A Soft Robotic Orthosis for Wrist Rehabilitation[1]

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1 Background

In the United States about 795,000 people suffer from a stroke each year [1]. Of those who survive the stroke, the majority experience paralysis on one side of their body, a condition known as hemiparesis. Physical therapy has been shown to restore functionality of the paretic limbs, especially when done early and often [2]. However, the effectiveness of therapy is limited by the availability of therapists and the amount of practice that patients do on their own.

Robot-assisted therapy has been explored as a means of guiding patients through the time-intensive exercise regimes that most therapy techniques prescribe. Several wearable, robotic orthoses for the hand and wrist have been developed and are still being developed today [3]. However, few of these existing solutions allow for any significant range of motion, and those that do only offer one degree of freedom. The assisted degree of freedom is almost always flexion/extension, despite the fact that supination/pronation is crucial in nearly all activities of daily living. In addition, current devices are often large, heavy, and uncomfortable for the wearer, presenting significant deterrents to practice.

This paper presents a soft wearable device for the wrist that provides motion-specific assistance with rehabilitation for hemiparetic stroke patients at home. Unlike conventional robot-assisted rehabilitation, this pneumatically actuated orthosis is portable, soft, and lightweight, making it more suitable for use outside of the clinic. In addition, this device supports all the degrees of freedom of the wrist, including supination and pronation, which are critical to many tasks.

2 Methods

After a review of prior art and the current literature on biomechanics, as well as consultations with occupational therapists and stroke patients, it was determined that an ideal device should be able to assist in multiple degrees of freedom while remaining lightweight and comfortable. In addition, the device should allow for customizable levels of assistance, to provide more effective treatment for users of varying ability.

The final design (Fig. 1) consists of a wearable portion tethered to an off-board power system. Crossing linear actuators on both the palmar and dorsal sides of the forearm allow the device to assist wrist movement. Any single motion can be achieved by activating a pair of actuators. For instance, flexion is achieved by activating the two actuators on the palmar side of the wrist. Supination is achieved by activating one actuator on the palmar side, and the opposite actuator on the dorsal side.

After numerous potential actuator types were reviewed, McKibben actuators (a type of pneumatic artificial muscle) were selected for their ease of manufacture, low weight, overall simplicity, and capability for straightforward integration with other pneumatic orthoses of interest [4]. Preliminary testing showed that $1/2$ in. outside diameter (OD) actuators would provide sufficient force, but concerns for user comfort necessitated investigating a more streamlined actuator configuration. More rigorous testing was done on an Instron 5544A Materials Testing System to determine the configuration of smaller diameter actuators that could output comparable levels of force (Fig. 2). While a single $1/4$ in. OD actuator provided insufficient force, the output from two such actuators in parallel was determined to be acceptable, considering data on wrist torques and moment arms. An operating pressure of 60 PSI was selected from additional characterization of contraction ratio as a function of pressure.

The textile interface is defined as the portion of the device that transmits the motion of the actuators to the user. It consists of a glove, an elbow sleeve, and an actuator tensioning mechanism.

The details of the anchoring points on both the glove and the elbow sleeve are of great importance (Fig. 3). Anchor position determines initial actuator length, which directly affects contraction length and thus range of motion. Anchor orientation determines the orientation of the force vector, and thus contributes to

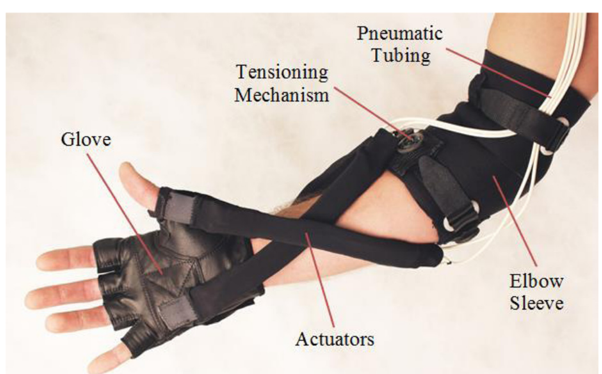

Fig. 1 Final wearable portion of device

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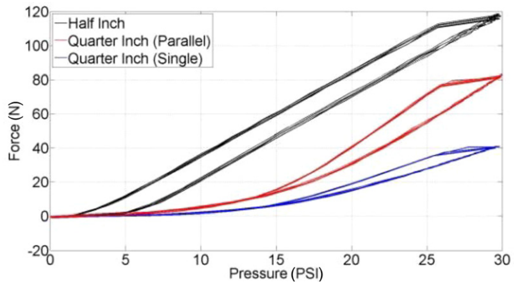

Fig. 2 Results of isometric testing on Instron machine

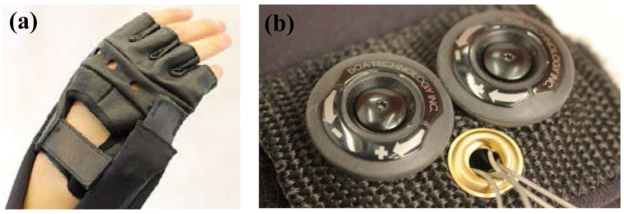

Fig. 3 (*a*) Anchoring points and (*b*) tensioning mechanism

the efficiency of the actuator. Anchoring points were first selected by intuition and basic geometric concerns, and refined through iterative prototyping.

The tensioning mechanism consists of four Boa Technology ratchets, sewn onto the elbow sleeve (Fig. 3). The small diameter wire from these ratchets passes through grommets on the sleeve, which act as pulleys, and connect to the actuators. This tensioning mechanism, in addition to allowing for custom modifications to the system based on differing arm lengths, allows the user to introduce slack into the system to ease the process of donning and doffing.

Control of the device is performed by an Arduino Mega 2560. An input signal is sent to the controller, which then interprets this signal and subsequently activates the pump and the relevant valves, pressurizing the appropriate actuators. The state of each actuator is constantly monitored by a pressure sensor, allowing the system to be configured to modulate the pressure in each actuator individually. In this way, users or clinicians can program different levels of assistance for different motions, allowing for precise matching of the level of assistance to the ability of the patient. As the patient gains more function, the system can subsequently provide less assistance, enhancing recovery.

3 Results

To confirm that the final prototype could achieve the required motions, the device was tested on a user. The user reported that the device did indeed assist in flexion/extension and supination/pronation, as well as radial/ulnar deviation. When the user was instructed to fully relax his wrist, the device was able to provide assistance over a range of 91 deg in flexion/extension, 78 deg in supination/pronation, and 32 deg in radial/ulnar deviation. The prototype was additionally tested on a wooden mannequin hand (Fig. 4) to rule out the possibility of inadvertent user assistance. Indeed, the mannequin hand also showed motion in all directions.

Given that stroke patients often have limited strength, keeping the distal weight of the device to a minimum was critical. The entire device weighs 2.26 kg (including the control hardware, which was not optimized for weight), while the wearable portion is 0.22 kg, and the weight of the device distal to the wrist is 0.09 kg.

The device was presented to a group of stroke patients for comments and feedback. In general, it was very well received, and the patients were impressed with how lightweight and low-profile it was. Many said that they would be open to wearing the device during therapy.

4 Interpretation

This paper has presented the first soft wrist orthosis that is able to actively assist users in all degrees of freedom. The device is a significant improvement over prior art in its ability to achieve multiple degrees of freedom while remaining lightweight and low profile.

Another group is developing a wrist orientation sensing system using soft, stretchable sensors [5]. As a proof of concept, the two systems were integrated so that a user's hand orientation was detected by the sensors and replicated on a wooden mannequin hand wearing the wrist orthosis. The success of this experiment

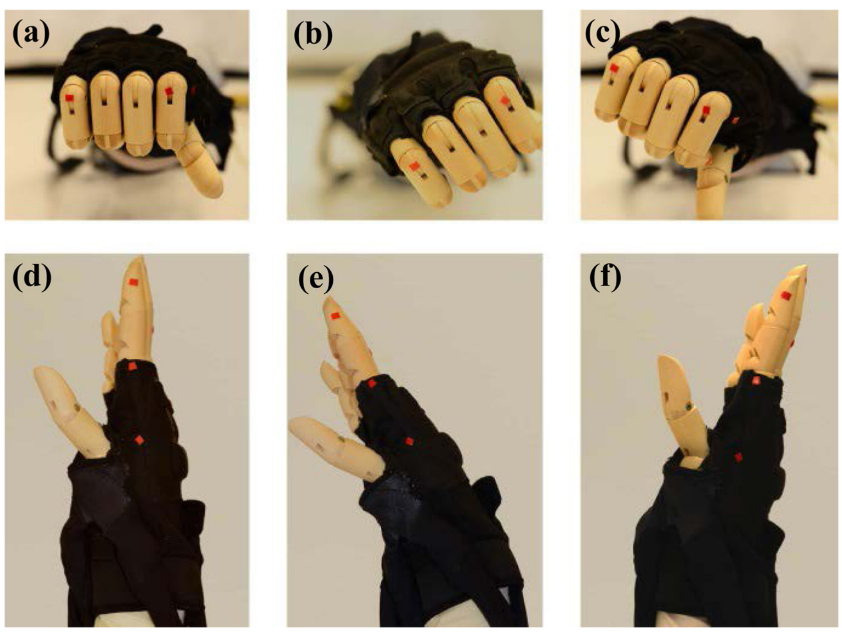

Fig. 4 (*a*) Device off, (*b*) supination, (*c*) pronation, (*d*) device off, (*e*) flexion, and (*f*) extension

was encouraging and suggests that future work on incorporating sensors into the device should be straightforward. One can envision how a small motion detected by the sensors could then be amplified by the device, restoring near normal wrist function.

In addition, significant development has been done on a pneumatically powered soft robotic glove [4]. Integrating the wrist orthosis with this glove would produce a more complete system, greatly enhancing the quality of life of stroke patients.

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