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# Design and development of a hand exoskeleton for rehabilitation following stroke

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**Abstract**

In Australia, a major cause of disability is the stroke and it is the second highest cause of death after coronary heart disease. Studies have predicted that form 2008 to 2017 more than 0.5 million people is likely to suffer from stroke in Australia. In addition, after stroke 88 % of the patients suffer from disability and stays at home. In this paper, a post stroke therapeutic device has been designed for hand motor function rehabilitation that a stroke survivor can use for bilateral movement practice. Out of twenty-one degrees of freedom of hand fingers, the prototype of the hand exoskeleton allowed fifteen degrees of freedom. The device is designed to be portable so that the user can engage in other activities while using the device. A prototype of the device is fabricated to provide complete flexion and extension motion of individual fingers of the left hand (impaired hand) based on the movements of the right hand (healthy hand) fingers. In addition, testing of the device on a healthy subject was conducted to validate if the design met the requirements.



*Keywords*: Hand exoskeleton, stroke, bilateral theraphy, rehabilitation.

**Nomenclature**

| | |
|---|---|
| DOFs | degrees of freedom |
| MCP | metacarpophalangeal |
| PIP | proximal interphalangeal |
| DIP | distal interphalangeal |
| MAL | motor activity log |

## 1. Introduction

Stroke can cause deficiency in various neurological areas and mainly it causes disability in the motor system [1]. A general state in most of the stroke survivor is paralysis of one side of the body. Motor rehabilitation research has shown that to speed up the recovery process of the upper limb function, activity dependent interventions can be used to assist the use of paralyzed limb [2]. To be able to understand and repair the hand motor function after a person undergoes stroke has been the major focus of rehabilitation research as human hand play a vital role in the daily life activities. Furthermore, in the rehabilitation of the hand motor function the major concern has been how to achieve the optimum restoration of hand

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function. While positive outcomes have been obtained from therapies in general, the stroke patients who have undergone harsh, moderate or mild motor deteriorations, an optional therapy known as bilateral movement training has demonstrated positive results. In addition, based on neurophysiological and behavioral mechanisms an immense assurance in hastening upper limb chronic stroke recovery has been shown by bilateral movement practice [3]. In comparison to unilateral training patients obtaining bilateral training indicated better improvement of the upper extremity functions and decrease in movement time of the damaged limb [4]. The major aim of the 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 plasticity of the human brain.

## 2. Activity-dependent intervention

Rehabilitation is important issue in the management of stroke patient. From results of animal study it has been shown that, if a motor cortex area of a monkey is affected it could use an alternative cortical areas to overcome the functional inability [5]. Neural plasticity may be rapid and gradual and this knowledge is very important to chalk out the rehabilitation training program for stroke patients. According to neurophysiology, synapse fallows some rules. Hebbian synapse rule states that specific synaptic junctions respond to activity (use) and inactivity (disuse) [6]. Distinctively neural plasticity changes develop from the Hebbian synapse rule. To be precise, information storage in neural networks is triggered by activity-dependent continuing alteration of synaptic efficacy. Considering the above mentioned statements it could be concluded that motor experiences, including rehabilitation interventions, considerably influence post stroke recovery levels [7]. A generalized idea concluded is that, the neurons that remains automatically linked to the damaged site increasingly take up the functions of the injured areas with progress of time and with increased connectivity.

Usually, the first three months following stroke is very vital for planning treatment modalities to restore the functions of the affected side in stroke patients. Afterwards, the patient reimburse the works of the affected side for daily activities by using the healthy side [8],where the healthy limb is purposefully inhibited or restricted to take of the work of affected side and pressure is created on the patient to use their affected limb vigorously. Outcome of this procedure is good [9]. In many cases motor functions were improved significantly [10].

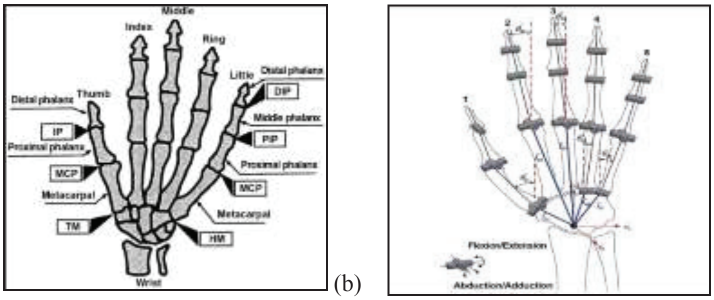
It has been shown from different studies that in case of healthy adult if two hands simultaneously work to perform something, with the influence of both psychological and neural mechanism, the outcome is better, which is a stimulus to think of to apply it in case of stroke patients. When two hands moves together something occurs due to some interactions in between, which is responsible for better action and that is the powerful temporal and spatial interactions. These includes: (a) a tendency towards rate and time locking between the limbs (b) amplitude coupling (i.e., a tendency toward same movement amplitudes when different amplitudes are designed to the two hands) (c) direction coupling (i.e., first choice to move the effectors in the same way) (e) mutual accommodation or obstruction between different geometric forms (i.e., circle and line) drown simultaneously with each hand [11]. It could be concluded that mirror-symmetrical movements are a classic coordination mode in the mode list of human. It has been observed in healthy adult that if dominant and non-dominant limbs are used together to draw a circle for some time, the performance of non-dominant limb is increased [12].

## 3. Current research on hand function rehabilitation

The research conducted in [13] had developed the design of a grip mechanism assistant device that can be employed for finger rehabilitation. The initial device consisted of the index and the thumb finger. Since the index and the thumb have a different extension and flexion movement, and different number of bones, different mechanism for each finger were developed [13]. In other work, a robotics based rehabilitation device have been developed that can perform the hand grasping and releasing based on the finger extension and flexion movement. The device employed the wire-driven mechanism to perform the finger extension and flexion movement. The device can assist repetitive finger extension and flexion movement during the rehabilitation period. The actuating system of the device enables the patient to control the movement by using the self-motion control concept [14].While in other research, a hand exoskeleton device has been developed for people who have partially lost the ability to control correctly the hand musculature. Based on EMG signals the system can understand the subject volition to move the hand and actuators can help the fingers movement in order to perform the task [15]. In the study conducted by Hommel et al a hand exoskeleton design has been developed where each finger has four degrees of freedom; flexion and extension in (MCP) joint, (PIP) joint, and (DIP) joint; and abduction/adduction in MCP joint [16].

## 4. Kinematical model of the hand

The human hand is highly articulated. To model the articulation of fingers, the kinematical structure of hand should be modeled. A hand kinematical model had been developed by [18] as shown in fig.1 (b). This kinematical model has 27 Degrees of Freedom (DoFs). Each of the four fingers has four DoFs. The distal interphalangeal (DIP) joint and proximal interphalangeal (PIP) joint each has one DoF and the metacarpophalangeal (MCP) joint has two DoF due to flexion and abduction. The thumb has a different structure from the other four fingers and has five degrees of freedom, one for the interphalangeal (IP) joint, and two for each of the thumb MCP joint and trapeziometacarpal (TM) joint both due to flexion and abduction. The fingers together have 21 DoFs. The remaining 6 degrees of freedom are from the rotational and translational motion of the palm with 3 DoFs each [17].

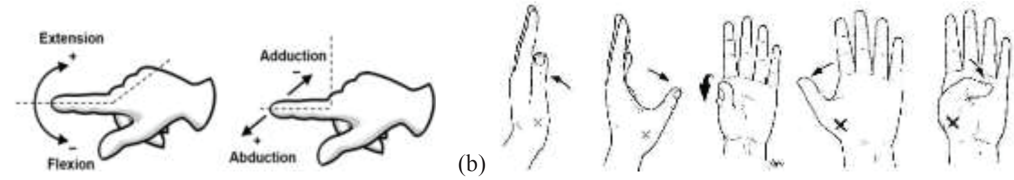



(a) (b)

Fig. 1. (a) Anatomy of human hand , (b) kinematical model of the human hand [18].

## 5. Human hand finger motions

The basic flexion/extension and abduction/adduction of the thumb and fingers are performed by the articulation of the 21 DOFs just described. As shown in fig.2 (a), the flexion/extension motions are used to describe rotations toward and away from the palm, which occur at every joint within the hand. The abduction is the movement of separation (e.g., spreading fingers apart), and the adduction motion is the movement of approximation (e.g., folding fingers together). The abduction/adduction only occurs at each finger's MCP joint and at the thumb's MCP and TM joints. Another two internal DOFs are at the base of the fourth and fifth (ring and little finger's) metacarpals, which perform the curve or fold actions of the palm [18].




(a) (b)

Fig. 2.(a) Illustration of finger motions (Abduction/Adduction and Flexion/Extension) [18] , (b) Illustration of thumb motions (Abduction /Adduction and Flexion/Extension) [19].

As can be seen from the fig.2 (b) the thumb abducts and adducts in a plane perpendicular to the palm and the flexes and extends in a plane parallel to the palm.

Based on the human hand anatomy, kinematical structure, and constraints, the design objectives of our system are:

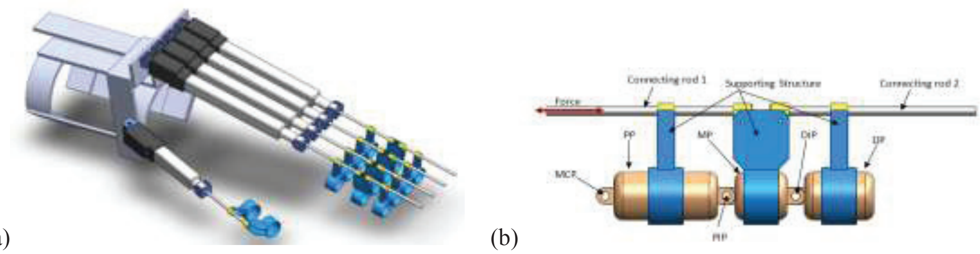
a. The system is based on finger flexion and extension motion and easy to operate and only require turn ON or turn OFF command and finger flexion data and does not require any communication with a computer.
b. The system should be lightweight (less than 2 Kg).
c. The stroke patient should be able to move their both hand freely while wearing the system.
d. With minimal change of the design, the system needs to fit for various hand sizes and be portable.
e. The system needs to allow the hand to have minimum 15 degrees of freedom (DOFs).

## 6. Design of the device

As the device has to allow the patient to control the motion (flexion/extension) of the impaired hand fingers based on the motion of the unimpaired hand fingers, the complete design of the device is separated in three sections. The first section is the computer aided design of the exoskeleton that will be fitted on the impaired hand of the patient, the second section is the control glove deign that will be fitted on the healthy hand of the patient and third section is control system design.

### *6.1. Computer aided design of the hand exoskeleton*

The design of the bilateral movement assistive device is based on the simplicity, easy attachment and fit for all concepts. Index, middle, ring and little fingers have same extension and flexion movement, and same number of bones, as a result same mechanism for these four fingers have been developed which can be seen in the fig.3 (a). The thumb has a different structure from other fingers, and as a consequence, 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 "HomecraftRolyan". The final design concept is based on the improvement that had been made by analyzing the results obtained from the simulation process. The design and simulation of the device had been conducted using "SolidWorks" software.

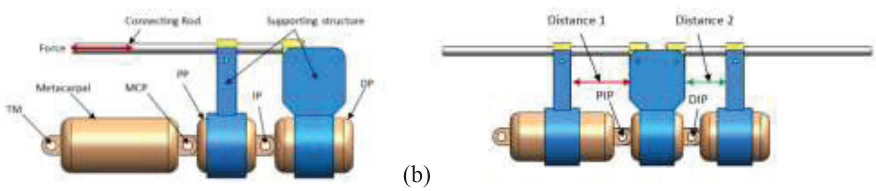



(a) (b)

Fig. 3. (a) Initial design of the hand exoskeleton, (b) Initial design concept of the index finger.

As shown in fig.3 (b), the index finger flexion/extension mechanism contains three supporting structures that are located at Proximal Phalange (PP), Middle Phalange (MP) and Distal Phalange (DP) and two connecting rods. The connecting rod 1 connects the proximal phalange with the middle phalange and the connecting rod 2 connects the distal phalange with the middle phalange. The force that is shown in connecting rod 1 is from the linear actuator. The 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 Phalange supporting structure to move to the right thus causing the finger to flex. On the other hand, when the linear actuator will pull the connecting rod causing it to move from right to the left, thus the Middle phalange supporting structure will also move to left causing the finger to extend. The thumb flexion/extension mechanism is somewhat similar to the index finger mechanism with some modifications made to it as illustrated in fig.4 (a). It contains two supporting structures that are located at the Proximal Phalange (PP) and Distal Phalange (DP) and one connecting rod. Furthermore, the connecting rod connects the Distal Phalange with the Proximal Phalange. When the linear actuator will extend it will cause the connecting rod to move to the right, this will also cause the distal phalange supporting structure to move to the right, and as a result, the thumb will be flexed. On the contrary, when the linear actuator will retract the distal phalange supporting structure will be pulled to the left and this will cause the thumb to be extended.

The index finger is selected for simulation to represent the other fingers; middle, ring and little finger which have the similar arrangement between the bones in the hand anatomy. For the above mechanism when the distance between Proximal Phalange and Middle Phalange supporting structure (i.e. Distance 1) will increase the corresponding PIP joint flexion will




(a) (b)

Fig. 4. (a) Initial design concept of the thumb, (b) Finger mechanism parameters to analyze for simulation.

also increase. Similarly when the distance between Distal Phalange supporting structure and Middle Phalange supporting structure (i.e. Distance 2) will increase the corresponding distal interphalangeal (DIP) joint angle will also increase. For natural flexion of the finger, the DIP joint should flex 2/3 times the PIP joint has flexed. Based on the above observations and constraints two simulation of the index finger mechanism has conducted. In fig. 5, two visual simulation results are shown. The force to the connecting rod 1 is provided from the linear actuator stroke and the position of the index finger mechanism after running the simulation for 3 seconds is shown in the left side of fig. 5. On the other hand, in the second simulation three rotary motors were placed at MCP, PIP and DIP joint of the index finger. The motor 1 and 2 were set to same speed and the speed of motor 3 was set to two third the speed of motor 2 to simulate the constraint of finger motion. The final position of the index finger after running the simulation for 1.36 seconds is shown in right side of the fig. 5. The first simulation was conducted to analyze what the actual response of the finger mechanism would be when subjected to force from the linear actuator. Furthermore, the second simulation was conducted to approximate how distance 1 and 2 will

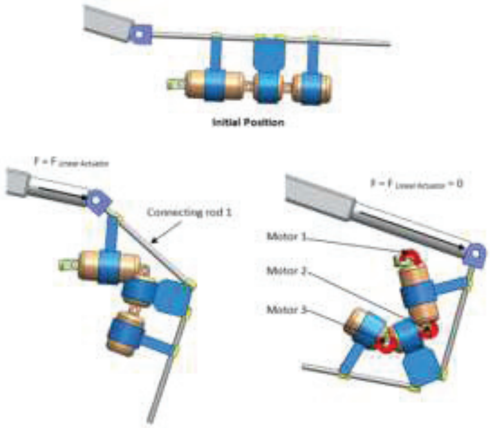
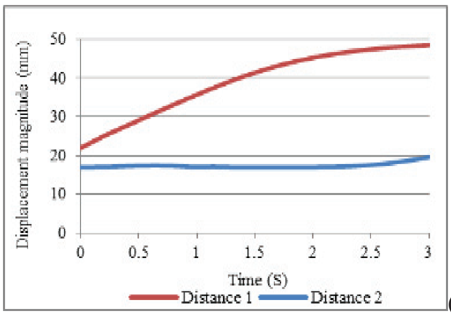



Fig. 5. Simulation results (visual output).

change when a person tries to flex the finger without the assistance of the force from the linear actuator. The quantitative results of simulation 1 and 2 are shown in fig. 6. From fig. 6 (b) it can be noticed that without the assistance of the linear actuator, when the finger is flexed, the distance 2 increases with the increment of distance 1. On the other hand, from Fig. 6 (a) it can be seen that when force was applied to the finger mechanism in order to flex the finger distance 2 did not increase with the increase of distance 1. As the displacement magnitude between distal phalange and middle phalange is very small it indicates that the DIP joint will flex very little with the current finger mechanism. Design options for full flexion of the DIP joint of the index finger includes either to use a spring between the distal phalange and middle phalange as shown in fig. 7 (a) or use a L-shaped like structure as shown in fig. 7 (b). By considering the two design options the option to use the L-shaped like structure has chosen as the spring would provide constant force to the distal phalange supporting structure which might cause the structure to come out during operation. Also as the spring stiffness changes over time it will reduce the reliability of the device. The final design of the exoskeleton is shown in fig. 8 (a).

(a)


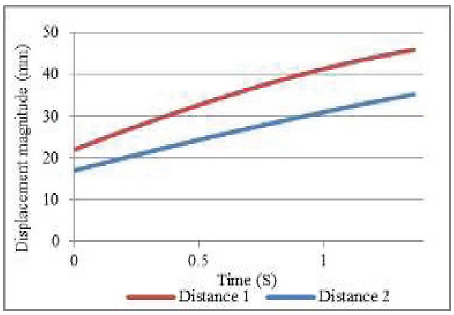
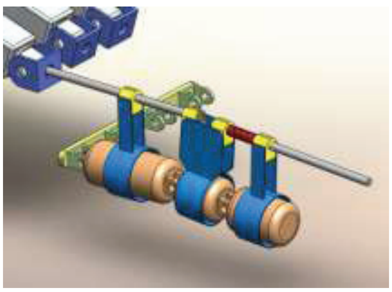

(b)



Fig. 6. a) Simulation 1 result, b) Simulation 2 result.

(a)


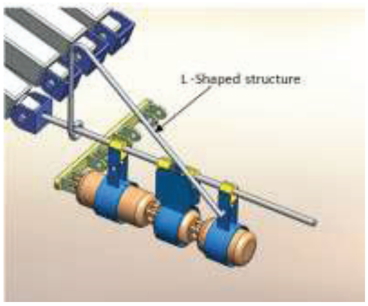
(b)



Fig. 7. a) Spring mechanism to achieve full DIP flexion, b) L-shaped structure to achieve full DIP flexion.

### *6.2. Control glove design*

The controller glove will be a right hand standard commercially available glove that will provide a tight fit to the user. The controller glove will have flex sensors in each of the fingers to accurately determine the position of the finger as shown in fig. 8 (b). The flex sensors provide a resistance of 10K Ohms when flat and a variable resistance of up to 110K Ohms when fully flexed. A 5 V supply will be sent into a 10k Ohm resistor in series with the Flex sensor. The output voltage will be sent to the Microcontroller to determine the position of the finger. Additionally, an OpAmp will be used with the voltage divider configuration to reduce the error. This same set up will be used for all five fingers. The position of the finger found by the microcontroller will determine the amount of flexion of extension that the linear actuators provide to the exoskeleton.

(a) (b)

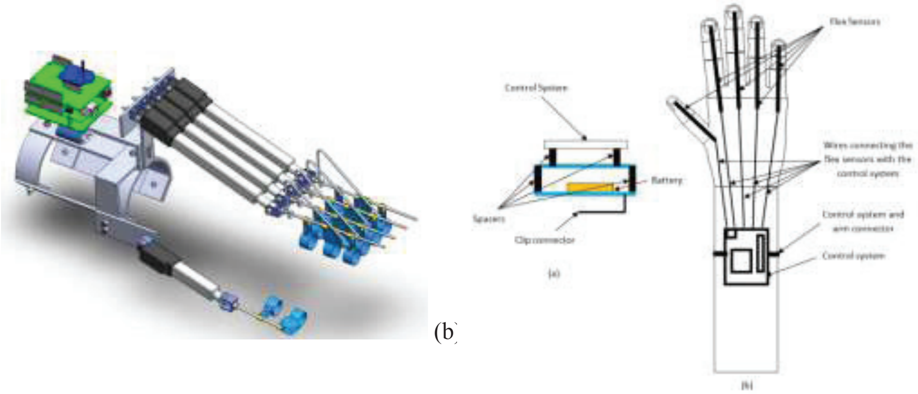


Fig. 8. (a) Final design of the exoskeleton, (b) Control glove design.

### *6.3. Control system design*

The ATmega 328 microcontroller will be used for development of the control system. The position of the right hand fingers will be determined by the flex sensors and sent to the microcontroller unit. Based on the values received from the flex sensors the microcontroller unit will calculate how much the linear actuator stroke should be extended or retracted. By using radio transmitter and receiver data will be sent wirelessly to the other microcontroller placed at the left hand. Finally the microcontroller on the left hand will control the movement of the linear actuators based on the data received.

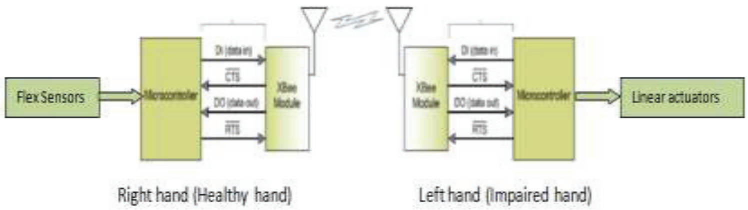



Fig. 9. Control system flow chart.

## 7. Prototype construction and testing

The main structure of the hand exoskeleton was constructed from Aluminum. Aluminum was chosen for prototype construction to keep the weight of the device minimum. The finger flexion splints were bought from "HomecraftRolyan" and changes were made to its structure in order to achieve the desired flexion/extension motion. The final assembled exoskeleton is shown in fig. 10 (a).The exoskeleton was able to achieve full flexion/extension motion of every finger. The prototype of the control glove is shown in fig. 10 (b). A leather glove is modified so that flex sensors could be attached to each fingers. The control system was mounted on the arm by using wrist band and a Perspex base. 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 that is mounted on the wrist.

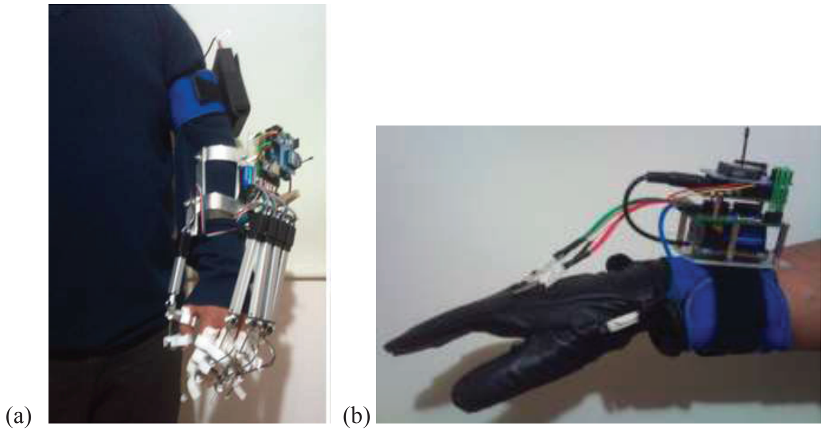



Fig. 10. (a) Prototype of the hand exoskeleton, (b) Prototype of the control glove.

## 8. Conclusion

Development of hand motor function rehabilitation device is based on simple design, easy attachment and universal, has been presented in this paper. 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 currently it has open loop control. Although the device can perform the extension and flexion movement it cannot perform abduction/adduction movement as a consequence more work needs to be done on the device in order to achieve complete 21 Degrees of freedom (DOFs) of the hand fingers. Testing of the device on actual stroke survivors and further discussions with the therapist for suggestion is necessary for modification.

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