DESIGN AND ANALYSIS OF A SOFT ROBOTIC GLOVE FOR REHABILITATION THERAPY

A Thesis by

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DESIGN AND ANALYSIS OF A SOFT ROBOTIC GLOVE FOR REHABILITATION THERAPY

The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Biomedical Engineering.

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DEDICATION

To my mom, my dad, and my older brother in thanks for their lifelong friendship and loving support
“I can do all things through Christ who strengthens me” Philippians 4:13
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First and foremost, my gratitude is to Christ for being my rock and my strength throughout this project and every hour of every day. Thank you to my parents, Linda and James, for their generous help, encouragement, and financial support. Thank you to my brother, Andrew, and my lab mates, Parshuram, and Jordan, who offered moral and technical assistance during this project. Special thanks to my adviser, Dr. Desai, for his guidance and technical support throughout this project. I also extend my gratitude to Dr. Sindhu Burugupally and Dr. Yongkuk Lee for their time and advice as part of my graduation committee.
ABSTRACT

Strokes often lead to hemiparesis of the hand. This renders individuals unable to actively flex or extend the affected hand’s fingers. Currently the only option for improvement is therapy to improve the neuromuscular connection and maintain ROM (Range of Motion). Conventional therapy is costly and time consuming. It involves in person visits and at home exercises. Soft robotics has a significant potential in rehabilitative and assistive exoskeletons. The flexible materials deliver a gentle, accessible therapy, minimizing possible injury and increasing the possibility of recovery. This research aimed to design and evaluate an optimized pneumatically actuated soft robotic glove for rehabilitative tasks which will execute the motion of the hand. While there are existing soft robotic gloves, this unique design will allow users to self-actuate their therapy through re-extending the hand using a layer of flexible steel. The resistive layer causes the fingers to return to a straightened position after the pneumatic actuator has released the air pressure which causes it to curl. This design underwent prototyping, evaluation, and human subject testing. This glove, tested by 10 unimpaired subjects, assisted in extension while minimally impairing the glove’s flexion performance. The actuations consistently achieved an average peak of 75° or greater during passive assisted motion. An addition of the steel layer lowered the blocked tip force by an average of 18.13% for all five fingers. The maximum blocked tip force with the steel ranged from 12.7-14.1 N. During passive assisted testing, participants accomplished 80.75% of their normal active flexion ROM when neglecting outliers with the steel lined glove. This data shows strong evidence that this glove would be appropriate to advance to human subject testing on those who do have post stroke hand impairments.
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1. INTRODUCTION

1.1 Stroke and Rehabilitation

Each year, nearly 800,000 people experience a stroke in the U.S. [1,2] wherein an estimated 90% are left with some type of a disability [3]. Two high risk factors of a stroke are age and obesity [4,5,6]. With the average life expectancy increasing due to increased technology and health care [5], an increasing average population worldwide [5], and the rate of obesity increasing 30.5% to 41.9% from 2017 –2020 [6], the number of people experiencing strokes is likely to increase [7]. A stroke occurs when the blood supply to part of the brain is blocked or reduced preventing brain tissue from getting oxygen and nutrients. An example of a stroke caused by a blood clot created from a diseased artery is diagramed below.

![Figure 1.1 Diagram annotating the process of blood clot causing a stroke](image)

Figure 1.1 Diagram annotating the process of blood clot causing a stroke [8]
Stroke, along with spinal cord injury and cerebral palsy, is one of the leading causes of paralysis [9]. An estimated 5.4 million persons live with paralysis in the US [10]. Up to 80% of stroke survivors have a residual deficit in movement function of the arm and hand [11]. Residual damage is so extensive that one study found about 65% of patients cannot incorporate an affected hand into their daily activities even six months after a stroke. [11]

“Motor recovery starts immediately after stroke onset, and follows a relatively predictable pattern, regardless of stroke type (hemorrhagic or ischemic, cortical, or subcortical; Twitchell, 1951)” [12,13]. Brunnstrom analytically explained the stages of motor recovery, starting with flaccidity to full recovery of motor function [12,13,14].

![Figure 1.2 Brunnstrom Stages of Motor Recovery](image)

Functional return also occurs proximal/distal and proceeds in sequence from mass patterns to discrete movements voluntarily [12]. For therapy to be most effective it must be initiated as soon as possible to include neuroplasticity stimulation, repetition, and
Neuroplasticity is defined as the brain’s ability to relearn through stimulation of the senses, such as kinesthetic movement [15] and tactile stimulation.

Hand paresis is also a side effect from stroke which causes an inability to move the fingers of the affected hand due to the damaged neuromuscular connection [16]. The hand’s functionality is often the slowest to return as the hands are located farthest from the central nervous system, or CNS, in the upper extremities [16]. Neuroplasticity exercises are categorized as Passive, Active, or Active Assisted Range of Motion [15]. These exercises produce a pathway to reconnect the brain to the body through movement [15]. Passive Range of Motion, or PROM, uses outside forces only, such as a person, or a passive motion machine to move the body part while the participant exerts no effort [17,18]. Active Assisted Range of Motion, AAROM, requires a combination of assistance from an outside force and by the person executing the exercise. Active Range of Motion, AROM, is movement of a joint achieved by the owner of the body part [17,18]. A personalized protocol of ROM exercises is implemented as the body attempts to heal from a stroke [17]. Traditional post stroke therapy involves daily one on one passive, active and assisted hand therapy to maintain range of motion, relax, stretch, and strengthen the hand [11] This requires patients to work with a therapist in person as well as on their own. If the patient does not comply with the self-administered therapy in addition to the therapist’s treatments, the therapy is minimally effective. Unfortunately, often patients are depressed, exhausted, distracted, and forgetful, or noncompliant for other reasons after experiencing the trauma of a stroke. The more therapy a hand experiencing paresis receives early after the impairment, the higher the chances of recovery and regaining usage [12]. Overall, treatment is time consuming, costly and must
be initiated immediately after the stroke to be most effective [11]. Many therapists report that most patients do not comply with the recommended self-administered therapy resulting in limited success in the return of neuromuscular functional [20,21].

A technological therapeutic solution to minimize the need for daily human interaction and supplement the amount of therapy accessible and administered is a robotic exoskeleton, specifically a soft robotic glove. Current commercial rehabilitation and assistive devices are based on conventional, rigid robotics, which often incorporate exoskeleton structures. Such devices, however, can be mechanically complex, costly, large, cumbersome, heavy, and must be customized.

While many designs and experimental research of pneumatic gloves exist, there is still a need for improvement upon existing designs including simplified designs, cost effective, practical fabrication, mobility, and user friendliness. Most all existing soft robotic hands can assist with finger flexion, but few have addressed finger extension. Extension is defined as a movement bringing the members of a limb into or toward a straight condition [22]. When a stroke has damaged the brain’s motor neurons that communicate with the affected muscles, the muscles most common response is to pull the hand into abnormal spastic hand postures [23].
“Loss of the ability to extend the fingers and thumb after stroke is a critical impairment observed by clinicians and is a common complaint from patients” [24]. “The eventual ability to grasp after stroke is strongly related to how far the digits can be actively extended against gravity” [24]. Without extension the hand lacks the ability to open, a functional act required in most hand movements ranging from simple, grasping a doorknob to complex, typing on a keyboard. Lack of extension can also result in hand spasticity and contractures.

Spasticity is a post stroke muscular disorder, though part of the recovery process, it varies in each patient and is characterized by muscle tightness and stiffness [12]. If the patient does not receive neuroplasticity exercises the hand may curl and clench into a tight fist, resulting in a painful hand contracture [19]. Therapy has historically used splints [19] such as adjustable finger aligners to aid in returning fingers to extension, but the outrigger is intrusive and the force is often too strong to allow flexion, resulting in a nonfunctional dynamic splint.
Other gloves such as the VTS provides mechanical, vibratory input which increased voluntary finger flexion, but not extension [26]. Current robotic gloves tend to facilitate either flexion or extension, but not both. Another approach to increase post stroke finger extension is pharmacologically. Though Botox injections relax muscles studies show injections to spastic finger flexors weakens grip strength in an already muscularily compromised hand [27].

An ideal therapeutic robotic glove should aid in both finger flexion and extension. This design supplies adequate force to safely and gently augment the curling and straightening of the fingers safely and gently in an impaired hand. This soft robotic hand therapy device is designed to transfer adequate force to the fingertips without any intermediate mechanisms. Building on the design of Gerges et al., the fabrication of this glove is simple and quickly achievable [28]. The design allows for accessible and straightforward adjustments and mending as well as easy prototyping. The glove maintains a low weight.
of 149 g including the steel ribbon inserts. The thorough testing of this design provides a strong feasibility study and indication that the glove will prove advantageous in the next phase of human subject testing. All innovations must include evaluating the assisted extension and flexion with sufficient human subject testing in phases before the glove can be implemented in real stroke therapy. The goal is that this glove, which has integrated flexible steel strips to the linear actuators, will incorporate a safe and easily implemented device to assist the digits in returning to extension during hand therapy and transform hand therapy accessibility. In doing such, the glove will significantly increase successful rehabilitative hand therapy for post stroke patients.

1.2 Soft Robotics:

There are many types of robot assisted hand therapy available through technology. When looking specifically at hand technology, the devices can be categorized into rehabilitative or assistive, active or passive, electrical or pneumatic, and rigid or soft. Robotic devices can provide active or passive assistance or resistance. In the case of assistive devices, the robot will help the joints move in the intended direction of the therapeutic exercise in order to help the patient complete the exercise. In resistive devices, the robot will counter the intended direction of the exercise in order to help the patient increase their strength. Passive devices mainly serve to stabilize the motion of the exercise while active focus on assisting the motion.

Devices can be categorized into rehabilitative and assistive. Rehabilitative technology serves as a therapeutic device in order to heal the hand through physical exercises and therapy similar to those which would be performed or advised by an occupational therapist. These devices are a supplement and extension of traditional physical therapy.
For example, a robotic glove that guides the hand along flexion and extension exercises so patients can receive those rehabilitative motions more consistently and frequently during their recovery. Assistive technology is a long term technology that would assist the patient in everyday tasks after their impairment. For example, a robotic glove that increases gripping strength when activated in order to help patients hold onto objects in daily tasks such as carrying a cup from point A to B. These technologies require different design parameters because they have differing requirements and goals.

Soft robotics versus rigid robotic devices refer to the material used in the device. Rigid robotics refer to the traditional motor driven non-flexible robot. In the realm of therapeutic hand technology, rigid robotics often incorporate linkages, cables, or both. While these robots have high durability, efficiency, accuracy, and reliability they are bulky and less flexible than soft robotic gloves. Finally, the alignment of an axis of rotation with each finger and its respective robotic joint is challenging and requires customization of each robot. If a misalignment presides, it can create dangerous contact between the device and user, resulting in discomfort and injury [11].

Soft robotic gloves are made from a flexible material, often rubber or silicone. They utilize fluid pressure, pneumatics or hydraulics, to create the driving force of the robot. Often unique and specially designed geometries and variations of materials are encompassed that will cause the robot to go from one shape at the de-pressurized state to another shape when pressurized. The pressurization can cause the robot to elongate, shorten, curl, twist, and other motions. Soft robotics offer a huge advantage over rigid robotics in the realm of hand therapy due to the detailed multi-jointed and fragile nature of the hand. When a finger bends, there are three separate joints at work, while this would seem easily
transferred to a rigid link system, there is a high risk because each rigid joint must align with each joint on each finger perfectly to prevent risk of further injuring the hand. Since each person’s hand varies in size, this would indicate every glove would need to be carefully custom made. This is not time or cost effective, especially given the time sensitive nature to post stroke physical therapy. In contrast, the soft robotic glove is a flexible material which gently pushes on the patients fingers to create a slight bend, there is no need to match the rigid links of the hands bones because the soft robot will conform to them. This mechanical compliance allows the soft robotic glove to be relatively universal for general hand sizes (i.e. small medium large) instead of needing to be customized. The flexible gentle material allows the soft robots to interact safely with sensitive human features such as injured and impaired fingers. Finally, the nature of soft robotics requires less sophisticated control systems than rigid systems. Less customization, simplified control systems, and reduced safety hazards also result in a lower manufacturing and production cost.

The specific field of soft robotics this project explores is referred to as fluidic elastomer actuators, or FEAs. Fluidic elastomer actuators are also referred to as elastic inflatable actuators, or EIAs. These actuators are made up on elastomers, in this case silicone, which have low elastic modulus, large strain, and high toughness. [29]. The rubbers and silicones utilized as soft robotic materials usually possess elastic modulus’s between 10^-5 and 10^-7 Pa [29]. FEAs are usually anisotropic, meaning they are made of two or more materials each of which have a different modulus of elasticity. The layer with a higher modulus of elasticity becomes the strain limiting layer while the material with the higher modulus of elasticity will deform upon pressurization and allow for the motion to occur.
One element that has been widely tested and varied within publications of assistive and rehabilitative robotic glove is the control system. There are many different sensors and control system types that alter the human-machine interface dramatically. Common control systems used within soft robotic gloves include sensor stimulated, general authoritative, and primary-secondary.

Flex sensors, pressure sensors, and force sensors readings can be incorporated into the control system to implement better user control and safety as well as improve the quality of rehabilitative or assistive performance. Flex sensors provide data on the position of the hand and what angle the sensor is bend to. Flex sensors work by the resistance value inside the flex sensor changing proportionally to the bending angle of the flex sensor. Pressure sensors are able to read the current pressure in the pneumatic system. These are specifically very useful in the realm of soft robotics as one of the main safety and malfunction concerns is an over pressurization of the actuators resulting in their bursting. While this bursting is unlikely to injure the hand, the sudden change in force and loud noise could cause a negative reaction and weariness towards using the glove. Flex sensors and force sensors have been used within sensor stimulated control systems. Flex sensors and force sensor detect the bending angle of the fingers and the force applied by the fingers onto objects, respectively, to control the actuation of the device.
Primary secondary control systems were used in Gerges et al. to allow the patient to control their impaired hand with their healthy hand via flex sensors stimulation [28]. When the flex sensors on the healthy hand sensed a signal above a certain angle threshold, the control system would actuate the mirrored finger on the impaired hand. This would allow patients to administer therapy to themselves via their unimpaired hand. By placing a glove lined with flex sensors on each finger, the healthy hand is able to perform the desired motion. When the flex sensors on the healthy hand sense the bending motion, that information is transferred to control system and soft robotic glove on the impaired hand as the desired input. Then, if it is a feedback loop control system, there will be flex sensors on the impaired hand which will send back information on the obtained position of the impaired glove to the system and the system will adjust as needed. This specific control system mimics mirror therapy as the patient is able to watch their hands perform the task via their own neuromuscular intentions.
Another type of sensor-stimulated control system involve EEG or EMG. These sensors have been utilized to detect human intent via the muscles or neurological stimulus. These signals are then used as the input for the control system of the device [28].

The final option for a control system is to have a direct control system which outputs the intention for which finger(s) to actuate based on a pre-determined or randomized code within a program such as Matlab or Simulink. In this direct control system, the user does not indicate the intentions other than when to start and stop the therapy. This type of direction can be useful for passive therapy due to the unexpected output by the participant. If the control system is user controlled or executes the therapy in an expected order, the participant can anticipate the output rather than letting the passive therapy do the work.

Figure 1.6: Flow diagram showing the reviewed options for control systems used in soft robotic gloves
2. LITERATURE REVIEW

Soft robotic hand designs have increased significantly in the past 5 to 10 years with many improvements and unique innovative designs and implementations. However, publications involving soft robotic gloves can be traced as early as 2005, T Noritsugu - Symposium on fluid power, who designed a pneumatic soft mechanism, a soft robot hand and a wrist rehabilitation device have been developed as a wearable power assist glove. Since then, new designs have included actuators that utilize restraint layers such as fiber wrapping [30,31,32,33], actuators made from geometric molds [28], gloves with double bladders for extension [33], gloves with torque compensating layers for extension [33], and much more.

Starting in 2013, Polygerinos et al. developed multi-segment soft actuators that have expanding and bending segments using the fiber-reinforcements [30]. This actuator uses two inextensible materials. The first rubber layer molded around a hemi-circular steel rod. Woven fiberglass glued to the flat face to serve as the strain limiting layer. After molding the first rubber layer, fiber reinforcements were added to the surface and a Kevlar fiber was wound in a double helix pattern around actuator. The wrapped was then encapsulated in a silicone layer.
Figure 2.1: Soft fiber-reinforced bending actuator in pressurized (a) and unpressurized (b) state [30]

This publication also explored the analytical modeling of the explicit relationship between input pressure, bending angle, and output force. The geometry of the actuator’s inner chamber was evaluated within the analytical model and prototypes. Their analysis of actuator cross-sectional shapes compared rectangular (RT), circular (FC), and hemi-circular (HC) shapes using the same cross-sectional area [30].
Figure 2.2: (a) shown left to right are the rectangular (RT), circular (FC), and hemi-circular (HC) shaped cross sections used in the actuators analysis [30]. (b) Efficiency comparison of the different actuator shapes.

It was found based on analytical modeling that the hemi-circular shape was the most effective. As seen in Figure 2.2 part b, the lower bending resistance shows the need for less pressure to achieve a larger curl and therefore the most effective shape for the purpose of the soft robotic glove [30].

The glove design from Polygerinos et al. was able to achieve a maximum bending force tip of 8 N at a hydraulic pressure of 345 kPa. The weight of this glove was 285 g. This force was reported to be sufficient for rehabilitative hand positioning exercises but not for grasping and manipulating objects. The pressure required was notably higher than other designs which is not energy or cost effective [32].

Wang et al. continued researching this using the same actuator design from Polygerinos discussed in the previous paragraph in 2016 [34]. Further modeling the design then
testing the actuators with flex sensors. They improved the testing data for this design and documented the output force versus pressure at the varying fixed position angles of the actuator as well as the output of the force depending on the bending angle. They found that 180 degrees required the most pressure and output the lowest force compared to 90 degrees which required the least pressure for the largest output of force. The data relationship is shown in the figure below.

![Figure 2.3: Isometric test results for the actuator at fixed position of 90, 135, and 180 degrees including the experimental, analytical, and FEM modeling results][34]
Figure 2.4: Isotonic test results for the actuator at fixed pressures ranging from 60 kPa to 241 kPa [34]

In 2016, Yap et al. released a soft robotic glove which only administered extension [35]. The pneumatic soft robotic actuators were fastened to the palmar side of the hand. This glove was able to administer 4.25 N of force in the direction of extension. This glove was designed for people experiencing clenched hand impairments [35].

In 2016, Yap et al. also published results for a fabric-reinforced pneumatic actuators with a corrugated top fabric layer. This design causes the top fabric layer to limit the radial expansion of the glove when pressurized. By using only silicone and fabric, the actuator was able to achieve a maximum bending tip force of 9.12 N at a lower pressure of 120 kPa. The fabric used had a modulus of elasticity or Young's modulus of 0.5 N/mm [35].
Figure 2.5: Actuator design showing the silicone air chamber and the fabric layers on top and bottom [35].

Heung et al. designed a soft robotic glove with fiber wrapping, 2 actuator chambers, and 2 torque compensating layers made of A2 steel at the bottom to assist with extension. The two areas of flexion and extension were measured to match the PIP and MIP joints in the finger [33].

Figure 2.6: Exploded view of the double segmented actuator designed by Heung et al. showing the actuator body, fiber wrapping, and the torque-compensating layers [33]
The diagram of their model shows the torque compensating layers of steel that are placed below the actuator. This model uses two actuator chambers which are placed of the MCP and PIP joints to focus on bending only in those areas and to require less pressure for smaller chambers [33]. Shown below is some of the graphs produced by Heung et al. in this publication. The graphs show the pressure vs angle for varying lengths of MIP and PIP air chambers.
Figure 2.7: Pressure in MPa and angle in degrees relationship with varying lengths of air chambers for the MCP (A) and PIP (B) joint segments [33]

In comparing the results for the MCP and PIP lengths for output angle as pressure increases, the data shows an increase in output angle at given pressure for the longer lengths of air chambers. For these lengths tested, the longer the MCP and PIP air chamber length, the larger the bending angle the actuator can accomplish at a given pressure [33].
Table 2.1 Comparison of soft robotic glove designs published in the past three years

<table>
<thead>
<tr>
<th>Reference</th>
<th>year</th>
<th>DOF</th>
<th>Tip force output</th>
<th>Pneumatic or hydraulic</th>
<th>Pressure required (kPa)</th>
<th>weight</th>
<th>Extension method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polygerinos et al [30]</td>
<td>2013</td>
<td>1</td>
<td>1.21 N</td>
<td>P</td>
<td>43</td>
<td>160 g</td>
<td>none</td>
</tr>
<tr>
<td>Polygerinos et al [32]</td>
<td>2015</td>
<td>1</td>
<td>8 N</td>
<td>H</td>
<td>345</td>
<td>285 g</td>
<td>none</td>
</tr>
<tr>
<td>Wang et al. [34]</td>
<td>2016</td>
<td>1</td>
<td>8 N</td>
<td>H</td>
<td>345</td>
<td>285 g</td>
<td>none</td>
</tr>
<tr>
<td>Zhao et al [36]</td>
<td>2016</td>
<td>1</td>
<td>5 N</td>
<td>P</td>
<td>270</td>
<td>/</td>
<td>none</td>
</tr>
<tr>
<td>Yap et al [37]</td>
<td>2016</td>
<td>1</td>
<td>4.25 N</td>
<td>P</td>
<td>100</td>
<td>150 g</td>
<td>Pneumatic (no flexion)</td>
</tr>
<tr>
<td>Yap et al [38]</td>
<td>2017</td>
<td>1</td>
<td>9.12 N</td>
<td>P</td>
<td>120</td>
<td>180 g</td>
<td>none</td>
</tr>
<tr>
<td>Cappello et al [39]</td>
<td>2018</td>
<td>1</td>
<td>15 N</td>
<td>P</td>
<td>172</td>
<td>77 g</td>
<td>active</td>
</tr>
<tr>
<td>Heung et al [33]</td>
<td>2019</td>
<td>1</td>
<td>/</td>
<td>P</td>
<td>200</td>
<td>207 g</td>
<td>Torque comp layer</td>
</tr>
<tr>
<td>Gerges et al [28]</td>
<td>2019</td>
<td>1</td>
<td>9.5 N</td>
<td>P</td>
<td>180</td>
<td>120 g</td>
<td>none</td>
</tr>
<tr>
<td>Chizik et al [40]</td>
<td>2021</td>
<td>1</td>
<td>14 N</td>
<td>P</td>
<td>120*</td>
<td>196 g</td>
<td>spring layer of metal</td>
</tr>
</tbody>
</table>

There are a large variety of robotics that utilize extension however most of them are not soft robotic gloves. Instead, many of them are rigid robotic exoskeletons or prosthetics. The chart below highlights a variety of these designs in which finger extension is implemented.
Table 2.2: Comparison of robotic hand and glove designs which implement extension

<table>
<thead>
<tr>
<th>Method of extension</th>
<th>Design purpose</th>
<th>description</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor + Pully</td>
<td>Robotic hand exoskeleton</td>
<td>Wearable rigid Robotic Glove Design Using Surface-Mounted Actuators</td>
<td>2020</td>
</tr>
<tr>
<td>Heung et al [33]</td>
<td>Torque compensating layer</td>
<td>Assistive glove for weakness/injury</td>
<td>2019</td>
</tr>
<tr>
<td>Cappello et al [39]</td>
<td>Double bladder</td>
<td>Assisting hand function after spinal cord injury with a fabric-based soft</td>
<td>2018</td>
</tr>
<tr>
<td></td>
<td>(pneumatic chamber) system</td>
<td>robotic glove</td>
<td></td>
</tr>
</tbody>
</table>

Studying the current designs, experimental analysis, and mechanical functions of current pneumatic gloves and related soft robotic technological publications, some extension mechanisms were identified. In the field of extension mechanisms, the other commonly implemented extension mechanisms are tendons. These are more common in rigid robotic exoskeletons than soft robotic exoskeletons. These utilize strings or chords to contract and expand the finger joints much like the biological tendons in the hand would.

For example, Park J et al. produced a wearable finger actuating glove using surface-mounted tendon actuators designed for rigid robotic hands or prosthetics [41]. The actuator unit in this design involves a motor, motor holder, pulley, and two tendon
strings for flexion and extension. This glove was designed to be combined with a “robot hand skeleton” to form a robotic hand. They evaluated the glove by finger doing a touch sensitivity test where the strength was tested by exerting the highest force at the fingertip and measuring with a force sensor. The contact force was recorded at the rate of 1 kHz and the mean of the fingertip maximum contact force for five trials was $8.84 \pm 0.23$ N [41].

Figure 2.8: a photo of the glove designed by Park et al. as a wearable finger actuating glove using surface-mounted tendon actuators designed for rigid robotic hands or prosthetics [41]
There have been few successful soft robotic gloves however that have been able to integrate the tendon mechanism into soft robotics because the strings need to be a soft flexible material. One publication utilized Kevlar threat, which is strong and flexible, and guided the thread through tunnels within to the glove along each finger. The tunnels were placed so that the flexion and extension of the finger could be facilitated when certain strings were tightened by the electrical motors attached at the end. Utilized an electrical motor pulley system has a higher risk than utilizing silicone actuators and spring material such as sheet metal for motion because there is a risk of injury if the force is overexerted. Further, upon failure, the tendon model could risk locking the hand into certain positions whereas the flexible glove is a pliable material which does not hold any shape when unpressurized.
Finally, other unique designs for extension include pneumatic and spring mechanisms seen in [35, 42]. However, those designs do not align directly with the purpose of post-stroke paresis therapy as that designed for this paper. Yap et al created a pneumatic extension mechanism geared towards the design of a Soft Robotic Glove for Hand Rehabilitation of Stroke Patients with Clenched Fist Deformity Using Inflatable Plastic Actuators. This glove was able to reach an extension torque of 1.03 Nm and did not facilitate flexion [35]. Park S. et al. sought to “present and evaluate transmission mechanisms by which exotendons can overcome hand spasticity for functional tasks with low motor forces and no rigid joints” [42]. Their design consisted of springs attached on the distal and middle phalanx anchored at the back of the hand as pictured in the figure below.

![Baseline Design of Exotendon](image)

Figure 2.10: Baseline design of the Exotendon designed by Park et al in 2018 [42]

While there are many soft robotic gloves in development, they lack user friendliness and safety and therefore are not on the market. To address the challenge of user friendliness I plan to create a lightweight, easy-to-use soft pneumatic actuating glove. To ensure user safety I will incorporate a control system which monitors the actuations through pressure
and flex sensors, providing feedback on the current position. Finally, this glove will undergo testing for passive assisted range of motion using human subjects. The human testing will consist of qualitative user evaluation data and quantitative analog data from rehabilitation exercises, further discussed in the methodology. Utilizing the improvements and developments from prior years, the goal of this design is to develop an enhanced unique soft robotic glove design which implements the use of steel ribbon to assist in facilitating extension without inhibiting the movement of flexion.

Altogether, the design of the glove has many parameters to meet to be a feasible design for personal rehabilitation use. These parameters include making the system wearable, the glove easily donned and doffed, a control system that will make the glove safe, effective and manufactured at a feasible cost.

3. METHODOLOGY

3.1 Design:

The objective of this project is to create a therapeutic soft robotic glove that facilitates extension without compromising flexion in post stroke rehabilitation. Optimizing a soft pneumatic glove with steel ribbons requires two general categories be taken into consideration. These include those to satisfy the technical parameters and to satisfy the practical requirements. To satisfy the technical parameters, this glove needs to reach or exceed the standards set by previous designs discussed in the Literature Review. Technical parameters include the actuation pressure required for of the actuators, the output flexion force, and achievable range of motion. To satisfy the practical components of this design, cost, comfort, and ease of use, materials research and live testing must be completed.
According to Polygernios et al. the flexion force needed to manipulate objects of daily living is between 10-15 N [30]. For rehabilitative purposes, as this design is geared towards, the required amount of force would be less since the goal is to simply bring the fingers through range of motion. However, depending on the time passed since the stroke incident, patients can have spasticity and stiffer joints. Therefore it is hard to estimate the force needed since it will vary with each participant. It is estimated that the force required for a patient in the flaccid hand state would require the same amount as an unimpaired persons hand at rest. A patient receiving therapy directly following the indecent would begin in this flaccid state as discussed in the introduction.

Practically, the glove needs to be cost effective and easily fabricated. For both practicality and user friendliness, the glove needs to be transportable and light weight.

Most soft robotic gloves follow a similar base design. Generalized, this design consists of a soft robotic flexible and expandable air chamber with a constraining material fastened to one part of the actuator. As the actuator is pressurized, the unrestrained part of the actuator expands while the non-expandable part restrains linear expansion, producing a bending motion in the geometry. The design choices in this work consisted of the materials used, the shape and length of the actuators, the geometry of the air chamber. Finally, this design needed to implement a method of returning the fingers to extension after having been curled.

The final design consisted of a nylon fabric glove with actuators attached to the five fingers of the glove. There were three important layers for each of these attachments. The layer lowest, closest to the dorsal side of each finger, was the flexible steel layer. This was a thin strip of flexible stainless steel curved upwards lateral-medial wise. This layer was
attached via a pocket and therefore removable or interchangeable. The steel layer served the purpose of promoting extension of the finger after flexion. The next layer up was a fabric layer embedded into the actuator with silicone. This layer was one way stretch nylon fabric and served the purpose of restraining the silicone on the bottom surface of the actuator to constrain expansion on the bottom layer. On top of the fabric was the silicone actuator with a semi-circular air chamber inside. The actuator creates the flexion motion of the finger when actuated.

Figure 3.1: Diagram showing the make-up of the layers of the soft robotic actuator finger

The material used for the actuator body in the mold was Dragon Skin 10 silicone as used in [47] due to the cost and simplicity of implementation. Dragon Skin 10 silicone is a very strong and stretchy material with high elasticity. Dragon Skin 10 has a hardness of 10 A which is the lowest Dragon Skin produced. Dragon Skin is also skin safe and does not require a vacuum chamber or heating to cure.

Silicone is a very elastic material and therefore is able to be deformed into a new shape and return to its original shape and size when the force causing the deformation is removed. The force causing deformation in this case is air pressure, which inflates the chamber inside the actuator body and causes the actuator to expand [43]. Similarly, the resistance material added to the bottom layer of nylon coated flexible steel also returns to its original shape after deformation of a certain axis. Similar to the steel found in snap bracelets and measuring tapes, the steel layer snaps back to a straight sheet when bent at any point. The geometry of the sheet of metal used also has a U shaped curve which
adds to the stiffness and elastic force which drives the metal back to the straightened position.

Figure 3.2: Front and Side view of the Shape of the Flexible Steel Layer

Retractable reels that coils back in when extended were considered but places tension on the string when curled were considered as well but a reliable way to connect a string to the tip of the finger was not discovered. Due to the nature of the coil, the force is transferred to tip of the finger rather than even distributed along the length of the finger as with the flexible stainless steel. This force distribution could result in injury and discomfort whereas the flexible stainless steel is a smaller force load that is distributed and brings the finger back into place in a slower and more controlled manner.

Retractable reels that coil back in when extended were considered, but the recoil created too much force in a short period of time. Due to the nature of the coil, the force is transferred to tip of the finger rather than even distributed along the length of the finger as with the flexible stainless steel. This retractable reel force distribution could result in injury and discomfort whereas the flexible stainless steel is an evenly distributed smaller force load which returns the finger back into place in a slower and more controlled manner.

Due to the condition of post stroke patients, the return motion of the hand needs to be slow and gentle. If therapy moves the muscle too quickly or forcefully, it can elicit abnormal muscle tone which can cause more spasticity [12].
The silicone actuators were based around the design of Gerges et al [28] due to the efficacy of Gerges’ published results and easily accomplished fabrication mold design. The actuators were dimensioned to mimic the length and width of average human fingers [28].

![Figure 3.3: dimensions of height and width of the actuators for each of the four fingers](image)

The mold was for the silicone actuator was altered from the design of Gerges [28]. The inner rod was re-designed so it could be 3D printed lying flat rather than upright. This allowed the rod to be bendable due to the long length of the 3D printed layers. This made the process of removing the rod after the solidification of the silicone much more achievable. This also made the rod easier and faster to 3D print.
Figure 3.4: mold rod design compared to rod design used in [28]

This design uses a pneumatic chamber rod which has a combined semi-circle and rectangle cross-section based on the design from Gerges [28]. The semicircular cross section was selected based on results from Polygernos et al. [30].

Figure 3.5: Diagram of the cross sectional area of the actuator including the fabric and steel layer at the bottom
3.2 Analytical Modeling

3.2.1 Cross section

Polygerinos et al. studied the modeling of soft fiber-reinforced bending actuators in which the cross sectional shapes of the pneumatic chambers were assessed [30]. Their model defines a consistent cross sectional area of $a^2$, a ratio between rectangular edges, $v$, and an assumed wall thickness of $t=a/4$, input air pressure of $P_{in}$, and bending torque $Ma$. They used the following equations shown in equations below to model the estimated moment applied to the distal surface of the actuator when pressurized [30].

\[
M_{a}^{RT} = \frac{0.5}{v} a^3 P_{in}
\]
\[
M_{a}^{HC} = 0.34 a^3 P_{in}
\]
\[
M_{a}^{FC} = 0.72 a^3 P_{in}.
\]

Figure 3.6: Equations and diagramed associated cross sections where RT is a rectangular cross section, HC is a hemi circular cross section, and FC is a circular cross section [30].

HC was found to require the least amount of pressure to achieve the same bending angle as FC and RT. Thus, concluding that the most efficient shape to achieve the most torque for a consistent pressure is a hemi circular shape [30].
Figure 3.7: Data comparing actuators with three different cross sections each of the same area in the performance of bending resistance for varying bending angles [30]

3.2.2 Actuator with steel layer

The modeling of soft fiber-reinforced bending actuators put the material characteristics, achievable bending angle, and expected bending torque output of the actuators into terms of mathematical equations. These equations closely follow that of Heung et al. in their modeling of a soft robotic actuator with a steel layer underneath. The model used in Heung et al. was a square shaped pneumatic chamber and actuator and a flat steel layer. The model has been adapted to use the semicircular shaped air chamber and actuate as well as a curved piece of metal.

The static diagram can be used to find the expected maximum angle given a known amount of pressure by using the summation of torques occurring at the bend. This includes taking the moment caused by the forces of pressure, material stress, and steel about the actuator.

\[
M_{\text{pressure}} + M_{\text{stress}} + M_{\text{layer}} = 0 \quad [33]
\]

\(M_{\text{pressure}}\) is the moment created from the input pressure, \(M_{\text{stress}}\) is the bending moment created by the internal principle stresses from the materials, and \(M_{\text{layer}}\) is the moment created by the stainless steel layer.
In order to model the actuator, the cross sectional area variables were defined as \( t \), the thickness of the silicone wall, \( r \), the inner chamber radius, and \( h \), the thickness of the stainless steel layer [33]. For the moment caused by pressure, the curvature of the steel is neglected and estimated as a consistent height from the neutral axis for simplicity. This is reasonable due to the significantly larger thickness of the actuator in comparison to the steel. Note this is not the case in the illustration as \( h \) has been made thicker for the purpose of being able to visually represent the parameters.

![Diagram](image)

**Figure 3.8**: Diagram showing the parameters used in the calculation for moment created by air pressure for the semicircular cross section actuator and semicircular shaped air chamber. Representation is not drawn to scale.

In order to find the moment created by the pressure, the semicircular shape must be integrated from 0 to \( r_p \), where \( r_p \) is the radius of the air chamber and 0 represents the point of the neutral axis shown in figure 3.8.

\[
M_{\text{pressure}} = \int_A (P)(l) \, dA \quad [28]
\] (2)
Where $P$ is the input pressure, $A$ is the area of the air chamber, and $l$ is the length of the moment-arm from the neutral axis. Adding the parameters resulted in the equation shown below where $t$ is the thickness of the actuator walls and $h$ is the height of the steel layer.

$$M_{\text{pressure}} = S_0^P \left( \sqrt{r_P^2 - y^2} \right) (P \left( y + t + \frac{h}{2} \right) \, dy \right)_{[33]}$$

(3)  

$$M_{\text{pressure}} = \left( \frac{r_P^3}{3} + \frac{\pi r_P^2 t}{4} + \frac{\pi r_P^2 h}{8} \right) P$$

(4)  

The final mathematical representation for the moment created by pressure, $M_{\text{pressure}}$, is a direct function of pressure however is not a function of the bending angle theta.

The torque created by the steel layer is given by the bending moment of the longitudinal stress in the steel layer. This can be modeled similar to [33] as a thin plate model adapted from the Kirchoff-Love model [33].

$$M_{\text{layer}} = \frac{E I \theta}{4(1 - \nu^2) L} \quad [33]$$

(5)  

Where $M_{\text{layer}}$ is the bending moment of the steel layer, $E$ is the young’s modulus of the materials, $\nu$ is poisson’s ratio, $L$ is the length of the steel layer, and $I$ is the second moment of area. In Heung et al. the steel layer has a cross section of a rectangle with a width of $b$ and a height of $h$. For this model the second moment of area was found by estimating the U shape as a hollow half circle.

$$I_{\text{semicircle}} = \frac{\pi r^4}{8} \quad (6)$$

$$I_{U\text{-shape}} = \frac{\pi r_{\text{lo}}^4}{8} - \frac{\pi r_{\text{ll}}^4}{8} \quad (7)$$
The second moment of area for the U shape was found therefore by taking the second moment of area of a semicircle and subtracting the moment of area of a smaller circle inside where \( r_o \) and \( r_i \) are the radius of the outer and inner semicircles, respectively.

![Diagram showing the parameters used in the calculation for moment created by curved steel layer for the upside down U shaped cross section. Representation is not drawn to scale.](image)

Inserting the second moment of area formula for the moment caused by the steel layer gives the moment for the upside-down U shaped steel layer, \( M_{\text{layer}} \):

\[
M_{\text{layer}} = \frac{E \left( \frac{\pi r_{Lo}^4}{8} - \frac{\pi r_{Li}^4}{8} \right) \theta}{4(1 - v^2)L} = \frac{E \left( \frac{\pi r_{Lo}^4}{8} - \frac{\pi r_{Li}^4}{8} \right) \theta}{32(1 - v^2)L}
\]  

The final moment, \( M_{\text{stress}} \) is given by the internal principle stresses which can be based around the materials used. The silicone rubber Dragon Skin 10 can be modeled using the Ogden first-order hyperplastic model [33, 44].

\[
W(\lambda_1, \lambda_2, \lambda_3) = \frac{\mu_1}{\alpha_1} \left( \lambda_1(\alpha_1) + \lambda_2(\alpha_1) - 3 \right) \text{ where } \mu_1 = \frac{2\mu}{\alpha_1} \text{ [33]}
\]  

Where \( \alpha_1 \) is the strain hardening exponent and \( \mu \) is the small strain shear modulus. In order to obtain these values, a uniaxial compression test must be performed. Heung et al. obtained values for Dragon Skin 30, whereas Dragon Skin 10 was used in these
actuators. The Dragon Skin 30 has 3 times more hardness, measured in A, than Dragon Skin 10. The values found in Heung et al. were $\alpha_1 = 5.8$ and $\mu_1 = 75$ kPa. $\lambda_1, \lambda_2, \lambda_3$ are the axial, circumferential, and the radial stretches, respectively. Estimating the Dragon Skin material as incompressible $\lambda_1, \lambda_2, \lambda_3 = 1$ and $\lambda^{-1} = \lambda_3$. The circumferential strain is negligible due to the fabric layer similarly to the fiber wrappings in [33]. $\lambda_2 = 1$. The bending moment created by the stress in these three directions is given by $M_{\sigma_i}$ below.

$$M_{\sigma_i} = \int_{A} \sigma_i l dA ; \quad \text{where } i = 1, 2, 3 \ [28] \tag{10}$$

The axial stress $\sigma_1$ is treated as the principle stress and assumed to contribute the most bending moment to the stress moment in the direction of interest [33] and therefore the circumferential and the radial stress are negated. Only the axial stress, $\sigma_1$ is considered in the equation model for stress related moment where $\sigma_1$ is given by

$$\sigma_1 = -p + \lambda_1 \left( \frac{dW(\lambda_1, \lambda_2, \lambda_3)}{d\lambda_1} \right) = \mu_1 (\lambda^{\alpha_1} - \lambda^{-\alpha_1}) \ [33] \tag{11}$$

The equation for principle stretch $\lambda$ was given by [33] as the following:

$$\lambda = \frac{y + R}{R} = \frac{\theta y}{L} + 1 \ [33] \tag{12}$$

Where $\theta$ is the bending angle, $L$ is the length, and $R$ is the bending radius of the actuator. With this substitution, the equation for axial stress, $\sigma_1$, must be solved numerically. The following equation was approximated by a first-order MacLaurin series expansion at $y=0$ by Heung et al. [33]:

$$\sigma_1 \sim \frac{2\mu_1 \alpha_1 \theta}{L} y \ [33] \tag{13}$$
Since the silicone material along the bottom of the actuator contributes a negligible amount of stress compared to that of the top and sides of the actuator body, the bending moment along the bottom of the actuator can be neglected [33]. Due to the way the actuator curls, the top and side walls of the actuator are the areas where the material is put under the most stress. Everything below the neutral axis in figure 3.10 was considered the bottom layer of the actuator and was neglected in this model.

![Diagram showing the parameters used in the calculation for moment created by the material stress of the top section of the actuator. Representation is not drawn to scale.](image)

The moment from stress equation was adapted from [33] to represent the semicircular geometry of these actuators. By subtracting the statement for the inner radius of the actuator body from that of the inner radius body, the following equation was developed to represent the stress created by the top portion of the silicone body of the actuator. The simplification of the expression for $M_{\text{stress}}$ is shown below.

$$M_{\text{stress}} = \int_0^{r_{\sigma o}} (\sqrt{r_{\sigma o}^2 - y^2})(\sigma_1)dy - \int_0^{r_{\sigma i}} (\sqrt{r_{\sigma i}^2 - y^2})(\sigma_1)dy \quad (14)$$
\[
M_{\text{pressure}} + M_{\text{stress}} + M_{\text{layer}} = 0
\]

Putting together the expressions for all three of the moments from pressure, stress, and the metal layer gives the following:

\[
\frac{r_p^3}{3} + \frac{\pi r_p^2 t}{4} + \frac{\pi r_p^2 h}{8} P + \left(\frac{2\mu_1 \alpha_1 \theta}{3L}\right) (r_{so}^3 - r_{si}^3) + \frac{E (\pi r_{Lo}^4 - \pi r_{Li}^4) \theta}{32(1 - v^2)L} = 0
\]

Finally, solving for theta provided an expression to predict theta based on the pressure gives the following equation:

\[
\theta = \frac{\left(\frac{r_p^3}{3} + \frac{\pi r_p^2 t}{4} + \frac{\pi r_p^2 h}{8}\right)(-P)}{\left(\frac{2\mu_1 \alpha_1}{3L}\right) (r_{so}^3 - r_{si}^3) + \frac{E (\pi r_{Lo}^4 - \pi r_{Li}^4)}{32(1 - v^2)L}}
\]

### 3.3 Apparatus Fabrication:

This fabrication technique was comprised many layers. The first required the silicone pneumatic actuator with slits on the top and a hemi circular air chamber to be created in a 3D printed mold. Next, a single direction extensible fabric layer was added to the actuator as well as tubing to connect the chamber to the pressurization system. The third
layer a tension resisting layer of flexible stainless steel. Finally, the soft robotic actuators were attached to a glove and circuitry and air pressure system.

In order to create the silicone actuators, liquid silicone is poured over 3D printed molds and allowed to cure to take the shape of the mold. The 3D printed molds designed in SolidWorks® were dimensions designed towards a “medium finger and hand size” based on the research from [28]. Dragon Skin 10 Medium (DS10-M Smooth-On inc.) was used as the material for the synthesis of the actuators due to the quick and easy curing time; many other silicones require vacuum chambers and heating units. Dragon Skin silicone also has a lower shore hardness value at 10 A. This reduces the pressure requirement for the actuator as compared to that of other soft robotic actuators made of elastomers with a higher shore hardness. Utilization of the dragon skin material and 3D printed PLA allowed for many prototypes, and therefore a variety of geometries and sizes for optimization. Given the rapid prototyping nature of this experiment, the molds were all 3D printed on the MakerBot with a + - 0.2mm accuracy using PLA material. After extensive testing, the mold would theoretically be machined or created with a higher quality material and printer to improve accuracy and efficiency. An improved mold could be used repeatedly to make many actuators, be placed within a vacuum chamber to remove the air bubbles, and heated to set the silicone faster.

The mold fabrication design was inspired by previous designs proposed in [28,30,33, 37]. The molds are made of two parts: the body mold and the chamber rod. The body mold determines the outer geometry of the actuator, while the rod determines the shape of the void inside the actuator. The body was designed with slits that direct and facilitate the bending direction of the silicone body. To create the actuators, the dragon skin was made
according to instructed volume measurements and allowed to set within the mold for 24 hours. While the silicone was still wet, a layer of one-way-stretch fabric was plastered to the actuator with a very thin layer of silicone to create a layer for restraining the expansion of the actuator along the bottom and therefore enhancing the bending action.

Figure 3.11: SolidWorks view of the mold design for actuator with rod
The one-way-stretch nylon served the purpose of restraining the silicone on the bottom surface of the actuator to constrain expansion on the bottom layer. The actuators were
sewn to the glove, being attached via the surrounding fabric layer and careful not to create any punctures within the actuator body. Finally a thin layer of flexible stainless steel with a slight U shaped curvature from the medial to lateral aspect of each finger was added to the bottom of the actuator by inserting it into the pocket between the fabric of the glove and the fabric of the actuator. The peak of the curve was oriented upwards towards the actuator.

Figure 3.14: Photos displaying final glove assembly with stainless steel inserts (yellow)

The soft robotic glove was connected to an electro-pneumatic system mounted of a wooden platform. The hardware in this system consisted a micro air pump (Keyukang Electronic Co.), miniature solenoid valves, pneumatic pressure sensors (MPX 5500 DP) and an Arduino Mega 2560 microcontroller and four-channel IRF540N MOSFET boards. Micro air pump was powered by a 12-volt lithium ion battery and had a maximum pressure rating of 120 kPa. The air pump was able to expel air flow at a rate of 8 L/min. The
apparatus involved the pump connecting pneumatically to five 3 way pressure valves. Those pressure valves were then pneumatically connected to the pressure sensors. The 5 pressure sensors each pneumatically connected to the tubing for one of the five the soft robotic actuators. According to the parts NPX data sheet, the pressure sensors had a pressure range rating of 0-550 kPa, a response time of 1 mS, and an error of +-2.5%. The pressure valves, sensors, and MOSFETs were connected and powered by the Arduino board which was able to provide 5 V via the desktop computer. The Arduino board received power from the computer as well as fed the pressure sensor and flex sensor data into the computer programs. This data was recorded and saved through Simulink. The flex sensor circuit connected through the Arduino Mega 2560 microcontroller. The flex sensor circuit utilized 6.8 kΩ resistors. The flex sensor circuit was powered by a 5 V power supply. The five flex sensors were 2.2 inches long and non-stretchable. The diagrams for the connections of the pressure sensors and flex sensors can be found below in.

Figure 3.15: Diagram for pressure sensor MPX5500 DP
Simulink was used to control the soft robotic actuators on the glove by turning the air pump on and off and opening and closing the valves, monitor the pressure readings, and record the pressure and flex angle data. Unity software was used to create a program that would randomly output prompts for each of the five fingers five times. When a certain finger was prompted, a photo of this finger appeared on the screen and the name of the finger, ie “Thumb,” “Index,” “Middle,” “Ring”, or “Pinky”. This provided the participant with a stimulus for their motions when doing the ROM tests. The Unity code interfaced with Simulink to provide digital inputs associated with each finger, ie the “thumb” prompt would provide a digital input “1” to Simulink. These inputs were connected to a Matlab code in which the outputs controlled which valves should open and closed. Based on the input number associated with a specific finger, this Matlab code would open the valve associated with that finger to allow the pump to pneumatically activate that finger. The Simulink software was integrated the pressure readings into a for-loop which kept the pressure from surpassing a set number. The limits used in this testing was 100 kPa for the thumb, index, ring, and pinky. The middle finger was set to a limit of 120 kPa. These
limits were determined through pilot testing which evaluated what the pressure limit of each actuator length was before popping as well as what pressure was sufficient to induce bending. The flex sensor data was uploaded to, monitored, and recorded in Simulink. The flexor data was monitored through a Simulink scope during the trial in order to ensure all the flex sensors were functioning properly. The pressure sensor readings were also monitored on Simulink through numerical displays to ensure functionality and accuracy. There were many instances where the pressure sensors would not zero or the flex sensors began having a lot of noise in the data and the trial would need to be started over. The data including the time, angle values for each finger, pressure sensor values for each finger, and the Unity stimulation was compiled into a .mat file in the Simulink code. This data was analyzed in a mat lab code.

3.4 Experimental Design:

3.4.1 Blocked Tip Force:

In order to measure the output force of the glove, the blocked tip force (BTF) measurement was obtained for each of the geometries of the pneumatic chambers as well as the final design with and without the flexible stainless steel for each length of finger. The standard measurement for soft robotic actuators is the blocked tip force, or BTF to test their force output abilities [35, 37]. This allows measurement and comparison of the actuators ability generate sufficient force and torque to assist in finger flexion. The BTF is a measurement of the force produced at the tip of the actuator when pressurized. The BTF measurement prevents the actuator from creating a bending motion in order to maximize the pressure at the tip where it would be distributed throughout the glove. In this apparatus, the actuator was placed between a compressive plate on top of it and flat
surface below. The compressive plate was placed on top of the actuator and tied down to keep the actuator from inflating and bending anywhere except for the exposed distal tip which is allowed to protrude off of the bottom surface. Underneath the protruding tip of the actuator was the load cell. The transducer load cell had a limit of 20 kg and was connected using an Arduino Uno board. The load cell converted the force output by the tip of the actuator into a weight reading in grams. This was standardized through a calibration. The setup can be viewed in the figure below.

![Apparatus showing the experimental set up of blocked tip force measurements using load cell](image)

Figure 3.17: apparatus showing the experimental set up of blocked tip force measurements using load cell
Figure 3.18: close up of the blocked tip force apparatus where the tip of the actuator exposed and is barely floating above the load cell and the rest of the length of the actuator is restricted

Figure 3.19: Load Cell Circuitry Apparatus utilized in the Actuator Tip Force Output Measurements [45]

The load cell circuit was built according to Figure 3.9. The code utilized for calibration was obtained from an open source online and reading the load cell can be found in the
appendix [45]. The controlled variables in this experiment were the software used. For every actuator trial, the load cell was re-calibrated to a 50 g weight. Once the calibration was complete, the actuator was placed on a flat platform with the tip touching the load cell sensor. The actuator was constrained so only the tip of the finger would bend. The output force was documented continuously every 0.1 second on the serial monitor measured once the air pressure was started.

In order to convert the output of g to newton, it was assumed there was no acceleration acting upon the force by using the stable. The data collected was averaged over the period of time when the force had stabilized allowing the neglect of addition acceleration outside of gravity. Within the data analysis the output in grams from the load cell was multiplied by 0.0098066 in order to convert the grams to newton using gravity.

The data was analyzed to find the peak forces output within each pressurization of the actuator for each trial. There were six trials for each actuator size, three without the stainless flexible steel layer and three with. One trial consisted of the actuator starting at 0 kPa and being pressurized to up to 150 kPa while all parts of the actuator were blocked from expanding except for the tip. The overall maximum value and average peak value over the three trials was found for each of these experimental sets of data. To further evaluate the actuators, two actuators of equal length but larger chamber were tested and compared without involving the stainless steel layers. Three trials were taken for each of these actuators pressurized force output as well and compared in the results section. The index and ring finger actuators have the same dimensions and therefore were grouped into one trial.
3.3.2 Human subject testing:

The purpose of the human subject testing was to execute a feasibility study towards the efficacy of the glove within real life applications. Specifically, the implementation of the extension metal layer was evaluated to test if it output a sufficient extensive force to return the participants hand in order to perform repetitive motion therapy. In order to implement human subject testing, an IRB form was submitted and approved before testing. The testing parameters included only test subjects without history of neuromuscular disability, stroke, hand injury, or hand impairment between 18 to 60 years of age. The participants placed their wrist at a neutral support position over a raised platform where their hand hung off the edge of the platform. Their hands were kept in pronation for all trials and instructed to leave their hand at rest when not actively moving their finger during the range of motion trials. The testing consisted of five trials. These five trials were executed in varying order as to remove influence involving the fatigue or stretching of the participant's hand during the trials. In each trial, a Unity code was utilized to provide prompts or input values to the control system in which each of the five fingers was prompted five times in random order.

To ascertain the optimal position for testing 2 priorities were considered. The first was maximizing test results and the second was replicating the situation in which the pneumatic glove will foreseeably be used by post stroke patients. Finger movements occur around two main axes: flexion /extension and abduction/ adduction [46]. Flexion is the act of bending or state of not straightened while extension is the opposite an unbending movement or straightened position [47]. Abduction is movement of a body part.
away from the median plane and adduction is the movement towards the median plane [47].

In addition to flexion/extension, abduction/adduction the thumb has an additional movement. The movement of opposition/reposition which mainly offers the hand an increase in grasping and manipulating a variety of objects [49].
Figure 3.21: Movements of the thumb [50]
The subject’s wrist was positioned in neutral to maximize a resting position and assist in allowing fingers to flex and extend independently of one another.

Figure 3.22: Neutral position of the wrist [51]
The movements of the forearm are pronation / supination and are completed by the radio-ulnar complex, influenced by some specific shoulder positions. (figure 3.13 below) Supination, palm side facing the ceiling with the elbow flexed, was not as desirable an option as it may have impeded the pressure of the flex actuators. Pronation was also preferred as healthy hands approach most objects in pronation to grasp it.

To maximize the accuracy and consistency of the test results subjects were tested seated with their right shoulder slightly abducted and their elbow flexed resting on a box on a chair shown in the figure below.

![Image](image.png)

Figure 3.23: Position used for human testing and supination/pronation of forearm [52] This combination of relaxed positions allowed test subjects to sit comfortably in a side chair and assisted in isolating the desired movements of individual finger flexion and extension. In anticipation of the eventual user, a post stroke patient the process of motor recovery was considered.

Stroke patients initially experience flaccid muscles, followed by the development of patterned muscle movements, or synergies [12,13,14,53]. Synergies could be defined as a spatial configuration of the hand shape that is common across the various tasks [14,54].
Figure 3.24: Synergy or pattern of movements elicited by a brain not effected by a stroke to pick up an object. B: A synergy without vision is similar to a synergy on a post stroke patient. It requires more steps that must be broken down into smaller hand movements such as extension/ flexion, and abduction/adduction. [55]

These synergies are how the affected hand relearns purposeful movements. As spasticity develops patients are drawn into various degrees of abnormal hand flexion and pronation making it difficult to extend fingers, hence the preferred position of finger flexion and forearm pronation. Ideally the pneumatic glove should replicate normal movement.

The metacarpal heads were situated along the outer ridge of the box to allow space for the fingers to flex. Testing consisted of randomized isolated pressure applied to the dorsal side of an individual digit. Therefore, it was necessary to provide enough space to allow digits to move independently. All positions were chosen to maximize comfort and facilitate
relaxation as subjects were asked to allow the pneumatic glove to provide all hand movement.

There were three ROM trials and two pneumatic trials. In the ROM trials, the pneumatic pump was kept off and the participant was told to flex the prompted finger to the furthest to the furthest of their capabilities while remaining in their range of comfort. The participant was sat in front of a screen with their hand in pronation on the raised platform in which these prompts were given for 4 seconds with 4 second long breaks in between prompts. The first ROM trial was with only a nylon glove with flex sensors attached to record the angles. For the second and third ROM trials, the pneumatic glove was placed over the flex sensor glove to test the restrictions the pneumatic glove placed on the ROM. The second ROM was the pneumatic glove with the steel inserts and the third was without the steel inserts.
Figure 3.25: Active unassisted ROM human subject testing in three conditions of no pneumatic glove, pneumatic glove without steel ribbon insert, pneumatic glove with steel ribbon inserts (shown left to right)

For the pneumatic trials, the soft robotic glove was actuated via the air pumps following the control code. The participant wore the pneumatic glove over the flex sensor glove with their hand in the prior mentioned position and was instructed to keep their arm and hand at rest. The bending angle of each finger using flex sensors was recorded through the entire test through the glove with flex sensors attached worn underneath the pneumatic glove. The unity prompts fed into the Simulink control system activated the bending actuators at random one at a time. Each finger movement was curled about 5 separate times in random order. The same process was observed for this glove once with the steel inserts and once without the steel inserts. The participants were also asked to complete a brief qualitative survey at the end regarding the comfort and efficacy of the glove.
The angles achieved along with the pressure values were recorded throughout the pneumatic flexions for the two pneumatic trials via Simulink. The pressure values were monitored on a display in Simulink and the peak values were monitored on a scope chart from Simulink during these trials.
4. RESULTS

4.1 Blocked Tip Force:

The result showed for the Blocked Tip Force Measurements that the addition of the steel layer lowered the blocked tip force by an average of 18.13% for all five fingers.

Table 4.1: Percent decrease in blocked tip force when adding steel layer

<table>
<thead>
<tr>
<th>Percent decrease in blocked tip force when adding steel layer</th>
<th>Middle</th>
<th>Index/ring</th>
<th>Thumb</th>
<th>Pinky</th>
<th>Average All Fingers</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.14%</td>
<td>17.61%</td>
<td>18.65%</td>
<td>21.13%</td>
<td>18.13%</td>
<td></td>
</tr>
</tbody>
</table>

The index/ring fingers were tested as one actuator because the mold dimensions for those actuators were the same. The middle showed the smallest change in blocked tip force at 15.14% percent decrease when adding the steel while the pinky showed the largest difference with a 21.13% difference.

![Average Maximum Blocked Tip Force for 3 Trials](image)

Figure 4.1: Comparison of blocked tip force per actuator of each finger with and without the layer of stainless flexible steel.
4.2 Human subject testing:

Ten people participated in the human subject testing for this experiment. The study participants averaged an age of 38 years old and ranged from ages 23-60 years old. The pool of subjects was of 60% male and 70% right hand dominant. No participants showed a history of hand injury, neuromuscular issues, or stroke paresis as required. The subjects had a wide variety of hand sizes. Their finger lengths were recorded and averaged in the table below. On average, the thumb and pinky were shorter than the length of the gloves corresponding fingers while the index, middle, and ring fingers were greater than that of the glove.

Table 4.2: Average length of the participants’ fingers compared to the length of the gloves used with standard error

<table>
<thead>
<tr>
<th></th>
<th>thumb</th>
<th>index</th>
<th>middle</th>
<th>ring</th>
<th>pinky</th>
</tr>
</thead>
<tbody>
<tr>
<td>average for all</td>
<td>6.31 ± 0.23</td>
<td>9.15 ± 0.40</td>
<td>9.99 ± 0.35</td>
<td>9.44 ± 0.36</td>
<td>7.22 ± 0.48</td>
</tr>
<tr>
<td>participants</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flex sensor glove</td>
<td>6.5 ± 0.25</td>
<td>9 ± 0.25</td>
<td>9.5 ± 0.25</td>
<td>8.5 ± 0.25</td>
<td>8 ± 0.25</td>
</tr>
</tbody>
</table>

4.2.3 ROM human subject testing:

In testing the ROM, the baseline (no pneumatic glove condition) data showed, on average, the ROM was smallest at the pinky. In order from smallest average ROM peak angle achieved to greatest, the order went from pinky at 52 degrees, middle at 68 degrees, ring at 79 degrees, index at 87 degrees, and thumb at 91 degrees. The pinky
showed the least variation in the 3 conditions tested whereas the pinky showed the largest variation in the 3 conditions results. In comparing the differences between the average ROMs accomplished in the three different conditions for the unassisted trials, the thumb, index, middle, and ring show a variance within 10 degrees or less for all three conditions. The pinky shows a variance of 34 degrees between the trials.
Table 4.3: Average maximum angle in degrees for 10 subjects' ROM trials comparing 3 cases of no pneumatic glove, with pneumatic glove with steel, and with pneumatic glove without steel

<table>
<thead>
<tr>
<th></th>
<th>Average angle (degrees)</th>
<th>Standard error (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thumb</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>no pneumatic glove</td>
<td>91.03</td>
<td>5.05</td>
</tr>
<tr>
<td>with pneumatic glove without steel</td>
<td>92.33</td>
<td>5.40</td>
</tr>
<tr>
<td>with pneumatic glove with steel</td>
<td>96.18</td>
<td>4.10</td>
</tr>
<tr>
<td><strong>Index</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>no pneumatic glove</td>
<td>87.20</td>
<td>5.61</td>
</tr>
<tr>
<td>with pneumatic glove without steel</td>
<td>91.54</td>
<td>4.83</td>
</tr>
<tr>
<td>with pneumatic glove with steel</td>
<td>97.39</td>
<td>3.53</td>
</tr>
<tr>
<td><strong>Middle</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>no pneumatic glove</td>
<td>68.60</td>
<td>5.48</td>
</tr>
<tr>
<td>with pneumatic glove without steel</td>
<td>76.62</td>
<td>6.24</td>
</tr>
<tr>
<td>with pneumatic glove with steel</td>
<td>74.49</td>
<td>6.21</td>
</tr>
<tr>
<td><strong>Ring</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>no pneumatic glove</td>
<td>79.01</td>
<td>6.83</td>
</tr>
<tr>
<td>with pneumatic glove without steel</td>
<td>83.96</td>
<td>6.94</td>
</tr>
<tr>
<td>with pneumatic glove with steel</td>
<td>82.51</td>
<td>7.16</td>
</tr>
<tr>
<td><strong>Pinky</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>no pneumatic glove</td>
<td>52.40</td>
<td>3.78</td>
</tr>
<tr>
<td>with pneumatic glove without steel</td>
<td>82.79</td>
<td>8.38</td>
</tr>
<tr>
<td>with pneumatic glove with steel</td>
<td>86.25</td>
<td>7.34</td>
</tr>
</tbody>
</table>
The graph below shows the angle reading from the flex sensor of the five nonsequential trials for each finger for subject 01 and subject 4 comparing 3 cases of no pneumatic glove, with pneumatic glove with steel, and with pneumatic glove without steel. For the purpose of visual comparison for the results of each individual finger, the five nonsequential instances have been placed alongside one another. These two sets of data showed the largest and smallest differences between the conditions consistently. Subject 01 consistently shows a trend of “no glove” condition shown in blue being about 40 degrees or more lower than those trials with the pneumatic glove shown in red and green. Subject 04, in contrast, consistently a trend of “no glove” condition shown in blue being about 20 degrees or less lower than those trials with the pneumatic glove shown in red and green for the thumb, index, and ring finger. Subject 04 shows a larger decrease for no glove condition for the cases of the middle finger and pinky finger.
Figure 4.2: Range of Motion for 5 nonsequential instances of participant actuated finger curling with no pneumatic assistance for 3 different conditions of wearing no pneumatic glove (shown in blue), wearing the pneumatic glove with steel inserts (shown in red), and wearing the pneumatic glove without the steel (shown in green) for subject 01.
Figure 4.3: Range of Motion for 5 nonsequential instances of participant actuated finger curling with no pneumatic assistance for 3 different conditions of wearing no pneumatic glove (shown in blue), wearing the pneumatic glove with steel inserts (shown in red), and wearing the pneumatic glove without the steel (shown in green) for subject 04.
4.2.2 Pneumatic Assisted Human Subject Testing:

Figure 4.4: Best fit line of angle vs pressure for 10 subjects using averaged point-slope intercept m and b values for five the fingers

In comparing the best fit line of angle vs pressure using averaged point-slope intercept m and b values for all of the subjects shown in figure 4.5, the slopes all follow a positive trend of increasing pressure results in increasing angle. The thumb, index, middle, and ring finger produce lines for with and without the steel that stay within about 10 kPa of one another for any given angle. The pinky is an outlier in this trend, as the ‘with steel’ trial produced an almost flat line slope of 0.008.

Another comparison of the pneumatic conditions for with and without steel were the peak angles achieved for each condition during their trials as displayed in the table below.
Table 4.4: average peak angles and associated pressure values averaged for 10 subjects for each of the 5 fingers compared between 2 conditions of pneumatic actuator with and without the steel layer.

<table>
<thead>
<tr>
<th>finger</th>
<th>condition</th>
<th>average values for peak angle, associated pressure, and standard error</th>
<th>% difference of with vs without steel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>angle (degrees)</td>
<td>standard error for angle</td>
</tr>
<tr>
<td>thumb</td>
<td>without steel</td>
<td>61.17</td>
<td>3.97</td>
</tr>
<tr>
<td></td>
<td>with steel</td>
<td>58.95</td>
<td>4.43</td>
</tr>
<tr>
<td>index</td>
<td>without steel</td>
<td>85.80</td>
<td>4.12</td>
</tr>
<tr>
<td></td>
<td>with steel</td>
<td>87.02</td>
<td>5.39</td>
</tr>
<tr>
<td>middle</td>
<td>without steel</td>
<td>64.81</td>
<td>4.92</td>
</tr>
<tr>
<td></td>
<td>with steel</td>
<td>60.46</td>
<td>4.39</td>
</tr>
<tr>
<td>ring</td>
<td>without steel</td>
<td>69.70</td>
<td>6.86</td>
</tr>
<tr>
<td></td>
<td>with steel</td>
<td>55.56</td>
<td>5.22</td>
</tr>
<tr>
<td>pinky</td>
<td>without steel</td>
<td>97.97</td>
<td>6.69</td>
</tr>
<tr>
<td></td>
<td>with steel</td>
<td>74.11</td>
<td>5.89</td>
</tr>
</tbody>
</table>

Table 4.4 compares the average peak angle and the associated pressures by finding the percent difference. For the thumb, middle, ring and pinky finger, the “without steel” produced a larger average peak angle than the “with steel” conditions. However, the “with steel” peaked at a lower pressure for those cases. Following same trend as the other data, the pinky is an outlier in the case of table 4.3 comparing the cases of with and without steel where the percent differences for the pinky angle is 24% with a very small difference in pressure of -1.85%. The middle finger in this table also shows a significantly larger angle difference in comparison to the thumb, index, and middle finger, however the associated pressure is also significantly increased and therefore follows the trend of the other fingers.
Table 4.5: Percentage of “no glove” condition ROM met by peak angles during pneumatic actuation Trials with and without steel layer

| Percentage of Ungloved Baseline ROM Accomplished with Pneumatic Actuation |
|-----------------------------------------------|---------------|
| Finger                          | Condition     | Percentage (%) |
| thumb                          | without steel | 67.20          |
|                                | with steel    | 64.76          |
| index                          | without steel | 98.40          |
|                                | with steel    | 99.79          |
| middle                         | without steel | 94.48          |
|                                | with steel    | 88.13          |
| ring                           | without steel | 88.22          |
|                                | with steel    | 70.33          |
| pinky                          | without steel | 186.97         |
|                                | with steel    | 141.44         |
| Average                        | without steel | 107.05         |
|                                | with steel    | 92.89          |
| Average not including pinky    | without steel | 87.07          |
|                                | with steel    | 80.75          |

On average, the pneumatic actuations without the steel layer reached a peak angle that was 7% higher than the participants baseline ROM. The pneumatic actuations with the steel layer reached an average peak angle that was 7.2% lower than the participants baseline ROM.

The mathematical model from the methodology was calculated in Matlab for pressure values 0-120 kPa and plotted against the experimental data for the ring finger and index finger as shown in the plots below. Due to the uncertainty of the parameters $\alpha_1$ and $\mu_1$, the strain hardening exponent and small strain shear modulus, respectively, from the lack
of information available on these values for Dragon Skin 10, values for Dragon Skin 30 silicone were utilized rather than Dragon Skin 10. The values for Silicone Dragon Skin 30 of $\alpha_1 = 5.8$ [55] and $\mu_1 = 75449$ Pa [55] were used with assumed negligible difference for Silicone Dragon Skin 10, which has 1/3 the hardness rating of Silicone Dragon Skin 30. To test the effect of the parameter most related to hardness, the strain hardening exponent, the value was also plotted as 1/3 the value and 3 times the value. Poisson's ratio and Young's modulus were estimated to be those of C1095 steel alloy [68]. The length used was L= 150 mm which is the same as that of the index and ring actuators used in the experimental data. These outcomes were plotted in the graphs shown below.

Figure 4.5: Theoretical model of pressure vs bending angle for actuator with steel layer graphed alongside the experimental of a pressure vs bending angle for actuator with steel layer for the index finger.
Figure 4.6: Theoretical model of pressure vs bending angle for actuator with steel layer graphed alongside the experimental of a pressure vs bending angle for actuator with steel layer for the ring finger
Figure 4.7: Theoretical model of pressure vs bending angle for actuator with steel layer graphed alongside the experimental of a pressure vs bending angle for actuator with steel layer for the pinky finger.
Figure 4.8: Theoretical model of pressure vs bending angle for actuator with steel layer graphed alongside the experimental of a pressure vs bending angle for actuator with steel layer for the thumb finger
Figure 4.9: Theoretical model of pressure vs bending angle for actuator with steel layer graphed alongside the experimental of a pressure vs bending angle for actuator with steel layer for the middle finger.

The mathematical model from the methodology section for bending angle for actuator with steel layer graphed for pressure values of 40 to 120 kPa compared to the experimental data for the actuator with steel for the fingers shows the experimental data to show a much higher resulting bending angle at a given pressure. The $\alpha_1$ increased by a multiple of 3 produced the closest result to the experimental data of the three $\alpha_1$ values tested. However, the theoretical data was still significantly lower than the experimental data.
4.2.3 Qualitative Results of human subject testing:

Upon the end of their testing, the participants were asked to complete a brief survey about their experience with the glove. The table displays the average rating given to each category.

Table 4.6: Averaged survey results of subjects when asked to rate the pneumatic glove on comfort level where 5 is the most comfortable and 1 is the least.

<table>
<thead>
<tr>
<th>Subjects’ Comfort Rating of Glove</th>
<th>Flexion</th>
<th>Extension</th>
<th>At Rest</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>average score</td>
<td>standard deviation</td>
<td>average score</td>
</tr>
<tr>
<td>thumb</td>
<td>4.50</td>
<td>1.08</td>
<td>4.6</td>
</tr>
<tr>
<td>index</td>
<td>3.90</td>
<td>1.6</td>
<td>3.8</td>
</tr>
<tr>
<td>middle</td>
<td>4.5</td>
<td>0.97</td>
<td>4.4</td>
</tr>
<tr>
<td>ring</td>
<td>4.1</td>
<td>1.2</td>
<td>4.5</td>
</tr>
<tr>
<td>pinky</td>
<td>4.5</td>
<td>1.08</td>
<td>4.9</td>
</tr>
</tbody>
</table>

The participants were asked to give an overall score of comfort of the glove, in which 4.4 was the averaged answer. When asked to rate “Is the soft robotic glove heavy? On a scale of 1-5 where 5 is the heaviest” the participants replied with an average score of 3.8. At the end of the survey was an optional section that allowed participants to provide any other feedback or comments they had on this study. The comments included one note
that the participant thought their fingers were too short for the glove to give accurate results. No other significant comments were made.

5. DISCUSSION

5.1 Data Analysis

The results in testing the tip force output of the load cell performance showed that the addition of the flexible steel layer creates a resistance that reduces the bending force of the actuator. This reduction, however, is not significant enough to take the bending force created outside the range of sufficient force. The estimated necessary force to curl a finger ranges about 10-12 newton [47]. Measurements of the averaged maximum blocked tip force ranged from 12.7-14.1 N with the layer of steel and 15.7 - 17.2 N without the steel.

In evaluating the blocked tip force measurements in table 4.1 and figure 4.1, there is a trend between length of actuator and the percent decrease in blocked tip force when adding the layer of stainless steel. In order of length, the pinky and thumb are the same length and the shortest of the three lengths created. Therefore, the largest difference in blocked tip force between the trials with and without the steel occurred in the two shortest actuators, the thumb and pinky. The smallest difference in blocked tip force between the trials with and without the steel occurred in the longest actuator, the middle finger.

In the design of this study, it was known that the target audience this glove is designed for would not be within the qualified pool of participants. The study participants averaged an age of 38, ranging from age 23-60. According to Stanford health care, the majority of stroke patients are older than 65 years of age. While this glove is designed for those with hand impairment, no eligible participants were allowed to have a history of hand injury,
neuromuscular issues, or stroke paresis. While this population does not accurately represent the pool of people this glove is designed for, this study provided a strong baseline of data in investigating the efficacy and limitations of the glove when put into practice on varying hand sizes, strengths, and other characteristics. Furthermore, utilizing participants without hand impairment allowed for the opportunity of comparing the pneumatic gloves range of motion to that of an unimpaired person’s baseline ROM.

The baseline ROM data showed the thumb having the greatest range of motion in figure 4.2. This was expected due to the anatomy of the hand. The thumb’s metacarpal bone is connected via a saddle joint whereas the other fingers are connected via hinge joints. This allows the thumb to have a larger range of motion. It is also regularly used in everyday tasks and therefore the flexion of the thumb is a familiar movement for most people.

![Figure 5.1: anatomy of the hand for reference of digits and joints [56]](image)
On the contrary, the dramatic difference in range of motion is not as explicable based solely on anatomy. While the pinky is the smallest and less used in daily tasks for individual flexion, the range of motion is relatively comparable to that of the other hinged fingers [18]. One possible explanation for the very small ROM recorded for the pinky finger is due to the flex sensor placement. Since the pinky tended to be shorter than the length of the glove as seen in table 4.2, the flex sensor usually extended beyond the edge of the pinky. The flex sensors were found to give stronger signals if bend at the tip. For one subject, the pinky flex signals were not showing up at all until the glove was pulled all the way down and fixed at the wrist to keep the pinky reaching the end of the flex sensor. It was noted this subject had small hands and thin fingers for the size of the glove. While the glove was pulled as far down the wrist as possible for each subject, the webbing between the index, middle, and ring would usually restrain the glove before the pinky could fill the pinky hole in the glove. As seen in table 4.2, the gloves spaces for the index, middle, and ring were usually shorter than the length of the finger while the pinky was longer. The tightness of the glove could also affect the results as some people have wider fingers than others. In the case of thinner fingers, the finger would have more space to move within the glove before pulling the fabric taught and moving the flex sensor.

The length issue of the glove on the pinky also provides an explanation for the dramatic change in range of motion seen in the pinky in when the pneumatic gloves were added. Since the silicone actuator provides a stiff material over the flex sensor which matches its length, the actuator causes the tip of the flex sensor to bend when it is flexed increasing the angle reading of the flex sensor.
The data of subject 01 vs subject 04 displays the large differences in range of motion per subject occurring within the human subject testing. Factors for these differences could include hand size, finger lengths, range of motion, and effort on part of the subject.

In comparing the best fit line of angle vs pressure using averaged point-slope intercept m and b values for all of the subjects shown in figure 4.5, the slopes all follow a positive trend of increasing pressure results in increasing angle. This trend is comparable to the publications in [28, 30, 33, 37] and was expected given the design of the actuators. The thumb, index, middle, and ring finger produce lines for with and without the steel that stay within about 10 kPa of one another for any given angle showing that there is not a significant difference in the amount of bending angle achieved for a given pressure. The outlier in this data in the pinky finger. The 'with steel' trial produced an average slope of 0.008 which was practically a flat line. This would indicate there is no increase in angle given an increase in pressure, however, the flat line occurs at a high pressure near 100 kPa. Therefore, this instead indicates the angle has already achieved a high value by the time the data begins to record the pressure and angle values. This could be attributed to the same issue that was occurring with the range of motion trials where the edge of the pinky glove is not filled by the finger length. The empty fabric at the tip of the glove is extremely easy for the glove to bend with a very small amount of pressurization. As such, the angle jumps to a high value with very small amounts of pressure and the recording only displays data after that quick jump. The steel layer exaggerates that effect immediately taking the small force and jumping to a 90 degree angle due to the geometry and material of the steel layer.
Most importantly, the steel layer was able to actively assist the extension of the glove while minimally impairing the glove’s ability perform flexion motions and reach a sufficient flexion angle. The results from the human subject testing showed a consistently achieved an average peak of 75 or greater for each finger while implementing the steel layer.

Finally, the mathematical model from the methodology section for bending angle for actuator with steel layer graphed for pressure values of 40 to 120 kPa compared to the experimental data for the actuator with steel shows the experimental data to show a much higher resulting bending angle at a given pressure for all five fingers. Due to the uncertainty of the parameters $\alpha_1$ and $\mu_1$, the strain hardening exponent and small strain shear modulus, respectively, from the lack of information available on these values for Dragon Skin 10, values for Dragon Skin 30 silicone were utilized rather than Dragon Skin 10. The difference between these two silicones is their hardness rating of 30 vs 10. Dragon Skin 30 is harder and therefore could have required more pressure to bend. As such, the parameter most related to hardness, the strain hardening exponent, was varied by a multiple of 1/3 and 3 to see how this would have affected the outcome. The $\alpha_1$ increased by a multiple of 3 produced the closest result to the experimental data of the three $\alpha_1$ values tested. However, the theoretical data was still significantly lower than the experimental data. The discrepancy between the experimental data and theoretical data in turn, was then attributed to the weight of the finger inside the glove. Since the orientation of human subject testing put the force of the fingers weight in the direction of bending, it would have created a higher bending angle. The mathematical model did not take the weight of the finger into consideration.
Finally, this design is able to be compared to other publications previously discussed in the literature review. This allows for a direct appraisal of the resulting output of the gloves performance. Table 5.1 shows various publications of soft robotic glove designs in comparison to this design, referred to as Rieger 2022 in the last row.

Table 5.1: Table comparing the characteristics and results of similar soft robotic glove designs and publications

<table>
<thead>
<tr>
<th>Author and Reference</th>
<th>Year Published</th>
<th>Tip Force Output</th>
<th>Pressure Required (kPa)</th>
<th>Weight</th>
<th>Extension method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polygerinos et al [32]</td>
<td>2015</td>
<td>8 N</td>
<td>345</td>
<td>285 g</td>
<td>none</td>
</tr>
<tr>
<td>Wang et al. [34]</td>
<td>2016</td>
<td>8 N</td>
<td>345</td>
<td>285 g</td>
<td>none</td>
</tr>
<tr>
<td>Zhao et al [36]</td>
<td>2016</td>
<td>5 N</td>
<td>270</td>
<td>/</td>
<td>none</td>
</tr>
<tr>
<td>Yap et al [38]</td>
<td>2017</td>
<td>9.12 N</td>
<td>120</td>
<td>180 g</td>
<td>none</td>
</tr>
<tr>
<td>Heung et al [33]</td>
<td>2019</td>
<td>/</td>
<td>200</td>
<td>207 g</td>
<td>Torque compensating layer</td>
</tr>
<tr>
<td>Gerges et al [28]</td>
<td>2019</td>
<td>9.5 N</td>
<td>180</td>
<td>120 g</td>
<td>none</td>
</tr>
<tr>
<td>Chizik et al [40]</td>
<td>2021</td>
<td>14 N</td>
<td>120</td>
<td>196 g</td>
<td>spring layer of metal</td>
</tr>
<tr>
<td><strong>Rieger</strong></td>
<td><strong>2022</strong></td>
<td><strong>12 N</strong></td>
<td><strong>120</strong></td>
<td><strong>149 g</strong></td>
<td>Steel layer</td>
</tr>
</tbody>
</table>

5.2 Areas for improvement:

While this novel glove has shown much promise given these results, it also has much room for improvement. The margin for error within the fabrication of the silicone actuators...
leads to a wider-than-desired tolerance within the final product. The plastic rod does not print consistently at a 90 degree angle and this leads to a need to adjust the rod. Another issue which rose within 3D printing the parts is the holes 3D printed for the rods often had to be manually enlarged or printed larger than desired in order to fit the rod snuggly. For many of the molds, tape and hot glue were used in order to keep the rod straight down the center. This is only performed to the accuracy of the eye as to what “looks straight.” Having the rod and therefore the chamber tilted within the body of the actuator leads to slight curling towards the left or right in the pressurized state.

Another possible issue with the fabrication are the air bubbles. While Dragon Skin states it does not need to be cured in a vacuum chamber, Dragon Skin is designed for use in costume and molds. It is not designed with inflation in mind. Some of the actuators inflate created inflated more in certain areas than others causing an uneven bending motion in the finger. One possible explanation is that an air bubble created an empty space near the rod and therefore an imperfection in the rod chamber. If the rod chamber is not a consistent geometry, one area of the actuator will expand differently than the others.

Another fabrication concern to be considered in the future is the encasing and sealing of the steel. The edges of the nylon coated steel ribbon are sharp because they have been trimmed to fit the lengths of each finger and create a minor safety concern. In future designs it would be advisable to create a thicker fabric pocket or edge protector. Hot glue and silicone were tried around the flexible steel in order to create a protective sealant however neither adhered well enough to stay through the repeating bending and straightening process.
Finally, due to the consistent length and position of the flex sensors on the glove, the angle reading was subject to variability of the participants hand size and finger lengths. For instance, someone with relatively shorter fingers did not have fingers which extend the full length of the gloves fingers when the between finger web space had been matched with the gloves. As a result, the flex sensor would read a curling when the finger itself had not been flexed. Instead only the empty tip of the glove had been flexed. This effect was consistently present in the data for the pinky finger. Further the flex sensors had much noise at lower angles due to the rubbing of fabric on top of it. This noise made it difficult to accurately analyze the resting angles of the glove. In future studies, a motion capture, visual recording, or laser sensing apparatus could be used to obtain very precise data on the angles achieved in testing the range of motion and using the soft robotic glove. This would provide better data of the efficacy of the steel layer towards extension between flexions.

6. CONCLUSION

6.1 Concluding Statement:

Through prototyping, evaluation, and unimpaired human subject testing, this design has shown sufficient potential and promising results. The steel layer was able to assist the extension of the glove while minimally reducing the glove's ability to perform flexion motions. It also reached a sufficient force and flexion angle during the human subject testing of 10 healthy unimpaired subjects. The results showed a consistently achieved average peak of 75 or greater for each finger while the subjects' hands were at rest during multiple trials of pneumatic assisted flexion. The blocked tip force results ranged from 12.7-14.1 N for the different sized actuators for each finger. This data shows strong
evidence that this glove would be appropriate to advance to human subject testing on those who do have post stroke hand impairments.

The ability to successfully transfer this therapeutic glove to use with post stroke patients relies on the potential combination of inducing muscle memory and exteroceptive stimuli via the elastic property of steel ribbon. Exteroceptive stimuli of the flexion of the soft robotic glove and the extension of the steel ribbon facilitates movement and provides sensory feedback. In this case the return of the steel strips to their straight position after bending deformation mimics digit extension. As affected hands are worked through the process of PROM, AAROM their muscles will be facilitated by the external stimuli of the steel strips to recall and implement the action of finger extension.

The aging population combined with other health risk factors which attribute to the high occurrence rate of stroke point to the need for new and improved rehabilitative and assistive technology. The expenses of and accessibility to occupational therapy limits the recovery of the subjects, especially during times such as COVID-19. It has been statistically shown that patients who receive therapy immediately after having a stroke improve much faster and are able to achieve a higher level of neurological return and functional improvement. At home rehabilitative therapy is possible and needed in today’s world. Seemingly small impairments like a dysfunctional hand can have life changing consequences in both physical abilities and mental health. Similarly, small advances in technology such as this therapeutic glove can have large impacts on those impairments.
6.2 Future Research:

Future research in this area could evaluate the effect of different stiffnesses of the steel layer. This could be done by stacking multiple layers of steel on top of one another or by obtaining materials of different stiffnesses. The curved geometry of the steel could also be altered and evaluated for the most effective design.

This experimental design is lacking the testing of the left hand and could be expanded to test the left hand in addition. However, since the participants tested were all unimpaired and healthy, the hands should produce similar results for each side. Majority of the test subjects were right handed, however there was no significant difference in ROM results for those right handed versus left handed. If brain signals such as EEG were taken into account, the testing of the left hand would hold significance. Future studies would also need to include an older population as hand paresis and stroke becomes more likely with aging. Finally, in the interest of sanitary practices, a latex glove can be worn for each patient underneath the soft robotic glove if the glove was to be reused for more patients.

The next step for this design would be to begin human subject testing on those with post stroke hand impairment. Further studies would need to be conducted on people experiencing hand paresis or impairments in order to get accurate results on the efficacy on the therapy applied by the glove and the range of motion it is able to output on a patient with limited range of motion. Patients with hand paresis have the possibility of stiff joints, pain with moving, spasticity, and other complications. All of which must be taken into consideration before applying the glove therapy to the patient or determining if the glove is appropriate for their condition.
REFERENCES
REFERENCES


REFERENCES (continued)


APPENDICES
Arduino Code used for load cell calibration and measurements:

/****************************************************************************
HX711_ADC
Arduino library for HX711 24-Bit Analog-to-Digital Converter for Weight Scales
Olav Kallhovd sept2017
****************************************************************************/

This example file shows how to calibrate the load cell and optionally store the calibration value in EEPROM, and also how to change the value manually. The result value can then later be included in your project sketch or fetched from EEPROM.

To implement calibration in your project sketch the simplified procedure is as follow:
	LoadCell.tare();
	//place known mass
	LoadCell.refreshDataSet();
	float newCalibrationValue = LoadCell.getNewCalibration(known_mass);
*/

#include <HX711_ADC.h>
#if defined(ESP8266)|| defined(ESP32) || defined(AVR)
#include <EEPROM.h>
#endif

//pins:
const int HX711_dout = 4; //mcu > HX711 dout pin
const int HX711_sck = 5; //mcu > HX711 sck pin

//HX711 constructor:
HX711_ADC LoadCell(HX711_dout, HX711_sck);
const int calVal_eepromAdress = 0;
unsigned long t = 0;

void setup() {
    Serial.begin(57600); delay(10);
    Serial.println();
    Serial.println("Starting...");

    LoadCell.begin();
    //LoadCell.setReverseOutput(); //uncomment to turn a negative output value to positive
    unsigned long stabilizingtime = 2000; // preciscion right after power-up can be improved
    by adding a few seconds of stabilizing time
    boolean _tare = true; //set this to false if you don't want tare to be performed in the next
    step
    LoadCell.start(stabilizingtime, _tare);
    if (LoadCell.getTareTimeoutFlag() || LoadCell.getSignalTimeoutFlag()) {
        Serial.println("Timeout, check MCU>HX711 wiring and pin designations");
        while (1);
    }
    else {
        LoadCell.setCalFactor(1.0); // user set calibration value (float), initial value 1.0 may be
        used for this sketch
        Serial.println("Startup is complete");
    }
    while (!LoadCell.update());
    calibrate(); //start calibration procedure
}

void loop() {
    static boolean newDataReady = 0;
    const int serialPrintInterval = 0; //increase value to slow down serial print activity

    // check for new data/start next conversion:
    if (LoadCell.update()) newDataReady = true;
}
// get smoothed value from the dataset:
if (newDataReady) {
    if (millis() > t + serialPrintInterval) {
        float i = LoadCell.getData();
        Serial.print("Load_cell output val: ");
        Serial.println(i);
        newDataReady = 0;
        t = millis();
    }
}

// receive command from serial terminal
if (Serial.available() > 0) {
    char inByte = Serial.read();
    if (inByte == 't') LoadCell.tareNoDelay(); //tare
    else if (inByte == 'r') calibrate(); //calibrate
    else if (inByte == 'c') changeSavedCalFactor(); //edit calibration value manually
}

// check if last tare operation is complete
if (LoadCell.getTareStatus() == true) {
    Serial.println("Tare complete");
}

void calibrate() {
    Serial.println("****");
    Serial.println("Start calibration:");
    Serial.println("Place the load cell an a level stable surface.");
    Serial.println("Remove any load applied to the load cell.");
    Serial.println("Send 't' from serial monitor to set the tare offset.");

    boolean _resume = false;
}
while (_resume == false) {
    LoadCell.update();
    if (Serial.available() > 0) {
        if (Serial.available() > 0) {
            char inByte = Serial.read();
            if (inByte == 't') LoadCell.tareNoDelay();
        }
    }
    if (LoadCell.getTareStatus() == true) {
        Serial.println("Tare complete");
        _resume = true;
    }
}

Serial.println("Now, place your known mass on the loadcell.");
Serial.println("Then send the weight of this mass (i.e. 100.0) from serial monitor.");

float known_mass = 0;
_resume = false;
while (_resume == false) {
    LoadCell.update();
    if (Serial.available() > 0) {
        known_mass = Serial.parseFloat();
        if (known_mass != 0) {
            Serial.print("Known mass is: ");
            Serial.println(known_mass);
            _resume = true;
        }
    }
}

LoadCell.refreshDataSet(); //refresh the dataset to be sure that the known mass is measured correct
float newCalibrationValue = LoadCell.getNewCalibration(known_mass); //get the new calibration value
Serial.print("New calibration value has been set to: ");
Serial.print(newCalibrationValue);
Serial.println(" use this as calibration value (calFactor) in your project sketch.");
Serial.print("Save this value to EEPROM adress ");
Serial.print(calVal_eepromAdress);
Serial.println("? y/n");

_resume = false;
while (!_resume) {
    if (Serial.available() > 0) {
        char inByte = Serial.read();
        if (inByte == 'y') {
#if defined(ESP8266)|| defined(ESP32)
            EEPROM.begin(512);
#endif
            EEPROM.put(calVal_eepromAdress, newCalibrationValue);
#if defined(ESP8266)|| defined(ESP32)
            EEPROM.commit();
#endif
            EEPROM.get(calVal_eepromAdress, newCalibrationValue);
            Serial.print("Value ");
            Serial.print(newCalibrationValue);
            Serial.print(" saved to EEPROM address: ");
            Serial.println(calVal_eepromAdress);
            _resume = true;
        }
        else if (inByte == 'n') {
            Serial.println("Value not saved to EEPROM");
            _resume = true;
        }
    }
}
}
Serial.println("End calibration");
Serial.println("*****");
Serial.println("To re-calibrate, send 'r' from serial monitor.");
Serial.println("For manual edit of the calibration value, send 'c' from serial monitor.");
Serial.println("*****");

void changeSavedCalFactor() {
  float oldCalibrationValue = LoadCell.getCalFactor();
  boolean _resume = false;
  Serial.println("*****");
  Serial.print("Current value is: ");
  Serial.println(oldCalibrationValue);
  Serial.println("Now, send the new value from serial monitor, i.e. 696.0");
  float newCalibrationValue;
  while (_resume == false) {
    if (Serial.available() > 0) {
      newCalibrationValue = Serial.parseFloat();
      if (newCalibrationValue != 0) {
        Serial.print("New calibration value is: ");
        Serial.println(newCalibrationValue);
        LoadCell.setCalFactor(newCalibrationValue);
        _resume = true;
      }
    }
    _resume = false;
  }
  Serial.print("Save this value to EEPROM adress ");
  Serial.print(calVal_eepromAdress);
  Serial.println("? y/n");
  while (_resume == false) {
    if (Serial.available() > 0) {
      char inByte = Serial.read();
      if (inByte == 'y') {
#if defined(ESP8266)|| defined(ESP32)
EEPROM.begin(512);
#endif
EEPROM.put(calVal_eepromAdress, newCalibrationValue);
#if defined(ESP8266)|| defined(ESP32)
EEPROM.commit();
#endif
EEPROM.get(calVal_eepromAdress, newCalibrationValue);
Serial.print("Value ");
Serial.print(newCalibrationValue);
Serial.print(" saved to EEPROM address: ");
Serial.println(calVal_eepromAdress);
_resume = true;
}
else if (inByte == 'n') {
    Serial.println("Value not saved to EEPROM");
    _resume = true;
}
}
}
Serial.println("End change calibration value");
Serial.println("****");
}

Source: HX711 with a Four Wire Load Cell and Arduino | Step by Step Guide. - YouTube
HX711 with a Four Wire Load Cell and Arduino | Step by Step Guide.