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A Hand Exoskeleton for Stroke Survivors' Activities of Daily Life*

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Abstract— **Stroke is a leading cause of disability in the U.S. Hand impairment is a common consequence of stroke, potentially impacting all facets of life as the hands are the primary means of interacting with the world. Typically, therapy is the prescribed treatment after stroke. However, a majority of stroke survivors have limited recovery and thus chronic impairment. Assistive, rather than therapeutic, devices may help these individuals restore lost function and improve independence and engagement in society. Current assistive devices, however, typically fail to address the greatest barriers to successful use with stroke survivors. In the hand, weakness and incoordination arise from a seemingly paradoxical combination of limited voluntary activation of muscles and involuntary neuromuscular hyperexcitability. Thus, profound strength deficits can be accompanied by substantial forces opposing the intended movement. The assistive device presented in this paper can provide both sufficient flexion and extension assistance to overcome these barriers. A single actuator for each digit provides flexion or extension assistance through push-pull cables guided along the dorsal side of the hand. User intent can be decoded from Electromyographic (EMG) signals to drive the device throughout the movement. EMG control is customized to the capabilities of each user by examining the voluntary EMG workspace.**

I. INTRODUCTION

Every 40 seconds, someone in the US experiences a stroke. This high incidence rate, combined with the prevalence of resulting significant impairment, makes stroke the leading cause of major, long-term disability for Americans [1]. While the stroke may produce a variety of deficits, hand impairment is common and is a primary contributor to chronic disability following stroke, due to the prominence of the hands in performing activities of daily living [2]. Despite current therapy efforts, 45% of stroke survivors will have limited manual dexterity 18 months after the stroke [3].

Thus, assistive devices may prove beneficial for restoring function for stroke survivors. Improved functional capabilities achieved with an assistive device could improve the quality of life for stroke survivors and reduce reliance on a caretaker. While a number of assistive devices have been developed for the hand, many focus on generating grasp forces (flexion) to help individuals with spinal cord injury [4, 5] or hand impairments [6-8]. While stroke survivors may exhibit weak grasp [9, 10], greater functional impairment arises from deficits in producing finger extension [10, 11] and object release [12]. Extensor weakness, arising from reduced voluntary excitation of extensor muscles [10], is compounded by involuntary, aberrant activation of finger flexor muscles. Thus, substantial extension assistance may be needed to achieve net extension. In a prior study of 95 stroke survivors with chronic hand impairment, over 75% of the participants produced a net finger flexion torque when trying to create a maximal finger extension torque [13] and this torque could exceed 2 N.m.

A number of hand exoskeletons do provide assistance for flexion and extension, but many rely on passive extension, such as that produced by springs, that may be insufficient to produce finger extension for the stroke survivors most in need of an assistive device [14, 15]. Additionally, the lack of active extension force makes it difficult to assist in creating properly directed fingertip grip forces, which require contributions from both finger flexors and extensors. Other devices rely on actuators or cables on the palmar side of the hand that may interfere with object grasp or touch sensation [4, 5, 8]. Current devices that actuate both flexion and extension from the palmar side are not portable [16] or restrict unactuated degrees of freedom (DOF) [17, 18].

To address the needs of stroke survivors, we sought to develop a soft-hard, hybrid hand exoskeleton that could actively assist both flexion and especially extension from the dorsal side of the hand while maintaining a relatively low profile and allowing movement of unassisted DOF. We describe the design and initial efforts to measure mechanical performance.

II. DESIGN

A. Actuation

The device presented here moves the fingers through bidirectionally actuated cables (BAC) (Fig. 1). Using a single actuator for each digit, the BAC-Glove provides flexion and

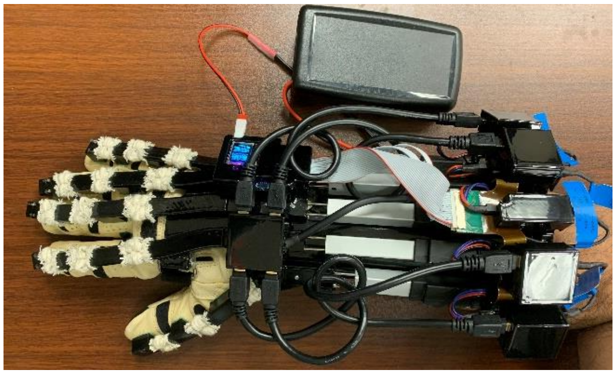

Fig. 1. The BAC-Glove is self-contained on the arm, aside from the indicated battery pack.

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extension assistance by employing wire rope push-pull cables (Loos & Co, Pomfret, CT). These cables have sufficient flexibility to accommodate the full physiological range of motion of each joint while remaining stiff enough to propagate a pushing force to flex the digit. The cables run through conduit located on the dorsal side of the digit (Fig. 2). Due to these rigid cable guides, designed in Solidworks (Dassault Systèmes SE, Vélizy-Villacoublay, France) and then 3D printed, the cables can both push the finger into flexion and pull the finger into extension. Two cables are used for each digit to increase lateral stability of the cable guides with respect to the finger. These rigid guides also serve other functions: 1) maintaining the desired joint moment arms, 2) preventing the cable from rubbing across the joint, and 3) preventing joint hyperextension during pulling. The printed cable guides were bonded to a lightweight leather glove (Bionic Glove Technology, Louisville, KY) to interface with the hand.

As the finger joints flex, a gap naturally forms between consecutive rigid cable guides. When pushing, this gap could result in buckling of the cable. To prevent this, deformable cotton sleeves reside between the guides (Fig. 2). The cotton sleeve strongly resists stretch, thereby preventing cable buckling during digit flexion, while imposing minimal impedance to compression during digit extension.

Each of the five cable pairs is translated using a linear actuator (L12 by Actuonix, Saanichton, BC, Canada) to enable independent control of each digit. In order to reduce the size and weight of the device, the shaft of the actuator was removed and replaced with steel needles that slide inside the shaft guide. The cables are connected to these needles (Fig. 3). Each actuator is mounted on a 3D printed fixture mounted to a wrist splint. A load cell (L113B-30KG by Forsentek Co., Shenzhen, China) situated between the motor and the fixture measures the force exerted on the cables. The 3D-printed wrist splint maintains the wrist in a functional posture. We have observed that providing external wrist support alone can lead to increased maximal pinch force generation in stroke survivors, presumably by supporting the wrist extensors so that greater extrinsic finger flexor activation can be employed without causing the wrist to flex.

B. Controller

A custom controller board powered by a 32-bit microcontroller (PIC32 by Microchip Technology, Chandler, AZ, USA) drives the actuators and samples the signals measuring cable force and displacement. The device can be operated in different modes depending on the goal of the user. The Stretch mode dynamically stretches finger muscles by rotating from specified flexion to extension limits for each digit. This stretching may provide at least temporary improvement in hand motor control [19]. The Force mode maintains a constant level of extension assistance for each digit [20]. The assistance can be set manually or according to the measured force level required to passively rotate each digit into extension. In the EMG mode, the user directly controls glove movement through the creation of EMG signals. Selection of mode and modification of parameters can be performed through an external device. We have created a custom graphical user interface (GUI) in MATLAB (MathWorks, Natick, MA, USA) to display data collected by the BAC-Glove and to set parameters for exoskeleton control. The microcontroller board on the BAC-Glove communicates wirelessly through a Bluetooth Low Energy module (BLE113 by Silicon Labs, Austin, TX, USA) with the GUI to receive control inputs and store data.

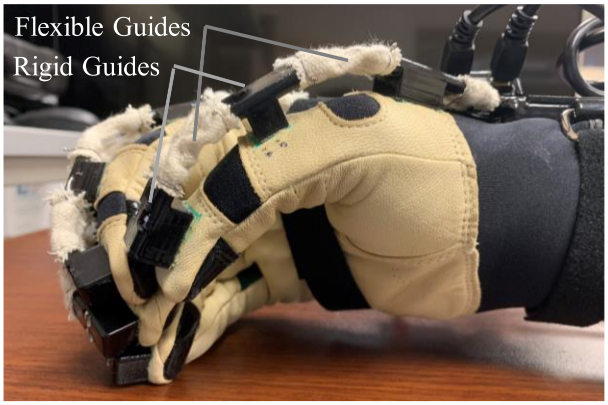

Fig. 2. Flexible guides prevent from cable buckling.

C. EMG Control

EMG provides a natural means of controlling assistive devices. In the EMG mode, the user can control assistance provided by the BAC-Glove through creation of specific EMG signals. The raw EMG signals, acquired from passive electrodes, are processed with custom circuits on printed circuit boards that amplify, filter, and rectify each signal. The amplitudes of the resulting EMG envelopes are sampled by the PIC32.

As stroke survivors typically have difficulty creating specified muscle activation patterns, we have developed a paradigm for customizing control signals to the capabilities of the user. The voluntary muscle activation space of the user is characterized by having the user perform a variety of hand tasks (guided by images) while the EMG signals are recorded. Principal component (PC) analysis is then used to find the two PCs that explain the largest amount of variance in the EMG data set collected during this exploratory period. These two PCs are chosen to serve as the target vectors defining a hyperplane within the EMG workspace. EMG activation patterns are subsequently projected onto this hyperplane in real-time in order to control the glove (Fig. 4). By moving within this hyperplane, the user can select the desired grasp and control the velocity at which the movement is performed.

For an initial application of the BAC-Glove, a set of distinct grasps were chosen for assistance by the BAC-Glove. These grasps were selected based on their relevance to performance of tasks daily life and to test the capabilities of the BAC-Glove. The four grasps were: 1) power grasp, 2) two-

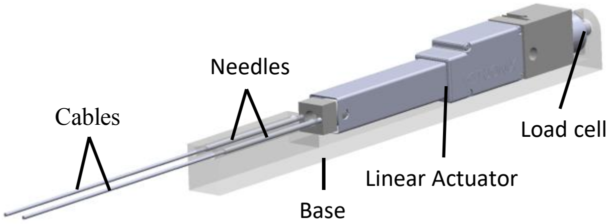

Fig. 3. Linear actuator actuates the needles and the cables and load cell measures the force.

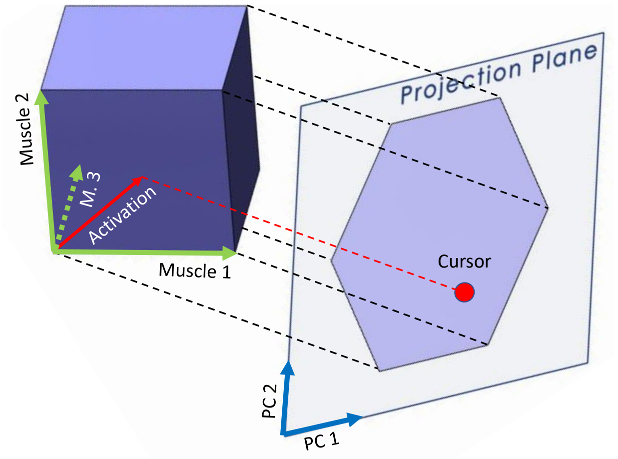

Fig. 4. Cursor position is calculated by projection the muscle activation vector onto the projection plane formed by the target PCs.

digit (palmar) pinch, 3) three-digit pinch, and 4) single-finger pointing and pressing. The user selects the grasp type by creating an EMG activation pattern corresponding to the desired sector of the control hyperplane. To facilitate learning this control, we developed a GUI (in MATLAB) that represents the projection of the current EMG activation pattern as a cursor on a screen and the grasp sectors as regions on the computer screen (Fig. 5a). Once the cursor hovers in a sector for 1s, the controller switches to the grasp execution mode and moves the fingers to the base gesture for that grasp. In the visual representation, the cursor must be moved to the "open" or "close" sector (Fig. 5b). The distance of the cursor from the origin controls the speed of the opening or closing of the grasp and its direction. Activating all the muscles over a threshold triggers a return to the grasp selection mode.

III. VALIDATION

A. *Protocol*

As an initial evaluation of the device, benchtop testing was performed in order to quantify the amount of flexion and extension assistance that the BAC-Glove could provide. With the hand of a human participant in the glove, the fingertip of the index finger was secured to a 6-axis load cells (SI-80-4, ATI Industrial Automation, Inc. Apex, NC). The wrist was fixed in neutral flexion/extension and ulnar/radial deviation by the splint of the BAC-Glove. Straps placed across the forearm resisted arm and hand translation while maintaining the forearm at 20° of pronation. In this posture, the elbow was flexed roughly 90°, while the shoulder was abducted about 70°. The participant was instructed to remain relaxed throughout the procedure.

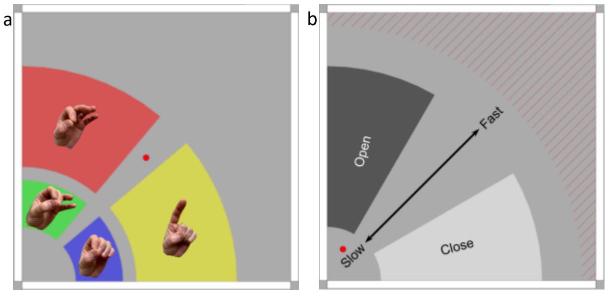

Fig. 5. a) User selects desired grasp in grasp selection mode and b) controls speed and direction of the grasp in grasp execution mode.

Maximum isometric fingertip force applied by the BAC-Glove to the fingertip was measured at three different index and middle fingers postures, produced by 20%, 40%, and 60% of full cable extension. These postures corresponded roughly to joint postures of metacarpophalangeal (MCP) angle, proximal interphalangeal (PIP) angle, and distal interphalangeal angle (DIP) of: (10°, 5°, 10°), (20°, 15°, 20°), and (20°, 25°, 20°). This process was repeated for the middle finger. Inverse kinetics was used to calculate the torque at different joints of the finger from the recorded load cell data and the joint angles. To quantify the direction of the force created at the fingertip, the angle between the normal force vector (with respect to the long axis of the distal finger segment) and the fingertip force vector was calculated.

To measure grip and pinch forces created by the device, a dynamometer was positioned in the hand to measure force, while the glove created the desired grasp. The Hydraulic Hand Dynamometer (Jamar, Clifton, NJ) was used to measure peak grip force and a pinch gauge (B&L Engineering, Santa Ana, CA) recorded peak pinch force. Again, the participant was instructed to keep his hand relaxed inside the glove during the procedures.

B. *Results*

The BAC-Glove created substantial fingertip force in both flexion and extension for the two digits tested (Fig. 6). Fingertip forces were similar across the index and middle fingers but varied with finger posture. Flexion force was greatest at the most extended posture (approaching 8 N), while extension force was greater at the flexed postures (reaching 12 N). The device generated extension or flexion torques across the MCP, PIP, and DIP joints simultaneously (Table I). The computed MCP torques for extension exceeded 0.5 N-m across postures and reached 0.9 N-m. MCP flexion torque was greatest at the most extended posture (0.6 N-m) and decreased for the most flexed posture (0.2 N-m).

Peak grip force created by the BAC-Glove was 20N. The device created 5N of force for 2-finger pinch and 10N of force for 3-finger pinch.

C. *Discussion*

The BAC-Glove is an assistive device designed to address functional hand deficits, particularly in stroke survivors. The device can actively assist both digit flexion and extension with a single actuator for each digit. Actuation and force transmission occurs entirely on the dorsal side of the hand,

TABLE I. FINGERTIP FORCE AND TORQUE VALUES GENERATED IN THE INDEX FINGER.

Posture		**Joints Torque (N.m)**			**Force (N)**	
Actuator Length	***Direction***	***MCP***	***PIP***	***DIP***	***Ampl.***	***Direct.***
20%	Extension	-0.52	-0.37	-0.31	4.88	45°
	Flexion	0.64	0.41	0.31	7.22	40°
40%	Extension	-0.86	-0.55	-0.46	11.63	37°
	Flexion	0.37	0.21	0.16	4.7	27°
60%	Extension	-0.75	-0.47	-0.45	11.44	41°
	Flexion	0.2	0.12	0.11	2.92	35°

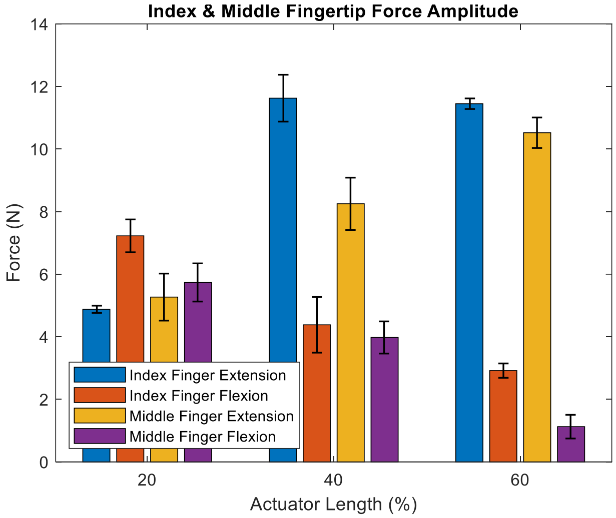

Fig. 6. The mean amplitude of the extension and flexion forces for index and middle fingertips at different lengths of the actuator. Error bars indicate the standard deviation of values.

thereby freeing the palmar surface for object grasp and manipulation. All of the digits are actuated independently to provide more force and flexibility in executing different grasps. The device can operate in a number of different modes, including under EMG control. The EMG control scheme is designed with the limited muscle activation space of stroke survivors in mind, as it concentrates on the most accessible region of the muscle activation workspace for each user.

Bench testing confirmed that the BAC-Glove capable of providing substantial finger extension assistance in addition to finger flexion assistance. The glove was able to generate up to 12 N of extension force in a single digit. This translated into more than 0.5 N-m at the MCP joint of the index finger across postures. These values are in the range of what might be required to overcome involuntary flexor activity during attempted finger extension [13]. The created flexion was smaller, although it did reach roughly 8N of fingertip flexion force and 0.6 N-m of MCP torque for the most extended posture tested. These values decreased for more flexed postures. The flexion force was directed more normally than many stroke survivors can achieve voluntarily [21], which is beneficial as the normal direction helps to keep objects from slipping out of the grasp. Having the BAC-Glove create less shear force in relation to normal force would improve grasping.

While force generation is ultimately limited by motor size, losses also occurred within the structure of the glove itself. Shear forces led to excessive stretch in the glove during actuated finger flexion. This also resulted in occasional twisting of the intermediate rigid cable guides, with a detrimental effect on the direction of the force applied on the fingers and the resulting torques, as well as on the peak fingertip flexion force that could be generated. In a future design this situation could be improved by increasing coupling between the user and the device through a glove with better fit and less compliance.

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