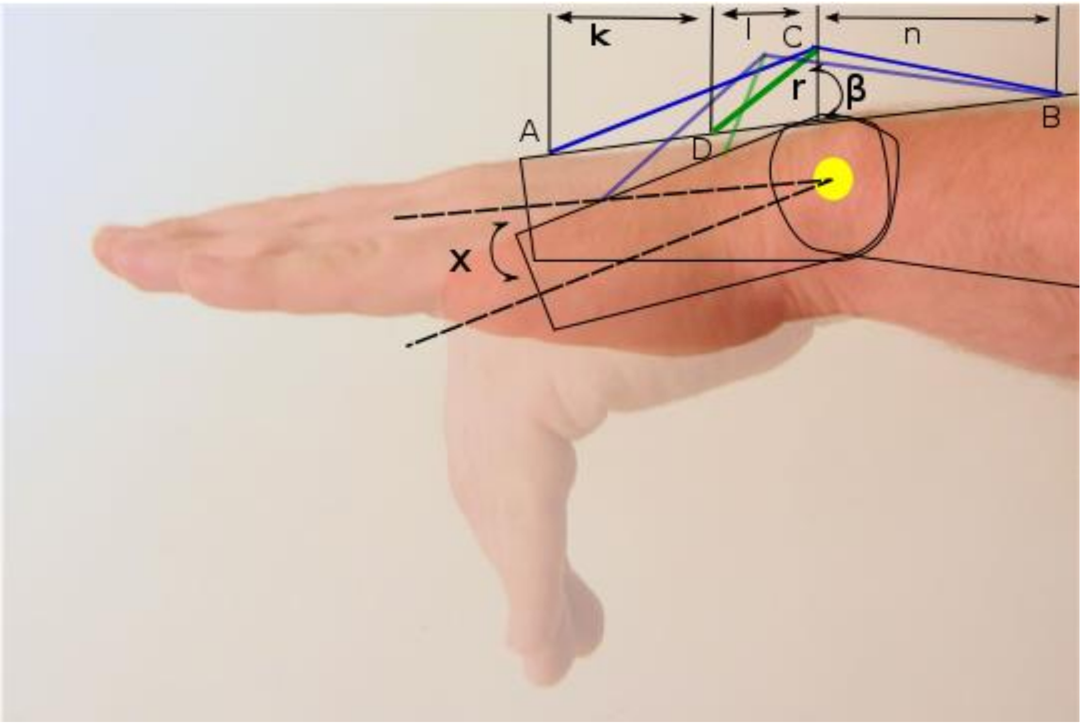
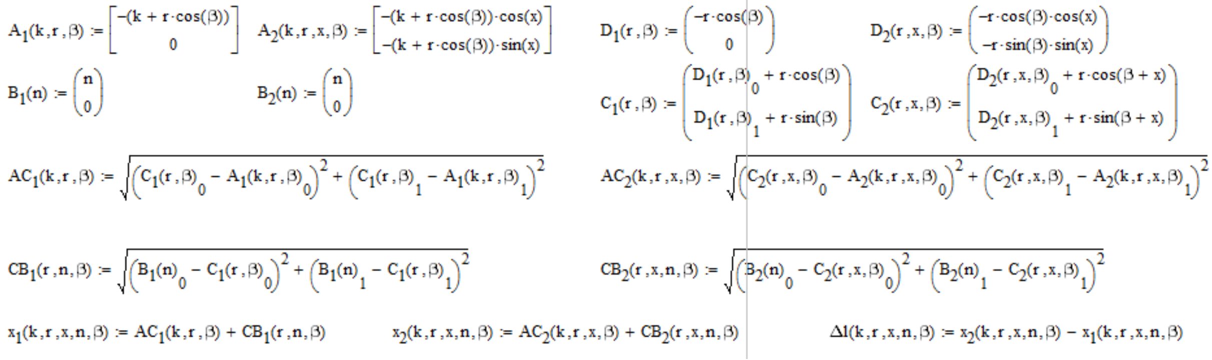


Figure 50(repeated) Blue cable over green bar attached to metacarpals angled over the wrist

Figure *50*Figure 114 shows the derivation of the change in length formula for the angled bar toward the forearm mounted to the metacarpals. Point A is defined by lengths k and r, angle β, and is dependent on wrist angle x. Point B is defined by length n. Point C is defined by length r, angle β and is dependent on x.



$$A_1(k,r,\beta) := \begin{bmatrix} -(k + r\cdot\cos(\beta)) \\ 0 \end{bmatrix} \quad A_2(k,r,x,\beta) := \begin{bmatrix} -(k + r\cdot\cos(\beta))\cdot\cos(x) \\ -(k + r\cdot\cos(\beta))\cdot\sin(x) \end{bmatrix} \quad D_1(r,\beta) := \begin{pmatrix} -r\cdot\cos(\beta) \\ 0 \end{pmatrix} \quad D_2(r,x,\beta) := \begin{pmatrix} -r\cdot\cos(\beta)\cdot\cos(x) \\ -r\cdot\sin(\beta)\cdot\sin(x) \end{pmatrix}$$

$$B_1(n) := \begin{pmatrix} n \\ 0 \end{pmatrix} \quad B_2(n) := \begin{pmatrix} n \\ 0 \end{pmatrix} \quad C_1(r,\beta) := \begin{pmatrix} D_1(r,\beta)_0 + r\cdot\cos(\beta) \\ D_1(r,\beta)_1 + r\cdot\sin(\beta) \end{pmatrix} \quad C_2(r,x,\beta) := \begin{pmatrix} D_2(r,x,\beta)_0 + r\cdot\cos(\beta + x) \\ D_2(r,x,\beta)_1 + r\cdot\sin(\beta + x) \end{pmatrix}$$

$$AC_1(k,r,\beta) := \sqrt{\left(C_1(r,\beta)_0 - A_1(k,r,\beta)_0\right)^2 + \left(C_1(r,\beta)_1 - A_1(k,r,\beta)_1\right)^2} \quad AC_2(k,r,x,\beta) := \sqrt{\left(C_2(r,x,\beta)_0 - A_2(k,r,x,\beta)_0\right)^2 + \left(C_2(r,x,\beta)_1 - A_2(k,r,x,\beta)_1\right)^2}$$

$$CB_1(r,n,\beta) := \sqrt{\left(B_1(n)_0 - C_1(r,\beta)_0\right)^2 + \left(B_1(n)_1 - C_1(r,\beta)_1\right)^2} \quad CB_2(r,x,n,\beta) := \sqrt{\left(B_2(n)_0 - C_2(r,x,\beta)_0\right)^2 + \left(B_2(n)_1 - C_2(r,x,\beta)_1\right)^2}$$

$$x_1(k,r,x,n,\beta) := AC_1(k,r,\beta) + CB_1(r,n,\beta) \quad x_2(k,r,x,n,\beta) := AC_2(k,r,x,\beta) + CB_2(r,x,n,\beta) \quad \Delta l(k,r,x,n,\beta) := x_2(k,r,x,n,\beta) - x_1(k,r,x,n,\beta)$$

Figure 114: Derivation of equation to determine change in cable length of metacarpal bar angled over wrist configuration

Figure 115 depicts graphs showing the effects of changing k, r, n, and β on the change in length. The optimal guess values are as follows: k=10, r=40, n=10, and β=π/12. As seen in the first graph, the change in length function in not very dependent on the value chosen for k. In this case, the value output from Maximize was used as the guess value.

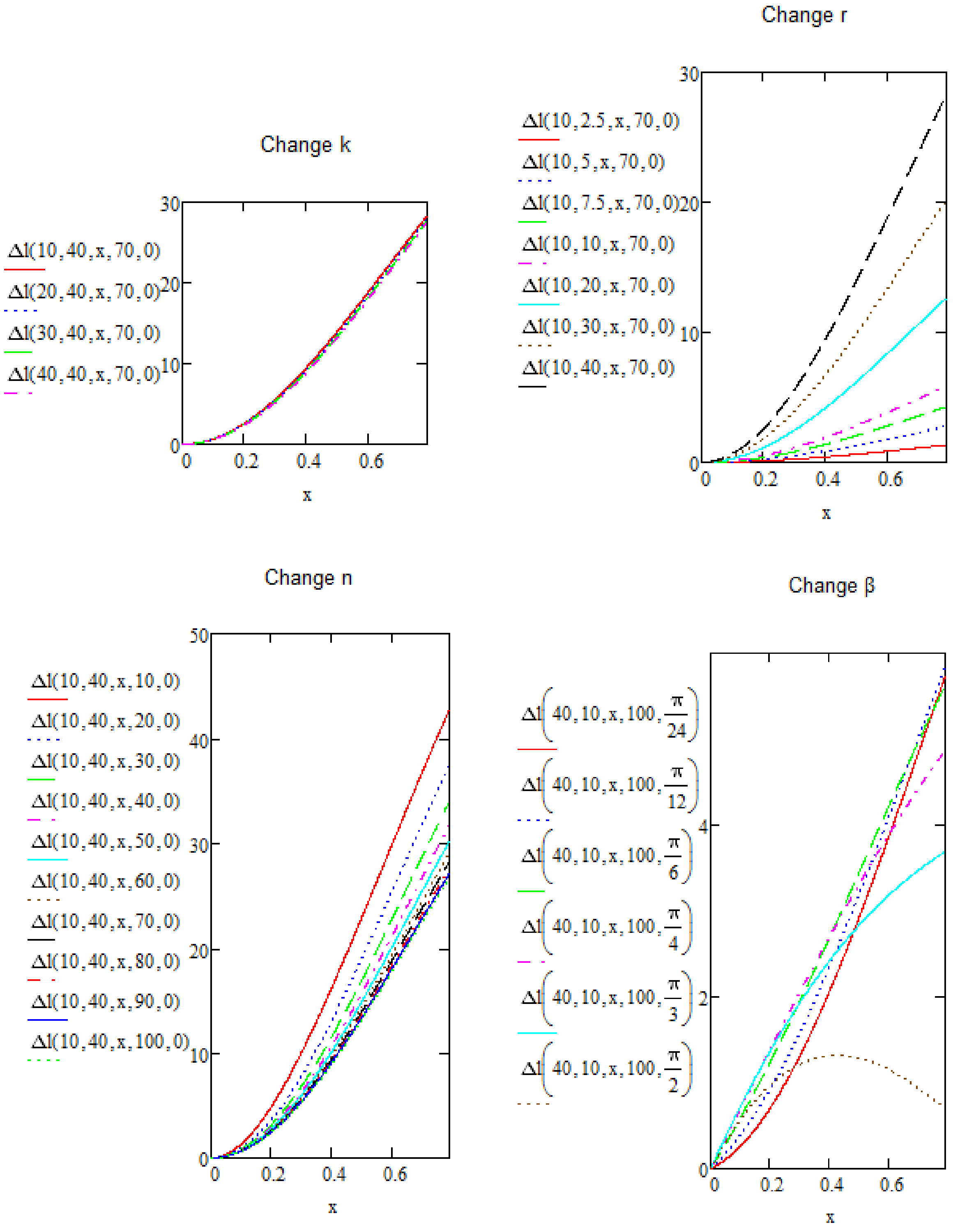
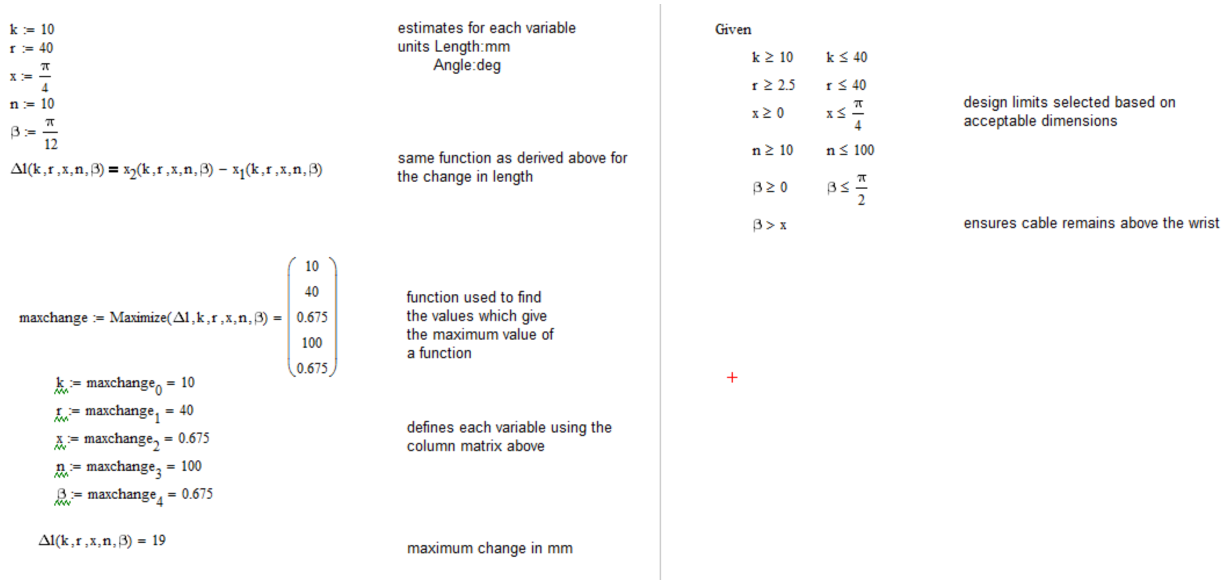


Figure 115: Graphs showing the effect of single variable changes on change in cable length as a function of wrist angle for configuration 2



$k := 10$
$r := 40$
$x := \frac{\pi}{4}$
$n := 10$
$\beta := \frac{\pi}{12}$

estimates for each variable
units Length:mm
Angle:deg

$\Delta l(k,r,x,n,\beta) \equiv x_2(k,r,x,n,\beta) - x_1(k,r,x,n,\beta)$

same function as derived above for the change in length

Given

$k \geq 10 \quad k \leq 40$
$r \geq 2.5 \quad r \leq 40$
$x \geq 0 \quad x \leq \frac{\pi}{4}$
$n \geq 10 \quad n \leq 100$
$\beta \geq 0 \quad \beta \leq \frac{\pi}{2}$

design limits selected based on acceptable dimensions

$\beta > x$

ensures cable remains above the wrist

$$maxchange := Maximize(\Delta l, k, r, x, n, \beta) = \begin{pmatrix} 10 \\ 40 \\ 0.675 \\ 100 \\ 0.675 \end{pmatrix}$$

function used to find the values which give the maximum value of a function

$k := maxchange_0 = 10$
$r := maxchange_1 = 40$
$x := maxchange_2 = 0.675$
$n := maxchange_3 = 100$
$\beta := maxchange_4 = 0.675$

defines each variable using the column matrix above

$\Delta l(k,r,x,n,\beta) = 19$

maximum change in mm

Figure 116: MathCAD calculation determining the maximum change in cable length and the corresponding value for each variable for configuration 2

Configuration 3: Angled bar toward forearm, rotating wrist mount

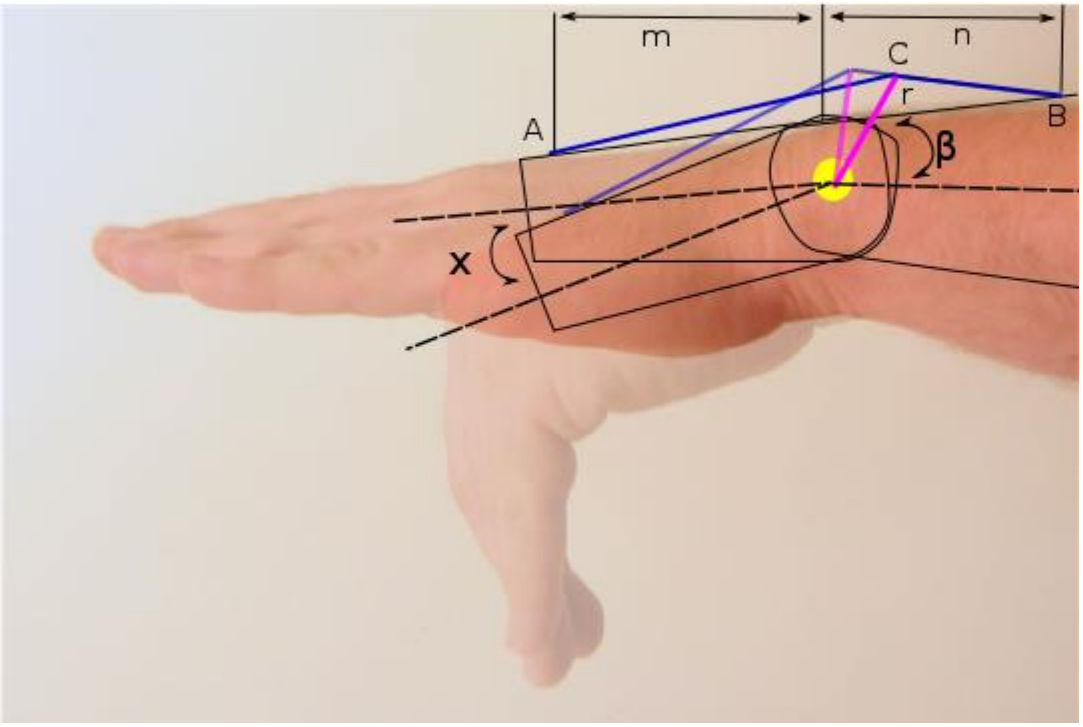
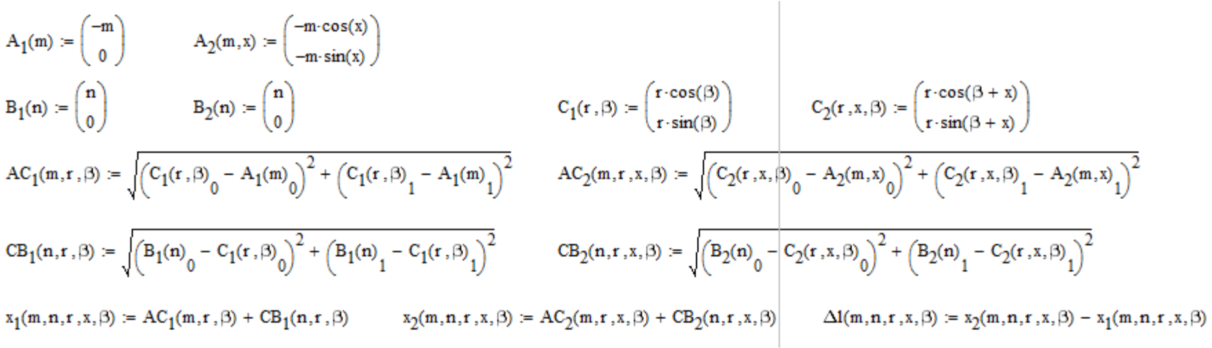


Figure 51(repeated) Blue cable over pink bar attached to metacarpals at the wrist angled toward the forearm

Figure 117 shows the derivation of the change in length formula for the bar mounted to the metacarpal piece at the wrist angled toward the forearm. Point A is defined by length m and is dependent on wrist angle x. Point B is defined by length n. Point C is defined by length r, angle β and is dependent on x.



$$A_1(m) := \begin{pmatrix} -m \\ 0 \end{pmatrix} \qquad A_2(m,x) := \begin{pmatrix} -m\cdot\cos(x) \\ -m\cdot\sin(x) \end{pmatrix}$$

$$B_1(n) := \begin{pmatrix} n \\ 0 \end{pmatrix} \qquad B_2(n) := \begin{pmatrix} n \\ 0 \end{pmatrix} \qquad C_1(r,\beta) := \begin{pmatrix} r\cdot\cos(\beta) \\ r\cdot\sin(\beta) \end{pmatrix} \qquad C_2(r,x,\beta) := \begin{pmatrix} r\cdot\cos(\beta + x) \\ r\cdot\sin(\beta + x) \end{pmatrix}$$

$$AC_1(m,r,\beta) := \sqrt{\left(C_1(r,\beta)_0 - A_1(m)_0\right)^2 + \left(C_1(r,\beta)_1 - A_1(m)_1\right)^2} \qquad AC_2(m,r,x,\beta) := \sqrt{\left(C_2(r,x,\beta)_0 - A_2(m,x)_0\right)^2 + \left(C_2(r,x,\beta)_1 - A_2(m,x)_1\right)^2}$$

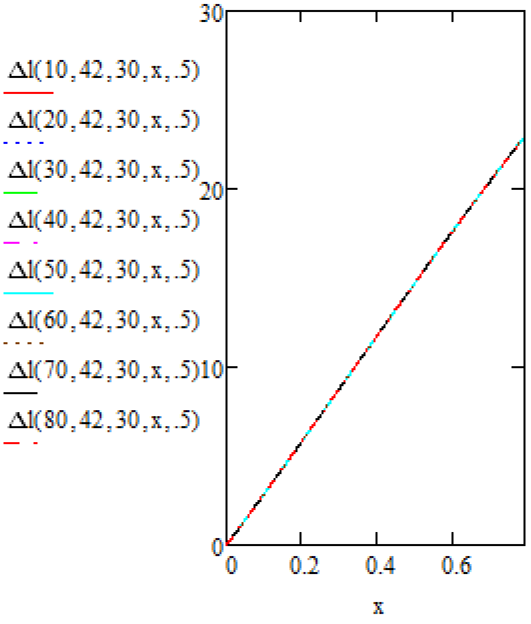
$$CB_1(n,r,\beta) := \sqrt{\left(B_1(n)_0 - C_1(r,\beta)_0\right)^2 + \left(B_1(n)_1 - C_1(r,\beta)_1\right)^2} \qquad CB_2(n,r,x,\beta) := \sqrt{\left(B_2(n)_0 - C_2(r,x,\beta)_0\right)^2 + \left(B_2(n)_1 - C_2(r,x,\beta)_1\right)^2}$$

$$x_1(m,n,r,x,\beta) := AC_1(m,r,\beta) + CB_1(n,r,\beta) \qquad x_2(m,n,r,x,\beta) := AC_2(m,r,x,\beta) + CB_2(n,r,x,\beta) \qquad \Delta l(m,n,r,x,\beta) := x_2(m,n,r,x,\beta) - x_1(m,n,r,x,\beta)$$

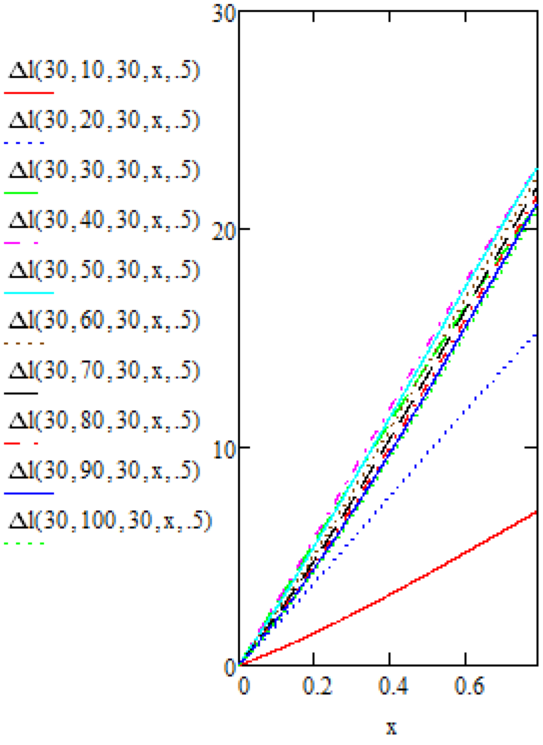
Figure 117: Derivation of equation to determine change in cable length of rotating bar at wrist angled toward forearm configuration

Figure 118 depicts graphs showing the effects of changing m, n, r, and β on the change in length. The optimal guess values are as follows: m=30, n=40, r=30, and β=π/6. The change in length function's dependence on m based on the first graph is almost negligible and the dependence on n seen in the second graph for values of 30 and above is slight.

Change m



Change n



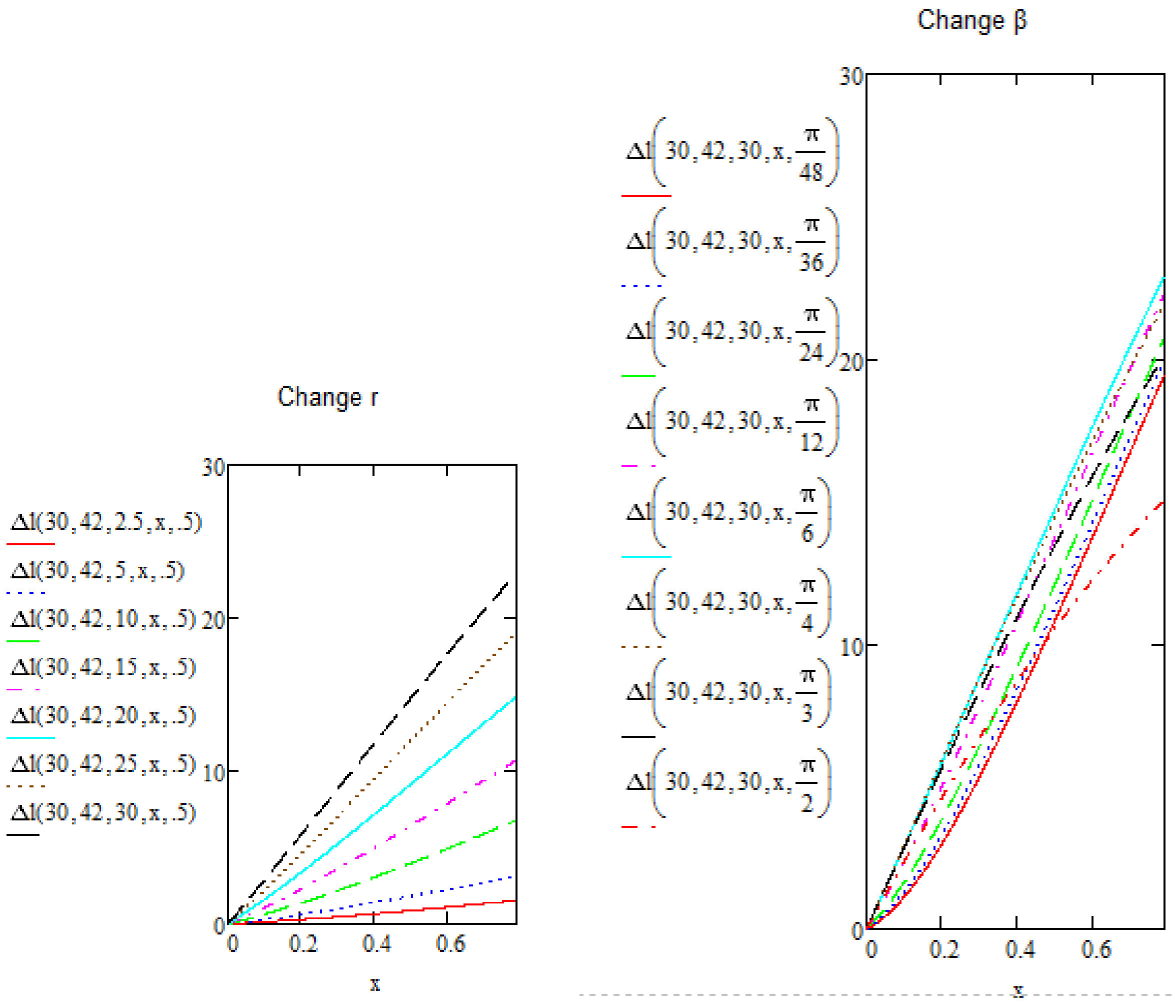
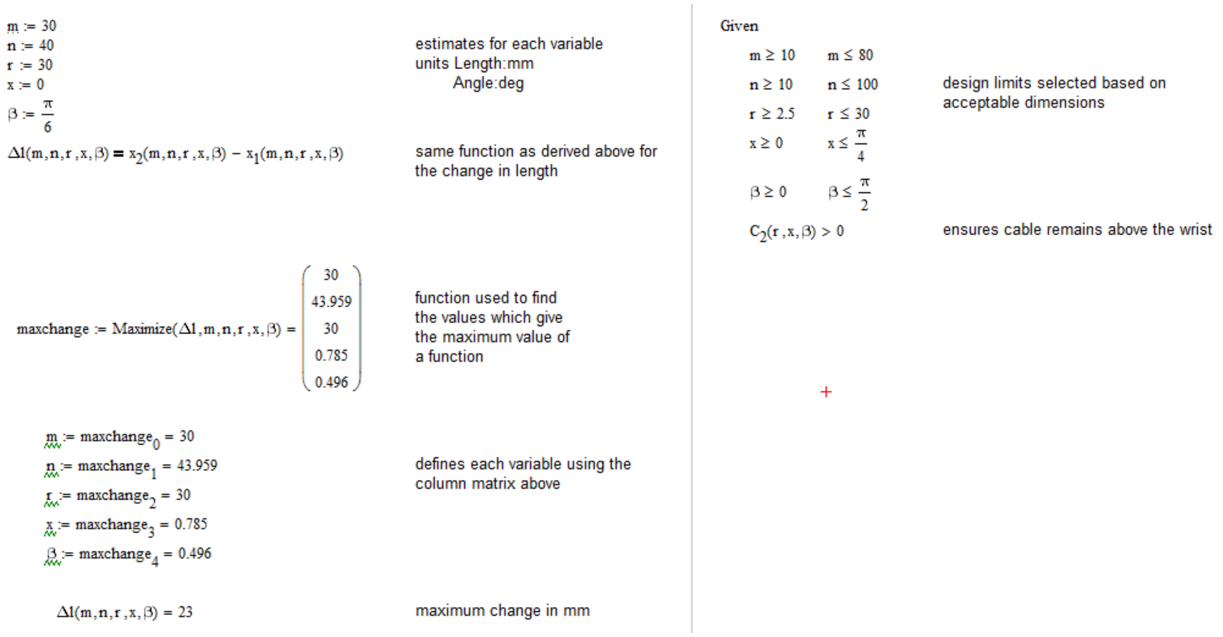


Figure 118: Graphs showing the effect of single variable changes on change in cable length as a function of wrist angle for configuration 3



$m := 30$
$n := 40$
$r := 30$
$x := 0$
$\beta := \frac{\pi}{6}$

estimates for each variable
units Length:mm
Angle:deg

$\Delta l(m,n,r,x,\beta) \equiv x_2(m,n,r,x,\beta) - x_1(m,n,r,x,\beta)$

same function as derived above for the change in length

$$maxchange := Maximize(\Delta l,m,n,r,x,\beta) = \begin{pmatrix} 30 \\ 43.959 \\ 30 \\ 0.785 \\ 0.496 \end{pmatrix}$$

function used to find the values which give the maximum value of a function

$m := maxchange_0 = 30$
$n := maxchange_1 = 43.959$
$r := maxchange_2 = 30$
$x := maxchange_3 = 0.785$
$\beta := maxchange_4 = 0.496$

defines each variable using the column matrix above

$\Delta l(m,n,r,x,\beta) = 23$

maximum change in mm

Given

$m \geq 10$ $m \leq 80$
$n \geq 10$ $n \leq 100$
$r \geq 2.5$ $r \leq 30$
$x \geq 0$ $x \leq \frac{\pi}{4}$
$\beta \geq 0$ $\beta \leq \frac{\pi}{2}$

design limits selected based on acceptable dimensions

$C_2(r,x,\beta) > 0$

ensures cable remains above the wrist

Figure 119: MathCAD calculation determining the maximum change in cable length and the corresponding value for each variable for configuration 3

Configuration 4: Angled bar toward palm, fixed wrist mount

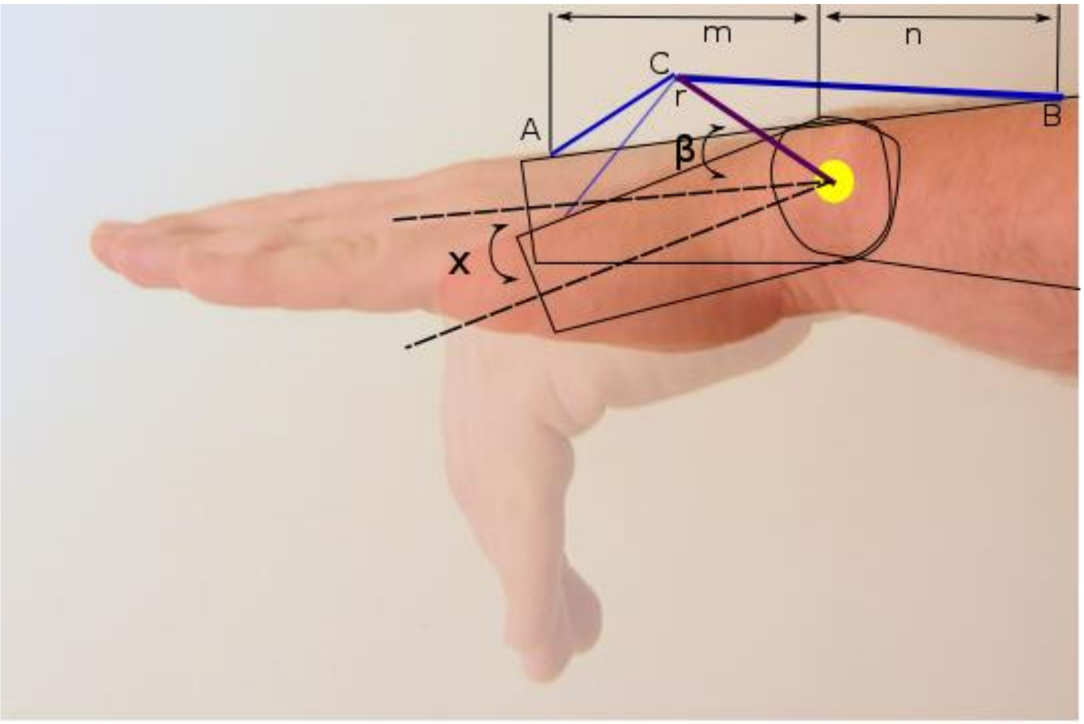
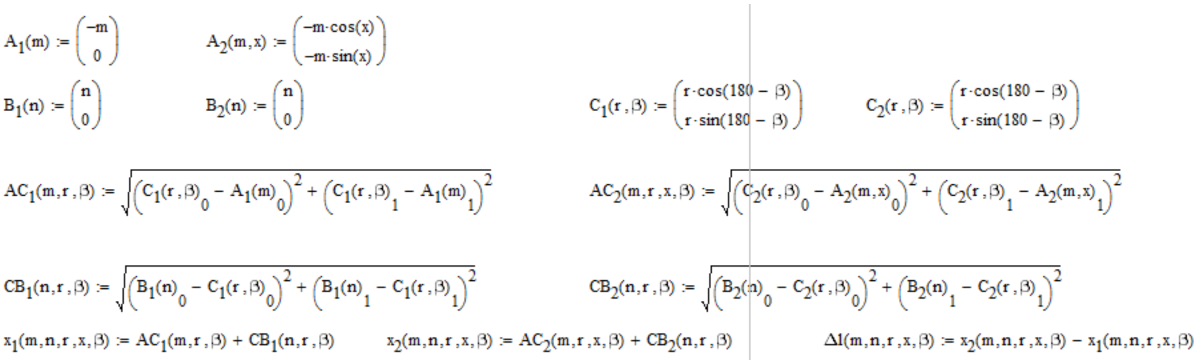


Figure 52 (repeated) Blue cable over purple bar attached to forearm at the wrist angled toward metacarpals

Figure 120 shows the derivation of the change in length formula for the bar mounted to the forearm at the wrist angled toward the metacarpals. Point A is defined by length m and is dependent on wrist angle x. Point B is defined by length n. Point C is defined by length r and angle β. Point C is not dependent upon wrist angle.



$$A_1(m) := \begin{pmatrix} -m \\ 0 \end{pmatrix} \qquad A_2(m,x) := \begin{pmatrix} -m \cdot \cos(x) \\ -m \cdot \sin(x) \end{pmatrix}$$

$$B_1(n) := \begin{pmatrix} n \\ 0 \end{pmatrix} \qquad B_2(n) := \begin{pmatrix} n \\ 0 \end{pmatrix} \qquad C_1(r,\beta) := \begin{pmatrix} r \cdot \cos(180 - \beta) \\ r \cdot \sin(180 - \beta) \end{pmatrix} \qquad C_2(r,\beta) := \begin{pmatrix} r \cdot \cos(180 - \beta) \\ r \cdot \sin(180 - \beta) \end{pmatrix}$$

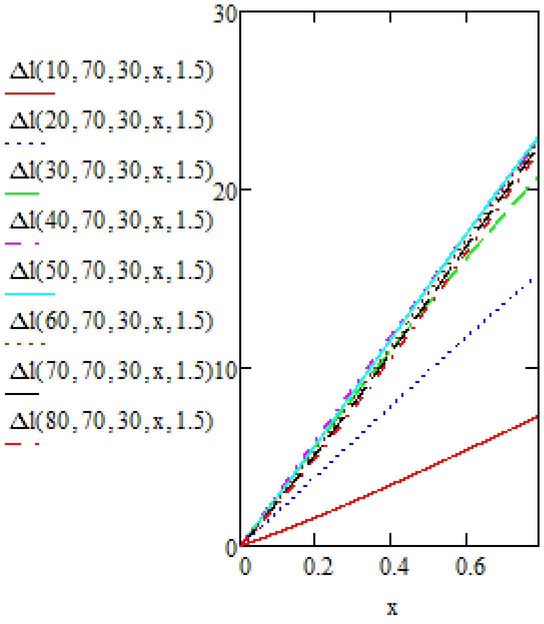
$$AC_1(m,r,\beta) := \sqrt{\left(C_1(r,\beta)_0 - A_1(m)_0\right)^2 + \left(C_1(r,\beta)_1 - A_1(m)_1\right)^2} \qquad AC_2(m,r,x,\beta) := \sqrt{\left(C_2(r,\beta)_0 - A_2(m,x)_0\right)^2 + \left(C_2(r,\beta)_1 - A_2(m,x)_1\right)^2}$$

$$CB_1(n,r,\beta) := \sqrt{\left(B_1(n)_0 - C_1(r,\beta)_0\right)^2 + \left(B_1(n)_1 - C_1(r,\beta)_1\right)^2} \qquad CB_2(n,r,\beta) := \sqrt{\left(B_2(n)_0 - C_2(r,\beta)_0\right)^2 + \left(B_2(n)_1 - C_2(r,\beta)_1\right)^2}$$

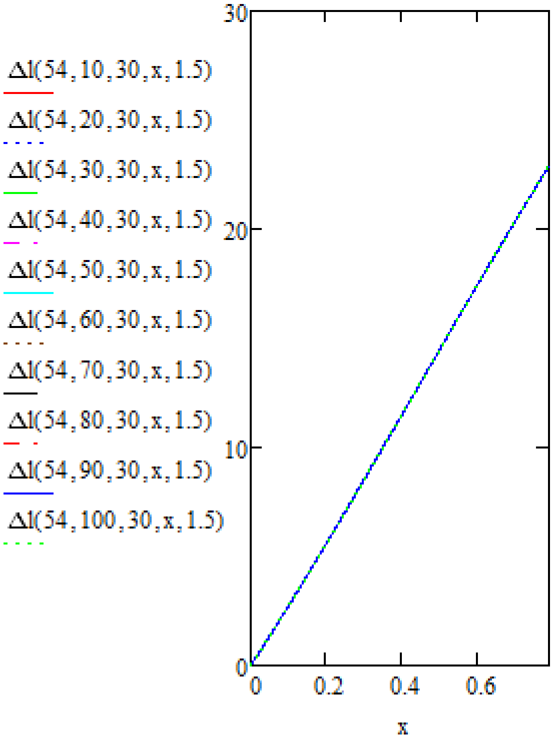
$$x_1(m,n,r,x,\beta) := AC_1(m,r,\beta) + CB_1(n,r,\beta) \qquad x_2(m,n,r,x,\beta) := AC_2(m,r,x,\beta) + CB_2(n,r,\beta) \qquad \Delta l(m,n,r,x,\beta) := x_2(m,n,r,x,\beta) - x_1(m,n,r,x,\beta)$$

Figure 120: Derivation of equation to determine change in cable length of fixed bar at wrist angled toward metacarpals

Figure 121 depicts graphs showing the effects of changing m, n, r, and β on the change in length. The optimal guess values are as follows: m=70, n=70, r=30, and β=π/2. Varying values of n all produce an almost identical change in length as shown by the second graph.



Change m



Change n

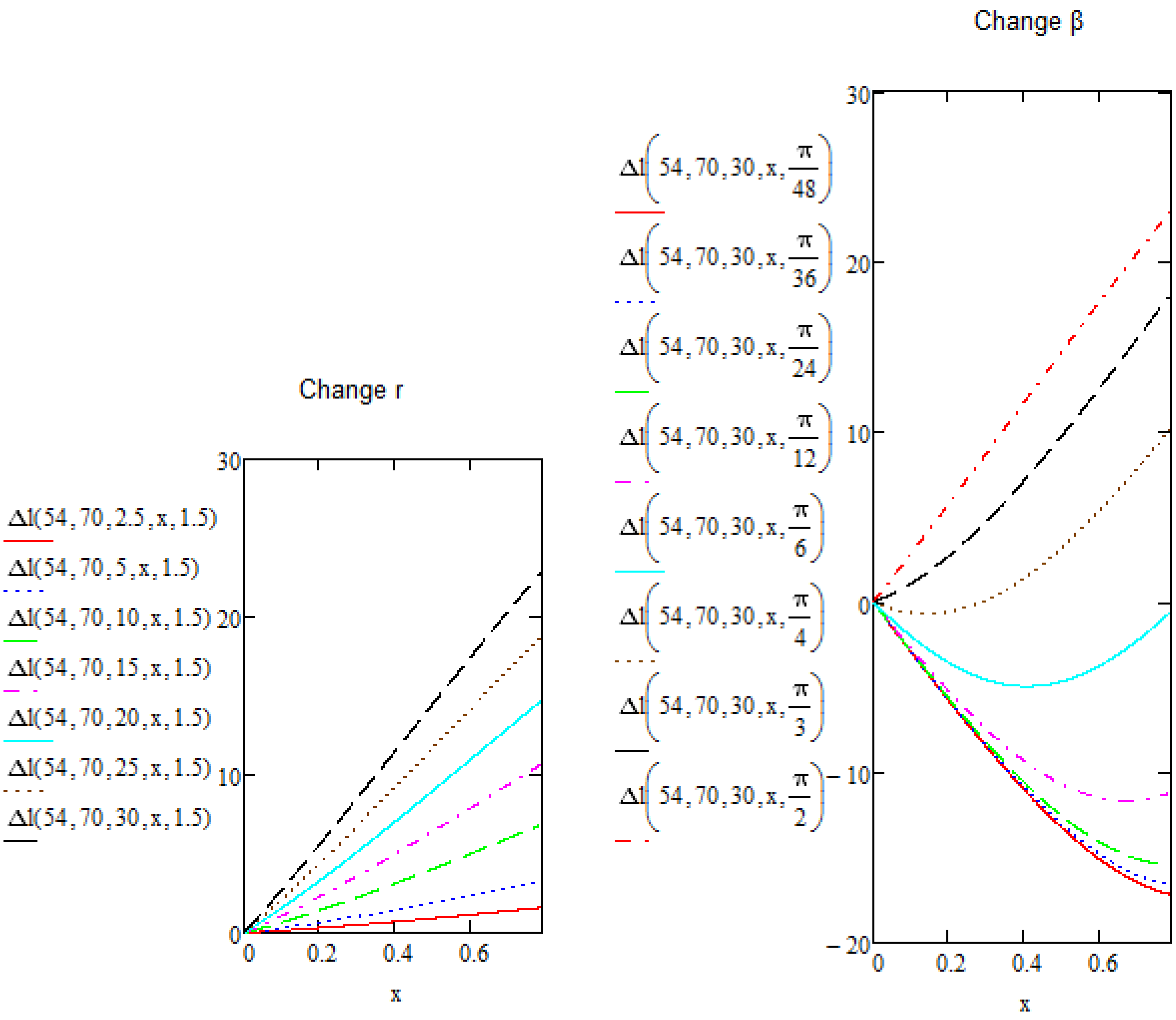
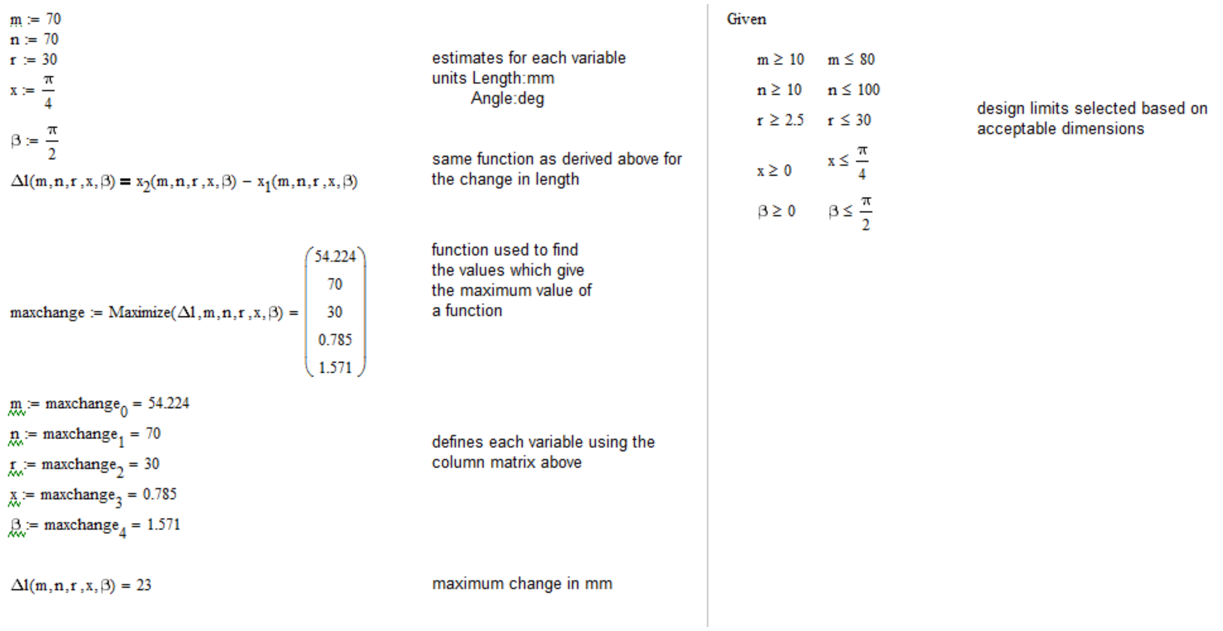


Figure 121: Graphs showing the effect of single variable changes on change in cable length as a function of wrist angle for configuration 3



$m := 70$
$n := 70$
$r := 30$
$x := \frac{\pi}{4}$
$\beta := \frac{\pi}{2}$

estimates for each variable
units Length:mm
Angle:deg

$\Delta l(m,n,r,x,\beta) \equiv x_2(m,n,r,x,\beta) - x_1(m,n,r,x,\beta)$

same function as derived above for the change in length

$$\text{maxchange} := \text{Maximize}(\Delta l, m, n, r, x, \beta) = \begin{pmatrix} 54.224 \\ 70 \\ 30 \\ 0.785 \\ 1.571 \end{pmatrix}$$

function used to find
the values which give
the maximum value of
a function

$m := \text{maxchange}_0 = 54.224$
$n := \text{maxchange}_1 = 70$
$r := \text{maxchange}_2 = 30$
$x := \text{maxchange}_3 = 0.785$
$\beta := \text{maxchange}_4 = 1.571$

defines each variable using the
column matrix above

$\Delta l(m,n,r,x,\beta) = 23$

maximum change in mm

Given

$m \geq 10$ $m \leq 80$
$n \geq 10$ $n \leq 100$
$r \geq 2.5$ $r \leq 30$
$x \geq 0$ $x \leq \frac{\pi}{4}$
$\beta \geq 0$ $\beta \leq \frac{\pi}{2}$

design limits selected based on
acceptable dimensions

Figure 122: MathCAD calculation determining the maximum change in cable length and the corresponding value for each variable for configuration 4

Configuration 5: Angled bar toward palm, rotating wrist mount

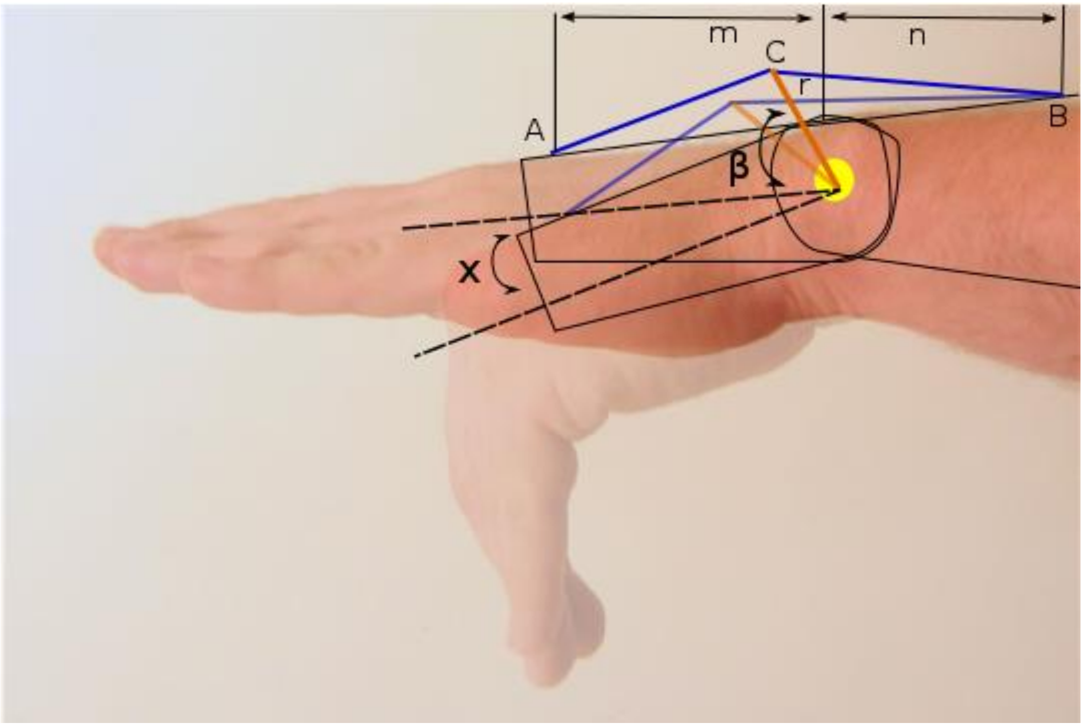
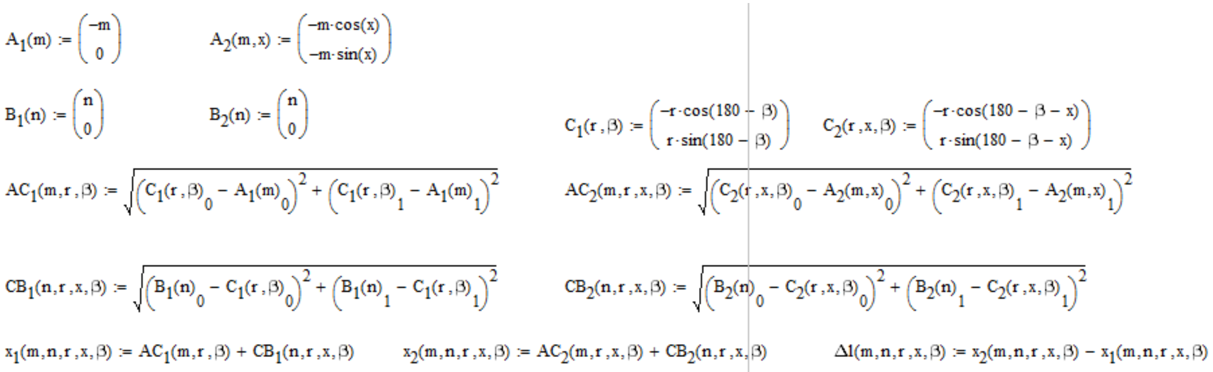


Figure 53 (repeated) Blue cable over orange bar attached to metacarpals at the wrist angled towards metacarpals

Figure *53* Figure 123 shows the derivation of the change in length formula for the bar mounted to the metacarpals at the wrist angled toward the metacarpals.. Point A is defined by length m and is dependent on wrist angle x. Point B is defined by length n. Point C is defined by length r, angle β and is dependent on x.



$$A_1(m) := \begin{pmatrix} -m \\ 0 \end{pmatrix} \qquad A_2(m,x) := \begin{pmatrix} -m\cdot\cos(x) \\ -m\cdot\sin(x) \end{pmatrix}$$

$$B_1(n) := \begin{pmatrix} n \\ 0 \end{pmatrix} \qquad B_2(n) := \begin{pmatrix} n \\ 0 \end{pmatrix}$$

$$C_1(r,\beta) := \begin{pmatrix} -r\cdot\cos(180-\beta) \\ r\cdot\sin(180-\beta) \end{pmatrix} \qquad C_2(r,x,\beta) := \begin{pmatrix} -r\cdot\cos(180-\beta-x) \\ r\cdot\sin(180-\beta-x) \end{pmatrix}$$

$$AC_1(m,r,\beta) := \sqrt{\left(C_1(r,\beta)_0 - A_1(m)_0\right)^2 + \left(C_1(r,\beta)_1 - A_1(m)_1\right)^2}$$

$$AC_2(m,r,x,\beta) := \sqrt{\left(C_2(r,x,\beta)_0 - A_2(m,x)_0\right)^2 + \left(C_2(r,x,\beta)_1 - A_2(m,x)_1\right)^2}$$

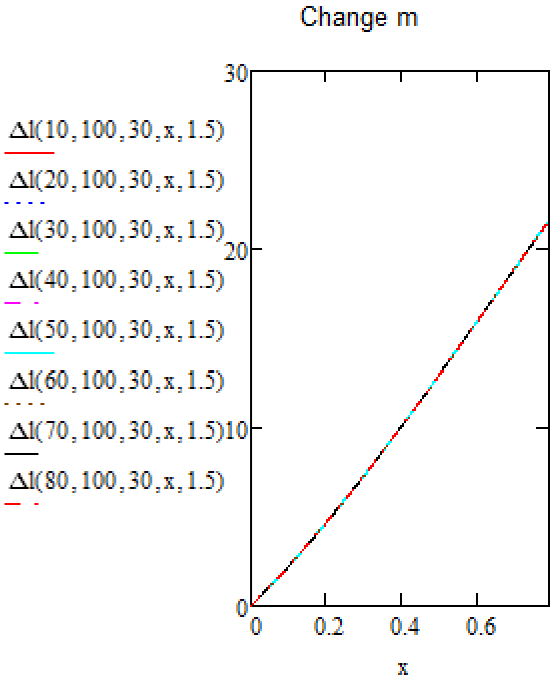
$$CB_1(n,r,x,\beta) := \sqrt{\left(B_1(n)_0 - C_1(r,\beta)_0\right)^2 + \left(B_1(n)_1 - C_1(r,\beta)_1\right)^2}$$

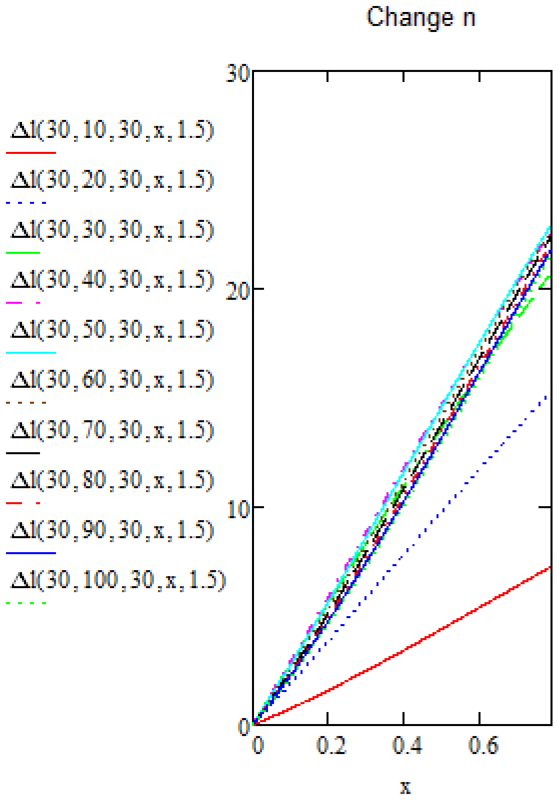
$$CB_2(n,r,x,\beta) := \sqrt{\left(B_2(n)_0 - C_2(r,x,\beta)_0\right)^2 + \left(B_2(n)_1 - C_2(r,x,\beta)_1\right)^2}$$

$$x_1(m,n,r,x,\beta) := AC_1(m,r,\beta) + CB_1(n,r,x,\beta) \qquad x_2(m,n,r,x,\beta) := AC_2(m,r,x,\beta) + CB_2(n,r,x,\beta) \qquad \Delta l(m,n,r,x,\beta) := x_2(m,n,r,x,\beta) - x_1(m,n,r,x,\beta)$$

Figure 123: Derivation of equation to determine change in cable length of rotating bar at wrist angled toward metacarpals

Figure 124depicts graphs showing the effects of changing m, n, r, and β on the change in length. The optimal guess values are as follows: m=70, n=70, r=30, and β=π/2. Varying values of n all produce an almost identical change in length as shown by the second graph.


Change m
ΔI(10,100,30,x,1.5)
ΔI(20,100,30,x,1.5)
ΔI(30,100,30,x,1.5)
ΔI(40,100,30,x,1.5)
ΔI(50,100,30,x,1.5)
ΔI(60,100,30,x,1.5)
ΔI(70,100,30,x,1.5)
ΔI(80,100,30,x,1.5)
30
20
10
0
0
0.2
0.4
0.6
x


Change n
ΔI(30,10,30,x,1.5)
ΔI(30,20,30,x,1.5)
ΔI(30,30,30,x,1.5)
ΔI(30,40,30,x,1.5)
ΔI(30,50,30,x,1.5)
ΔI(30,60,30,x,1.5)
ΔI(30,70,30,x,1.5)
ΔI(30,80,30,x,1.5)
ΔI(30,90,30,x,1.5)
ΔI(30,100,30,x,1.5)
30
20
10
0
0
0.2
0.4
0.6
x

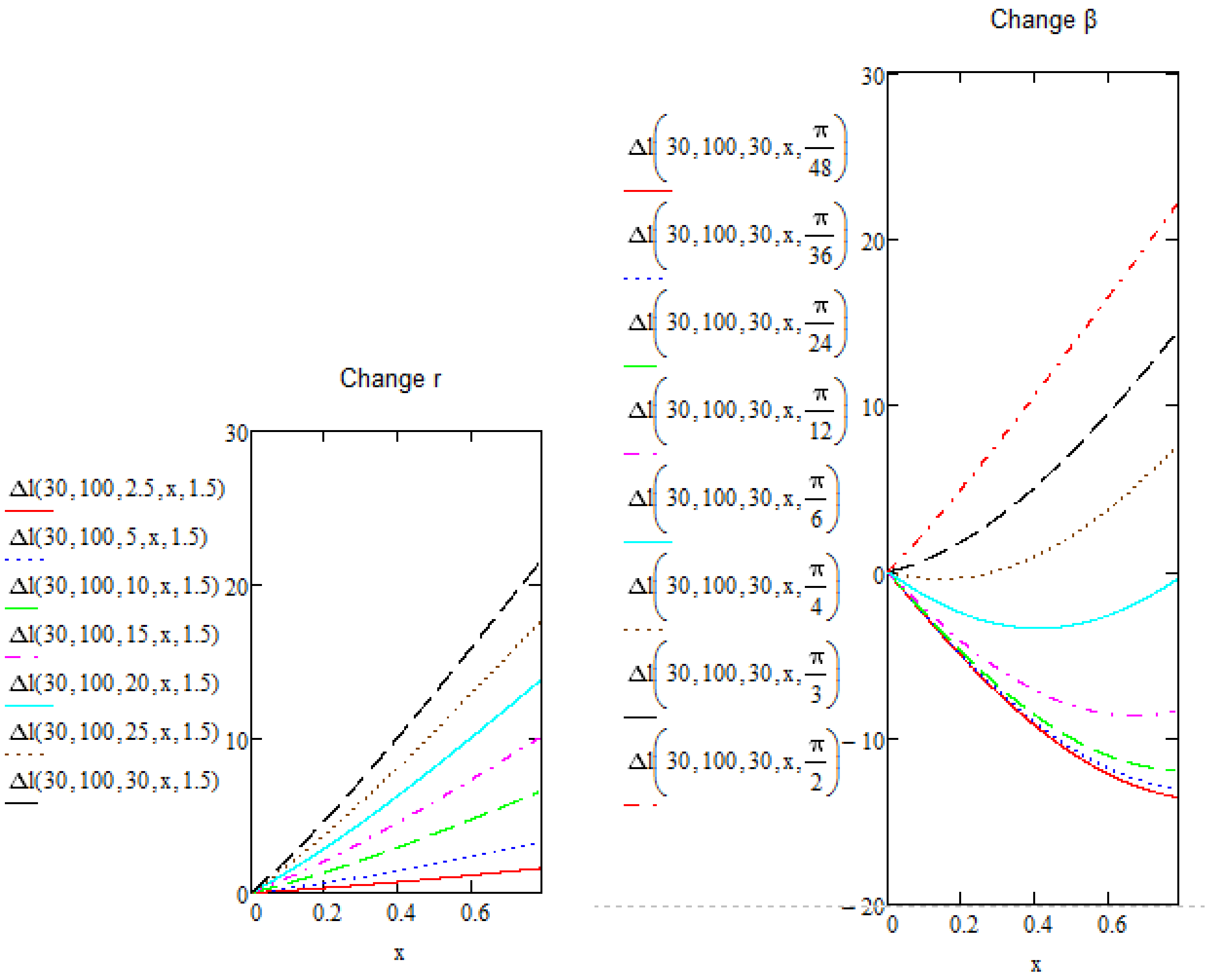
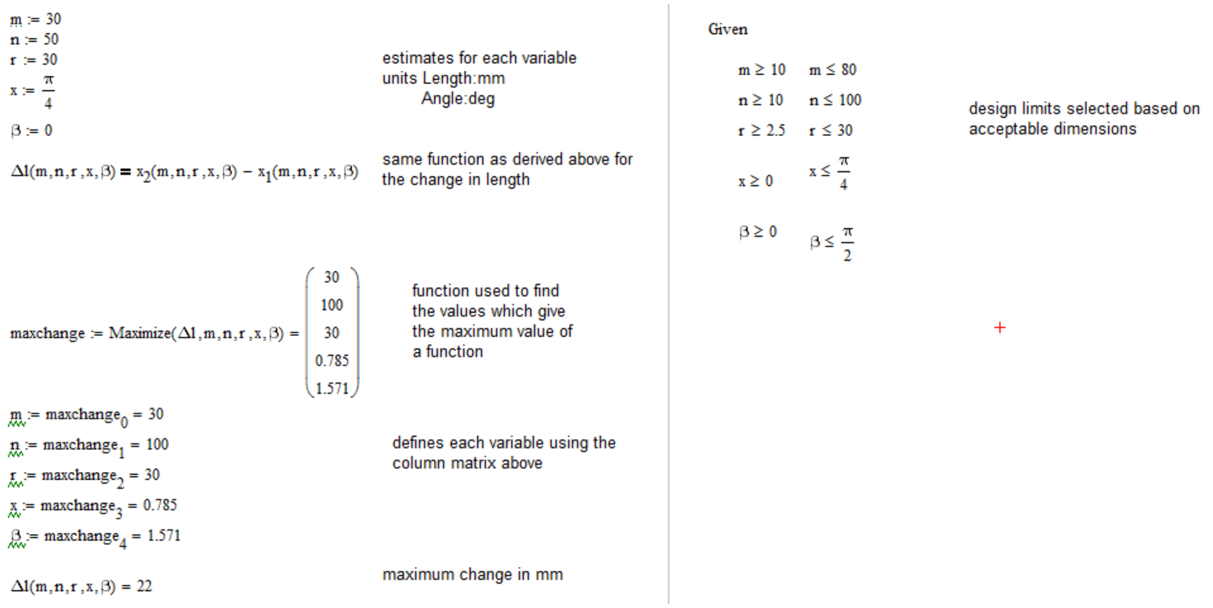


Figure 124: Graphs showing the effect of single variable changes on change in cable length as a function of wrist angle for configuration 4



$m := 30$

$n := 50$

$r := 30$

$x := \frac{\pi}{4}$

$\beta := 0$

estimates for each variable
units Length:mm
Angle:deg

$\Delta l(m,n,r,x,\beta) \equiv x_2(m,n,r,x,\beta) - x_1(m,n,r,x,\beta)$

same function as derived above for the change in length

$$maxchange := \mathrm{Maximize}(\Delta l,m,n,r,x,\beta) = \begin{pmatrix} 30 \\ 100 \\ 30 \\ 0.785 \\ 1.571 \end{pmatrix}$$

function used to find the values which give the maximum value of a function

$m := maxchange_0 = 30$

$n := maxchange_1 = 100$

$r := maxchange_2 = 30$

$x := maxchange_3 = 0.785$

$\beta := maxchange_4 = 1.571$

defines each variable using the column matrix above

$\Delta l(m,n,r,x,\beta) = 22$

maximum change in mm

Given

$m \geq 10 \quad m \leq 80$

$n \geq 10 \quad n \leq 100$

$r \geq 2.5 \quad r \leq 30$

$x \geq 0 \quad x \leq \frac{\pi}{4}$

$\beta \geq 0 \quad \beta \leq \frac{\pi}{2}$

design limits selected based on acceptable dimensions

Figure 125: MathCAD calculation determining the maximum change in cable length and the corresponding value for each variable for configuration 5

Appendix D: Finger and Thumb Functional Decomposition

Table 36: Functional Decomposition of Fingers

In a functional device:	**Fingers**	
The user undertakes some non-hand motion when hand motion is desired	Type of activation movement	Wrist Motion (Flexion/Extension)
		Wrist Motion (Abduction/Adduction)
		Elbow Motion
		Shoulder Motion
then		
The motion is transferred from the external site to the hand mechanism	Translation of movement from activation to mechanism	Cable
		Springs
		Cable and Spring
		Adjustable forearm mounting
then		
Motion of the fingers is driven via the translation method. Fingers are moved along a certain path dependent upon	Mechanism causing finger/hand movement	Cables
		Finger Linkage
		Torsional Springs
		SMA
then		
The mechanism must be attached to the hand in order for the force to be transferred	Attachment to user	Glove
		Ring
		Finger Sleeves
		Rigid finger channel

Table 37: Functional Decomposition of Thumb

		Thumb		
	Continuous motion coupled to fingers	Contiunuous motion uncoupled from fingers	Incremental motion uncoupled from fingers	Fixed
Type of activation movement	Wrist Motion (Flexion/Extension)	activated by contralateral hand	activated by contralateral hand	Unnecessary
	Wrist Motion (Abduction/Adduction)			
	Elbow Motion			
	Shoulder Motion			
Translation of movement from activation to finger/hand movement	Cable	Unecessary	Unecessary	Unecessary
	Springs			
	Cable and Spring			
Mechanism causing finger/hand movement	Cables	Linear slide	Ratchet System	Unnecessary
	Finger Linkage	Gear System	Gear System	
	Compression Springs	Pulley System	Beach chair arm mechanism	
	SMA			
Attachment to user	Glove	Glove	Glove	Glove
	Ring	Ring	Ring	Ring
	Finger Sleeves	Finger Sleeves	Finger Sleeves	Finger Sleeves
	Rigid finger channel	Rigid finger channel	Rigid finger channel	Rigid finger channel
				Brace

Appendix E: Cable Length Calculations

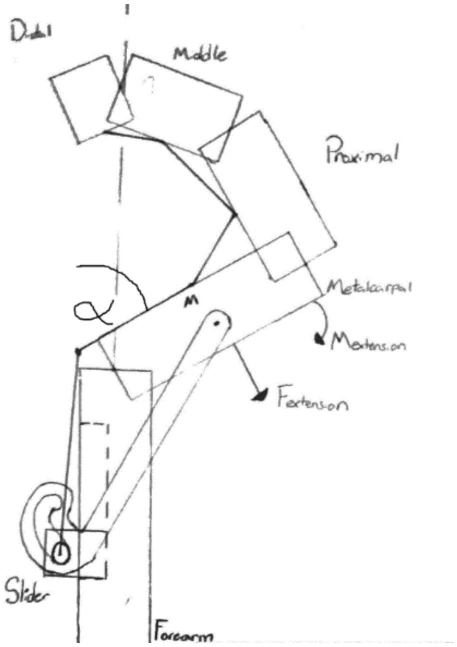


Figure 31: Internal band system with closed hand (Repeated)

Using Law of Cosines to deterimine cable length

$d := 1$ Length of Distal Finger Joint

$m := 1$ Length of Medial Finger Joint

$p := 2$ Length of Proximal Finger Joint

$h := 2.9$ Length of Metocarpal

$\theta_1 := 0$ angle between distal and medial joint

$\theta_2 := 0$ angle between medial and proximal joint

$\theta_3 := 0$ angle between proximal and metacarpal

$\theta_{wrist} := 0$

$c_{dm} := \sqrt{.5 \cdot d^2 + .5 \cdot m^2 - 2 \cdot d \cdot m \cdot \cos(180 - \theta_1)} = 1.482$ cable length between medial and distal

$c_{mp} := \sqrt{.5 \cdot m^2 + .5 \cdot p^2 - 2 \cdot m \cdot p \cdot \cos(180 - \theta_2)} = 2.212$

cable length between medial and proximal

$c_{ph} := \sqrt{.5 \cdot p + .5 \cdot h^2 - 2 \cdot p \cdot h \cdot \cos(180 - \theta_3)} = 3.485$

cable length between proximal and metacarpal

wrist

$C_{total1} := c_{dm} + c_{mp} + c_{ph} = 7.18$

$d := 1$ Length of Distal Finger Joint

$m := 1$ Length of Medial Finger Joint

$p := 2$ Length of Proximal Finger Joint

$h := 2.9$ Length of Metocarpal

$\theta_1 := 70$ angle between distal and medial joint

$\theta_2 := 70$ angle between medial and proximal joint

$\theta_3 := 90$ angle between proximal and metacarpal

$c_{dm} := \sqrt{.5\cdot d^2 + .5\cdot m^2 - 2\cdot d\cdot m\cdot \cos(180 - \theta_1)} = 1.731$ cable length between medial and distal

$c_{mp} := \sqrt{.5\cdot m^2 + .5\cdot p^2 - 2\cdot m\cdot p\cdot \cos(180 - \theta_2)} = 2.549$

cable length between medial and proximal

$c_{ph} := \sqrt{.5\cdot p + .5\cdot h^2 - 2\cdot p\cdot h\cdot \cos(180 - \theta_3)} = 3.225$

cable length between proximal and metacarpal

$C_{total2} := c_{dm} + c_{mp} + c_{ph} = 7.506$

$C_{total2} - C_{total1} = 0.326$

Appendix F: Bone Forces/Moments

The force placed on the user's hands by the device is relevant when considering safety. To establish a reasonable force threshold, we utilized a Wagner Force Dial Hand Held Dynamometer to calculate a force parallel to the bone that was tolerable. Ideally, the device's force at one point on the hand will not approach these thresholds. The test was done by forcing the dynamometer into each phalange on the back of the fingers until there was noticeable discomfort. The tip of the dynamometer that was forced into the fingers was a 0.25in diameter circle (equal to an area of 0.049in^2). The calculated force is distributed over that area, which is indicative of the possible forces that could be encountered in our design. Forces acting on the fingers would be distributed across an area, much like these experimental forces. We have identified the distal phalange of the pinky finger as having the lowest tolerance, Table 38. As a result, the tolerable force for that phalange is deemed to be the maximum force we would deem acceptable in our design.

Table 38 Maximum tolerable force on fingers

Finger	Joint	Tolerable Force (lb)	Tolerable Force (N)
Index	Proximal	5	22
	Medial	4.75	21
	Distal	4.75	21
Middle	Proximal	5.25	23
	Medial	4.75	21
	Distal	4.5	20
Ring	Proximal	4.75	21
	Medial	4.75	21
	Distal	4.25	19
Pinky	Proximal	4.75	21
	Medial	3.75	17
	Distal	3.5	15

Appendix G: Design 2 Calculations

$F_{ACTIVATION} = 29\,N$

* assuming 45° WRIST angle

$T_{cable} = 29 \sin 45$

$T_{cable} \approx 20.5_{N}$

METACARPAL $\sum F_x = 0 = 20.5 + F_{4M}\cos(45) + F_{DM}X$

PROXIMAL $\sum F_x = 0 = -F_{PM_x} + F_{DP}X - F_T \cos 30$

$\sum F_x = 0 = -F_{PMx} + F_{DPx} - 17.75$

4TH BAR $\sum F_x = 0 = -(F_{4M}\cos 45) - F_{D4}(\cos 45)$

DISTAL & MEDIAL $\sum F_x = 0 = F_{D4}\cos 45 \quad (-F_{DPx}) + F_{OUT}\,x$

So,

$$F_{D4}\cos(45) = -F_{4M}\cos(45)$$

$$\downarrow$$

$$20.5 + F_{4M}\cos(45) + F_{PMx} = 0$$

$$20.5 + F_{PMx} = -F_{4M}\cos(45) = F_{D4}\cos(45)$$

$$\downarrow$$

$$F_{D4}\cos(45) - F_{DPx} + F_{out} = 0$$

$$20.5 + F_{PMy} - F_{DPx} + F_{out} = 0$$

$$F_{PMx} = F_{DPx} - 20.5 - F_{out}$$

$$\downarrow$$

$$-F_{PMx} + F_{DP_x} - 17.75 = 0$$

$$\cancel{-F_{DPx}} + 20.5 + F_{out} + \cancel{F_{DPx}} - 17.75 = 0$$

$$20.5 - 17.75 = -F_{OUT}$$

$$\boxed{F_{OUT\,x} = -2.75\,N}$$

METACARPAL $\Sigma F_y = 0 = F_{4M}\sin(45) + F_{PMY}$

PROXIMAL $\Sigma F_y = 0 = -F_{PMY} + F_{DPY} - F_T\sin 30$

4TH EXT $\Sigma F_y = 0 = -F_{4M}\sin(45) - F_{O4}\sin(45)$

DISTAL & MEDIAL $\Sigma F_y = 0 = F_{O4}\sin(45) - F_{DPY} + F_{OUT}Y$

So, $F_{O4}\sin(45) = -F_{4M}\sin(45)$

$$\downarrow$$

$$-F_{4M}\sin(45) + F_{PMY} = 0$$

$$F_{PMY} = -F_{4M}\sin(45) = F_{O4}\sin(45)$$

$$\downarrow$$

$$F_{O4}\sin(45) - F_{DPY} + F_{OUT}(Y) = 0$$

$$F_{PMY} - F_{DPY} + F_{OUT} = 0$$

$$F_{PMY} + F_{OUT} = F_{DPY}$$

$$\downarrow$$

$$-F_{PMY} + F_{DPY} - F_T\sin(30) = 0$$

$$\cancel{-F_{PMY}} + (\cancel{F_{PMY}} + F_{OUT}) - F_T\sin 30$$

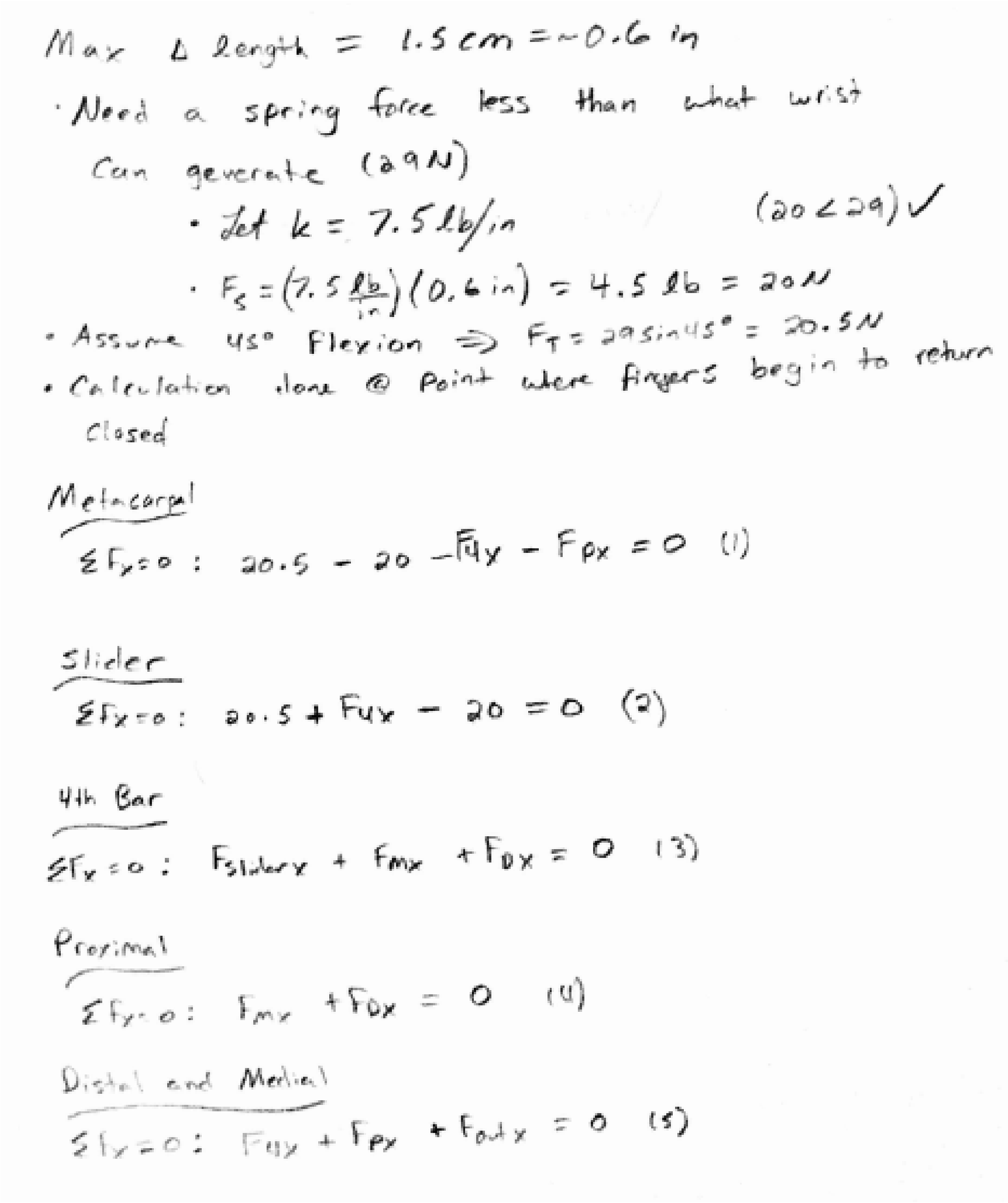
$$F_{OUT} = F_T\sin 30$$

$$\boxed{F_{OUT\,y} = 10.25}$$

$$F_{OUT} = \sqrt{(-2.75^2) + 10.25^2)}$$

$$\boxed{F_{OUT} = 10.6\ N}$$

Appendix H: Design 3 Calculations



Max Δ length = 1.5 cm =~ 0.6 in

- Need a spring force less than what wrist can generate (29N)
  - Let $k = 7.5\ lb/in$ (20 < 29) ✓
  - $F_s = (7.5\ \frac{lb}{in})(0.6\ in) = 4.5\ lb = 20N$
- Assume 45° Flexion $\Rightarrow F_T = 29\sin 45° = 20.5N$
- Calculation done @ Point where fingers begin to return closed

Metacarpal

$\Sigma F_x = 0:\quad 20.5 - 20 - F_{4y} - F_{Px} = 0 \quad (1)$

Slider

$\Sigma F_x = 0:\quad 20.5 + F_{4x} - 20 = 0 \quad (2)$

4th Bar

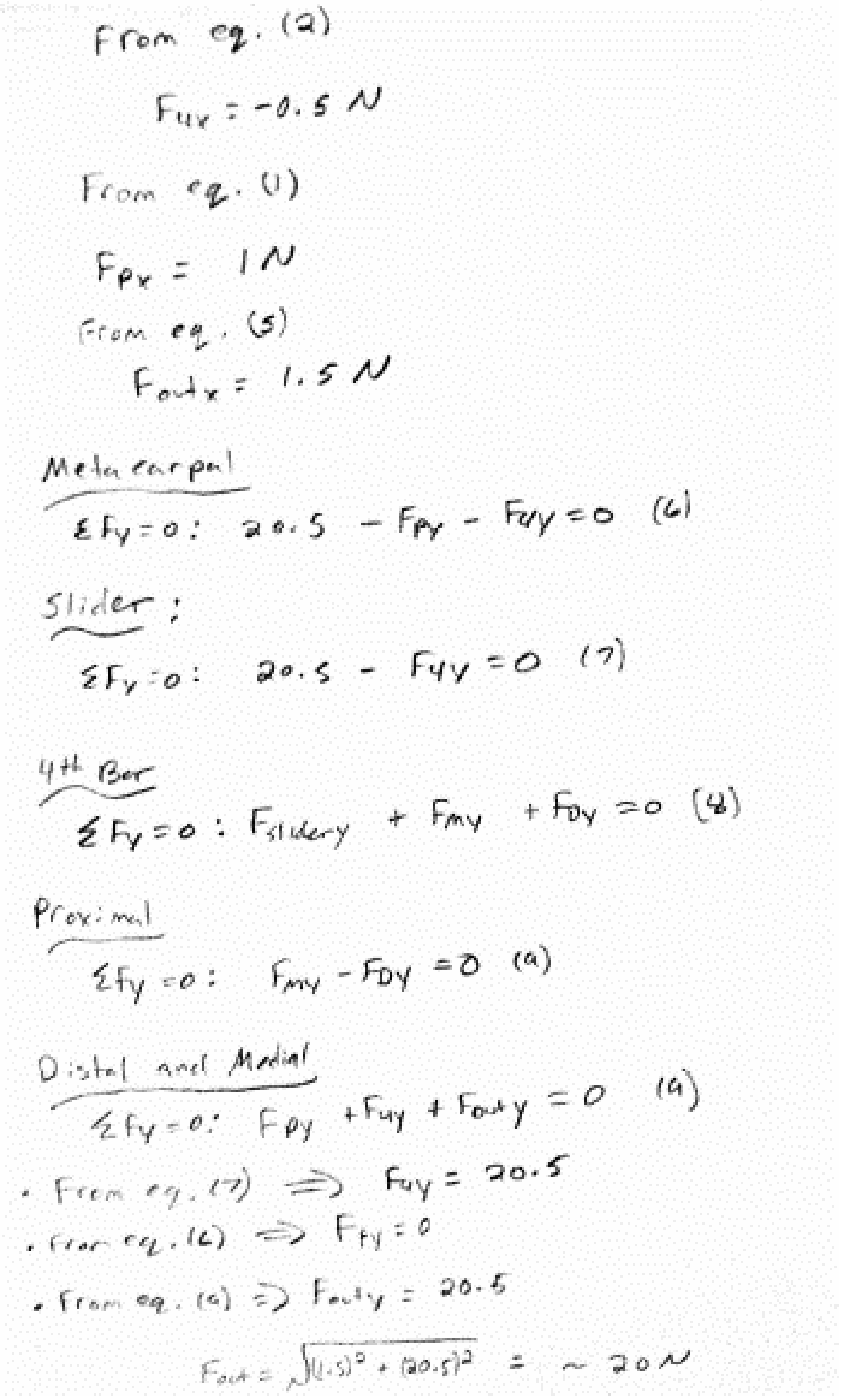
$\Sigma F_x = 0:\quad F_{slider\,x} + F_{Mx} + F_{Dx} = 0 \quad (3)$

Proximal

$\Sigma F_x = 0:\quad F_{Mx} + F_{Dx} = 0 \quad (4)$

Distal and Medial

$\Sigma F_x = 0:\quad F_{4x} + F_{Px} + F_{out\,x} = 0 \quad (5)$



From eq. (2)

$F_{4x} = -0.5\ N$

From eq. (1)

$F_{Px} = 1 N$

From eq. (5)

$F_{out\,x} = 1.5\ N$

Metacarpal

$\Sigma F_y = 0: \quad 20.5 - F_{Py} - F_{4y} = 0 \quad (6)$

Slider:

$\Sigma F_y = 0: \quad 20.5 - F_{4y} = 0 \quad (7)$

4th Bar

$\Sigma F_y = 0: \quad F_{slider\,y} + F_{my} + F_{Dy} = 0 \quad (8)$

Proximal

$\Sigma F_y = 0: \quad F_{my} - F_{Dy} = 0 \quad (9)$

Distal and Medial

$\Sigma F_y = 0: \quad F_{Py} + F_{4y} + F_{out\,y} = 0 \quad (9)$

- From eq. (7) $\Rightarrow$ $F_{4y} = 20.5$
- From eq. (6) $\Rightarrow$ $F_{Py} = 0$
- From eq. (9) $\Rightarrow$ $F_{out\,y} = 20.5$

$F_{out} = \sqrt{(1.5)^2 + (20.5)^2} = \sim 20 N$

This calculation was done at the largest grip envelope, when the wrist has been flexed to 45 degrees and the fingers begin to return to the closed position. This position is where the grip force would be a maximum. This calculation assumes a change in cable length of 1.5 cm or 0.6 inches. Persons with smaller hands would obviously generate less force in this design as the spring would not compress at far for the same 45 degrees of flexion. Therefore, it is expected for this maximum calculated force of 20 N to be lower for most users. This calculation serves the purpose of proving that a force of 20 N can be produces through this design. Additionally, the calculation serves the purpose of showing that a spring constant of approximately 7.5 lbs/in would be sufficient. McMaster Carr sells springs of 1 inch or less that have a spring constant near this value. Therefore, springs could be purchased for the manufacture of this design and there would be no need to manufacture custom springs.

Appendix I: Testing Protocol

Evaluation of Functional Requirements

Power Grip Envelope Test: With device on, have the user flex wrist, while seated, to form power grip around a cup (approximately 90 mm in diameter) on a tabletop. Next, have the user again flex wrist, while standing, to form power grip around a railing (approximately 30 mm in diameter). This test is meant to determine how well the device allows the user to form an adequate power grip envelope. This test will also potentially show how easily one can use the device, and if they can perform these tests using only the hand with the device on it (after thumb has been positioned). Note that this test does not require the user to pick up objects or perform tasks as these capabilities will be evaluated in additional tests.

Functional Requirement(s): 1, 4, 7, 8

Steps:

- Step 1: Don device
- Step 2: Move thumb into position 1 (power grip position) using contralateral hand
- Step 3: Flex wrist to close fingers and form grip around cup on tabletop
- Step 4: Extend wrist to return to neutral position
- Step 5: Move to railing, flex wrist to close fingers and form grip around railing
- Step 6: Extend wrist to return to neutral position

Evaluation: Observation and Survey Questions

	User 1	**User 2**	**User 3**
Was user able to form grip around cup? (Yes/No)			
Did the user appear to struggle in any way? How so?			
Was user able to form grip around railing? (Yes/No)			
Did the user appear to struggle in any way? How so?			

Table 39: Power Grip Envelope Test - Blank

a. Did you experience any difficulty forming a grip around the cup or railing? Explain.

b. How do you feel about using your wrist to move your fingers?

c. Do you feel you could learn to use the device better over time?

d. How long do you think it might take you to get used to using the device?

Pincer Grip Envelope Test: With device on, have user flex wrist, while sitting, to form pincer grip around a plastic egg (approximately 45 mm in diameter) on a tabletop. Next, have user form pincer grip, while sitting, around a pen (approximately 7.5 mm in diameter) located on table top. This test is meant to determine how well the device allows the user to form an adequate pincer grip envelope. Note that this test does not require the user to pick up objects or perform tasks as these capabilities will be evaluated in additional tests.

Functional Requirement(s): 1, 2, 7, 8

Steps:

- Step 1: Don device
- Step 2: Move thumb into position 2 (pincer grip position) using contralateral hand
- Step 3: Flex wrist to close fingers and form grip around plastic egg on tabletop
- Step 4: Extend wrist to return to neutral position
- Step 5: Move hand towards pen, flex wrist to close fingers and form grip around pen on tabletop
- Step 6: Extend wrist to return to neutral position

Evaluation: Observation and Survey Questions

	User 1	User 2	User 3
Was user able to form grip around plastic egg? (Yes/No)			
Did the user appear to struggle in any way? How so?			
Was user able to form grip around pen? (Yes/No)			
Did the user appear to struggle in any way? How so?			

Table 40: Pincer Grip Envelope Test - Blank

a. Did you experience any difficulty forming a grip around the plastic egg or pen? Explain.

Power and Pincer Grip Force Test: This test seeks to evaluate if the device can produce 20 N of force in both the power and pincer grips.

Functional Requirement(s): 3, 5

Steps:

- Step 1: Don device
- Step 2: Move thumb into position 1 (power grip position) using contralateral hand
- Step 3: Flex wrist to close fingers in power grip on force sensing device
- Step 4: Record value

- Step 5: Extend wrist to move fingers back to neutral position
- Step 6: Move thumb into position 2 (pincer grip position) using contralateral hand
- Step 7: Flex wrist to close fingers in pincer grip on force sensing device
- Step 8: Record value
- Step 9: Repeat multiple times

Evaluation:

Ease of Don/Doff Test: This test will be used to determine how easily the device can be donned and doffed by a user. This test will be timed to evaluate the ease of donning and doffing the device for multiple users. Users will also be able to practice donning and doffing the device 5 times to become comfortable before the test begins.

Functional Requirement(s): 9

Steps:

- Step 1: Have user don device (begin timer)
- Step 2: Stop timer and record time when device is donned properly
- Step 3: Have user doff device (begin timer)
- Step 4: Stop timer and record time when device is doffed properly
- Step 5: Repeat test 5 times (The initial 5 practices do not count towards the results as the user is just learning to use the device.)

Evaluation: Timed Measurement and Survey Questions

	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**
Time to Don Device (s)					
Time to Doff Device (s)					

Table 41: Ease of Don/Doff Test - Blank

a. Describe any difficulties you experienced while donning/doffing the device?

b. Do you feel that donning/doffing the device became easier each time?

c. Is there anything that could make the device easier for you to don/doff?

Extended Use Test: Have person wear device around for extended period of time (preferably for 8 hours). This test will be used to determine possible areas on the user’s hand or wrist that could become irritated or sore from wearing the device. This test will also serve to measure the usability of the device throughout a user’s day, understand what tasks the user had difficulty completing, what tasks the user was able to do with the device on, and the user’s feelings about the aesthetics of the device.

Functional Requirement(s): 10

Steps:

- Step 1: Don device
- Step 2: Wear device for extended period (8 hours) using it to perform all possible tasks throughout day
- Step 3: Doff device

Evaluation: Survey – Given after 8 hours of wearing device

The device can be evaluated for meeting the Design Specifications mostly through measurement and examination. For example, the weight of the device and any protrusions on the device can easily be measured with a scale and a ruler. Cost can also easily be evaluated once the final prototype has been manufactured. Design Specifications 8 and 9 (water resistant and withstanding a drop of 1.5 m) will require additional tests, however.

Evaluation of Design Specifications

Device Weight Test: The final device will be weighed to test whether or not it meets the requirement outlined in Design Specification 3. The first test will weigh the entire device and the second test will weigh just the components that would sit atop the hand.

Design Specification(s): 3

Steps:

- Step 1: Zero scale
- Step 2: Place device on scale
- Step 3: Record Measurement

Evaluation: Scale Measurement

	Entire Device	**Hand Pieces**
Mass (g)		
Weight (lb)		

Table 42: Device Weight Test - Blank

Cost to Construct the Device: The amount of money used to manufacture the final prototype as well as the total amount of money used throughout the project will be added up.

Design Specification(s): 5, 6

Steps:

- Step 1: List all materials and costs in table
- Step 2: Sum all costs

Evaluation: Addition of Costs

All Prototypes				Final Prototype			
Part	**Qty.**	**Price/Qty.**	**Cost ($)**	**Part**	**Qty.**	**Price/Qty.**	**Cost ($)**
		Total:				**Total:**	

Table 43: Cost Evaluation - Blank

<u>Device Drop Test:</u> The final device will be dropped from a height of 1.5 meters onto a hard surface to determine if it can withstand drops as outlined in Design Specification 9.

Design Specification(s): 9

Steps:

- Step 1: Hold device 1.5 meters above hard surface
- Step 2: Drop device
- Step 3: Examine for any broken pieces
- Step 4: Repeat 5 times

Evaluation: Observation – We will observe the device during and after each drop to make sure no parts are broken or deformed.

<u>Device Protrusion Measurement Test:</u> All protrusions on the device will be measured using a ruler or set of calipers to determine if the device meets Design Specification 10 which says that no protrusions should be larger than 3 cm. For this test, we consider a protrusion to be anything extending above the envelope of the metacarpal piece or forearm piece, as well as anything extending outside the forearm or hand in the longitudinal direction.

Design Specification(s): 10

Steps:

- Step 1: Examine device for any protrusions
- Step 2: Measure protrusion and record value
- Step 3: Repeat until all protrusions have been measured

Evaluation: Length Measurement

	Protrusion 1	**Protrusion 2**	**Protrusion 3**
Description/Location			
Length (cm)			

Table 44: Protrusion Measurement – Blank

Design Specifications 7 and 8 have been met as the materials used for the device were selected to meet these requirements. The remaining Design Specifications (1, 2, 4) will be evaluated by the group members through examination after designing and developing a working device. For example, the group members can determine if the orthosis can easily be made to fit various hand sizes. Also, the group members can determine if special tools would be required for maintenance.

Appendix J: Testing Results

Power Grip Envelope Test Results:

Table 45: Power Grip Envelope Test Results

	Tyler
Was user able to form grip around cup? (Yes/No)	Yes
Did the user appear to struggle in any way? How so?	The user was only able to achieve approximately 80 mm. However, this is due to smaller hands rather than device limitations
Was user able to form grip around the roll of tape (30 mm diameter)? (Yes/No)	Yes
Did the user appear to struggle in any way? How so?	The user showed difficulty picking up the roll of tape unless it was elevated or moved to the edge of the table.

Pincer Grip Envelope Test Results:

Table 46: Pincer Grip Envelope Test Results

	Tyler
Was user able to form grip around roll of tape (45 mm diameter)? (Yes/No)	Yes
Did the user appear to struggle in any way? How so?	No, there was no signs of struggle seen
Was user able to form grip around pencil? (Yes/No)	Yes
Did the user appear to struggle in any way? How so?	The user had difficulty picking up the pencil unless it was elevated or moved to the edge of the table.

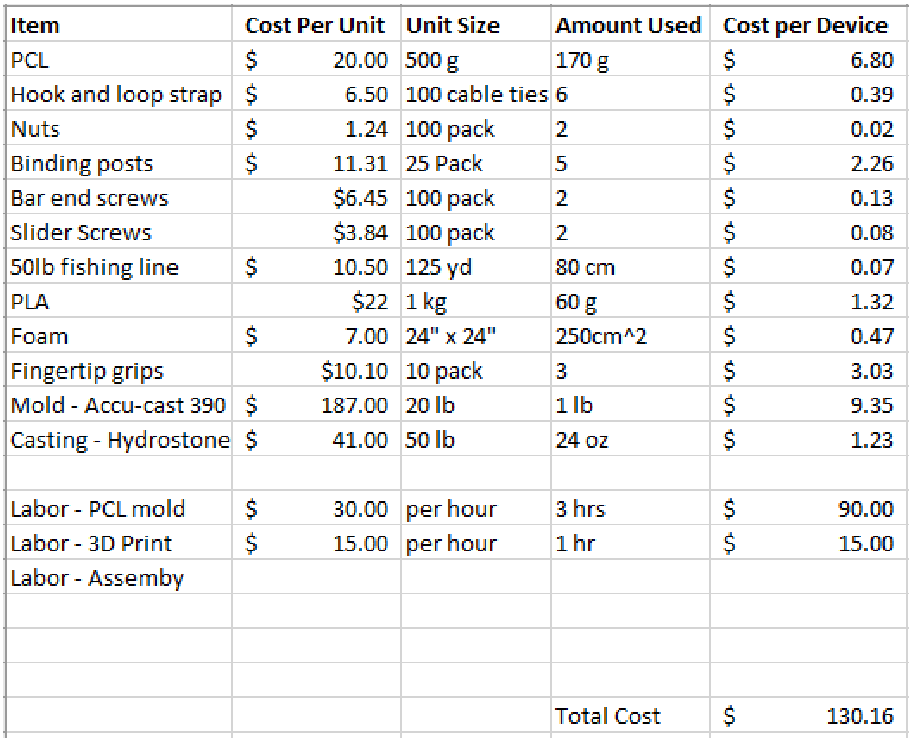
Don/Doff Test Results:

Table 47: Don/Doff Test - Results

User: Tyler	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Average**
Time to Don Device (s)	37	47	37	32	37	38
Time to Doff Device (s)	23	23	23	21	22	22

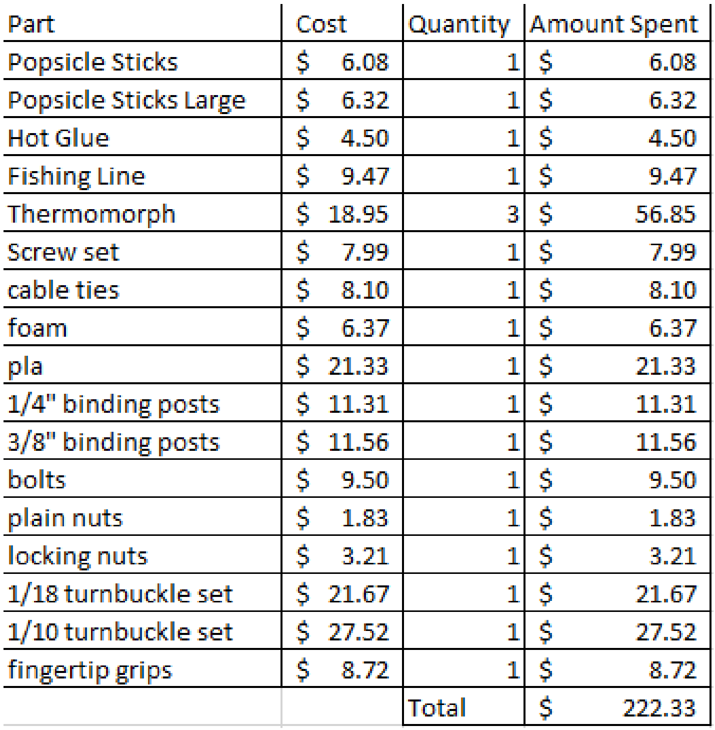
Cost to Construct Results:

Table 48: Cost to Produce Final Prototype – Results (Detailed)



Item	Cost Per Unit	Unit Size	Amount Used	Cost per Device
PCL	$ 20.00	500 g	170 g	$ 6.80
Hook and loop strap	$ 6.50	100 cable ties	6	$ 0.39
Nuts	$ 1.24	100 pack	2	$ 0.02
Binding posts	$ 11.31	25 Pack	5	$ 2.26
Bar end screws	$6.45	100 pack	2	$ 0.13
Slider Screws	$3.84	100 pack	2	$ 0.08
50lb fishing line	$ 10.50	125 yd	80 cm	$ 0.07
PLA	$22	1 kg	60 g	$ 1.32
Foam	$ 7.00	24" x 24"	250cm^2	$ 0.47
Fingertip grips	$10.10	10 pack	3	$ 3.03
Mold - Accu-cast 390	$ 187.00	20 lb	1 lb	$ 9.35
Casting - Hydrostone	$ 41.00	50 lb	24 oz	$ 1.23
Labor - PCL mold	$ 30.00	per hour	3 hrs	$ 90.00
Labor - 3D Print	$ 15.00	per hour	1 hr	$ 15.00
Labor - Assemby				
			Total Cost	$ 130.16

Table 49 Total cost of all materials ordered



Part	Cost	Quantity	Amount Spent
Popsicle Sticks	$ 6.08	1	$ 6.08
Popsicle Sticks Large	$ 6.32	1	$ 6.32
Hot Glue	$ 4.50	1	$ 4.50
Fishing Line	$ 9.47	1	$ 9.47
Thermomorph	$ 18.95	3	$ 56.85
Screw set	$ 7.99	1	$ 7.99
cable ties	$ 8.10	1	$ 8.10
foam	$ 6.37	1	$ 6.37
pla	$ 21.33	1	$ 21.33
1/4" binding posts	$ 11.31	1	$ 11.31
3/8" binding posts	$ 11.56	1	$ 11.56
bolts	$ 9.50	1	$ 9.50
plain nuts	$ 1.83	1	$ 1.83
locking nuts	$ 3.21	1	$ 3.21
1/18 turnbuckle set	$ 21.67	1	$ 21.67
1/10 turnbuckle set	$ 27.52	1	$ 27.52
fingertip grips	$ 8.72	1	$ 8.72
		Total	$ 222.33

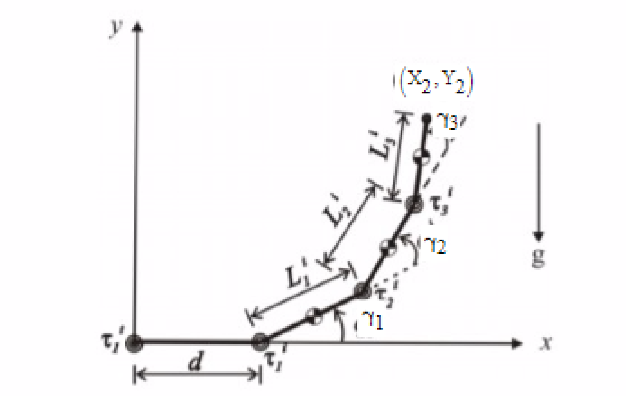
Appendix K: 2D Position Analysis

Kinematics of Hand System

I based the following calculations off of the 2D Index finger and thumb model derived in Chen, 2008. The primary assumptions are:

1. The 2D model accurately relates the desired movement of the hand
2. The thumb moves as a 2 Joint linkage
3. The Coordinate system is centered on the joint between the thumb metacarpal and metacarpal with the positive X along the metacarpal and positive Y in the direction of the inside of the hand.

Analysis of the Metacarpals, proximal, medial, and distal Phalanges



Solving for position of the Index/ pointer

Given

Solving for:

$\gamma_2 := 70\text{deg}$	Estimate Joint 2 angle (Variable)
$\gamma_1 := 20\text{deg}$	Joint 1 Angle of Proximal , Fixed
$\gamma_3 := 40\text{deg}$	Joint 3 angle (Held Constant)
$d := 6.8\text{cm}$	Metacarpal Length
$l_1 := 2.5\text{cm}$	Length of Proximal Segment
$l_2 := 1.9\text{cm}$	Length of Medial Segment
$l_3 := 1.7\text{cm}$	Length of Distal Segment
$X := 8\text{cm}$	Location of Finger Tip (X)
$Y := 8\text{cm}$	Location of Finger Tip (Y)

Forward Kinematics

$$X(\gamma_2) := d + l_1 \cdot \cos(\gamma_1) + (l_2) \cdot \cos(\gamma_2 + \gamma_1) + (l_3) \cdot \cos(\gamma_3 + \gamma_2 + \gamma_1)$$

$$Y(\gamma_2) := l_1 \cdot \sin(\gamma_1) + (l_2) \cdot \sin(\gamma_2 + \gamma_1) + (l_3) \cdot \sin(\gamma_3 + \gamma_2 + \gamma_1)$$

The forward kinematic equations as a function of γ_2 yields the coordinates of the finger tips

$Z := 0\text{deg}, 10\text{deg} .. 90\text{deg}$

X(Z) =		Y(Z) =	
11.785	cm	2.977	cm
11.376		3.403	
10.9		3.751	
10.371		4.011	
9.804		4.175	
9.218		4.238	
8.629		4.198	
8.056		4.057	
7.517		3.819	
7.027		3.49	

These are the location in the defined X,Y plane of the finger tips for a rotation from 0 to 90 degrees.

Analysis of the Thumb Location

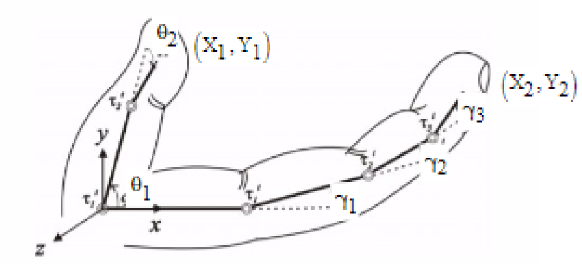


Figure 1. Schematic Diagram of Thumb and Index Finger

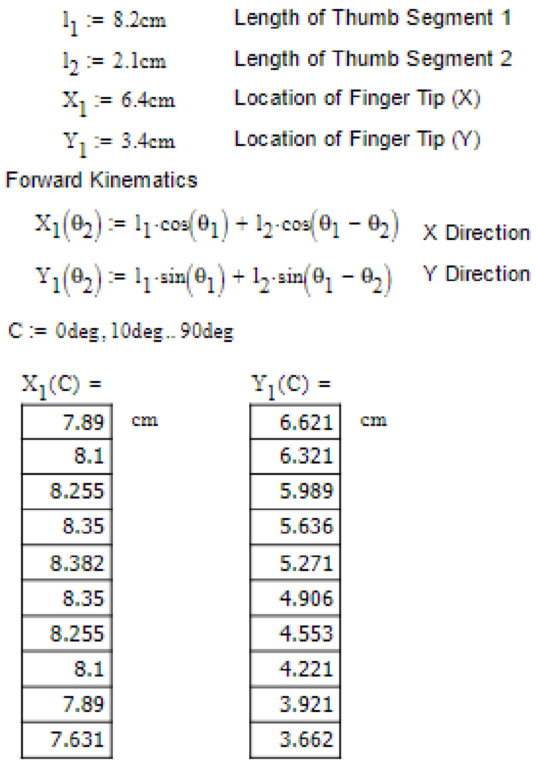
Solving for the position of the Thumb

Solving for:

$\theta_1 := 40\text{deg}$ Fixed Joint 1 Angle

$\theta_2 := 60\text{deg}$ Estimate Joint 2 angle

Constants



$l_1 := 8.2\text{cm}$ Length of Thumb Segment 1

$l_2 := 2.1\text{cm}$ Length of Thumb Segment 2

$X_1 := 6.4\text{cm}$ Location of Finger Tip (X)

$Y_1 := 3.4\text{cm}$ Location of Finger Tip (Y)

Forward Kinematics

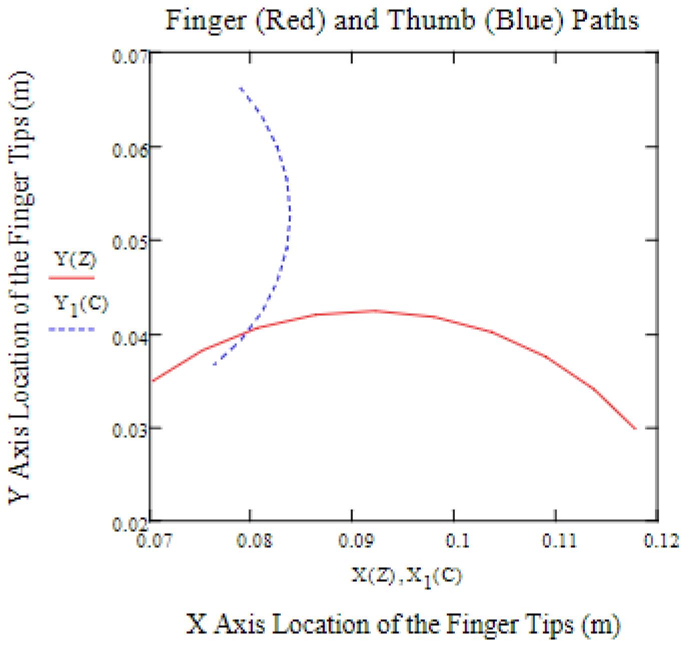
$X_1(\theta_2) := l_1\cdot\cos(\theta_1) + l_2\cdot\cos(\theta_1 - \theta_2)$ X Direction

$Y_1(\theta_2) := l_1\cdot\sin(\theta_1) + l_2\cdot\sin(\theta_1 - \theta_2)$ Y Direction

$C := 0\text{deg}, 10\text{deg}..\,90\text{deg}$

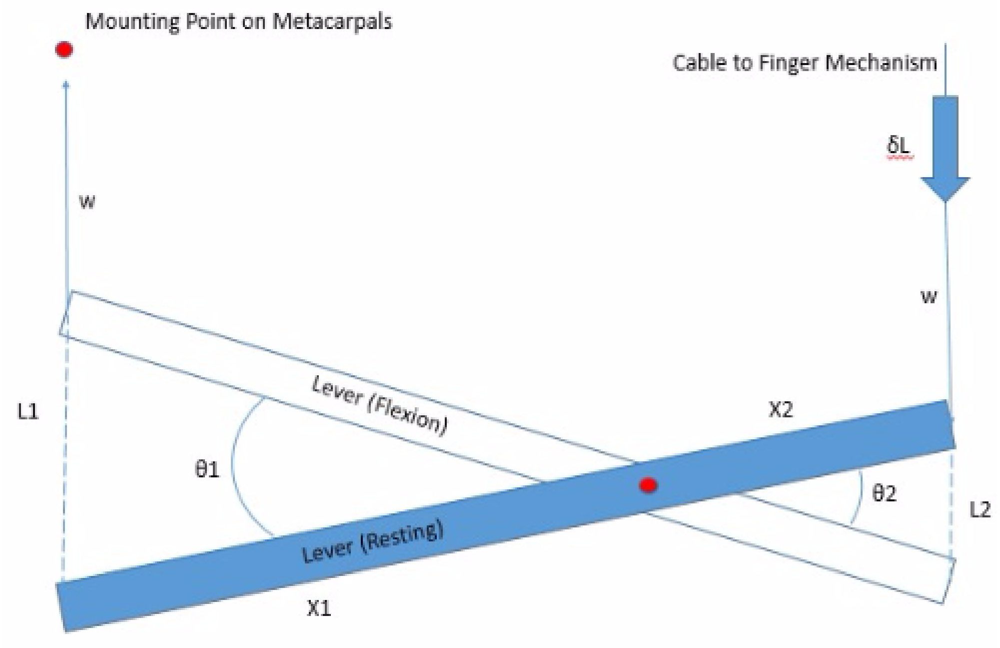
$X_1(C) =$ (cm)	$Y_1(C) =$ (cm)
7.89	6.621
8.1	6.321
8.255	5.989
8.35	5.636
8.382	5.271
8.35	4.906
8.255	4.553
8.1	4.221
7.89	3.921
7.631	3.662

Graphing both the equations for the fingers(Red) and the thumb (Blue) locations, we find the point of intersection where the index finger will meet the thumb. This proves that the devices movement can support the pincer grip. This intersection occurs when the fingers are bent about 75 Degrees and the thumb is bent about 85 Degrees.



Appendix L: Force Analysis

This analysis looks finds the minimum wrist deflection in order to achieve the desired force in the hand Orthosis device.



Variable Definitions:

$\delta L := .7\text{cm}$	the total amount of change in distance necessary to rotate the finger mechanism 90 degrees. This value was found in the design of the finger mechanism
$M := 3$	The lever ratio (mechanical advantage) used to generate the requisite amount of tension in the finger mechanism. For the lever, the Mechanical Advantage is equal to the length of the left side of the lever (X1) over the length of the right side of the leve (X2)
$w := 1\text{cm}$	The change in length of the string when running over the wrist. This applies to both sides of the lever since the cable runs over the wrist in 2 locations. This problem uses 1cm as the estimate value for evaluation
$L_1 := w$	L1 is the vertical displacement of the lever's left side. This value is equal to the change in length of the cable due to the wrist (w) since it is the driving factor in this model.
$L_2 := \frac{L_1}{M}$	The total linear displacement of the right side of the lever based on the ratio of the longer lever ratio over the mechanical advantage.

X_1	The length of the left side of the lever (longer side); to be solved for based on final val of w
X_2	The length of the right side of the lever (shorter side); to be solved for based on final value of w
θ_1	The angle of rotation of the left side of the lever.
θ_2	The angle of rotation of the right side of the lever.

Solving for the minimum required wrist deflection

Given

$L_2 = (w - \delta L)$ Equation based on the geometric constraints shown in figure 1

$\mathrm{Find}(w) = 1.033 \cdot \mathrm{cm}$ w represents the minimum amount of wrist movement necessary to rotate the finger mechanism 90 degrees.

$w := 1.033\mathrm{cm}$

Determining Length of the Lever

In order to determine the overall length of the bar, set the Theta values to the maximum and minimum values.

Maximum angle is limited to 90 degrees since it is the largest theta that generates a pure linear vertical movement.

$L_1 := w$

$\theta_1 := 90\mathrm{deg}$

Using the Law of Sines:

$$X_1 := \frac{L_1 \cdot \sin\left(\frac{180 - \theta_1}{2}\right)}{\sin(\theta_1)}$$

$$X_2 := \frac{X_1}{M}$$

Defining the length of the smaller lever segment in terms of the mechanical advantage of the Lever.

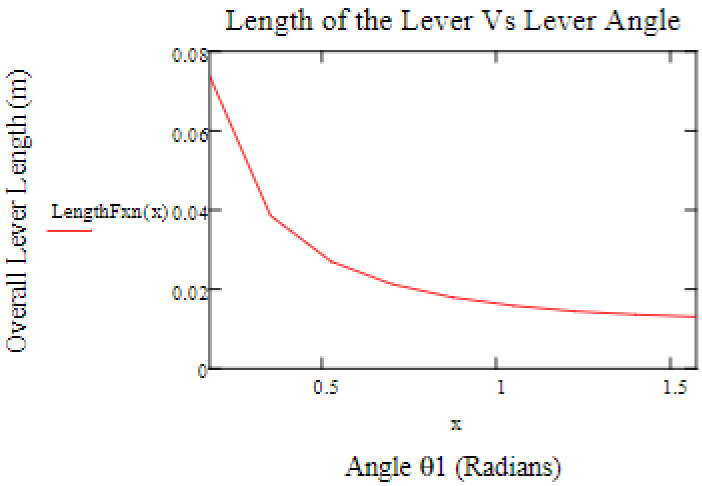
$\mathrm{LeverLength} := X_1 + X_2 = 1.307 \cdot \mathrm{cm}$ Overall Lever Length based on these conditions

$$\mathrm{LengthFxn}(x) := \frac{L_1 \cdot \sin\left(\frac{180 - x}{2}\right)}{\sin(x)} \cdot \left(\frac{4}{3}\right)$$

Equation to find the total bar length based on the angle of θ1 x := 10deg,20deg..90deg

LengthFxn(x) =

7.374	·cm
3.859	
2.698	
2.128	
1.797	
1.588	
1.45	
1.361	
1.307	



Based on this information, the total length of the bar can range from a minimum of 1.3cm to 7.4 cn based on the desired maximum desired θ1 vale