Compact Design of A Lightweight Rehabilitative Exoskeleton for Restoring Grasping Function in Patients with Hand Paralysis

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Research

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Abstract

Background

Millions of individuals suffer from upper extremity paralysis caused by neurological disorders including stroke, traumatic brain injury, spinal cord injury, or other medical conditions. In order to restore motor control and enhance the quality of life of these patients, daily exercises and strengthening training are necessary. Robotic hand exoskeletons can substitute for the missing motor control and help to restore the functions performed in daily operations. They can also facilitate neuroplasticity to help rehabilitate hand function through routine use. However, most of the hand exoskeletons are bulky, stationary, and cumbersome to use.

Methods

We have utilized a recent design of a hand exoskeleton (Tenoexo) and modified the design to prototype a motorized, lightweight, fully wearable rehabilitative hand exoskeleton by combining rigid parts with a soft mechanism capable of producing various grasps needed for the execution of daily tasks. We have tested the performance of our developed hand exoskeleton in restoring hand functions in two quadriplegics with chronic cervical cord injury.

Results

Mechanical evaluation of our exoskeleton showed that it can produce fingertip force up to 8 N and can cover 91.5 degree of range of motion in just 3 seconds. We further tested the robot in two quadriplegics with chronic hand paralysis, and observed immediate success on independent grasping of different daily objects.

Conclusions

The results suggest that our exoskeleton is a viable option for hand function assistance, allowing patients to regain lost finger control for everyday activities.

Background

Many people around the world suffer from hand function impairment caused by neurological disorders such as stroke [1], traumatic brain injury [2], and spinal cord injury [3], which limits their ability to perform basic daily activities. Due to the rehabilitation plateau of these individuals the remaining ability of the hands are not expected to further increase, despite undertaking conventional procedures to regain hand function such as orthopedic surgery, medicine, or physical and occupational therapy [4]. Therefore, these individuals live with their remaining abilities and by compensatory techniques to complete everyday activities. Additionally, assistive tools such as feeding utensils, key turners, and writing devices are often used by these individuals to improve independence and safety in activities of daily living (ADL) [5].

By enhancing the efficiency on practical gripping capabilities, wearable robotic hand exoskeletons increase the user's independence [6]. In recent years, robotic technology has been adopted for physical rehabilitation to provide enhanced treatment and comprehensive recovery of these individuals [7]. Different robotic systems for the upper limb have been recently introduced especially to the acute and chronic stroke survivors. By powering the hand movements to accomplish everyday activities, assistive exoskeletons have shown the ability to improve the quality of life in patients with cervical cord injury [8]. However, these robotic systems like Hand of Hope [9], FESTO (FESTO, Esslingen, Germany), Milebot (MileBot, Hand Rehabilitation Exoskeleton Robot, Shenzhen, China), Handy Rehab (HandyRehab, Hong Kong, China) and etc. are very bulky and cumbersome to use.

Over the last two decades significant research has been conducted to design and develop upper-limb wearable exoskeletons for rehabilitation purposes [10]. The technology is however still challenging in the areas of mechanism design, sensing, and human-robot interaction, despite the strong efficiency and growing market for upper-limb exoskeletons. Some of the important aspects of designing an ergonomic exoskeleton device are mechanical architecture and kinematic analysis [11]. Exoskeletons for assistive hands in the current state-of-the-art often used rigid connection mechanisms. Mechanical links are used in linkage-based devices to create finger-flexion-like motions through kinematic chains [12]. Since forces, especially force directions, can be precisely controlled, this is advantageous for safe interaction. However, rigid link structures have a low degree of conformity and a high form factor by their very existence [5]. One of the most common actuation mechanisms embedded in soft exosuit is a tendon/cable-driven

mechanism, which typically involves several actuators [13, 14]. Such mechanisms are naturally lightweight and low-profile. However, the applied forces, especially the force directions, are difficult to manage correctly, posing a danger to the user [5]. A pneumatic actuator could save significant weight while producing high torque. However, this type of actuator adds more complications to the controller's design. Furthermore, heavy pumps and/or compressed gas tanks, can compromise the system's portability, oil/lubricant contamination may occur, and downtime/maintenance is increased [5, 15]. Hydraulic actuators may be able to meet the need for even more torque production, especially for augmenting human capabilities. Its control is less accurate than electric motors, similar to pneumatic actuators, and incompressible liquid from a pump may contaminate the whole device, jeopardizing protection [15]. Because of the difficulty and flexibility of the human hand, choosing the mechanism and type of actuators to create robotic exoskeleton to handle and assist hand movements is still a big challenge.

In the present study, by modifying the design of a recent exoskeleton developed by Bützer et al. (2021), we prototyped an advanced compact, cost effective, lightweight, fully wearable rehabilitative hand exoskeleton. First, we designed the finger mechanism with a strong focus on safety, convenience, and usability in everyday life then completed the exoskeleton and tested the performance of our system in terms of grip types, range of motion (ROM), fingertip force and weight. Finally, we tested usability in everyday life, including convenience, safety, and weight, and looked into the immediate impact on the functional ability of two individuals with neuromotor hand impairments with chronic cervical spinal cord injury (SCI). At the end, we compared our exoskeleton to similar works, highlighting the benefits and limitations.

Methods

I. Design

A. Design Requirements for exoskeleton

Among patients with various neuromotor disorders (e.g., SCI, stroke, and brachial plexus injury), the form and level of necessary assistance for everyday activities varies significantly in the presence of spasticity, contractures, muscle tone, and joint stiffness in the hand [5]. Hence, in the present study, we tried to design the exoskeleton in a way that most individuals can use it in daily activities. In this section, from the literature, studies, and functional tests with previous designs in patients with neuromotor hand impairments, we extracted detailed criteria for the design case. By considering the following requirements, we proposed a useful device for patients.

Types of the functional grasping: Vergara et al. [16] and Bullock et al. [17] found that we need four grasping tasks (palmar pinch, medium wrap, parallel extension, and lateral pinch [denomination of Feix et al. [18]] and a flat hand in order to perform over 80% of all grasping tasks in everyday life.

Range of motion (ROM): Bain et al. [19] found that the functional range of motion of the fingers, to perform 90% of the activities are 19° – 71° , 23° – 87° and 10° – 64° at the metacarpophalangeal (MCP), proximal interphalangeal (PIP) and Distal interphalangeal (DIP) joints respectively. Feix et al. [18] examined current human grasp taxonomies and combined them into a new taxonomy known as "The Grasp Taxonomy." They demonstrated the thumb's important function in performing different grasping types, by rearranging grasps according to the thumb's Adduction-Abduction motion [20].

Grasping force: The human hand's functional use is needed for a wide range of daily tasks such as grasping objects, feeding, dressing, and washing. Bützer et al. [1] discovered that 10 N of fingertip force is needed to lift items weighing up to 1 kg, such as water bottles (to drink).

Weight: It is important to create a lightweight exoskeleton in order for the user to find it more comfortable to wear. Other hand exoskeletons usually weigh between 300 g to 5 Kg [5, 21].

Safety: At all times, a hand exoskeleton must ensure the user's safety. The exoskeleton's mechanical and control mechanisms must account for normal finger joint motions and hand size. Furthermore, mechanical limitations must ensure that finger joints are not subjected to excessive pressures [22].

Comfort: Since the user must wear the brace during activity, a hand exoskeleton must be convenient for the user. The device's kinematics and ergonomic nature must ensure that it does not induce discomfort or exhaustion [12].

B. Three-layered sliding spring mechanism

The main mechanism for gripping movements and providing the necessary fingertip force is the flexion/extension of the fingers and it is challenging to develop a mechanism which can mimic the finger flexion and extension. Inspired by the exoskeleton developed by Bützer et al. [5], to design a lightweight exoskeleton, we used 3 layered sliding springs (Fig. 1) to imitate human finger flexion and extension.

The mechanism is composed of two main parts: blades and solid bodies (Fig. 1A). On top of the fixed spring blade, two sliding springs are placed. The relative length of the springs changes as the sliding spring is moved, resulting in spring bending. Bending can be localized in three parts together with the springs using rigid elements linking the two springs, resulting in a final motion that mimics the flexion/extension of a human finger (Fig. 1B-C).

We have designed a V-shape configuration (Fig. 2) with two angled sliding springs, to produce the desired fingertip force with the three-layered sliding spring mechanism.

The required torque in the joints in the three-layered sliding spring system increases with finger length for a given fingertip force. A higher torque can be achieved to produce adequate fingertip force by increasing the moment of inertia I_x of the rectangular profile of the springs.

$$I_x = \frac{w * t^3}{12}$$

Where t thickness and w is width of the blade.

By increasing t or w , I_x increases, which allows us to produce more fingertip force. The sliding spring blades' width and thickness have rotated by an angle $\theta=35^\circ$, so that the moment of inertia in the spring blade axis $I_{x'}$ remains constant while the moment of inertia perpendicular to the finger flexion/extension plane I_x increases. Also, blades have distance (d) with the axis of rotation (x - y) which we considered in our final equation $I_{x''}$ (Fig. 2C):

$$I_{x''} = \cos^2(\theta) * \frac{w * t^3}{12} + \sin^2(\theta) * \frac{w^3 * t}{12} + wt(d)^2$$

We utilized cold rolled stainless steel strips (grade 301, Jiangyin Transens Metal Products Co., Ltd., Jiangsu, China), with more than 1700 MPa tensile strength and hardness between 557–600 HV, for spring blades and used 3D printers to produce rigid bodies (black nylon material, VPrint 3D, Hong Kong). In the finger mechanism, we used 2 blades with 4 mm width and 0.3 mm thickness as sliding blades and 6.5 mm width and 0.2 mm thickness stainless steel strip as a fixed blade.

C. Finger mechanism

To assist the users with finger flexion and extension, we designed a finger mechanism for each finger by using a lead-screw mechanism to push and pull the sliding blades (Fig. 3). This mechanism consists of a motor with an M3 screw on it, a lead, 3D printed parts, and blades (Fig. 3A). We connected the blades to the lead and installed brass threaded insert (Shenzhen Huaxianglian Hardware Co., Ltd., Guangdong, China) into the lead in order to make it move forward and backward with the motor shaft rotation (Fig. 3B).

According to the previous study [5] of the evaluation of maximum fingertip force in the function of the input force, we assumed that the required input force to make the blades slide and produce necessary fingertip force is about 60 N. To identify suitable motor for our mechanism we used following equation:

$$T = F * \frac{Dm}{2} \left(\frac{L + \mu * \pi * Dm}{\pi * Dm - \mu L} \right) + \left(\frac{F * Dm * \mu}{2} \right)$$

Where T is torque, D_m pitch diameter of screw, L lead and μ coefficient of friction.

Based on the equation above, we utilized a 12v DC motor (Shenzhen Sinlianwei technology co. LTD, Shenzhen, China) with the stall torque of 1.2 Kg.cm and angular speed of 800 rpm to move the blades and make the mechanism bend.

D. Thumb abduction and adduction

The function of thumb is extremely crucial in hand activity, especially in ADLs that require gripping or pinching. The thumb must be able to abduct and adduct as well as be used in pad opposition (e.g., precision pinch) or side opposition to perform these more commonly used grip forms (e.g., lateral pinch). The thumb mechanism of our exoskeleton is divided into two main motions. To perform flexion and extension in the thumb, we used the same 3 layered mechanisms, whereas, to execute abduction and adduction, we connected the thumb to the main body in such a way that it has rotational motion in the carpometacarpal (CMC) joint (Fig. 4A). By using a spring blade which has the ability to rotate around the point where it is connected to the thumb (Fig. 4B) and a slider which is moved by a small geared motor (Fig. 4C) with stall torque of 1.3 Kg.cm and rotational speed of 148 rpm (Fuzhou Bringsmart Intelligent Tech. Co., Ltd, Fuzhou, China), we produced a force on the rigid body of the mechanism, near the MCP joint that made the thumb mechanism rotate around the CMC joint to mimic abduction/adduction motion (Fig. 4D).

To move the slider, we used two strong fishing wires (wires were mounted in such a way that they passed through the grooves created in the main body to move the slider) connected to the slider and the motor. The blade was almost fully within the main module while the thumb was abducted (Fig. 4D situation I). When the slider was moved by a motor, the spring blade was pushed out of the main body and abducted the thumb (Fig. 4D situation II and III).

E. Ring and little finger mechanism

We removed the finger mechanism for the little finger in order to have space in our exoskeleton to place a small motor to move the slider for thumb abduction and adduction. Instead, we created an extra part that was connected to the ring finger mechanism allowing to bend the little finger alongside with the ring finger (Fig. 5).

F. Hand fixation

To apply as little pressure to the intrinsic hand muscles as possible when wearing the robot and securing the user's hand and fingers, we used straps for each finger (Fig. 6I) and one wide strap in the palm parallel to the abductor pollicis brevis muscle (Fig. 6II). We also recommended the patients wear cotton gloves underneath the robot for more comfort.

G. EMG control

Control commands for the actuators of our hand exoskeleton is taken from surface EMG signals. The EMG signals can be recorded by surface electrodes placed on different arm, hand and shoulder muscles based on each individual's residual motor condition after a cervical cord injury [23]. For instance, a C5 injury preserves innervation of shoulder and elbow flexors while C6 injury spares wrist extensors and C7 injury spares elbow extensors.

EMG electrodes are interfaced with a low noise instrumentation amplifier (INA128, Texas Instruments Inc., Dallas, USA). EMG signals are then filtered (10–500 Hz Bandpass) and amplified ($\times 1000$) by an operational amplifier (OPA188, Texas Instruments Inc., Dallas, USA) before digitized by a microcontroller (STM32F103, STMicroelectronics, Geneva, Switzerland) for real-time bio-signal processing (Fig. 7) to distinguish the most possible intended hand motion (i.e. hand opening or closing). For bio-signal processing, a linear envelope detection strategy is applied where the EMG signal is first rectified ($|X_i|$) and then smoothed using following equation:

$$MA_n = \frac{\sum_{i=1}^n D_i}{n}$$

Where, n is the number of periods in the moving average and D_i demand in period i .

The control strategy for grasping is based on the maximum voluntary contraction (MVC) signals and is triggered by an adjustable threshold. When the EMG amplitude crosses the preset MVC value, a trigger is sent to the driver circuit (DRV8833, Texas Instruments Inc., Dallas, USA) to run the motors to execute a grasping or hand opening function (Supplementary video 1).

II. Experimental methods

A. Measuring the types of grasping and the ROM of hand exoskeleton

Each joint of our hand exoskeleton is designed to flex to a maximum of 70 degrees in order to achieve the necessary range of motion. However, the length of the sliding blades, limits the total flexion. Hence, we measured the average finger flexion/extension angle to assess the ROM of the fingers. To evaluate finger mechanism, first we tested it on a healthy individual (male, 25 years old, right-handed). The participant's finger was in relaxed status and the mechanism performed the finger flexion and extension from the original position (finger was in extended position) to the flexed position. Next, we evaluated the exoskeleton for different grasping types. We tested the functionality of the executable grasp types by asking the study participant to grasp a number of objects with the assistance of the exoskeleton. We chose objects which are used in daily activities, such as a spoon, bottle of water, paper cup, pen, cellphone, and key (Fig. 8).

B. Fingertip force measurement

To evaluate the output force produced by finger mechanism, we tested the mechanism in a custom benchtop setup (Fig. 9). After the finger mechanism of the exoskeleton was completely assembled, we fixed the finger mechanism and a load cell on the test bench (Hunan Tech Electronic co., LTD., Changsha, China) with two plates and an interface board (Arduino Uno, Arduino LLC, Italy). To make the mechanism flex and measure the output force, we attached power supply to the motor of the finger mechanism. We then measured the fingertip force for different input voltages (5–12v).

C. Measuring the dimension and specifications of the finger mechanism and whole exoskeleton robot

To make the exoskeleton portable and comfortable, the robot should be small and lightweight. In order to evaluate the size and weight of the robot, after evaluating the fingertip force and ROM, we measured the size and the weight of the exoskeleton.

D. Test on end users

Two chronic quadriplegics with cervical cord injury evaluated the hand exoskeleton device for normal ADL and functional tasks. Both participants had lesions at around C5-C6 cervical level (American Spinal Injury Association Impairment Scales: A and C) and were male with an average age of 32.5 ± 10.6 , injured over 2 years. Both participants had severe hand impairments and could actively flex and extend their fingers.

In order to control the robot by the study participants, we first evaluated their forearm EMG signals. We connected the EMG electrodes on the patients' hand and recorded the EMG signals using an oscilloscope. We then programmed the microcontroller based on their EMG and assessed the robot's ability to help the grasping functions. In the test, 5 objects (Fig. 8) were used to emulate daily activities such as picking up a key, self-feeding, and holding objects such as a bottle, pen, cup and a spoon. The participants were first asked to grasp the objects without the help of the exoskeleton and later with the assistance of the exoskeleton.

Results

A. ROM and types of grasping

We designed the finger mechanism in a way that each joint is able to flex up to 70 degrees in order to accomplish the needed range of motion. However, the entire flexion is limited by the length of the actively moving spring. The bending motion with and without the finger mechanism were measured in the same experimental setup to compare to the human natural bending motion. On the human finger the maximum angles to grasp key, observed were $60 \pm 3^\circ$ at the MCP, $35 \pm 3^\circ$ at the PIP and $25 \pm 3^\circ$. As a result, we measured

the overall finger flexion/extension angle and found that the maximum flexion in the MCP, PIP, and DIP joints was 50, 32.5, and 9 degrees, respectively (Fig. 10).

B. Fingertip force

The force produced by the finger mechanism is very important since the robot should produce enough force to help patients to grasp and lift objects. For self-feeding the needed force to hold and lift a bottle of water weighing 1 Kg, the robot should produce at least 10 N fingertip force. To evaluate the force produced by the exoskeleton, we measured the maximum fingertip force of the index and middle finger mechanism. Figure 11, illustrates that the maximum force produced by the mechanism in 12v was around 8 N.

C. Size and weight of the exoskeleton

After assembling the exoskeleton, we measured the size and weight of the robot. Since we used 3D printing technology and also utilized 3 layered sliding blade mechanisms to mimic finger flexion and extension, the final exoskeleton weight was 228 grams. The size of the main body, including the index, middle, and ring finger mechanism, was 190 × 85 × 25mm and the size of the thumb mechanism was 130 × 17 × 15mm.

D. Users’ performance

Both of our study participants had chronic hand paralysis unable to do ADL independently, and hence required significant assistance for daily living. We found that their flexor digitorum superficialis and extensor digitorum muscles still had residual EMG activities during volitional intent of finger flexion and extension even though they could not move their fingers significantly. Both participants were asked to clinch their fists for 3 seconds (Fig. 12, gray area) and then relax their hands. Figure 12 shows the forearm muscle activities of these study individuals during intention of opening and closing their hand. We used these forearm EMG signals to control the hand exoskeleton.

We then evaluated these users for accomplishing daily tasks such as self-feeding, operating the key and holding different objects with different shapes and sizes. We found that both users were unable to grasp and hold most objects regardless of their size or weight (Table 1). However, when fitted with the robot exoskeleton, both participants succeeded in holding and operating all the object including the one that they could hold without the hand exoskeleton (Table 1). Furthermore, our tests indicated that the exoskeleton could assist in performing the four most used grip types: palmar pinch, medium wrap, parallel extension, and lateral pinch.

Table 1. Users’ grasping performance without and with exoskeleton

Item No.	Object	Weight (g)	Patient 1		Patient 2	
			Without Exo.	With Exo.	Without Exo.	With Exo.
1	Key	11.5	✓	✓	✗	✓
2	Pen	6.8	✗	✓	✗	✓
3	Paper cup	9.5	✓	✓	✓	✓
4	Spoon	3.7	✗	✓	✗	✓
5	Bottle of water	500	✗	✓	✗	✓

✓: Individual could grasp and hold the object. ✗: Individual could not grasp and hold the object.

Discussion

Similar to the robot developed by Bützer and colleagues [5], in our design, we used a V-shaped 3-layered spring blades mechanism. We, however, eliminated the cumbersome cables mechanism to allow the robot to be compact and lightweight. In addition, we included a versatile mechanism to perform thumb abduction and adduction movements to assist users in executing the most frequently utilized grasp types. Our design is comparable to the other existing hand exoskeletons (Table 2). The mechanical evaluation of the finger mechanism showed that our design can provide a functional range of motion by bending the user's finger up to 91.5 degrees in 3 seconds. Also, the finger mechanism can produce up to 8 N fingertip force which can help the user to grasp and lift objects such as keys, paper cop, spoon, a full 500 mL water bottle etc. (Supplementary video 2). We also showed that the exoskeleton presented in this study can assist users, especially individuals with cervical SCI, in daily activities immediately after wearing it. Hence, no pre-training is needed.

Table 2
comparison of recent exoskeletons with our exoskeleton

Exoskeleton	DOF	Number of actuators	Actuators	Transition	ROM	Controller	Type of control	Maximum Fingertip force (N)	Weight (gr)
Our Design	5	5	DC motor	three-layered sliding spring mechanism	Up to 91.5 degrees	Arduino	EMG sensors	Up to 8	228
RELab tenoexo [5]	3	2	DC motor	three-layered sliding spring mechanism	Up to 105 degrees	Arduino Yun Mini	EMG	6.4	148
Hand of hope [9]	5	5	Linier DC motor	Rigid Links	Up to 120 degrees	N/A	EMG	N/A	500
Flexo-glove [24]	4	4	DC motor	Tendon-driven	N/A	ATmega2560 microcontroller	EMG	22 N pinch force, 48 N power grasp force	330
Mano [25]	5	5	Servomotor	Bowden cables	70% of normal hand ROM	Arduino Mega 2560 Rev3	EEG	20	50
Exo-Glove Poly [26]	2	2	DC motor	Tendon-driven	~ 164	Micro controller (TMS320F2808)	Analog switch	10.3	104
HandMATE [27]	5	5	Linier actuator	Rigid links	~ 190 degrees	Teensy 3.6 microcontroller	Custom Android app	~ 2.45	340
N/A: Not Available									

However, one of the main limitations of our design is the control system. It utilizes simple linear envelope of surface EMG signal which can be variant between the users and thus need individual adjustments. In the future, a more advanced EMG classification such as artificial intelligence can be implemented to allow more reliable control to individual fingers or the robot. Another limitation maybe the fingertip force which is expected to be 10 N to lift items weighing up to 1 Kg [5] whereas our finger mechanism of the robot currently produces up to 8 N.

Conclusion

In this article, we presented a modified design of a lightweight wearable hand exoskeleton to improve grasping function of patients with hand paralysis. We tested the exoskeleton on two participants with severe hand impairments and evaluated the functionality and usability of the robot in the ADL. The results strongly support the functionality restoration and usability of the robot in performing daily activities.

Abbreviations

ADL: activities of daily living, ROM: range of motion, SCI: spinal cord injury, MCP: metacarpophalangeal, PIP: proximal interphalangeal, DIP: Distal interphalangeal, CMC: carpometacarpal, MVC: maximum voluntary contraction

Declarations

Ethics approval

All the experimental procedures in the current study, were in accordance with the guidelines and approval of the Human Subjects Ethics Sub-committee of The Hong Kong Polytechnic University.

Consent for publication

Not applicable.

Available of data and material

The datasets of the experiments in the current study are available from the first author on request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

VN and MA designed the study. MP, YP and MA conceived the experiments. VN performed the experiments. MA supervised the project. VN and MA analyzed the data and wrote the manuscript. All authors read and approved the final manuscript.

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Figures

Figure 1

A) Three layered spring blade mechanism utilized for finger flexion and extension. The main finger mechanism consists of stainless-steel spring strips (two sliding spring blades on top of one fixed blade) and solid bodies. B-C) The relative length of the springs changes as the sliding spring is moved, resulting in spring bending. The motion mimics the flexion/extension of a human finger.

Figure 2

A) Finger flexion/extension plane, which finger mechanism rotate based on this plane. B) The cross-section area of the finger mechanism and arrangement of the blades. C) Needed axes and dimensions to calculate the moment of inertia of the sliding blades.

Figure 3

A) Lead screw mechanism used to push and pull the sliding blades. the mechanism consists of one DC motor with M3 screw on it and Lead. B) A brass threaded insert is installed into the lead to allow it to move forward and backward with the rotation of the motor shaft.

Figure 4

Thumb abduction and adduction will help patients to perform up to 80% of daily activities by executing 4 main grasping types. A) The thumb mechanism is connected to the main body in such a way that we have rotational motion in the CMC joint. B) The blade, which pulls and pushes the thumb finger mechanism, has the ability to rotate around the point where it is connected to the thumb. C) By using a spring blade and a slider which is moved by a small geared motor, we produced a force on the rigid body of the mechanism near the MCP hand joint to perform thumb abduction and adduction. D) When the slider is within the hand module, the thumb is completely adducted (Situation I). When the slider is moved, the spring is pushed out of the main body of the robot and then by a pushing mechanism makes the thumb abduct (Situation I & II).

Figure 5

To bend the little finger, an extra part was attached with the ring finger mechanism.

Figure 6

Straps for each finger mechanism (I) and one wide strap in the palm parallel to the abductor pollicis brevis muscle (II) was used in the exoskeleton.

Figure 7

Schematics of EMG control module. EMG signal is preamplified by an instrumentation amplifier then filtered and amplified by the operational amplifier before digitized by a microcontroller. After detecting the envelope, control triggers are sent.

Figure 8

A key, pen, paper cup, spoon, and bottle of water were used to test the functionality of the hand exoskeleton.

Figure 9

Benchtop setup for measuring fingertip forces as a function of voltage. A variable power supply (not shown) was used to apply different voltages to the motor, and a load cell was used to measure the fingertip force.

Figure 10

The overall finger flexion/extension angle was measured, and the maximum flexion in the MCP, PIP, and DIP joints, respectively, was 50, 32.5, and 9 degrees.

Figure 11

The result of fingertip force measured for the index and the middle fingers at 5 to 12 voltages.

Figure 12

Flexor digitorum superficialis and extensor digitorum muscles activities of two participants during intention of opening and closing their hands. The Gray box illustrates the muscle activities during 3 seconds of contraction.

Supplementary Files

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