Design of a Wearable Robotic Glove for Rehabilitation

Petchpansa Chotisathiantham, Yujun Lai, and Gavin Paul *

Abstract

This paper presents the design and prototype of a wearable robotic glove, integrating additive manufacturing (AM) processes to enhance the customisability and bio-compatibility of the glove. Each feature of the design is tested and evaluated to achieve the optimal design which assists the user to achieve their desired grasp. The glove is lightweight, sleek in design, customisable, comfortable to wear, and simple to use as a result of employing AM in the fabrication process. AM enables bespoke parts to be constructed and assembled quickly with soft and flexible material, as well as allowing designs to be easily revised. Experimental results show that the glove is able to perform the four frequently used grasp types and grasp various primitive-shaped objects. Overall, the prototype is able to demonstrate a simplistic design that can provide sufficient force during flexion and extension of the fingers to assist users with lowered hand mobility.

1 Introduction

The human hand is essential to perform Activities of Daily Living (ADLs), such as eating, typing, and grasping. Unfortunately, one of the many possible consequences of stroke and injury-related disabilities is the impairment of hand function [Ong and Bugtai, 2018]. The loss of hand function may inhibit a person's ability to self-care and result in lifelong dependency on others to carry out everyday tasks. This can lead to decreased life satisfaction, quality of life and life expectancy [Correia *et al.*, 2020]. Studies have shown that repetitive exercises of finger movements have enabled patients to regain hand functionality [Lum *et al.*, 2012]. However, this involves a series of tasks that require trained professionals to administer, and lasts for several months to years. This can become inconvenient for the patient to complete. Ultimately, the desire to receive such frequent professional treatments is reduced and their progress to recovery diminishes [Oubre *et al.*, 2020].

To overcome the roadblocks of conventional therapies, robotic devices have been incorporated to enhance the training experience and aid the patient in completing the exercise regimen independently [Lum *et al.*, 2012]. They allow patients to engage with their individual needs and encourage frequent and long-term compliance with the treatment [Oubre *et al.*, 2020].

This paper introduces the design and prototype development of a wearable robotic glove, that integrates AM processes to personalise the glove. The final glove design is tested to evaluate its ability to both facilitate hand rehabilitation exercises, and to provide enough force to actuate the fingers independently. The rest of the paper is as follows: Section 2 outlines related works, Section 3 highlights the design process, while Section 4 details the methodology and presents the results. The discussions are in Section 5, followed by the conclusion in Section 6.

2 Literature Review

Technological advancements in assistive technologies have lead to numerous developments towards robotic devices for hand rehabilitation. These robotic devices are aimed at supporting individuals with low hand control and low grasp strength to perform ADLs, rather than providing treatment for a specific diagnosis [Lum *et al.*, 2012]. A major design challenge for these robotic devices is the high complexity of the hand. Past devices which focused on the high degrees of freedom have failed to accommodate all types of joint configurations achievable by the hand [Li *et al.*, 2019; Tang *et al.*, 2013]. One approach to overcome this challenge is simplifying the device to have fewer controlled joints. The Hand Wrist Assistive Rehabilitation Device (HWARD) achieves this by grouping the four fingers as a single unit about the

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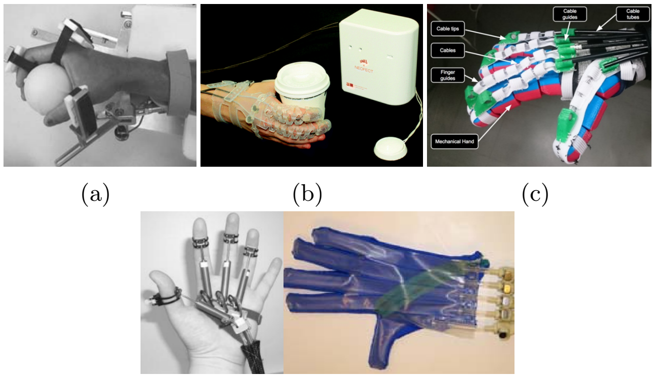
*All authors are with the UTS Robotics Institute (UTS:RI), University of Technology Sydney, Australia. Corresponding author: `yujun.lai@uts.edu.au`

metacarpophalangeal (MCP) joint, using only two actuators [Takahashi *et al.*, 2005]. A similar approach was taken by the Exo-Glove Poly II (EGPII) which controls 3 cable-actuated fingers to assist in grasping objects [Kang *et al.*, 2019]. Flexion and extension are achieved by a dual-slack enabling actuator pulling and pushing the cable antagonistically, while changing cable lengths are accommodated by the diamond patterns along the fingers.

Another approach is actuating only the fingertips, allowing individual fingers to be controlled by applying forces to the fingertips. However, this limits control to the middle and proximal joints of the finger and can create abnormal hand postures. The Hand Robotic Exoskeleton (HRE) uses a flexible lining wrapped around the hand to secure the device and actuate the cable-guided fingers using linear motion [Ong and Bugtai, 2018]. Similarly, the Rutgers Master II (RMII) utilises pneumatic pistons to generate the forces to cause flexion and extension [Bouzit *et al.*, 2002].

An alternate perspective is to promote finger flexion, a task which is most challenging for stroke survivors, by only assisting during extension. The Pneuglove (PG) achieves this by applying a unidirectional air pressure to each individual finger for extension, and releasing the valve during flexion [Connelly *et al.*, 2009].



(a) (b) (c)

(d) (e)

Figure 1: Various wearable robotic gloves for hand rehabilitation: (a) HWARD, (b) EGPII, (c) HRE, (d) RMII, and (e) PG.

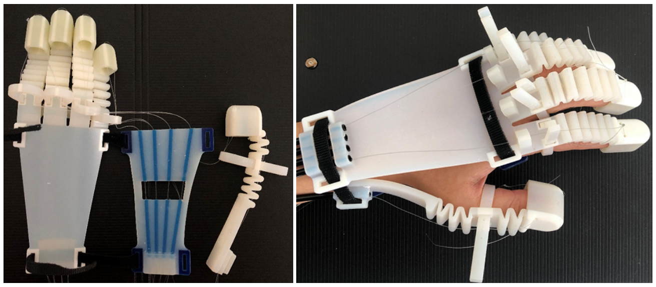
2.1 Additive Manufacturing

Additive manufacturing (AM), also known as three-dimensional (3D) printing, is a manufacturing process where a thin layer of material is progressively deposited onto the preceding layer to form the desired 3D part. AM offers flexibility during manufacturing as a single bespoke part can be economically produced, despite highly complex geometry, near-net-shape, and multi-density properties. Thus, AM is beneficial in biomedical applications since they can precisely mimic complex shapes and allow devices to be personalised to individual needs [Giubilini *et al.*, 2021].

3 Design Requirements

The goal of the wearable robotic hand is to assist in performing therapy exercises, in particular, opening and closing the hand. Tackling the complexity of the human hand has lead to designs which are bulky, heavy, and rigid, compromising comfort to accommodate a greater Range of Motion (ROM) [Correia *et al.*, 2020]. An optimal design requires the glove to:

- Provide sufficient force onto each finger to assist with the opening and closing of the hand;
- Be easily customisable;
- Be simple and sleek in design; and
- Provide comfort for prolonged periods of use.



(a) (b)

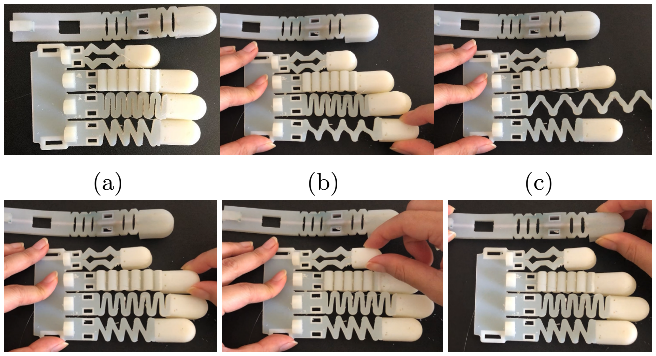
Figure 2: (a) The wearable robotic glove components (left to right): dorsal pad, palmar pad and thumb (straps are inserted on the fingers); and (b) the robotic glove worn on the hand.

3.1 Glove Design

The glove consists of a dorsal pad, palmar pad, thumb, and five straps, as shown in Fig. 2(a). The dorsal pad, palmar pad, and thumb are assembled using Velcro to form the glove, and fitted on the hand (Fig. 2(b)), ensuring the glove is easily fitted and adjustable for users with different hand sizes. All glove components are 3D-printed with Agilus30, VeroWhite and VeroBlue material using a Stratasys J750 (Stratasys, Minnesota, USA).

The dorsal pad features a wave pattern along each finger that extends from the hand to the fingertips. The thumb also features the wave pattern between the tip and the base of the thumb. This pattern enables the material to stretch when the finger is flexed and to protect the hand from skin abrasion during the actuation of the glove. The fingertips are designed to secure two cables on the dorsal and palmar sides of the fingertips.

Cable guides are placed at the base of the fingers and the wrist, and tubes are inserted into the cable guides at the wrist to protect the cable and ensure that they do not tangle when connected to the actuation system. The straps are designed to secure the wave pattern to the hand by inserting it into the two square holes at the proximal joint of the finger, which can be adjusted to fit different finger thickness. The hole at the center of the straps also assists in guiding the cable from the fingertips to the actuation system.


(a) (b) (c)

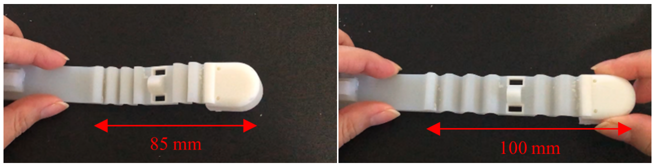
(d) (e) (f)

Figure 3: Different structural designs under consideration for the finger patterns: (a) all fingers patterns under normal state, (b) to (f) finger pattern from bottom to top being stretched with near-identical force.

The palmar pad has four circular channels through the middle of the body (blue areas in Fig. 2), which allows the cables that connect the actuation system to the fingertips via the guides at the center of the strap. All the holes in the dorsal pad, palmar pad, thumb, and straps are fabricated with the maximum material hardness. This increases the durability and strength of the components, and mitigates wear and tear effects from sustained cable actuation. The remaining section of each component is fabricated with Shore hardness A50, so the glove is soft and flexible, thus ensuring user comfort during rehabilitation therapy. Numerous design features are evaluated to determine the final glove design.

3.2 Finger Patterns

Fig. 3 (a) shows five different patterns which were evaluated to determine the stiffness of the material during flexion. This is to maximise the durability of the glove and lower the required actuation force. Each design was tested manually to replicate the flexion and extension movements of the fingers, applying an approximately identical amount of force to each design. The designs in Fig. 3(d), (e), and (f) indicate little to no stretching, making them unsuitable. Fig. 3(b) shows a design with adequate stretching. However, weak points appeared at the sharp corners of the design, which lead to material tearing after a few minutes of repeated stretching and releasing. The design in Fig. 3(c) is most flexible; however, the thinness of the material may result in tearing over time with continuous use.



(a) (b)

Figure 4: Revised finger pattern design from Fig. 3(d): (a) finger at normal state; and (b) finger stretched.

The tests indicate that the pattern in Fig. 3(d) showed the highest potential as the most durable design. Hence, this design was chosen and revised to be thinner to enable the material to stretch more easily (Fig. 4).

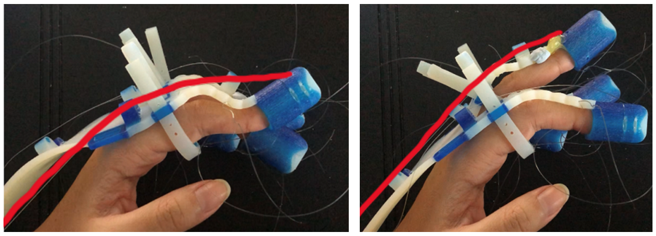

(a) (b)

Figure 5: The two different fingertip configurations considered for the wearable robotic glove. The cable (in red) is secured: (a) at the edge of the fingertip of the index finger, and (b) close to the DIP joint of the middle finger.

3.3 Fingertips

Two fingertip configurations were evaluated to best replicate natural finger extension movement when actuated. The two configurations differ in where the cable is secured: the first (Fig. 5(a)) is secured at the edge of the fingertip while the second (Fig. 5(b)) is secured close to the distal interphalangeal (DIP) joint. Testing was performed by manually pulling on the cable to mimic the extension movement. In the first configuration, there was a risk of hyperextension of the DIP joint, while the second design lifted the fingertip more naturally with no apparent risk of hyperextension. Hence, the second fingertip configuration was selected for the final design.

3.4 Cable Guides

Cable guides were extruded as far away (7mm) from the dorsal pad as possible to maximise the moment arm of the fingers. However, the location of the cable guides will also affect the moment arms of the glove during flexion. Four cable guide location configurations (Fig. 6) were evaluated to minimise the amount of actuation force required for flexion/extension. This enables the size of the actuators to be lightweight.

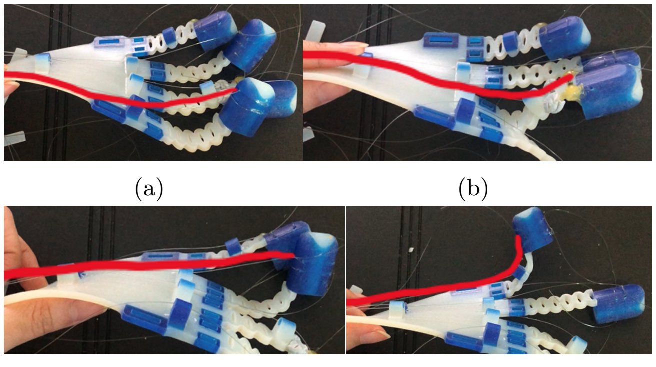

(a) (b) (c) (d)

Figure 6: The design of the cable guides located at: (a) proximal joint, (b) distal joint, proximal joint and middle of the dorsal pad, (c) proximal joint and middle of the dorsal pad, and (d) proximal joint. The red lines indicate the path of the cable in each of the fingers.

Fig. 6(b) and (d) shows that guides near the tip of the finger limited the perpendicular distance of the cable, and the guides at the middle of the dorsal pad are redundant in guiding the cable along the hand. Fig. 6(a) and (c) shows that the cable has the largest perpendicular distance when the cable guide is placed at the proximal joint. This configuration was selected for the final design. We conclude that cable guides located at the tip of the fingers and the middle of the pad were unnecessary.

3.5 Actuation System

Each finger is actuated with a stepper motor (NEMA17), stepper motor driver (L298N), pulley hub, and a 12 V battery. Two cables running from the fingertip at the dorsal side and the palmar side are connected to the pulley hub mounted on the motor in opposing directions. The motor drives both cables simultaneously to achieve flexion and extension. A microcontroller (Teensy 4.0) is used to program the glove to perform the required rehabilitation exercises. The movement of each finger is controlled by integer values between 0 and 120, indicating maximum extension and flexion states respectively, which correlate with each finger's ROM.

3.6 Comparison against Existing Designs

AM is incorporated in the design and fabrication of the wearable device to take advantage of its ability for rapid prototyping, high complexity, precision, customisability, and bio-compatibility. Existing designs from literature are used to compare the proposed wearable glove design to highlight the benefits of AM as outlined in Table 1.

The proposed design meets all the desired features and AM is shown to be advantageous in creating a custom, biocompatible device for the proposed design.

Table 1: Comparison of features across various assistive devices for hand rehabilitation. (A) HWARD, (B) EG-PII, (C) HRE, (D) RMII, (E) Proposed design.

Features	(A)	(B)	(C)	(D)	(E)
Personalised	No	Yes	Yes	No	Yes
Soft Material	No	Yes	No	No	Yes
All fingers actuated	Yes	No	Yes	No	Yes
Low production time	No	No	Yes	Yes	Yes
Less than 5 components	No	Yes	No	Yes	Yes
One step fabrication	No	No	No	No	Yes

4 Testing and Results

4.1 Grasp Types

The glove was tested to identify its assistive capabilities during hand rehabilitation therapy. This test was split into two parts: 1) to test if the glove can perform common grasp types that are required in ADL, and 2) to test if the glove can pick up objects that are used in the standardized Action Research Arm Test (ARAT) to assess upper extremity performance [Yozbatiran *et al.*, 2008]. Since the tests were aimed at assessing how much the glove can assist in performing rehabilitation exercises, the subject was asked to relax their fingers and not exert any force while the glove was actuated.

The four most frequently used grasp types to perform ADLs are palmar pinch, medium wrap, parallel extension, and lateral pinch (Fig. 7) [Bützer *et al.*, 2021]. The first test was conducted by programming these four grasp types into the actuation system, achieving the finger configurations. Fig. 8 shows the subject performing the grasp types while wearing the glove.

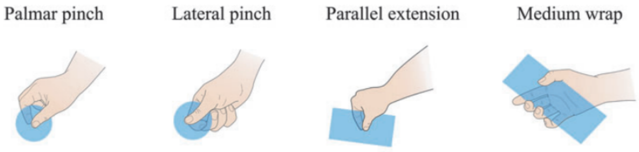


Figure 7: The four most common grasp types in ADLs.

In the second test, the glove was programmed to allow individual fingers to wrap around a primitive-shaped object placed on the hand as required. This test measures the impeding effect of the glove when grasping the objects. They include three various sized blocks, a cricket ball, a cylinder block, two various sized tubes, a washer and bolt, a glass, a marble, and a ball bearing. The glove was able to hold 10 out of the 12 objects with a selection of the objects that were held shown in Fig. 9. The glove failed to hold spherical objects, like the marble and glass, due to the squareness of the fingertip covers which could not mould around the shape of the object and keep it in place.

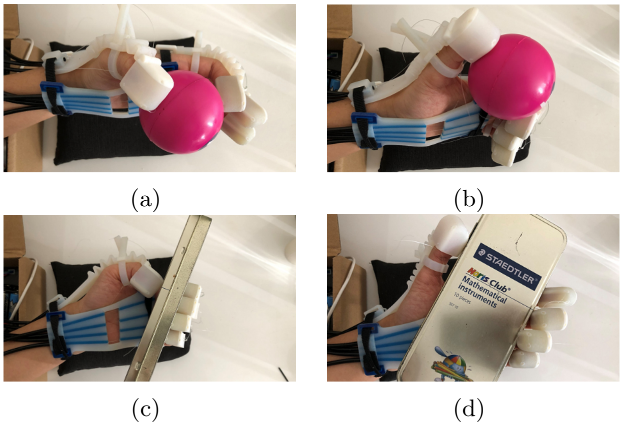


Figure 8: Glove worn by the subject and performing the four grasp types: (a) palmar pinch, (b) lateral pinch, (c) parallel extension, and (d) medium wrap.

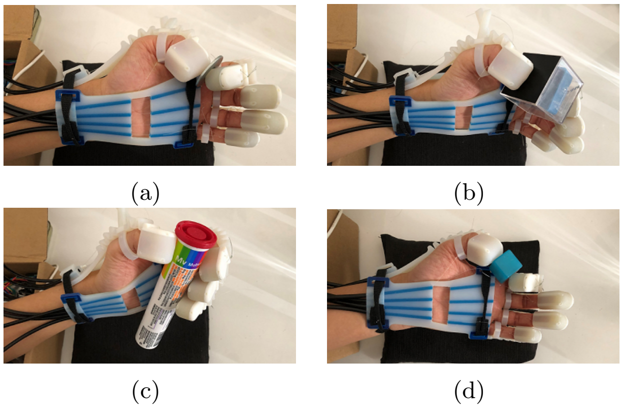


Figure 9: The glove holding different objects: (a) washer, (b) medium block, (c) large tube, and (d) small block.

4.2 Grip Strength

One potential concern with the glove design was that the user's grasp force may be diminished when wearing the glove and impede the effectiveness of the rehabilitation therapy. The test was conducted by asking the subject to grasp the dynamometer with the left hand as strongly as possible for three seconds then relax. Then the subject was asked to wear the glove on the left hand and repeat the same process. This procedure was repeated three times. The subject was able to grasp an average of 12.6 kg without the glove and 8.33 kg with the glove. It was found the fingertip covers of the glove inhibited the full ROM to close their fist.

4.3 Range of Motion

This test aimed to measure the ROM for hand flexion performed by the glove to ensure that the glove can execute all the necessary rehabilitation exercises. A goniometer was used to measure the ROM of each finger at the MCP, proximal interphalangeal (PIP), and DIP joints. The test was conducted by asking the subject to perform a loose fist and the ROM of each finger was measured. Then, the subject was asked to wear the glove and relax their fingers. Each finger was programmed to perform full flexion and the ROM of each finger was then measured and the results are presented in Table 2.

Table 2: ROM of the fingers with and without the glove.

Fingers	Without glove			With glove		
	MCP	PIP	DIP	MCP	PIP	DIP
Index	80	107	60	60	107	40
Middle	85	110	70	60	110	30
Ring	90	107	60	75	107	30
Little	80	95	85	55	85	30
Thumb	-	60	80	-	60	50

5 Discussion

The incorporation of AM in the fabrication of the glove enabled it to be soft, flexible and simple in design, which can be easily fitted and adjusted to different hand sizes. The material of the glove, and the detachable actuation system, also allows it to be easily maintained, an essential factor for clinical use. AM also enabled quick and simple adjustments to be made during design revisions, highlighting its potential for personalisation.

In the grasp type test, the glove successfully demonstrated its capability in aiding the hand to perform rehabilitation exercises. The four most used grasp types and 83% of the objects used in ARAT were achievable by the glove. The test also assumed that the subject had no hand mobility to find the maximum functionality of the glove. This reinforces the glove's objectives to provide assistance for users with low hand mobility when performing regular hand movements.

The main drawback of the glove was the shape and thickness of the fingertip covers. Wearing the glove lowers the ROM of the DIP joint, which affected the subject's grip strength. Another drawback was found when testing the glove's ability to hold circular objects since the shape of the fingertip covers could not contour to the shape of the objects and hold them in place. The fingertip covers were also found to cause the fingertips to heat up due to friction.

6 Conclusion and Future Work

This paper presented the design and prototype of a wearable robotic glove aimed at providing assistance for hand movements to enhance rehabilitation therapy. The design features, testing procedures, and fabrication process of the glove were defined and validated. The glove was able to assist finger flexion and extension to achieve the desired grasping task. The glove design is lightweight, customisable, and simple to use as a result of using AM as the fabrication process. AM enabled flexible design revisions, and facilitated multi-material prototypes to be fabricated quickly. Overall, the glove was able to demonstrate a simplistic design that provided sufficient force to help users with impaired hand mobility to perform finger flexion and extension for rehabilitation therapy.

Future work include improving the fingertip design to improve user comfort and provide better grip when grasping circular objects. Exploring possible tensioning systems for the cables can also improve the reliability of the actuation system.

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