Flexo-glove: A 3D Printed Soft Exoskeleton Robotic Glove for Impaired Hand Rehabilitation and Assistance

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Abstract— **This paper presents a compact and streamlined design of a soft exoskeleton glove for assistance in activities of daily livings and also rehabilitation purposes of patients with hand function impairment. Most of the existing hand exoskeletons have focused on either providing a customizable and modular design or making it portable to be used outside the hospital environment. We have developed a design of an exoskeleton glove that combines both of these features in one compact design. This was achieved by using a parameterised CAD design of glove, 3D printing of soft (i.e. compliant) materials, design a bidirectional cable driven spooling system and integrating them together in a modular fashion. The overall weight of the Flexo-glove is 330g including battery and is able to provide 22N pinch force, 48N power grasp force and object grasp size of up to 81mm in diameter. The device has two control modes: intention-sensing via wireless sEMG for assistive mode and externally-directed via an accompanying smartphone application for rehabilitation (repetitive exercise) programs, both managed through Bluetooth communication. The effectiveness of the proposed design is evaluated in performing cylindrical, hook, and pinch grasps on various objects.**

I. INTRODUCTION

Partial upper-limb paralysis is a common symptom in patients of stroke, spinal cord injury and muscular dystrophy. Each year since 2004, about 610,000 people experience new stroke in the USA and this number is projected to grow with the aging population [1]. Majority of these people incur a disability in upper extremity which severely restricts their independence and ability to complete everyday tasks.

Studies showed that physical therapy can help in regaining the upper-limb function, with recommendations for more task-based exercises to help with motivation of patients in using their upper extremity [12]. Hand rehabilitation in particular allows performing task-based exercises.

Currently, there are several factors which hinder the effectiveness of the hand rehabilitation: the process is time consuming and may be expensive; it can be difficult to access due to travel and time constraints; it is fatiguing, especially for those experiencing a fatigued baseline; and, it can be imprecise as measures of a patients incremental progress is difficult to quantify. Due to this costly and laborious practice for patients, most do not continue for long enough to recover maximum function.

Recent developments in wearable robotic exoskeletons have great potential in addressing these issues through automating rehabilitation therapy and providing physical assistance for patients. A number of hand rehabilitation and assistance devices have been commercialized to date such as SaeboFlex, Bioness H200 and Hand of Hope. Many similar devices have been studied in research laboratories but not manufactured for commercial use [10]. All of these devices are using metal rigid links sitting parallel to the proximal, intermediate and distal phalanges of each of the fingers to provide structure. This can provide the benefits of independent control over each phalange displacement. However, these devices are heavy, bulky and generally they do not adapt well due to person to person variations in hand dimensions. This happens to be one of the most common complaints about similar devices [2]. In addition, they are restricted to be used in the clinical settings due to their large size, weight and lack of portability [11].

Therefore, current research works on hand rehabilitation and assistance devices focus on two main features: *customizability* to fit different hand dimensions and *portability* to make it usable in performing daily tasks outside the hospital especially as assistive device. While most of the older research and commercial devices consisted of a rigid-linked exoskeleton with plastic or fabric padding for contacts with the hand [3], [4], current research is moving towards softer, more form-fitting materials. This evolution is the result of a desire for lighter, more comfortable gloves, along with a desire for a greater design flexibility.

Considering the customizability feature, a polymer-based wearable glove [6] was developed to assist with grasping motions for people with spinal cord injuries. A soft pneumatic assistive glove which is modular and customizable was proposed in [7]. Similar devices are also developed using fabric-based gloves [8]. These devices, however, are not readily portable due to their bulky actuation systems.

Other the hand, portable exoskeleton soft gloves [11], [9] are also studied, which lack the customizability compared to [6], [7]. A thorough review of the existing hand rehabilitation devices is provided in [10] which shows that each of these devices is lacking one of the features mentioned above.

In this paper, we have developed a modular, customizable and portable tendon-driven soft exoskeleton glove for both hand rehabilitation and assistance. The glove is fabricated using 3D printing of flexible thermoplastic polyurethane (TPU) which can be customized in an automated procedure

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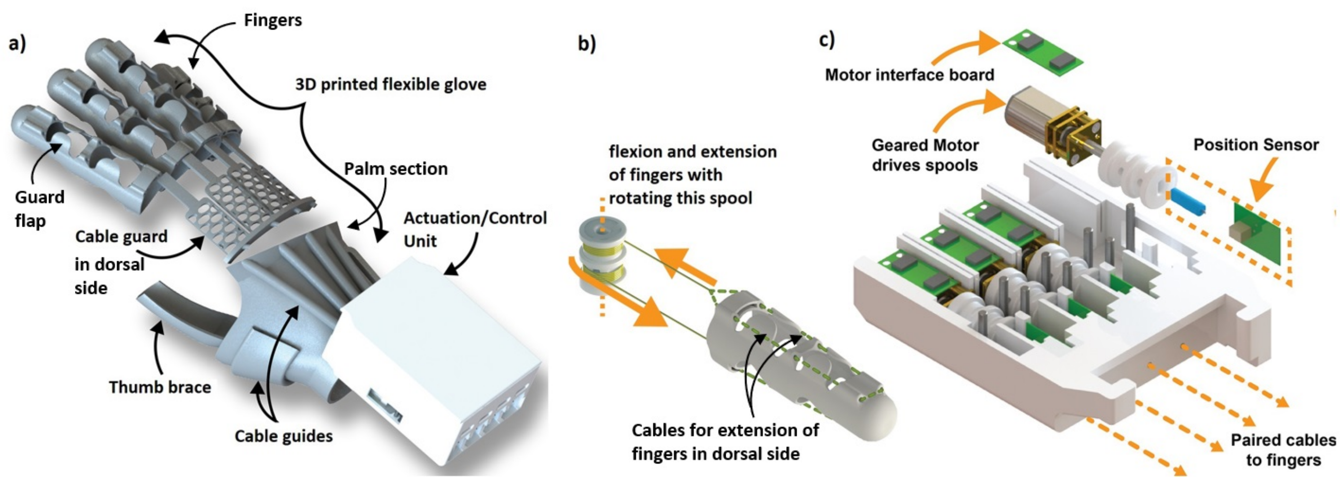

Fig. 1. Flexo-glove diagram: a) Overall assembly, b) Finger actuation, c) Actuation unit

for different hand dimensions and can be connected to the actuation system in a modular fashion. It can also be used as an assistive or rehabilitation device due to its capability in providing bidirectional finger movements.

II. Overall Flexo-glove Design

The overall Flexo-glove assembly is shown as a diagram in Fig. 1(a) which consists of two main components: 3D printed flexible glove and actuation/control unit. Each of this components is explained in the following subsections.

A. *Flexible 3D printed glove*

The flexible glove module which serves as cable guides for flexion and extension of fingers consists of the palm section, mesh-like cable guard, fingers and semi-rigid thumb brace as shown in Fig. 1(a).

The palm section of the flexible glove provides an interface between the actuating fingers and the actuation/control unit. In order to guide the actuation cables to the finger tips, cable guides were printed on both sides of this section. These tubes were to force the cabling around the curves of the hand.

A mesh-like cable guard structure is used to connect the cable guides in the palm section of the flexible glove to the ones in the fingers. The mesh-like structure not only allows stretching along its length during flexion and extension of the hand, it also makes the glove breathable to ensure comfortable wearing for extended amounts of time.

In design of cable guides in fingers of flexible glove, we should ensure that there is no contact between cables and the skin during flexion and extension of the hand. As shown in Fig. 1(b), on the dorsal sides of the finger, there are two cables moving parallel to each other and join in the intermediate crimp. If only one cable was to be used on the back of the fingers then contact would be made between the knuckles. In addition, guard flaps, as shown in Fig. 1(a), will protect the skin from any possible contact with actuation cables due to the flexibility of the glove.

The thumb brace in this design is held in a semi-rigid structure to provide a surface for the glove to push against in forming a grip. The position and orientation of this structure is designed to provide different grasps including cylindrical, spherical and pinch.

To design a glove that is flexible and comfortable to wear and robust in long-term operation, the major factor to be considered is the choice of the material. Considering these requirements, the material of glove is chosen to be in Thermoplastic Polyurethane (TPU) with Shore hardness 90A. Different sections of the glove is 3D printed and glued together which is shown in Fig. 2(a)-(b).

B. *Actuation/Control Uni (ACU)*

In the chosen design for the glove, four active independent degrees of freedom, one per finger, are implemented. Note that the thumb is held static on a semi rigid support and is not actuated. In order to provide these four independent active degrees of freedom, four actuators were required. The chosen actuators in this design were four micro DC motors. These were chosen for their size (10*12*30mm3), weight (10g) and small sturdy gearboxes (298:1) (Pololu Micro Metal Gearmotors) (Fig. 1 (c)). In order to separate the hand dimension sensitive part, i.e. the flexible glove, from the actuation unit, the design is kept modular and the actuation unit placed on the wrist. The tendon-driven mechanism is considered as the actuation method due to the lack of rigid links for force transmission.

The gearing ratio of the motors was chosen such that the most power could be delivered from the motors (5 kg-cm) whilst still being able to spool cables at a fast-enough rate. This rate had to be fast enough such that the speed of flexion of fingers could approximate the average speed of a healthy hand. This decision is linked with the spool design. The spool chosen has a diameter of 10mm. This, in addition to the chosen gearing, provides adequate force for performing activities of daily living (as detailed in Section IV) whilst taking less than 2 seconds to form a grip.

In order to achieve bidirectional movement for each finger with spooled cable transmission, two spools on a single motor shaft were designed to have two cables moving in

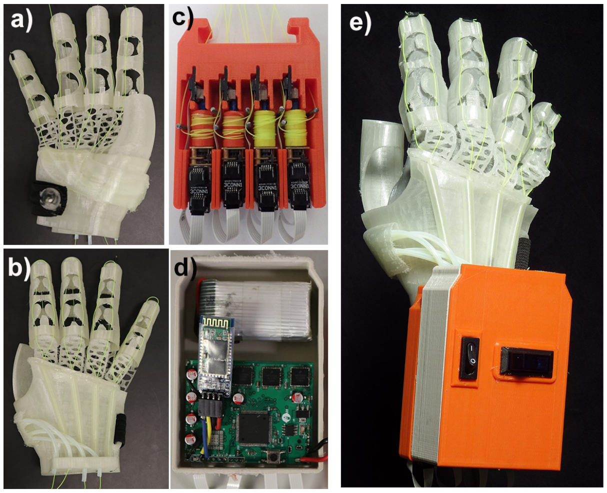

Fig. 2. Flexo-glove prototype: a) Front view of flexible glove, b) Back view of flexible glove, c) Actuation unit, d) Control unit, e) Overall assembly

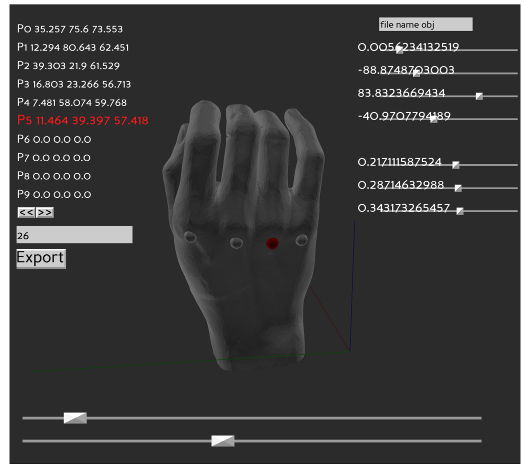

Fig. 3. User interface for selecting points of interest in 3D scanned hand

opposite directions wound upon them (Fig. 1(b)). One of these cables would flex the fingers from the palmar face whilst the other would extend the fingers from the dorsal face. This removes the need for two motors to pull the cable in opposite directions. Therefore, only four motors were required (instead of eight), which helped to reduce the weight and size of the device (Fig. 2(c)).

The control unit (Fig. 2 (d)) consists of a custom designed PCB, a Bluetooth and a pack of 7.4V LiPo battery. For driving four DC motors and receiving required feedback in a compact space, a custom PCB designed with an ATmega2560 microcontroller, four current-sense feedback motor drivers, and four connectors to receive analog signals from four multi-turn potentiometers (position sensors).

III. Customisability of the Glove

In order to be able to manufacture the flexible glove in a short amount of time to fit users of different hand dimension, an automated process was proposed, where measured hand dimensions can be imported into a parameterised CAD model and used to generate the glove model. For this purpose, first the impaired hand is scanned using a 3D scanner to obtain accurate scanned model of the hand (in STL format). Then, in order to automate the measuring process of user hand dimensions, a python program was written to process the scanned model by selecting key points on the scanned model of the hand. These key points of interest are the base of the wrist at front and back of the hand, the knuckles, the creases in the palm, and the position of thumb joint in the palm. The user interface of this program for selecting the points is shown in Figure 3. In addition, the diameter of the finger in the base and tip of the fingers and the length of each finger should be measured. Once this procedure had been completed, the data is exported into a spreadsheet that can be read into the parameterised model of the flexible glove in the SolidWorks to generate a preliminary model for the flexible glove of the Flexo-glove to be 3D printed.

This automated process for the flexible glove design is particularly useful for the clinician as this allows the generation of a form-fitted glove for the patient without any background knowledge in CAD software. In addition, the flexibility of the material used for the glove can allow for some variation in finger lengths and knuckle widths.

IV. Flexo-glove Performance Evaluation

In this section, performance of the Flexo-glove is evaluated in performing activities of daily living (ADLs) with the most common grasps [13] and providing required grasping force.

In order to evaluate the performance of the Flexo-glove in grasping objects with different shapes, a simple qualitative experiment had been designed. To set up this experiment, the Flexo-glove is firstly initialised to the fully extended configuration, an attempt will then be made to grasp the test object by actuating the motor to flex the fingers. The resulting grasp will then be recorded and evaluated against different test objects. Results of this qualitative experiment is shown in Fig. 4. The results show that Flexo-glove users are able to perform cylindrical grip for grasping cylindrical objects with different diameters and shapes (Fig. 4(a)-(c)). Also, they are able to grip spherical objects with relatively small diameter (Fig. 4(e)-(f)) although for larger objects it cannot provide a solid hold due to the restriction on the thumb position. The glove is also able to provide a solid hook grip (full shopping bag of approx. 5kg), due to the internal gearing of the motors, without back driving the motors (Fig. 4(d)). Finally, key pinches are also possible from the glove, which suggests that the user is able to pick up thin items such as credit cards and keys during ADLs (Fig. 4(g)-(h)).

In order to test the grasping force of the Flexo-glove for completion of generic ADLs, the requirements identified in [5] should be satisfied: 20N pinch force, 40N cylindrical grasp force and maximum object grasp size of 76mm. To do so, we used a device with two flat surfaces and two force sensitive resistors in between to measure the force applied during pinch and cylindrical grasping. The results show that the motors can produce 22N pinch force and 48N grasping

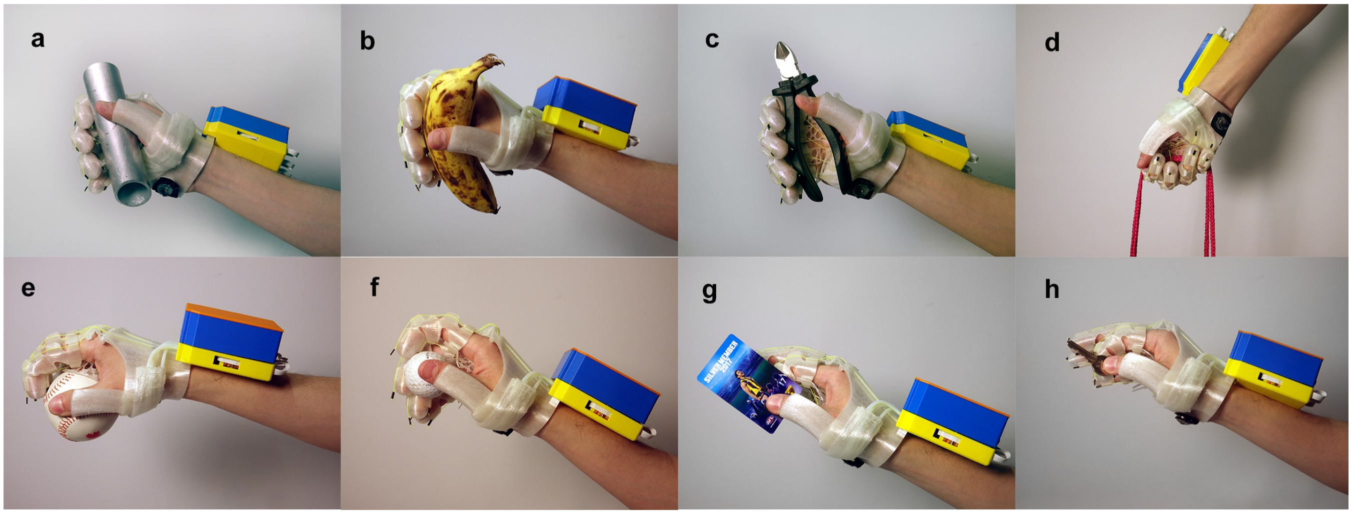

Fig. 4. Griping test with versatile objects: a,b,c) Cylindrical power grasping; d) Hook grip; e,f) Spherical grasp; g,d) Card and key pinch grip

force which are greater than the forces outlined for ADL requirements. The glove also allows grasping a cylindrical object of up to 81mm in diameter.

V. User Control Interfaces and Feedback

The microcontroller in control unit is programmed in two control modes: intention-sensing via sEMG and externally-directed via an accompanying smartphone application. Both modes are managed through the smartphone app. The app handles establishing Bluetooth communication to the control board as well as data-logging and controlling input functions.

The intention-sensing mode uses a sEMG sensor positioned on the users forearm. The current sEMG channel in use is the MyoBand, a commercial sEMG sensor that includes an interface to calibrate different poses and analyse raw sEMG signals to classify the motions of the wearer.

Directed exercise mode uses a pre-set exercise routine or motion from the smartphone app to aid the motion of the patients hand. Passive exercises (meaning the patient does not need to exert effort through the motion) can be used when the patient has limited control over their hand or as part of a varied routine. Actuation commands are sent from the phone to the motor control board with no input required from the patient. During a session, occupational therapists constantly observe patients in order to give feedback to patients. In line with that, the device is designed to capture data during operation to give the clinician a full report on how the patient is progressing. Time data on finger force and position are captured and stored on the phone for later review. This data could be used by the clinician to interpret the patients progress and adjust their exercise regimen accordingly.

VI. Conclusions

In this paper, we presented design and characterisation of a flexible exoskeleton glove for assistance and rehabilitation of patients with impaired hand function. Modular design of the Flexo-glove significantly simplifies the customisation process for different hand shapes since the actuation/control unit remains unaltered and the flexible glove is produced in an automated procedure via 3D printing method. Grip strength and range of motion of the glove satisfy the requirements in performing activities of daily living. Compact and high power-to-weight design of the Flexo-glove with overall weight of 330gr also allows a portable device which can be used outside the clinic.

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