Hydro Muscle Hand Brace

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Abstract

Orthotics have recently advanced with the combination of soft-robotics and hydraulics. Utilizing WPI’s own “Hydro Muscle” technology, this robotic brace aims to help patients with hand disabilities by providing fluid-powered exo-musculature assistance. Our goal was to perform specific gestures that provide a disabled patient with the force required to perform daily activities. Custom hydraulically-powered finger muscles were created and integrated into a thin glove, maintaining a lightweight and low-profile composition. This glove successfully manipulated all five fingers into three predetermined gestures, with adequate force to support activities of daily life.
Acknowledgements

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I would also like to acknowledge and thank Evan Stelly for his assistance in the second half of this project. I consider him an honorary and essential member of this team, whose knowledge of robotics was crucial to the success of this project.

Lastly, I would also like to thank Ellie Clarrissimeaux for her willingness to assist and her constant dedication in bringing this project to completion.
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Chapter 1: Introduction

Hands are used for everything. From self-sustaining activities to work and entertainment, hands are necessary for every daily task. Thus when a disease or trauma occurs that prevents the complete utilization of this limb, it has a large impact on a person’s quality of life. Conditions such as carpal tunnel and arthritis cause weakened or loss of hand strength. Other events such as strokes or more fully debilitating trauma can cause full or partial paralysis in the arms and hands. Treatments for these conditions with the aim to regain original strength and motion are not entirely successful. Physical therapy is often used to regain strength in patients who have muscle damage and nerve damage. However, for patients with permanent unfixable injuries, not many physically assistive options exist.

Current technology for hand disabilities most often include inert devices. Passive braces are common, which hold the disabled hand stable and allow basic scooping and pressing motions instigated from the user’s forearm (if abled). In the case of stroke patients, devices can help keep the hand open to prevent possible clenching due to involuntary muscle contractions. Dynamic braces are used for therapy, and incorporate spring resistance to help regain lost muscle. Other devices act as passive extensions of the body with tools for daily living attached. But fully orthotic devices that actively create motion in the user’s fingers are rare to come by, and many are still in development [1].

Our motivation for this project was to replace these insufficient passive devices by creating an orthotic device that instigates motion in a disabled user’s hand. The few devices that exist that perform this function use air pneumatics or electric motors to create motion. Since these modes of actuation tend to cause rather rapid and rigid movement, our team decided that using hydraulics would create the most natural biological motion in the user’s hands. We were determined to utilize WPI’s own invention of Hydro Muscles in our design, since previous braces using this technology had been successful. It would also give us the ability to design a low-profile, biologically compliable device, given the size and flexibility of Hydro Muscles.
Chapter 2: Background

2.1 Disabilities

Over the course of our life, the mobility and strength of our hands change naturally. Typically, hand strength peaks at a young adult age and declines after mid-life. With this natural aging comes joint stiffness from the diminishing of synovial fluid, and muscle atrophy from the decrease of hormones and usage. However, there are a multitude of diseases and conditions that result in an earlier onset of hand functionality loss. The most common of diseases that affects hand mobility and strength is arthritis. Arthritis is the number one cause of disability in America [2]. This condition causes joint inflammation and thus makes it difficult and painful for individuals to flex and extend their fingers. Joints often become stiff as a result.

Another common reason individuals lose hand functionality is because of strokes. Strokes are the country’s number one cause of long-term disability [3]. They often cause paralysis or weakness in the limbs, primarily the hand and fingers. Often times, hands contract into a clenched fist position and thus become unusable. Common treatments for this are physical therapy and hand braces. “Mirror Therapy” is a treatment where both hands are placed on a table, and a mirror is used to reflect the working hand in place of the disabled hand. When the brain watches the flexion and extension of the moving hand, it is tricked into thinking it is the paralyzed hand. This helps the nerves to regain plasticity [4]. This same concept is used in physical therapy, where watching and feeling one’s paralyzed hand being manipulated by a exo-musculature brace can help regenerate nerves and movement. Other conditions that result in hand loss include carpal tunnel, spinal cord injury, and muscular dystrophy.

Figure 1: Mirror Therapy is used to regain plasticity in a Stroke patient’s paralyzed hand [5]
2.2 Existing Devices  
Several different categories exist to differentiate types of assistive hand brace devices. For example, there are simple passive braces and there are dynamic braces. The most basic of passive braces are splints, which are rigid structures that fixate a user’s hand, wrist, or fingers into a specific orientation. These are most often used in the case of injury to bone tissue, but are also used to stabilize the hands of those who have arthritis or have experienced stroke. It provides a stable platform for bone regeneration, reduces movement and thus pain, as well as providing protection from further injury.

Figure 2: Standard Wrist Brace on Arthritis Patient [6]

Another form of a simple passive device is one with a tool fixture attachment. A user can slide a strap on their hand which has attached to it a spoon, knife, pointer, or gripper device. The motion from their forearm directs the tool and allows them to perform actions that would have otherwise required dexterity or hand strength. The user is now able to use objects such as utensils, hair brushes, and tooth brushes. This device is known as a “Universal Cuff”, and is most often used by a stroke or arthritis patient with weakened hand strength or range of motion [7].
On the other hand, there exist dynamic splints that are used for more muscular and neuromuscular injuries. These braces often utilize simple machines such as springs, hinges, or elastic material in order to allow movement in the fingers and thumb. These dynamic braces are best suited for rehabilitation purposes. For muscle injury, these braces provide resistance and guided movement to help redevelop muscle. For those with arthritis, these braces provide overall stability in the hand as well as help to regain mobility in stiff joints. In those with neuromuscular damage, being able to practice motion helps to regain plasticity in the nerves, helping them to regenerate. The SaeboStretch Dynamic Splint allows flexion of the fingers, and encourages the fingers to extend back into their original position, preventing the common “fetal position” that can occur in hands after stroke. The Saeboplex does similarly, but allows individual motion in each finger with a sophisticated series of springs and pulleys [8].
We took inspiration from the few active hand braces that exist in research today. One of these devices is the Soft Robotic Glove from the Wyss Institute at Harvard University. This glove uses fiber-reinforced rubber tubing, which when expanded, curls anteriorly around a less flexible layer of rubber. Five artificial muscles of this design are strapped to the user’s fingertips, and provides flexion by hydraulic power. It is controlled using electromyography sensors that are located in a band around the forearm, which detects muscle twitches that correspond to user intent [10].

![Figure 5: SaeboFlex Dynamic Splint [9]](image)

![Figure 6: The Soft Robotic Glove from the Wyss Institute at Harvard University [10]](image)
2.3 Hydro Muscle

Hydro Muscles are hydraulically powered artificial muscles, invented by WPI’s own Popovic Labs in 2014. Each Hydro Muscle consists of two basic components, a stretchable inner tube and non-stretchable outer sleeve. The stretchable inner tube is standard latex tubing, which when pressurized with fluid will expand like a balloon. The outer non-stretchable sleeve is comprised of standard polyester fabric, which wraps around the tube and prevents it from expanding radially. However, some slack in the fabric is left along the axial length of the tube, similar to how a shirt sleeve would look when pushed up one’s arm.

As a result, when the combination of these components is pressurized with fluid, the tube is constricted from expanding outwards in a radial direction, and thus the only direction the fluid can travel is longitudinally. The tube expands length-wise by filling the slack in the fabric, fighting against the elastic force of the latex normal to the direction of expansion. When the muscle is depressurized, the latex tube springs back into its original length, forcing the fluid out of the muscle. Through this process, hydro-muscles create biologically analogous motion and forces using purely soft components and minimal weight.

![Relaxed](image1)

**Relaxed**

![Pressurized](image2)

**Pressurized**

Figure 7: An illustration of Hydro Muscle Expansion

Because of the longitudinal expansion of the muscle, forces are exerted in line with the same direction of extension. When the tube is depressurized, even greater forces pull the muscle back into place because of the elasticity of the inner tube. This spring-back ability of the muscles provides an advantage over other artificial muscle alternatives; only one pressurization is necessary for creating motion in two directions; the potential energy that builds up in the latex
during the extension phase is used to bring the finger back to its original state when depressurized [11, 12, 13].

2.4 Summary

Options to increase the quality of living for digitally disabled individuals do exist in today’s market. However, these devices are either passively helpful, used solely for physical therapy, or are bulky and uncomfortable. Actively powered glove devices are a new development in the field, but use air pneumatics or tendon and motor control. Our inspiration is to incorporate Hydro Muscle into an elegant exo-musculature brace to produce biologically similar motion. If successful, this could combine the roles of physical therapy braces and fully active orthotic braces into one device.

Chapter 3: Project Objectives

3.1 Objectives

To create a hand brace that can successfully assist a disabled person, many factors must be taken into account. One of the first and most important components of our project involved user comfort. This is a factor often overlooked in the research industry, as reaching numerical goals and applying new innovation is often in the forefront of many engineers’ minds. However, our objective in building this brace is to provide a comfortable and user-friendly device that is not only more powerful than existing devices, but is also more natural-feeling for the user. For this reason, the basis of our design will include no rigid components, so as to provide the greatest flexibility and compliance for the users. Rigid components such as hinges, 4-bar linkages, and bone-like structures will be avoided, since these often result in discomfort, bulkiness, and need for customization between users. Complicated and robotic-looking devices may also be intimidating to disabled individuals and may make them less likely to wear in public for fear of embarrassment and drawing attention. This brace will be a low profile, elegant looking solution and aims to blend seamlessly into their daily life.

Secondly, the artificial muscles must generate enough motion in the fingers to be usable. This motion must allow the fingers to reach positions where fingertips make contact with each
other and the thumb, as well as any object that may impede between them. For this reason, as much of the palmar side of the hand brace must be open to allow sense of touch. With the loss of the user’s original functionality, retaining as much sensory ability as possible is very crucial. This will allow the user to still feel aware and in control of the artificial device that encompasses their fingers.

We also decided that the brace would perform three distinct gestures, moving the fingers into positions required to grasp, relax, and pinch. These movements include the “Key Grasp”, where each finger is flexed while the thumb is adducted over the lateral edge of the index finger and flexed to pinch down. This position is also known as the Lateral Pinch, and allows a person to firmly grasp a key, card, or paper over a larger surface area than two fingertips. Another gesture chosen was the “Three-Jawed Chuck”, also known as Palmar Prehension [14]. This position flexes the thumb, index finger, and middle finger to a single point, allowing for a strong pinch between three points. This allows for a more defined and stable pinch for extracting and picking up objects. To further break down the variables needed to accomplish these positions, it was necessary to choose a specific speed and range of motion for the finger actuation. The range of motion was determined by angles of the fingers in each gesture. The speed was chosen based on what would feel natural to the user as well as gradual and controllable.

![Figure 8: A Depiction of the Key Grasp and Three-Jawed Chuck Respectively](image)

A second factor to consider is force. In order for the hand brace to be helpful to a disabled user, it must provide adequate force needed to do daily actions. Since our design incorporates Hydro Muscles, the location, direction, and length of the muscles on the brace would determine the amount of force produced. Hydro Muscles create force in the direction of their expansion, and also in the opposite direction when they contract. However, the chosen hand gestures need force to be directed perpendicular to the horizontal position of the fingers. Thus a
A large portion of this project was dedicated to finding a solution for redirecting the force of Hydro Muscles perpendicular to the fingers and through the fingertips [11].

3.2 Summary

During the brainstorming stage of the project, it was decided that the device should comply to a set of goals in order to be successful. These goals included standards for overall brace aesthetics, specific measurement goals for force, motion, and speed, decisions for how the brace is controlled, as well as 3 gestures to be accomplished. The following is a summary of these goals and their numerical correspondents.

1.) Our primary goal for movements include:
   a.) “3 jawed chuck”, also known as palmar prehension
   b.) “Key grasp”, also known as lateral grasp
   c.) Standard anatomical position, with fingers relaxed and thumb abducted

2.) Our primary goal for the range of motion of the finger is to reach 80 degrees angle at a velocity of at least 0.78 rad/s

3.) Our primary goal for force is for each finger to exert at least 10N.

4.) Our primary goals for material characteristics:
   a.) Mass of the brace on the hand to be no more than 200g
   b.) Overall brace must be flexible and open at the palmar surface.

Chapter 4: Methodology

4.1 Materials

4.1.1 Construction of Hydro Muscles

From the beginning of the design phase, it was known that Hydro Muscles would be the primary source of actuation in the hand brace. However, as discussed previously, the difficulty in using Hydro Muscle is that the force it exerts lies in the same direction as its expansion. This would not be useful in strength-augmenting functions of fingers, since force needs to be exerted
perpendicular to the finger and not in line with it. If the force of the Hydro Muscle is not redirected, then the brace would exert a poking-like motion on objects, which would not suffice for our pinching and grasping goals. Thus the bulk of the project centered around how to fabricate and attach a new set of Hydro Muscles that would redirect force perpendicularly to the fingers.

Many different revisions of Hydro Muscle design and position were tested in order to accomplish this goal. A right-handed wooden manikin model was used to mount the Hydro Muscles in order to determine their impact on movement. A standard wrist brace was used to mount the muscle prototype. The first working prototype used a standard Hydro Muscle with standard parachute fabric, approximately the length of the index finger. In order for the muscle to cause angular deflection in the finger and not just linear displacement of itself, the distal end of the muscle was plugged and attached to the fingertip. To secure the length of the muscle to the finger, tape was temporarily wrapped around both entities along each phalange (3). A small, 10mL syringe was attached to the muscle through a small medical tube and secured by luer locks.

Figure 9: Hydro Muscle Prototype relaxed and pressurized, respectively
It was observed that when the muscle was pressurized with water, the muscle would only expand where it was not secured. This occurred above the knuckles, where the Hydro Muscle would bulge outward in a snake-like fashion. This curve of the muscle would intersect more perpendicularly to the next phalange of the finger, causing the finger to flex downwards. At first it seemed as though this “snaking” of the muscle was not beneficial, as it was uncontrollable and inconsistent. However, it was the first step in creating a non-linearly expanding Hydro Muscle.

The next prototype centered around the observation that expansion of the Hydro Muscle only occurs where bunching in the fabric exists. If the sleeve is taught, then there is no extra room for the muscle to extend. In this way, we attempted to control where exactly the bulging in the Hydro Muscle occurred. Since the first prototype proved that expansion at the knuckles would result in flexion of the fingers, this second prototype would focus on how to control the “snaking” so it only occurred at specific points, and at the angle of flexion desired. This was done by bunching the excess sleeve fabric only above the knuckles. The most slack was allowed in the MCP joint (where the metacarpals meet the most proximal phalange) so as to promote the largest amount of flexion in the largest joint. Less slack was allowed in the joints moving distally.

The observations of this prototype were similar to the first. However, it was noted that the “snaking” was more controlled, as the expansion only occurred at the points where the bunching was isolated. It was also observed that more bunching was needed at the MCP joint than the others, since the entire weight of the finger was being moved at this point. Overall, this prototype proved that segmenting the Hydro Muscle into expanding and non-expanding sections allows for control over the location and degrees of motion of each joint.

The final design for each Hydro Muscle took into account the observations from each prototype before it. A new polyester fabric was used for the sleeve, one with a higher thread count and a silkier finish to prevent tears in the stitching when pressurized. Instead of using a sewing machine to create consistent stitching throughout the length of the Hydro Muscle sleeve, hand stitching was used. This allowed for the bunching of the sleeve to be isolated to very specific areas of the sleeve. These areas of bunching were no longer arbitrary areas of rolled up sleeves. Instead, defined ripples were ironed into the fabric along the points corresponding to knuckle locations. These ironed ripples, similar to pleats in a skirt, were then gathered and sewed at one point. With the other side of the fabric folded and one side secured at a single knot, the
fabric could expand in a shape similar to a Chinese paper fan. These areas of expansion were aligned above each knuckle of each finger. Measurements were made using the author’s own finger dimensions.

Figure 10: Ironed Pleats on Hydro Muscle Sleeve, after being sewn and before being sewn, respectively.

Then the latex tubing was threaded through the sleeve. Straight stitches were then applied between the sewed pleats. A hose adapter was used to plug the proximal end of the muscle, while a standard bolt was used to plug the other end. Single row 0.25” plastic hose clamps were used at both of these points to create an airtight seal. The muscles were then filled with water and connected to the rest of the hydraulic system through luer lock medical tubing. Below is a picture of the components used in these new Hydro Muscles.

Figure 11: Components of new Hydro Muscle (from top to bottom, sleeve, latex tubing, clamps, and hose adapter)
4.1.2 Attachment and Placement of Hydro Muscles

A standard right handed football glove was used for the foundation of the final hand brace. This model was chosen because while the top surface had many ridges that would provide a sturdy point of muscle attachment, the palmar face was purely rubber. This allowed for holes to be cut out along the pads of each of the finger tips.

A total of 5 new Hydro Muscles were created, one to flex and extend each finger. One other small original Hydro Muscle was created for thumb adduction and abduction. Its distal end was mounted to the tip of the thumb, while its proximal end was attached near the proximal end of the index finger’s flexion muscle. All six muscles were attached by hand using thread and needles. Each sewn pleat was attached directly above the corresponding knuckle. The distal end of the muscle was sewn directly to the fingertip of the glove. The proximal end of the muscle, where the adapter for the tubing existed, a basic hose mounting was attached using glue and then
subsequently sewn onto the glove. This hose mounting prevented rotation in the muscle so as to ensure the flexion happened along a vertical plane.

Figure 13: Fully constructed Hydro Muscle Hand Brace on user

4.2 Hydraulic System

4.2.1 Linear Actuator

The linear actuator used in our hydraulic system is the HIWIN 12V 200mm actuator. This actuator extends at a top speed of 12mm/sec and weighs 1.27kg. This actuator is connected to a 50mm plastic medical syringe by a PVC pipe, and when extended, pushes the plunger of the syringe to excrete water out of the other end. This syringe is then connected to a series of tubing that leads to the solenoid valves where the water is redirected to the fingers. This linear actuator provides a large amount of consistent force, far sufficient enough to create the 90psi necessary for finger flexion.

Figure 14: Linear Actuator
This linear actuator design was chosen after a series of other tests with alternative water pressurizing methods. A water pump and reservoir system was first attempted to displace and pressurize fluid within the muscles. However, with the small amount of fluid being displaced (approximately 10mL for each finger) as well as the pump resources available to the lab, it was determined that this method would be difficult to control and was not compact enough for our application. The benefit of using a linear actuator and syringe is that the fluid being displaced can be precisely measured and controlled, and simpler sensors such as limit switches can easily be integrated into the system.

4.2.2 Solenoid Valves

The solenoid valves used for this system were the Dorot 12V two way hydraulic valves. These connected to tubing on either side and when received signal, switched an internal gate either on or off. By default, these valves are open, and will allow water to flow through until turned off. When turned off, these valves tend to leak through the top fissure, but this was solved by plugging it with epoxy.

For our system’s purposes, a total of two solenoid valves were used. In order to perform the 3 positions aforementioned, the fingers were divided into two groups:

1.) Fingers and Thumb: Flexion/Extension

![Figure 15: Solenoid Valve](image)
2.) Thumb: Adduction/Abduction

It was decided that the system would be easiest to control if all of the finger flexors were grouped together, instead of controlling each finger separately. Since the “3 Jawed-Chuck” requires that the thumb, index finger, and middle finger all make contact, this can be performed when the ring finger and pinkie finger are flexed as well. Also, the “Key Grasp” requires that all fingers be flexed. Thus, since each gesture can be performed with all of the fingers either flexed or extended simultaneously, it was decided that only one solenoid would be used for finger flexion and extension. This includes the thumb, since thumb flexion will always occur at the same time as finger flexion in both gestures.

The first solenoid allowed the passage of water into all muscles lying on the “top” of the hand, (in anatomical position, this is the posterior side). When pressurized, these muscles will expand and cause full flexion in all fingers, including the thumb. When depressurized, the elastic potential in the latex of the muscles will promote extension of the fingers back into their original position.

The second solenoid is solely devoted to the second thumb muscle, which rests diagonally between the thumb and index finger. When pressurized, this muscle extends and causes the abduction of the thumb away from the centerline of the hand. This induces a “relaxed” position of the thumb, as when hands are not being used there is naturally a gap between the fingers and thumb. When depressurized, the muscle shrinks and adducts the thumb back to its original position to make contact with the index finger. This is what makes the “key grasp” position possible.

![Figure 16: Depiction of Hydraulic System for Hydro Muscle Groups](image)
4.3 Control

To control the finger positions of the device, many types of sensors and controls were considered. Since this is the first revision of this design, a simple system of an Arduino Uno, Arduino Motor Shield, a breadboard, and digital sensors was constructed. This microcontroller allowed for the coding of the linear actuator, giving us control over its speed and direction.

Table 1: Arduino Uno Technical Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microcontroller</td>
<td>ATmega328P</td>
</tr>
<tr>
<td>Operating Voltage</td>
<td>5V</td>
</tr>
<tr>
<td>Input Voltage (recommended)</td>
<td>7-12V</td>
</tr>
<tr>
<td>Input Voltage (limit)</td>
<td>6-20V</td>
</tr>
<tr>
<td>Digital I/O Pins</td>
<td>14 (of which 6 provide PWM output)</td>
</tr>
<tr>
<td>PWM Digital I/O Pins</td>
<td>6</td>
</tr>
<tr>
<td>Analog Input Pins</td>
<td>6</td>
</tr>
<tr>
<td>DC Current per I/O Pin</td>
<td>20 mA</td>
</tr>
<tr>
<td>DC Current for 3.3V Pin</td>
<td>50 mA</td>
</tr>
<tr>
<td>Flash Memory</td>
<td>32 KB (ATmega328P) of which 0.5 KB used by bootloader</td>
</tr>
<tr>
<td>SRAM</td>
<td>2 KB (ATmega328P)</td>
</tr>
<tr>
<td>EEPROM</td>
<td>1 KB (ATmega328P)</td>
</tr>
<tr>
<td>Clock Speed</td>
<td>16 MHz</td>
</tr>
<tr>
<td>LED_BUILTIN</td>
<td>13</td>
</tr>
<tr>
<td>Length</td>
<td>68.6 mm</td>
</tr>
<tr>
<td>Width</td>
<td>53.4 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>25 g</td>
</tr>
</tbody>
</table>


Using digital sensors gives the user or demo operator control over both the linear actuator and solenoids. The right side of the control panel controls the linear actuator, whereas the left side controls the opening and closing of the solenoids. When held down, the green button labeled “Forward” turns on the linear actuator at a speed of ___ to push water out of the syringe and into the muscles, causing flexion. The black “Back” button does exactly the same, but in the reverse direction, suctioning the water back into the syringe to depressurize the muscles. When neither
button is pressed, the linear actuator stops all movement and holds the position of the muscles in whatever state they are pressurized. If the actuator attempts to extend the piston further than the syringe setup allows, a limit switch will hit and disable any further movement.

![Figure 17: Arduino Uno with Motor Shield, Breadboard circuit, and Control Panel](image)

The switches on the right side of the panel are labeled with which gesture it controls. To organize which solenoid actuated which position, the table below was constructed. When the top switch is turned to off, the solenoids return to their default position of open. The Off switch should only be used when the linear actuator is in its furthest back state. When a position is desired, the linear actuator must start at this default position, then a switch can be slid into position to turn on the corresponding solenoids. Only then can the linear actuator can be pushed forward to pressurize the chosen muscles.

<table>
<thead>
<tr>
<th>Solenoid 1 (All flexors)</th>
<th>Relaxed</th>
<th>Key Grasp</th>
<th>3 Jawed Chuck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
</tr>
<tr>
<td>Solenoid 2 (Thumb adduction)</td>
<td>Open</td>
<td>Closed</td>
<td>Open</td>
</tr>
</tbody>
</table>

This Arduino and shield are powered by a PC through USB connection. The linear actuator is powered using a Wanptek DC Power Supply. This power supply has a maximum of 60V, but our
purposes only required a voltage of 12V. This setup requires a transformer; our system used the PowerBright Step Up & Step Down Transformer Power Source, particularly the 110V port.

![Step Up & Down Transformer and DC Power Supply](image)

Figure 18: Step Up & Down Transformer and DC Power Supply, respectively

4.4 Summary

The Flexion Hydro Muscles were specially constructed with isolated ripples in order to bend like fingers without the use of rigid parts. A total of 5 of these Flexion muscles were attached at the joints to a flexible glove, while a single original Hydro Muscle was attached diagonally from the tip of the thumb to the knuckle of the index finger. Together, these muscles create flexion and extension of the fingers, as well as abduction and adduction of the thumb. Separately, they are controlled by two solenoids connected to an Arduino Uno and power source. The user interface to control the system consists of buttons for the linear actuator, and switches for the solenoid positions.

Chapter 5: Experiments

5.1 Motion

The tests for motion were performed by analyzing finger angle and gesture position. To determine whether the three gestures were successful, contact and no contact points were observed. For the Three-Jawed Chuck position, it was visually noted whether the index finger, middle finger, and thumb made contact. Their angle of flexion was also noted. To test their contact, an object was placed within the grip to determine whether or not it would be useable to a disabled individual.
5.2 Force

To calculate force, a standard force sensor was used, and values were read from the Arduino serial window. The values outputted from the sensor were in Ohms. To calibrate the sensor, varying weights of known values in kilograms were placed on the sensor. The resistances outputted for each weight were graphed corresponding to their known weights. The resulting curve was of a logarithmic function. Next, the force sensor was attached to a wooden block and was placed within the grip of the glove. When the muscles flexed, the fingertip of the middle finger made contact with the sensor perpendicularly. This value of the resistance was recorded and then plotted on the graph to determine the force output in Newtons.

Figure 19: Force sensor mounted to block is positioned for testing before the fingers flex.
5.3 Summary

To test the strength of our brace and to determine whether we succeeded in reaching our goals of producing the specified gestures as well as adequate force, we completed a series of experiments. These experiments were not performed on a human hand; rather, a skeletal model of a hand was modified to become flexible at the joints, and was covered in modeling clay to mimic flesh. Numerical values and visual observations were recorded.

Chapter 6: Results and Conclusions

6.1 Results

The observations for the motion test showed that the fingers performed in a way that matched our goals. The index finger and middle finger flexed at an angle of more than 80 degrees for each knuckle. These combined with the flexion of the thumb provided a stable point of contact to successfully perform the “Three-Jawed Chuck”. The adduction of the thumb was sufficient enough to create contact between the left side of the index finger and the pad of the thumb. This resulted in a successful “Key Grasp”. The default position of each muscle depressurized while the thumb was abducted was also successful, as the fingers returned to a fully outstretched position with no contact between them.
However, the observations for the force testing were not as successful. The goal was to reach 10N of force, but the data only outputted a maximum of 770 Ohms. When plotted on the graph, this corresponds to 5.23 Newtons. This means that the brace fell short of its 10N goal by nearly half.

6.2 Conclusions
The motion produced by the Hydro Muscle hand brace met all of the goals set forth at the beginning of the project. The essential fingers for gestures met and exceeded the requirement for flexing 80 degrees from the vertical plane. These fingers also made contact in the correct points for each gesture, enough so to place objects and have them remain stably gripped. All of this
happened within the specified time of 0.78 rad/s. The brace itself also weighed significantly less than 200g.

The force produced by the Hydro Muscle hand brace did fall short of the 10 Newton goal. Only reaching approximately 5.23N, this was a significant decrease in what was expected of the muscles. However, this test was not performed on a fully biologically analogous structure. If performed on a human test subject, this force output could be significantly larger. Also, 5N is still a significant amount of force, and does provide a range of functionality for a user who would be otherwise disabled.

6.3 Summary
The tests for motion reached our goals of the three gestures, “Three-Jawed Chuck”, “Key Grasp”, and “Standard Position”. However, our goal for force outputted by the muscles fell short by about half, only creating 5.23N. Since over half of the goals were successfully met, and considering that this is a first generation project completed by a one-person team, the overall result of the project can be considered satisfactory.

In terms of potential patient use however, this project should be considered successful beyond the numbers. Since so many conditions could benefit just from basic motion in a paralyzed hand, this brace could provide significant results in neuroplasticity throughout therapeutic use. In physical therapy applications, the movement from this brace could help people with arthritis lessen pain and regain degrees of motion in their joints, while stroke patients could potentially regain nerve plasticity and thus movement in their weakened or paralyzed limbs. If this project is to be continued, the original force goal could be reached as well as the overall system be fine-tuned enough for daily use.
Chapter 7: Recommendations

For future direction, our team hopes that another MQP will expand upon the design created in this initial project. Since this is the first rendition of the Hydro Muscle Hand Brace, it is only a proof of concept design. We hope that with the next team of students will come the improvements that we wish we had enough resources, time, and laborers for. Our recommendations for future improvements are as follows:

1.) Fine-tune the glove and Hydro Muscles to reach the goal of creating 10N of force.
2.) Integrate pressure sensors into the tubing after the solenoid valves. This could allow feedback control for to stop pressurization when the muscles reach approximately 90psi. Doing this could allow autonomous control, ridding the need for user timing to dictate when the actuator stops. This could also act as damage control to preserve the muscles from overfilling.
3.) Integrate force sensors into the tips of the fingers. This could allow another form of feedback to the system, and would help judge whether the fingers have encountered obstacles or abruptions in their trajectory. This would allow users to collect data as well as protect the muscles themselves.
4.) Downsize the overall linear actuator and syringe system into a more compact, lightweight, and ultimately portable design. We believe this could be done with a small scale pump and water reservoir. The ultimate goal is to make the entire system wearable and comfortable, and perhaps potentially marketable.
5.) Create a systematic method for Hydro Muscle manufacturing that requires less manual labor. Along these lines, also create a way for muscle attachment on glove to be modular, so switching out broken or leaky muscles can be done efficiently and without the need for sewing.
6.) Future endeavors could possibly rid of the need for any button or switch control by integrating EMG or other biologically compatible control systems.
Chapter 8: References


Chapter 9: Appendix

9.1 Arduino Pin Configuration

Table 4: Arduino Motor Shield Pin Descriptions

<table>
<thead>
<tr>
<th>D 1</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>D 2</td>
<td>N/A</td>
</tr>
<tr>
<td>D 3</td>
<td>N/A</td>
</tr>
<tr>
<td>D 4</td>
<td>Actuator “Back” button</td>
</tr>
<tr>
<td>D 5</td>
<td>Actuator “Forward” button</td>
</tr>
<tr>
<td>D 6</td>
<td>N/A (non-operative)</td>
</tr>
<tr>
<td>D 7</td>
<td>Finger Flexion Solenoid</td>
</tr>
<tr>
<td>D 8</td>
<td>“Key Grasp” Panel Switch</td>
</tr>
<tr>
<td>D 9</td>
<td>“Off” Panel Switch</td>
</tr>
<tr>
<td>D 10</td>
<td>LED for Force Sensor (Testing)</td>
</tr>
<tr>
<td>D 11</td>
<td>Thumb Adduction Solenoid</td>
</tr>
<tr>
<td>D 12</td>
<td>Actuator Limit Switch</td>
</tr>
<tr>
<td>D 13</td>
<td>Force Sensor (Testing)</td>
</tr>
</tbody>
</table>

9.2 Code

```cpp
int solenoidPin1 = 11; //This is the output pin on the Arduino we are using for the thumb solenoid
int solenoidPin2 = 7; //this is the output pin on the Arduino we are using for the fingers solenoid
const int switchPin1 = 8; //pins on Arduino for the switches (for buttons and switches DO NOT USE PIN 13, 0, or 1
const int switchPin2 = 9;
const int buttonPin1 = 4; //pins on Arduino for buttons
const int buttonPin2 = 5;
const int limitPin = 12;

int switchState1 = 1; //variables that hold position of each switch
int switchState2 = 1;
int buttonState1 = 1; //variables that hold position of each button
int buttonState2 = 1;
int limitState = 0;
```
//for actuator
// PWM is connected to pin 3.
const int pinPwm = 3;
// DIR is connected to pin 2.
const int pinDir = 2;

// Speed of the motor.
static int iSpeedf = 100;
static int iSpeedb = -50;

void setup() {
    Serial.begin(9600);
    // sets solenoids as outputs
    // sets switches (solenoids control) as input
    // set buttons (actuator control) as output
    pinMode(solenoidPin1, OUTPUT);
    pinMode(solenoidPin2, OUTPUT);
    pinMode(switchPin1, INPUT);
    pinMode(switchPin2, INPUT);
    pinMode(buttonPin1, INPUT);
    pinMode(buttonPin2, INPUT);
    pinMode(limitPin, INPUT);

    // for buttons, plug ground to ground and button power to the pin
    digitalWrite(buttonPin1, HIGH);
    digitalWrite(buttonPin2, HIGH);
    digitalWrite(limitPin, HIGH);
    // set up for actuator
    pinMode(pinPwm, OUTPUT);
    pinMode(pinDir, OUTPUT);
}

void loop() {

    // serial prins are just used for trouble shooting
Serial.print(switchState1);
Serial.print("      ");
Serial.print("button2");
Serial.print(switchState2);
Serial.print("   ");}

if(buttonState1 == LOW && buttonState2== HIGH){
analogWrite(pinPwm, 100);
digitalWrite(pinDir, HIGH);
}
Serial.println(switchState1);
Serial.println(switchState2);
if(limitState==0){
  limitState = digitalRead(limitPin);
  switchState1 = digitalRead(switchPin1);
  switchState2 = digitalRead(switchPin2);
  buttonState1 = digitalRead(buttonPin1);
  buttonState2 = digitalRead(buttonPin2);

//control actuator
if(buttonState1 == HIGH && buttonState2== LOW){
analogWrite(pinPwm, 100);
digitalWrite(pinDir, LOW);
}
else if(buttonState1 == LOW && buttonState2== HIGH){
analogWrite(pinPwm, 100);
digitalWrite(pinDir, HIGH);
}
else{
analogWrite(pinPwm, 0);
digitalWrite(pinDir, LOW);
}

//control solenoid
if (switchState1 == LOW && switchState2 == LOW) {
digitalWrite(solenoidPin1, LOW);  //Switch Solenoid ON
digitalWrite(solenoidPin2, LOW);  //Switch Solenoid OFF
else if (switchState1==HIGH && switchState2 == LOW) {
    digitalWrite(solenoidPin1, LOW);    //Switch Solenoid ON
    digitalWrite(solenoidPin2, HIGH);     //Switch Solenoid off    //Wait 1 Second
}
else if (switchState1==LOW && switchState2 == HIGH){
    digitalWrite(solenoidPin1, HIGH);    //Switch Solenoid OFF
    digitalWrite(solenoidPin2, LOW);     //Switch Solenoid ON
}
else if(switchState1==HIGH && switchState2 == HIGH){
    digitalWrite(solenoidPin1, LOW);    //Switch Solenoid OFF
    digitalWrite(solenoidPin2, LOW);     //Switch Solenoid OFF
}
else if(limitState==1){
    analogWrite(pinPwm, 0);
    digitalWrite(pinDir, LOW);
}
limitState = digitalRead(limitPin);
switchState1 = digitalRead(switchPin1);
switchState2 = digitalRead(switchPin2);
buttonState1 = digitalRead(buttonPin1);
buttonState2 = digitalRead(buttonPin2);
//Serial.println(limitState);