Biologically Inspired Soft Robot for Thumb Rehabilitation

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1. Background

More than 130,000 people have strokes each year in the United States [1]. Of these victims, 76% are left with disabilities that cost the nation over $54 billion in lost work and medical fees. One prominent disability is upper extremity hemiplegia, which occurs among approximately 50% of stroke sufferers [2]. Robotic technology has the potential to provide an automated platform for controlled rehabilitation and assisted, task-oriented therapy.

Several systems have been designed to assist in patient articulation of an impaired hand using rigid robotic components. While these products have been successful in articulating the pure bending motions of the four fingers, the limited capabilities of rigid technologies fail to reproduce the complicated motion path [5] of the thumb during opposition grasp (see Figure 1). This is the most important articulation for normal hand function and specifically for picking up everyday objects. To date, robotic systems for thumb rehabilitation have not been widely investigated [3] apart from some recent work [4] that used a multi-joint rigid robot.

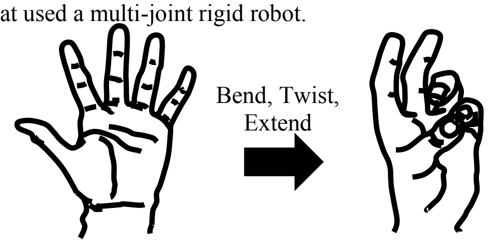

Figure 1: Thumb motion required for opposition grasp

The soft robotic thumb rehabilitation system presented in this paper is a task-oriented therapeutic device that replicates and restores correct thumb motor function for patients with neurologically caused hand disabilities.

2. Methods

Discussions with physical therapists and patients identified a need for a controllable robotic system to assist a neurologically impaired thumb in performing functional operations for at-home task-oriented therapy. First and foremost, the device must follow the motion path of a healthy thumb. The device must also be comfortable, durable, and externally controllable. The final design (see Figure 2) consisted of a soft robotic actuator, a conformable neoprene padded aluminum attachment with Velcro straps, and a control system.

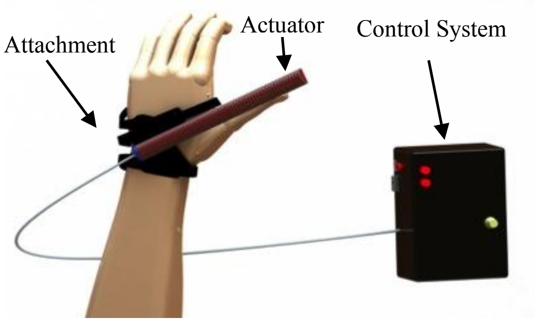

Figure 2: Model of full rehabilitation device

The most essential specification of the design was replicating a healthy thumb's natural motion path during opposition grasp. It was hypothesized that the overall motion path of the thumb during opposition grasp could be represented as a combination of bend (thumb flexion), twist (thumb rotation), and extension (skin stretching). A biological kinematic study using eight independent electromagnetic sensors [3D Guidance TrakSTAR] was performed on a healthy thumb during opposition grasp to the index finger and to the small finger. The motion paths measured were broken down into bend, twist, and extension, and their values became the minimum and maximum functional requirements respectively. These requirements were: 25 - 70 degrees of bend, 15 - 25 degrees of twist, and 0.4 - 0.5 inches of linear extension.

Given the inherent limitations of traditional robotic components, soft multi-material fluidic actuators were investigated for their increased compliance, customizability, and safety. Several different soft robotic actuators exist and were evaluated. For this application, a fiber-reinforced actuator was found to be the most effective and efficient in terms of single actuator durability, force, and motion path customizability.

The fiber-reinforced actuator was made from an elastomeric chamber with a flexible strain layer (fiberglass cloth, FG-C0427S, US Composites, FL, USA) adhered to the bottom, which was then wrapped with a strain material (Kevlar thread, KEV693NATL00S, The Thread Exchange, NC, USA) to restrict expansion in certain directions, and covered with a flexible outer protection layer. A cross sectional model of a basic, soft bending, fiber-reinforced actuator can be seen in Figure 3, exhibiting the inner chamber, the structural elastomer, the strain wrapping, the strain layer, and the protective outer layer.

Through experimentation, a fabrication technique was developed to create soft actuators with a maximum inflatable pressure of 50 psi (345 kPa) capable of producing the desired bend, twist, and extension motion paths. An actuator with double helical strain wrapping and a strain layer along the bottom produced a bending motion. An actuator with a single helical strain wrapping and a strain layer along the bottom produced a twisting motion.

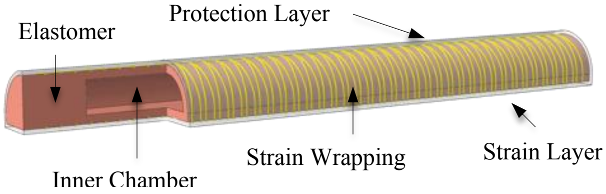

Figure 3: Cross Section of Strain Wrapped Actuator

The actuators were segmented and combined in series to produce a single actuator with an overall motion path that was the linear sum of the component contributions from each segment. Consistent with the functional requirements, the final actuator was designed to mimic the overall motion path of a healthy thumb during opposition grasp while positioned along the top surface of an impaired thumb (see Figure 4).

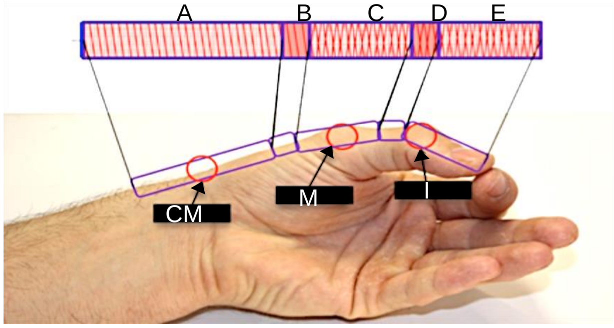

Figure 4: Actuator and Thumb Joint Design Layover
(A) 3" Twist Bend **(B)** 0.5" Twist Extend **(C)** 1.5" Bend **(D)** 0.5" Extend **(E)** 1.5" Bend

The actuator was integrated into a lightweight hand fixation system consisting of a conformable neoprene-padded aluminum plate with Velcro straps around the palm for rigid attachment to the hand. Three small Velcro straps attached the proximal end of the actuator firmly to the thumb itself to apply articulation force to the appendage (see Figure 5).

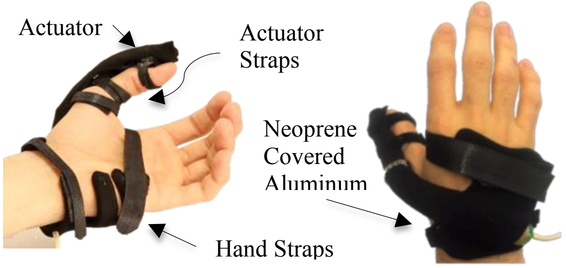

Figure 5: The developed hand attachment with the incorporated segmented soft actuator

A compact control box enabled portability and in-home use of the system. The pressure from an external compressor was transferred to the soft actuator through flexible pneumatic tubing and the user was able to regulate the pressurization of the actuator to control the motion of the thumb.

3. Results

An analysis was performed to compare the overall motion path of the unaided thumb to that of the same thumb while being assisted by the device. The sample participant simulated paralysis by being totally passive, attached the soft robotic thumb rehabilitation system to the thumb, and through varying the pressure was able to achieve opposition grasp to the index finger, achieve opposition grasp to the small finger, and pick up several everyday objects. The maximum and minimum opposition grasps (to small finger and to index finger) were achieved at pressures well within the functional limitations of the actuator.

Opposition grasp to the index finger was performed at a pressure of 30 psi (207 kPa) and opposition grasp to the small finger required 42 psi (290 kPa). Picking up a 2-Newton water bottle required 30 psi (207 kPa) and rigidly grasping a spoon was achieved at 40 psi (276 kPa). All these pressures are well within the 50 psi (345 kPa) maximum for safe operation.

Using the same tracking techniques implemented to characterize the motion path of the unaided thumb, the segmented soft actuator was characterized in terms of its ability to perform the expected bend, twist and extension. The performance of the actuator attached to a passive thumb at 207 kPa (30 psi) met or slightly exceeded the measurements for normal thumb motion during opposition grasp to the index finger. The motion called for values of bend, twist, and extend of 25°, 15°, and 0.4" and the system produced values of 40.7°, 16.8°, and .41" respectively.

4. Conclusions

In this paper, a biologically inspired soft robotic thumb rehabilitation system was shown to have the capability to reproduce the motion path of a thumb during opposition grasp. Through linear combination of basic motion strain-wrapped actuators, a soft robotic design could be fabricated to fit a complex motion path. Integrating this with a lightweight hand fixation and a compact control system produced a promising prototype for a wearable, at-home, task-orientated thumb rehabilitation device. Future work will involve optimizing the actuator to more accurately match thumb motions as well as studying the effects of varying hand size and tasks on actuator motion requirements.

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