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Soft Actuated Foot Exoskeleton for Ankle Rehabilitation

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ABSTRACT

Technological advancement has made rehabilitation robotics possible. Robots can now help patients to proceed with their physiotherapy treatment with less assistance from physiotherapists. Soft robots are made from material similar to living organisms to improve safety between human and robot interaction. A soft robotic foot exoskeleton using pneumatic fiber braided bending-type actuator was developed in this study. Focusing on dorsiflexion ankle stretching movement, several actuator positioning was performed to gain the maximum ankle angle. MPU6050 sensor was used to detect the ankle dorsiflexion angle. Without any load, the bending-type actuator was able to bend and meet end-to-end of the tip. ITV0031-2ML valve was used as the connecter between air pressure supply and electronic circuit. Several experimental setups have been used in this study to obtain the maximum ankle dorsiflexion angle. The average maximum dorsiflexion angle from healthy volunteers was 8-degree, and Phase II experimental setup was able to drive a maximum of 6-degree dorsiflexion angle.

Key words : Ankle rehabilitation, bending-type actuator, dorsiflexion angle, foot exoskeleton, soft actuator**.**

1. INTRODUCTION

Foot drop is the inability to lift the front part of the foot, which causes the toes to drag along the ground while walking. Foot drop happens because of the weakness or paralysis of the muscles that lift the foot. Treatment for foot drop may include lightweight braces, physical therapy or surgery. Physical therapy, a restorative process that seeks to push recovery is used to strengthen the foot and leg muscles, which may help patients to improve their ability to walk again.

Previous study demonstrated that stretching or physical therapy helps to improve the joint range and walking speed of stroke patients [1]. To treat foot drop, both patient and therapist work together to help the patient strengthen his/her foot and ankle muscles. A study showed that improvement occurred after one month of continuous treatment [2]. Treatment should be continued even after the patient is discharged.

A form of workouts known as a range–of–motion (ROM) exercises is implemented by the therapist to improve the movement of a specific joint to keep the patients' muscles and joints strong and flexible. Passive, active, and active assists are the types of ROM exercises. Exercise or physical stretching is often carried out by a physical therapist manually. The muscles are stretched with the appropriate force to avoid another injury. There are three ways to obtain the ankle range of motion: goniometry, weight-bearing, and instrumented techniques [3]. Plantarflexion and dorsiflexion are the main ankle movements that help people walk. Normal ROM for dorsiflexion is between 0 to 20°. Knee position can affect the range of motion of the ankle [4]. It shows that the ankle dorsiflexion at 90° knee position can achieve a higher angle than the neutral position of the knee joint.

Rehabilitation robots can help patients to have their treatment without seeing therapists. With technology advancement, many rehabilitation robots were invented to speed up recovery and regain the walking ability of stroke patients [5]–[13]. The most critical ankle-foot movements in walking are plantarflexion and dorsiflexion. J. Yoon, B. Novandy, C. Yoon *et al.* [9] proposed a six-degree-of-freedom (DOF) rehabilitation robot, which composed of upper limb device, two footpad devices, and body support system enabling dorsi-plantar flexion, abduction-adduction, and eversion-inversion movements.

Previously, rigid robots and machines were used with limited ability to elastically deform and adapt their shape to external constraints and obstacles [10]–[12]. When using an electromagnetic motor in rehabilitation robot and the electrical motor supply is disturbed while a system is running, the position of the ankle will not return to resting position. The patient's leg may be in a dangerous position. A pneumatic system is used to reduce risk and injury [14]. When a pneumatic-type actuator pressurized by an electro-pneumatic regulator is used, the load applied to the foot can be removed, and it will return to its initial position right after the power supply is shut off as the air in the actuator is removed [5]–[7], [14]–[19]. Soft actuators are pneumatic actuators made from material similar to living organisms that are extensible, which make soft robots able to deform and act as muscle. Due to their high flexibility, the safety offered by the material between human and robot interaction is improved [20].

McKibben muscles are made from flexible, lightweight materials. This type of muscles can contract or extended as air pressure fills up the air pressure tube. As McKibben muscle can be easily driven by an air compressor, it has been used widely in many applications [21]–[23]. Typically, the McKibben muscles are able to produce higher force, but they have a short contraction ratio. A high–contraction ratio pneumatic artificial muscle (HCRPAM) [24] produced to gain both a larger output force and contraction ratio. A contraction and extension actuator [25] need to be attached together to gain a bending mechanism as driven by pressure.

A bending–type soft actuator [18] that use fiber reinforcement shows a promising flexibility and force capability. The actuator was able to get one-sided bending motion as it consists of fiber-reinforcement inside the silicone rubber. This study proposes a user-friendly rehabilitation exoskeleton utilizing bending-type soft actuators focusing on main ankle-foot movement, dorsiflexion. Two soft bending–type pneumatic actuators were designed, fabricated, and controlled for dorsiflexion movement.

2. SOFT FIBER BRAIDED BENDING ACTUATOR DESIGN CONCEPT

Fiber braided bending type actuator (FBBA), a kind of soft bending-type actuator is made from a combination of extending and contracting characteristics [14]–[18]. For the contraction mechanism, the lower the braided angle, the more contracted the actuator will be. Meanwhile, the bending motion can be high if the braided angle for extending actuator increases. Therefore, the braid-ed angle implemented in the actuator design of this study is the maximum angle that helps the actuator to achieve the maximum bending angle. Figure 1 shows the proposed actuator design with air hollow section at the center.

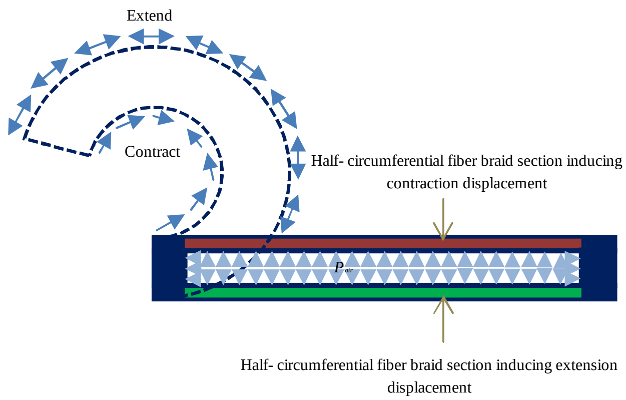


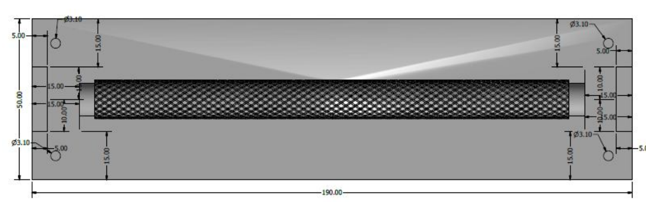
Figure 1: Fiber reinforcement bending mechanism

This actuator consists of three cylindrical layers. Between the inner and outer layer, there is one fiber reinforcement layer that helps to produce the bending motion. The inner layer expands like a balloon in all directions. Therefore, the inner layer is wrapped to restrict the radial direction expansion and can only expand in an axial direction. As both actuators contain different braid sections combined, the actuator bends toward the contraction side when it is pressurized. Then, it will turn to its initial state as the pressure is removed.

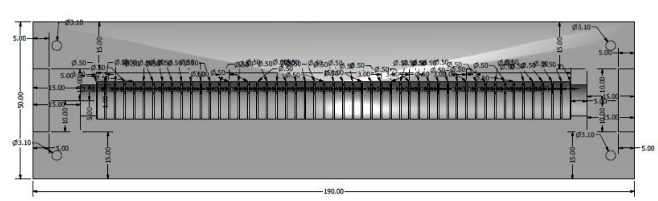
3. METHODOLOGY

3.1 Fabrication of Fiber Braided Bending Actuator

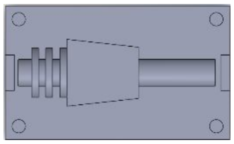
An inner rubber layer mold, outer layer mold, and two end caps molds were designed to fabricate an FBBA. Figure 2 presents the molds that were designed in AutoCAD. The machining process was done by a CNC machine.



(a)



(b)



(c)

Figure 2: Top view of mold designs of (a) 35-degree, (b) 90-degree and (c) end cap

The fabrication process is summarized, as shown in Figure 3. The fabrication of soft actuator started by mixing material A, silicone rubber KE1603 A, and material B, KE1603 B weighted 1:1. The mixture is poured into the mold, which then placed into the vacuum chamber to remove the trapped air. After the vacuum is off, the mold is removed, and any bubble on the surface needs to be popped as air bubble can lead to error in deformation due to the formation of holes on the rubber layer. The removing of trapped air process needs to be repeated until there is no more bubble on the surface. The molds are then heated and put through the solidification process in the oven at a specific temperature for a few minutes. Finally, the mold is removed as the solidified mixture has cooled down.

Figure 3: Rubber fabrication process

The knitting process was done by interlacing and twisting the fibers from one side to another with a fiber separator of each section. Next, the fiber pattern lining on the surface of the inner rubber layer is added. This procedure persisted until the end of the actuator body. Figure 4 shows the fiber knitting angle. The contraction part covers 220-degree of the actuator circumference with 90-degree of fiber angle. While the remaining circumference known as extension part is covered by 35-degree fiber angle.

Figure 4: Fiber reinforcement layer

3.2 Circuitry and Connection

Figure 5 shows the electrical and pneumatic connection for the whole system. The system starts with an input of the desired angle, which is inserted through a keypad. The first output is the LCD Display to show the desired angle and the current angle gained by the ankle at that time. The valve receives two input signals-electrical and pneumatic. The pneumatic supply will continuously supply the same amount of pressure. Therefore, an electrical signal is needed to control the pneumatic supply from the valve, which transfers the pneumatic pressure to the actuator. The actuator will then start to bend and move the ankle's dorsiflexion angle. Figure 6 shows the circuit connection for each electronic component.

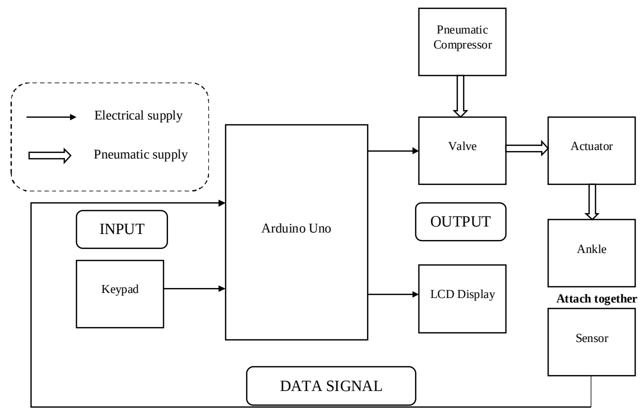


Figure 5: System block diagram

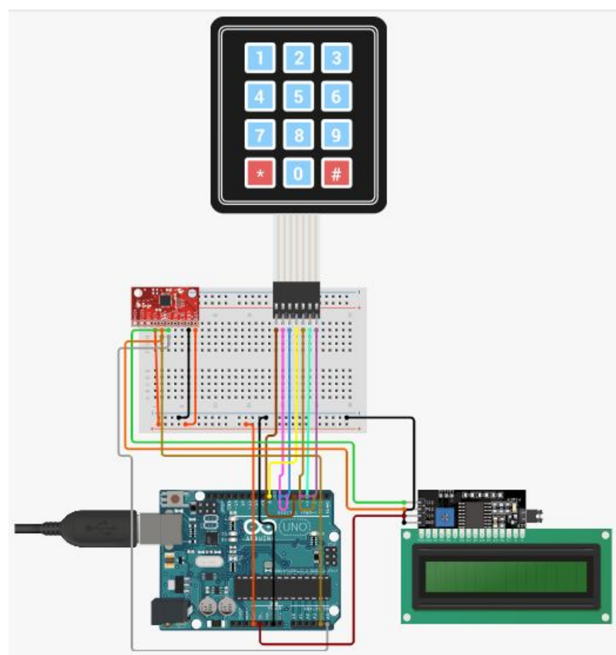


Figure 6: Electronic circuit connection

3.3 Experimental Setup for Ankle Dorsiflexion Angle Measurement

An experiment was conducted to determine the maximum bending angle that can be detected by an MPU6050 sensor from a healthy ankle. The volunteers were instructed to wear the foot exoskeleton (without actuator) attached with the MPU6050 sensor, as shown in Figure 7, to gain the maximum ankle dorsiflexion angle. Angle was measured using inertial measurement unit rather than video camera due to large data capacity requires by image processing technique [26]. The healthy volunteers were instructed to sit down and make sure that their knee was on 90-degree and 180-degree. Sensor data were acquired while each participant performs the dorsiflexion movement five times. The first two data were used as a practice and discarded from the analysis.

The experiment was conducted with the presence of an actuator comprises the three experimental setups. The first setup was where the actuators were actuated without having to flex any load from the foot, as shown in Figure 8. Figure 9 shows another two setups with the exoskeleton worn by the subjects. Figure 9 (a) and (b) differs by the placement of the FBBAs. Both experiments were conducted to determine the best soft actuator positioning to pull the ankle and complete the rehabilitation process.

Figure 7: Foot exoskeleton

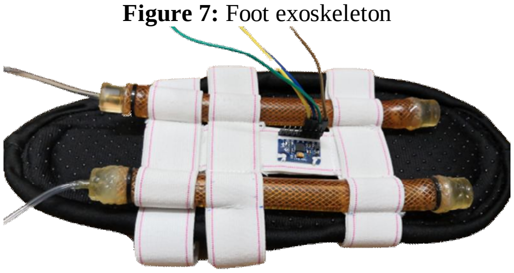


Figure 8: Experimental setup of foot exoskeleton without load (foot)

(a)

(b)

Figure 9: Displacement of FBBA during the experiment with load attachment as in (a) Phase I, actuators on right foot, and in (b) Phase II, actuators were on the right leg

3.4 Control Strategy

Figure 10 shows the overall control system of this project. When the keypad was pressed to set the desired angle, the pressure regulator generated voltage for the valve. After the valve received different voltage values, the actuator was given different air pressure values. As the actuator began to bend, the ankle was then pulled. When the MPU6050 sensor detected the displacement, it generated the actual ankle angle in real-time. Both desired and actual angles were displayed on the LCD.

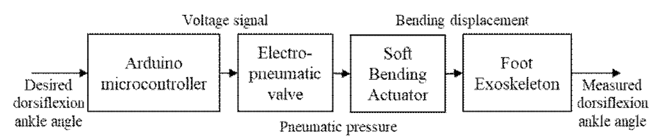


Figure 10: Block diagram of the open loop of the foot exoskeleton control system

4. RESULTS AND DISCUSSION

Data collected based on methodology were recorded and analyzed. The result and data analysis will determine the best actuator position that could help to drive ankle dorsiflexion motion.

4.1 Ankle Dorsiflexion Angle Measured without Actuator Attachment

Data collected from healthy subjects were calculated to find their average from three trials conducted for each subject. The average ankle angles were recorded in Table 1. The mean value of the dorsiflexion angle calculated from 10 average dorsiflexion angle data was 8-degree. Equation (1) used to calculate the mean of ankle dorsiflexion angle.

Mean, $\bar{x} = (\Sigma x_i)/n$ (1)

Table 1: Average ankle dorsiflexion angle of 10 healthy subjects

Subject	Average Angle [degree]
1	9
2	9
3	7
4	7
5	6
6	7
7	9
8	9
9	8
10	8

4.2 Bending Displacement of Soft Actuator

To pressurize the FBBA, one of the end-cap need to be held to ensure the actuator bends at one side only. Figure 11 shows the displacement of the actuator when pressurized at every increment of 50 kPa air pressure. The tip of the FBBA could meet the other end if the pressure supply is more than 0.24 MPa. The actuator shows a linear relationship between pressure and voltage. As shown in Figure 12, the pressure increases when the voltage increased.

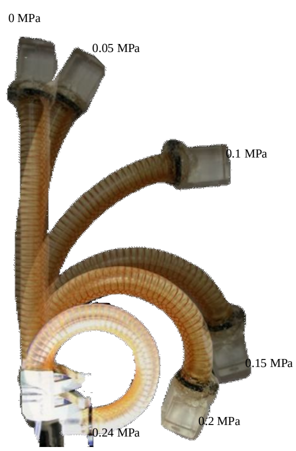


Figure 11: Displacement of FBBA

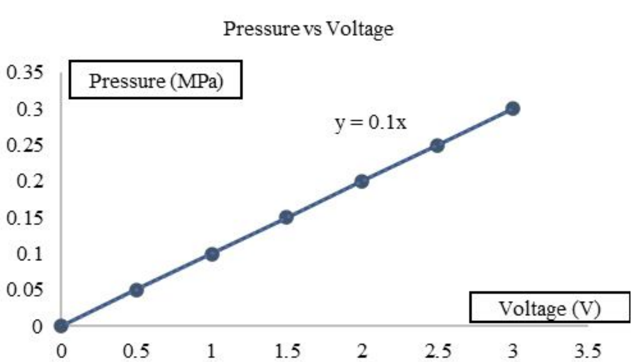


Figure 12: Linear relationship between pressure and voltage

4.3 Ankle Dorsiflexion Angle Displacement Measured with Actuator Attachment

Data collected were recorded and calculated to obtain the average value. From Figure 13, it was apparent that the ankle degree in-creases as the pressure supplied increased. Without any load attached, as shown in Figure 8, the actuator was able to bend and obtain more than 20-degree of dorsiflexion angle. However, when the exoskeleton is worn, the exoskeleton was only able to pull the ankle around 2-degree during experiment Phase I. After changing the position of the actuator, as in experiment Phase II, the actuator could pull the ankle up to 6-degree. Figure 14 (a) and (b) show the average data for both experimental phases. Experiment Phase II was able to perform dorsiflexion exercise and almost reached the maximum dorsiflexion angle possible for healthy subjects.

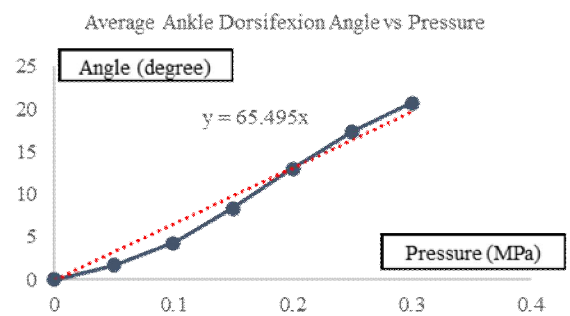
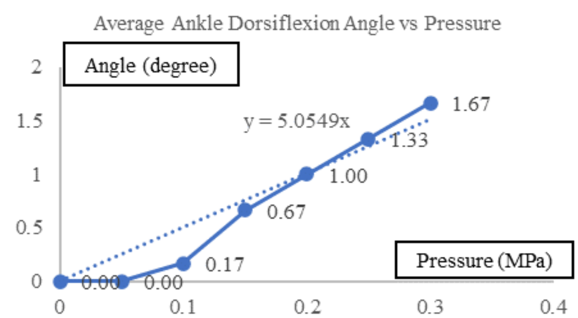
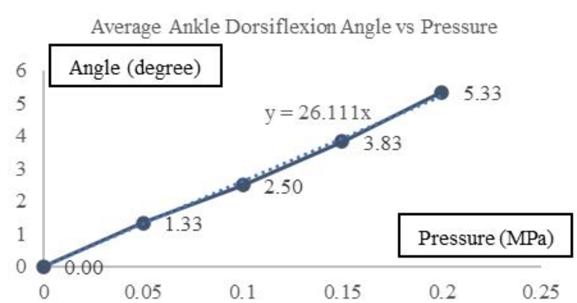


Figure 13: Average experimental results without load attached



(a)



(b)

Figure 14: Experimental results with load attached using setup of (a) Phase I and (b) Phase II

The experimental setup in Phase II was able to get better dorsiflexion angle than the experimental setup in Phase I. This might be due to the strap position. In Phase I, the actuator is held at the bending part. It might be the cause that the actuator was unable to bend to the maximum and pull the ankle to perform the dorsiflexion ankle movement. Meanwhile, in the experimental setup Phase II, the actuator is held only at the end cap where the air pressure tube is connected. Therefore, the actuator is able to bend more and gets more dorsiflexion angle. Figure 15 and 16 show the displacement of the ankle as a result of the dorsiflexion force produced by the foot exoskeleton based on Phase I experimental setup and Phase II experimental setup.

(a)

(b)

Figure 15: Displacement of Foot Exoskeleton resulted from Phase I experimental setup: (a) original relaxed position at 0 MPa, (b) actuated position at 0.2 MPa

(a)

(b)

Figure 16: Displacement of foot exoskeleton resulted from Phase II experimental setup; (a) original relaxed position at 0 MPa, (b) actuated position at 0.2 MPa

5. CONCLUSION

After several experimental setups, it was shown that the FBBAs utilized in the foot exoskeleton was able to actuate up to 0.3 MPa using Phase I setup, and up to 0.2 MPa using Phase II setup. Furthermore, FBBAs show low performance in Phase I setup, as the exoskeleton was able to pull the ankle at only 1-degree out of 8-degree at 0.2 MPa air pressurization. However, an acceptable performance was observed in Phase II setup with the achievement of 5.33-degree dorsiflexion ankle out of 8-degree. This shows that the positioning of FBBAs plays an important role in gaining more dorsiflexion angle.

Few recommendations are proposed to improve the exoskeleton. The thickness of the outer layer of the actuator can be increased so that more pressure can be supplied into the actuator, which will cause an increase in the actuator's bending angle and ankle dorsi-flexion angle. Next, the control scheme can be further optimized to automate control using PID scheme.

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