INTECH
open science | open minds

OPEN ACCESS
ARTICLE

International Journal of Advanced Robotic Systems

Design and Development of a Bilateral Therapeutic Hand Device for Stroke Rehabilitation

Regular Paper

Akhlaquor Rahman[1] and Adel Al-Jumaily[1,*]

1 School of Electrical, Mechanical and Mechatronic Systems, Faculty of Engineering
and Information Technology, University of Technology, Sydney, Australia
* Corresponding author E-mail: Adel.Al-Jumaily@uts.edu.au

Received 18 Dec 2012; Accepted 04 Jul 2013

DOI: 10.5772/56809

Abstract The major cause of disability is stroke. It is the second highest cause of death after coronary heart disease in Australia. In this paper, a post stroke therapeutic device has been designed and developed for hand motor function rehabilitation that a stroke survivor can use for bilateral movement practice. A prototype of the device was fabricated that can fully flex and extend metacarpophalangeal (MCP), proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints of the fingers, and interphalangeal (IP), metacarpophalangeal (MCP) and trapeziometacarpal (TM) joints of the thumb of the left hand (impaired hand), based on movements of the right hand's (healthy hand) fingers. Out of 21 degrees of freedom (DOFs) of hand fingers, the prototype of the hand exoskeleton allowed fifteen degrees of freedom (DOFs), with three degrees of freedom (DOFs) for each finger and three degrees of freedom (DOFs) for the thumb. In addition, testing of the device on a healthy subject was conducted to validate the design requirements.

Keywords: Flex Sensor, Hand Exoskeleton, Stroke, Bilateral Therapy, Rehabilitation

1. Introduction

Studies have shown, in Australia and various other countries around the world, that most adults who are suffering from disability have experienced a stroke. A significant amount of research has been done on stroke because its causes deficiencies in various neurological areas and disability in the motor system [1]. A major focus of rehabilitation research has been to understand and repair hand motor function after a person has had a stroke, since the human hand plays a vital role in the daily activities of a person's life. Furthermore, in the rehabilitation of hand motor function, the major concern has been how to achieve optimum restoration of hand function. A general state in most stroke survivors is paralysis of one side of the body in the upper limb.

Motor rehabilitation research has shown that to speed up the recovery process of upper limb function, activity dependent interventions can be used to assist the use of paralysed limb [2]. Furthermore, while positive outcomes have been obtained from therapies such as constraininduced movement, it nonetheless bears some limitations, as this type of therapy is mainly applicable for stroke patients with mild motor damages [1]. On the other hand, for stroke patients who have undergone harsh, moderate or mild motor deteriorations, an optional therapy known as bilateral arm training has demonstrated positive results. In addition, based on neurophysiological and behavioural mechanisms, an immense assurance in hastening upper limb chronic stroke recovery has been shown by bilateral movement practice [3]. Additionally, in comparison with unilateral training, patients obtaining bilateral training indicated better improvement of the upper extremity functions and a decrease in the movement time of the damaged limb [4].

The major aim of this paper is to design and develop a post stroke remedial system that can assist the stroke patient to flex/extend each digit of the impaired hand based on the flexion/extension movement of the healthy hand fingers. By performing bilateral movement training, the hand motor function of the impaired limb of the stroke survivor can be enhanced due to the plasticity of the human brain.

2. Neural Plasticity

With a change of environment, neurons change their framework, tasks and orderliness. This is called neural plasticity, also known as brain plasticity [5]. In other words, it is the reinforcement or deterioration of nerve connections or new nerve cells in response to external stimuli. Modern neurology deals with plasticity, i.e., reinforcement or deterioration or accumulation of nerve connections for the successful treatment of brain damage. One of the characteristics of neurons is that the function of the affected nerve is taken over by the intact nerve, leading to natural healing and restoration [5].

3. Activity-dependent intervention

Rehabilitation is the most important issue in the management of stroke patients. Significant advances in rehabilitation programmes have been blocked due to insufficient knowledge of the neurophysiological mechanisms working in favour of motor recovery [6]. Among the different approaches, activity-dependent motor rehabilitation interventions are thought to represent progress in terms of rehabilitation of hand and arm function after stroke.

From results of different studies it can be concluded that not only injury-related reorganization, but also the individual motor experiences of motor neuron can be affects the functions of the motor cortex. It has been shown from animal studies that if the motor cortex area of a monkey is affected, it is able to use an alternative cortical area to overcome the functional inability [7]. Neural plasticity knowledge is very important for developing the rehabilitation training programme for stroke patients. According to neurophysiology, synapse fallows some rules. Particular synaptic junctions react to movement and immobility, according to the rule of Hebbian synapse [8]. Additionally, according to this rule, modifications in brain plasticity typically build up. To be precise, information storage in neural networks is triggered by activity-dependent that, continuing alteration of synaptic efficacy. It can therefore be concluded that the recovery process after stroke is significantly affected by various interventions used for rehabilitation [9].

Much research has been conducted both on humans and animals to better understand what actually happens in neuron levels following treatment to restore functions of the affected side in stroke conditions. It has been concluded that neurons remaining automatically linked to the damaged site increasingly take up the functions of the injured areas over time that creating increased connectivity.

Usually, the first three months following stroke is vital for planning treatment modalities to restore motor function. Afterwards, the patient reimburses the function of the affected side for daily activities by using the healthy side [10].

Among many treatment options, constrained-induced movement therapy sees the healthy limb purposefully inhibited in taking on the function of the affected side, thereby creating pressure on the patient to use their affected limb [11-13]. This type of work has been done by different researchers in different parts of the world; it has been found that both early and late functional movement benefits occur.

4. Bilateral training for stroke rehabilitation

A range of studies have shown that, in the case of a healthy adult, if two hands simultaneously work to perform something, with the influence of both psychological and neural mechanisms, the outcome is better. This outcome should be considered on the context of stroke patients. When two hands move together, some effect occurs due to the arangement of hands interactions. This psychological and neural mechanisms occur is responsible for better action and that is the powerful temporal and spatial interactions between the limbs.

Whether or not improvement in the damaged limb of a stroke survivor can be achieved by the pairing of muscles that are homologous has been a question of major interest. Additionally, it has been observed in healthy adults that if dominant and non-dominant limbs are used together to draw a circle, the functionality of the non-dominant limb improves for a period of time [14]. Moreover, functional gain of the impaired limb has been reported for Parkinson's disease and spastic hemiplegia when the impaired limb is paired with the unimpaired limb.

In stroke patients, the neural networks are exhausted due to damaged neurons. In this case, if both healthy and unhealthy limbs are used at the same time to perform work, activation of the healthy hemisphere will stimulate the damaged hemisphere and assist it in regaining working capacity by neural plasticity. The outcomes of simultaneous use of both healthy and unhealthy limbs have been mixed. Some studies have reported that speed and ease of movement of the impaired limb have improved when paired with the unimpaired limb. In other studies it was found that if practice of simultaneous use of both healthy and unhealthy limbs continued for some time, the paretic limb provides some negative influence on the normal limb; thus, the performance of healthy limb is decreased. These inconsistent results might have resulted from the difference in the difficulty of the tasks and the intensity of damage of the patients in various study groups [3].

In order to complete a 360° extension motion of the finger/wrist, two different recovery methods were designed for chronic stroke patients; the first method involved moving the damaged limb unilaterally with the help of neuromuscular stimulation, while the second method required paired movement of the impaired and unimpaired limb (i.e., bilateral movement).

In a study done by [3], from the pretest-posttest design, improved motor functions were displayed by chronic stroke patients who were in the coupled bilateral movement group. Furthermore, participants who received bilateral therapy demonstrated better functional gain than participants who received unilateral therapy. Evidence of improved motor capabilities were identified by observing patients that received bilateral therapy and who had better results in the block and box test, and who also demonstrated reduced response times of the motor compared to the unilateral group. Furthermore, display of Electromyography (EMG) patterns in the affected limb during wrist contraction clearly expressed points in favour of the coupled protocol group [3].

It has been shown from different studies that, in the recovery process of stroke patients, the healthy hemisphere plays a significant role in increasing the recovery and performance of the damaged limb; this has been proven by observing the after effects of the bimanual training programme. Bilateral isokinematic training intervention (BIT) is a procedure in which bilateral movement is practised. Studies have proved the success of bilateral isokinematic training intervention and three experiment studies were conducted, each with a baseline phase and an intervention phase. The patient showed considerable improvement as a result of bilateral isokinematic training intervention [3].

In order to compare the functional improvements that can be achieved from unilateral and bilateral movement practice, 12 partially paralyzed stroke patients were assigned the task of placing cylindrical wooden rods on a shelf. Some stroke patients executed the task by using only the impaired limb; the rest of the patients completed the task by using both the healthy and impaired limb together. From the results of the study, it was found that patients who performed the task using only their impaired limb gained no noticeable functional improvement in the impaired limb. On the other hand, patients who performed the task using both the impaired and healthy limbs together demonstrated shorter movement time and improvement in the function of the damaged limb [3].

Additionally, research using different bilateral movement procedures showed positive training effects. Additionally, these results support an earlier study where bilateral arm training with rhythmic auditory cuing (BATRAC) exercise was used and in which considerable improvement in the motor function was observed in the majority of test subjects.

Furthermore, positive outcomes have been obtained by a different type of bilateral training where the damaged wrist was flexed and extended passively, depending on the active flexion or extension movement of the healthy wrist. In addition, functional development in the impaired limb was observed in 55% of hemiplegic stroke patients [3]. On the contrary, no noticeable functional recovery in 30 stroke patients (both acute and chronic) was observed after a single session of bilateral therapy. Similarly, minor gain in the impaired limb after bilateral training session was reported. Furthermore, when stroke patients in different stages of revival (i.e., chronic, subacute and acute) were assigned various upper extremity tasks, the test results demonstrated large variation and little functional development among the participants [3]. However, it can be argued that the small sample size and large inter-participant variations regarding location of lesion, severity of primary damage and time lapsed after onset of stroke might have been responsible for the lack of significant effects.

Although in some of the studies no functional gain in the impaired limb was reported, in the majority of the studies, considerable functional motor gain was observed in hemiplegic stroke patients. Ongoing studies clearly indicate that bilateral movement therapy has a profound effect on the rehabilitation of stroke patients who are suffering from partial paralysis.

5. Past research on hand function rehabilitation

Hands and their functioning are crucial for a number of daily living activities. Stroke and its effects cause a loss of motor functions in the hand. In order to recover lost functioning, hand exoskeleton rehabilitative training systems are needed. The hand exoskeleton design should comply with human hand anatomy. In addition, lightweight and safety issues must also be taken into account.

Some exoskeleton bio-mechanical designs for part of the hand or for the whole hand have been developed. For finger design only, LI Jiting developed a system for the index finger where a parallelogram mechanism was employed to avoid complicated kinematics of finger joint motions with an adjustable joint limit. The exoskeleton is able to accommodate various hand sizes. High level motion control with both active and passive rehabilitative motions has been realized in Jiting's system [15]. In other research, a one degree-of-freedom (1-DOF) thumb figure rehabilitation exoskeleton has been developed [16]. In this case, the exoskeleton has been designed with a closed mechanism for spatial motion. The index finger module of HANDEXOS is detailed in [17]. The design of the index finger module was designed by means of anthropomorphic kinematics of the human hand and minimization between the human and exoskeleton rotational axes misalignment. An under-actuation system was adopted in this system and transmission is based on steel wire ropes routed through spiral-spring Bowden cables requiring few control variables.

For design of the whole hand, 18 DOFs of hand assistive robot has been developed [18]. The robot aims to rehabilitate thumb, fingers and hand-wrist coordinated motions. In this development, a self-motion control (symmetrical master–slave motion) assistance training strategy is employed. The robot is integrated with a virtual reality interface with audio-visual instruction to enhance the effectiveness of the rehabilitation exercises. In other research, a passive hand rehabilitation device (HandSOME) was developed [19]. It uses a series of elastic cords that apply extension torques to the finger joints and compensates for flexor hypertonia. Another light-weight hand exoskeleton was developed [20]. In this development, the design of the exoskeleton was employed as a jointless structure and the device was constructed without any conventional pin joint. An under-actuation mechanism was employed to actuate movement of the fingers. Another under-actuated mechanism hand exoskeleton with 4-DOF and one active degree that provides full range of motion of all fingers was developed [21]. Another hand exoskeleton was designed where multiple grasps are performed by means of a novel synchro-motion pulley system. [22].

For the purpose of finger rehabilitation, the design of an assistive device that can provide assistance in grasping has been developed [23]. The design of this rehabilitation device consists only of thumb and index finger parts, as the index finger has the same number of bones and hand anatomy as the other three fingers (i.e., middle, ring and little). Furthermore, as the structure of thumb and index finger is different, two different mechanisms were developed.

By using finger flexion and extension movement, a hand function rehabilitation device has been developed that can open and close the hand. The device particularly targets stroke patients who have paralysis in one side of their body. The device is capable of flexing and extending the hand fingers repetitively by using a wire driven mechanism. Furthermore, the device can also assist the patient to perform bilateral movement [24].

For individuals who have temporarily lost the ability to control the hand muscles properly due to spinal cord injury or stroke, a rehabilitation device has been developed that operates based on EMG signals. Furthermore, intended hand motions are recognised by the device and actuators help the fingers to perform the desired hand motion, for example, flexion or extension [25].

For the purpose of hand rehabilitation from injuries, a hand exoskeleton device has been designed and developed [26]. The device allows four degrees of freedom for each finger (i.e., 2 DOF at MCP joint and 1 DOF at PIP and DIP joint).

In our design and development of a hand exoskeleton, this paper addressed the shortcomings of releated work and developed a novel fifteen degrees of freedom hand using a new concept of full flexion by using an L-shaped structure rather than employing spring usage. Four fingers have the same mechanism, while the thumb has a different mechanism, since it has a different structure from the other fingers

6. Human hand anatomy and degrees of freedom

From the anatomy of the human hand shown in Figure 1, it can be seen that the index, middle, ring and little finger have three phalanges, while the thumb only has two phalanges. Furthermore, it is evident from the anatomy of the human hand that it consists of segments that are held together by joints. A kinematical model of the hand is therefore required to model the articulation of fingers. A hand kinematical model that has been developed is shown in Figure 2 [27].

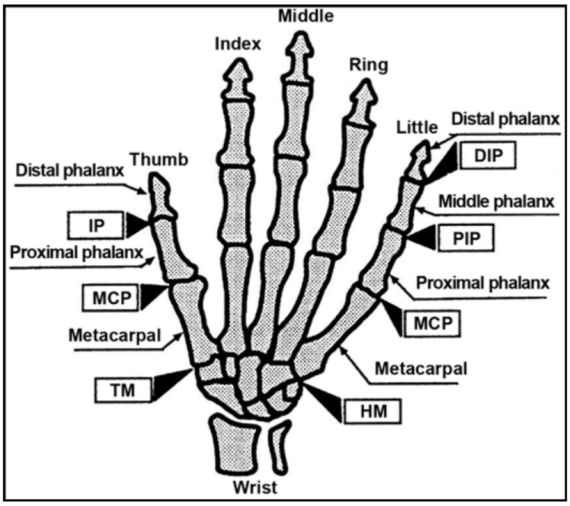

Figure 1. Anatomy of human hand

There are 27 degrees of freedom in the hand kinematical model, as shown in Figure 2. There are in total 21 degrees of freedom for the fingers; the rest of the degrees of freedom are from translation (3 DOF) and (3 DOF) for rotation of the palm [19]. The index, middle, ring and little finger each has four degrees of freedom. In addition, the proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints of these fingers have one degree of freedom and the metacarpophalangeal (MCP) joint of these four fingers has two degrees of freedom.

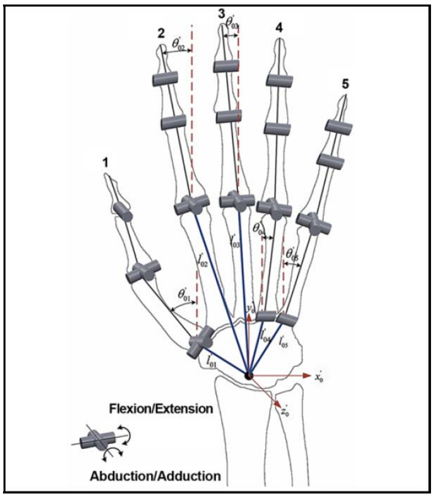

Figure 2. Kinematical model of the human hand

The PIP and DIP joints have one degree of freedom; consequently, these joints can only perform flexion or extension motion. The MCP joint has two degrees of freedom and it can additionally perform abduction/adduction motion [28]. The bone arrangement of the thumb is different from the other fingers; the thumb has five degrees of freedom. The trapeziometacarpal (TM) and metacarpophalangeal (MCP) joints of the thumb has two degrees of freedom and the interphalangeal (IP) joint has one degree of freedom.

7. Hand finger motions

By articulation of the 21 degrees of freedom of the hand's fingers, the Abduction/Adduction and Flexion/Extension motions are created as shown in Figure 3. Flexion movement refers to rotating the fingers in the direction of the palm, while extension movement refers to rotating the fingers away from the palm. Furthermore, flexion/extension motion occurs at each of the four joints of the finger. Abduction motion refers to spreading the fingers apart from each other, while adduction motion refers to bringing the fingers close to each other. Moreover, abduction and adduction motion occurs at the metacarpophalangeal joint of the fingers. In addition, the abduction/adduction of the thumb occurs at the metacarpophalangeal and trapeziometacarpal joints [19].

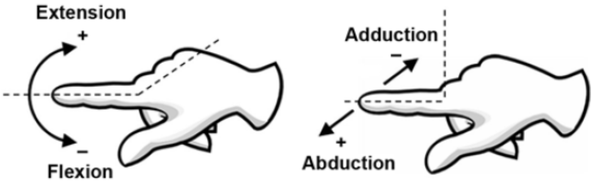

Figure 3. Illustration of finger motions (Abduction /Adduction and Flexion/Extension)

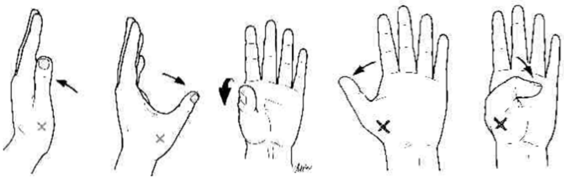

Figure 4. Illustration of thumb motions (Abduction/Adduction and Flexion/Extension)

Figure 4 shows that flexion/extension motion of the thumb occurs in a plane parallel to the palm, while abduction/adduction motion of the thumb occurs in a plane perpendicular to the palm [21].

8. Human hand constraints

Random gestures cannot be made by the hand, as there are some limitations with regard to finger motion. For instance, the ring finger bends when we try to bend the little finger and there is a limitation on how much we can bend our fingers backwards. The usual hand motions are defined by these constraints.

The constraints of the human hand can be separated into three different categories. The first category of constraints concerns the limitations that are imposed on the hand due to its anatomy. This is called static constraint. The second category of constraints, which is also known as dynamic constraints, are limitations that are enforced on the finger joints when they are in motion. The third category of constraints is natural hand motion, which concerns the usual movements of the human hand [28].

8.1 Static constraints

As mentioned earlier, static constraints are associated with the limitations that are enforced on finger motion due to the hand's anatomy. These constraints can be expressed by the following set of equations [28]:

$$\begin{gathered} 0° \le \theta_{MCP\_F} \le 90° \\ 0° \le \theta_{PIP\_F} \le 110° \\ 0° \le \theta_{DIP\_F} \le 90° \\ -15° \le \theta_{MCP\_AA} \le 15° \end{gathered} \qquad (1)$$

In the above equations, the F subscript refers to flexion motion and the AA subscript refers to abduction or adduction motion of the fingers. From the above equations it can be seen that minor abduction/adduction motion occurs in the metacarpophalangeal joint of the middle finger; consequently, for the middle finger, the following estimation can be made:

$$\theta_{MCP\_AA} \approx 0° \qquad (2)$$

Furthermore, as the DIP, PIP and MCP joints of the middle, ring, index and little fingers have single degrees of freedom, all of these joints translate in a single plane.

8.2 Dynamic constraints

Dynamic constraints are enforced on the finger joints when the fingers are in motion. Additionally, these constraints can be further divided into inter finger and intra finger dynamic limitations. Joints of the same finger have some limitations among themselves and these constraints are known as intra finger constraints. As shown in Figure 5, for natural flexion of the fingers, the distal interphalangeal joint should flex two thirds as much as the proximal interphalangeal joint has flexed [20].

Figure 5. Relationship between distal and proximal interphalangeal joint rotation angle

On the other hand, the joints of the different fingers have some limitations among themselves and these constraints are known as inter finger constraints. An example of such a constraint is that the metacarpophalangeal joint of the middle finger is forced to flex when the metacarpophalangeal joint of the index finger flexes.

8.3 Natural hand motion constraints

These kinds of constraints occur due to the usual movement of the human hand; to date, no work has been done to quantify these constraints. Furthermore, these constraints are the result of normal hand motions and different from the dynamic constraints that are enforced on the hand due to its anatomy [28]. An example of such a constraint is when a person tries to make a fist, he/she flexes all the fingers together rather than flexing one finger at a time. Furthermore, while these kinds of constraints vary among different individuals, the variation is negligible. Additionally, these kinds of constraints cannot be explained by using equations.

9. Design Objectives and Scope

With consideration to human hand anatomy, our design objectives and scope are:

a) Based on the flexion and extension of the unimpaired hand's fingers, flex and extend the impaired hand's fingers of the stroke patient.
b) The remedial system will be used by stroke patients that have limited hand motor function in one side of the body. Our system deals with the left side.
c) The system should be easy enough to operate so that an occupational therapist can train stroke patients on how to use it at home (i.e., in terms of operation, it should only require turning an ON or OFF command and finger flexion data from the user).
d) The system should not require any communication with a computer.
e) The system should be lightweight (less than 2kg).
f) The stroke patient should be able to move both their hands freely while wearing the system.
g) With minimal change in design, the system needs to fit various hand sizes.
h) The system needs to allow the hand to have at least 15 degrees of freedom (DOFs).
i) The system needs to be portable and the user should be able to move around a room while wearing the device.

10. Design of the device

As the device has to allow the patient to control the motion (flexion/extension) of the impaired hand's fingers based on the motion of the unimpaired hand's fingers, the complete design of the device is separated into three stages. The first stage is the mechanical design of the exoskeleton that will be fitted on the impaired hand of the patient. The second stage is the control glove deign that will be fitted on the healthy hand of the patient. The third stage is control system design.

10.1 Computer aided design of the hand exoskeleton

Index, middle, ring and little fingers have the same extension and flexion movements and the same number of bones. Thus, the same mechanism has been developed for these four fingers and is shown in Figure 6. The thumb has a different structure from all the other fingers; consequently, a different mechanism has been developed for the thumb. The basic structure ideation of the flexion/extension mechanism originated from the finger flexion splint made by "Homecraft Rolyan". The final design concept is based on the improvement that was made by analysing the results obtained from the simulation process. The design and simulation of the device was conducted using the computer aided-design software "SolidWorks".

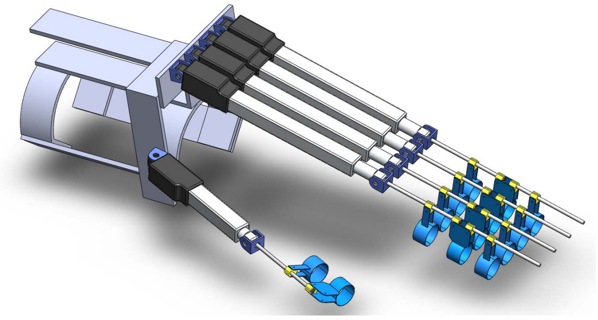

Figure 6. Initial design of the hand exoskeleton

The index finger was selected for simulation to represent the other fingers – middle, ring and little finger – which have similar arrangement between the bones in the hand's anatomy.

As can be seen from Figure 7, the index finger flexion/extension mechanism contains three supporting structures, which are located at the proximal phalanx (PP), middle phalanx (MP) and distal phalanx (DP), as well as two connecting rods. Connecting rod 1 connects the proximal phalanx with the middle phalanx, while connecting rod 2 connects the distal phalanx with the middle phalanx.

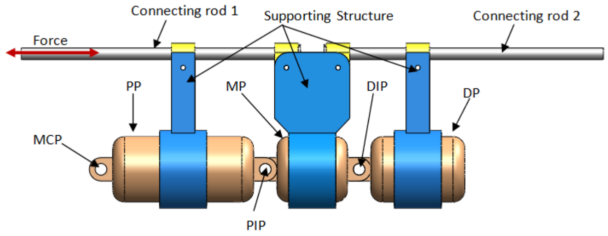

Figure 7. Initial design concept of the index finger

The force that is shown in connecting rod 1 is from the linear actuator, which will be mounted on the arm of the user as shown in Figure 6. Connecting rod 1 can slide from left to right and vice versa, and when force is applied from left to the right, it will cause the middle phalanx's supporting structure to move to the right, causing the finger to flex. On the other hand, when the linear actuator pulls the connecting rod causing it to move from right to the left to the middle, the phalanx supporting structure will also move to the left, causing the finger to extend. While the above mechanism can achieve full flexion/extension of the metacarpophalangeal (MCP) joint and proximal interphalangeal (PIP) joint, how much flexion/extension of the distal interphalangeal (DIP) joint can be obtained by the mechanism is still unknown. To be able to determine the flexion/extension of the DIP joint, a computer simulation of the current mechanism is required.

Considering the natural flexion of the finger, as Figure 8 illustrates the finger mechanism, when the distance between the proximal phalanx and middle phalanx supporting structure (i.e., Distance 1) increases, the corresponding proximal interphalangeal (PIP) joint flexion will also increase. Similarly, when the distance between the distal phalanx supporting structure and middle phalanx supporting structure (i.e., Distance 2) increases, the corresponding distal interphalangeal (DIP) joint angle will also increase. For natural flexion of the finger, the DIP joint should flex 2/3 times as much as the PIP joint. Based on the above observations and constraints, two simulations of the index finger mechanism were conducted.

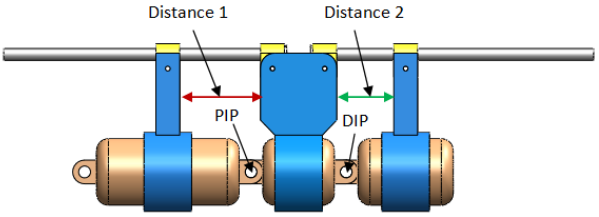

Figure 8. Finger mechanism parameters to analyse for simulation

Figure 9 shown a visual output of the results of the two simulations. In the first simulation, force to connecting rod 1 was provided from the linear actuator stroke and the position of the index finger mechanism after running the simulation for 3 seconds, as shown on the left side of Figure 9. In the second simulation, three rotary motors were placed at MCP, PIP and DIP joints of the index finger. Motors 1 and 2 were set to the same speed and the speed of motor 3 was set to two thirds the speed of motor 2 in order to simulate the constraint of finger motion. The final position of the index finger after running the simulation for 1.36 seconds is shown on right side of Figure 9.

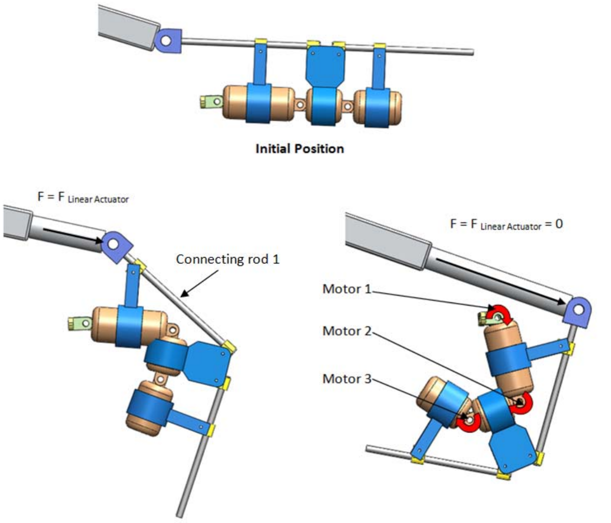

Figure 9. Simulation results (visual output)

The first simulation was conducted to analyse what the actual response of the finger mechanism would be when subjected to force from the linear actuator. The second simulation was conducted to approximate how distances 1 and 2 would change when a person tried to flex the finger without the assistance of the force from the linear actuator. The quantitative results of simulations 1 and 2 are shown in Figures 10 and 11.

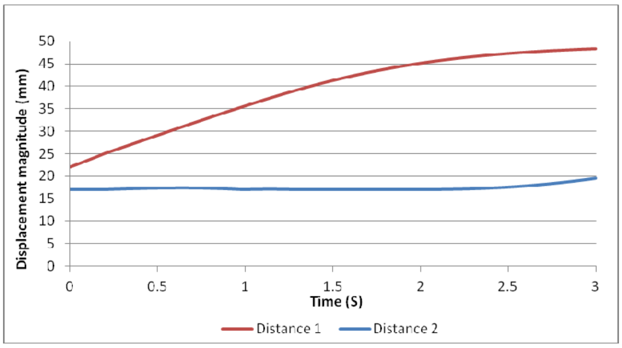

Figure 10. Simulation 1 result

Figure 11 illustrates that without the assistance of the linear actuator when the finger was flexed, distance 2 increased along with the increase in distance 1. On the other hand, Figure 11 shows that when force was applied to the finger mechanism in order to flex the finger, distance 2 did not increase alongside the increase of distance 1.

As the displacement magnitude between distal phalanx and middle phalanx was very small, it indicated that the DIP joint will flex very little with the current finger mechanism. Thus, the design options for full flexion of the DIP joint of the index finger includes either using a spring between the distal phalanx and middle phalanx (as shown in Figure 12, left), or using a L shape structure (as shown in Figure 12, right).

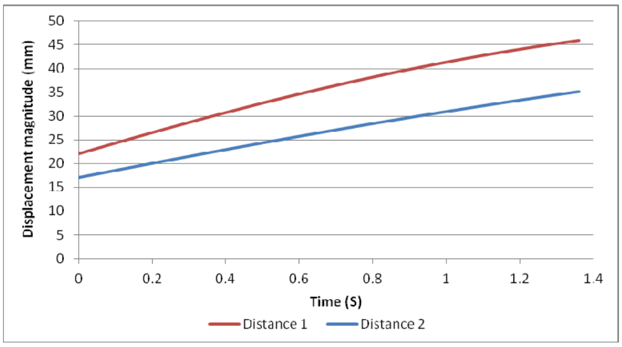

Figure 11. Simulation 2 results

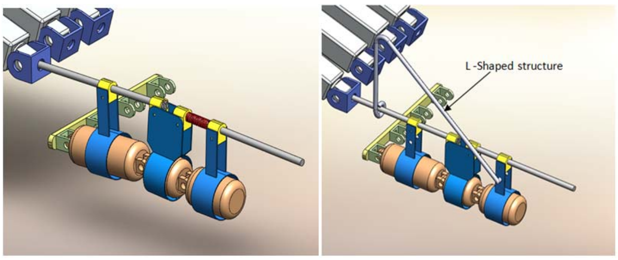

Figure 12. Spring mechanism to achieve full DIP flexion; L-shaped structure to achieve full DIP flexion

The option to use the L-shaped structure was chosen, as the spring would provide constant force to the distal phalanx supporting structure, which might cause the structure to come out during operation. In addition, as the spring's stiffness will change over time, it will reduce the reliability of the device.

The thumb design is shown in Figure 13. The thumb flexion/extension mechanism is somewhat similar to the index finger mechanism, with some modifications made to it. It contains two supporting structures that are located at the proximal phalanx (PP) and distal phalanx (DP), and one connecting rod.

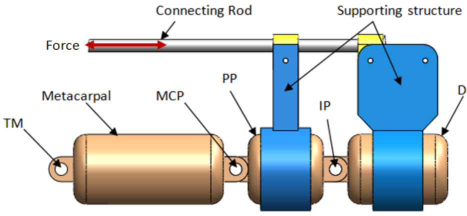

Figure 13. Initial design concept of the thumb

Furthermore, the connecting rod connects the distal phalanx with the proximal phalanx. When the linear actuator extends, it will cause the connecting rod to move to the right, which will also cause the distal phalanx supporting structure to move to the right. Thus, the thumb will be flexed. Contrarily, when the linear actuator retracts, the distal phalanx supporting structure will be pulled to the left, which will cause the thumb to be extended. The final design is shown in Figure 14.

In terms of designing the hand exoskeleton's degree of freedom, Figure 15 shows the DOF that the hand's fingers will have when wearing the exoskeleton, where each joint represents 1 DOF. Furthermore, each of the joints can be flexed by the exoskeleton. After analysing how many degrees of freedom the hand will be constrained by the exoskeleton, it was found that it would constrain 6 DOFs of the fingers; as a result, it can be concluded that the exoskeleton can achieve full flexion and extension motion of the hand fingers with 15 DOF.

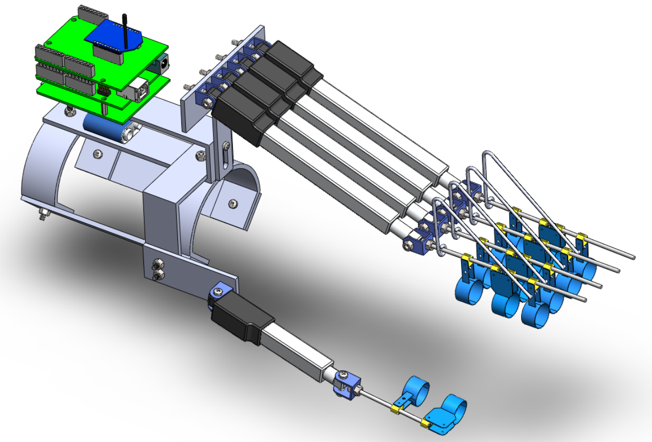

Figure 14. Final design of the exoskeleton

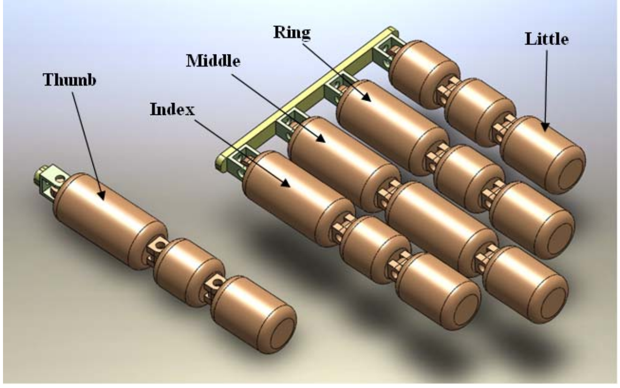

Figure 15. Degrees of freedom of the hand after wearing the exoskeleton

10.2 Control glove design

The purpose of the control glove is to give the patient control over flexing/extending his/her impaired hand's fingers through movement of the healthy hand's fingers.

As flexion or extension movement have to be sensed, flex sensors will be used with each finger, as shown in Figure 16. The flex sensors will be inserted inside a custom made hand glove, which will have pockets in each finger so that the flex sensors can be inserted into them.

The output of the flex sensor will then be sent to the microcontroller for further processing. The microcontroller will be mounted on the arm with the help of a clip connector and armband, as shown in Figure 16.

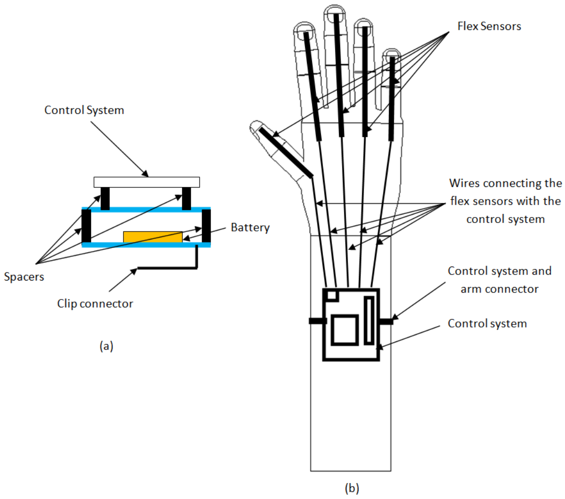

Figure 16. Control glove design concept

The operating principle of the flex sensor works based on the changing of the sensor resistance. As the sensor is flexed, its resistance increases; this change in resistance can be used to detect how much the fingers have flexed, as shown in Figure 17.

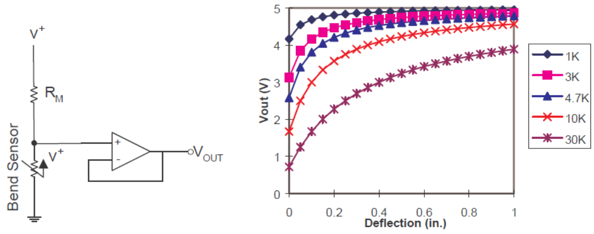

Figure 17. Output voltage versus deflection of the flex sensor

For the purpose of detecting deflection, the flex sensor is used in the voltage divider configuration, as shown in Figure 17. The deflection sensitivity range can be adjusted by the R_M resistor. An operational amplifier is suggested to be used with the flex sensor, as the low bias current of the operational amplifier decreases inaccuracy due to source impedance of the flex sensor as voltage divider.

10.3 Control system design

The ATmega 328 microcontroller was used for development of the control system. The position of the right hand fingers is determined by the flex sensors and sent to the microcontroller unit. Based on the values received from the flex sensors, the microcontroller unit calculates how much the linear actuator stroke should be extended or retracted. Using a radio transmitter, receiver data is sent wirelessly to the other microcontroller placed at the left hand. The 2.4GHz XBee module will be used for radio transmitter, thereby allowing consistent and straightforward communication between microcontrollers. Each XBee has to be assigned a unique ID and will also have information about the other Xbee it will be communicating with, as well as its special personal area network (PAN) ID. It was taken in account that all Xbees that are communicating with each other have to be included in the same personal area network. Finally, the microcontroller on the left hand controls the movement of the linear actuators based on the data received. Figure 18 illustrates the flow chart of the program for the microcontrollers of the hand exoskeleton and control glove. The system uses an open loop controller. Figure 19 shows the data transmission framework between the two parts of the system.

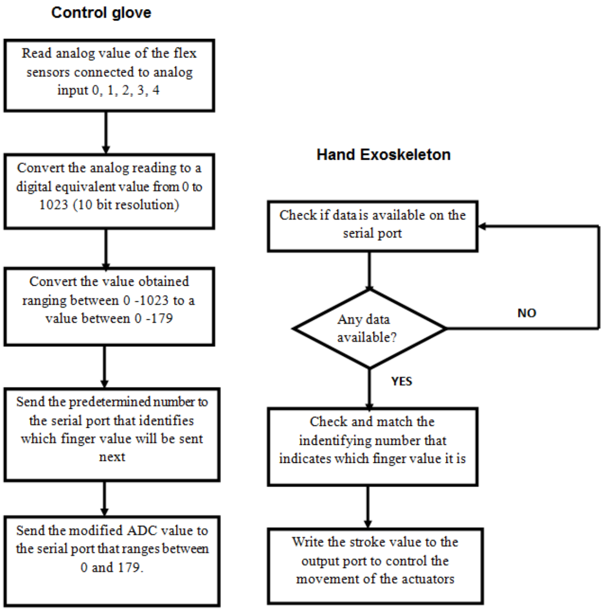

Figure 18. Hand exoskeleton and control glove microcontroller program flow chart

11. Prototype testing

The completed prototype of the hand exoskeleton was mounted on the hand as shown in Figure 20. The device allowed for complete flexion/extension of the hand fingers. The only problem faced during testing was that the L-shaped structure did not remain vertical during motion of the fingers; however, this can be improved. All the design objectives were achieved, including a light weight of 1.8kg; this includes the battery, which can be allocated separately (see Figure 20).

Figure 20. Testing of the hand exoskeleton

The mounting of the control glove is shown in Figure 21. The glove was able to accurately determine the flexion of the fingers. Furthermore, the signals sent by the flex sensors were successfully processed in the microcontroller, which was mounted on the wrist during testing, as shown in Figure 22.

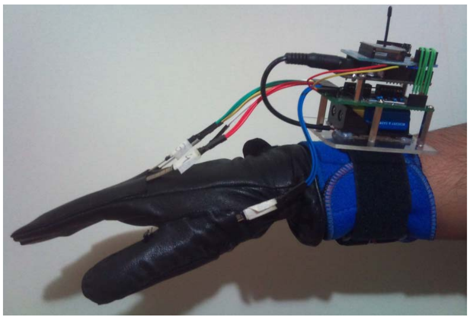

Figure 21. Testing of the control glove

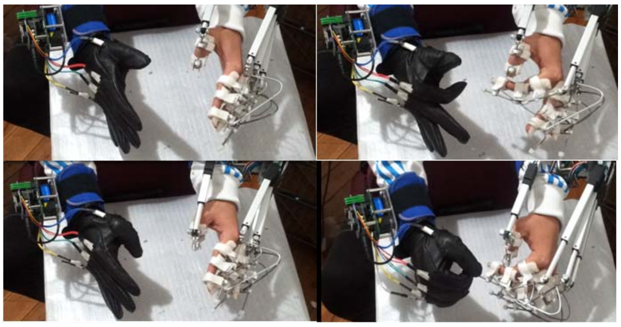

Figure 22. Complete system testing

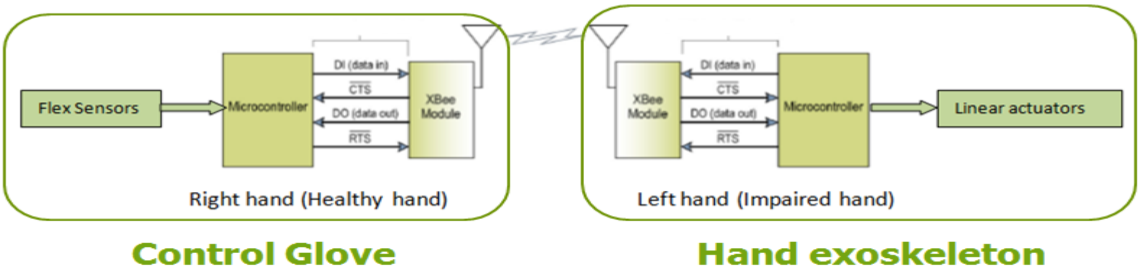

Figure 19. Data transmission system framework

12. Other applications of the device

The rehabilitation device developed in this paper can be used for various other hand rehabilitation exercises. The device can be used for unilateral training of the impaired hand. One possible implementation would be to use EMG electrodes in the impaired hand's biceps and thereby assist the patient in performing the desired hand motion. Furthermore, brain signals can be used to perform flexion/extension motion of the hand.

13. Conclusion

This paper presented a hand function rehabilitation device design. The major aims work were to design a device that could fit various hand sizes and be both portable and lightweight. The device was able to achieve full flexion/extension motion of the four fingers and thumb of the left hand, based on the motion of the identical digits of the right hand. For the prototype construction of the arm mount of the exoskeleton, aluminium was chosen, as it is lightweight. In order to achieve better accuracy, feedback control needs to be developed in future, as the device currently has open loop control. Although the device can perform extension and flexion movement, it cannot perform abduction/adduction movement; therefore, more work needs to be done on the device in order to achieve complete 21 degrees of freedom (DOFs) of the hand's fingers. Testing of the device on actual stroke survivors, as well as further discussions with therapists for suggestions are necessary for modification.

14. References

[1] Geurts, A.C, Hendricks, H.T, Limbeek, V.J., Zwarts, M.J. (2002) Motor recovery after stroke: a systematic review of the literature. Arch. Phys. Med. Rehabil. 83: 1629-1637.

[2] Schaechter, J.D. (2004) Motor rehabilitation and brain plasticity after hemiparetic stroke. Progress in Neurobiology. 73: 61-72.

[3] Cauraugh, J.H., Summers, J.J. (2005) Neural plasticity and bilateral movements: a rehabilitation approach for chronic stroke. Progress in Neurobiology. 75: 309-320.

[4] Cauraugh, J.H., Garry, M.I., Hiraga, C.Y., Loftus, A., Kagerer, F.A., Summers, J.J. (2007) Bilateral and unilateral movement training on upper limb function in chronic stroke patients: a TMS study. Journal of the Neurological Sciences. 252: 76-82.

[5] Hallett, M. (2001) Plasticity of the human motor cortex and recovery from stroke. Brain Research Reviews. 36: 169-174.

[6] Winstein, C.J., Wing, A.M., Whitall, J. (2003) Motor control and learning principles for rehabilitation of upper limb movements after brain injury. In: Boller, F., Grafman, J., Robertson, I.H., editors. Handbook of Neuropsychology. pp.77-137.

[7] Nudo, R.J., Wise, B.M., SiFuentes, F., Milliken, G.W. (1996) Neural substrates for the effects of rehabilitative training on motor recovery after ischemic infarct, Science. 272: 1791-1794.

[8] Cooper, S.J., Donald, O. (2005) Hebb's synapse and learning rule: a history and commentary. Neurosci. Biobehav. Rev. 28: 851-874.

[9] Benner, T., Cramer, S.C., Dijkhuizen, R.M., Finklestein, S.P., Hilliard, T.S., Kraft, E., Rosen, B.R., Schaechter, J.D. (2002) Motor recovery and cortical reorganization after constraint-induced movement therapy in stroke patients: a preliminary study. Neurorehabilitation Neural Repair. 16: 61-72.

[10] Taub, E., Uswatte, G., Elbert, T. (2002) New treatments in neurorehabilitation founded on basic research. Nat. Rev. Neurosci. 3: 228-236.

[11] Liepert, J., Uhde, I., Graf, S., Leidner, O., Weiller, C. (2001) Motor cortex plasticity during forced-use therapy in stroke patients: a preliminary study. Journal of Neurobiology. 248: 315-321.

[12] Coupar, F., Langhorne, P., Pollock, A. (2009) Motor recovery after stroke: a systematic review. Lancet Neurol. 8: 741-754.

[13] Liepert, J., Miltner, W.H.R., Bauder, H., Sommer, M., Dettmers, C., Taub, E., Weiller, C. (1998) Motor cortex plasticity during constraint-induced movement therapy in stroke patients. Neuroscience Letters. 250: 5-8.

[14] Summers J.J., Semjen, A., Carson, R.A., Thomas, J. (1995) Going around in circles: the dynamics of bimanual circle drawing. In: Glencross D, Piek J, editors. Motor Control and Sensory Motor Integration. pp. 231-253.

[15] Li, J., Wang, S., Wang, J., Zheng, R., Zhang, Y., Chen. Z. (2012) "Development of a hand exoskeleton system for index finger rehabilitation," Chinese Journal of Mechanical Engineering, vol. 25, pp. 223-233.

[16] Yihun, Y., Miklos, R., Perez-Gracia, A., Reinkensmeyer, D. J., Denney, K. and Wolbrecht, E. T. "Single Degree-of-Freedom Exoskeleton Mechanism Design for Thumb Rehabilitation," in Engineering in Medicine and Biology Society (EMBC), 2012 Annual International Conference of the IEEE, 2012, pp. 1916-1920.

[17] Chiri, A., Vitiello, N., Roccella, S., Vecchi, F., Carrozza, M. C. "Mechatronic Design and Characterization of the Index Finger Module of a Hand Exoskeleton for Post-Stroke Rehabilitation," Mechatronics, IEEE/ASME Transactions on, V. 17, 2012, pp. 884-894.

[18] Ueki, S., Kawasaki, H., Nishimoto, Y., Abe, M., Aoki, T., Ishigure, Y., Ojika, T., Mouri, T. "Development of a Hand-Assist Robot With Multi-Degrees-of-Freedom for Rehabilitation Therapy" ,Mechatronics, IEEE/ASME Transactions on, V 17,2012, pp. 136-146.

[19] Brokaw, E. B., Black, I., Holley, R. J., Lum, P. S. "Hand Spring Operated Movement Enhancer (HandSOME): A Portable, Passive Hand Exoskeleton for Stroke Rehabilitation," IEEE Transactions on Neural Systems and Rehabilitation Engineering, on, vol. 19, pp. 391-399, 2011.

[20] HyunKi, I., Kyu-Jin, C., KyuRi, K., Bumsuk, L. "Jointless structure and under-actuation mechanism for compact hand exoskeleton," in Rehabilitation Robotics (ICORR), 2011 IEEE International Conference on, 2011, pp. 1-6.

[21] Iqbal, J., Tsagarakis, N., Caldwell, D. "Design of a Wearable Direct-driven Optimized Hand Exoskeleton Device," in ACHI 2011, The Fourth International Conference on Advances in Computer-Human Interactions, 2011, pp. 142-146.

[22] Burton, T., Vaidyanathan, R., Burgess, S., Turton, A., Melhuish, C. "Sensitivity Analysis of a Parametric Hand Exoskeleton Designed to Match Natural Human Grasping Motion," Advances in Autonomous Robotics, pp. 390-401, 2012.

[23] Mohamaddan, S., Osman, M.S. (2008) Development of Grip Mechanism Assistant Device for Finger Rehabilitation. Service Robotics and Mechatronics. pp. 95-100.

[24] Komeda, T., Mohamaddan, S. (2010) Wire-Driven Mechanism for Finger Rehabilitation Device. International Conference on Mechatronics and Automation, pp. 1015-1018.

[25] Folgheraiter, M., Gini, G., Mulas, M. (2005) An EMG-controlled Exoskeleton for Hand Rehabilitation, In the 9th International Conference on Rehabilitation Robotics, Chicago, IL, USA. pp. 371-374.

[26] Hommel, G., Kondak, K., Wege, A. (2006) Development and Control of a Hand Exoskeleton for Rehabilitation. Human Interaction with Machines, pp. 149-157.

[27] Chen, I.M., Li, K., Lim, C.K., Yeo, S.H. (2010) Development of finger-motion capturing device based on optical linear encoder. Journal of Rehabilitation Research & Development. 48: 69-82.

[28] Lin, J., Wu, Y., Huang, T.S. (2000) Modeling the Constraints of Human Hand Motion, Beckman Institute.