Hand Assistive Rehabilitation Pneumatic Exoskeleton (HARPE) for Stroke Patients

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Abstract- **Stroke is the third leading cause of death in the United States[1]. Usually individuals suffering from stroke have functional impairment of the hand, which significantly degrades quality of life and independence. To restore the functional use of the affected hand, a robotic-assisted therapy device, Hand Assistive Rehabilitation Pneumatic Exoskeleton (HARPE), was developed for stroke patients suffering from both severe and moderate hand spasticity. The HARPE device consists of three pneumatic actuators, (i.e. air muscles) to control the extension, intrinsic flexion, and extrinsic flexion movements of the hand. The contraction and relaxation of the air muscle is controlled by opening and closing of solenoid valves which are programmed through an Arduino microcontroller. The HARPE device initiates either through patient's minor hand movements or by utilizing the flex sensor controller glove on the unimpaired hand. This paper presents the design of the HARPE device from different prototypes of the device to the final prototype and recommendations for future improvements.**

Keywords - Stroke, air muscle, rehabilitation, robotic, exoskeleton, hand.

I. INTRODUCTION

Physical therapy is used to help patients recover after a stroke incident. Some new and improved rehabilitation methods aim to reduce the patient's time with the therapist while still increasing the exercise time. One of these methods uses robotic-assisted therapy to mimic the patient's hand movements[2]. The existing device that was modified was an exoskeleton hand device which was being used for stroke rehabilitation research. The existing hand device was modified to include pneumatic air muscles that would be controlled by solenoid valves though a programmable microcontroller. The proposed device was to contain a feedback control system that would use a string potentiometer transducer to measure current length of the muscle, and regulate air pressure accordingly.

Through brainstorming, the problem statement was determined to be that troke survivors suffering from functional hand impairment are in need of devices that can help restore normal hand functions, and rehabilitation that can improve their treatment to dramatically increasing the survivors' quality of life. As such, the design statement for the project is to create a clinical stroke rehabilitation device to facilitate hand rehabilitation exercises, specifically that safely opens and closes the hand and fingers with natural and controlled motion at a lower cost than existing devices.

II. PROPOSED DESIGN

The concept design proposes a glove device that is controlled by an Arduino microcontroller which can be programmed by a PC and utilizes seven air muscles to control different hand movements (see Figure 1). Three air muscles control intrinsic flexion, extrinsic flexion, and extension of the fingers. The other four air muscles control the extension, flexion, abduction, and adduction movement of the thumb. The amount of force needed for targeted movements depends on the diameter of the air muscles and their length. Depending on the movement, the air muscle would need to contract between 1 and 2.5 inches under 55 psi (the pressure of 'medical air' found in hospitals).

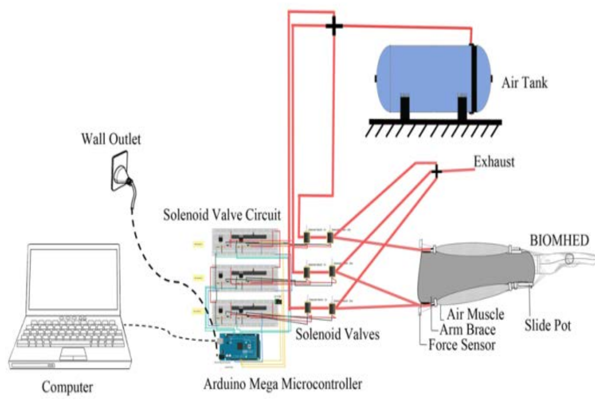


Figure 1: HARPE Complete System Schematic

The flow rate of pressurized air to the air muscle would be dependent on the observed contraction time and would be controlled to be within safe perimeters to be empirically determined. In order to allow the air muscles to fit on the patient's forearm and allow the patient to freely move without discomfort, the length of each air muscles was planned to be between 5 to 8 inches. Since many parts of the device is placed on the patient's forearm, the total weight of these parts must not exceed 1 lb. For the seven air muscles to function, a total of 14 solenoid valves are needed, two per air muscle (one inlet and one outlet). For the feedback control system, each of the 7 string potentiometers measures a change of 2.5 inches. The force produced by the air muscle is approximately 5 pounds for the finger movements and 2 pounds of the thumb movements, enough to overcome a stroke patient's muscle spasticity. As a safety precaution, the lengths of cable required to complete a particular motion (excursion lengths) would be measured before the device was used. These values would be set as the maximum lengths of contraction for the air muscles (see Table 1).

Table 1: Design specifications for HARPE

Description	Specification
Air muscle contraction (<55 psi	1 - 2.5 in. (31%)
Air muscle inner diameter	1 in. or less
Air muscles length	5 - 8 in.
Total weight	≤ 1 lb
Air muscle force	5 pounds
Potentiometer measurement range	change of 2.5 in.
Max pressure for pressure tubing	80 psi
Length of pressure tubing	6 ft
Solenoid valve input voltage	12VDC
Solenoid valve response time	15ms
Air tank capacity	> 55psi
Forearm brace length	10 in (avg forearm size)
Forearm brace upper / lower circumference	11.02(upper) 7.08 (lower)

III. Design Implementation

During the first two months, the design effort focused on optimizing the air muscles and electronic control of The HARPE device. The optimization of the air muscles was accomplished through materials research and prototype testing. An air muscle design that contacted 31 percent of its total length was successfully created. This achieved percentage is very close to the theoretical maximum contraction of this kind of air muscles.[3] Pneumatic valves were also researched and after deciding on a valve configuration, a circuit was designed that would allow the valves to be used with a microcontroller.

The air muscles were comprised of two main components: silicon rubber tubing and woven vinyl mesh. Several different diameters of 'soft' silicon tubing were tested, to get a better understanding of how length and diameter affected the percent contraction. An initial order of 'soft' silicon tubing with a wall thickness of 1/8th inches was placed and after testing ½ inch, 1 inch, and 1 ½ inch inner diameter (ID) tubing, the 1 inch diameter tubing produced the largest percent contraction per length at 27 percent contraction. 1 inch, 1 ¼ inch, and 1 ½ inch woven vinyl mesh was tested on the 1 inch ID silicon tubing to find the optimum combination, since the 1 ¼ inch mesh appeared to be constricting the movement. Additional silicon tubing was purchased from McMaster, this time 'very soft' with an ID of 1 inch and a wall thickness of 1/16 inch. The contraction was optimized to 31 percent of the total length using the 1 inch ID 'very soft' tubing in combination with 1 ½ inch woven mesh. An 8 inch air muscle was then fabricated (Figure 2) and, after attachment to the glove device[4], provided enough contraction for all of the necessary motions of the hand previously discussed.

Figure 2: Final Air muscle Prototype

To control the contraction length, accomplished by changing the pressure within the air muscles, solenoid valves were specified and purchased. Two 1/4" 12VDC, normally closed solenoid valves were placed in a configuration as shown in Figure 3. The first valve released pressure from the compressor to the air muscle, and the second valve acted as an exhaust relief, releasing pressure from the muscle to the environment.

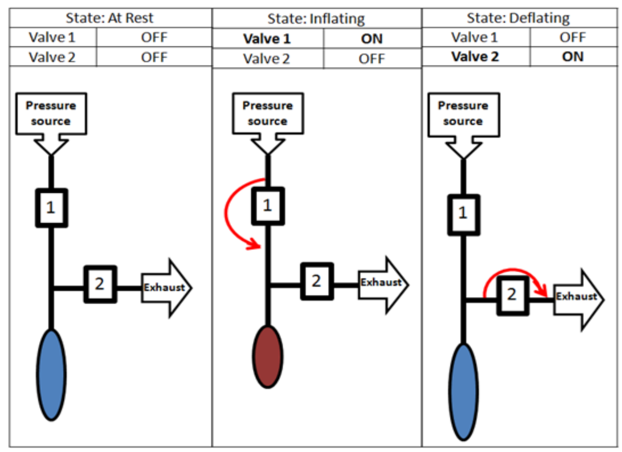


Figure 3: Pneumatic valves system configuration.

The circuit used to control the solenoid valves is shown in Figure 4. This circuit used two voltage supplies: 5V and 12V. The 5V power supply was in series with a 300Ω resistor and provided input for the base of a transistor. The solenoid valve was then connected to the transistor collector with diode was connected in parallel to prevent transient burst from damaging the sensitive components. A 12 VDC source was connected to power the solenoid valve upon actuation by the microcontroller output.

With the optimization of the muscles and design of the valve system complete, the mechanical portion of the project was mostly finished. Under the guidance of the project advisor, the primary control of the device was changed to force measurement, a change from the original plan of using length measurement. However, for user safety, a simple method of contraction length detection was still added to the system. These electronic inputs and outputs were controlled by an Arduino controller.

The next stage of design focused on development and testing of the solenoid valve circuit, Arduino microcontroller programming, and the design of the linear transducer. Initially, only one air muscle was tested to determine if the microcontroller was successfully programmed to control the opening and closing of the solenoid valves which pressurize the air muscle. The air muscle was able to control each movement of the exoskeleton hand device, and the contraction speed of the muscle was determined by the flow rate of the solenoid valves. After successful completion to control the contraction of one air muscle, the design was expand to control two additional air muscles, which would simulate the intrinsic and extrinsic flexion of the hand.

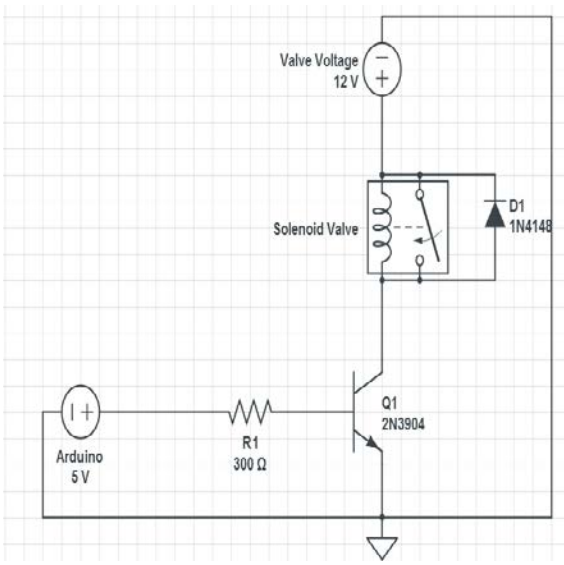


Figure 4: Transistor circuit to control solenoid valve.

The solenoid valves were controlled by the Arduino microcontroller, which was programmed using the Arduino programming software. To adjust the flow rate of the solenoid valves, the Pulse Width Modulation (PWM) conversion was applied. PWM conversion determines the length of time that the solenoid valve are opened and closed. As long as the time was greater than the response time of the valves, the valves would successfully operate. A default time of 1 second was set for the primary valve to open and 0.3 seconds for it to close. By changing the time value of the primary valve through the Arduino software, it allowed us to control the speed of the air muscle contraction. When the air muscle would fully contract, the exhaust valve would open for 4 seconds and then close.

For the feedback system, the linear displacement of the air muscle was measured while the device was operating. This prevented the air muscle from contracting too much, potentially leading to injuries resulting from over-extension of the patient's hand. Initially, the linear displacement was going to be measured using a string potentiometer. Due to extremely high cost of the string potentiometer (start cost of $100 per), a decision was made to use slide potentiometers instead. The lever of the slide potentiometers was connected to the air muscle, allowing the linear potentiometer to slide as the muscle contracts and pulls the cables. The different values produced by sliding the lever across the slide pot were read and interpreted by the Arduino microcontroller. The maximum extension value could vary for each patient so in the beginning of each test, the patient would fully extend their hand, and the maximum contraction length values would be set and entered as the "for loop" final value. This will serve as an end command for the device, allowing the primary valve to close and exhaust valve to open.

The brace was created using thermoplastic. The length of the brace was 9.5 inches, the upper circumference (at the elbow) was 11.02 inches, and the lower circumference (at the wrist) was 7.08 inches (Figure 5). A velcro strap was inserted inside a small slip on the brace to keep the brace in a fixed position. Also, foam padding was added to the inside of the brace for patient comfort. The brace color was changed from white to black to reduce reflections for future motion capture studies.

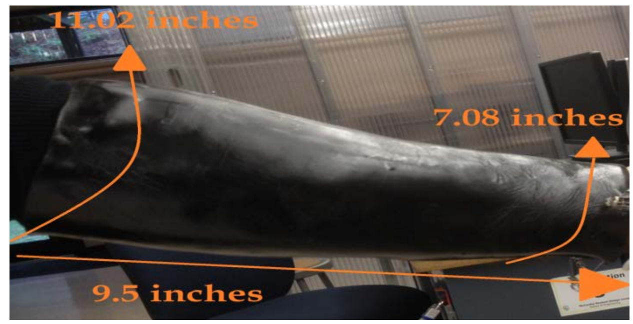


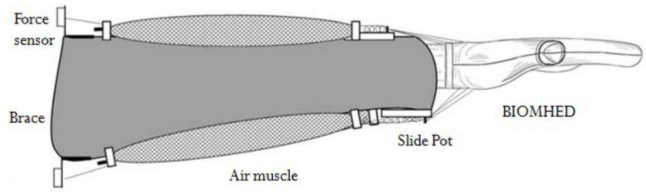
Figure 5: Thermoplastic Arm Brace

IV. Systems Integration

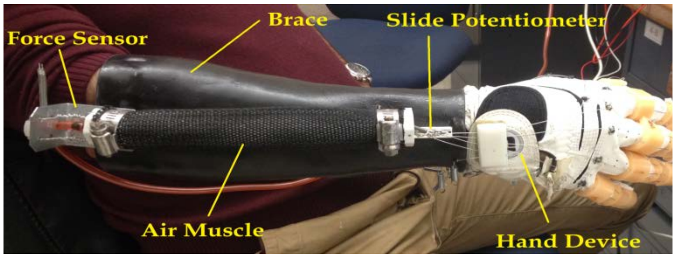
Once the individual sub-components (i.e. solenoid valve circuit, Arduino programming, linear transducer, brace) were completed, the entire device was integrated into one system. The air muscles were mounted onto the brace using an L bracket which served two purposes: first, as an anchor for the air muscle, and second, as a frame for the force sensor (compression sensor). This sensor will provides the system with force measurement throughout the entire movement and serves as a safety feature to prevent the muscle from exceeding safe forces.

The L bracket with the force sensor was then placed behind the brace and the air muscle was connected to the aluminum cables of the L bracket. The slide potentiometer was connected to the air muscle and was used initially as a linear measurement for safety purposes. A small spring with a high spring constant was added to the air muscle cap to enable the patient to initiate the device through small movements. A steel cable was also connected to the cap of the air muscle to the ring of the hand glove, which served to pull the glove when the air muscle was initiated.

All the major components to the HARPE design were placed on the brace, and the last step was to add guide wires to prevent the air muscle from moving. High resistant galvanized wire was and connected from the brace to the screw eyes on the cap of the air muscle. This allowed the air muscle to shorten without any restrictions, but kept the guide wire in tension so the air muscle would in fixed position. The final design included only the extension air muscle and all the safety components were successfully incorporated in the HARPE system (Figure 9).



(a)



(b)

(c)

Figure 10: HARPE prototype: (a) original concept drawing, (b) top view, and (c) side view.

V. DEVICE DESIGN TIMELINE & COST:

A timeline for the HARPE project is provided in Table 2.

Description	September					October					November				Dec	
Lit Review / Research	x	x														
Air Muscles: Design/Test		x	x	x	x	x										
Electronics: Solenoid						x	x	x								
Arduino Programming								x	x	x	x	x				
Arm Brace Design				x	x	x	x	x	x							
System/ Sensor Integration												x	x	x	x	
Device Testing													x	x	x	x

Table 2: Timeline to Design HARPE

Overall, three were numerous different materials used to make the HARPE prototype. These include the Arduino Mega microcontroller, silicon tubing, mesh, high pressure tubing, solenoid valves, electronic components, and various fittings. The overall total cost of the HARPE prototype was $285.05.

VI. CONCLUSION

In conclusion, a hand assistive rehabilitation pneumatic exoskeleton device for stroke patients was successfully designed and built over the course of the Fall 2013 semester. The HARPE system consisted of air muscles that replaced electric motors from the previous device. These pneumatic actuators were controlled by a set of solenoid valves that were in turn controlled by the Arduino Mega microcontroller. The system also consists of a force sensor and linear measurement sensor, which enhances the HARPE's safety and aided in the initiation of movement. In preliminary tests on healthy subjects, the HARPE was successfully able to fully extend the subjects hand after detecting slight movements by the subject. The system was also able to prevent over extension of the hand. It was also possible to read the tensile force between the air muscle and the cables of the glove.

The air muscle contraction percentage was enough to perform the different movements. The air muscle's size (length and diameter) was suitable for placement on the patient's arm. It was also able to generate enough force to overcome stroke patient's muscle spasticity. The device was light and did not restrict the subject's movement. Finally, the potentiometer was able to measure the previously specified range of contraction.

The next step with the HARPE device is to integrate additional air muscles to control thumb movements. An emergency kill switch will be added to shut down the device for additional safety in case the microcontroller fails. The HARPE system must be modified to incorporate medical air instead of an air tank. Finally, bend sensors are suggested to be placed on the patient's unimpaired hand for second initiation. This would be helpful for patients with severe spasticity who cannot initiate the movement using their impaired hand.

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