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MODEL-BASED SYSTEMS ENGINEERING OF A HAND REHABILITATION DEVICE

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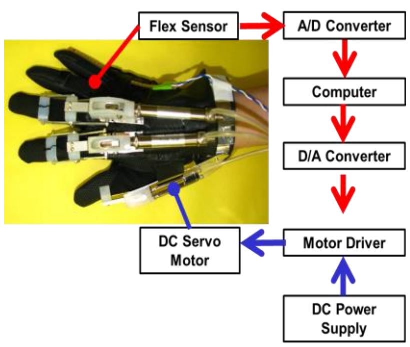
Graphical abstract



Abstract

We have developed a robotic exoskeleton to restore and rehab hand and finger function. The robotic exoskeleton is a hybrid actuated mechanism rehabilitation system, in which each finger is attached to an instrumented lead screw mechanism allowing force and position control according to the normal human setting. The robotic device, whose implemented is based on biomechanics measurements, able to assist the subject in flexion and extension motion. It also compatible with various shapes and sizes of human's finger. Main features of the interface include an integration of DC servo motor and lead screw mechanism which allows independent motion of the five fingers with small actuators. The device is easily transportable, user safety precaution, and offer multiple mode of training potentials. This paper presents the measurements implemented in the system to determine the requirements for finger and hand rehabilitation device, the design and characteristic of the whole system.

Keywords: Continuous Passive Motion (CPM), active robotic exoskeleton, spasticity, hand function

1.0 INTRODUCTION

We have developed a robotic exoskeleton to restore and rehab hand and finger function. The robotic exoskeleton is a hybrid actuated mechanism rehabilitation system, in which each finger is attached to an instrumented lead screw mechanism allowing force and position control according to the normal human setting. The robotic device, whose implemented is based on biomechanics measurements, able to assist the subject in flexion and extension motion. It also compatible with various shapes and sizes of human's finger. Main features of the interface include an integration of DC servo motor and lead screw mechanism which allows independent motion of the five fingers with small actuators. The device is easily transportable, user safety precaution, and offer multiple mode of training potentials. This paper presents the measurements implemented in the system to determine the requirements for finger and hand rehabilitation device, the design and characteristic of the whole system.

Post stroke rehabilitation at the acute stage usually starts with one-to-one therapies conducted by physiotherapists in acute-care clinics [3]. To reduce the total cost of the treatment, patients are typically sent back to their home when their ability to walk is improved, even though they have not fully recovered the function of upper extremity, especially the distal segments, such as hands and fingers [4]. In many cases, it will take a long period of time to recover the function of flexion, extension, abduction, and adduction of the fingers [5]. Thus, leaving the fingers in a flexed or extended position leads to difficulties in

ADL, such as feeding, dressing, grooming and personal hygiene.

One of the approaches in solving the finger disabilities and injuries is undergoing a finger rehabilitation [6]. The finger rehabilitation is physiotherapy approach which aims to partially or entirely recover the finger motor function of the patient [7]. The physiotherapy approach is based on how to manipulate the paretic limb which is supported by a physiotherapist. The approach may be accomplished with daily rehabilitation frequently for up to several months, depending on the severity of the finger and the condition of the patient [8]. In order to recover to a normal life, the patient needs time and undertaking the consistent rehabilitation assisted by a physiotherapist [9]. However, since the number of the physiotherapists is limited, it will not be easy for the patient to do the which needs to be supported by a physiotherapist all the time. Due to the limited numbers of physiotherapists [10], there are needs to develop a rehabilitation system where the patient can have their own rehabilitation exercises without aids from a therapist [11]. Furthermore, most of the literature reviews on hand rehabilitation robotic devices focus on the recovery of motor functions, specifically the extension and flexion movements of the hand. However, there are limited established approaches or publications available on the recovery of the sensory functions of the hand. In other words, the recovery of the sensory functions of the hand has yet to be explored by researchers. Therefore, improvements in the sensory functions of the hand are just as crucial to the recovery of the motor functions of the hand.

In this paper will discuss on the development process of the design concept, simulation and the fabrication of the device. The initial prototype of the device is also included. Since the exoskeleton only performs a flexion and extension thru the mechanism, the modification of the exoskeleton will be conducted in order to qualify as an index finger rehabilitation device. The design concept determined by these specifications is described in Section II. The choice of materials, the actuation system, and the implemented control schemes are described in Section III. Experiments were conducted with the interface to evaluate its performance (Section IV).

2.0 SYSTEM FUNCTIONALITY

This section describes the specific functions [12] of the robotic system in rehabilitating the motor function of muscle in each fingers of human hand. The key function of a hand exoskeleton device is the ability to decrease the stiffness of the contracture finger. The stiffness of the muscle in human finger need to reduce according to normal human finger orientation, thus the robotic exoskeleton must be able to reproduce the flexion and extension of the finger movement repetitively. Besides, the device must be able to detect angle of the flexion and extension in order to measure the trajectories [13] for index, middle, ring and small fingers while performing the movement. As shown in Figure 1, the sub-functions of the robotics exoskeleton consist of the ability to control angular velocity and producing a normal range of motion for the finger depend on each input angle on finger joint. The point of view from the occupational physiotherapist and the feedback from the healthy subjects are important to avoid incongruity during training session with real patients.

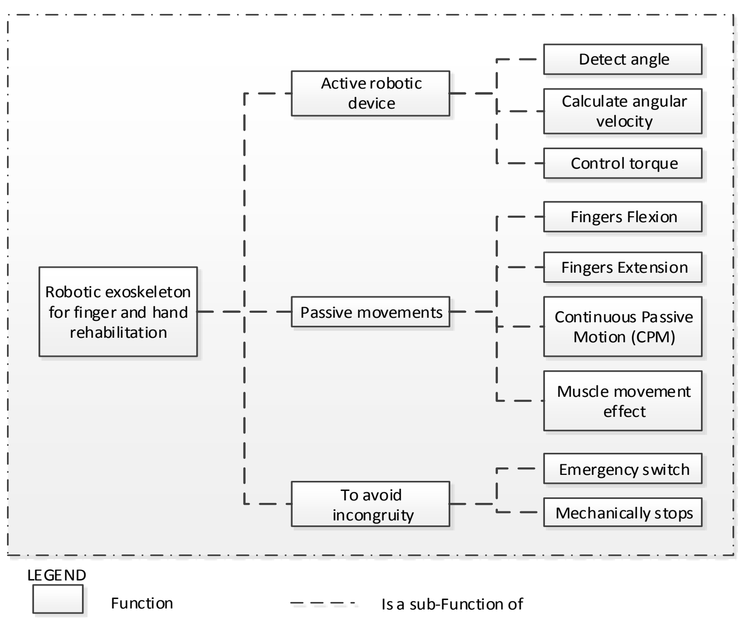


Figure 1 Functions of robotic exoskeleton for finger and hand rehabilitation

3.0 ROBOTIC EXOSKELETON PROTOTYPE

This project is a pilot study to improve the finger rehabilitation. The project starts with a mechanical design of exoskeleton for an index finger. The main idea of the design is to perform an extension and flexion of the finger based on mechanisms that can transmit the force from the actuators.

In this study, we investigated a new type of a robust hand and finger rehabilitation device which can control a human hand to do flexion and an extension motion. Our hypothesis by enforcing the correct flexion and extension motion, it can help patients with hand and finger muscle problems to close their hand and open hand correctly and improve healing. Most hand and finger devices for rehabilitation available on the market uses the passive control system. Unfortunately, the active control systems are costly and need a bigger space to install, not portable and not suitable to use at home. Therefore, the current study for the first time attempts to produce a robust, low cost device employing an active control system with a DC motor integrated with lead screw mechanism.

An actuation system consist of a DC servo motor integrated with lead screw mechanism (Figure 3) has been developed to realize the functions in aforementioned criteria. The architecture of the actuation system is illustrated in Figure 2. The prototype is shown in Figure 4.

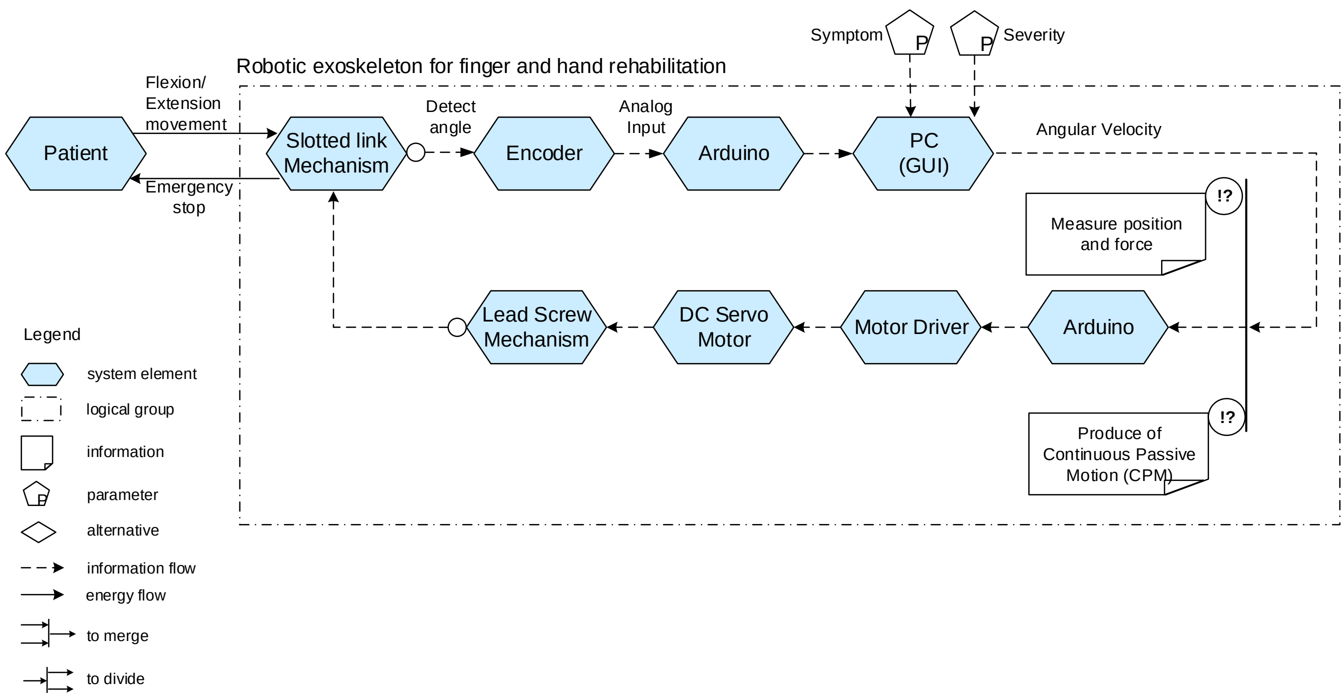


Figure 2 System architecture of a DC servo motor integrated with lead screw mechanism in robotic exoskeleton for finger and hand rehabilitation

3.1 DC Servo Motor

A DC servo motor acts as an actuator to drive the lead nut in lead screw mechanism in order to repetitively flexion and extension a human finger. When the actuator actuate the mechanism, lead screw will convert rotary input motion to linear output motion. The nut is constrained from rotating with the screw, thus as the screw is rotated the nut travels back and forth along the length of the shaft. Depending on the level of severity, the DC servo motor provides a constant stiffness against the force given by the subjects' finger.

To further realize the real training session, variations in stiffness and angular velocity is added by applying the torque control via DC servo motor to provide continuous passive motion (CPM) helping subjects reduce joint stiffness of the fingers together and individually.

3.2 Lead Screw Mechanism

When determining the amount of input torque required to produce an amount of output linear force, there are many factors to consider. The following equations provide a practical approach in making force and torque calculation in lead screw mechanism. Equation (1) was used to approximate the total force involving in the system.

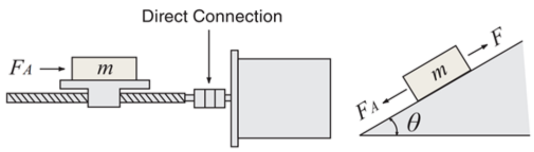


Figure 3 Free Body Diagram (FBD) of lead screw mechanism with force action reaction effect

$$F_T = F_A + F_E + F_F \qquad (1)$$

Here F_T is total force, F_A represents acceleration force, F_E is external force, and F_F is friction force. External force due to clockwise (CW) and counter clockwise (CCW) motion of DC servo motor shaft direct connection with coupling in horizontal applications which is the requirements in extension and flexion of the finger. Friction force required to overcome all of the friction in the load bearing system with a low friction bearing system, this can be negligible. The total force must be below the compressive trust rating of the lead screw chosen. A modest factor of safety should be added to the total force. Thus, unexpected dynamic loads are safely handled by the lead screw mechanism system. The torque, T required to move the mechanism system can be approximated by Equation (2), where F_T is total force, L represents lead and, e is efficiency of lead screw assembly.

$$T = F_T \frac{L}{2\pi e} \qquad (2)$$

The torque required should be well below the torque rating of the motor chosen. A modest factor of safety should be added to the torque required hence unexpected dynamic loads are safely handled by the driving system.

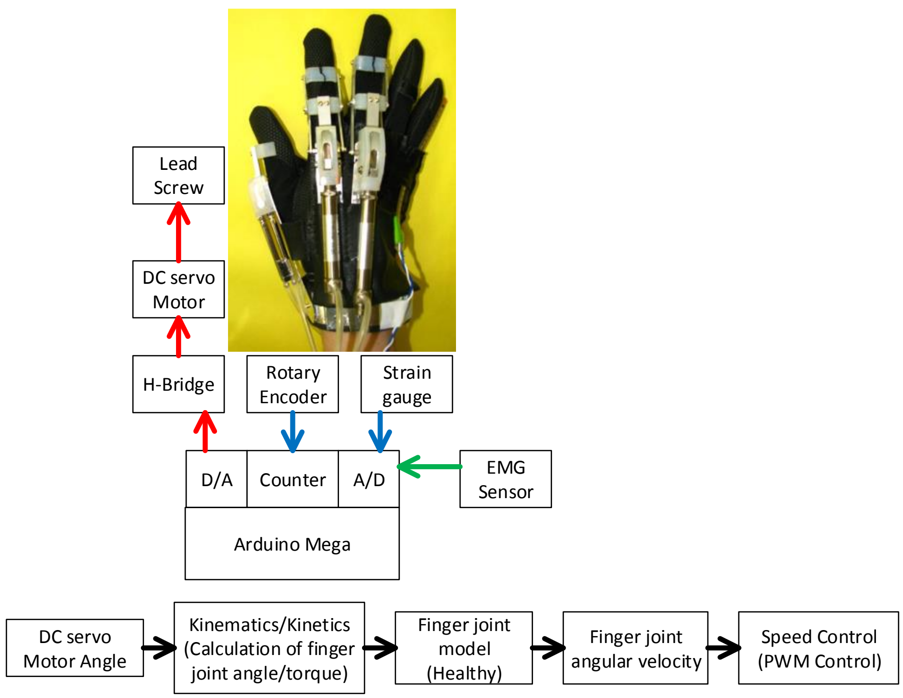


Figure 4 Prototype of robotic exoskeleton for finger and hand rehabilitation

3.3 Control System

The prototype was developed with three operation modes for each individual finger. Each mode has different control system. In order to explain the hybrid actuation strategy implemented in the system, the control system design for different level of spasticity which is explained as illustrate in Figure 5.

Figure 5 shows the lead screw mechanism allows three operation modes for every single finger. The implemented lead screw mechanism allows three operation modes for every single finger. In the passive training mode, the robot exoskeleton based device will guide the extension and flexion movement for patients who do not have voluntary hand and finger motions. At the moments, the patient's hand and finger must in the fixed position of the robotic exoskeleton based device. Therefore, a Velcro strap is used for fixation purpose.

The active training mode is operated when the robotic exoskeleton based device does not need to assist the patient's movement. Stroke patients who have mild effects and almost recovered can train for the extension and flexion motions in this mode. When the patient attempts to move their finger or hand, the value of EMG (Electromyography) sensor increases to exceed the value of threshold. However, if the EMG sensor does not exceed the threshold value, this will be an indicator that the user could not complete the passive and active training mode.

The patient-driven (active assisted) mode can be operated using the movement intention for patients with minimal voluntary hand and finger movements. When a patient attempts to move their finger in extension or flexion motion, the device will detect the patients's will through the EMG sensors.

4.0 SYSTEM PERFORMANCE.

This section presents measurement results in terms of joint angle produced by the actuation system of the lead screw mechanism in the robotic exoskeleton for hand and finger. These results shows plot of the experimental measurement of joint angle obtained from device versus time Figure 6 and 7). The device joint angle increased according to the voltage supplied to the encoder. We observed that there had been a linear relationship between the voltages supplied to the encoder with joint angle produced by the device. Each operation mode can be distinguished through observation of the level of slope and speed that contribute to their discrete characteristics.

The prototype was developed with three operation modes for each individual finger. Each mode has a different control system. In order to explain the active actuation strategy implemented in the system, the control system design for different level of spasticity which is explained as illustrate in Figure 5.

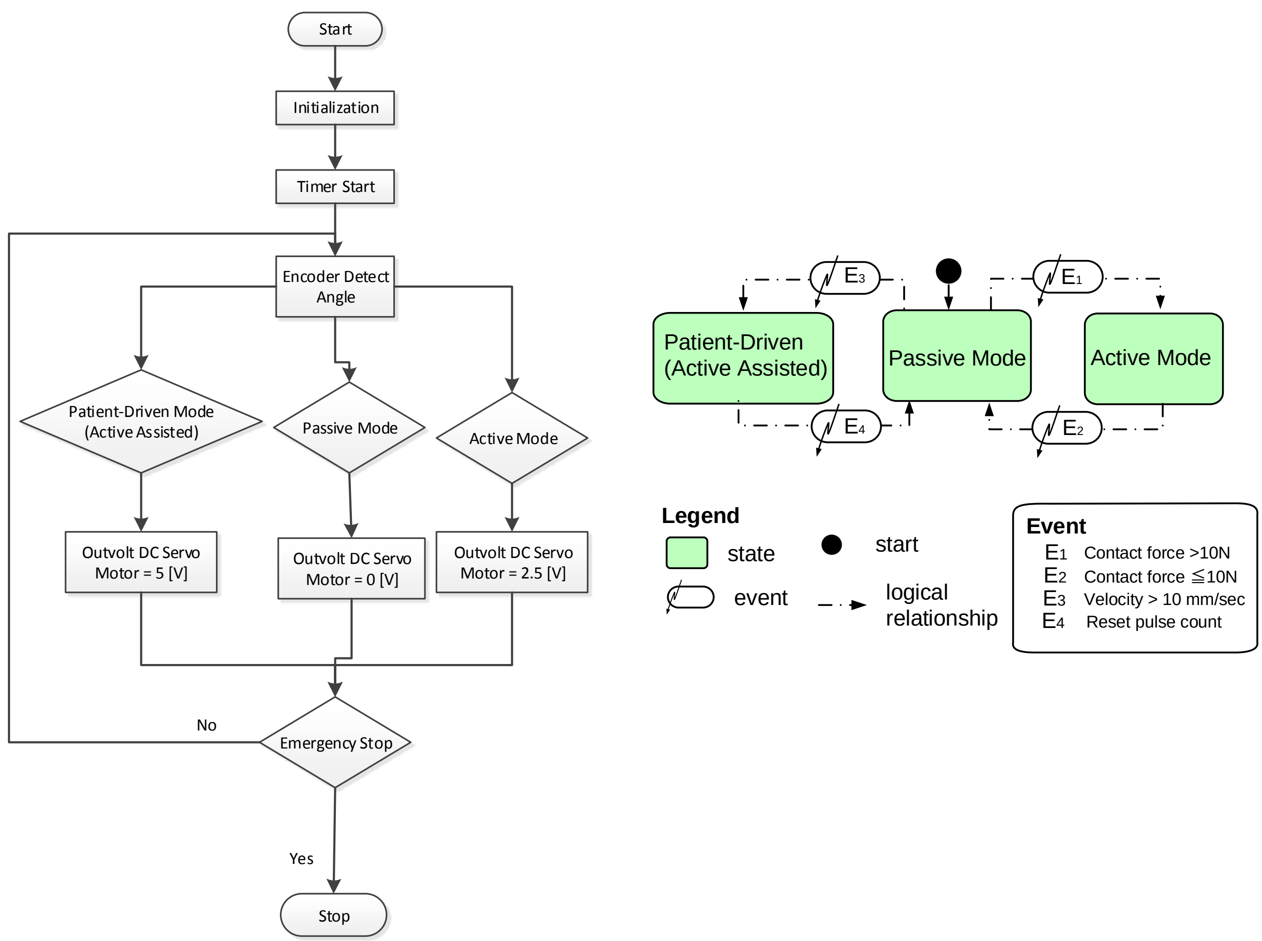


Figure 5 Flowchart described control programming pseudo code of robotic exoskeleton for finger and hand rehabilitation

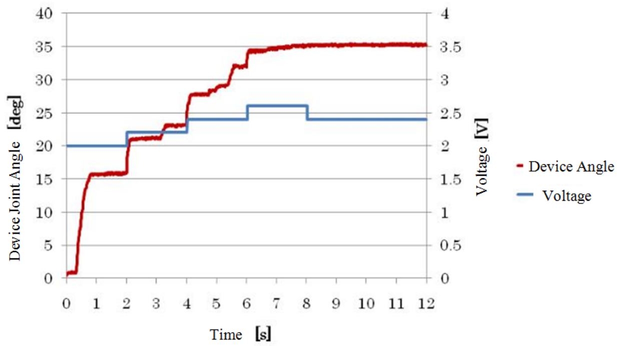


Figure 6 Experimental results for active mode of index finger

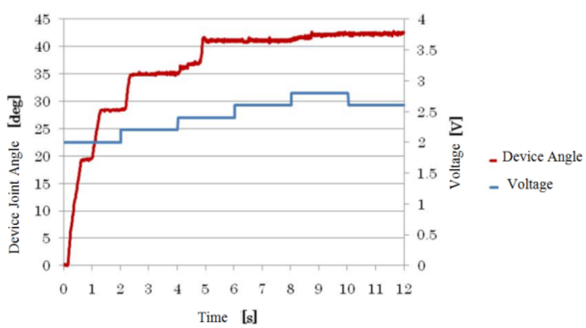


Figure 7 Experimental results for passive mode of index finger

5.0 CONCLUSION

An actuation control strategy integrated with DC servo motor and lead screw mechanism has been developed to actuate the flexion and extension of the finger in rehabilitation. By independently control the DC servo motor and utilizing the behaviour of lead screw mechanism, the system is provide with a range of bandwidth to operate in different modes.

An active actuation control strategy, integrated with geared DC servo motor and lead screw mechanism has been developed to actuate the flexion and extension of the finger in rehabilitation. By independently controlling the DC servo motor and utilizing the behavior of a lead screw mechanism, the system is provided with a range of bandwidth to operate in different modes. In this paper, a robotic rehabilitation device that assists stroke patients in recovering their extension and flexion motions of motor functions was proposed. Also, a novel patient-driven mode based on the intention movement from the patients detected using EMG sensors was proposed in order to engage directly in neuroplasticity.

In the proof of concept study conducted by therapists and healthy subjects, it was found that the proposed device actuated with the patient-driven approach could be beneficial for hand rehabilitation. Our proposed device has several limitations. It is needed to adopt adaptive control strategies for each patient's capabilities. Further research focused on investigating the rehabilitative effect of the proposed device will be undertaken through working with targeted stroke patients and constructing solid evidence of the proposed device's benefits using functional sensory devices to validate the level of recovery.

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