Additions and Improvements to the Mechanical Design of the FINGER Exoskeleton

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Authorization to Submit Thesis

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Abstract

Rehabilitation robots are important tools for post stroke movement training and efficacy quantification. The Finger INdividuating Grasp and Exercise Robot (FINGER) is a robotic exoskeleton designed to administer and study finger movement training. Developed nearly a decade ago and used for numerous investigative studies, the FINGER exoskeleton is currently in the process of being updated. This thesis covers design improvements to the FINGER 8-bar mechanisms, development of novel finger cuffs, and initial solid-model design prototyping of a spherical 5-bar mechanism for thumb training.

The 8-bar mechanisms that FINGER uses to actuate the index and middle fingers were redesigned with thicker links to increase rigidity and to reduce high stress concentrations. The joints of the mechanism were modified to use larger bearings with an extended inner race, allowing them to be easily spaced without the need for shims. The mechanism was also modified to extend an additional fifteen degrees to allow the user to fully open their index and middle fingers.

Feedback from patients and clinicians about the fit and function of FINGER has been used to redesign the finger cuffs to be more comfortable, and to be easier to don and doff. This was achieved by adding BOA® ratchet dials which use braided metal cables that size the cuffs; the cables loop over a hook on the opposite side. The cable is covered by a leather strap which increases comfort, keeps the cable properly aligned, and prevents direct contact between the cable and the skin.

Thumb trajectory information, recorded using a marker-based motion capture system, was used for the kinematic design of a spherical 5-bar mechanism. This mechanism will be actuated by the same linear actuators as FINGER, which are fixed to a platform on which FINGER is secured. A proposed design, including the location of these actuators, is presented. The thumb is connected to the mechanism through a cuff with a BOA® dial and a leather strap, similar to the finger cuffs. The thumb cuff rotates freely so the thumb can assume a comfortable orientation.

Acknowledgements

I would like to acknowledge all those who have helped me throughout the course of my graduate studies. I would like to thank Dr. Wolbrecht, my major professor, Dr. Perry, and Dr. Odom for their assistance and guidance over the course of both my graduate and undergraduate studies. I would like to thank Vish Ketkar, my research partner, as well as the members of the Blue Sabino research group, who have made working on the project a joy. I would also like to thank Dr. Odom's ME 504 class for the spring of 2020, as well as Selso Gallegos, for their assistance on making drawings and machining links for the updated FINGER robot.

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Dedication

This thesis is dedicated to my family and friends, without whose support I would have never made it this far.

Table of Contents

Table of Figures

Chapter 1: Introduction

1.1: Background

An estimated 7.2 million Americans over the age of 20 have suffered a stroke, and this number is predicted to rise by an additional 3.4 million by 2030 [1]. In the United States it is estimated that 795,000 people experience a stroke each year. Recent medical advances have reduced the mortality rates of stroke; between 2005 and 2015 stroke deaths fell 2.3%, while the age-adjusted death rate decreased by 21.7% [1]. Stroke is a leading cause of long-term adult disability worldwide, and with increasing survival rates the need for low-cost, comprehensive patient rehabilitation is growing [2].

A common side effect of stroke is impairment of upper-limb motor control. The severity of the impairment can be lessened with rehabilitative therapy, which is more effective in the acute stage of recovery (<6 months) [2]. There is strong evidence that task-oriented training greatly improves recovery [2], and stroke rehabilitation seems to be most effective when the patient shows high levels of engagement and motivation with the rehabilitation process [3]. Furthermore, the process of setting relevant goals for the patent is an essential part of the recovery process [3] [4]. Comprehensive stroke rehabilitation is an expensive and time-consuming process, which requires trained therapists to oversee recovery and assist with training.

1.2: Robotic Stroke Rehabilitation

Recent research has demonstrated the potential to offload some of the post stroke therapy work from clinicians to robotic devices. Robotic-assisted training has been shown to be as good as, or in some cases marginally better than standard training methods [5]. Robotic devices can automate the repetitive aspects of therapy and can also be used as scientific instruments to study the factors influencing functional recovery. The use of robots alongside standard training methods can help clinicians work with several patients at the same time, or even allow patients to train at home [6]. It has been shown that neuroplasticity (reorganization of neural connections, pathways, and function) occurs when patients repeat movements more than 300 times a day [7]. Patients benefit from increased movement repetitions during a standard one-hour physical training session as long as a therapist or robotic device can mitigate fatigue and discomfort while encouraging patient involvement [8][9]. The optimal number of repetitions can be more easily met, and exceeded, using robot assisted therapy. One study [10] showed that patients could perform, on average, 734 movements in a single session while retaining patient involvement. This large increase in movement repetition has been shown to be safe [8][11]. Using robot-assisted therapy in this way can help patients, and their attending therapists, retain their strength throughout a day of training, allowing them to maximize physical training in during their recovery.

In rehabilitation applications exoskeleton robots typically attach to the user and can actuate and/or record the position of the limb. Use of exoskeleton robots can provide quantifiable data related to patient impairment and recovery, data which previously has been difficult for clinicians to obtain [5]. Hand exoskeletons play a critical role in rehabilitation, as regaining finger dexterity allows patients to resume the activities-of-daily-living (ADLs). Hand exoskeletons may be generally classified as rigid or soft. Rigid exoskeletons use rigid links to transfer the motion of an actuator to the fingers of the hand. Soft exoskeletons use pneumatics or cables to drive soft robotic systems. Some devices incorporate both rigid and soft elements; for a review of hand and wrist exoskeletons, see [12] and [13].

Rigid exoskeletons are the most common forms of rehabilitative exoskeleton. The rigid links of the exoskeleton are typically attached to the back of the user's hand, leaving the fingertips and palm free to feel and interact with objects. Rigid mechanisms need to match their centers of rotation to the joints of the finger to prevent injury to the user. This can be achieved using a mechanism that aligns its rotation axes with each finger joint. However, this requires the mechanism to be on the side of the finger, which makes actuating multiple fingers a crowding challenge [12]. An example of a robot that uses the finger's centers of rotation is the HANDEXOS robot, detailed in [14]. Another option is to create a remote center mechanism at each finger joint. This approach requires space behind the user's hand to create a mechanism that rotates around the same axes as the fingers. A robot that uses this method is described by Ueki et al. in [15].

Soft robots use flexible materials that can bend and move to organically match the user's movement. The use of flexible materials removes the need to match the center of rotation of the user's hand. These can be actuated by cable, pneumatics, or hydraulics and are commonly attached to the back of a glove [13]. Cable driven soft robots use actuators to drive cables which are routed through, or around, a glove, similar to the HANDEXOS robot, but without the rigidity of the metal components. Pneumatic or hydraulic driven exoskeletons use the deflation or inflation of custom-made inflatable actuators. These inflatable actuators are designed to expand/contract through a specific motion [13]. The Wyss Institute glove [16] uses pneumatic actuation to allow the finger to flex naturally.

1.3: The FINGER Rehabilitation Device

The Finger INdividuating Grasp and Exercise Robot (FINGER) is a rigid exoskeleton designed to assist with grasp training. The robot consists of two single-degree-of-freedom 8-bar mechanisms that attach to the back of the index and middle fingers. Each mechanism is driven using a Servo Tube Dunkermotoren STA1116-168-S03C linear actuator, which is highly backdriveable and directly force controllable [17]. Each mechanism has two finger cuffs, which attach to the proximal and middle phalanges of a user's finger. The proximal cuff is rigidly mounted to the mechanism, while the middle cuff rotates to match the angle of the user's finger as their hand closes. There are three existing variations of FINGER, one of which includes single axis load cells, located between the finger cuffs and the output links of the mechanisms, to measure the forces between the mechanism and the user's finger.

FINGER has been used in several studies and has been shown to be a useful tool for varied task assistance [18], proprioception assessment [19], strength testing [20], and assist-as-needed control [21]. FINGER was initially tested using a computer game similar to *Guitar Hero,* in which patients were prompted to hit a note by moving their index, middle, or both fingers to a specific position at a specific time. The study showed that patients that used FINGER improved significantly, and that more severely impaired individuals improved the most [18]. Another study, involving 37 participants ranging from 22 – 87 years of age [19], used FINGER as a proprioception assessment device. It was found that the older participants had trouble with proprioception when they could not see their fingers. Another use for FINGER is in patient strength testing. FINGER was used in [20] to measure the maximum voluntary contractions of 26 individuals who had suffered from chronic stroke. The study found that the product of finger strength and individuation, referred to as finger capacity, is a strong indicator of hand function. Assist-as-needed control systems can be used alongside FINGER to improve patient participation. This was shown in [21] where four healthy, unimpaired, subjects attached to FINGER attempted to match their finger position to a graphic of their fingers on a screen. The study showed that the controller could be tailored to individuals, allowing FINGER to adjust the amount of assistance it provides to increase participation.

This thesis presents design improvements to the existing FINGER robot and preliminary work on the addition of a thumb training exoskeleton to be used be used in conjunction with FINGER. The work is presented in three main chapters: the FINGER mechanism improvements, the finger cuff redesign, and the thumb module addition. The mechanism design improvement chapter includes details regarding improved strength, stiffness, and durability and an increased range-of-motion in extension. The finger cuff redesign chapter presents a paper submitted to the International Conference on Intelligent Robots and Systems (IROS) 2020 conference about the creation of a comfortable and easy to use finger cuff. The thumb module addition chapter describes the prototype design of a spherical five-bar mechanism that adds thumb training to the existing FINGER robot.

Chapter 2: FINGER Design Improvements

2.1: Introduction

The FINGER mechanism has been used in several studies with those who have suffered a stroke [17]–[20], [22]. Repeated use of FINGER has caused significant wear and tear on the mechanism and other components and has highlighted some areas for improvement. Both clinicians and patients have provided feedback regarding the fit and function of the FINGER device. Using the information collected from this feedback helped identify two categories for improving the FINGER Design. The first category was mechanism quality (rigidity, durability, backdriveability, and smoothness); the second category was patient-robot connection (donning and doffing, finger-cuff comfort, and general

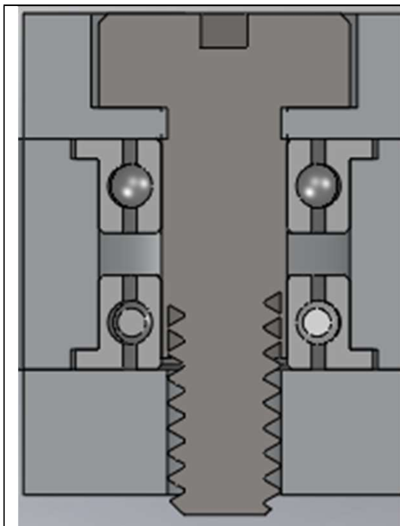
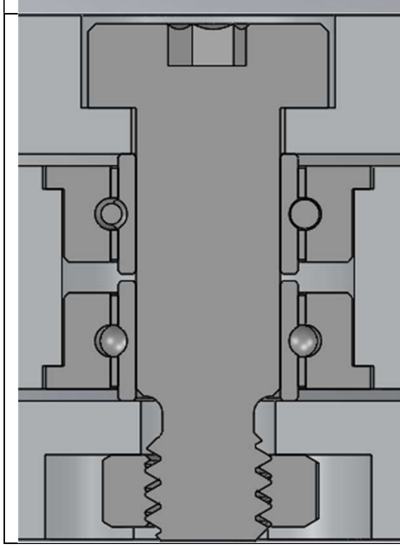
	Original Joint Design: Inner and outer links are connected at rotation axes using two ABEC-5 rated flanged bearings (McMaster number 57155k205). These bearings have a flanged diameter of 0.296 in., an outer diameter of 0.25 in., an inner diameter of 0.125 in., and are 3/32 in. thick. The joint is held together using a flathead 1/8 in. precision shoulder bolt which threads into the bottom link. The outer and inner links are separated by a single 316 stainless steel shim, 0.01 in. thick (not shown). The top and bottom links of these joints are 0.13 in. thick. The inner link has a thickness of 0.23 in. and contains the two press fit bearings.
	Updated Joint Design: Inner and outer links are connected at rotation axes using two ABEC-5 rated flanged bearings with extended inner rings (McMaster number 57155k335). These bearings have a fanged diameter of 0.422 in., and outer diameter of 0.375 in., an inner diameter of 0.1875 in., the bearing is 1/8 in. thick, and the inner race is 0.156 in. thick. The joint is held together using a 0.1875 in. precision shoulder bolt, which is threaded into a nut that fits in a slot machined into the lower outer link. The top and bottom outer links are 0.18 in. thick, and the inner link is 0.29 in. thick and contains the two press fit bearings.

Figure 2.1: Section views of the original and updated versions of the FINGER mechanism joints. The top row shows the original version of the joint, which is currently in use on FINGER. The bottom row shows the updated design which strengthens and stiffens the mechanism joints.

Figure 2.2: Damaged links on the FINGER robot. The link showing wear on the right was missing a shim and the bearing and was rubbing against the nearby links.

patient comfort). This chapter describes the efforts made to improve the mechanism quality (strength, stiffness, and durability) of the FINGER robotic device and to increase the range-of-motion during finger extension.

2.2: FINGER Mechanism Update

Through repeated use of the FINGER robot, several areas for improvement have become apparent. There have been several cases of bearings wearing out and needing to be replaced throughout the mechanism. Furthermore, one of the FINGER robots had a base link break on one of the mechanisms. These issues were addressed by modifying the existing links to use larger bearings that have an extended inner race, and by thickening the mechanism links and removing areas of high stress concentration.

The bearings used on the existing FINGER mechanism are shown in the top row of Figure 2.1. The small size of the shims used to separate links makes them difficult to properly place, and their size makes them easy to lose. Inspection of the FINGER robot used in this research found that several joints were missing shims, increasing the wear on these links considerably (Figure 2.2). To remedy this problem the bearings were replaced with larger flanged bearings with extended inner rings (see Figure 2.1). The new bearings are significantly thicker (133%) than the previous bearings. The raised inner race of the bearing eliminates the need to use shims and reduces the play in each joint. To incorporate these larger bearings the mechanism was redesigned to be both wider and thicker (Figure 2.3). Additional design modifications were included to increase durability.

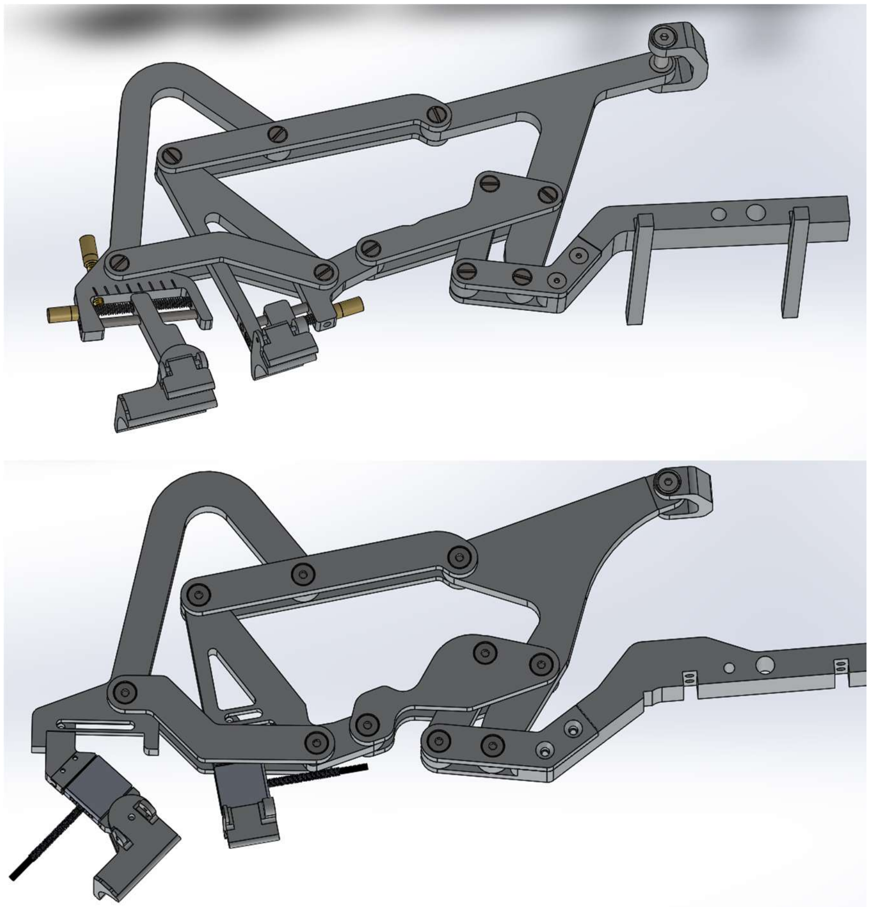


Figure 2.3: The original mechanism (Top) and the modified mechanism (bottom). The modified mechanism has larger bearings and wider links and has been modified to include load cells.

The 8-bar-mechanim design was further modified to increase the range of motion during finger extension. During testing of opening the hand fully to record thumb data it was found that an additional fifteen degrees of motion allows for a more natural open palm. The design of the base link was modified to allow an additional fifteen degrees of extension, allowing the user's hand enough range of motion to fully open their palm. The angle change required the base links to be moved back towards the forearm, so the mechanisms stay roughly in the same location (Figure 2.4). The new design was validated using 3D printed prototypes of the base link to determine if the change was comfortable.

The existing FINGER robot was upgraded to include load cells, similar to the design of another version of FINGER. The existing model uses two 25-pound FUTEK LSB200 load cells. These load cells have been discontinued by FUTEK, and their new version is significantly more expensive, has

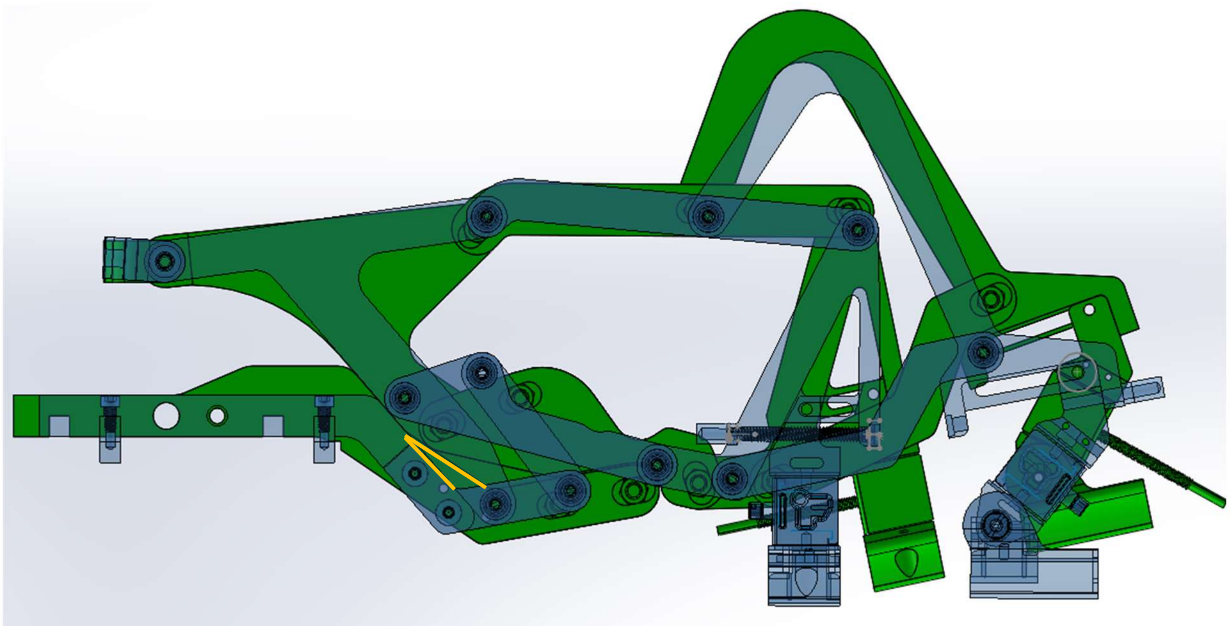


Figure 2.4: This image shows the old and the new mechanisms overlapping. The green mechanism represents the new design, while the transparent blue represents the original mechanism. The fifteen degree change is shown by the yellow lines.

metal housings with increased thickness causing them to interfere with the surrounding links, and uses a proprietary cable designed to work only with their amplifier. Due to these changes an alternative load cell was sourced. The selected load cell is the 25-pound LSB miniature s-beam force sensor by Flintec. These load cells are similar to the old FUTEK design and were easily adapted to suit the new mechanism design. The load cell mounting points were changed to work with the new thickness, while keeping the attachment to the finger cuffs the same as the old thickness.

2.3: Mechanism Analysis

In one of the FINGER robots, the base link of a mechanism failed across the counterbored holes for the mounting bolts. To remedy this, the counterbores were removed, and the mechanism was strengthened across the weak point. Finite element analysis (FEA) was performed on each version of the links to highlight the weak points of the old design, and to demonstrate how the new design improves the strength of the link.

To begin the analysis, the mechanism was imported into the Synthesis and Analysis of Mechanisms (SAM) software. This import was performed by members of Dr. Edwin Odom's ME 504 class during the Spring semester of 2020. The SAM model was then used, along with the data recorded by [23], to estimate the load applied to the base link. These data show that the proximal and middle load cells experience a similar 5 lb force in opposite directions (Figure 2.6). This information was applied to the SAM model along with a 10 lb force applied at the actuator pivot to represent the actuator resisting the

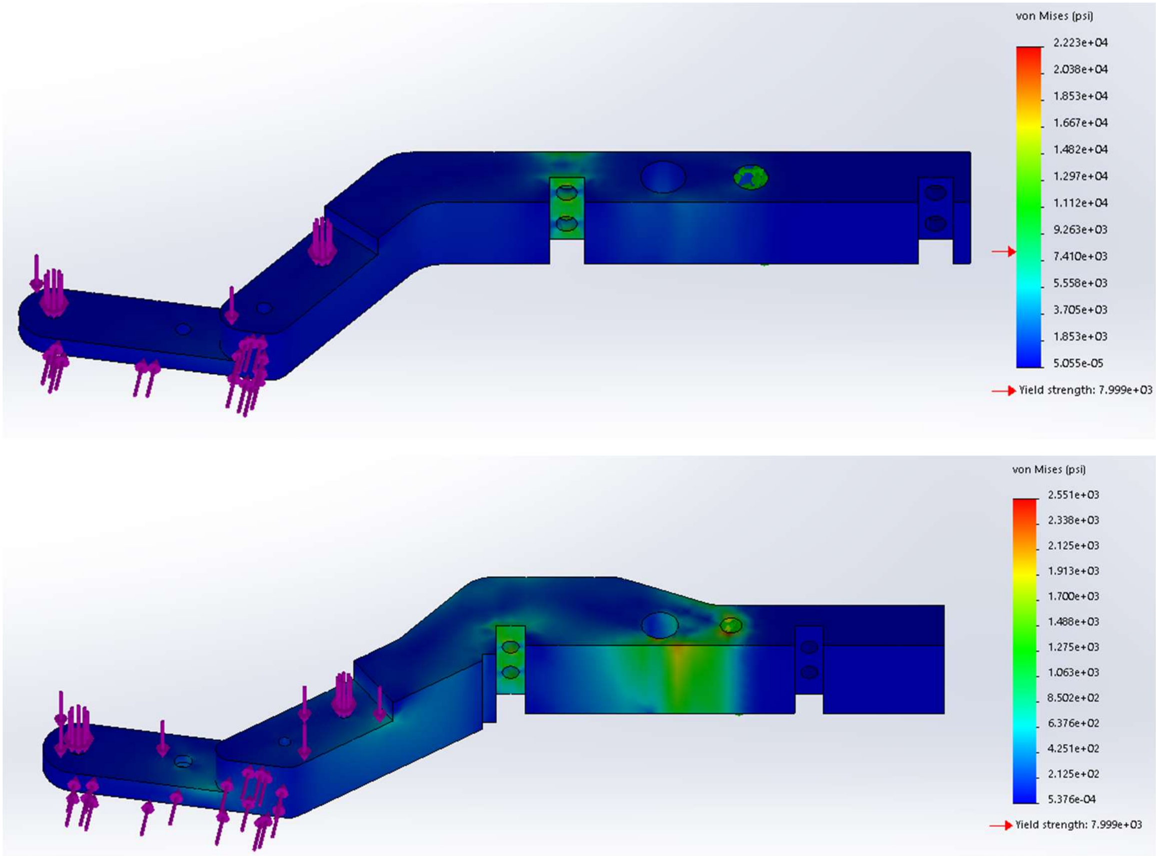


Figure 2.5: The FEA analysis of the original and the new base links. The loads are applied to the bottom face of the link, and to the two top flat planes of the link. These represent the user's hand fully extended, pulling on the mechanism. The original link has a maximum stress of 22300 psi, whereas the new design has a maximum stress of 2551 psi.

mechanism's movement. This analysis showed that the maximum load the base link experiences in this experiment is 7.5 lbs. This number was increased to 8 lb for the FEA, and another 2 lb force was added downwards to represent the weight of a user's hand in the mechanism. The results shown in Figure 2.5 were generated using the FEA package in the 2019 edition of Solidworks. The original design has a maximum stress of 22.3 kpsi, which exceeds the yield strength of the aluminum, whereas the new design has a maximum stress of 2.551 kpsi. A shortcoming of this FEA is that the load was placed on the underside of the links, which is not how the load would be distributed by the actual mechanism.

2.4: Conclusion

This chapter covered the improvements made to the FINGER Mechanism. The mechanism was modified to increase the range of motion during finger extension, as well as to improve the rigidity and strength of the mechanism. The mechanism was strengthened by increasing link size and by including ore wear resistant bearings. The link that had failed in the past was analyzed using Solidworks built in FEA package. The modifications were shown to decrease the stress concentrations considerably.

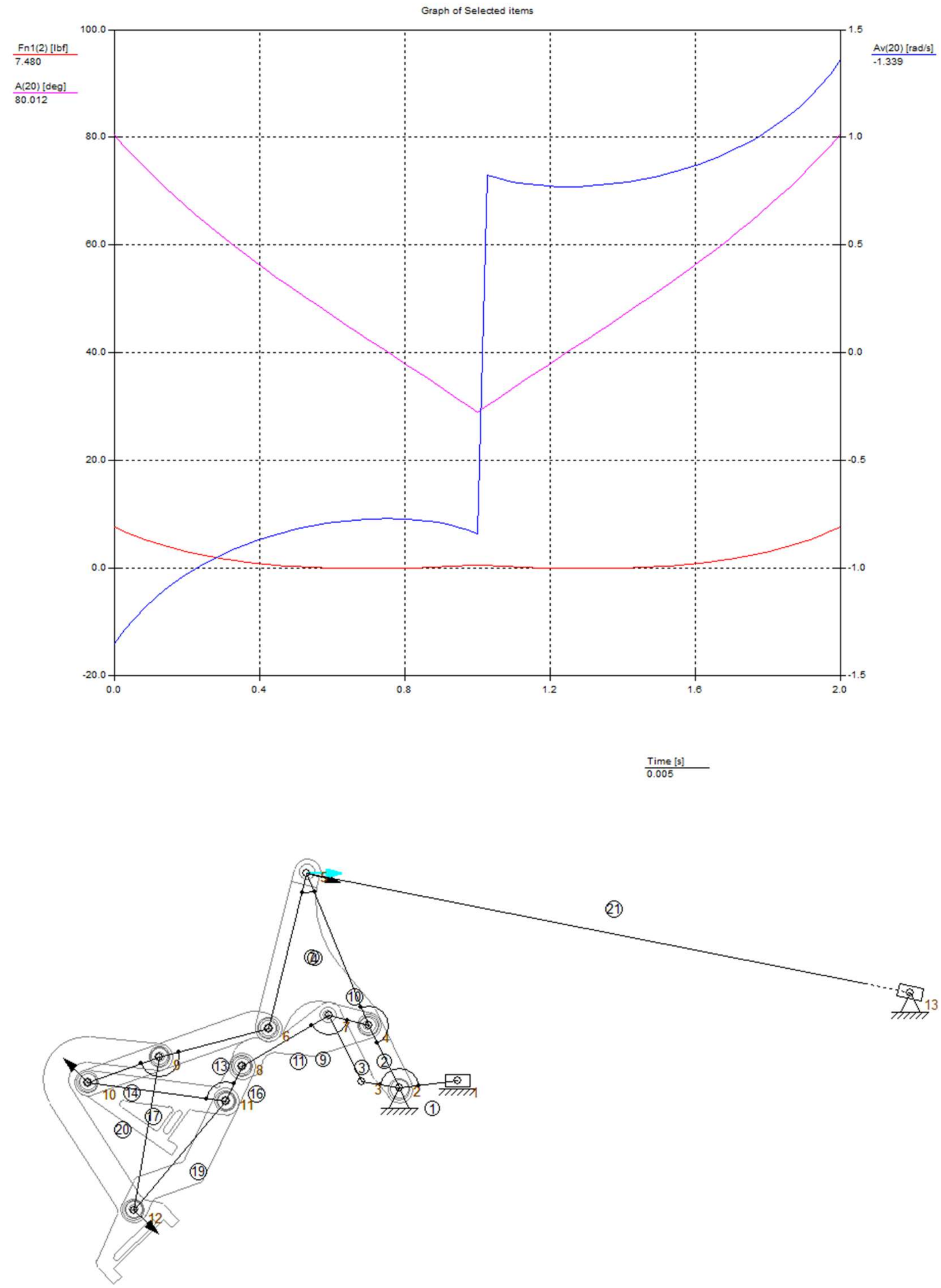


Figure 2.6: The results of the SAM software analysis on the mechanism. The loads are placed at the joints closest to the attachment points of the finger cuffs. The top image shows the graph SAM makes as the mechanism moves through its range of motion, while the bottom image shows how the mechanism is illustrated in the software. The discontinuity in the graph is where the mechanism reverses direction.

Chapter 3: Finger Cuff Design

This chapter was submitted to the International Conference on Intelligent Robots and Systems (IROS) 2020, titled "Finger Cuff Design for Stroke-Rehabilitative Robotics". Some text has been added/modified to improve readability as part of the total thesis.

3.1: Abstract

This paper describes the design and prototype development of an improved finger cuff for the Finger INdividuating Grasp and Exercise Robot (FINGER). The finger cuff secures the proximal and middle phalanges of the index and middle fingers of the subject to the robot. The existing cuff design is analyzed for ease of donning and doffing, comfort, adjustability, and stability of the connection to the robot. Several areas for improvement are identified, and an improved design is presented. A 3D printed prototype is developed, and further modifications are identified to improve performance and streamline manufacturability. The new finger cuff design replaces the existing strap with a BOA® S2 ratchet dial, which creates a more secure connection between the subject's finger and robot and allows for finer adjustments. Furthermore, custom laser-cut leather envelops the BOA® cable and the cuff, significantly improving comfort and ease of donning and doffing.

3.2: Introduction

An estimated 7.2 million Americans over the age of 20 have suffered a stroke, and this number is expected to rise by an additional 3.4 million by 2030 [1]. A common problem after stroke is upper-body motor impairment. This impairment can be lessened through task-oriented training and therapy [2]. Movement training after stroke can be an expensive and uncertain process, highlighting the need for targeted therapies and research. Robots can automate the strenuous and repetitive aspects of movement therapy and have been shown to be competitive with traditional movement therapy in terms of functional recovery, including opening and closing a patient's hand [5]. These robots can also provide quantifiable data, which can help researchers learn more about stroke recovery [12].

Over the last several decades, numerous robotic devices have been developed for post-stroke movement training of the wrist, hand, fingers, and thumb [24]. Researchers have used these devices to investigate a wide range of approaches for hand function rehabilitation [25] that utilize different control strategies [26]. One commonality between these devices and studies is the need to connect the human to the robot. Such connections are typically designed ad-hoc, and although some significant research in this area has been conducted [27] [28], it remains an important area for further research attention.

A. FINGER

The Finger INdividuating Grasp and Exercise Robot (FINGER) is a stroke rehabilitation exoskeleton consisting of two single degree-of-freedom (DOF) 8-bar mechanisms that guide the index and middle fingers independently through grasping motions [17]. The robot attaches to the proximal and middle phalanges of the index and middle fingers. FINGER uses highly backdriveable actuators, allowing for a variety of robotic therapy approaches, including assist-as-needed control [21], patient strength testing [20], and proprioception assessment [19].

B. Review of Existing Finger-to-Robot Attachment

Hand rehabilitation after a stroke has been a focus of rehabilitative robotics in the last decade, and numerous different robots have been developed [24] [12]. These robots use a wide array of methods to attach the patient to the robot. Common connection methods include hook-and-loop straps (e.g. Velcro), gloves, and rigid cuffs.

Hook-and-loop straps provide a simple, inexpensive, and robust mounting method used in many robots [29] [14] [15]. The straps can be easily adjusted to fit different hand sizes, and they can be easily replaced. The downsides are that the loops can fray, and it may not be the most comfortable material to wrap tightly around one's fingers. Depending on how the hook-and-loop straps are attached to the robot, it may also be difficult to achieve a stable interface between the human and robot. An advantage of the hook and loop straps is that they allow for designs which leave the fingertips unobstructed, allowing the user to retain their sense of touch during movement training.

Another popular method for connecting a hand to a robot is to use a glove [30]. In this method, the robotic device attaches to an off-the-shelf glove, which is typically modified in a variety of ways. This eliminates or reduces the need for a specialty finger cuff or mounting mechanism. Furthermore, gloves are typically inexpensive, comfortable, and provide ample contact surface area for securing the digits of the hand. The glove, however, needs to be properly sized to the patient to avoid slipping and

Figure 3.1. Proximal (right) and middle (left) cuffs currently employed on FINGER. The original foam padding has been removed.

misalignment. Furthermore, when used with people who have suffered a stroke, it may be difficult to don and doff the glove, depending on the severity of the patient's impairment and tone. The use of a glove may also restrict the user's sense of touch.

The final common method is to simply have the finger or thumb held in place with a rigid cuff or ring [31], [32], [33]. The bulk of the exoskeleton is generally held in place with a strap (e.g. hook and loop), while the fingers and/or thumb are attached to rings. These rings can be exchanged for different sizes, which is necessary to accommodate the variance of the statistical population of the human hand. The donning and doffing process can be improved using rings as well, if done in a method similar to [32], where only the tips of the fingers are attached to the robot by the rings, although this method may impede the user's sense of touch.

While these methods all work well, they each have their downsides. For a finger attachment method to be widely applicable, it would need to improve upon these common mounting methods. This paper focuses on the improving the finger-to-robot attachment of the FINGER robot, but the concepts can be extrapolated to other devices and locations of human-to-robot connection. Specifically, the existing finger/thumb cuff design of FINGER is evaluated in four categories: ease of donning and doffing, comfort, adjustability, and rigidity/stability of the connection to the robot. Then, we present design goals, the iterative design process, and conclude with a final prototype cuff design.

3.3: Methods

A. Critical Evaluation of FINGER's Existing Cuffs

The existing finger cuffs of FINGER are machined from aluminum, with a ratchet strap used to hold the finger in place. The strap is made of a modified MXL series timing belt and is tightened using a spring-loaded ratchet that can easily be released (Figure 3.1). Each mechanism on FINGER has two of these cuffs, one for the proximal phalanx and one for the middle phalanx of the finger. These cuffs have been used on FINGER since it was first designed in 2013 [21]. Using the criteria categories identified in the previous section to review this design reveals some areas for improvement.

1. Evaluation of Donning and Doffing

The ease of donning and doffing with the current cuff design could be improved. For a clinician to don a patient, the straps need to be fully removed from the ratchet, wrapped around the finger, and then re-inserted into the ratchet. The straps have a small angle at which they properly engage with the spring-loaded ratchet, which makes grasping the straps of the lower cuffs awkward and difficult to adjust quickly. The doffing process is noticeably easier, as the ratchet release is pressed down, fully releasing the strap, allowing the patient to move their finger away.

2. Evaluation of Cuff Comfort

The aluminum used for the existing cuffs is not comfortable during prolonged use. This can be mitigated by attaching a soft foam to the aluminum. However, the foam tends to break down after repeated use, leaving a sticky residue. Even with the foam, the pressure along the edge of the cuff can cause discomfort over time. The ratchet strap itself is made of a flexible timing belt material that is reasonably comfortable when tightened against the skin. If patients are experiencing discomfort, or if their fingers are too small for the strap to hold tightly, foam can be placed along the strap to increase comfort.

3. Evaluation of Adjustability

The timing belt strap has a tooth pitch of 2.032 mm (0.08"). This functions as the adjustment resolution. In some cases, the comfortable tightness falls between two teeth on the belt, which causes the cuff to be too loose or too tight. The ratchet release makes it difficult to only release the ratchet by a single notch, so there is the opportunity for the strap to be readjusted incorrectly, necessitating repetition of the process.

4. Evaluation of Connection Rigidity

The proximal and middle cuffs each mount to the robot differently. The proximal cuff controls the position and angle of the proximal phalanx during grasping, and thus is rigidly attached to the robot. The middle cuff controls only the position of the middle phalanx, so that it is free to rotate to a comfortable angle during grasping. Thus, it is connected to the 8-bar mechanism via a passive revolute joint. Mechanisms between the 8-bar mechanism and both cuffs allow for finger length adjustment by moving the whole cuff forwards or backwards. The two cuffs can be adjusted independently of each other to ensure a comfortable fit.

B. Goals for Redesign

The analysis in the previous sections highlights several areas in the current finger cuff design in need of improvement, including: the ease of donning and doffing, the comfort, and the adjustability of the cuff. The design must also be compatible with the existing mechanical design of FINGER and not interfere with any performance attributes.

The redesign presented below addresses the donning and doffing ease by replacing the ratchet strap with a BOA® ratchet dial, the cable of which can be quickly looped over a patent's finger and adjusted by twisting the dial. To improve comfort, a leather strap covers the cables of the dial and a leather cover is placed over the rigid base of the cuff. The dial allows for bidirectional turning, one direction

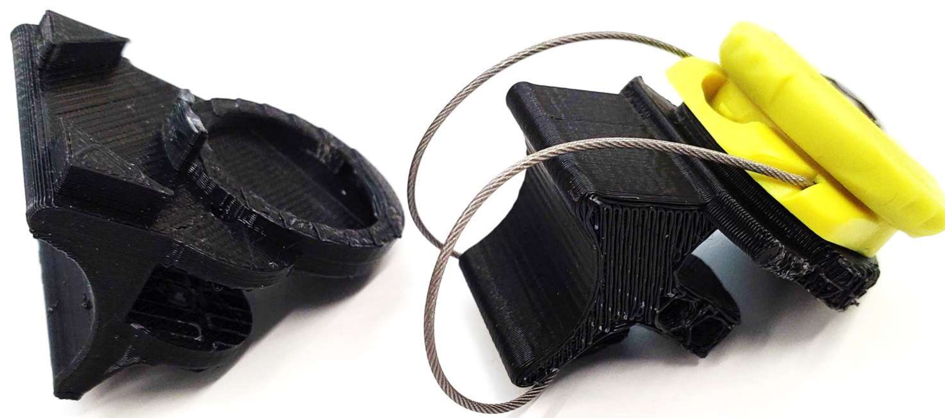


Figure 3.2. Initial middle and proximal cuff prototypes using the BOA® S2-S dial. The proximal cuff has the BOA® S2-S dial attached.

loosening the cable, which allows for faster and more accurate adjustment to a patient's fingers. The sections below describe the design process and prototyping in more detail.

C. Initial Prototype Design

The initial finger cuff prototype replaced the timing belt strap and ratchet with the S2 series BOA® lacing system, an off-the-shelf looped-cable tightening system used in a variety of products to replace laces and similar fastening systems. These dials can retract 20 cm of lace over 125 ticks, which is a ~150% resolution improvement (1.6 mm vs. 2.032 mm). The dials are 30 mm in diameter and 12 mm thick, with a cable diameter of 0.86 mm, making them small enough to be mounted to the FINGER mechanism. The S2 series BOA® dials may be twisted both clockwise and counterclockwise. This allows for quick and simple adjustment of the cable length and thus tightness of the finger/thumb cuff.

Initial prototypes were made using the BOA® S2-Snap dials (S2-S) which use a snap fixture to attach to a base. The cuff prototypes were designed with hook-like geometry on the underside of the cuff for the cable to be looped around, and to slide over as it is tightened (Figure 3.2). Both the proximal and middle cuffs were modified using this method, 3D printed, and installed on FINGER. One of the two

Figure 3.3. Evolution of cable-cover designs. Initial designs (left) of the cable covers used sewn seems, later prototypes used rivets (right). The 2nd from the right shows the extended leather cover.

Figure 3.4. Final prototypes using the BOA® S2 dials. The left cuff has the leather cable cover and leather base cover attached.

FINGER mechanisms was retrofitted with the new cuffs, allowing for a comparison between the prototype and the existing design. The BOA® cuff was found to be more comfortable, and easier to don and doff than the existing ratchet strap.

D. Cable Cover Prototype

The bare cables of the BOA® dials against the skin were found to cause discomfort over time. They were also difficult to properly space, as there was nothing holding them in place over the user's finger. To address these problems, a cable cover was developed. Several types of materials were considered for the cover, with leather being chosen for its durability, softness, and ease of manufacturing.

The cable covers are made from thin suede leather cut using a laser cutter. The cuffs are made in two parts, an upper and a lower. Original prototypes used soft thread to mate the two halves, but to improve manufacturability and durability they are now connected using 3 mm brass rivets. These rivets are placed to eliminate contact with the skin. The cable passes through the outer edges between the layers of the cuff, then over both layers for the majority of the length of the cuff. This keeps two layers of leather between the strap and the skin, increasing comfort. Examples of the strap's evolution can be seen in Figure 3.3.

Two designs were investigated to solve the discomfort with the metal cuff base. One method was to cover the metal by extending the leather cable cover, allowing the cover to wrap around the user's finger, stopping the metal from contacting the skin. The other method was to create a separate cover that wraps around the cuff base. The separate cover allows for easy removal and cleaning and is less of a hassle to adjust. For these reasons the separate leather cover for the base is used in the final prototype.

E. Final Prototype Design

While the S2-S BOA® dials functioned adequately, the snap geometry was difficult to reliably replicate. The final design was modified to use the standard S2 BOA® dial, which uses a bolt to mount to a base. This required design changes for mounting. Additional design modifications were also implemented to improve manufacturability. Specifically, the cuff was split into two halves: the mount for the dial, and the curved geometry for conforming the shape of the finger. The split allows for both easier 3D printing and easier machining of a final version. The leather cover was modified to be held in place by the bolts between the two sections, allowing it to be pulled tight to the cuff. The final design can be seen in Figure 3.4.

3.4: Discussion and Conclusion

The new cuff prototype improves on the previous design, allowing for a more comfortable fit, while being easier to don and doff. The 3D printed prototypes attached to FINGER made it possible to compare the two cuff designs. In comparisons between the two, the new prototype was more comfortable, and was easier to adjust to different finger sizes. The cable is easy to hook around the bottom of the cuff and can be easily removed by loosening the dial. The dials are easy to adjust on both the top and the bottom sides of the robot, allowing for quick adjustments to the fit. Future evaluation of the presented finger cuff prototype will include feedback from engineers, therapists, and patients who use the device in clinical settings.

While these cuffs are intended to replace the existing cuffs of the FINGER device, they may also be useful in other applications. The design can be easily modified to attach to different devices, allowing for a wide range of possible applications. Since the dials are off the shelf components, other research groups can implement them easily.

Figure 3.5. Close-up of FINGER showing two finger cuff prototypes on the index finger and the existing finger cuffs on the middle finger. The prototypes replace straps with BOA® dials and include laser cut leather for comfort.

Chapter 4: Thumb Mechanism Design

4.1: Introduction

To increase the functionality of FINGER, the kinematic design for a thumb training mechanism was developed, the paper describing this process was submitted to IROS 2020 [34]. The trajectory of the thumb was digitized using camera-based motion capture that utilized four reflective markers on a small plate attached to the dorsal side of the thumb. From the capture data a symmetric, spherical five-bar mechanism was designed that allows the thumb to curl naturally to touch either the index or middle finger (Figure 4.1). A prototype was designed to validate fit and function of this mechanism. The prototype includes a thumb cuff designed using the same principles described in Chapter 3.

4.2: Five-Bar Prototype

The kinematic design of the symmetric, spherical 5-bar presented in [34] consists of the home-position locations of the 5 axes, translation and orientation of the output frame, and the rotation angles during the curling motions. The mechanical design of the linkages must adhere to these kinematic parameters but can otherwise be designed to meet other design constraints and goals. In the case of this prototype model, the goal was to create a basic functional mechanism for evaluating fit and function. This prototype uses 3D printed links connected with the same bearings (McMaster number 57155k335) used to upgrade the FINGER 8-bar mechanisms. The five-bar was modeled using the 2019 version of Solidworks and was designed to avoid contact with the FINGER 8-bar mechanisms through the full range of motion of either mechanism. When actuated, the kinematics allow the user to touch either their index finger or middle finger.

The fixed rotation axes (ω_1 and ω_5) of the prototype are attached to an 80/20 aluminum extrusion tower with a 3D printed mount (Figure 4.2). This mount extends the driven axes (ω_1 and ω_5) away from the user and allows for vertical adjustment during evaluation. The actuators used to rotate the input axes ω_1 and ω_5 are Servo-Tube Dunkermotoren linear actuators, the same linear actuators used in FINGER. The servo-tube actuators are placed out of the way; the actuator for the first rotation axis is located below the FINGER platform while the actuator for the fifth rotation axis is located on top of the platform. The linear actuators are attached to pivots and are in plane with the end of the five-bar mount. The actuators are placed so they move through their entire stroke length over the required rotation of each axis, while keeping a large moment arm and minimizing pivoting of the actuator itself. The actuators have a stroke length of 271 mm, so the first axis has a crank arm of 144.95 mm and the fifth axis has a crank arm of 146.02 mm. The movement profile of the actuator for the fifth axis is adjusted as to not collide with the user's arm.

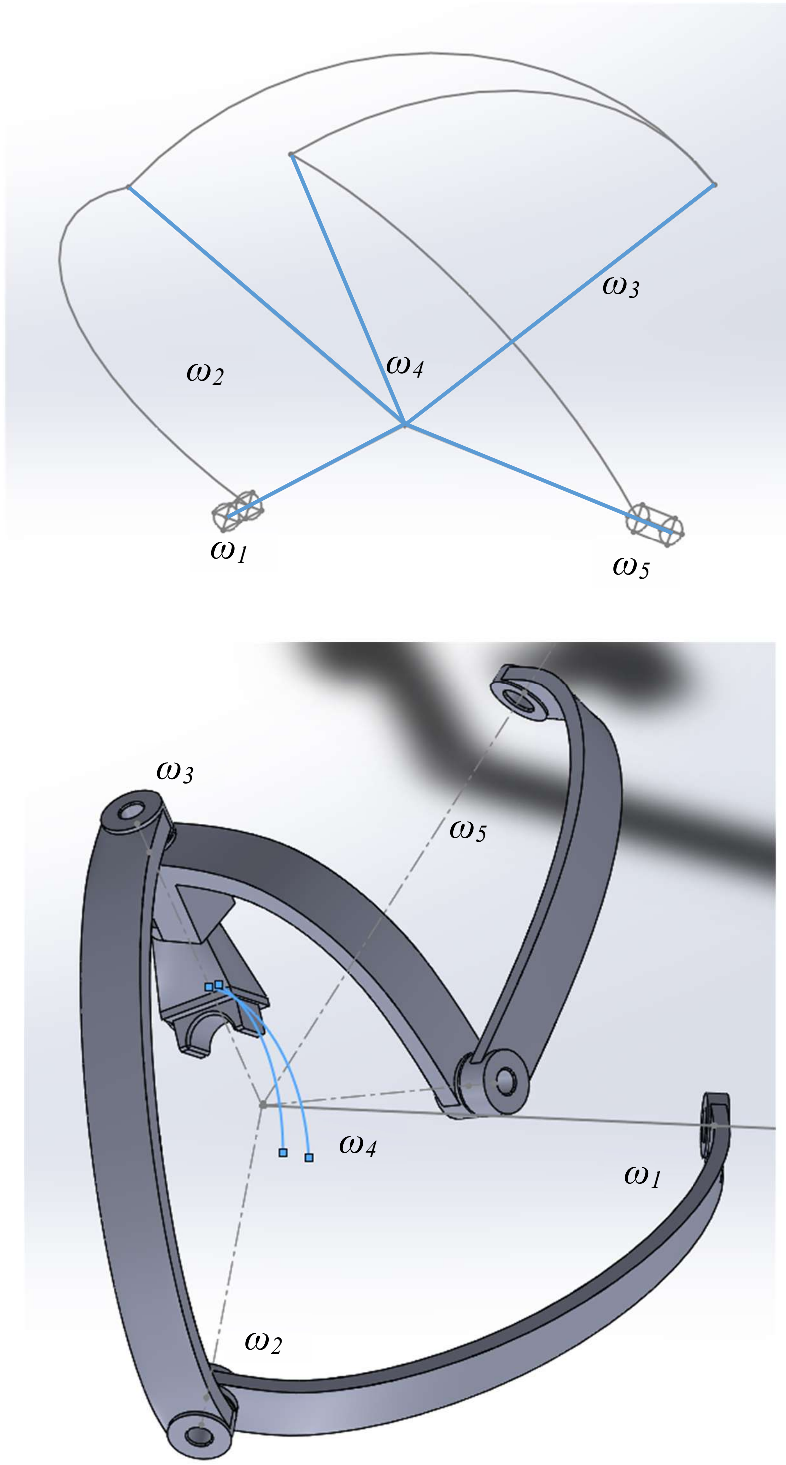


Figure 4.1: The axes of rotation of the spherical five-bar mechanism, as detailed in [33]. The top image shows the five interesecting rotation axes, highlighted in blue, and a wireframe view of the mechanism. The locations of axes ω_1 and ω_5 are fixed (shown as cylinders) and will be actuated by direct-drive linear actuators. The bottom image shows a preliminary solid model of the mechanism links assembled separately from the rest of the robot. The thumb paths are shown by the solid blue lines.

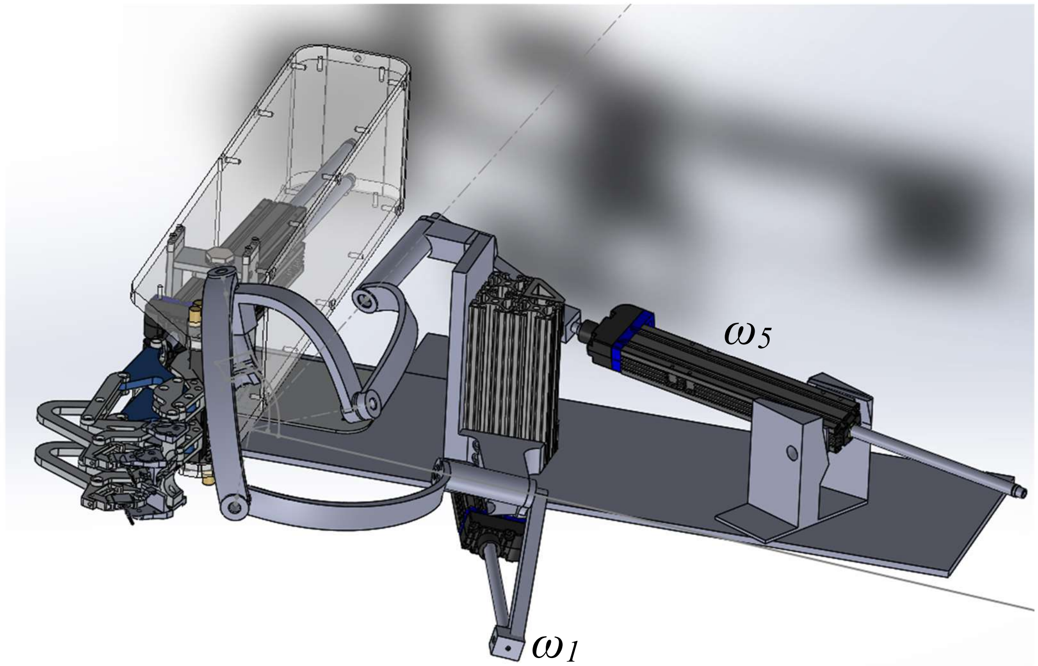


Figure 4.2: This image shows the 5-bar prototype mounted to the base plate with FINGER. The actuators, connected to ω_1 and ω_5, are placed such that the rods move through their entire range of motion.

4.3: Five Bar Thumb Cuff

The output of the spherical five-bar extends from the third joint axis and connects to the user's thumb. The thumb cuff rotates freely around this axis (ω_3) as there is a slight rotation (84° for the middle and 69.7° for the index) to the output frame during the curling motion of the thumb. The thumb cuffs are designed to be as comfortable as possible, while maintaining a secure and stable connection between the user and the five-bar mechanism. The cuffs include a BOA® dial attached to one side and a hook on the opposite, allowing for quick and easy adjustments to the fit of the cuff. A leather cover attaches to the cuff to add padding between the user's thumb and the printed cuff. To accommodate different hand sizes, the thumb cuff has several different versions. Each version changes the distance from the links to the thumb connection, allowing for adjustments between users, and has an attached BOA® dial (Figure 4.3). Each of the sizes of the cuff is designed to quickly attach and detach from the spherical five-bar for quick changeover between patients.

4.4: Conclusion

This chapter covered the development of a prototype for a thumb training mechanism. The prototype is the mechanical realization of a spherical five-bar mechanism, which was designed using motion-capture data of the thumb during grasping motions. The prototype was 3D printed and attached to

80/20 extrusion to allow for quick testing of the mechanism's fit and function. The prototype is fitted with custom thumb cuffs that are designed for comfort and stability.

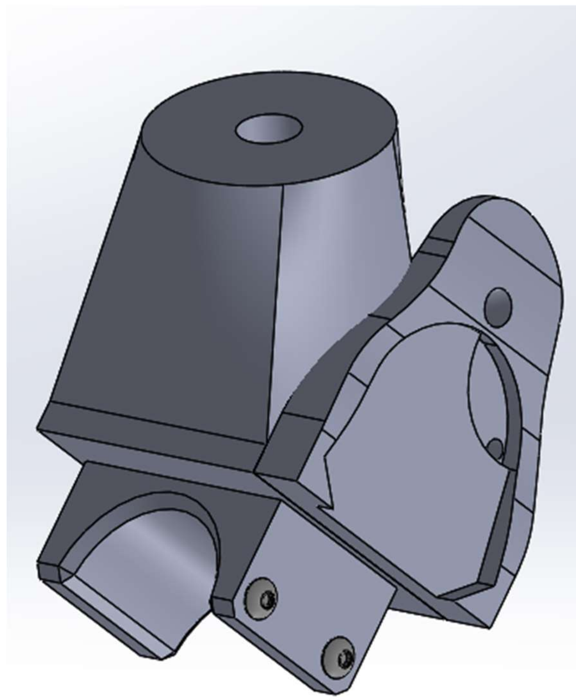


Figure 4.3: The thumb cuff designed for the the spherical five-bar mechanism. The thumb cuff is designed to be free to rotate, and is placed so that ω_3 intersects the center of the user's thumb. A leather cuff is designed to be placed over the portion of the cuff that is touching the user's hand. The cuff is held in place by 2-56 button head bolts, and conforms to the cuff's shape while the user's hand is attached to the robot. The BOA® dial attaches to the side of the cuff and is bolted in place.

Chapter 5: Conclusion

The work detailed in this thesis includes improvements and additions to the Finger INdividuating Grasp and Exercise Robot (FINGER). The 8-bar mechanisms of FINGER were redesigned to be stronger, and to use bearings which make proper link spacing easier. Furthermore, the design of several links were modified to increase the range-of-motion by 15 degrees in extension, facilitating a more natural open-hand position. The finger cuffs on the mechanism were updated to use BOA® ratchet dials and leather straps to increase comfort for the user and improving donning and doffing.

This thesis also presents the development of a mechanical prototype of a thumb training mechanism addition to FINGER. The prototype of the five-bar thumb mechanism shows promise of being used for human testing soon. Future work is required to finalize the mechanism design and test for fit and function with healthy subjects before the device can be tested in a clinical setting. It will also be necessary to design and build a platform to connect the thumb module to the FINGER robot.

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Appendices

The attached CD includes drawings for the updated mechanism links as well as drawings for modified hardware and the laser cut cuffs.