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Development of a Soft Robotic Shoulder Assistive Device for Shoulder Abduction

R.F. Natividad[1], C.H. Yeow[1,2], *Member, IEEE*

Abstract — **Cerebral Palsy (CP) is a perpetual disease that a patient endures throughout their entire lifetime. Motor impairment, that is a common symptom, must be permanently managed by the patient; however, evidence suggests that repetitive task practice (RTP) can help patients improve their motor skills. An initial version of a wearable, soft robotic, shoulder exosuit has been developed that may be used for RTP. The device is centered around an inflatable, fabric beam that facilitates abduction of the shoulder joint. The use of an inflatable beam has allowed the device to be extremely lightweight while still being able to deliver a considerable amount of bending moment. The actuator is initially in its deflated state; inflation of the actuator straightens it, applying a bending moment to the brachium that abducts the limb. Two overlapping sheets of fabric were hermetically sealed by applying localized heat at the edges. Actuators were then anchored to the shoulder and inserted to a sleeve attached to the brachium. Position control was achieved by applying varying magnitudes of pressure. Preliminary testing exhibited successful abduction on a mannequin and a healthy subject.**

I. INTRODUCTION

As much as 3.6 out of 1000 infants born are diagnosed with cerebral palsy(CP) [*1*]. CP patients suffer from a variety of symptoms which include degraded vision [*2*] — [3], behavioral problems [*3*], cognitive impairment [*4*] and decreased motor function [*5*]. This leads to a severely degraded quality of life and can possibly reduce lifespan. The persistence of the disorder means these symptoms will remain throughout a person's lifetime. Nevertheless, several treatments and management schemes are available. One possible approach to alleviate the impact of motor function impairment is through repetitive task practice (RTP) [*6*]. A robotic exosuit can be utilized to facilitate RTP.

A limiting factor in the development of exosuits is that conventional robotic devices do not possess the necessary flexibility or dexterity to correctly imitate human body kinematics. They involve the use of rigid, noncompliant links [*7*]- [*11*] that limit the amount of Degrees of Freedom(DOF) of traditional exosuits. The use of rigid links allows these designs to apply a great amount of force at the expense of flexibility. They prevent natural articulation of the joints and instead limit joint movement to that allowed by the rigid device. Any dissimilarity between the designed path and that of the joint can result in discomfort or injury to the user. Moreover, the nature of these devices comes with it an intrinsic complexity that render them uneconomical and impractical. Conversely, biological systems are rarely composed of rigid members but of nimble materials. This inherent adaptability allows them to perform complex movements. Any device that aims to imitate the motion of any biological system must also emulate the flexible nature of these systems.

Advances in the field of soft robotics have allowed researchers to better emulate the natural function of animals [*12*] — [*13*]. Soft robots use naturally flexible materials to provide actuation and thus allow a device to attain a high number of DOF. The more prominent archetypes in soft robotics are elastomeric actuators and cable-driven devices. The former are fluid driven and feature extremely high flexibility coupled with a low mass footprint. However, they can only apply a limited amount of force [*14*]. Alternatively, cable-driven devices have the ability to deliver a significant amount of force. Independently, they are limited to providing linear actuation only and are often used collectively if more complex motions are desired.

While the field is relatively new, a number of soft robotic devices for rehabilitative and assistive purposes have already been designed and showcased. These include stroke treatment suits for the hand [*15*] and feet [*16*], and an exosuit for gait assistance that can even be purposed to help soldiers carry their combat equipment. [*17*]**.** Another area of interest is the shoulder. Galinia et al. have previously developed a cable-driven, soft robotic shoulder sleeve [*18*].

An initial prototype of a simple, soft robotic device for shoulder abduction rehabilitation was conceptualized. The device is designed to perform repetitive shoulder abduction for the reduction of motor impairment in CP patients. Central to the design is a fabric-based, inflatable beam, configured to act as a soft robotic actuator. It combines the properties of both elastomeric actuators and cable driven devices; it is able to apply sufficient force to successfully abduct the shoulder joint while preserving natural articulation. Activation is done through injection of pressurized air such that the flexibility and stiffness vary accordingly with changes in the magnitude of pressure.

II. DEVICE SPECIFICATIONS

The primary component of the actuator was a fabric constructed out of thermoplastic polyurethane(TPU) fibers combined with a very thin polyurethane(PU) sheet (Jiangxing Inch Eco Materials, Item# N840D). Heat seals run along the perimeter, effectively creating an air chamber. A minute hole is present on the surface that allows the placement of a barbed pneumatic connector. The actual actuator utilized by the design weighs 35g. Its length and width are 510mm and 90mm respectively with a 5mm wide heat seal on each side. Besides

[1] R. F. Natividad and C. H. Yeow are with the Department of Biomedical Engineering, National University of Singapore, Singapore (e-mail: bienrf@nus.edu.sg, bieych@nus.edu.sg).

[2] C. H. Yeow is also with the Singapore Institute for Neurotechnology and the Advanced Robotics Center.

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trapping air, the heat seal area also serves as a mounting area. Overall, the uninflated chamber was 80mm wide by 500mm long. During inflation however, the air chamber transforms into a circular shape.

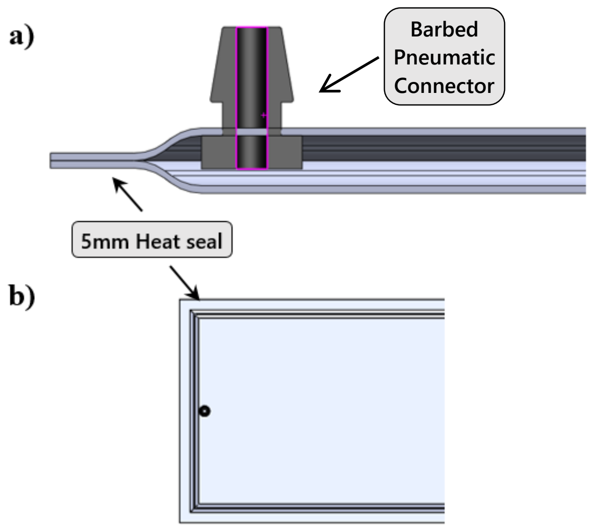

Figure 1. 3-D images of an uninflated actuator featuring the heal seal areas. a) cross section b) top view.

The actuator was attached to two locations on the body-the shoulder and the brachium. A straightforward design was utilized for integration onto the body. The design uses a jacket configuration wherein the actuator is sewn onto the jacket's shoulder area. A two-tiered sleeve was then placed on top of the jacket and was positioned along the elbow area. The sleeve was designed to be as short as possible with practicality and user comfort in mind. This allowed the sleeve to concentrate the weight of the arm along a shorter span of the beam to reduce the effect on beam deflection. While the bottom tier of the sleeve was placed on the elbow, the second served as a prismatic joint between the brachium and the actuator. This unconstrained design allowed relative motion with respect to the limb, thus effectively allowing the beam to act as a compliant robotic actuator**.** The sleeve was worn as shown in Figure 2.

Fabrication of the jacket assembly can be completed in less than one hour and only requires the use of commonplace tools. A layout was first drawn on two identical pieces of fabric and then cut to size. A sharp pin was then used to create a hole on one of the sheets; the barbed connector was forced into the aforementioned hole. The sheets were stacked vertically and were heat sealed by running a hand iron along the perimeter. The finished actuator was then sewn onto the jacket. The two-tiered sleeve was separately cut and sewn from cotton fabric.

Meanwhile, Figure 3 illustrates the positions of the applied and generated forces on the actuator. Upon inflation, the rigidity increases and a bending moment (M) is generated. A force (F_M) is the applied to the two tiered sleeve; the sleeve itself located at a distance (L) from the mounting point. If sufficient pressure is applied, it will attempt to abduct the arm until the bending angle (θ_B) is 0° (i.e. the actuator is straight). Concurrently, a shearing force(Rx) and a normal force(Ry) are generated on the mounting point. These forces will attempt to detach the actuator from the mounting point as well try to lift the jacket from the wearer's body. The magnitudes of these two forces can be determined by (1) and (2).

$$R_X=F_M L\sin(\theta_A) \qquad (1)$$

$$R_Y=F_M L\cos(\theta_B) \qquad (2)$$

At the current level of development, the device used a tabletop Haosheng Pneumatic AF 186 compressor to provide pneumatic power to the system. A Parker Hannifin Ten-X Miniature Pneumatic Solenoid Valve (914-232053-000), connected to a transistor based electronic switch rapidly switches between the valve's open and closed states to regulate the pressure. The system was primarily controlled by an Arduino Uno microcontroller that supplies a logic signal, using pulse width modulation (PWM), to the electronic switch.

The effect of gravity was constantly monitored with an Analog Devices ADXL335 three-axis accelerometer and was utilized to provide feedback information to the system. Upon initialization, the suit undergoes a calibration step wherein the actuator is completely deflated, allowing the arm to go to its resting position. The microcontroller then reads the accelerometer output to determine the direction of gravity. As the actuator is inflated and the arm is abducted, the effect of gravity on the accelerometer varies according to its orientation with respect to the ground. The three axes of the ADXL335 sensor were utilized to prevent inaccuracies that stem from the fact that as the jacket is worn, the accelerometer might not always be oriented as desired. The combination of the three axes as well as the initial calibration step ensures accurate readings regardless of the initial orientation of the sensor.

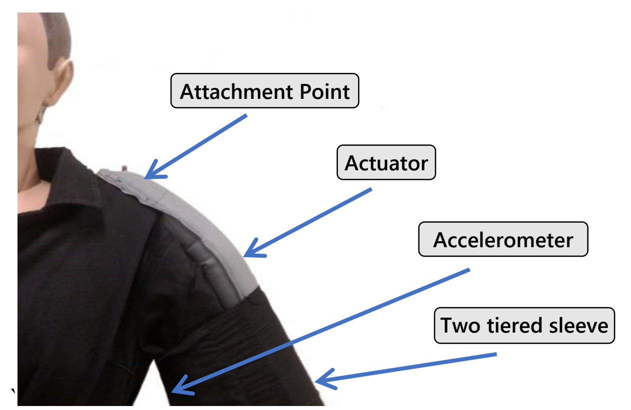

Figure 2. Soft Robotic Shoulder Assistive Device worn by a mannequin. A separate, two-tier sleeve is worn over the elbow. The actuator is inserted into the top sleeve and is also sewn into the jacket on the attachment point. An accelerometer, mounted onto the jacket, constantly measures the exosuits angular position with respect to the axis of gravity.

III. Preliminary Evaluation

A. Actuator Experimentation

Position control through pressure regulation was explored. An experiment was conducted on two samples of varying sizes. The air chamber of the first sample (Sample 1) was 40mm wide by 350mm long while the measurements of the second sample (Sample 2) were 80mm wide by 500mm long. The prototypes were mounted on a flat surface and were configured as cantilever beams with their supports extending

50mm onto the span of the beam. Weights were attached to a specific location along the span to simulate the effects of beam loads. Figure 5 illustrates the experimental setup.

TABLE I
DIMENSIONS OF EXPERIMENTAL SAMPLES

	Sample 1	Sample 2
Total Length (mm)	350	500
Uninflated width (mm)	40	80

Starting from the deflated state, pressure was increased to 5kPa. The pressure in the chamber was allowed to stabilize in order to get an accurate reading on the bending angle. The pressure was then increased by another 5kPa and the process was repeated until the chamber pressure reached 100kPa. An NXP MPX4250DP piezoresistive pressure sensor was integrated to the pneumatic line to monitor air pressure. Concurrently, a video camera continuously recorded the position of the actuator as the pressure varies. The Tracker (v4.91) video analysis tool by Open Source Physics processed the video footage to derive the angular position.

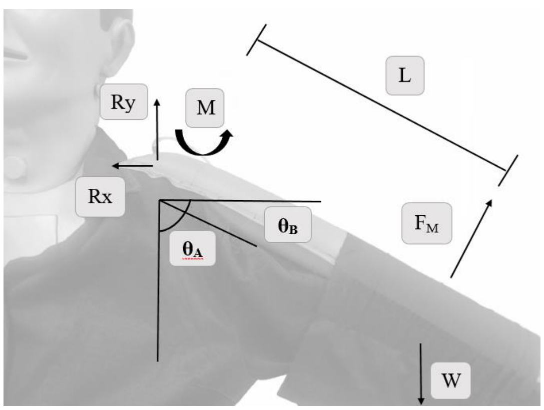

Figure 3. A diagram detailing the relevant forces acting on the actuator. The force F_M stems from the generated bending moment M. L is the distance of the center of the sleeve from the mounting point.

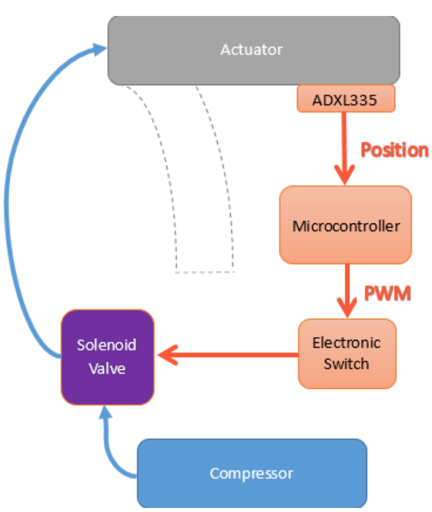

Figure 4. Schematic diagram of the control system. Orange lines denote electronic signals. Blue lines denote fluid flow.

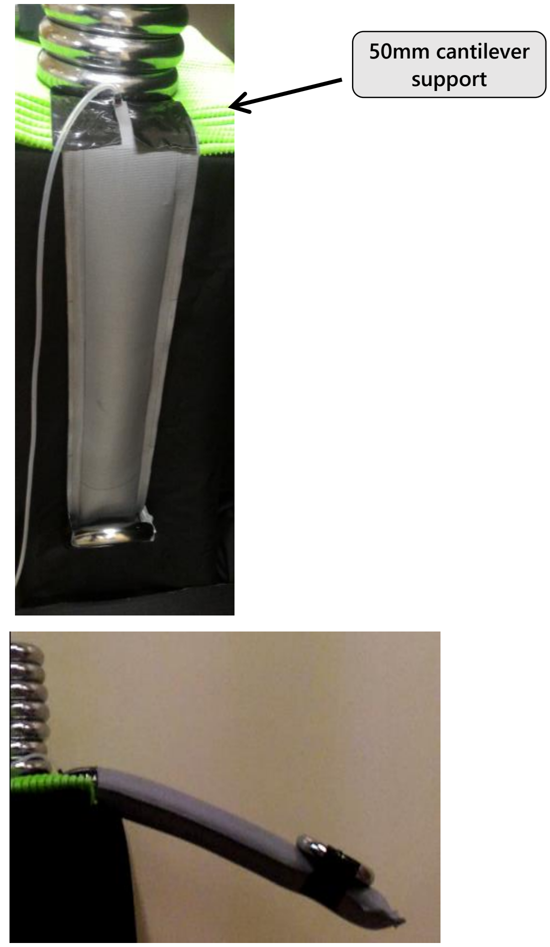

Figure 5. Top) The experimental setup is shown. Additional weights are used as a mounting mechanism. The setup did not restrict the inflation of the device but still provided sufficient restraining force. Bottom) Deflection under a moment load.

B. Pressure-Position Relationship

The initial observation obtained in the experiment was the presence of beam buckling at high bending angles. To be able to predict the effect of various pressure inputs, a model of an inflatable beam subjected under a moment load and an axial force must be adapted for this application. Such a model is beyond the scope of this study however. Nevertheless, results shown in Figure 7 present the relationship between bending angle and pressure. Results of the "Sample 2" experiments suggest however that the relationship may be asymptotic. It was observed that increasing pressure beyond a certain magnitude will no longer result in a decrease in bending angle. If this is indeed the case, a limitation is therefore naturally present for all actuators that must be compensated by the mechanical design of a device utilizing the inflatable beam design.

In any case, it is clearly shown that the behavior of the actuator is dependent on the moment load and the size of the air chamber; increasing the moment load for similarly sized actuators decreased their ability to carry the load.

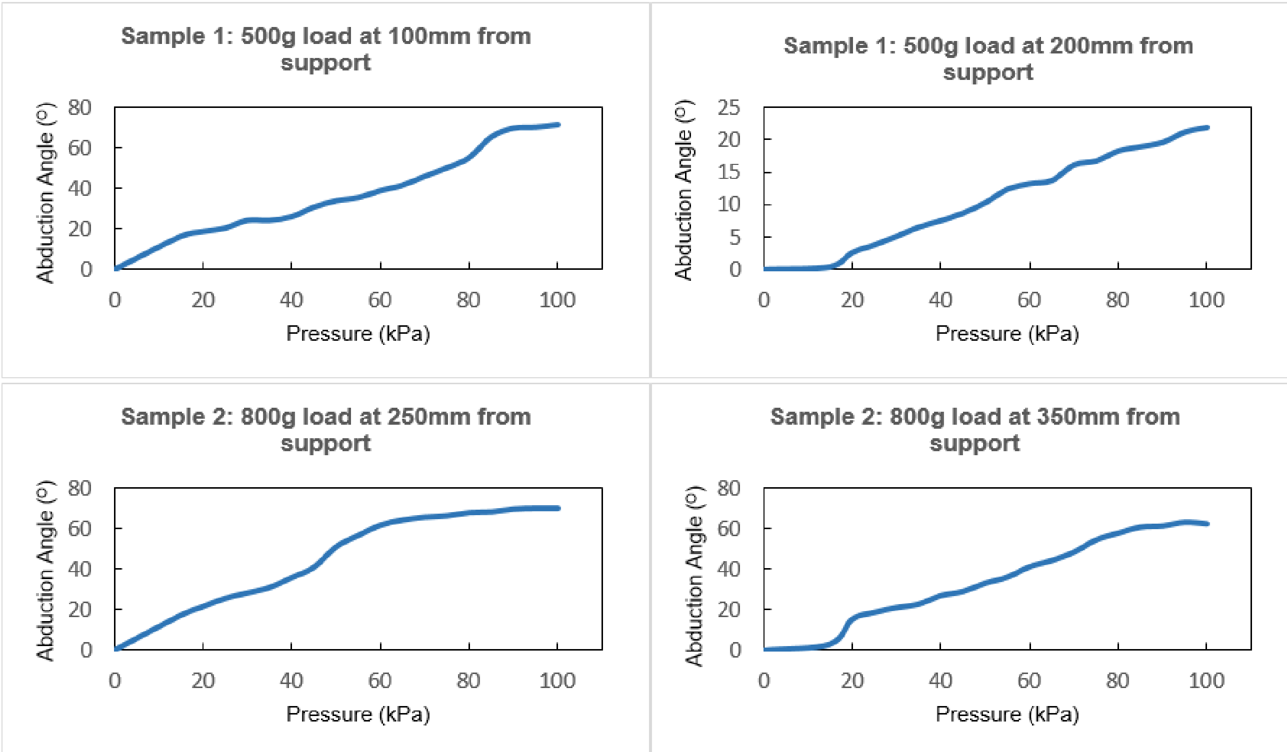

Figure 6: Results of the experiment for Sample 1 (40mm X 350mm) and Sample 2 (80mm X 500mm).

C. Device Performance

Initial testing of the device was conducted on a mannequin and a 24-year-old, male healthy subject. The mannequin arm had a mass of 1.47kg, centered at 280mm from the proximal end. Meanwhile, the total mass of the human subject was 64kg and had a height of 170.2cm. Methods published by Plagenhoef et al. were used to estimate the total mass of the arm to be 3.69kg and its center of mass to be 278.11mm from the proximal end [*19*]. Relying on the device alone, the arms were abducted by 35.45° and 30.62° respectively. However, significant dislodging of the jacket was observed; upon inflation, the jacket moves proximally towards the head. This suggests that the design is unable to completely resist the reaction forces as described by (1) and (2). As a result, the range of motion was limited.

Figure 8: Initial testing on healthy human subject. The dislodging of the jacket subject's shoulder limits the range of motion.

IV. Conclusion

A lightweight and unrestrictive device based on an inflatable beam was shown to be effective in facilitating shoulder abduction by the preliminary results. It features a simple design that can be rapidly produced using inexpensive household equipment. Moreover, it was also demonstrated that position control was possible by simply varying the pressure applied. The results also show that adjustments to the dimensions of the actuator resulted in an increase or decrease in load carrying capabilities, allowing optimization of the device according to the size and mass of the intended user.

Possible improvements can be identified however. Additional modifications to the jacket are needed if larger abduction angles are to be achieved. Future iterations could integrate a harness feature that transfers the load onto the groin region, preventing the jacket from dislodging. Alternatively, a more traditional belt design can be substituted for the harness. A tilted shoulder pad can also be integrated onto the jacket's mounting area to reduce the effects of beam deflection on the range of motion.

Future work is planned to increase the range of motion, as well as to integrate additional axes of motion. Furthermore, additional investigation regarding the behavior of an inflatable beam actuator will also be conducted. A study to quantify the function in CP patients is also planned. For such a study, multiple exosuits of varying sizes will be developed to accommodate the different anthropomorphic measures of patients. Moreover, scaled down versions of the exosuit will also be developed for children afflicted by CP. Additional control input schemes such as the use of electromyography will also be explored. Designs to adapt the device for assistive purposes will be investigated as well.

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