The Design and Characterization of a Soft Haptic Interface for Rehabilitation of Impaired Hand Function

by

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ABSTRACT

The human hand comprises complex sensorimotor functions that can be impaired by neurological diseases and traumatic injuries. Effective rehabilitation can bring the impaired hand back to a functional state because of the plasticity of the central nervous system to relearn and remodel the lost synapses in the brain. Current rehabilitation therapies focus on strengthening motor skills, such as grasping, employ multiple objects of varying stiffness and devices that are bulky, costly, and have limited range of stiffness due to the rigid mechanisms employed in their variable stiffness actuators. This research project presents a portable cost-effective soft robotic haptic device with a broad stiffness range that is adjustable and can be utilized in both clinical and home settings. The device eliminates the need for multiple objects by employing a pneumatic soft structure made with highly compliant materials that act as the actuator as well as the structure of the haptic interface. It is made with interchangeable soft elastomeric sleeves that can be customized to include materials of varying stiffness to increase or decrease the stiffness range. The device is fabricated using existing 3D printing technologies, and polymer molding and casting techniques, thus keeping the cost low and throughput high. The haptic interface is linked to either an open-loop system that allows for an increased pressure during usage or closed-loop system that provides pressure regulation in accordance with the stiffness the user specifies. A preliminary evaluation is performed to characterize the effective controllable region of variance in stiffness. Results indicate that the region of controllable stiffness was in the center of the device, where the stiffness appeared to plateau with each increase in pressure. The two control systems are tested to derive relationships between internal pressure, grasping force exertion on the surface, and displacement using multiple probing points on the haptic device. Additional quantitative evaluation is performed with study participants and juxtaposed to a qualitative analysis to ensure adequate perception in compliance variance. Finally, a qualitative evaluation showed that greater than 60% of the trials resulted in the correct perception of stiffness in the haptic device.

ACKNOWLEDGMENTS

My sincerest gratitude to everyone in the Bio-Inspired Mechatronics Laboratory, and the Neural Control of Movement Laboratory for their relentless support and guidance without which this project would not be possible. I would like to especially thank Dr. Polygerinos for his patience and mentorship, Dr. Santello for his expert advice, and Dr. Fu for his innovative ideations.

To my friends and family, thank you for believing even when I didn’t.

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PREFACE

The following thesis is the work I have put in for the development of a soft-haptic device for the rehabilitation of impaired hand function. I worked on this project for a year in the Bio-Inspired Mechatronics Laboratory and produced a peer-reviewed publication and a provisional patent. I was a first author in the *Frontiers Journal* publication that serves as the primary basis for this manuscript (Sebastian et al. 2017). The content from this publication is extracted and augmented in the different chapters of this thesis where it was deemed appropriate.

CHAPTER 1

INTRODUCTION

The human hand is a complex sensorimotor apparatus that consists of many joints, muscles, and sensory receptors. Such complexity allows for skillful and dexterous manual actions in activities of daily living (ADL). When the sensorimotor function of hand is impaired by neurological diseases or traumatic injuries, the quality of life of the affected individual could be severely impacted. For example, stroke is a condition that is broadly defined as a loss in brain function due to necrotic cell death stemming from a sudden loss in blood supply within the cranium (Hankey 2017). This event can lead to a multitude of repercussions on sensorimotor function, one of which being impaired hand control such as weakened grip strength (Nakayama et al. 1994; Jørgensen et al. 1995; Duncan et al. 1994; Foulkes et al. 1988; Legg et al. 2007; Wilkinson et al. 1997; Winstein et al. 2004). There are other causes of impaired hand function including but not limited to cerebral palsy, multiple sclerosis, and amputation (Fedrizzi et al. 2003; Taub et al. 2004; Krishnan and Slobodan 2008; Dezfuli et al. 2015; Murray et al. 1977). These impaired hand functions are not always a terminal condition and can sometimes be rehabilitated to a more functional state with the proper exercise and conditioning. The way the central nervous system learns to do this is similar to how other muscles in the human body get stronger with task-specific training. It has also been shown that recovery of lost sensory motor function relies on the plasticity of the central nervous system to relearn and remodel the brain (Warraich and Kleim 2010). Clinicians exploit this adaptability of the central nervous system to new stimulus using residual connections after an injury to help patients regain impaired functionalities such as grip strength during rehabilitative therapy.

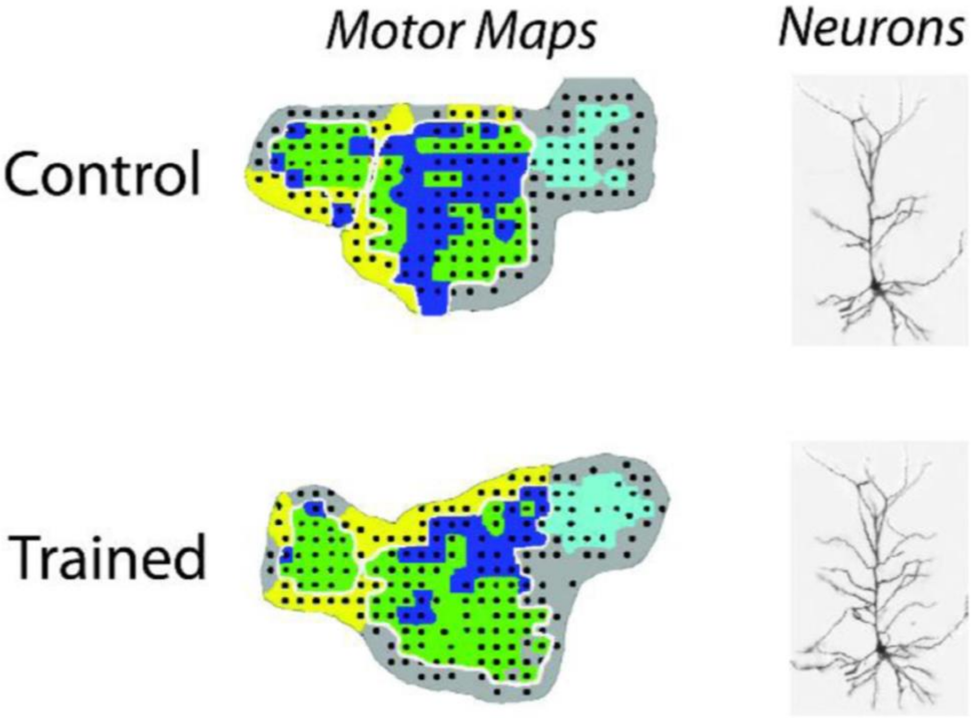

Figure 1: The schematic on the left shows the augmentation in the motor cortex for wrist-digit representation (green) in trained rat versus control animals. This training also facilitates dendritic growth in neurons, as seen on the right (Warraich and Kleim 2010)

Therefore, effective rehabilitation to help patients regain functional hand control is critically important in clinical practice. Specifically, there are several factors that are known to contribute to neuroplasticity (Kleim and Jones 2008): specificity, number of repetition, training intensity, time, and salience. However, existing physical therapy of hand is limited by the resource and accessibility, leading to inadequate dosage and lack of patients' motivation to seek these services or consistently follow the regimen. This has led to a growing interest in developing simple yet efficient rehabilitative devices that can be utilized in both clinical and home settings.

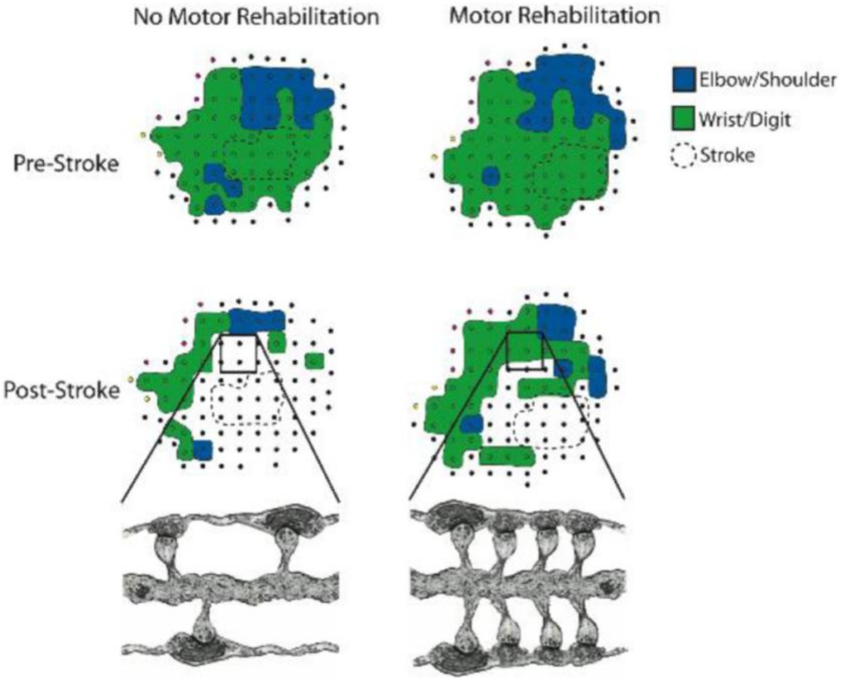

Figure 2: Schematic depicting rats that did not receive motor rehabilitation post-stroke (left column) and those that did (right column). An increased amount of synaptogenesis is observed in rats that received rehabilitation versus those that did not (Warraich and Kleim 2010)

Robot-assisted hand rehabilitation has recently attracted a lot attention because robotic devices have the advantage to provide 1) enriched environment to strengthen motivation, 2) increase number of accurate repetition through automated control, and 3) progressive intensity levels that adapts to patient's need (for a more comprehensive review, see Balasubramanian et al. 2010).

Specifically, haptic interfaces and variable stiffness mechanisms are usually incorporated into robotic rehabilitation devices to provide varying difficulties by adjusting force output or stiffness. For example, the *LINarm++* is a rehabilitative device that appropriates variable stiffness actuators (VSA) with multimodal sensors to provide changing resistance in a physical environment in which users performs arm movement (Malosio et al. 2016; Spagnuolo et al. 2017). This device also encompasses a functional electrical stimulation (FES) system which has been shown to promote motor recovery in upper limb rehabilitation (Popović and Popović 2006). The *Haptic Knob* is a device that trains stroke patients' grasping movements, and wrist pronation and supination motions by rotating a dial that is able to produce forces and torques up to 50 N and 1.5 Nm respectively, depending on the patient's level of impairment (Lambercy et al. 2009). The *GripAble* is a handheld rehabilitative device that allows the patient to squeeze, lift, and rotate to play a video game with increasing difficulty and gives feedback through vibration in response to the patient's performance (Mace et al. 2015, 2017). The MIT-MANUS, a planar rehabilitation robot, also has a hand-module that converts rotary motions to linear motions, and in turn allows for controllable impedance in the device (Masia et al. 2006). These devices and systems, however, are either costly and bulky due to complex mechanical design or have limited range of stiffness due to passive mechanical components (Malosio et al. 2016; Lambercy et al. 2009; Mace et al. 2017; Masia et al. 2006).

Therefore, this research project was set out with the aim of overcoming these limitations using novel soft robotics technology. Soft robotics is a rapidly growing field that utilizes highly compliant materials that are fluidic actuated to effectively adapt to shapes and constraints that traditionally rigid machines are unable to (Majidi 2014; Polygerinos et al. 2017; Iida and Laschi 2011; S. Kim, Laschi, and Trimmer 2013). This technology also allows traditional robotics systems to be developed with lighter weight without compromising its functionality.

The goal was to develop a device that has a variable range of stiffness that can be manually adjusted by the user without having to change the actual device itself. This is a common practice in hand rehabilitation where impaired users are given multiple objects of varying stiffness such as Thera-Putty for hand strengthening exercises (Moyer and Barnes 2008).

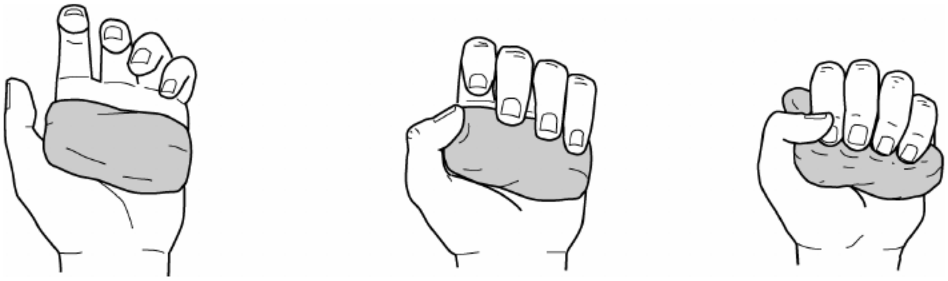

Figure 3: A full grip exercise being done with Thera-Putty (Moyer and Barnes 2008)

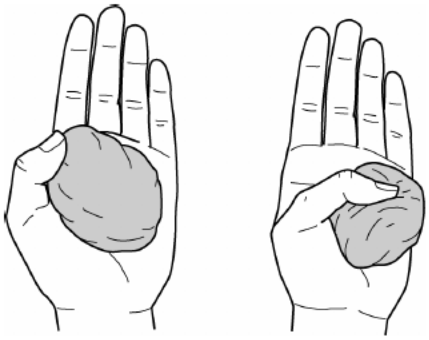

Figure 4: An isolated single digit, thumb, exercise being done with Thera-Putty (Moyer and Barnes 2008)

To achieve this goal the device needs to have a broad range of stiffness, especially, on the lower end of stiffness. This is something that current devices are unable to attain due to the rigid mechanisms that they incorporate. It is also imperative that the stiffness being incorporated into the device can be adequately perceived by the user. This specific goal is to be achieved using a haptic interface where the user can receive adequate feedback when the device is being utilized. Therefore, to ensure the efficacy of the device it was important to have human subject testing as part of the device's development process which will be highlighted in Chapter 6. This haptic device is also intended to have two modes of control: one that allows a dynamic pressure feedback while another that allows isometric pressure feedback. Incorporating more than a singular method of control allows for the device to be utilized by users with varying needs depending on the level of impairment they are experiencing.

Several soft-robotics devices have been developed to provide assistance to stroke patients, but none of these has been designed as resistive training devices. An example of an existing device includes the use of soft actuators that bend, twist, and extend through finger-like motions in a rehabilitative exoglove to be worn by stroke patients (Polygerinos et al. 2015; Polygerinos et al. 2015; Yap et al. 2017). A variable stiffness device that employs soft-robotics allows a greater range of stiffness to be implemented since there is minimal or no impedance to the initial stiffness of the device. Additionally, soft robotics methods allow devices to be manufactured with lowered cost and have much less complexity, thus suitable to be used not only inpatient but also outpatient hand rehabilitative services (Godwin et al. 2011; Taylor et al. 1996). Some of these devices and their technologies will be further discussed in Chapter 2.

i) Organization

This thesis is organized to first provide the background information about the project as a whole in Chapter 2. This includes the literature review done on current devices and the specific models this project used to benchmark. It is important to note at this point that no explicit functional requirements were set before this device was made. This was chiefly due to the fact that there is a lot of variation in existing variable stiffness devices and most of them fail to report crucial factors such as upper and lower limit of stiffness. This could also be partially attributed to the varying systems being incorporated into these devices, therefore, resulting in different stiffness measurements. Chapter 3 then discusses the justification behind the final device measurements that were decided on as well as how the design constraints were identified. This chapter also delineates the ideation process. Preliminary sketches of various prototype designs will be shown along with the reason they were either chosen or not.

Chapter 4 focuses on the methodology employed in fabricating the device. This includes the step-by-step procedure to develop the soft robotic actuator and the electronics assembly. Chapters 5 and 6 are concerned with introducing the reader to the two control systems and the characterization methods, respectively. Chapter 6 also includes the protocols used when testing the device with human subjects. Chapter 7 discusses the results obtained from the characterization as well as the human subjects testing. Chapter 8 delves into the conclusions that were drawn from the project thus far, and what directions it can be move towards in the future. An all-encompassing references section follows after the main chapters. The manuscript also includes appendices that contain information that is supplementary to the project.

CHAPTER 2

BACKGROUND RESEARCH

i) Introduction

Literature review had to be done in a few different areas before the device could be developed. The first area investigated was existing variable stiffness mechanisms. This was essential to understanding the upper and lower limit of stiffness in current mechanisms and identifying rooms for innovation. Once an effective variable stiffness mechanism was identified, a brief understanding of human perception of stiffness had to be explored. This information was not used to significantly enhance the design of the device. However, if the change of stiffness is not adequately perceived by the user then any innovation in variable stiffness design becomes irrelevant. Research was also done on the characterization method for stiffness to choose the most appropriate method this device. Then a review of existing variable stiffness devices for hand rehabilitation was done to understand methodologies that have been employed thus far. This includes exploring soft robotics rehabilitation devices that are not strictly for resistance training. Finally, to obtain the design parameters, an examination was done on human hand physiology and mechanics.

ii) Variable Stiffness Mechanisms

A few variable stiffness mechanisms were explored to understand current principles being implemented. This included exploring mechanical mechanisms as well to explore if any of these components, specifically the actuator(s), could be directly replaced with a soft-robotic component instead. It should be noted that traditionally mechanical variable stiffness actuators (VSA) fall into three primary categories: a group with actuators using preloaded spring, a group where the transmission between load and spring is manipulated, and a group where the physical properties of the spring is altered (Groothuis et al. 2014). There are a myriad of VSA designs in literature (see Vanderborght et al. 2013), therefore only a select few designs that fall in the three different groups are presented in this document.

The first preloaded spring design being explored is one that uses a timing belt to adjust the tension generated in springs of known elastic constant (Tonietti et al. 2005). The belt in this design is connected to a DC motor that can adjust its length and in turn control the force the preloaded spring exerts on the belt. A longer spring length therefore results in greater stiffness, and a shorter length results in lowered stiffness. An isolated single side of the three is shown in Figure 6 to better visualize the mechanism that allows for variable stiffness in the actuator. A few other VSA mechanisms this same group are explored but not included in this document including but not limited to the following (Grioli et al. 2008; Bram Vanderborght et al. 2009; Wolf et al. 2008).

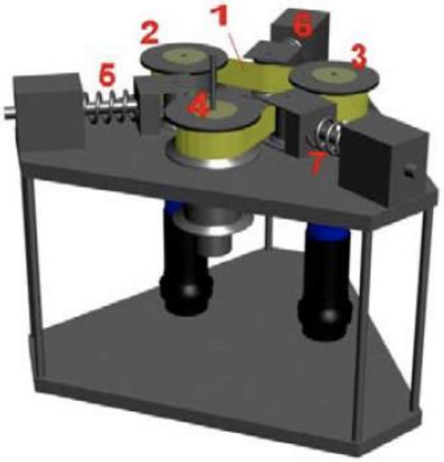

Figure 5: VSA conceptual modeling in perspective. Element 1 is the timing belt, 2 and 3 are the motor pulleys, 4 is the joint shaft, while 5, 6, and 7 are spring elements to adjust the stiffness of the belt (Tonietti et al. 2005)

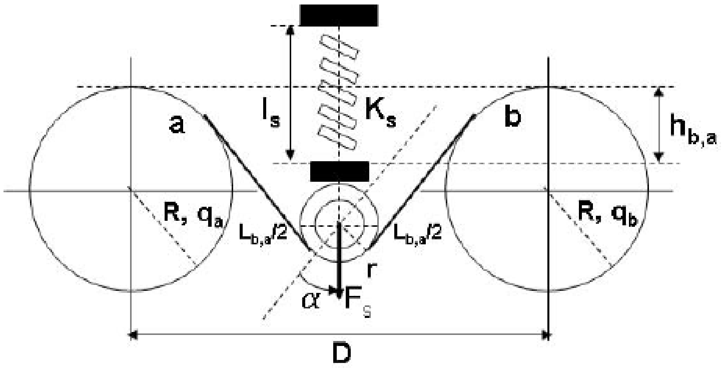

Figure 6: View of a single side to demonstrate the functionality of the variable stiffness mechanism. As the belt of a fixed length is tightened by the pulleys a and b, the preloaded spring reduces in length, ls, thus exerting greater force on the belt (Tonietti et al. 2005).

The second variable stiffness mechanism (VSM) being explored is one that falls in the group where the transmission between spring and load is changed. This VSM modifies traditional leaf springs to execute stiffness that range from zero (minimum) to infinity (maximum). This mechanism involves leaf springs that have a force couple being applied on both ends and support pins that can be displaced along the length of the leaf springs (Groothuis et al. 2014). A controllable motor with hypocycloid gears is used to adjust the support pins which affect the shape and force output of the leaf springs, therefore, altering the transmission between the load and springs. This effectively changes the stiffness of the "device" as a whole. When the points of support are directly overlapping in the middle of the leaf spring, the stiffness of the device is at its minimum, and the stiffness gradually increases as the support is moved away from the center point. When the support pins are at the extreme ends of the leaf spring the stiffness of the mechanism is at its maximum. This VSM is a concept and has not been integrated with an actuator, therefore, no actual device has been tested to show a change in stiffness. The realized VSM concept is presented in Figure 7. Other VSA mechanisms explore in this group include works by (Tsagarikis et al. 2010; B. Kim and Song 2010; S. S. Groothuis et al. 2014)

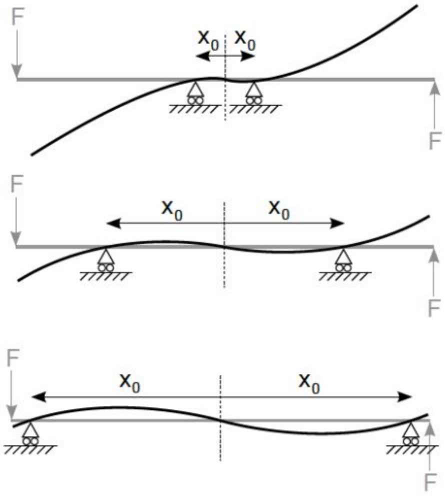

Figure 7: The gray line represents an undeflected leaf spring that transforms to a new shape (in black) when force is applied in opposing directions. The two triangle pins under the leaf spring can be displaced (along coordinates X_o) according to user needs (Groothuis et al. 2014)

The final VSA explored is one that falls in the group where the physical properties of the spring are altered. The specific VSA chosen as an example is the *Jack Spring* actuator (Hollander et al. 2005). This actuator focuses on varying the number of active coils in a spring thus manipulating the stiffness of the inactive region of the spring (Figure 8). A shaft is affixed to one end of the actuator and as the shaft is rotated it either adds or subtracts the number of active coils in the system, therefore, coupling displacement and stiffness. Additionally, the stiffness profile for this VSA is determined by characterizing the stiffness in each individual coil instead of looking at the stiffness profile of the entire spring. The shaft portion of the VSA can be actuated using a motor thus making it ideal for robotic systems (Figure 9). The utilization of this actuator for robotic systems such as a wearable ankle device to aid gait movement has also been shown for this actuator. This actuator is shown Other VSA explored in this category include works by (Choi et al. 2011; Morita and Sugano 1997).

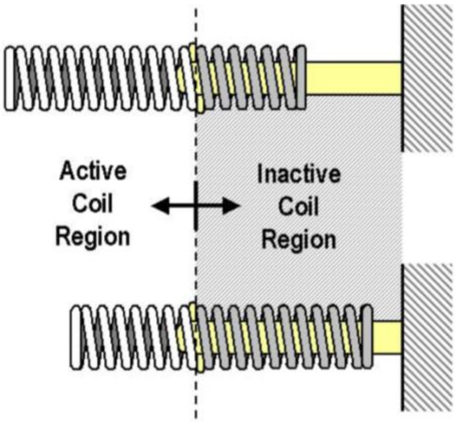

Figure 8: Diagram depicting the active and inactive regions of a spring. As the number of coils in the active region decreases the stiffness in the inactive region increases (Hollander et al. 2005)

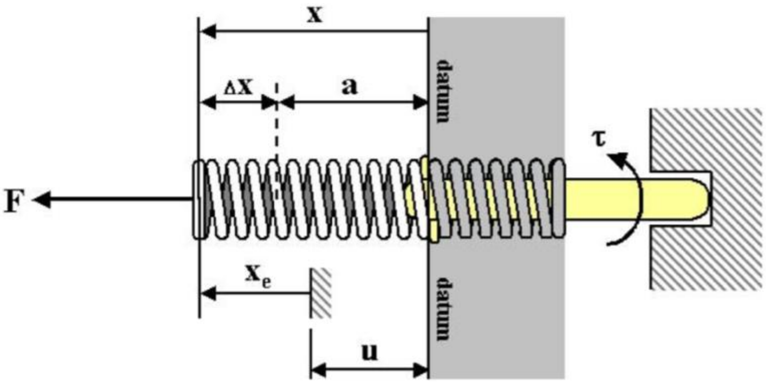

Figure 9: The Jack Spring actuator with its shaft attached to an external system to generate torque, τ. The spring in the active region is able to interact with the environment (Hollander et al. 2005)

iii) Perception of Stiffness and Stiffness Modeling

It was important to explore how stiffness is perceived by humans. This was especially true when the stiffness of the object is at a much higher value. For example, it is easy to differentiate the stiffness of a cotton ball and a plank of wood; however, the task gets more challenging when trying to discriminate the stiffness between a plank of wood and a sheet of metal of same thickness. Additionally, stiffness can be characterized in a few ways such as calculating the ratio of force exerted on the surface and the resulting displacement, identifying the material's *Young's Modulus*, and so on. Therefore, it is important to identify the right methodology for the particular device being designed.

It has been shown human perception of compliance is more reliant on stiffness for softer materials and *Young's Modulus*, which is the ratio of the pressure (force per unit area) applied on the object and its relative deformation, for harder materials (Bergmann Tiest 2010). This means that how much an object can be squeezed is a bigger factor for materials such as soft rubber, while the surface indentation is more focused on for objects that are harder. Therefore, since small strains are expected for this device, the compliance of the soft haptic interface can be characterized by the ratio of the force exerted on it and the resulting displacement (Bergmann Tiest 2010; Bergmann Tiest and Kappers 2009). The equation describing this characterization is shown in Equation 1, where k, Δx, and F represent stiffness, displacement and force applied, respectively.

$$\boldsymbol{k} = {}^{\boldsymbol{F}}\!/_{\boldsymbol{\Delta x}} \qquad \text{(Equation 1)}$$

iv) Hand Rehabilitation Devices

As it has been mentioned, there are robotic devices that have been developed for the rehabilitation of hand functions. Most of these devices are based on mechanical designs while there are a couple that are based on soft robotics designs. Two drastically different mechanical designs are described in this section while one of the soft robotic design is presented.

The first device is one that was developed by the Lambercy group called the *Haptic Knob* (Lambercy et al. 2009). This robotic device has an end-effector with two degrees of freedom designed to train grasping and wrist pronation and supination. The device is connected to a computer by a couple of moving parallelograms (Figure 10). The device allows users to either grasp the knob or rotate it. The device can measure up 30 N of force applied by the users and generate up to 50 N in opening and closing resistance, and up to 1.5 Nm in torque for the pronation and supination exercises. The device also allows attachment of various fixtures to allow training of different exercises such as pinch, lateral pinch, and so on.

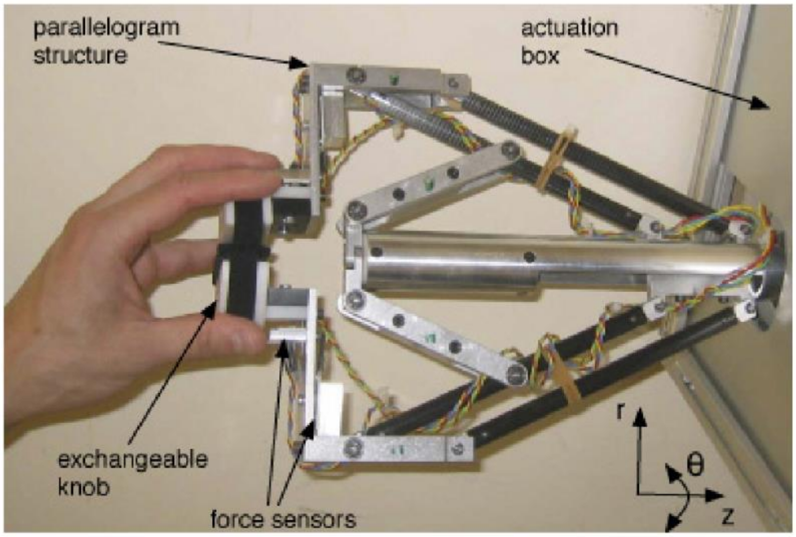

Figure 10: The Haptic Knob robotic device being grasped by a test subject (Lambercy et al. 2009)

The second device is called *GripAble* by the Mace group in Imperial College London (Mace et al. 2015). This device is pretty similar to the soft robotics haptic device presented in this document. It's a handheld device that promotes repetitive flexion and extension exercises in those with hand impairment. The device only has one degree of freedom but can provide resistant forces of up to 50 N. The device can be connected to a virtual interface so that users can complete tasks in the form of games for additional motivation factor. The games and device can be adjusted in difficulty to suit the user needs. A key feature in this device is that it detects very small movements, therefore, making it ideal even for those with severe neurological impairments.

Figure 11: The GripAble device model in both flexion and extension (Mace et al. 2015)

The soft robotic based variable stiffness device being presented is an exoglove to be used for home rehabilitation (Polygerinos et al. 2015). This device is made of silicone actuators to be worn by impaired users. The device aids users in grasping activities post a neurological impairment such as stroke. The actuators fit over individual fingers and can be pneumatically actuated separately depending on the user's needs. This device has low impedance when it is not actuated, and it can generate forces of up to 8 N. There has been a similar soft robotic based device that is not shown due to the similarity between both devices. The major difference between these devices is that the second is made with fabric actuator with plastic inner lining instead of silicone (Yap et al. 2017).

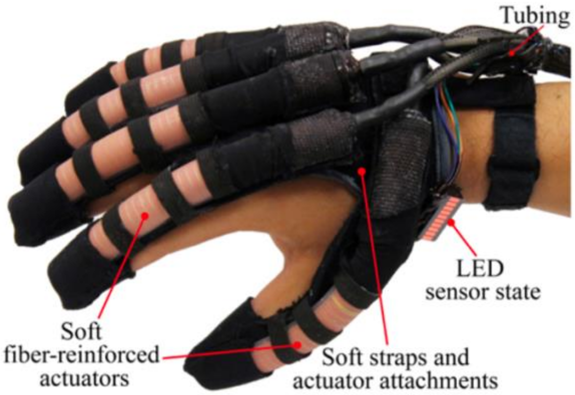

Figure 12: The prototyped soft robotic rehabilitation device (Polygerinos et al. 2015)

Table 1: Summary of key parameters of existing variable stiffness hand rehabilitation devices

	Haptic Knob	**MIT-MANUS**	**Elastomeric Exoglove**	**Fabric Exoglove**	**GripAble**
Mechanism	Rigid	Rigid	Compliant	Compliant	Rigid
Variable Stiffness	×	×	×	×	✓
Adjustable Stiffness Range	×	×	×	×	×
Degree of Freedom	2	8	3 per finger	2 per finger	1
Weight	Heavy	Heavy	Light	Light	Medium
Size	Large	Large	Medium	Medium	Small
Device Support	Mounted	Mounted	Handheld	Handheld	Handheld
Portable	×	×	✓	✓	✓
Haptic Feedback	×	×	×	×	✓
Low-Cost	×	×	✓	✓	✓
Max. Torque	1.5 Nm	0.8 Nm	n/a	1.24 Nm	n/a
Max. Force	50 N	50 N	~8 N	~9 N	~ 50 N

Table 1 summarizes key aspects about five existing hand rehabilitation devices based on what is provided in their respective literature (Lambercy et al. 2009; Masia et al. 2006; Polygerinos et al. 2015; Yap et al. 2017; Mace et al. 2015). The soft haptic device designed for this research project has more similar aspects to the *GripAble* than the other devices delineated in this table.

CHAPTER 3

DESIGN, FABRICATION & CONTROLS

i) Introduction

A few prototype concepts were modeled before a final design was chosen. These designs were conceptualized after evaluating existing variable stiffness mechanisms and devices. The designs are presented in this chapter and the finalized model is identified. The designs were evaluated qualitatively because the functional requirements for this haptic device could not be determined based on existing designs. This is mainly due to the large variability in haptic device designs and in the functionality of variable stiffness mechanisms. Variable stiffness haptic devices can be grouped together based on their mechanisms, but most of these products do not report their specifications such as range of stiffness, range of motion, grip aperture, sensitivity and so on. Therefore, values from literature was used to identify the design constraints for the final device.

Table 2: Functional requirements for a soft haptic device

Parameter	**Requirements**
DOF	At least 1 (grasping)
Control Methods	At least 2
Size (Height, Width)	~85 mm, ~40 mm
Portability	Portable for home and clinical use
Stiffness Range	Broad with option to adjust
Min. & Max. Stiffness	0 N/mm & 5N/mm
Weight	<0.5 kg,
Cost	<$200

ii) Prototype Concepts

The following prototype designs are presented as closely to the order they were initially conceptualized. The advantages and limitations of each design is detailed to provide a logical path towards the chosen final design. The model drawings are mere concepts and the possible iterations of a particular design are also discussed but not represented with figures.

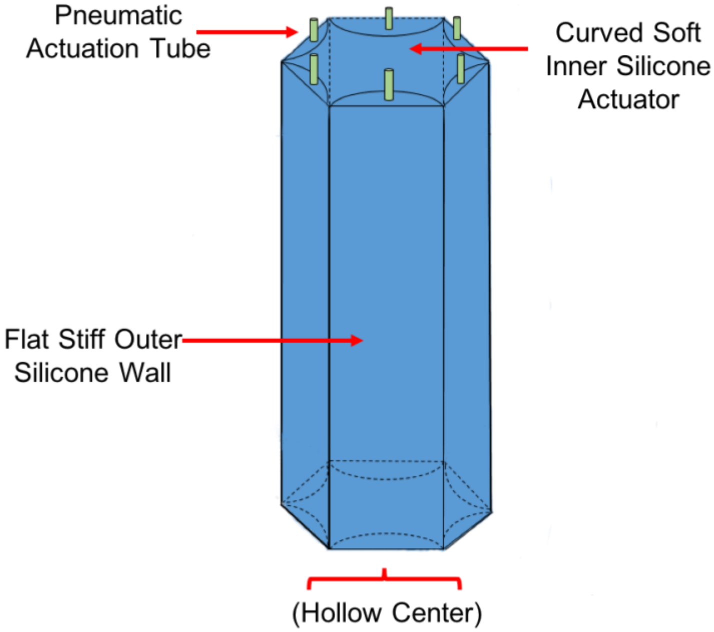

Figure 13: Concept 1, multiple chamber actuators with two layers of stiffness with a hexagonal skeleton

This design has a hexagonal design with 6 vertical actuators connected along their edges thus leaving a hollow middle region. Each chamber will be actuated independently using the pneumatic actuation tube that will be connected to an air compressor. The inner curved layer has room to expand when the air pressure is increased, thus reducing the hollow region and increasing the stiffness of the device when squeezed from the outer layer.

The primary concern with this design is finding a method to maintain the structural integrity of the device. The curve on the inner portion of the device would not actuate in a predictable manner due to the complicated nature of silicone. Additionally, since there are no vertical constraints on the inner curves, each chamber will be curving outward from the top and bottom especially since there are two varying stiffness layers. This results in an unpredictable device with loads in unforeseen areas which could include but not limited to the vertical connecting regions between each chamber.

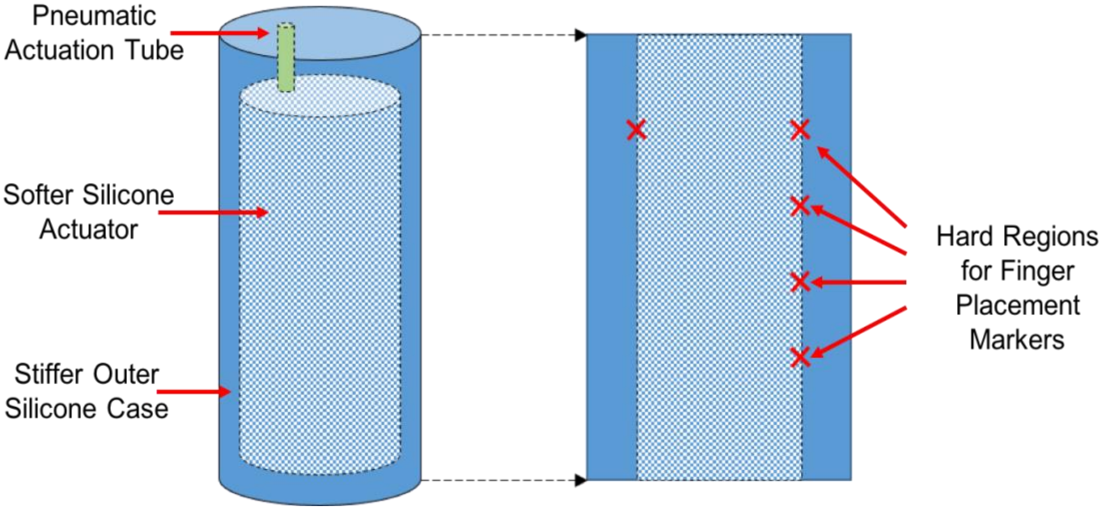

Figure 14: Concept 2, single chamber actuator with an outer shell and finger placement guides. The isometric perspective is shown on the left, while the cross section to identify finger placement guides is shown on the right

To overcome the complexity observed in Concept 1, this prototype switched to a single cylindrical actuator. This design includes an inner softer more compliant silicone cylinder while it is encased by a stiffer silicone. The idea of incorporating the case stems from the need for a horizontal and vertical constraint so that the structure of the device will be more predictable. Therefore, the pneumatic actuation tube will go through the case and the inner chamber. This concept also planned for the incorporation of markers to guide users to specific grasping regions. These regions could be fabricated with a hard material, so it could be felt from the outside. Additionally, it was thought that in future iterations sensors could be incorporated in this region.

However, this design would significantly decrease the stiffness range of the device. The outer shell would be imposing on the lower limit of the stiffness range. This is a major problem since one of the primary goals of the device is to have a broader range of stiffness compared to existing mechanically actuated variable stiffness devices.

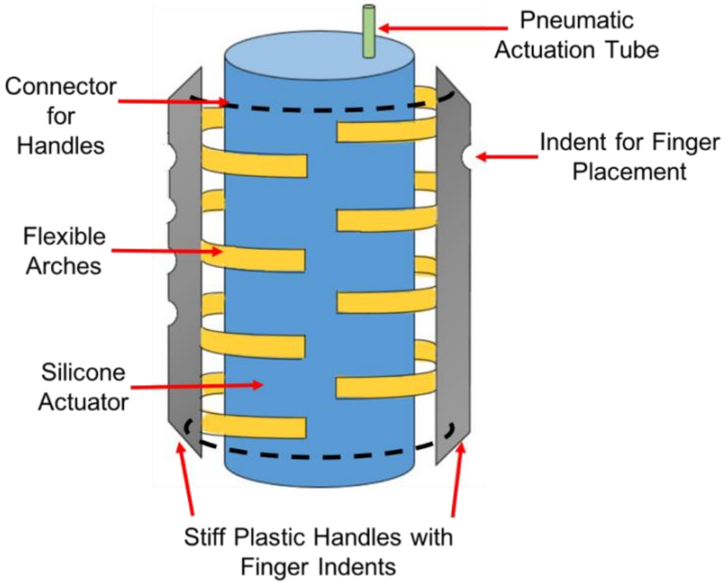

Figure 15: Concept 3, single chamber actuator with outer graspers connected by a compliant mechanism

Concept 3 was conceived concurrently with Concept 2. This design's stiffness mechanism is similar to that of Prototype 1 since the stiffness is directly related to the amount of free space available in the middle of the device, i.e. lesser space in the middle would increase the stiffness. This design uses two handles on the outside of the actuator instead of a shell. The handles have indentations to explicitly guide users towards the grasping region. The handles also have "teeth" that alternate in their alignment therefore allowing for maximum grasping range and in turn stiffness. The handles will have to be connected by a compliant mechanism such a thin spring like metal that is anchored to the silicone actuator. However, this design has the same limitation as Concept 2 in terms of having a lowered range of stiffness (even if a vertical constraint were to be included). This is due to the incorporation of a stiffer mechanical mechanism to connect the handles.

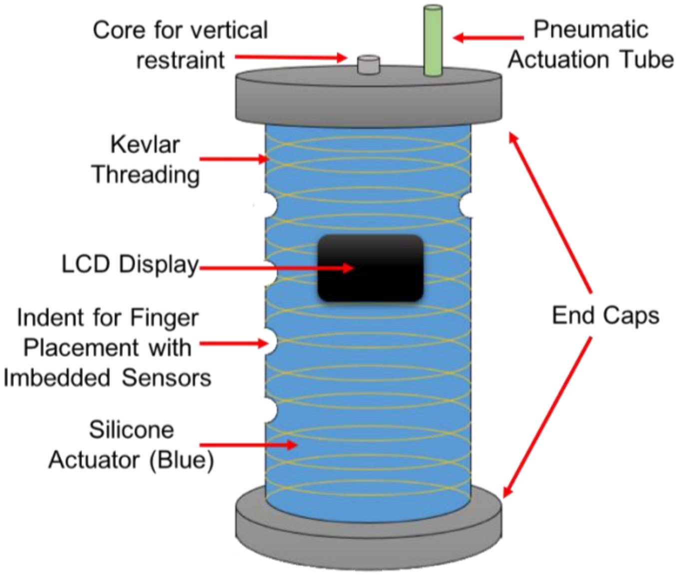

Figure 16: Concept 4, single chamber actuator with vertical and horizontal constraints and a force input display

This design uses solid discs on the top and bottom that are anchored through the middle with a rod. This rod will be the limiting range as to how far a user can squeeze the device in its most compliant state. For this design, the horizontal constraint is implemented using Kevlar threads that wind throughout the actuator body. This is informed by previous work in soft robotic actuators (Polygerinos et al. 2015; Connolly et al. 2015). Furthermore, this design includes indentations that are directly molded on the silicone actuator thus allowing for users to find the effective grasping region easily. These indentations will be imbedded with a force sensor to output the amount of force the user exerts on the LCD display. An LCD display was chosen for this design to induce a more accurate perception of stiffness in the user; since it has been shown that having visuals of force exertion and deformation on the surface provides better discrimination of stiffness in individuals (Bergmann Tiest 2010).

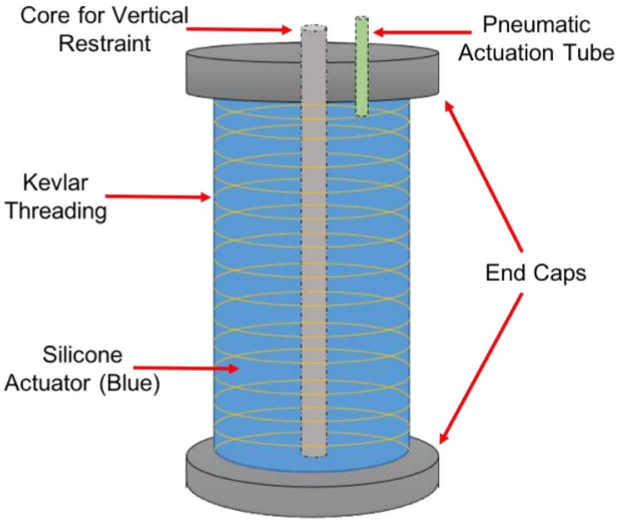

Figure 17: Concept 5, finalized prototype design with vertical and horizontal constraints without an LCD display

The finalized design is very similar to Concept 4. This design has the same vertical and horizontal constraints as Concept 4, but it does not include the LCD screen display or the force sensors. It was decided that including those additional features would interfere with the stiffness of the device, thus making the characterization process more difficult. Given that there are no devices similar to this one it is important to have an accurate characterization of the fundamental design before additional features are added. As for having guides for users to accurately identify the variable stiffness region, it was concluded that it could be done by proper characterization of the device. Therefore, once the stiffness across the device is mapped, the effective grasping can be identified, and the cutoff points can be labeled directly on the device. This will allow users to only grasp the device within this region thus maximizing the variable stiffness range on the device.

iii) Soft Robotic Haptic Interface Design

The device is designed as a cylindrical handle of 40 mm diameter since this diameter has been shown to be most effective in enabling high grip forces in humans (Seo et al., 2008). The average male hand width, defined as the distance from the second to the fifth metacarpophalangeal joints, is approximately 83 mm (Seo et al., 2008; Geetha et al., 2015). We designed the cylindrical device's height to be 120 mm. The approximately 40 mm additional length was added to: ensure the entire body of the device fits in a patient's grip, accommodate for hand widths larger than the average, and to account for higher stiffness in areas closer to the end caps of the device. The male hand width is used as the basis of the design since on average the male hand is larger than the female hand. The device is modeled using a computer-aided design (CAD) software before a mold was made for its body to be cast out of silicon elastomer material and the end caps are 3-D printed. The mold of the body included groves in a helical pattern along the body of the device to facilitate the fiber winding process during fabrication, as described in the fabrication section.

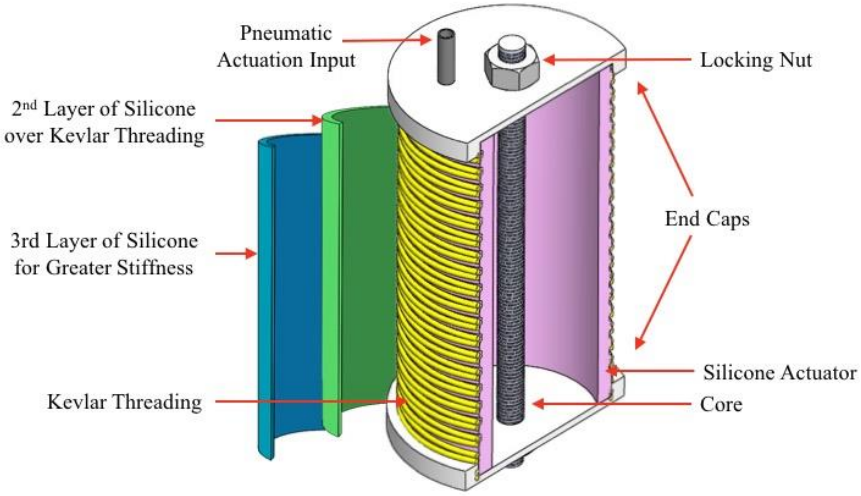

Figure 18: Cross-section of the CAD model used in the design for the soft haptic interface with labels of the key components

iv) Soft Robotic Haptic Interface Initial Fabrication

The body of the device is fabricated based on the multistep molding and casting technique that have been established for creating fiber-reinforced soft actuator (Polygerinos et al. 2015; Deimel and Brock 2013; Bishop-Moser and Kota 2015). from expanding vertically and horizontally, as well as to prevent bending and twisting motions. Instead of a hemisphere or a rectangle, the body of the mold is made in a circular design to achieve a cylindrical hand-held device, and 3D-printed (*Fortus 250MC* printer, Stratasys Ltd., MN, USA). The first layer is casted with the printed mold using a shore hardness 10A silicone rubber (*Dragon Skin 10*, Smooth-on Inc., PA, USA) with 2 mm thickness. End caps of 50 mm diameter and 5 mm thickness are 3-D printed (*Fortus 450MC* printer, Stratasys Ltd., MN, USA).

The caps included a 6-mm diameter hole in the center to introduce a 178 mm long threaded rode, acting as core, which is fastened on both ends with locking nuts. Additionally, a 3-mm diameter hole is made approximately 4 mm off the edge of the first hole to introduce a tube for pneumatic actuation. The end caps are attached to the body of the actuator using silicone adhesive (*Sil-Poxy Adhesive*, Smooth-on Inc., PA, USA). This adhesive is also used around the connecting parts to prevent air leaks, i.e., around base of the cap and the body, and at the ends of the core. A single *Kevlar* fiber of 0.38 mm diameter is wound along the groves made from the mold in a clock-wise and counter clock-wise directions, and a thin layer of silicone is applied on the threading to anchor it in place and prevent it from moving during actuation and grasping. A second layer 2-mm thick is made with the same casting techniques, but with a shore hardness 20A silicone rubber (*Dragon Skin 20*, Smooth-on Inc., PA, USA), and used as a sleeve over the first layer. The schematic of the mold and the molding process is further explained in Appendix E.

The first layer of the device is made with very flexible rubber to ensure the lower limit of the device's stiffness is kept at a minimum while it is directly exposed to pressure. However, the high compliance of the first layer compromises its structural integrity. Therefore, a secondary layer of the same compliance is made as a sleeve over the first. The user may utilize a third sleeve with less compliant materials to increase the upper limit of the device's stiffness range. The interchangeability of sleeves provides greater customization and adaptability for the user's specific needs. Additionally, the interchangeability feature allows for improved sanitary environments by allowing physicians to swap sleeves between patients quickly.

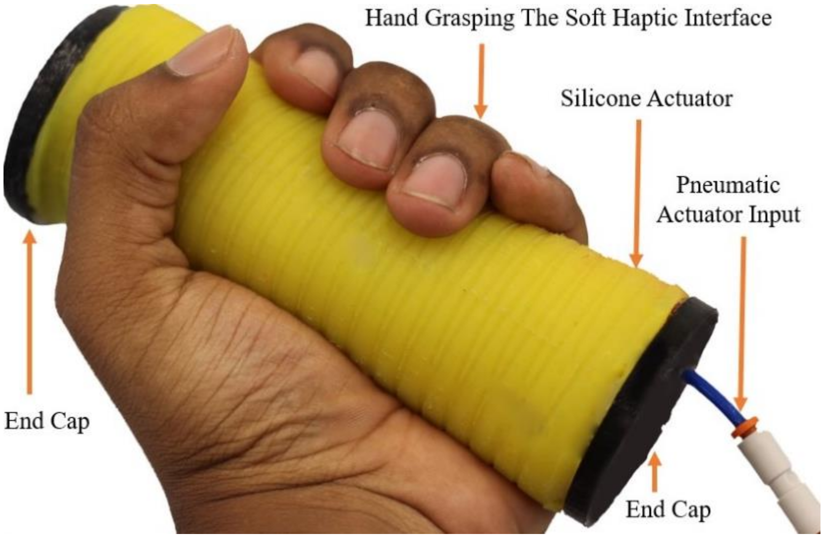

Figure 19: The prototyped soft haptic variable stiffness interface with a hand grasping it

v) Final Prototype Design and Fabrication

After the initial prototype was successful designed and fabricated, a final prototype was made using the same methodology. However, for this prototype only a single layer was fabricated using a silicone rubber of shore hardness 30A (*Dragon Skin 20*, Smooth-on Inc., PA, USA).

vi) Principle of Operation

There are two modes of operation of soft robotic haptic interface: 1) isometric and 2) constant pressure. The former mode is a system with no pressure regulation. Therefore, the device is given a starting pressure (greater than 0 kPa) and the internal pressure is allowed to increase with an increased force exertion on the device. This actuation system is shown on the open-loop control system block diagram in Figure 20. The latter mode of operation involves regulated pressure. Therefore, the device is given a starting pressure (greater than 0 kPa), and the internal pressure is maintained at that pressure as the hand grasping force exerted on the device is increased. This actuation system is shown on the closed-loop control system block diagram in Figure 21. To achieve these controls, an electronic box with the necessary electrical components was designed.

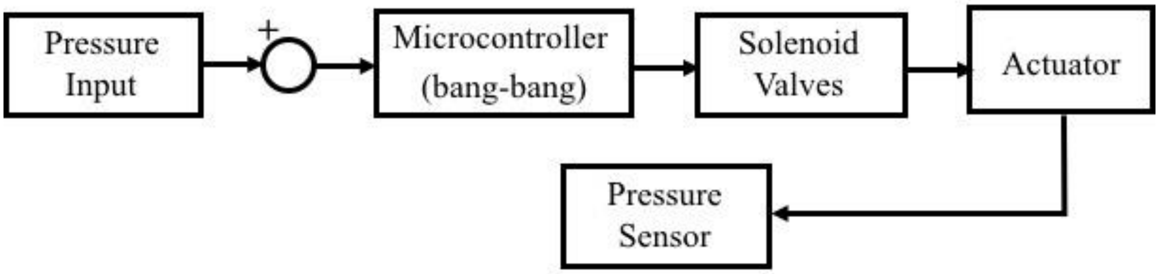

Figure 20: Open control loop scheme with a sensor to measure air pressure in the soft haptic actuator and close the solenoid valves with no further regulation

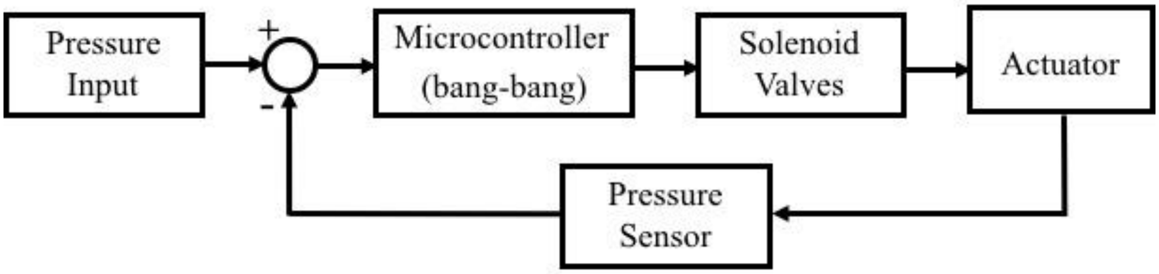

Figure 21: Feedback control loop scheme with a microcontroller to turn solenoid valves on or off for air pressure regulation using the information measured from the pressure sensor

vii) Constant Pressure Control

The design for the closed-loop system is achieved by employing solenoid valves to both pressurize and depressurize the actuator based on the user's input. To achieve rapid switches between the solenoid valves, a field effect transistor (FET) was utilized (*MOSFET 4*, ON Semiconductor Corp., Phoenix, AZ). The pressure input is fed through solenoid valves (*Series 11 Miniature Solenoid Valves*, Parker Hannifin Corp., OH, USA) before they split to equal pressures in the haptic interface and a fluidic pressure sensor (*ASDXAVX100PGAA5*, Honeywell International Inc., Morris Plains, NJ). The pressure sensor provides feedback to a microcontroller (*Arduino Uno R3*, Arduino LLC., Italy) to turn the solenoid valves on and off to regulate the pressure to an approximate accuracy of 0.69 kPa. When the pressure sensor reads the pressure input to be higher or lower than the desired preset input, it will depressurize or pressurize, respectively.

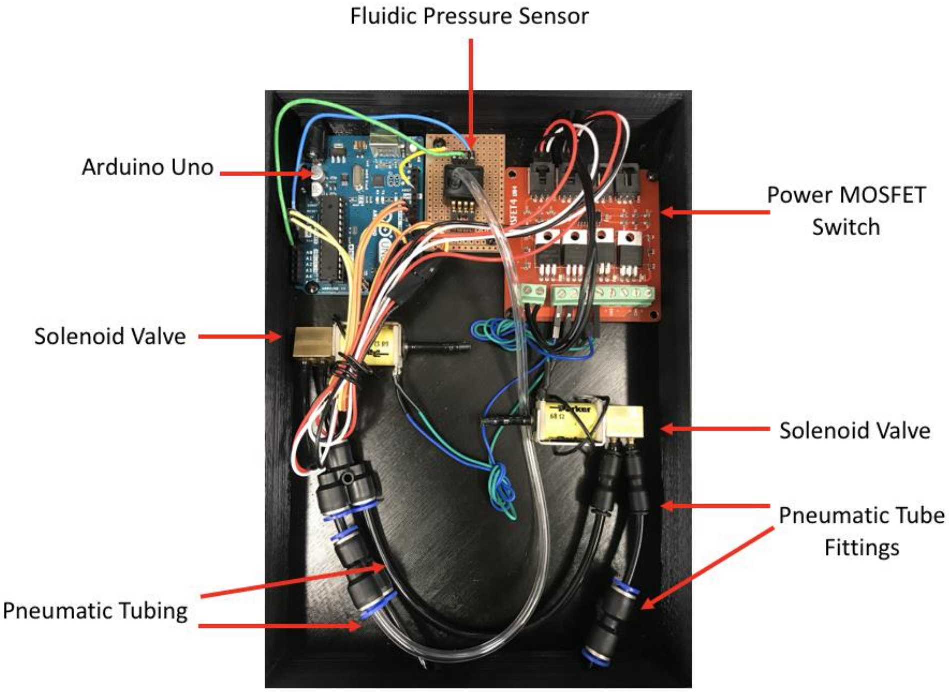

Figure 22: Electronic box with all the necessary components to run the two control modes for the variable stiffness device

viii) Isometric Control

In the open-loop mode, the same electrical box is utilized but a different form of regulation is implemented. For this setup the pressure input is fed through both solenoid valves, but the microcontroller is set to keep the depressurizing solenoid valve closed. This therefore prevents a pressure drop in the system once the initial pressure has been set. The open solenoid valve then splits the pressure equally to the fluidic pressure sensor and the haptic device. In this setup the rapid switch functionality of the FET is not utilized, rather a one-time binary function is implemented to keep one valve constantly closed and one open. The fluidic pressure sensor is utilized to monitor the pressure variations inside in the device to ensure it does not go too high or too low (due to leakage) during utilization of the device.

CHAPTER 4

CHARACTERIZATION & TESTING

i) Introduction

There are three primary focuses in terms of characterization and testing for this haptic device. The first is determining a model to be used to characterize the stiffness of the actuator and delineating a protocol that will fit this model. The second is to run experiments for the constant pressure and isometric control methods so that a chart could be developed for the user to effectively identify the stiffness they need and the constraints to be imposed on the device. The final one is to determine if the variation in stiffness is adequately perceived by healthy subjects, thus, validating the efficacy of the haptic device.

ii) Characterization

A stiffness characterization experiment was performed to determine the stiffness profile of the grasping area of the soft robotic haptic interface. This was done by marking the device's soft body with nine linear points with spacing of 15 mm in between in each point (Figure 23A). Point 1 is the point closest to the end cap on the side with a pneumatic tubing and Point 9 is at the furthest opposite end. The device is fixed in place by the core using a bar clamp with the marked points being exposed upwards. The clamp is attached to the lower grip of a uniaxial testing machine (*Instron 5944*, Instron Corp., High Wycombe, United Kingdom) while a probe of 6-mm diameter is attached on the upper grip (Figure 23B).

iii) Constant Pressure & Isometric Testing

For the constant pressure mode of operation, a similar test to the characterization experiment is performed but the closed-loop system is utilized instead. Additionally, the mid-point on the device (Point 5) is selected as the only probing location to record the resulting force. A total of three trials are performed, and the exerted force is averaged. This is repeated with pressurizations of 3.45, 6.89, 13.79, and 20.68 kPa.

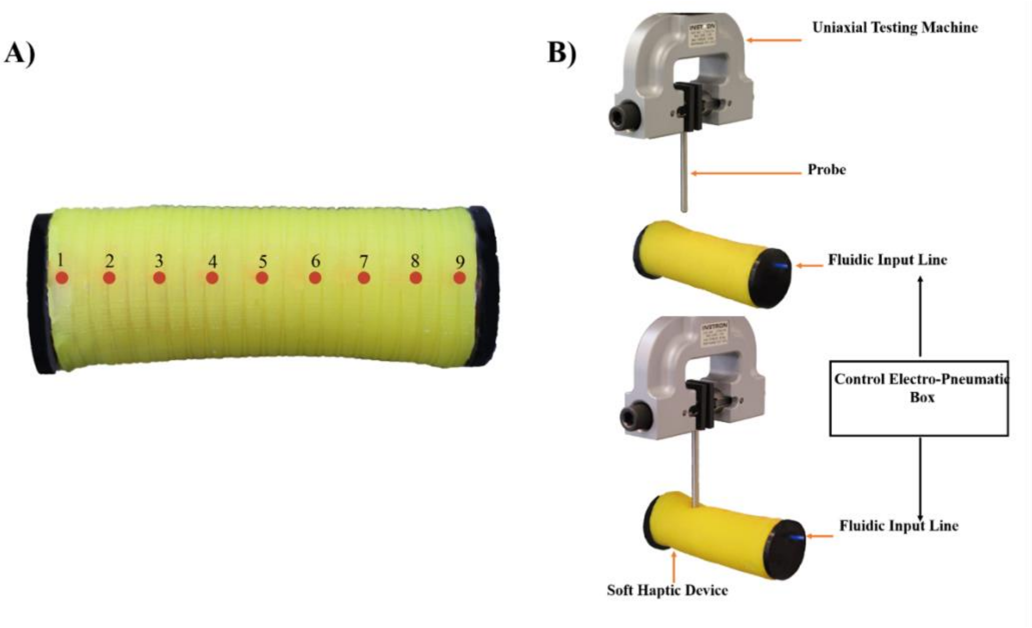

Figure 23: A) Top view of the device with probing points identified along the length of the soft haptic interface. B) Testing of the soft haptic device using a uniaxial testing machine (Instron 5944) before probing (top) and after probing (bottom).

For the isometric mode of operation, this quasi-static experiment is performed while using the open-loop system. This experiment also utilized the mid-point (Point 5) on the device as the only probing location. However, the probe is set to probe four times with 2.5-mm intervals between each vertical probing distance (starting at 2.5 mm) for a given starting pressurization. The resulting pressure and the force exerted on the device was then recorded. The stiffness per displacement is then calculated using Eq. 1 and plotted against the pressure recorded for that displacement. Three trials per displacement was performed, and the exerted force and pressure were averaged. This experiment was repeated with pressurizations of 3.45, 6.89, 13.79, and 20.68 kPa

iv) Efficacy of Device

To maximize the efficacy of this variable stiffness device, it is essential that the change in compliance is adequately perceived by the person using the device. This is because the essence of this technology is to have variance in stiffness that begins with as minimal resistance as possible to better the rigidity experienced in existing variable stiffness devices. Therefore, the end user needs to be able to readily differentiate the stiffness of the device from the lowest stiffness setting up to the highest. More importantly, perception of stiffness often involves a variety of somatosensory modalities such as mechanoreceptors, muscle spindles, and Golgi tendon (Jones and Hunter 1990; Bergmann Tiest and Kappers 2009), as well as the ability to coordinate joint positions and contact forces. Therefore, this type of tasks could have potential application in the rehabilitation of sensorimotor function of hands.

To test the stiffness perception, the soft haptic device was set at a constant pressure utilizing the open-loop control system. The stiffness per pressure setting (3.45, 6.89, or 20.68 kPa) is approximated to three distinct Shore Hardness (00-10, 00-30, and 00-50, respectively). Three cylindrical objects of Shore Hardness 00-10, 00-30, and 00-50 of the same dimensions as the soft haptic device were then fabricated but with a filled center. Under an Arizona State University institutional review board (IRB) approval (#1309009629), a written informed consent was obtained from healthy participants where they were asked to grasp the three filled cylindrical objects and then grasp the soft haptic device that is set at a pressure setting unknown to them. The number of attempts it took the subject to match it to the set Shore Hardness for the given pressurization is then recorded. This qualitative experiment is repeated with the same subject but at a different pressure setting. This experiment is conducted with 17 healthy participants who gave their full written and oral consent before participation.

CHAPTER 5

RESULTS & DISCUSSION

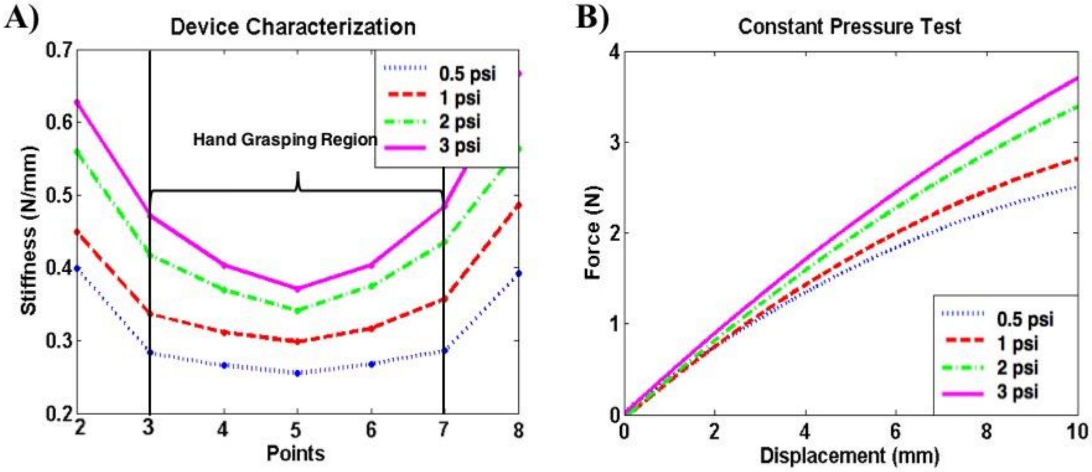

Figure 24: A) The device characterization for varying pressure inputs, with the effective variance in stiffness being between points 3 and 7. B) Force exerted on the soft haptic interface over a fixed displacement and regulated pressure for stiffness reference. The pressurizations of 0.5, 1, and 3 psi convert to 3.45, 6.89 and 20.68 kPa, respectively.

The stiffness profile versus the points on the device with varying pressures is presented in Figure 24. We expected the device to be stiffer as one moves away from the middle (Point 5) of the device. This expectation was consistent with experimental results from the characterization test of the soft haptic device (Figure 24A). The device has greater stiffness at points closer to the end caps and therefore the regions of effective variable stiffness can be identified between points 3 and 7 where the stiffness for each pressure appears to be relatively linear. The greater stiffness towards either ends of the device is mainly due to the influence of the bond between the end caps and the body of the actuator. For this reason, Points 1 and 9 were excluded from the data. The graph of the exerted force and displacement with varying pressures using the constant pressure system is presented in Figure 24B. Using this plot the end user has the ability to select a fixed stiffness value when using the soft haptic interface in a constant pressure mode to perform grasping exercises where the haptic feel remains the same irrespective of the grasping force exerted on the device.

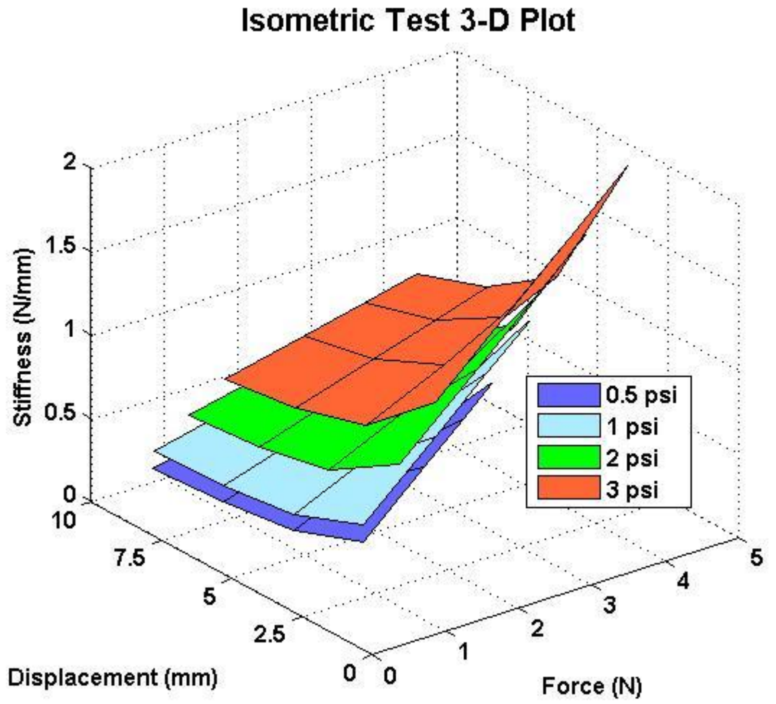

Figure 25: The variance in stiffness as the pressure in the soft-haptic interface is increased in the open-loop system. The pressurizations of 0.5, 1, and 3 psi convert to 3.45, 6.89 and 20.68 kPa, respectively.

Conversely, the stiffness reduced for every increment in displacement in the isometric testing (Figure 25), however, the drop was consistent for every pressure input. This validates the concept of a controllable increased stiffness with varying pneumatic actuation in the soft haptic interface, which enables the device to increase its stiffness when a gradual force is exerted on it. Overall, the two modes allow for stiffness values to be adjusted on demand to higher or lower ranges through variations of the initial stiffness of the sleeves and the internal pneumatic pressure.

Additionally, the efficacy of the device was tested using 34 test subjects to grasp the device at varying stiffness settings. Out of the 34 test subjects, 23 of them (or 68%) matched the stiffness of the device correctly in their first attempt as seen in Figure 26A. This number was then further broken down for the three stiffness settings and it was found that 67%, 73%, and 64% of the subjects matched the stiffness correctly in their first attempt for the Shore 00-10, Shore 00-30, and Shore 00-50 cylinders, respectively, as shown in Figure 26B.

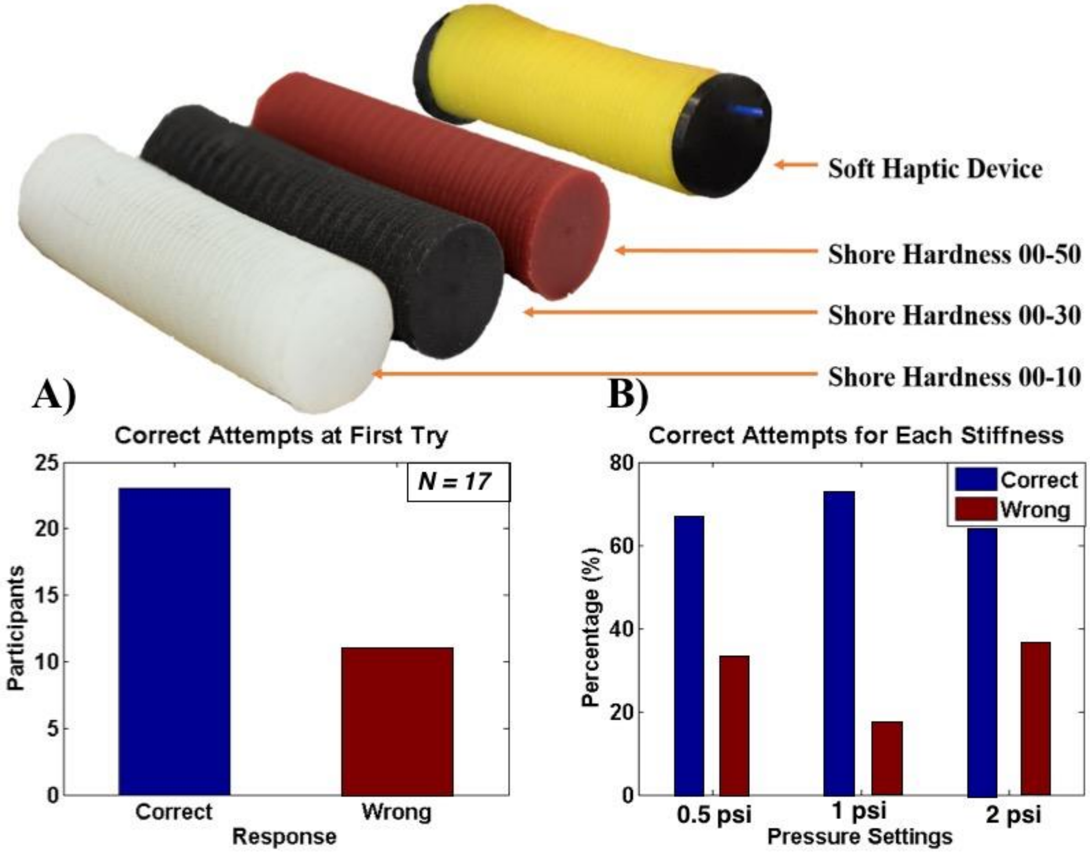

Figure 26: A) Cylindrical objects of Shore Hardness of 00-10, 00-30, and 00-50 (from left to right) and the soft haptic device for participants to grasp and compare stiffness. B) Bar plots showing the number of times participants matched the correct stiffness their first attempt (left), and the percentage of times participants got the stiffness correct versus the percentage of times participants got the stiffness wrong (right). The pressurizations of 0.5, 1, and 3 psi convert to 3.45, 6.89 and 20.68 kPa, respectively.

In this thesis, we presented the novel design of a variable stiffness haptic interface based on soft-robotics that is pneumatically actuated to assist hand rehabilitation. The fabrication process of this device is simple and cost-effective, approximately $100, since it closely adheres to existing multistep casting and molding techniques utilized for fiber-reinforced soft actuators. The utilization of highly compliant materials (silicone elastomers) allowed for the device to present stiffness ranges that existing variable stiffness devices are not able to achieve due to the rigidity of their mechanical designs (Malosio et al. 2016; Spagnuolo et al. 2017; Mace et al. 2015, 2017; Masia et al. 2006; Lambercy et al. 2009). Experiments were conducted to characterize the effective regions of variable stiffness in the soft haptic device due to design constraints that include regions of exponential stiffness. A closed-loop and open-loop control system were presented and tested.

Table 3: Set and achieved requirements for the soft haptic device

Parameter	**Requirements**	**Final Design**
DOF	At least 1 (grasping)	1
Control Methods	At least two	Constant Pressure and Isometric
Size	Able to be grasped in adult hands	✓
Portability	Portable for home and clinical use	✓
Stiffness Range	Broad with option to adjust	✓
Min. Stiffness	0 N/mm	0 N/mm
Max. Stiffness	5 N/mm	~0.7 N/mm
Weight, Height, Width	<0.5 kg, ~120 mm, ~40 mm	~0.2 kg, 120 mm, 40 mm
Cost	<$200	$100

Finally, the variance of stiffness in the device was tested with healthy subjects to ensure that the induced variance in stiffness translates adequately to a qualitative measure as well. One of the most challenging aspects of creating a device of variable stiffness is to ensure the variance in compliance is appropriately perceived by the users. This is challenging due to the multitude of factors involved in human perception of stiffness (Bergmann Tiest 2010; Jones and Hunter 1990). The experiment results show that healthy subjects could effectively distinguish the variance in stiffness of the soft haptic device, and that the qualitative measurement could be matched to a quantitative value (Shore Hardness). This allows for a more cohesive mapping of the soft haptic device, and therefore provide the device's user(s) the tool necessary to utilize the device effectively. Below the main findings and potential applications of this soft-robotics device for rehabilitation of sensorimotor function of hands is described.

i) Characterization

The central region (Points 3 to 7, Figure 23A) is characterized by an increasing stiffness that could be manipulated on demand by the end user or physical therapist in a controlled fashion by increasing the pressure input to the device. It is important to note that only four different pressure settings were tested in this work as a proof-of-concept. If desired, additional pressure settings can be utilized for this particular design. However, the maximum pressure input presented was 20.68 kPa so as to prevent the device from buckling under greater internal pressure. To increase the upper limit of the pressure input, a greater number of sleeves can be added to the device, sleeves of higher stiffness can be incorporated into the design, and/or the number of windings on the first layer could be increased. This once again proves the versatility of this device to be used in stroke rehabilitation given the importance of tailoring task difficulty or characteristics to individual patients' sensorimotor deficits

ii) Constant Pressure and Isometric Testing

The constant pressure test support using the device to calculate the stiffness a user can expect when using the device at a given regulated pressure. This could be eventually used to formulate a chart for quick reference if a particular setting is desired for a rehabilitative exercise to be performed. This setting can be utilized for strength training that requires a large number of hand grasping/squeezing repetitions since high repetitions have shown to increase neural plasticity in stroke recovery. The isometric mode provides the user with an option to increase the force needed to squeeze the device at a given pressure, thus being useful for users who need consistent increases in difficulty for each rehabilitative exercise. These two different modes can be utilized by the physician depending on the needs of the stroke patient. However, the results of this testing showed that the stiffness dropped for 2.5 mm increments in the displacement using the isometric system. Given that the stiffness increased during characterization which utilized the same control system, it appears that the pressure in the soft haptics is escaping when small displacements occurs in the device.

iii) Implication to Hand Rehabilitation

The collected results demonstrated great potential to use the proposed device in a variety of hand-rehabilitation exercises. For instance, patients who need fixed stiffness with increased repetitions of grasping exercise could use the constant pressure control mode; and patients who need increasing difficulty could utilize the isometric control mode. Furthermore, with simple sensor added to the device, patients can use it as a controller at home to perform exercises in combination with video games to mimic augmented reality feedback that currently exist for rehabilitation devices (Khademi et al. 2012). Lastly, the device has the unique feature that the entire grasp area is compliant due to the implementation of soft robotics techniques. Unlike hand rehabilitation devices with rigid mechanisms, the design could promote the practice of natural coordination among all fingers which is important in ADL tasks.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

The goal of this research was to develop a cost-effective and simple variable stiffness device to be used in clinical and home settings for the rehabilitation of hand impairments. It was also imperative for the device to have a wide range of stiffness and a haptic feedback system for the users so that the change is stiffness is adequately perceived. These objectives were met by incorporating soft robotics methodology to develop a single chamber actuator with vertical and horizontal constraints. The horizontal constraint was achieved using Kevlar fiber reinforcements while the vertical constraint was achieved by anchoring end caps with a steel-rod core.

The device is fabricated using cost-effective methods such as polymer casting and additive manufacturing (3-D printing). These fabrication techniques allowed for the device to be made quickly and also for future modifications to be incorporated with ease. The device was characterized to determine the effective grasping region as well as the range of stiffness based on the constraints presented in this document. Two control methods were developed to allow for the device to be used both at home and in clinical settings. The control modes are characterized in a way that provides users with a chart where desired stiffness can be achieved by setting the pressure input at pre-set levels. The device also allows for modification by the user if desired by adding layers to increase the upper limit of stiffness in the device without compromising the lower limit. Additionally, the device was run through preliminary testing with healthy subjects to ensure the change in stiffness is adequately perceived.

This device serves as an initial proof of concept, therefore, having a vast amount of room for optimization and improvement to meet various user needs. Future directions for this device includes fabrication with varying factors such as thickness and stiffness of materials, as well as an investigation on the effects of the number of windings and the pattern of winding on the device. This would allow for a greater effective variable stiffness region on the device. Varying the materials and fabrication methods would also allow for a more airtight device that could prevent pressure leaks, thus making the mechanical behavior of the device in the isometric mode more reliable. After comparing with *GripAble* the functional requirement set for the maximum stiffness to be achieved by the device was 5 N/mm, but it only attained approximately 0.7 N/mm. Therefore, future work also includes optimizing the design and material selection to allow the device to attain higher stiffness limits (Mace et al. 2015). It is important to note that soft robotics is not limited to silicone elastomer materials, despite it currently being one of the more popular in this field. Therefore, future iterations could also include redesigning the body of the actuator with fabric and testing its efficacy (Sridar et al. 2017; Sareen et al. 2017; Sanan et al. 2014).

Additionally, force sensors could be incorporated into the design to accurately map the region users would interact with the device, especially the force exerted under each digit. Flexible force sensors could either be embedded on the surface of the device, or also within the chamber itself. This allows for accurate mapping of force exertion by the user. A larger part of rehabilitation of hand functions include exercises that utilize more than a single DOF. Therefore, some design changes could be added to accommodate for these exercises. One design change could be the inclusion of multiple chambers inside the cylindrical body of the device that can be actuated individually. This will allow for adjustable stiffness in varying regions of the device thus promoting single digit exercises of the hand. Another design change that could potentially attain the same output would be to change the number and pattern of windings at different portions of the cylindrical actuator.

The final goal is to get this device to be accepted by clients on the market who are primarily clinicians and their patients. Therefore, some consideration should be given to the design and functionality of the device to convince users to make the switch to this proposed device. A big market for this would be to promote the device’s utilization at home, therefore, its portability feature should be honed. A functionality that would behoove this goal would be the ability to detach the handheld device from the control system. For example, the device could have a microcontroller and pressure regulator attached directly on its end-caps therefore eliminating the need for pneumatic tubing. Finally, the potential of the device for rehabilitation applications should be assessed by testing with patients with impaired hand function. This would also allow for dynamic testing of the device since the current results were obtained from discrete testing methodologies. With the incorporation of sensors, the device can also be assessed with impaired users to determine if small motions in the user’s hand is adequately translated to the device. This experiment should be run on a long-term basis so that substantial improvements in impaired patients can be seen.

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APPENDIX A

CO-AUTHOR PERMISSION

Permission was given from all co-authors to include materials from co-authored publication in this thesis document.

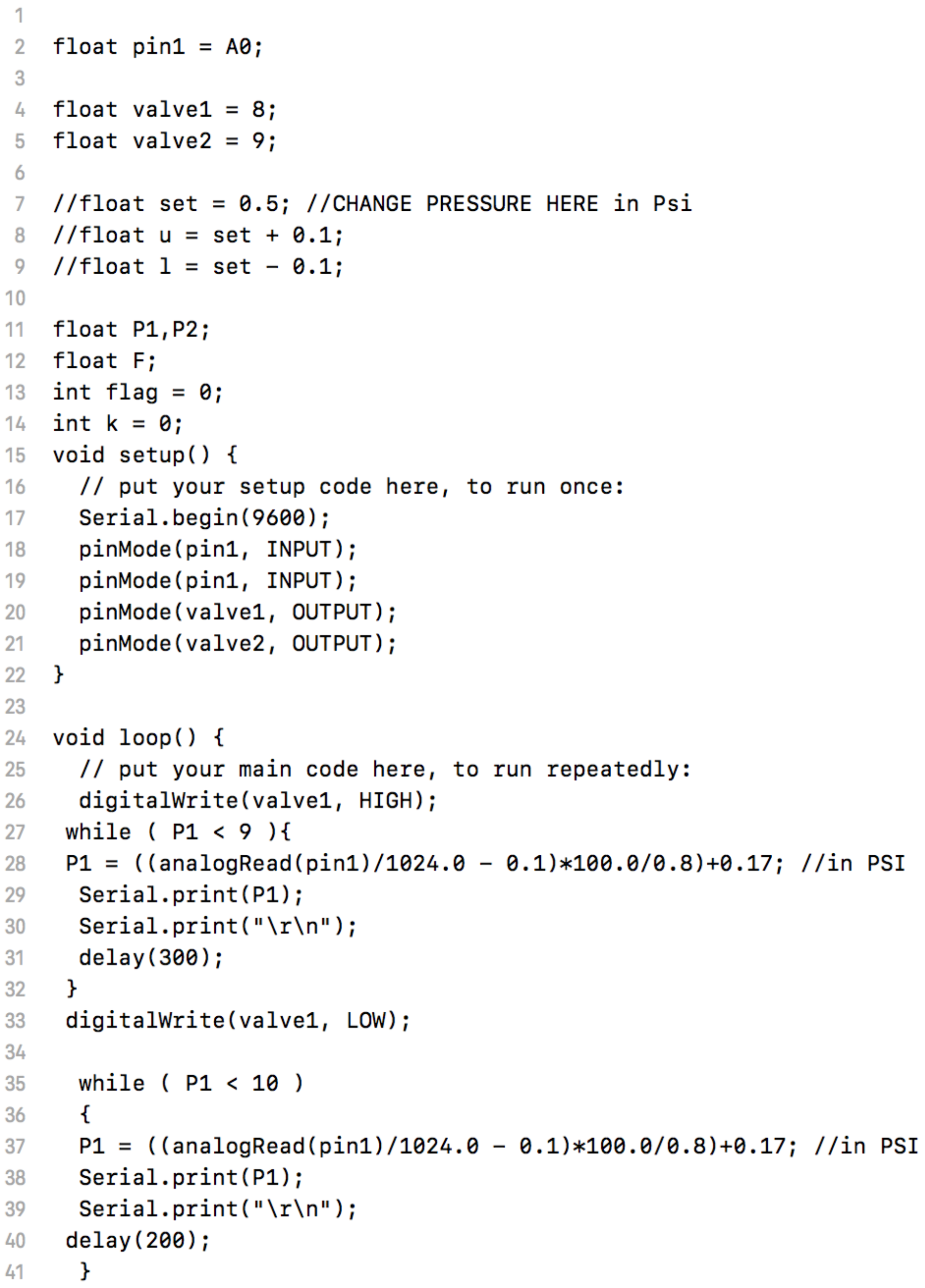
APPENDIX B

HUMAN SUBJECT TESTING

Under an Arizona State University institutional review board (IRB) approval (#1309009629), a written informed consent was obtained from healthy participants where they were asked to grasp the three filled cylindrical objects and then grasp the soft haptic device that is set at a pressure setting unknown to them.

APPENDIX C

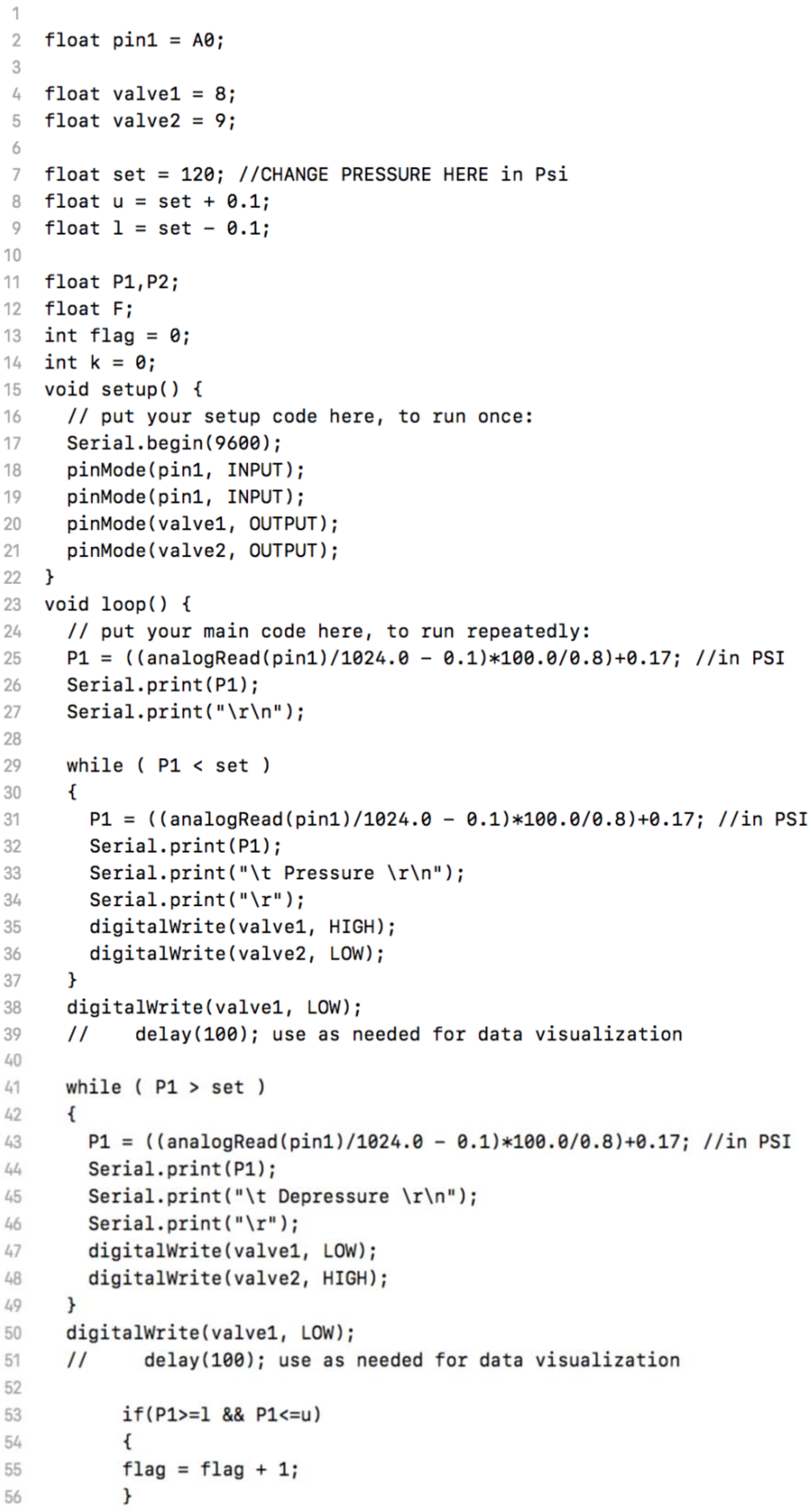
ISOMETRIC CONTROL CODE



```

float pin1 = A0;

float valve1 = 8;
float valve2 = 9;

//float set = 0.5; //CHANGE PRESSURE HERE in Psi
//float u = set + 0.1;
//float l = set - 0.1;

float P1,P2;
float F;
int flag = 0;
int k = 0;
void setup() {
  // put your setup code here, to run once:
  Serial.begin(9600);
  pinMode(pin1, INPUT);
  pinMode(pin1, INPUT);
  pinMode(valve1, OUTPUT);
  pinMode(valve2, OUTPUT);
}

void loop() {
  // put your main code here, to run repeatedly:
  digitalWrite(valve1, HIGH);
 while ( P1 < 9 ){
 P1 = ((analogRead(pin1)/1024.0 - 0.1)*100.0/0.8)+0.17; //in PSI
  Serial.print(P1);
  Serial.print("\r\n");
  delay(300);
 }
 digitalWrite(valve1, LOW);

  while ( P1 < 10 )
  {
  P1 = ((analogRead(pin1)/1024.0 - 0.1)*100.0/0.8)+0.17; //in PSI
  Serial.print(P1);
  Serial.print("\r\n");
 delay(200);
  }
```

APPENDIX D

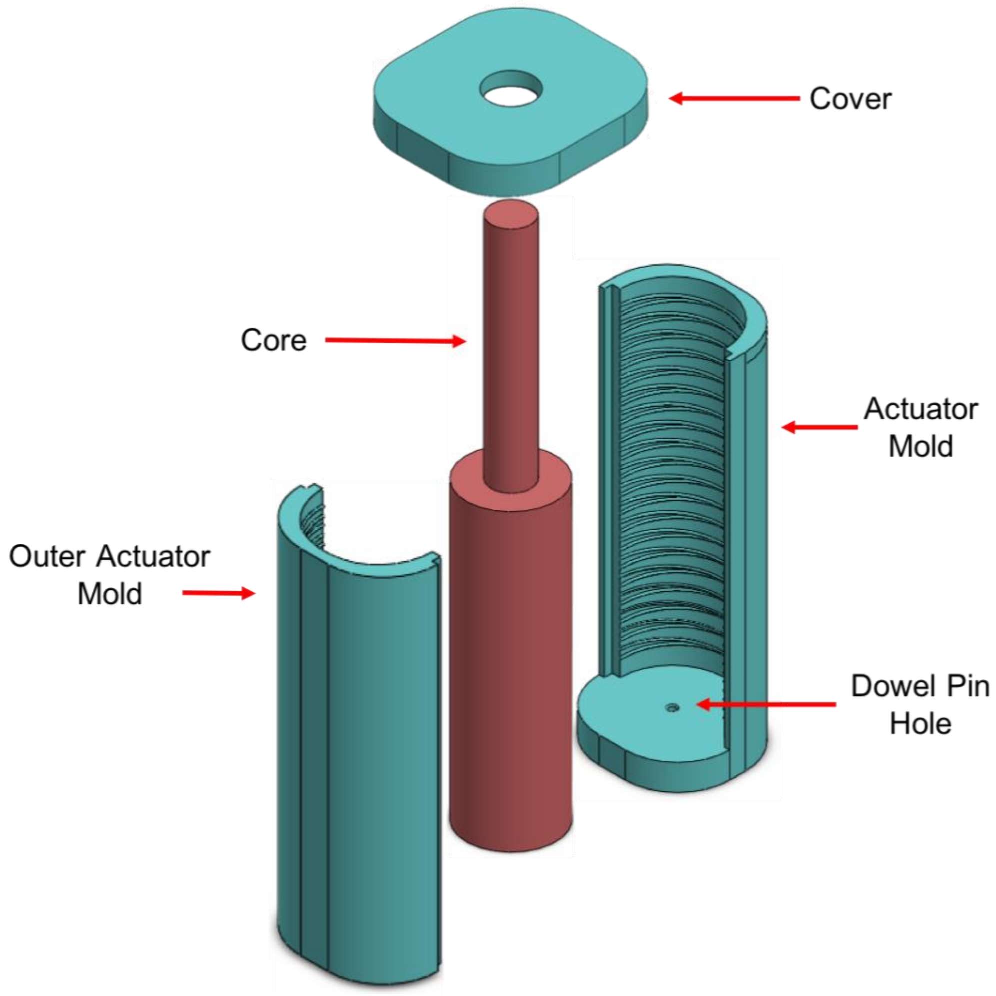
VARIABLE STIFFNESS CONTROL CODE



```

float pin1 = A0;

float valve1 = 8;
float valve2 = 9;

float set = 120; //CHANGE PRESSURE HERE in Psi
float u = set + 0.1;
float l = set - 0.1;

float P1,P2;
float F;
int flag = 0;
int k = 0;
void setup() {
  // put your setup code here, to run once:
  Serial.begin(9600);
  pinMode(pin1, INPUT);
  pinMode(pin1, INPUT);
  pinMode(valve1, OUTPUT);
  pinMode(valve2, OUTPUT);
}
void loop() {
  // put your main code here, to run repeatedly:
  P1 = ((analogRead(pin1)/1024.0 - 0.1)*100.0/0.8)+0.17; //in PSI
  Serial.print(P1);
  Serial.print("\r\n");

  while ( P1 < set )
  {
    P1 = ((analogRead(pin1)/1024.0 - 0.1)*100.0/0.8)+0.17; //in PSI
    Serial.print(P1);
    Serial.print("\t Pressure \r\n");
    Serial.print("\r");
    digitalWrite(valve1, HIGH);
    digitalWrite(valve2, LOW);
  }
  digitalWrite(valve1, LOW);
  //    delay(100); use as needed for data visualization

  while ( P1 > set )
  {
    P1 = ((analogRead(pin1)/1024.0 - 0.1)*100.0/0.8)+0.17; //in PSI
    Serial.print(P1);
    Serial.print("\t Depressure \r\n");
    Serial.print("\r");
    digitalWrite(valve1, LOW);
    digitalWrite(valve2, HIGH);
  }
  digitalWrite(valve1, LOW);
  //     delay(100); use as needed for data visualization

       if(P1>=l && P1<=u)
       {
       flag = flag + 1;
       }
```

APPENDIX E

MOLDING PROCESS



The schematic represents the molds used during the casting process of the actuator for the soft haptic device. The two halves of the actuator mold are first linked together and held together by elastic bands. The center is then filled with soft silicone before the core is inserted made to align with the dowel pin hole. The cover is then pressed down the top through the core and the mold is cured in the oven at 60°C for 1 hour. The actuator mold also has ridges designed on the inside in a helical design to allow for fiber reinforcements to be woven around the actuator after casting the silicone.