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Hemiplegia Patients Hand Rehabilitation Robot

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ABSTRACT

A hand rehabilitation robot (Medical training system) can be used for hemiplegia patients to recover hand joints' movement and assist in bending or stretching of each finger. Through the control system, it realizes a variety of movement forms to help single or multiple fingers for rehabilitation treatment. This essay is divided into three main sections. The first section describes the pathology of hemiplegia, as well as the process of rehabilitation in Rehabilitation Medicine and the Hand Rehabilitation Robot that can be used to assist physicians in the rehabilitation process. In the second section, it experimentally ascertains the trajectory of hand movements, along with identifying the maximum and minimum achievable angles for each joint of the hand. In the third section, it shows the design process of the Hand Rehabilitation Robot. During this phase, particular attention is given to the design of the connection rod, aligning it with experimentally derived maximum and minimum measurements. This approach aims to optimize the rehabilitation effect. Simultaneously, the development of the electronic control system is undertaken, facilitating precise and accurate control over the robot's functionalities. Finally, through the experimental study, it verifies the feasibility and reliability and can basically meet the hemiplegic patient's clinical rehabilitation needs.

Background and Significance

Due to economic and technological advancements, the issue of an aging population has escalated into a significant concern. In 2015, the World Health Organization (WHO) noted that there are 12.24% of the global population over 60 years old. This percentage is increasing year by year. The incidence of stroke is high in the aging population is 11.2% (World Health Organization, 2015). Among this aging population, there are many older adults suffer from Cerebral Vascular Accident (CVA). CVA is a group of acute cerebrovascular circulatory disorders caused by different etiologies. It may cause persistent localized neurological deficits in the cerebral hemispheres or brainstem, and its morbidity, mortality, and disability rates are remained high. Patients with stroke disease can present with a variety of neurological deficits, with hemiparesis and motor deficits being the most common. According to the China stroke surveillance report in 2019, the number of new stroke patients in China is about 2.5 million per year. By 2020, the number of stroke patients in China will reach 20 million people. In America, about 7.2 million Americans ≥ 20 years old have had a stroke. Approximately 800,000 people in the United States have a new or recurrent stroke each year. Data from 30,239 participants in the REGARDS cohort study (Reasons for Geographic and Racial Differences in Stroke) showed that 22.5% of the population >45 years old reported stroke symptoms, transient ischemic attack (TIA), or a recent or distant stroke (Adeoye et al., 2019). Additionally, the rapid development of society, the continuous construction of cities, increase the construction site accidents, traffic accidents, etc. also make people prone to brain injury such as limb paralysis in daily life.

Robot Assistant Therapy

While rehabilitative treatment tools have undergone recent development and updates, resulting in decreased mortality rates. However, the prevalence of disabilities remains high. At present, physical and occupational therapy have beneficial forms of treatment for these impairments, but they are labor intensive and expensive. Until recently, health care providers have reduced rehabilitation costs primarily by shortening inpatient hospital stays. Once the practical limit of abbreviated inpatient stays is reached, further efficiencies will be attainable chiefly by addressing clinical practices themselves. (Figure 1)

Figure 1. Stroke Patient during robot-aided therapy (H. I. Krebs et al., 2003)

Robot-assisted therapy for poststroke rehabilitation is a new kind of physical therapy, through which patients practice their paretic limb by resorting to or resisting the force offered by the robots (Basteris et al., 2014). The research on rehabilitation robots has emerged as a major research direction in modern rehabilitation medicine and medical engineering. For example, MIT-Manus is a machine in which a person sitting at a table puts the lower arm and wrist into a brace attached to the arm of the robot. From the experiments, scores for tests measuring increased movement were twice as high for patients in the experimental group as for patients in control group (H. Krebs et al., 2004). Furthermore, robot-assisted therapy has been greatly developed over the past three decades with the advances in robotic technology such as the exoskeleton and bioengineering, which has become a significant supplement to traditional physical therapy (Yue et al., 2017).

Basic theories of therapy

Acute cerebrovascular disease - commonly known as hemiplegia - is a complication in which the patients have some motor deficits, especially lower lingual muscles, facial muscles and one of the upper and lower limbs. The main cause of the disease is damage to the cortical motor centers of the cerebral hemispheres. Centers are damaged and are classified as mild, incomplete, or total paralysis. According to the condition of muscle strength, muscle strength is generally divided into six levels from 0 to 5.

Table 1. Muscle Strength Level (Williams, 1956)

Muscle strength	Description
0	Complete paralysis, no muscle contraction measured
1	Only muscle contraction is measured, but no movement is produced
2	The limbs can move parallel to the table, but cannot resist their own gravity, neither can they be lifted off the table
3	The limb can overcome the geocentric attraction and can be lifted off, but cannot resist the assistance
4	The limbs cannot completely do movements against external resistance
5	Normal

Based on observation and experiment, researchers developed a comprehensively process of recovering, which called Burrnstorm Stroke Recover Strategy. Here are the six steps shown in Table 2.

Tables 2. Stages of Stroke Recovery (Brunnstrom, 1966)

Stages	Definition	Description
1	Flaccidity	People can't move their muscle, that is limp and floppy
2	Onset of spasticity	A person's muscles may now tighten involuntarily in response to a stimulus, such as a prod with a finger. However, the person may also have difficulty relaxing their muscles.
3	Increased spasticity	Some of the person's muscles begin to tighten. It may be even harder to relax the muscles. However, a person may now have voluntary control over some of the basic muscle groups to manage limb movement, known as limb synergies.
4	Decreased spasticity	During this stage, involuntary muscle tightening decreases. The brain gets better at sending signals to specific muscles to move them voluntarily.
5	Increased complex voluntary movements	With involuntary muscle tightening now at a minimum, a person becomes more capable of performing complex muscle movements voluntarily.
6	Spasticity disappears, and coordination returns	A person's control of their movements almost fully returns to typical function. Involuntary muscle tightening disappears, and the person's movements become more coordinated.

From Table 2 we can get that with patients who are at stages between 1-5 need passive force to bend and stretch their fingers; thus, the hand habilitation robot can help them recover the ability to move and crab their hands.

Design Criteria

The purpose of the criteria is to specify which functions the robot needs to fulfill to provide a more appropriate treatment process for the patient.

Portability

Portability is a crucial requirement for this robot, enabling patients to easily transition between their home and workplace, thereby reintegrating into both work and society. The significance of portability lies not only in addressing the potential emotional distress experienced by patients due to prolonged medical treatment, but also in psychological challenges faced by caregivers. From the experiments in Ningbo China, primary caregivers of hospitalized stroke patients have varying degrees of mental health problems such as anxiety, depression, extroverted irritability, and introverted irritability, with anxiety and depression showing the most pronounced manifestations. Most primary caregivers are the patient's family members, mainly spouses or children, who are inevitably concerned about the patient's condition, ability to care for themselves, and whether they will die (Schulz et al., 2020). Additionally, the rehabilitation robot must possess a low mass since hemiplegic patients are unable to move effectively when burdened by heavy muscles. Consequently, the material's density should be minimized, and the utilization of metals and alloys should be reduced.

Safety

The interactive control creates a safe, comfortable, natural, and active training environment for the patient, which prevents the patient’s limbs from confronting the robot due to abnormal muscle activities, such as spasms and tremors and protects them from secondary injuries. Hence, certain criteria must be met by a hand rehabilitation robot:

1. Monitor the force exerted by patients to assess the magnitude of the generated force.
2. Have program that can cut all the power when the interaction forces exceed threshold.
3. Include an emergency stop button to instantly halt all exerted force.
4. Implement both mechanical and programmable position limits.

Comfortable

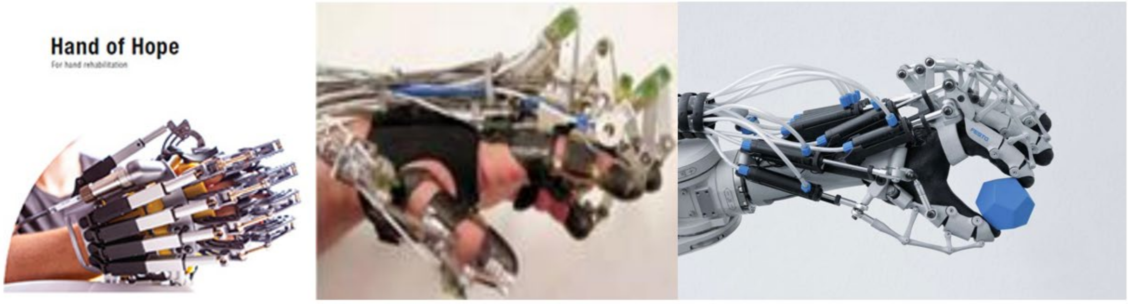
The design of the hand rehabilitation robot should align with the physiological attributes of the human hand. This alignment ensures that hemiplegic patients remain consistently comfortable and at ease throughout their hand rehabilitation training. Moreover, the design should encompass the diverse range of sizes found in patients’ hands, facilitating seamless adaptation across varying finger lengths and widths.

Accessible

The robot should be reasonably priced. This consists of two parts: the first part is that the price of manufacturing should be minimized, in which expensive materials such as carbon fiber should be avoided, and expensive control instruments such as stepper motors need to be avoided in the choice of drive motion. It's crucial to maintain a brief treatment duration while also ensuring a favorable treatment outcome.

Review of previous Hand Rehabilitation Robot

The prevailing configuration for hand function rehabilitation robots encompasses an exoskeleton-type structure, manifested through two primary modalities: terminal direct extension and multi-joint actuation. The driving force for these mechanisms is predominantly furnished by actuators, encompassing motors, cylinders, pneumatic muscles, and memory alloys. Each driving force mechanism presents distinct advantages and drawbacks. This passage will furnish a concrete instance of each motion actuator, followed by a comprehensive analysis of their respective merits and limitations.



(a) (b) (c)

Figure 2. (a)-Hand of Hope (from Medical EXPO https://www.medicalexpo.com/prod/rehab-robotics/product-77946-472601.html); (b)-Hand Rehabilitation of Technical University of Berlin (from TU Berlin https://pdv.cs.tu-berlin.de/HandExoskeleton/); (c)-ExoHand (from Festo https://www.festo.com/us/en/e/about-festo/research-and-development/bionic-learning-network/highlights-from-2010-to-2012/exohand-id_33631/)

Hand of Hope

The Hand of Hope (HOH) therapy device is used for neuromuscular rehabilitation of the hand and forearm that may help patients regain hand mobility through motor relearning. The HOH functions as a biofeedback device where surface electromyography (sEMG) sensors utilize a patient's own muscle signals to activate their desire to move their hand. Each finger of the hand is equipped with a dedicated micro-motor to provide motion drive, and it uses connecting rods to transmit the force, with a total weight of less than 800 grams. It also has active and passive two methods that can be used to rehabilitate. However, the use of electric motors to provide drive power for structural control is expensive. From the NeuroRehab Directory, the prices of the HOH therapy cost $10,000+.

Hand Rehabilitation of Technical University of Berlin

A developed by Wedge et al. at the Technical University of Berlin, Germany, adopts the idea of modular design, as shown in Fig 3. Each finger of this rehabilitation robotic hand is driven by one motor and pulled by two wire ropes, and the independent joint movements of the fingers are accomplished by driving three sets of planar four-bar mechanisms.

ExoHand

ExoHand was developed by Festo in Germany in 2012. It is an exoskeleton manipulator. The ExoHand utilizes eight double-action cylinders as drivers, and the connecting rod mechanism imitates the movement of human fingers under the movement of the cylinders. The ExoHand has a total of 17 degrees of freedom: four degrees of freedom for the thumb, four degrees of freedom for the index finger, and three degrees of freedom for each of the other fingers. By detecting the pressure in the cylinder and the displacement of the piston, the movement of the manipulator can be controlled in real-time.

Analyses of Human Hand Movement

Human Hand's Anatomy

Understanding hand anatomy is crucial for gaining insights into the impact of strokes and therapeutic approaches. The wrist comprises eight carpal bones that articulate with the radius and ulna to form a joint. It is further linked to five metacarpal bones that collectively constitute the palm of the hand. Each metacarpal bone is connected to a metacarpophalangeal joint (MCP). The fingers and thumbs are composed of phalanges. Typically, each finger possesses three phalanges, demarcated by two interphalangeal joints. Notably, the thumb has two phalanges and a single interphalangeal joint. The first joint close to the MCP is called the Proximal Interphalangeal joint (PIP). The joint is close to the end of the hand. There are fourteen joints for the whole hand. The join between Carpal and Metacarpal bones does not have any Degree of Freedom (DOF). The thumb is the only one with a Metacarpal joint with abduction/adduction of movement with respect to the sagittal plane. The rest of joints have one DOF, flexion and extension movement with respect to the frontal plane (Dunai et al., 2020). The human hand is very complex and sophisticated. The first step in creating a manual rehabilitation robot is to analyze the movement of the human hand and use the simplest mechanical structure to simulate the overall movement of the human hand. This is the only way to achieve the desired function and to make it suitable for clinical medical research. The human hand has a total of 21 degrees of freedom (DOF), but it is not possible to achieve all of them while keeping the structure simple and stable, so we need to further analyze the motion of the hand.

Hand's Kinematics Analyze

First, we need to analyze the degrees of freedom of the entire hand: Four fingers including the index, middle, ring, and little fingers both have same joints and the same DOF: DIP and PIP. Each joint has one DOF. The MCP joint has two degrees of freedom, that is, flexion and extension and ulnar/radial deviation (Rath, 2011). The thumb as an exception, has a total of five degrees of freedom, carpometacarpal (CMC) has three DOFs, and MCP and Interphalangeal (IP) have one DOF each.

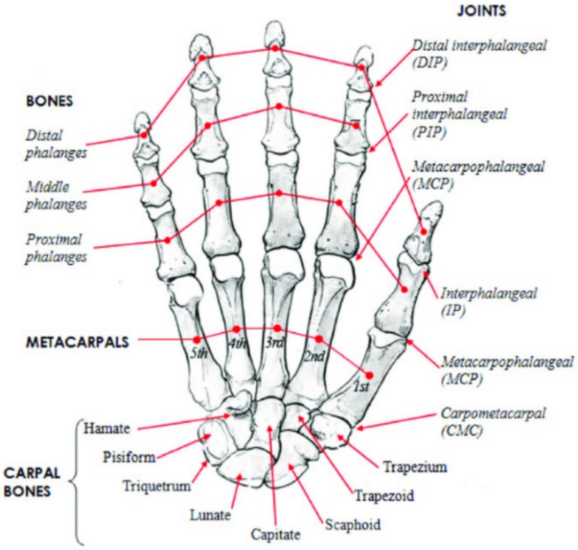


Figure 3. The structure of hand (Nanayakkara et al., 2017).

After becoming familiar with the joints of the hand that already have degrees of freedom, the individual movements of the hand can be analyzed. All fingers of a healthy hand can be flexed/extended and abducted/adducted (as Figure 3 and Table 3)

Table 3. The description of movement of hand

Name of movement	Description
Flexion	Moving the base of the finger towards the palm.
Extension	Moving the base of the fingers away from the palm.
Adduction	Moving the fingers toward the middle finger.
Abduction	Moving the fingers away from the middle finger.

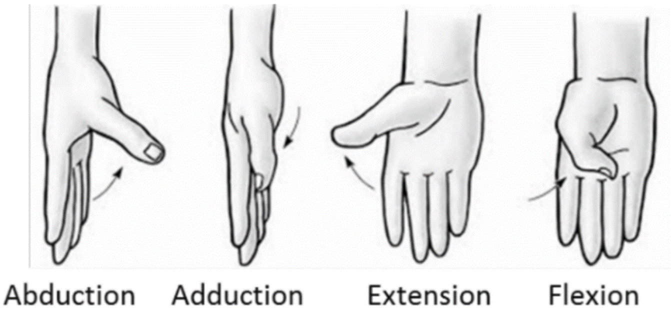


Figure 4. The motion of Abduction, Adduction, Extension, Flexion schema (Jarque-Bou et al., 2019)

Below are generally accepted values for a normal range of motion (ROM) for some individual joints as measured in degrees:

Table 4. ROM of each joint in each movement

Joint	**Movement**	**ROM (in degrees)**	**Range (in degrees)** (Ingram et al., 2008)
Metacarpophalangeal (MCP)	Abduction	25	-25——20
	Adduction	20	
	Flexion Extension	80 30	-30——80
Interphalangeal proximal (PIP)	Flexion Extension	120 120	0——120
Interphalangeal distal (DIP)	Flexion Extension	80 80	0——80
Metacarpophalangeal of thumbs	Abduction Adduction	50 40	-50——40
	Flexion Extension	60 60	0——60
Interphalangeal of the thumbs	Flexion Extension	80 90	0——80

Furthermore, the robot needs to be easy for people to wear, so the design needs to be sized to meet the normal specifications and dimensions of an adult's hand. This will not only prevent the rehabilitation robot from causing harm to people, but also reduce the need to make the rehabilitation robot fit better to the joints and bones to get better rehabilitation results.

Table 5. The structural parameters of adult's hand (in mm)

	MCP	**Proximal phalanges**	**PIP**	**Middle phalanges**	**DIP**	**Distal phalanges**
Thumbs	17-21	45-55	16-18	30-35	14-17	18-33
Index	16-20	43-50	15-17	24-30	12-15	23-26
Middle	17-21	44-51	16-18	25-31	13-16	24-27
Ring	16-20	43-50	15-17	24-30	12-15	23-26
Little	15-19	37-42	12-15	23-256	11-16	21-24

Hand’s Rehabilitation Robot DOF Setting

Because the degrees of freedom of the human hand are very complex, only a limited design of degrees of freedom is specified in this study. It makes the structure simple and can be used for clinical rehabilitation research. Through the above analysis process, the overall mechanical degrees of freedom are now specified, in the hand rehabilitation robot:

1. The index, middle, ring, and little fingers are having 4 DOF each. MCP, PIP, and DIP each have one DOF, which can execute flexion and extension.
2. The thumb has 3 DOF, and the Metacarpophalangeal can have both flexion/extension and abduction/adduction. MCP and IP will have each one DOF which executes as flexion/extension.
3. Total hand rehabilitation has 16 DOF.
4. The range of moving is determined by Table 4

Hand’s joints trajectory experiment

This is an experiment to measure finger trajectories and find out the minimum and maximum angle for each joint.

Experiment Prerequisite

An important goal of a rehabilitation robotic exoskeleton is to be consistent with the movements of a normal human hand. So, in this post experiments are done on hand joint motion tracking. From Table 5, we can get the values of hand dimensions. The length of the hand in 170mm is selected for this experiment. The experimental data to be obtained in this experiment is the angle of motion of each joint during different flexion processes. In this experiment, four fingers (index, middle, ring, and little) were photographed in the flexion process with a camera. Because extension is the opposite of the flexion process, it was not measured in this experiment.

Experiment Procedure

The hand is placed in front of a whiteboard. The frame rate of the camera is 60 fps, and the video resolution is 1080p. The entire movement of the hand is recorded, and pictures are taken every 0.5s.

Experiment Data

The experimental data are as follows, the whole process of flexion lasted 5.02s, and from the start of movement of any joint of the hand continued to all the joints stopped moving (the start and stop were judged by a high-speed camera in slow motion). A total of 11 photographs were taken of the entire process.

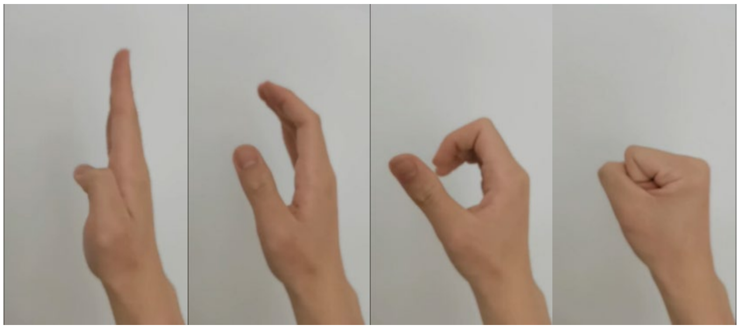


Figure 5. Four typical photos of experiments representing flexion (the left is the initial state, the right is the end state)

Because the position of each joint cannot be judged by its appearance, this experiment uses palm prints to determine where each joint is located. The distribution of palm prints is shown below:

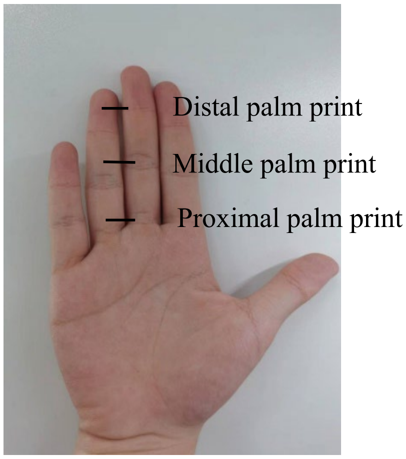


Figure 6. Palm pints for adults (the adult’s hand with distal, middle and proximal palm prints represents the distinction between DIP, PIP and MCP)

Using the index finger as an example, it is obviously divided into distal, middle, and proximal palm prints. The distal palm print can be approximated as the DIP position, the middle palm print as the PIP position, and the proximal palm print as the MCP position. In the experiment, because the position of the hand cannot be kept immobile, the MCP (proximal palm print) of the index finger is used as the reference point, and the subsequent photographs of the hand offset are moved to the reference point so that the accuracy of the experimental data can be guaranteed. As the hand is captured from a lateral perspective, the discrete phalanges appear as lines when illustrated. To symbolize these phalanges, the line connecting the midpoints of the hand's width is utilized as a representative line segment. Consequently, experimental outcomes can be visually depicted in the form of an image.

Experiment’s data analyzation

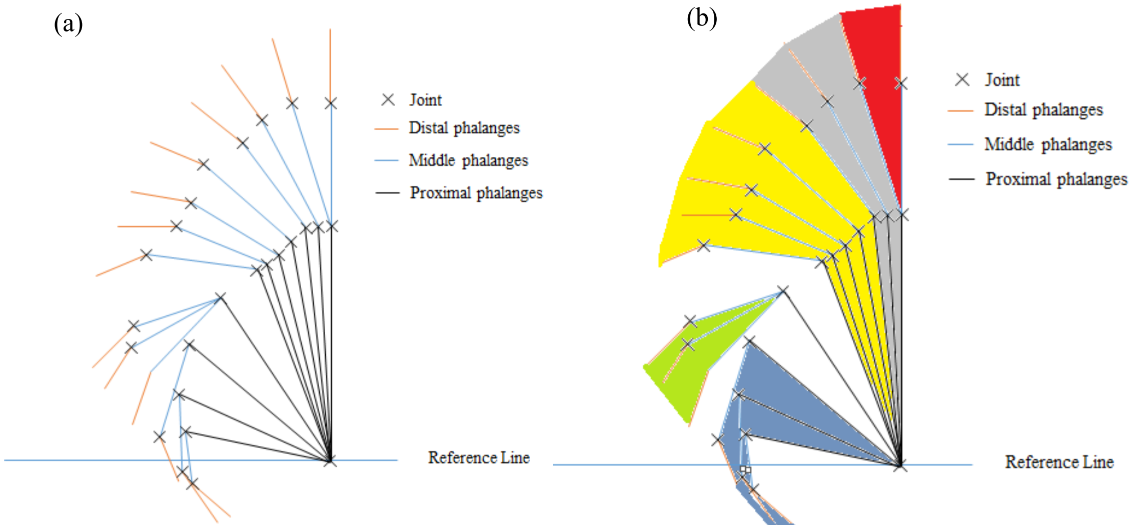


Figure 7. (a)-Experiment traces for joint of index finger (different color represents the different joints); (b)- The sketch map of five different stages in colors (each colors represents different steps of hand’s moving)

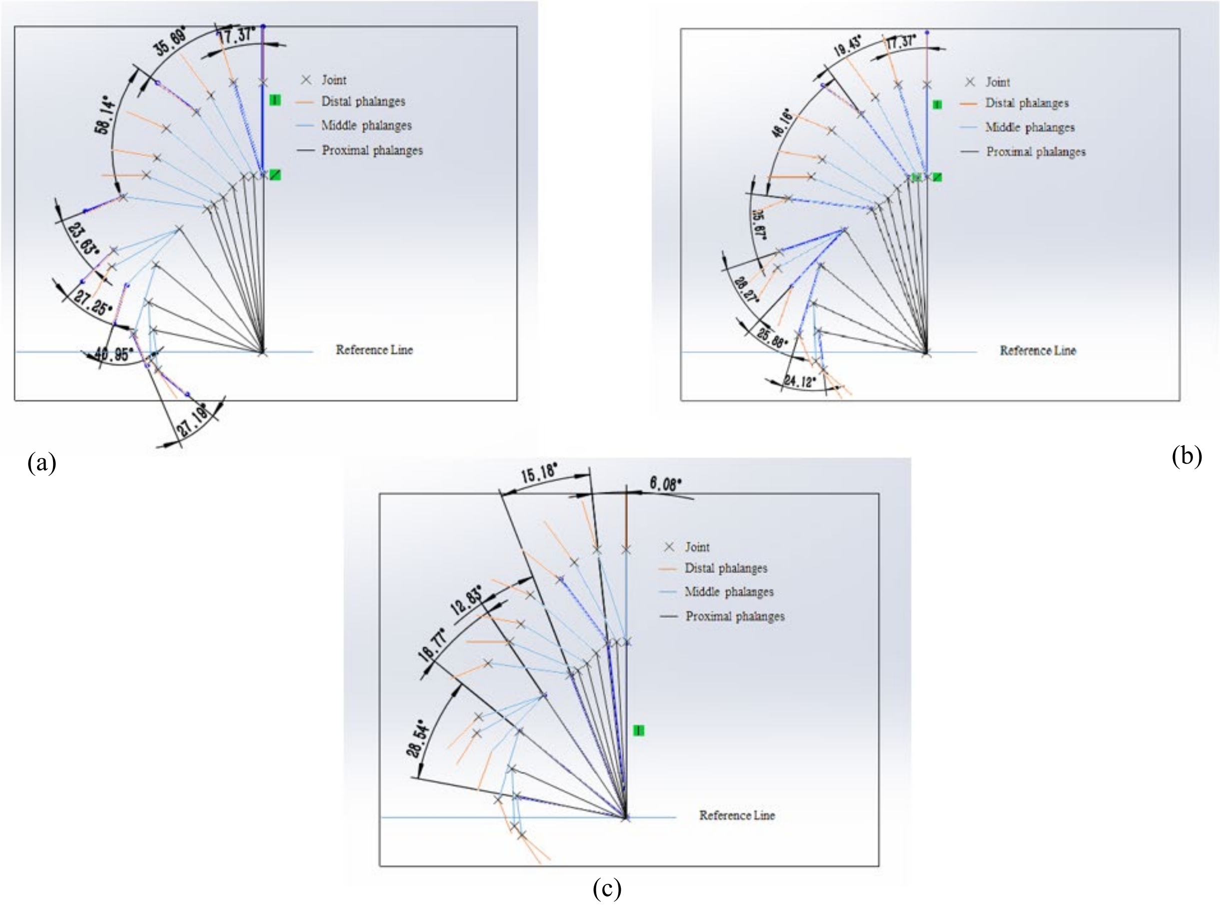
From Figure 7 (a), we can get the movement of the index finger in flexion very clearly. The rest of the three fingers (middle, ring, little) had the same trajectory as the index finger, so only the index finger experiment was completed.

Analyses with steps

The experiment’s data can be divided into five steps:
1. Start: proximal phalanges did not move, PIP joints started to move at an angle of 17.37°, and middle phalanges and distal phalanges remained relatively stationary. (The red area in Figure 7(b))
2. Gradual start movement: PIP joints changed their angle at a constant rate. The proximal phalanges begin to move at a small rate and the DIP joints begin to show angular changes of 35.69 ° (The grey area in Figure 7(b))
3. Sustained: The proximal phalanges continue to move at a small rate, but the angular acceleration of the PIP and DIP joints increases, and the fingers are flexed significantly. (The yellow area in Figure 7(b))
4. Gradual inward movement: The angular changes of the MCP stop, resulting in a brief cessation of movement of the proximal phalanges, and the middle phalanges and distal phalanges remain relatively static. phalanges stop moving briefly (0.5s), and DIP and PIP angles continue to decrease, (same as steps 4) (The green area in Figure 7(b))
5. Stop: angular acceleration of MCP, PIP and DIP joints continues to increase, and all three phalanges continue to move substantially until they stop. (The blue area in Figure 7(b))

After dividing into five steps, the angle of motion of each joint at each of the five steps can be analyzed in turn.
The angle formed by two different phalanges at different stages is the angle formed by the corresponding joint of that phalanges. So, we can measure the angle between phalanges using CAD to get the angle for the joint’s movement. Therefore, the angle formed by two different distal phalanges corresponds to the angular displacement of DIP; the

angle formed by two different middle phalanges corresponds to the angular displacement of PIP; and the angle formed by two different proximal phalanges corresponds to the angular displacement of MCP. So, it is possible to derive the start and end angles of each joint for each of five states of motion as well as the intervals of the angles.



(a)

(b)

(c)

Figure 8. (a)-Conclusion of DIP range of movements analysis from the experiment; (b)- Conclusion of PIP range of movements analysis from the experiment; (c)- Conclusion of MCP range of movements analysis from the experiment

After the measurements can be taken all the data can be organized in a table and now the results of the data with DIP are explained and illustrated.

Table 6. Combination of individual joint movements for DIP in different stages (in degree)

			Stage1: Start		State2: Gradual start movement		State3: Sustained		State 4: Gradual inward movement:		State5: Stop		Total angle
DIP	Start angle	End angle	0	17.37	17.37	53.06	53.06	111.2	134.82	162.07	203.03	230.22	230.22
	Total angle for one stage		17.37		35.69		58.14		27.25		27.19		

In table 6, the first row of the movement of the DIP in the process "Start" is divided into two parts. The first column shows the angle at the start and the second column shows the angle at the end. These angles are relative to the initial state of the hand movement (when the hand is straight, distal, middle, and proximal phalanges are in the same line) so the angle at the beginning is 0°. And, because some stages are not consecutive, such as stages 3 and 4 of DIP, the end angle in the middle of the previous stage is not the next start angle, and there is a 35.67° gap between them.

Combination analysis of all data

Table 7. Combination of individual joint movements in different stages (in degree)

			Stage1: Start		State2: Gradual start movement		State3: Sustained		State 4: Gradual inward movement:		State5: Stop		Total angle
DIP	Start angle	End angle	0	17.37	17.37	53.06	53.06	111.2	134.82	162.07	203.03	230.22	230.22
	Total angle for one stage		17.37		35.69		58.14		27.25		27.19		
PIP	Start angle	End angle	0	17.37	17.37	36.8	36.8	82.96	108.63	136.6	162.78	186.9	186.9
	Total angle for one stage		17.37		19.43		46.16		28.27		24.12		
MCP	Start angle	End angle	0	0	0	6.08	6.08	21.26	34.09	34.09	50.86	79.4	79.4
	Total angle for one stage		0		6.08		15.18		0		28.54		

Eventually, we can get the start and end angle of the motion of each joint at different stages and the angle interval of the overall motion.

Conclusion of experiment

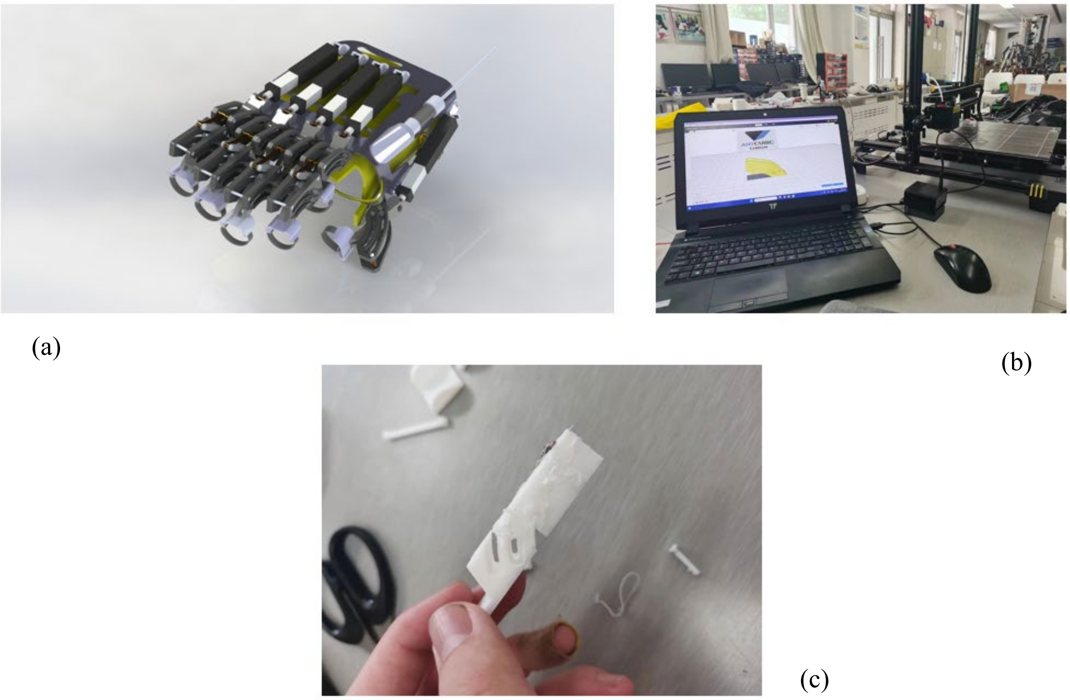
From Table 7, it is evident that the minimum and maximum angles for each joint's movement can be easily derived. Consequently, it becomes imperative to establish mechanical limits. These limits ensure that the joints do not exceed their designated maximum and minimum angles during operation, thereby mitigating the risk of secondary injuries to patients. And in each stage, different joints have different angles and angular speeds. The design of the connecting rod must align the experimentally measured outcomes for better recovery. In the description of each stage, we can find that the movement of hand joints is not consistent. Notably, the MCP experiences a momentary halt during the "Start" stage. Nonetheless, this interruption need not be factored into the design process. Because the aim of the hand rehabilitation robot is to restore the patient’s ability to grasp daily necessities such as glass bottles or phones. The "Start" stage holds little relevance in the context of grasping due to the modest 17.37° flexion angle of the DIP joint. While this minimal flexion angle proves suitable for gripping larger objects, it remains improbable that hemiplegia patients would require such precise grasping abilities given their prior hand injuries.

Designing of Hand Rehabilitation Robot

This part will show the whole design of the Hand Rehabilitation Robot, including the discoveries of Hand of Hope, the 3D model of the Hand Rehabilitation Robot, and the design of the electronic control system.

Discoveries of Hand of Hope's replication

The Hand of Hope have already published its CAD model in GrabCAD (a community in which designer can share their 3D model). The Hand of Hope used a linear actuator as power and used a metal connection rod to transmit the force, already discussed in the Review of the previous Hand Rehabilitation Robot section. So, it is worth replicating the Hand of Hope and it is possible to explore what advantages or proven solutions of existing technologies can be directly used in own Hand Rehabilitation Robot.



(a) (b) (c)

Figure 9. (a)- The model of Hand of Hope in Grab Cad; (b)- the printing progress of the main part in Hand of Hope; (c)- The main supporting part printed.

In Hand of Hope, the connection rod uses steel as a raw material. However, the use of steel in the experimental process will increase the production time and the overall cost, which does not meet the criteria. Therefore, in this experiment, Polylactic Acid (PLA) (3D printer material) was used, which not only reduces the cost but also is a suitable material, since PLA is lighter. In such cases, using PLA is also consistent with the criteria of portable. After all the printing had been done, the Hand of Hope problem was discovered. The Hand of Hope is machined with steel using precision equipment such as a machine tool, but on a 3D printer, errors are inevitable due to the longtime of printing. These errors are about 3mm, although these errors can be ignored in the daily printing process, every movement process of Hand of Hope needs to match the movement trajectory of the human hand. So, this error will seriously affect the movement. And the movement that doesn't match the movement trajectory of the human hand will cause secondary injuries, which doesn't match with the safety in the criteria. Furthermore, since Hand of Hope's mechanical limitations rely on the presence of grooves on the surface, when the bearing motion contacts the side of the groove, the motion is stopped. The curvature of the groove can be seen in the main support part (in Figure 9(c)), which is designed to have the small bearing inserted into the groove. However, this design is clearly cannot accomplished during replication because there is no way to insert the small bearing into the groove before the main support part is printed. Thus, it is not possible to replicate Hand of Hope if it must comply with the criterion.

The design of Hand Rehabilitation Robot

This part including the design of both mechanical part and the electronic control system.

Design of Robot's Connection Rod


(a) (b)

Figure 10. Novel Connection Rod-based Hand Rehabilitation Robot (Rendering after SolidWorks Photoview 360) (a)-Isometric photograph of Hand Rehabilitation Robot; (b) Side-views photograph of Hand Rehabilitation Robot.

From Figure 10(b), it can clearly get the side views of Hand Rehabilitation Robot. The white design of the tubular PLA on top is the connection rod. Connection Rod is divided into three parts, sorted by different joint and have different functions. The actuator of the hand function rehabilitation robot under study utilizes a planar linkage structure. With the planar four-link and five-link structure, the contraction/extension motion of the linear actuator of the drive system can be transformed into the reciprocating motion of flexion/extension of the rehabilitation robot. For the connection rod at the DIP position, the design is relatively simple, that is, the force of the PIP is transmitted directly to the DIP position through the connecting rod. Among them, the length of connection rod1 (as shown in Figure 11, same as below) is $28mm$; For PIP where the rod, and MCP at the stroke of the four-link mechanism, so that the structure has a degree of freedom of the planar reciprocating mechanism, can be passed to the MCP and PIP. This four-link mechanism belongs to the crank-rocker, which needs to meet the $s + l < p + q$; length of connection rod 2 is $18mm$, the length of connection rod 4 is 26mm, and the length of connection rod 3 is $38mm$, which makes it possible to comply with the crank-rocker standard. In the case of the MCP, the connection to the PIP relies on connection rod5 to provide force to connection rod3. Connection rod 4,5, and 6 form a drag-link planar four-link mechanism, and the lengths of connection rod 4 and connection rod 6 are equal, at $26mm$. The connection rod4 and connection rod6 are of equal length, $26mm$, and connection rod5 is $42mm$ long, which is consistent with the drag-link planar. The force applied point is at the rightmost point of the whole mechanism, which is directly connected to the linear actuator. For the whole mechanism, after the linear actuators are energized and start to move, the connection rod6 first starts to move counter-clockwise, where the angle of rotation of connection rod4 and connection rod6 is the same because the length of both connection rods is the same. After driving connection rod 3, it will continue to drive connection rod 2, because the angle between 2 and 3 is greater than 90 degrees, so it will drive the overall movement of the PIP joint. After the PIP moves, connection rod 3 will push connection rod 1, which in turn will push the DIP joint.

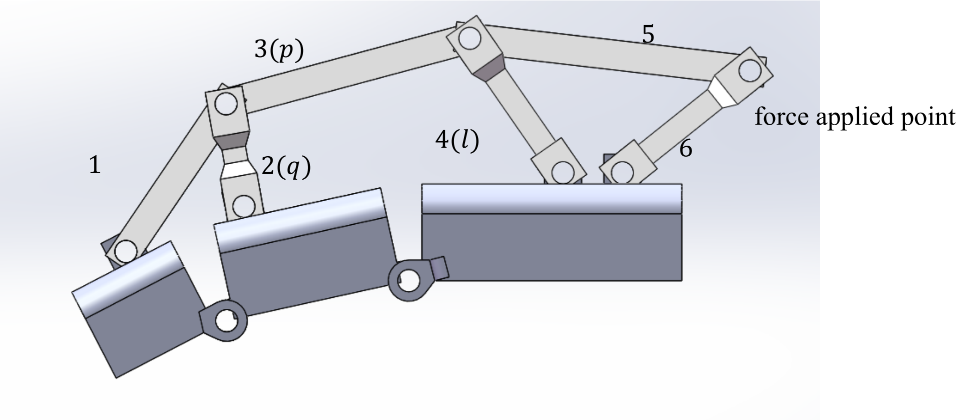
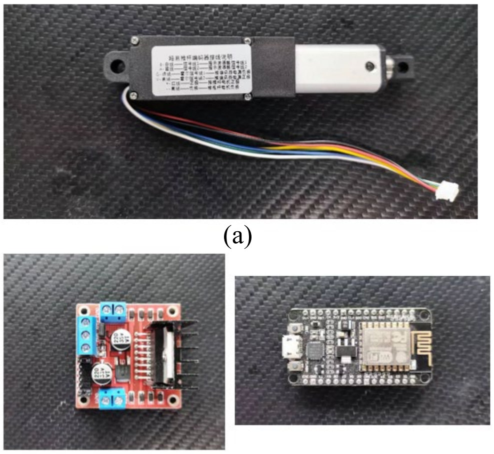


Figure 11. The connection rod in Hand Rehabilitation Robot (the right-side views photocopy in Solid-works without rendering)

Design of Electronic Control System


(a)

(b)

(c)

Figure 12. The Electronic control part of Hand Rehabilitation Robot (a)- Linear actuator with encoder; (b)- L298N; (c)- STM8266

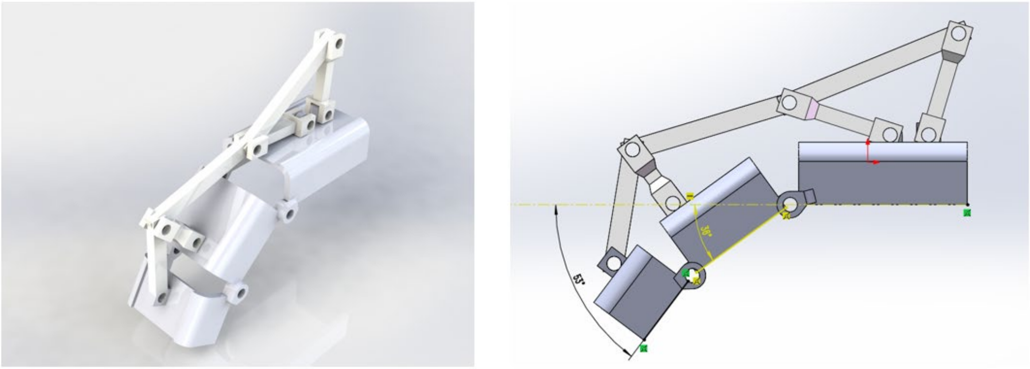
Firstly, the choice of material. As with the replication of Hand of Hope, we chose the material for the 3D printer, Polylactic Acid (PLA), which has a density of $1.25g/cm^3$. Compared to the density of carbon fiber, which is often used in other rehabilitation robotics, which is $1.8g/cm^3$, the density of PLA is smaller, so it will have a lighter weight, which is in line with the criteria of being portable. A roll of PLA costs around $5 (prices from www.Amazon.com, same as below). In comparison, a $300mm * 400mm * 3mm$ piece of carbon fiber costs $59.9, and the use of PLA also meets the accessible criteria of low manufacturing price. Secondly, the actuator uses an electric actuator with an encoder. The center distance between the front and rear holes of the electric actuator in the retracted state is $89mm$, and the center distance between the front and rear holes is $114mm$ after the power is extended, and the electric actuator's stroke is $25mm$. The reason for choosing a shorter stroke is that the connection rod can amplify the stroke's angle of work, in other word, the electric actuator only needs to move a little distance, DIP. And so on, and it will not be necessary to move the electric actuator to the center. PIP's and MCP's angle will be changed greatly. And the short stroke compared to the long stroke's price is lower, in line with the criteria in the accessible. Electric actuator speed in $4 - 15\ mm/s$, the reason for choosing a slow speed is to ensure more accurate control, to prevent the speed of too fast to cause injury. The actuator has a load limit of $120N$, which provides sufficient thrust and allows the machine to be stopped with maximum force in case of emergency. The use of encoders in electric actuators is one of the most important reasons for this. Electric actuators have five wires, V+, V-, and GND, with the remaining two Hall model wires, which can be read out to give a precise value of the motorized rotation, allowing for more precise control. By minimizing the error, it ensures that the patient is not harmed twice, in accordance with the criteria of safety. The drive module is an L298N, which is very popular in the engineering field and is used in many hand rehabilitation robots because of its low price and the possibility of connecting to an encoder. The force transfer method is a connection rod, which is a very traditional method used in many hand rehabilitation robots. However, unlike other robots, the connection rod can also play a role in limiting the role of the groove in the Hand of Hope is the same as the role of the bearings in the groove, the connection reaches the experimental maximum angle measured when the movement will stop, so that the trajectory of the movement of the human hand in line with the movement, but also to prevent secondary injuries caused. The main control board is STM8266. The reason is STM8266 can be connected to the Internet so that through the network can collect data and control both active and passive modes.

Checking the consistence with Experimental data

When the Hand of Rehabilitation Robot reaches its final position and stops moving (the angle between the connection rod2 and the PIP joint is 90°), it is necessary to measure the angle to see if it is the same as the angle measured in the previous hand's trajectory, in order to prevent exceeding the angle that causes secondary injuries to the patient as well as to achieve a large angle in order to enhance the therapeutic effect. Significantly, in this experiment, since the MCP is not able to move, we need to compare Stage 1 and Stage 2 in Table 7, when the MCP does not move or the movement is negligible.

Table 8. The consistence between hand's trajectory data and Hand of Rehabilitation Robot (in degree)

Joints	**Angle position**		**Stage1: Start**		**State2: Gradual start movement**		**Measurement from Hand of Rehabilitation Robot**	**The difference between measurement's data and experiments' data (%)**
DIP	Start angle	End angle	0	17.37	17.37	53.06	53	0.1132
	Total angle for one stage		17.37		35.69			
PIP	Start angle	End angle	0	17.37	17.37	36.8	36	2.222
	Total angle for one stage		17.37		19.43			



(a) (b)

Figure 13. The diagram of the end movement. (a)- The rendering diagram of Hand Rehabilitation Robot when movement ended. (b)- Measuring the angle between DIP and MCP, also the angle between PIP and MCP to test the design is consistent with Hand's Trajectory Experiment.

In comparison with Table 7, it can be seen that DIP moves in Stage 1 and Stage 2 at angles from 0°-53.06°, while from Figure 13(b) it can be concluded that the robot is designed for a maximum angle of 53°, which is the same as that measured by the hand trajectory experiment. Similarly, in comparison with Table 7, it can be seen that PIP moves from 0° to 36.8° in Stage 1 and Stage 2, while from Figure 13(b) it can be concluded that the robot is designed for a maximum angle of 36°, and at the same time, it is the same as the angle measured by the hand trajectory experiments. In Table 8, it can be seen that the difference between measurements' data and experiments' data is less than 3%.

Conclusion of Design Section

This rehabilitative robot was successfully designed and validated from physical hand movement experiments, with simulated motion angles corresponding to those experienced by real hands. This shows that the novel one connecting-rod design can achieve real hand motion-like movement by only using simple and interconnected designs.

Conclusion and Limitations

This article completes the whole process of designing a hand rehabilitation robot from basic experiment to construction. This novel connection rod-based robot can help hemiplegia patients to act with flexion and extension. The simple connection rod design on the DIP joints would use only one point of applied force. It also indicates that this robot sets a precedent for assistive robots, in general, to be designed around one applied force point. Without complex force exerted, this robot achieves portability, and safety, and can substantially shorten the period of therapy. The main part was to design the connection rod to make it conform to the data obtained from the experiments' data, which got minimum and maximum angles of PIP, DIP, and MCP movement. Also, this article found out that Hand of Hope has the disadvantages of not being replicable and expensive for normal people. To solve this problem, this novel Hand Rehabilitation Robot costs less than $50 to construct including the cost of motors and rods. Also, it can be replicated with a 3D printer easily since it does not have an embedded structure. In conclusion, the current novel robot design allows the patient's hand DIP and PIP joints and nearby muscles to be trained and is motorized for active output to exercise the patient's hand muscles.

This design has the following limitations: First, in the experimental part, because the points are judged by palm print, there will be some errors. Moreover, taking the center line of the finger width as the skeleton and depicting it with a straight line will inevitably cause some errors, and the frame rate of the video is not enough to cause the screen to be blurred and not be able to judge the position of the center line sometimes. The second point is that the design of the robot is not able to realize the goal, in which the DIP and PIP can move but can only reach the Satge 2, are not able to complete the overall clenching motion, and the MCP is not able to move due to the lack of an actuator, which is also a problem. Thirdly, due to time constraints, the abduction and adduction motions could not be accomplished, and there were fewer degrees of freedom. Finally, only passive rehabilitation was studied in this experiment, in other words, the movement of the motor drove the hand to perform the movement. No active study was conducted. That is, when the patient's hand tends to move, an electrical signal (EEG) can be received to assist. Compared to passive rehabilitation, active rehabilitation can guide the patient to recover faster in the later stages of rehabilitation.

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