Physical Therapy for Cerebral Palsy (PT4CP)

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During a research period of June-August 2020, a team of students from the Laboratory for Adaptation, Inclusion, and Robotics developed fabric-based pneumatic actuators for use in at-home physical therapy for children with spastic cerebral palsy. This paper focuses on the mechanical components of the device–specifically, what materials and productions methods are most effective in creating a useful, affordable actuator. It details the development of several working prototypes and what methods were used to test them, as well as what research remains to be done on this subject in the future.

1. Problem Statement

Cerebral palsy, or CP, is the most common physical disability among children, affecting one in 323 children in the United States. Of the three forms of CP, Spastic CP is by far the most common, making up 70 to 80 percent of diagnoses (Monheit, 2017). Spastic CP inhibits the neural impulses that tell muscles to relax, which causes stiffness and jerky movements. More specifically, two common symptoms of spastic CP are dystonia (uncontrollable muscle contractions, often causing twisting and repetitive movements) and joint contracture (shortening of the muscles, tendons, and ligaments) (Reiter, 2014). Both dystonia and joint contracture can cause pain and worsen over time if left untreated. Treatment for these symptoms usually involves bracing and daily range of motion (ROM) exercises to maintain the flexibility of the joint. While braces exist for most of the larger joints, such as the knees and the wrists, it is much harder to find braces that support the fingers. Those that exist are passive, simply holding the fingers in one position, as shown in Fig 1.1. Physical therapists often just use their own hands to stretch the fingers of clients with spastic CP. However, physical therapy appointments alone are often not enough to maintain flexibility, and braces that support the fingers are often inaccessible due to cost. The goal of this research, therefore, is to develop a safe, low-cost, effective way to actively move the fingers of a child with CP through their full range of motion.

Figure 1.1: Dorsal view of the Benik Volar Pan Extension Brace, designed to passively straighten the wrist and fingers (Benik).

1.1 Requirements

The most important requirement of the device was that it needed to be safe for children with CP to use. If it was unsafe, it could not be used. The secondary requirement was that it needed to be effective in treating the symptoms of spastic CP in the hands of children. The final requirement was that our device needed to be simple and inexpensive enough for the caretakers of users to build at home even if they had limited technical experience.

2. Summer 2019

The team working on the PT4CP project in Olin College's Laboratory for Adaptation, Inclusion, and Robotics (LAIR) consisted of Dylan Merzenich and Robin Graham-Hayes. As with this summer, their faculty advisor was Jeff Dusek. Throughout the course of the summer, the research team met several times with a 13-year-old girl in the Needham area with spastic quadriplegic CP. Through these visits with her and her family, the team learned about what treatment needs were not being met by current physical therapy practices.

The team chose to focus on designing a physical therapy device for the hands. They chose to base their design of soft robotics technology–developing silicone-based flexible pneumatic actuators, as shown in Fig 2.1.

The design for these actuators was based on the soft-robotics gloves created at Harvard's Walsh Lab in 2014 (Polygerinos). They were fabricated by first molding a small tube of silicone to act as the air pocket, open only at one end. Then strips of fiberglass were glued to one side of the silicone to limit stretching along that side, causing bending. Kevlar thread was then wrapped around the actuator in one clockwise and one anticlockwise spiral to reduce radial expansion and strengthen the actuator. The final steps were to cure a second layer of silicone around the actuator to seal everything together and to attach the nozzle and tubing. Though these actuators did bend when pressurized, they were time consuming to construct, with each one requiring several days to cure. They were also leaky and required high pressurization to achieve even slight bending. Due to these concerns with the silicone prototypes, the LAIR began to explore other soft robotics options during the fall semester, particularly fabric-based actuators.

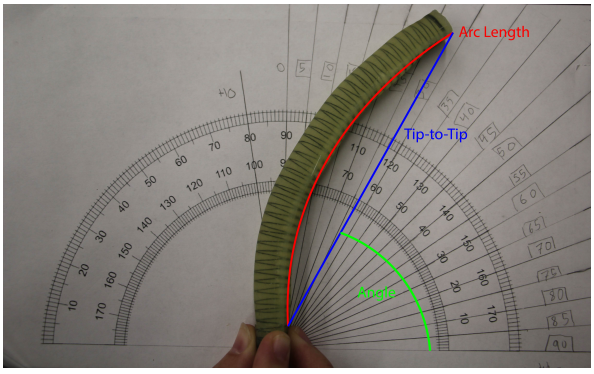

Figure 2.1: Silicone prototype setup to experiment with correlation between internal pressure and bending angle.

3. Summer 2020

The team continued to experiment with pneumatically-actuated soft robotics. The focus of its research, however, pivoted from silicone-based actuators to fabric based actuators. The three members of the summer research team took on one aspect of a robotic system: Sense, Think, and Act. The author focused on "Act"–building a simple fabric-based pneumatic actuator and determining how to attach it to a user's hand. The design for the fabric-based actuator was based on that developed by Cappello et al, as described below (2018). It was to consist of three layers of fabric and two plastic air bladders, as shown in Fig 3.1. The bladders served to contain the air supplied by an electric pump, pressurizing the interior of the fabric pockets. The difference between the knit and woven fabrics is shown in Fig 3.3. The first and middle layers of fabric are woven, and therefore do not stretch. When the bladder between these two layers is inflated, they limit its expansion, causing the actuator to straighten and stiffen. Inflating this bladder would extend the finger. The top layer of fabric is a warp-knit, which gives it the property of stretching preferentially in the longitudinal direction. When the bladder between this top layer and the woven middle layer is inflated, it again presses outwards against the layers of fabric. However, in this case the knit layer is able to stretch while the woven layer is not. This causes the actuator to curve downwards, away from the knit layer. Inflating this bladder would cause the fingers to bend. These effect of these actions can be seen in Fig 3.2.

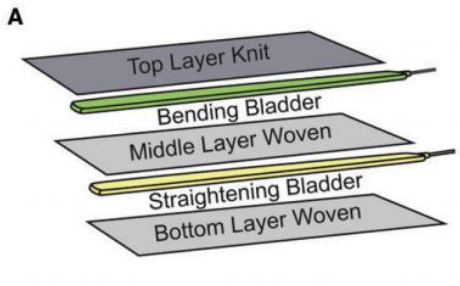

Figure 3.1: Diagram of layers of fabric and plastic, (Cappello, 2018).

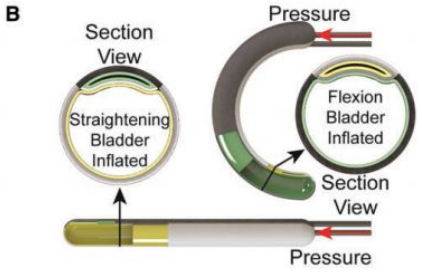

Figure 3.2: Diagram of the effects of inflating the flexion bladder and the straightening bladder, (Cappello, 2018).

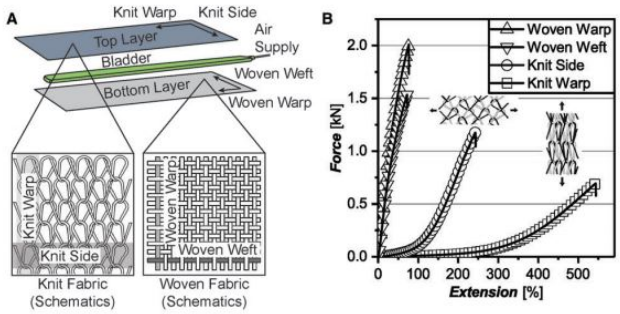

Figure 3.3: An illustration of the difference between knit and woven fabrics, with a graph of the force needed to reach a certain extension as a measure of stretch (Cappello, 2018).

3.1 Background Research

Leonard Cappello's "Exploiting Textile Mechanical Anisotropy for Fabric-Based Pneumatic Actuators" was the basis of the team's fabric-based-actuator design. The article describes research done at Harvard University in 2018, in which a glove was created that could bend and straighten the fingers using fabric-based pneumatic actuators sewn into the back of each finger of the glove as shown in Fig 3.4. It described the exact types of fabric that it used and in what dimensions. However, this article focused on the possibility of using this technology to assist people who had suffered a stroke, rather than people with CP. This meant that the glove was intended to move a more passive, relaxed hand than that of a person with spastic CP. The LAIR's device, therefore, had to be sufficiently powerful to counteract the high muscle tone of a person with CP. In addition, this article utilized a serger and laser cutter during fabrication–tools that most people lack access to. In order to meet the goal of making the device reasonably accessible for people to build themselves, it was necessary to find alternate fabrication methods. Furthermore, the article made no mention of sensors to detect the bending radius of the actuators, which would be important to incorporate in order to protect the user safety.

Figure 3.4: Glove with fabric-based actuators sewn along the backs of the fingers (Cappello 2018).

3.2 Prototyping and Experimentation

The first step in this summer's research period was to experiment with different materials for the fabric actuators. Initially, fabric scraps were used in an attempt to replicate the actuators in the Cappello article, as it was thought that this would be the best way to make the actuators easy to replicate. A simple woven piece of gingham fabric was used for the non-stretchy layer of fabric. Sections of an athletic t-shirt found to have a 2-way stretch (it only stretched along one axis) were used as the knit fabric. Fig 3.5 shows images of some early prototypes using these fabrics. Testing proved these initial prototypes to be almost entirely ineffective. After experimentation with other fabrics sent from the LAIR, it was discovered that the initial prototypes failed because the t-shirt fabric was not stretchy enough to cause bending. Overall stretch, therefore, is more important than directional stretch. The next step, upon this discovery, was to order samples of the two fabrics listed in the Cappello article to determine if it was possible to replicate their results.

Once the proper fabrics were acquired, it was essential to find a leak-proof method of attaching the rubber tubing to the plastic sheeting. Experimentation with many different solutions, including heat sealing, valves from bike and car inner-tubes, hollow bolts and rubber washers, and tape, (as shown in Fig 3.6) was largely unsuccessful. Prototypes made

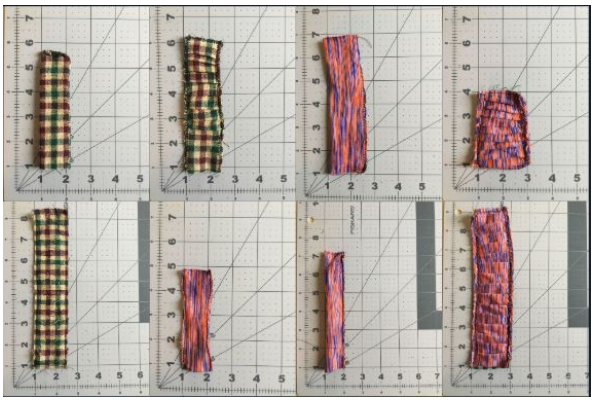

Figure 3.5: Early prototypes made from scrap woven (gingham) and 2-way stretch knit (pink) fabrics.

using these materials either leaked immediately or were unable to withstand a pressure of more than a few psi. The Cappello article used Loctite to solve this problem, but trials of a similar glue found it to be it both ineffective and difficult to work with, the latter of which did not meet the requirement of making the device easy to build at home.

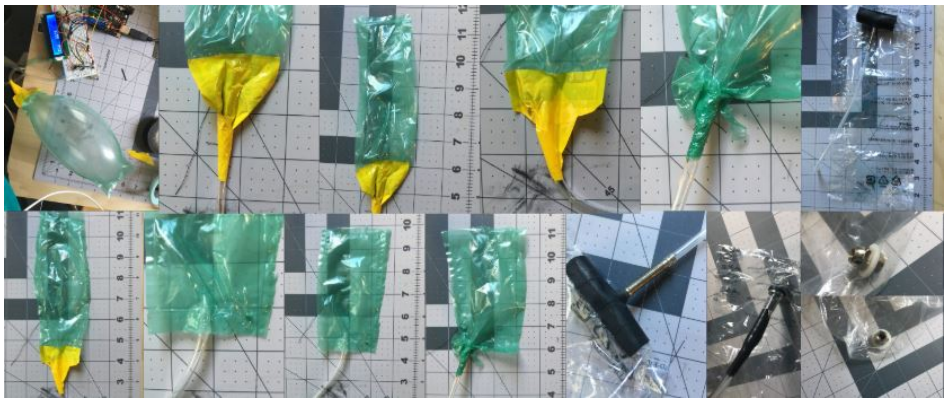

Figure 3.6: Ineffective prototypes of methods for attaching tubing to bladder.

The solution to this problem, found through much experimentation, is shown in 3.7. This connection is constructed by stretching the plastic over the opening of a brass or plastic tube connector and pushing the tubing is down over both the plastic and the connector. The tubing is tight enough over the connector to hold the plastic in place, preventing any leakage. Once this airtight seal is formed, the rest of the bladder can be heat-sealed around it. Sometimes it was necessary to puncture the layer of plastic stretched over the top of the connector with a pin to allow airflow before sealing the badder shut.

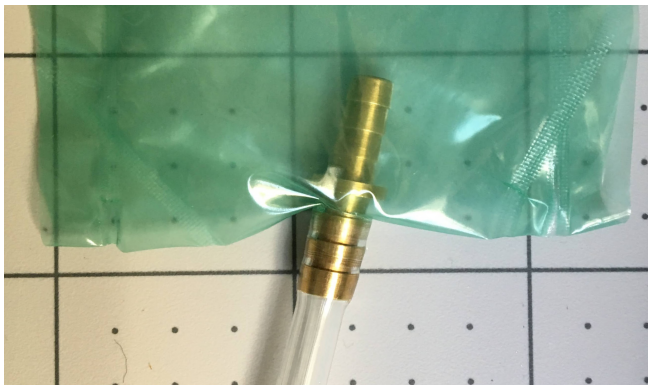

Figure 3.7: Prototype of airtight connection mechanism between tubing and bladder.

Once an airtight connection mechanism was found, it was possible to replicate the findings of the Cappello article and to begin experimenting with different actuator designs. Two of these designs can be seen in Fig 3.8 and 3.9.

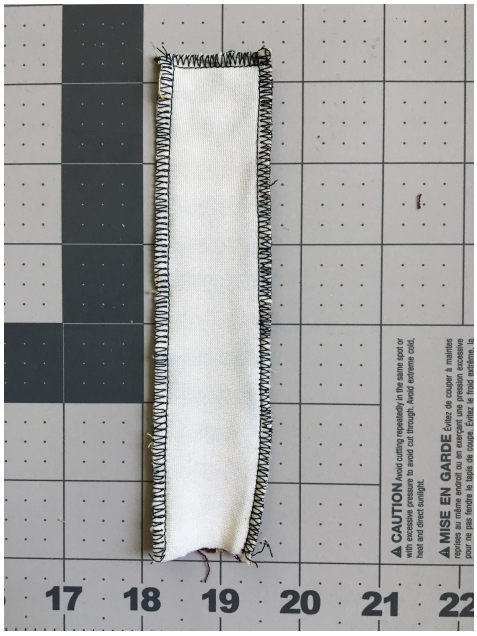

Figure 3.8: Actuator prototype constructed using the fabrics listed in the Cappello article.

Figure 3.9: Actuator prototype made using scrap woven fabric and pleated knit fabric from the LAIR similar to that in the Cappello article.

The actuator prototypes made during this phase of the research period were effective enough to make more reliable testing methods necessary. In order to determine the potential of these actuators to assist with physical therapy, it was important that one could determine the force and bending radius of the actuator at different pressures. An effort was made to test these prototypes, but the testing method was not reliable enough for the test results to be conclusive. Fig 3.10 shows a test setup which failed because the tip of the actuator could not be properly attached to the scale.

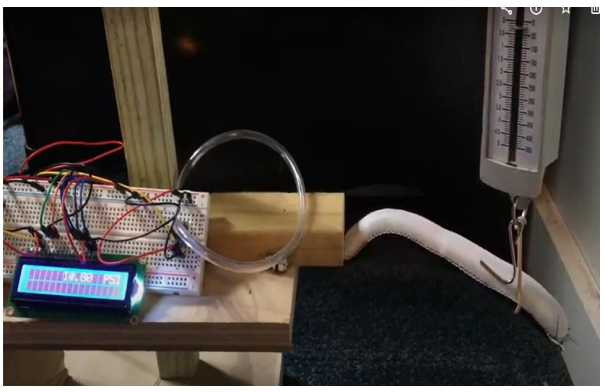

Figure 3.10: Setup intended to test the downward force generated by the tip of the actuator when pressurized.

Further prototyping and testing is required to quantitatively determine the effectiveness of these fabric actuators. This will inform future decisions about what materials and designs are most useful.

4. Next Steps

In the future, the focus of this research will shift from prototyping to testing and integration with the electrical and sensing components. Some of this work has already been done. Fig 4.2 shows a preliminary setup for testing correlation of pressure to bending angle which must be reconfigured in order to achieve accurate results. Fig 4.1 shows a simple setup for testing bending angle which uses a protractor printed on a piece of paper to measure the angle at the tip of the actuator. This too will be refined, perhaps to measure bending radius of the actuator as a whole rather than degrees of adduction at the tip of the actuator. It may also be useful to experiment with predictive modeling of the actuator's mechanics based on characteristics of different fabrics. In addition, further research will explore how the actuators might be attached to the hand. A basic prototype of this is shown in Fig 4.3.

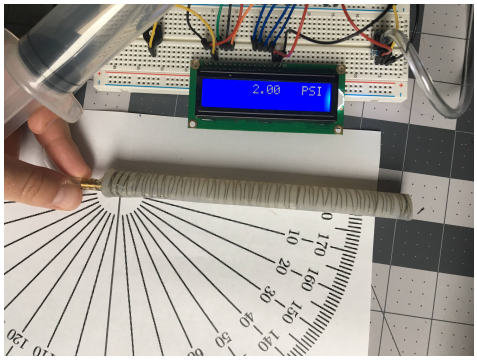

Figure 4.1: Basic setup for measuring degrees of actuator bending as pressure changes.

Figure 4.2: Mechanism for holding actuator in place to measure force generated.

Figure 4.3: Double-bladdered actuator attached to hand with elastic loop.

Acknowledgements

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