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Soft robotic glove for combined assistance and at-home rehabilitation

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HIGHLIGHTS

- Soft actuator design and fabrication that mechanically program desired motions.
- Hand motion study to conform and match actuators to fingers joint motions.
- Overall system including an open-palm glove and a portable power/control unit.
- Closed-loop nonlinear controller that regulates the actuator hydraulic pressure.
- Quantitative and qualitative evaluation of the soft robotic glove.

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ABSTRACT

This paper presents a portable, assistive, soft robotic glove designed to augment hand rehabilitation for individuals with functional grasp pathologies. The robotic glove utilizes soft actuators consisting of molded elastomeric chambers with fiber reinforcements that induce specific bending, twisting and extending trajectories under fluid pressurization. These soft actuators were mechanically programmed to match and support the range of motion of individual fingers. They demonstrated the ability to generate significant force when pressurized and exhibited low impedance when un-actuated. To operate the soft robotic glove, a control hardware system was designed and included fluidic pressure sensors in line with the hydraulic actuators and a closed-loop controller to regulate the pressure. Demonstrations with the complete system were performed to evaluate the ability of the soft robotic glove to carry out gross and precise functional grasping. Compared to existing devices, the soft robotic glove has the potential to increase user freedom and independence through its portable waist belt pack and open palm design.

1. Introduction

There are approximately four million chronic stroke survivors with hemiparesis or other similar conditions in the US today and another six million in developed countries globally [1,2]. For the majority of these cases, loss of hand motor ability is observed, and whether partial or total, this can greatly inhibit activities of daily living (ADL) and considerably reduce one's quality of life [2]. Improving hand function requires repetitive task practice (RTP) rehabilitation, which involves breaking a task down into individual movements and practicing these exercises (typically with an occupational therapist) to improve hand strength, accuracy, and range of motion [2,3]. These methods, however, are labor intensive, costly, and slow, often leading to challenges with patient compliance [2]. A system where patients can carry out exercises on their own — either at home or in the clinic — would make physical therapy more accessible, affordable, results driven, increasing the potential for better outcomes.

Clinical studies have shown that stroke patients who have robotic assistance when performing intense repetitive movements demonstrate significant improvement in hand motor functions [2,4–7]. Numerous robotic rehabilitation systems have been developed for the hand that consists of multi-degree-of-freedom exoskeletons [5–22]. Most of these devices require the biological joints to be aligned with those of the exoskeleton, while only a few have passive degrees of freedom or self-alignment features [3,16,23,24]. These systems are also typically expensive and are designed for in-clinic use as they are generally not portable. Moreover, the majority of these robotic devices require experienced oversight

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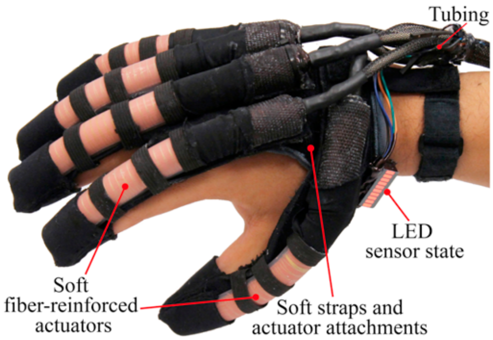

Fig. 1. The prototyped soft and lightweight robotic hand assistive device.

for patient safety since they use actuators that are less compliant than the joints themselves. However, their rigid mechanical design provides robust and reliable devices capable of exerting high forces that allow more challenging rehabilitation scenarios to be executed. For a more comprehensive view on the hand exoskeleton literature, the authors refer to review works of Heo et al. [25], and Maciejasz et al. [26].

Recently, a number of hand rehabilitation designs have followed an alternative approach to that of traditional exoskeletons. These designs combine soft gloves with either cables that connect to fingers and are driven by a number of motors located away from the hand [27–30], or soft pressurizable elastomeric actuators that support finger flexion or extension [31–36]. The latter is a new paradigm of soft robotics that combines classical principles of robot design and control with active soft materials to enable a new class of applications [37–44].

A soft wearable robotic device could lead to greater advances in at-home assistive activity and rehabilitation by providing: (a) more degrees of freedom and thus larger range of motion with single inputs (e.g. fluid pressurization), (b) safe human–robotic interaction due to the soft and compliant materials used for their fabrication, (c) low component cost due to inexpensive materials (e.g. fabrics, elastomers, etc.) and single actuation source to actuate all fingers (i.e. pump), (d) portability, and (e) ability to provide customizable actuation based on patient anatomy. This paper presents such a device that utilizes inexpensive hydraulic soft actuators made from elastomeric materials with fiber reinforcements to control the fingers (Fig. 1). The hydraulic soft actuators are mounted to the dorsal side of the hand, resulting in an open-palm design. Integrated fluidic pressure sensors measure the internal pressure of soft actuators and allow control of finger flexion/extension. All electromechanical components are mounted in a portable waist belt pack in order to enable untethered operation.

In Section 2 of this paper, a study on finger motion is described that is used to determine requirements for the design of actuators that match the finger and thumb joint motion of a healthy subject. Section 3 describes the soft actuator fabrication method and the design approach used to mechanically program the desired actuator motion. The overall system, including the open-palm glove and portable power/control unit, is presented in Section 4 and the closed-loop controller used to regulate the actuator hydraulic pressure is described in Section 5. Finally, Section 6, provides preliminary quantitative and qualitative evaluation of the soft robotic glove.

2. System requirements

The system performance requirements for a soft wearable robotic glove are grouped into three main categories: practical considerations, motion and force requirements, and control requirements. Summarized in Table 1, these requirements were obtained from a combination of experimental studies, review of the literature, and discussions with physicians/occupational therapists.

Table 1
Design requirements of a soft robotic glove.

Characteristic	Requirements
Practical design considerations [25,45]:	
Weight of glove	<0.5 kg
Waist pack weight	<3 kg
Profile of glove	<2 cm
Glove size	Customizable
Safety	Easy to don/doff Minimal ADL interference
Motion/force requirements [3,25,26]:	
DOFs	3 per finger
DOFs for thumb	2 bending, 1 rotating
Bending angle (thumb)	∼160°
Bending angle (middle)	∼250°
Speed of actuation (closed loop bandwidth)	0.5 Hz
Force range	Adequate to enable ADL
Control requirements:	
Hours of autonomy	2 h continuous, 4–6 h intermittent
Controller frequency	>10 Hz

2.1. Practical considerations

One of the main practical considerations is the weight of the soft robotic glove. Aubin et al. determined that weight of such a device mounted on a hand should not exceed 0.5 kg [45]. Any additional components of the system required for power, actuation or control can be distributed around the waist or the back and should weigh no more than 3 kg, which is the typical weight of portable consumer electronic products (e.g. laptop). The design should allow some customization to hand size to enable a user with limited hand function to don and doff the device easily. Additionally, it should be made with soft and compliant materials that do not resist finger motion when unpowered. For this study, the soft robotic glove was fitted to an adult male hand which in turn determined its geometrical profile constraints; that is ∼2 cm for actuator width and height so it does not exceed the finger width and height, and customized actuator lengths to fit each finger.

2.2. Motion and force requirements

To comfortably support hand flexion and extension the soft actuators need to follow the range of motion of a natural finger and generate adequate force to perform the appropriate movement. A number of hand studies in the literature provide measurements on the range of motion of finger joints [45–47]. Based on these literature measurements, the soft actuators must have three bending degrees of freedom (DOF) for each finger (i.e. index, middle, ring, and little finger). Similarly, at least two bending DOFs and a rotating one (combination of flexion and abduction) around the carpometacarpal (CMC) joint of the thumb are needed to enable opposition grasping.

As part of our prototype development of a soft robotic glove, we also conducted a range of motion hand study with a healthy participant to serve as a benchmark for the device. An electromagnetic (EM) tracking system was employed (TrakSTAR, Ascension Tech. Corp., Milton, VT) and small EM tracking sensors were positioned in a stretchable, thin silicone strip above the fingers. Five tracking sensors were used on each digit to measure flexion and skin extension. Three of these sensors were placed on top of each finger joint — metacarpophalangeal (MCP), proximal interphalangeal (PIP) and distal interphalangeal (DIP) — one was placed at the fingertip and the final one at the wrist (carpal level), to act as a reference point for all other sensors. For the thumb, two were placed on top of the interphalangeal (IP) and metacarpophalangeal (MCP) joints, one at