Design and Fabrication of a Three Dimensional Printable Non-Assembly Articulated Hand Exoskeleton for Rehabilitation

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Abstract— **Robotic rehabilitation has proven to be cost-effective in accelerating the rehabilitation process by eliminating the constant need for supervision by a therapist. This work aimed to design and develop a novel three-dimensional (3D) printable non-assembly five-fingered robotic hand exoskeleton for rehabilitation. A single degree-of-freedom (DOF) linkage was designed to actuate each finger with 3 output links that correspond to the three phalanxes of the human finger. We used a parametric modelling approach that suits the dimensions of individual's hand. The fabrication of this dynamic model was achieved by printing the complete assembly including all the driving links, output links, and joints. We manufactured a prototype and developed real-time actuation and control. The reported unique linkage design, combined with parametric modelling and 3D printing technology, will pave the way for mass customization of active assistive and resistive hand exoskeletons.**

I. Introduction

Hand exoskeletons can find rehabilitation applications in post tendon surgery, spinal cord injury, cerebral palsy, and multiple sclerosis. In post tendon surgery, hand exoskeletons can provide controlled active and passive extension and flexion motion to replace braces that use elastic bands, so as to prevent the repair from being ruptured, alleviate adhesions between tendon and sheath, and to offer programmed tendon excursion [1, 2]. In multiple sclerosis, hand exoskeletons can offer active assist in finger incoordination for example playing piano or performing other daily activities [3, 4].

The human hand is an intricately complex structure, consisting of 27 bones, 16 joints with 22 degrees of freedom [5-8]. For the purpose of rehabilitation, a hand exoskeleton should be able to exercise the finger flexion / extension tendons. Hence a hand orthosis should be able to actuate two joints of the thumb, namely the inter-phalangeal joint (IJ) and the metacarpophalangeal joint (MPJ), and three joints of each of the four other fingers, namely the metacarpophalangeal (MCP), proximal-interphalangeal (PIP) and distal-interphalangeal (DIP) joints.

Hand orthoses developed in recent years can be classified into two categories: endpoint interaction devices and exoskeleton devices. In the first category, the devices apply forces to the distal segments of the digits to carry out passive or active planar motion, where the patient's hand is strapped onto a stationary platform [9-12].

In the second category, an exoskeleton acts as an actuated mechanical system that is directly attached to the human hand, and the movements of the exoskeleton and the hand are coupled.

Exoskeleton devices can be direct-driven, cable-driven and linkage-driven, as well as driven by smart materials. In [13], shape memory alloys (SMAs) were used to drive a one-joint finger providing compact and simple solutions; but SMAs are not able to provide enough torque and are sensitive to temperature and humidity variation.

In direct-driven, each independent joint is driven by one motor that is mounted in-line with the joint [14, 15]. For a three-joint finger, the masses and volumes of three motors make the device heavy and bulky.

Cable-driven fingers effectively reduce the weight and dimensions by mounting the motors to a base (usually the palm) [16]. However, cable-driven fingers suffer from several drawbacks. First, two motors are required to actuate one joint due to pulleys only exerting force when under tension. If each finger is to have three independent joints, six motors are needed, resulting in a bulky device and complicated cable-routing system. Second, controlling the preload of cables is expensive throughout the device life cycle due to friction losses between the cables and pulleys and sheaths.

Linkage-driven fingers, where actuators are mounted to a base (usually the palm or the forearm), represent the future of hand exoskeleton. This design offers several advantages, especially regarding the assist-as-needed (AAN) control: high back-drivability, high force compliance, high bandwidth, low apparent inertia, and high force amplification rate.

Though linkage-driven fingers have been used in robotic hands, their application to rehabilitation still presents substantial challenges, because the majority of robotic fingers use compliance to deal with the enveloping grasp. Of the three finger joints, the DIP joint is actuated by passive spring. This design cannot be applied to hand rehabilitation, where all the three joints have to be actively actuated [17].

When the number of output links is three, some hand exoskeletons use three actuators for each finger, such as the 16-link finger linkage [18] and the four-fingered 18-DOF device [14]. However, the manufacturing and actuation

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cause substantial problems for these designs, and the weight and size poses another major issue, not to mention the incurred high cost.

Some other hand exoskeletons use two actuators for each finger, such as the 12-link finger linkage that consists of five planar mechanisms [19] and the glove with a supporting structure [20], the four-bar mechanism joint [21], and the 6-bar linkage [22]. Other designs see the PIP and DIP joints are coupled; thus, a four-bar linkage is used to drive the two joints. Each finger, however, still needs two actuators [23, 24].

Ideally, each finger is to have three output links driven by a single actuator, and the ranges of motion of the three output links cover the whole range of the human finger motion. This multi-objective design poses a substantial challenge to the robotics community. Some researchers designed fingers with only two active joints [25]. Another example is the 8-bar linkage 2 joint finger mechanism [26], which is confined to the back of the hand and successfully produces the desired angles and positions of the MCP and PIP joints.

The widespread use of 3D printers partially solves the fitting problem of a hand exoskeleton. The Exohand, which has all the principal physiological DOFs of a human hand, is customized to fit the hand of the individual user by being manufactured from polyamide in the selective laser sintering (SLS) process[27].

The preceding analysis revealed that linkage-driven fingers are most suits the needs of developing AAN training and customizable hand orthoses can solve the fitting problem without the intervention of specialists. Novel 3D printed hand orthoses, each of whose fingers is driven by one actuator and has three output links, have yet to be invented.

II. A Novel Single DOF 8-Bar 10-Joint Hand Orthosis with Three Output Links

A. *Overview of the Hand Orthosis*

Feasible planar linkages of one DOF for hand exoskeleton have been investigated by applying the Grubler's formula [28, 29]. The types include 6-bar 7-joint, 8-bar 10-joint, 10-bar 13 joint, 12-bar 16-joint, etc. With the increase of the number bars and joints, design and manufacturing become more difficult.

We designed the hand orthosis to have the simplest mechanical structure without scarifying functionality. Each of the index, middle, ring, and pinky finger consists of a single DOF 8-bar 10-joint linkage with three output links. The thumb consists of a single DOF 6-bar 7-joint with two output links. This yields a portable and self-contained system, allowing the patient to carry it around to practise daily activities, as in Fig. 1.

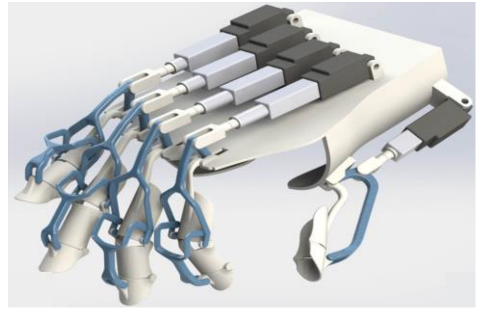

Figure 1. The simplest hand exoskeleton that exercises 14 joints of the human hand

This approach is unique in that each finger has three output links that corresponds to three phalanxes of the human finger. The number and specific finger can be printed according to the specific problems of the patient. In addition, the mechanism is confined to the dorsum of the hand allowing the mechanism to be manufactured with minimal size and minimal sensory feedback interference. Combined with the intended location of the linear actuators (back of the wrist/arm), this design allows the device to be constructed with low apparent inertia to the intended subjects so that we may maximally exploit the high bandwidth and force controllable ability of the linear actuator.

This hand exoskeleton differs from traditional approach in the following aspects. First, we adopted the parametric design for all the parts. We measured the parameters, including the length of each phalange, of the human hand. We then used 3D design software, SolidWorks 2014, to generate all the parts that would be used for the hand exoskeleton to match this individual user, as in Fig. 2.

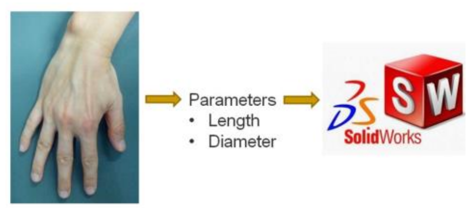

Figure 2. The parametric design of the hand orthosis

Second, we designed the model to be 3D printable. Hence we were able to print the complete hand exoskeleton, including all the links and joints. Our design was optimized for a Projet® 3510 HDPlus that has a 16-micron print resolution with the VisiJet plastic materials that are UV-cured with melt-away white wax as support material [30]. Actuators were then attached to the 3D printed hand orthosis, as in Fig. 3.

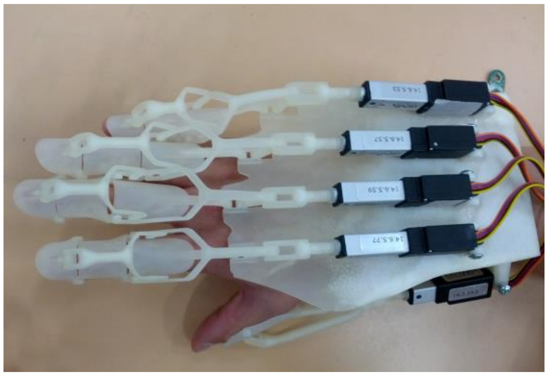

Figure 3. A 3D printed prototype of the hand orthosis

B. *Finger and Thumb Mechanisms*

The mechanism that drives the index, middle, ring, and pinky fingers is an 8-bar 10-joint single DOF linkage, as in Fig. 4, where each circle in red colour represents a revolute joint and a double-ended arrow represents a prismatic joint. The joints J_9, J_8, and J_5 correspond to the DIP, PIP, and MCP joints of the human finger respectively.

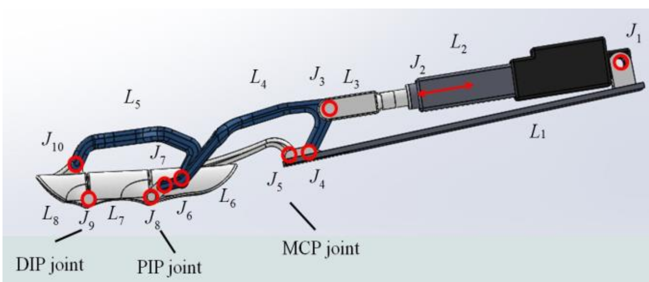

Figure 4. A single DOF 8-bar 10-joint linkage to drive each finger in fully extended and closed configurations

The mechanism that drives the thumb is a single DOF 6-bar 7-joint linkage, as in Fig. 5. The joints J_5 and J_6 correspond to the IJ and MPJ joints of the human thumb respectively.

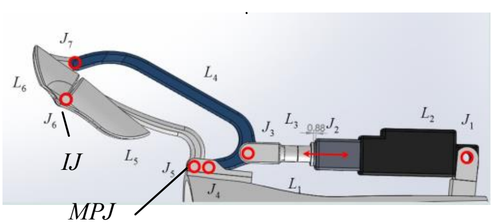

Figure 5. A single DOF 6-bar 7-joint linkage to drive the thumb

A demonstration video can be viewed at https://youtu.be/1PmYrq2B26A

III. ACTUATION AND CONTROL

We aimed to produce a compact/portable device by using an Arduino Mega microcontroller [31] and Firgelli P-series L12 servo linear actuators that have inbuilt encoders to provide the absolute positon feedback [32].

A control unit was constructed to house the motor divers, microcontroller and 12V battery. Intelligent control of the robotic hand orthosis was achieved through a combination of embedded systems programming on the Arduino microcontroller.

Traditionally the manipulation of actuators though a graphical user interface usually involves using dials and slider, however this approach in not intuitive and provides little feedback on the front end. A sophisticated graphical interface was developed with the ability to manipulate the exoskeleton by using the application programming interfaces from SolidWorks. Positions of each motor could be extracted and sent over serial ports to manipulate the physical model in near real time. Furthermore the ability for therapists to record and replay movement patterns tailored towards patients was added in the interface. This was achieved by monitoring and recording the set points of the orthosis in the 3D model and simply looping though and repeating these positions until the program was stopped.

IV. DISCUSSIONS AND FUTURE WORK

The parametric modelling approach allows the dynamic customization of the exoskeleton to adapt to individual's anthropometric differences and the number of fingers involved. However, we designed and manufactured this reported version by manually measuring the human hand and entering the parameters into a text file. Future work will involve software development that automatically extracts the dimensions of the hand from a 3D scan and outputs the dimensions into a text file, aiming to automate the entire design and manufacturing process.

The shapes and parameters of the driving links determine the maximum force/torque applied to each finger joint. The first prototype showed in Fig. 3 is still not robust enough to be used in real rehabilitation. We are currently using finite element analysis to optimize each driving link to achieve proper torque output at each joint without scarifying the portability and lightness of the device.

Currently no force feedback is possible using the existing infrastructure; therefore future work would involve development of a closed-loop force control algorithm. This could be achieved by mounting force sensors on each finger or mounting a strain gauge on the piston of the linear actuator. By maintaining a force set point, the device can detect the intended motion of the patient and therefore provide assistance of the intended movement. Furthermore as the force set point can be adjusted using a potentiometer the device can be calibrated for patients with varying degrees of impairment or be adjusted according to each stage of rehabilitation.

The control unit was made using a breadboard and Arduino microcontroller. However in future revision of the design a printed circuit board could be manufactured that compacts the control unit down to a size to easily fit on the anterior surface of the hand. This control unit would contain both the circuitry and actuators and could be attached onto any printed orthosis. By doing so the orthosis will become a single standalone device allowing it to adapt to a variety of different post-surgical situation.

The thumb linkage only provides flexion/extension of the inter-phalangeal joint and metacarpophalangeal joint. A spatial linkage for the thumb would need to be developed if thumb circumduction is included.

V. Conclusions

This work demonstrated a cross-disciplinary approach to design and develop a novel hand exoskeleton for rehabilitation. The combination of a parametric design and 3D printing resulted in a customizable hand exoskeleton adapted to individual's anthropometric differences. A novel single DOF 8-bar 10-joint linkage with three output links was invented for finger actuation, yielding a simple and compact device. This cross-disciplinary approach meets the challenge of mass customization of active hand exoskeletons.

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