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A NOVEL DESIGN OF A ROBOTIC GLOVE SYSTEM FOR PATIENTS WITH BRACHIAL PLEXUS INJURIES

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ABSTRACT

This paper presents the design of an exoskeleton glove system for people who suffer from the brachial plexus injuries in an effort to restore their lost grasping functionality. The robotic system consists of an embedded controller and a portable glove system. The glove system consists of Linear Series Elastic Actuators (SEA), Rotary SEA and optimized finger linkages to provide motion to each finger and a coupled motion of the hand and the wrist. The design is based on various functionality requirements such as being lightweight and portable for activities of daily living, especially for grasping. The contact force at each fingertip and bending angle of each finger are measured for future implementation of intelligent control algorithms for autonomous grasping. To provide better flexibility and comfort for the users, abduction and adduction of each finger as well as flexion of the thumb were taken into consideration in the design. The glove system is adjustable for different hand sizes. The micro-controllers and batteries are integrated on the forearm in order to provide a completely portable design solution.

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1 INTRODUCTION

Brachial plexus injury (BPI), which is mostly caused by motor vehicle accidents and extreme sporting accidents [1], is a severe peripheral nerve injury affecting upper extremities causing functional damage and physical disability [2]. Individuals who suffer from brachial plexus injury have a lack of muscle control and feeling or sensation in the arm, hand and wrist. Previous studies have found that surgical options have had success restoring shoulder and arm function, but less so in returning sensation and mobility to the hand and wrist due to the long distance of the working nerves from the zone of injury to the target. [3]

Using wearable devices is a promising approach to help patients restore their functional abilities for activities of daily living (ADL), especially for grasping. In the past decades, numerous robotic rehabilitation exoskeletons for the hand have been developed, which include about 46 devices declared as daily assistive devices [4]. Compared with stationary devices [5] [6], wearable devices are designed to be worn and carried for a long time to help patients with their simple ADL. Therefore, besides the basic functionality requirements, higher demands for reduced size, reduced weight, and increased comfort and durability need to be achieved.

Recently, a number of hand rehabilitation designs have followed an alternative approach to that of traditional exoskeletons. Soft robotic gloves [7] [8] [9] [10], due to a reduced number of degrees of freedom, good wearability provided by compliant materials and low cost, have become one of the popular rehabilitation devices and have caught researchers' attention. However, these design innovations cannot avoid using thick inflatable segments over the fingers in order to induce bending. Besides, the requirements to use compressors and air storage cylinders to operate them limit the glove's portability and the user's mobility [11]. Similar challenges exist in other devices driven by hydraulic or pneumatic actuators. Cable-driven and bowden-driven gloves, such as SAFER [12], CyberGrasp [13] and RAS system [14], use a soft glove mechanism without rigid frames to help restore the functionalities of the hand. However, the additional requirements of uncomfortable pre-tensioning, unexpected shear forces caused by hard broken cables/tendons, and bulky actuation units worn on the back of the hand, decrease their wearability. The Bravo [15] and Hope4Care [16] gloves use direct linkage as the motion transmission method, but they are bulky and heavy.

Given the shortcomings of previous wearable devices, we propose a new exoskeleton glove system design that is compact, multi-functional and user friendly for grasping. This paper presents the design details of the RML glove V2. The glove is driven by SEAs, which is the evolution of the mechanism first presented in [17]. The compliant spring elements in the SEA allow the user to be comfortably assisted by the glove and provide force feedback for intelligent control. The linkage system couples the motion of the metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints into one degree of freedom fastened alongside the finger and has been optimized in previous work [18]. Besides the basic bending mechanism of each finger, passive abduction and adduction [19] degrees of freedom have been implemented. To achieve better grasping performance, the coupled motion of the wrist and the hand have been taken into account. Furthermore, the micro-controller and battery were integrated on the wrist for portable use. Voice command control was also implemented to provide ease of use. Fig. 1 shows the overview of the entire glove system.

The main contribution of this paper is the detailed consideration of the system's design evolution in hardware and mechanism aspects with the combination and improvement of previous research [17], [18], [20], [21]. These along with other design improvements including the addition of a rotary SEA design, the use of smaller micro-controllers and the implementation of voice activation make our proposed glove system portable, lightweight and more capable than before. It also paves the way for developing a hand rehabilitation learning system that is capable of learning patterns from recorded fingertip motions and contact forces data to assist the user in grasping different objects. The rest of the paper is organized as follows: In section 2, the requirements

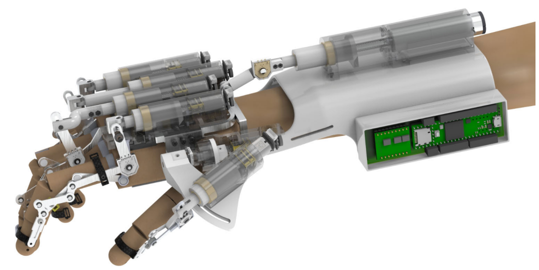

Figure 1. RML Glove System Overview

of the system are described. In section 3, section 4 and section 5, the design of the entire glove system is introduced including two types of SEAs, linkages and the full glove. Section 6 introduces the micro-controller design for the glove system. Lastly, section 7 concludes the paper.

2 APPLICATION REQUIREMENTS AND SYSTEM OVERVIEW

The proposed glove system focuses on restoring the grasp functionality for BPI patients with their ADLs. Based on the research that will be discussed in the hardware selection subsection, we chose nine common objects from several classes, such as a cup, book, pen, etc., depending on their shapes. The current design can provide up to 20N of contact force on each finger. To achieve the goal of grasping small objects, and also considering the whole size of the finger linkage and SEA, the maximum bending angle of the metacarpophalangeal (MCP) joints is 38° which is equivalent to holding a 24mm diameter cylinder. The coupled motion of the hand and the wrist with 25° in wrist extension and 15°in wrist flexion needs to be by the glove system based on previous research [22]. The passive abduction and adduction of the fingers are applied to provide more comfortable experience for patients during grasping.

The proposed glove system consists of SEAs at the actuation units and optimized finger linkages at the outputs. The deformation of the SEA is calculated by the difference between the encoder of the motor and the bending angle of the MCP joint, measured by a miniature rotary potentiometer. The direct force that is applied on each fingertip is measured by deformation of the SEA. The current angle of each joint is calculated by the MCP joints because each of the linkage mechanisms consists of a single DOF mobility. With the force on the fingertip and bending angle, the state of the glove system is known.

3 SERIES ELASTIC ACTUATOR (SEA) MECHANICAL ANALYSIS

The perspective view in Fig. 2 shows the components of the Linear SEA. Here, the screw nut, two wave disk springs and the output shaft are firmly connected and move as one slider on the leadscrew, powered by a motor installed at the distal end. The glove needs to power the fingers and wrist in extension and retraction, as the hands of patients who suffer from the brachial plexus injuries are supple. Particularly, based on our previous research [22], the rotation around the carpometacarpal (CMC) joint is important for the thumb movement and the completion of a full grasp. Thus, the SEAs need to provide and measure forces or torques for the five fingers, wrist, and thenar. Two types of SEAs were designed, Linear SEA and Rotary SEA, to acquire linear force measurements and rotary torque measurements, respectively. The control scheme of the mechanism is shown in Fig. 3. The displacement of the SEA is measured by the reading differences between the potentiometer on the linkage and the motor encoder.

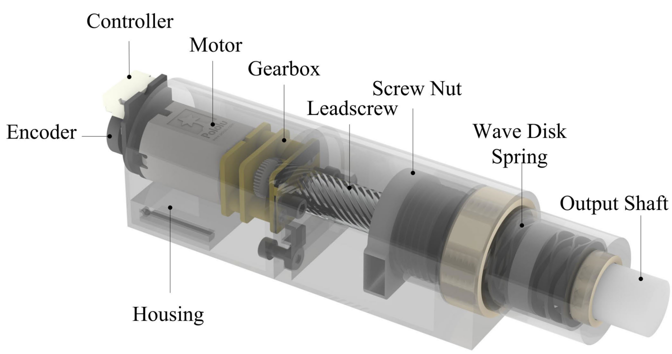

Figure 2. Perspective View of the Linear SEA. Working principle of the Linear SEA: the screw nut guided by leadscrew connects the output shaft. The spring between the output shaft and screw nut is compressed when there is contact with an object and measures the force by its deformation at the same time.

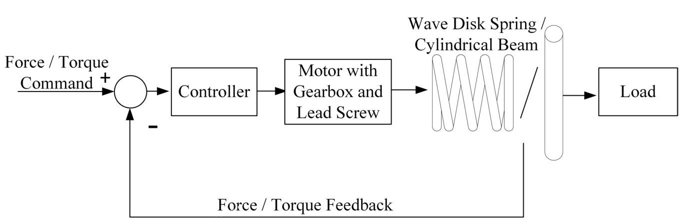

Figure 3. Control Scheme of the SEA.

For the Linear SEA, the output motor torque is transmitted to output force through a gearbox, lead screw and wave disk spring. Considering the regular leadscrew load lifting calculation,

$$\tan(\lambda) = \frac{l}{\pi d_m} \tag{1}$$

$$F_{raise} = \frac{2T}{d_m}\eta_s\left(\frac{1-\mu\sec\alpha\tan\lambda}{\mu\sec\alpha+\tan\lambda}\right) \tag{2}$$

The output force F_o and speed v_o at the SEA output shaft, related to the input torque T_m and speed n_m from the motor under no load, can be calculated according to:

$$F_o = \frac{2T_m i}{d_m}\left(\frac{1-\mu\sec\alpha\tan\lambda}{\mu\sec\alpha+\tan\lambda}\right)\eta_s\eta_g\eta_m \tag{3}$$

$$v_o = \frac{l n_m}{60i} \tag{4}$$

where,

l – lead of the lead screw
d_m – pitch diameter
λ – lead angle
α – thread angle
μ – friction coefficient
i – reduction rate
η_s – efficiency of lead screw
η_g – transmission efficiency
η_m – efficiency of motor combination

The transmission efficiency is defined as the ratio of the output force and the input force.

The housing and the lead screw nut were custom made. The springs were integrated in the screw nut with the output shaft. Because grasping forces are measured rather than extension forces, only the second spring located near the actuator provides the compliant function. The first spring works as a buffer for restoring the hand motion after a grasp. The lead screw nut was assembled by threaded connection.

The Rotary SEA (Fig. 4) consists of five components. The inner RSEA is basically a shaft with different diameters. It consists of a tap at one end to be attached to the DC motor and a hole of appropriate diameter on the other end to hold the beam in place. The outer RSEA is designed like a cap with slots perpendicular to the cylinder's axis and a hole along the axis of the cylinder for the inner RSEA rotation. The cylindrical beam passes through the hole in the inner RSEA and is held in place by the slots present in the outer RSEA. The slots provide resistance for beam deflection. The cover is attached with the outer RSEA with screws and tapped holes.

The main principle of the rotary Sea is to use the deflection of a cylindrical beam to measure the torque applied by the thumb mechanism's DC motor. When the glove isn't grasping any object there will be no deflection in the beam. But, when the glove comes in contact with an object, a specific amount of torque needs to be applied depending on the shape and texture of the object to be grasped. When the thumb comes in contact with the object, a reaction torque will be generated by the contact force. This will, in turn, try to rotate the outer RSEA with respect to the inner RSEA. This rotation will be resisted by the cylindrical beam present inside which will result in a deflection. This deflection can be related to the anglular rotation by the outer RSEA through the equation $s = r\theta$.

The angle rotated by the inner RSEA can be measured through the encoder attached to the actuator and compared with the angle rotated by the outer RSEA obtained from the encoder attached to its shaft. The cylindrical beam can be modelled as a cantilever beam and is divided into two sections for analyzing it. It is assumed that two opposing forces act on the tips of the cylindrical beam due to reaction forces from the outer RSEA and additional two opposing forces at the center of the beam due to reaction forces from the inner RSEA. The equation relating the torque to the angular rotation of the outer RSEA with respect to the inner RSEA is given by

$$T = 6EIR^2\theta/L^3 \quad (5)$$

where,

T – Torque

E – Elastic Modulus of the cylindrical beam

I – Area Moment of Inertia of the cylindrical beam

R – Mean radius of the outer RSEA

L – Half of the length of the cylindrical beam

θ – Angular position of outer RSEA with respect to inner RSEA

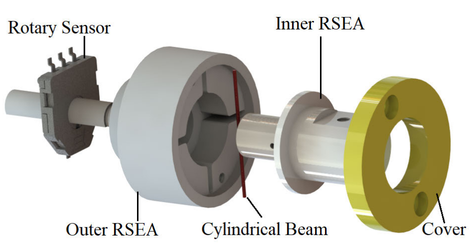

Figure 4. Exploded view of the Rotary SEA (RSEA).

4 HARDWARE SELECTION

The power of each finger comes from the motor combination. Thus, the motor selection is based on how much force should be applied on each fingertip. According to the research from DiDomenico et al. [23], people could exert roughly 40N poke force on each finger. However, that force is much higher than what people actually need for daily activities, especially for simple grasps. Because our glove focuses on helping people with daily use, several common objects were collected to test how much force is needed for grasping and lifting the objects. The objects are shown in Fig. 5 and the table shows the weight and needed force for each object. The friction coefficient of a fingertip is 0.47 as provided in [24]. As can be seen, the maximum force for grasping and lifting some selected objects is under 22N. To achieve better performance, the glove was designed to apply 20N on each finger.

Table 1. Weight and Lifting Force of Selected Objects

	Weight(N)	Lifting Force(N)
Phone	1.87	3.98
Apple	1.51	3.21
Cup	3.01	6.40
Book	10.14	21.58
Can	3.65	7.77
Box	0.70	1.49
Headphone	2.20	4.68
Bowl	5.28	11.23
Pen	0.10	0.21

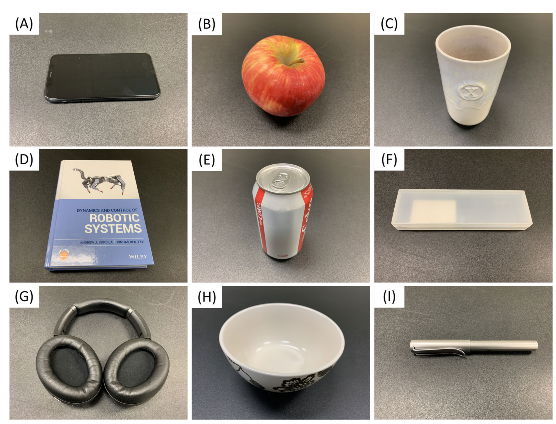

Figure 5. Selected Daily Using Objects: (A) Phone, (B) Apple, (C) Cup, (D) Book, (E) Can, (F) Box, (G) Headphone, (H) Bowl, (I) Pen.

Considering the mechanical advantage, the output of the SEA should be around 60N. To maintain a small transmission

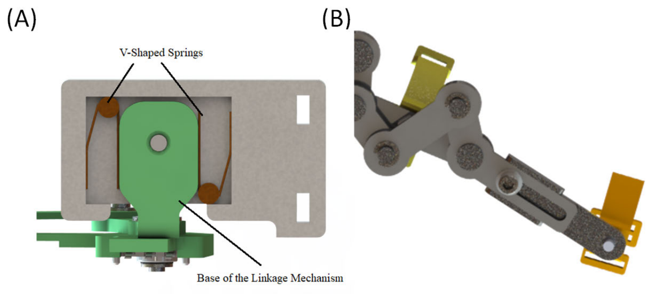

Figure 6. (A) Implementation of passive abduction and adduction mechanism using v-shaped springs placed on each side of the base of the linkage mechanism, (B) Adjustable distal link consisting of a pin and a slot mechanism.

system and to provide a quick response time while providing sufficient output force, the lead screw ($l = 20$mm, $d_m = 5.5$mm, $\alpha = 30°$, $\mu = 0.2$, $\eta_s = 0.78$) and wave disk spring ($k = 7.64$N·mm, $load = 60$N) have been selected. Due to no movement when a grasp is completed, stall torques were taken into consideration. Based on the previous discussion, Pololu motors that can provide 490 N·mm torque were chosen. The force under 60N can be measured and the maximum output force is 90N for handling more challenging tasks. The overall dimension of Linear SEA is $56 \times 19 \times 19$ mm^3 at its initial position. For the Rotary SEA, the same motor was selected based on torque calculations for holding a 1kg object. A cylindrical beam made of stainless steel of 18 mm length and 0.4 mm diameter was chosen.

5 EXOSKELETON LINKAGE DESIGN

The exoskeleton consists of rigid linkage mechanisms for each finger. These linkages are attached to the side of the fingers. This allows the entire exoskeleton to be slim and lightweight. The length of each link was optimized to follow the finger's natural bending profile as closely as possible. Details regarding the linkage mechanism can be found in [20].

The base links of the mechanisms have been modified to allow for abduction and adduction in the index, ring and little fingers for additional flexibility and comfort while performing different grasps. The mechanism consists of the base of the linkage mechanism being held in position with the help of V-shaped springs on both sides as depicted in Fig. 6 (A)

The last link of each mechanism is attached to a slot with a screw which allows it to extend in and out to accommodate different finger lengths. The rings at the end of each mechanism which attaches the fingers to the linkages, are capable of passive rotation which will help in accommodating slight variations in angles made by the distal phalanges with the last link of the linkage mechanisms (Fig. 6 (B)).

The base of the glove is made out of neoprene elastic sheet

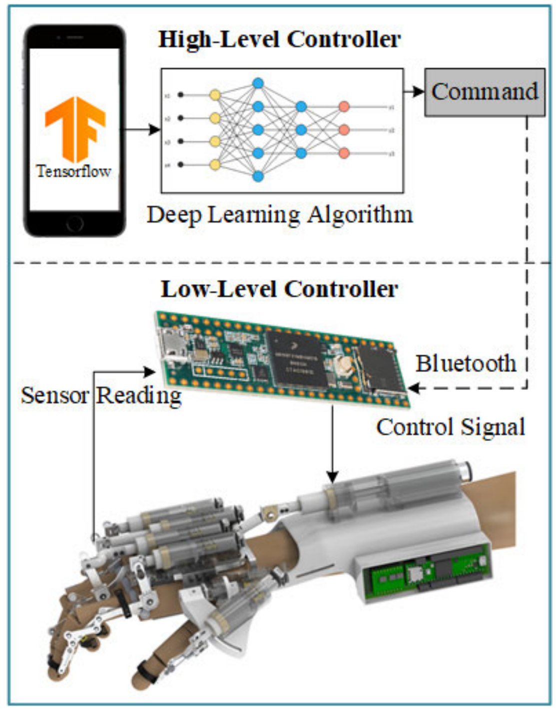

Figure 7. Electronics System Overview

to provide elasticity. All the Linear SEAs are attached to this elastic base with screws. This will allow the glove to be complaint enough to fit different hand sizes.

6 ELECTRICAL DESIGN AND CONTROL

The electronics design of THE RML glove V2 is portable, low latency, and modulated. All the electronics are embedded on the RML glove V2. The electronics design is modulated, and each part can be easily replaced. To control the RML glove V2, no cable connections are required from outside of glove. The onboard micro-controller will be responsible for sensor reading and perform low-level control, including force control, deformation detection, and grasp stability control. Real-time system is used to minimize the latency of sensor reading and provide the ability of parallel computing. The on-board micro-controller will receive commands from a smartphone through Bluetooth connection. High-level voice command system will be performed by a smartphone. The structure of the RML control system is described in Fig.7

To produce sufficient power and torque to move the RML glove V2, Pololu gearmotor (380:1, 12V) is used for the finger SEA and Maxon motor (brushless, 12V) is used for the wrist SEA with their compatible controller, respectively. Encoders are attached to all motors with the help angular potentiometer to measure the angle of each finger and wrist as well as deformation of the SEAs. An IMU is used to detect the angular velocity

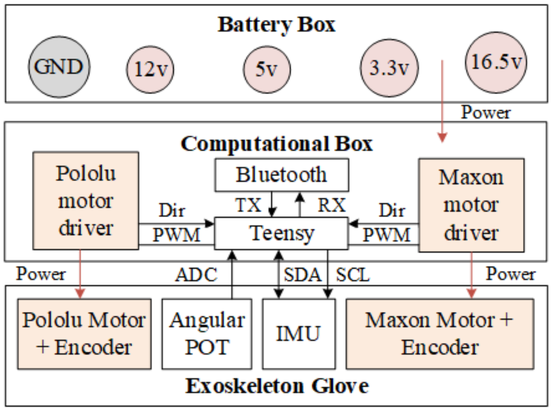

Figure 8. Block Diagram of the Hardware System.

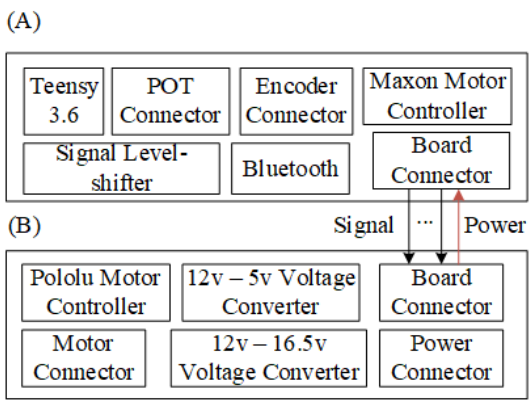

Figure 9. (A) Top Layer PCB Component Overview. (B) Bottom layer PCB Component Overview.

of the RML glove V2. A microcontroller called Teensy was selected to read data from sensors and perform low-level control. A bluetooth device communicates with a smartphone to provide high-level control. The block diagram of the RML glove V2 electronics design is provided in Fig. 8. To place all the components on the computational box while minimizing the size, a 2-layer PCB is designed. The components overview of each layer is shown in Fig. 9.

To minimize the latency and provide the ability of parallel computing, FreeRTOS is used as the real-time system on the Teensy micro-controller. Encoders are read through external interrupts. Angular Potentiometers are read through ADC based on timer interrupt. The IMU is read through I2C and the Bluetooth is read through UART. Both IMU and Bluetooth have a dedicated thread. There are two more threads to perform force control and grasp control. The real-time system task diagram is shown in Fig. 10.

The force control thread uses encoder data to perform standard PI control on the motors. The grasp control thread can perform the deformation detection and grasp stability control.

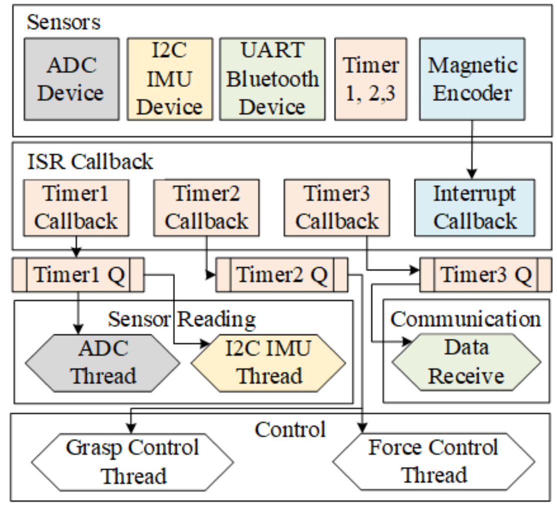

Figure 10. Real-time System Task Diagram.

7 CONCLUSION AND FUTURE WORK

The proposed rehabilitation glove system has significant potential to restore hand functionality in a population underrepresented in prior robotic glove and exoskeleton studies due to the localized yet complete nature of their nerve damage and the wide variability in resulting impairment. Our research aims to remedy the shortcomings in previous strategies to create a lightweight and portable robotic hand exoskeleton device. The requirements for the glove system, the design of the SEAs and whole hand exoskeleton and the design of the micro-controller were discussed. We believe that the proposed system is innovative and comfortable to wear due to its combination of portability and dexterity, enabled by novel actuation and control methodologies developed by our team. The glove system will be integrated and tested in the future. The intelligent control of the glove system based on perception of contact forces and hand posture, and voice activation will be implemented in future research.

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