5ER-O32: Hand Exoskeleton Design for Stroke Patient Rehabilitation

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Abstract

This research aims to study and design a strengthened mechanical device so called “hand exoskeleton” for stroke patients. The stroke patients lose control of their hands because of blood clot or bleed in the brain which can leave devastating damage. The device is used to rehabilitate stroke patients who are wearing it and doing physical therapy. The structure of the hand exoskeleton is described. There are several type of hand exoskeleton has been proposed by the researchers currently. The serial link type is selected in this research. Essentially, the control of the mechanism is proposed. When volunteers wear the hand exoskeleton, the mechanical actuator units receive the control signals from the control unit. Next, they instruct the pneumatic actuators to work. The path trajectory controller is performed to minimize the error between the desired and actual path. As a result, the volunteer's hands stretch and contract as desired as if they were working naturally.The hand exoskeleton shows its performance quite impressive.

Keywords: Hand Exoskeleton, Stoke, Rehabilitation

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Introduction

In United State, one in every 190 people is currently living with loss of limp. In 2005, 1.6 million persons were living with the loss of their limbs. In Australia, studies have predicted that from 2008 to 2017 more than 0.5 million people likely suffered from stroke. After the stroke, 88% of the patients suffered from disability and have to stay at home. The second's cause of loss of the limb is stroke.

In Thailand, there is rapidly increasing of patients with Cerebrovascular Disease (CVD) or stroke patients [1,2,4]. From Thai Public Health Statistics in 2015, high blood pressure and cerebrovascular disease is the second cause of death in Thailand. Nonetheless, disability adjusted life year in 2013 was caused by cerebrovascular disease which is the third rank in male and the second rank in female [1].

Stroke can cause a deficiency in various neurological areas and mainly it cause disability in the motor system. [1] A general state in the most of the stroke survivor is paralysis of one side of body. The motor rehabilitation research has shown that to speed up to recovery process of the hand function, activity dependent intervention can be used to assist the use of paralyzed hand. [2]

Over the past several years, there has been a study on the creation of mechanical devices for the rehabilitation of stroke patients together with study of mathematical modeling and the application of a wide range of mechanical control devices. For example Md Akhlaquor Rahman et al. [2] invented linkage hand exoskeleton using linear motors as power source. Macello Mulas et al. [3] invented linkage hand exoskeleton using servo motors as power source. Jianyu Yanng et al.[4] invented tendon mechanism hand exoskeleton using servo motors with cable as power source. R. Conti et al. [5] invented 1-DOF hand exoskeleton using servo motors as power source. From the past research, it has been found from the invention of hand exoskeleton that motor is still widely used as actuator .This cause the devices is quite large and not easy to use including the force gained too less to picking things at hand. It may not be able to use in daily life. Thus, it needs to improve the performance of the devices by using other power source. Mathematical model and controller of hand exoskeleton for rehabilitation patient with stroke aims to invent a prototype of hand exoskeleton using pneumatic system as power source and study the efficiency of the device to evaluate the suitability of the application to the patient. As well as a device for treat patients to reduce the burden of caregivers and the needs of patients who want to help themselves as much as possible. Mathematical model and controller of hand exoskeleton for rehabilitation patient with stroke is important to help patients move their hands and use the normal routine, Because of losing of hand control in human will have difficulties to many daily activities and dramatically affect their mind. Patients who use the device can return to their daily routine as a treatment for the body and mind as well.

Methodology

Hand Exoskeleton Design

The device's objective is the device allows the patient to do flexion/extension the impaired hand's finger of those patients. The complete design of the device is separated in two sections. The first section is the computer aided design of hand exoskeleton that will be fitted on the impaired finger hand of the patient, the second section is the controller design to control hand exoskeleton to movement the finger of the patient.

- Computer Aided Design of hand Exoskeleton

The concept design of the hand exoskeleton is based on the simplicity, easy to use and fit for all finger of the patient (Thumb, Index, Middle, Ring and little) that will be moved at the same flexion and extension. All design is based on the same concept. The design will use the serial linkage which is attached to these fingers and on the hand. This model has few linkages and very light weight which is easy to control. The device has three linkages for each finger. The first linkage is the distal support that design for the patient finger's tip to fit into and easy to wear. The next linkage is main linkage that controls the position of finger's tip. This linkage is designed to be strong and can move the patient's finger. The last linkage is the support of the device that sits on the back hand. This linkage connects all the links on the impaired hand and connects to the pneumatic actuator. The device building from PLA plastic that is strong and low cost.

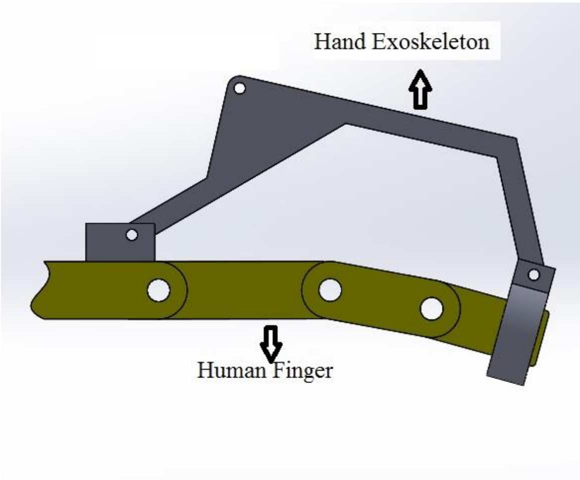

Figure 1 Serial linkage attached to distal hand exoskeleton

Figure 2 Prototype of hand exoskeleton

Figure 3 Hand Exoskeleton on Volunteer's Hand

- Mathematical Model

By using math model, researchers can model the physical system, here the hand exoskeleton. The model can be used to analyze the behavior of the hand exoskeleton. Understanding the behavior of the device, we can redesign the proper prototype suitable to be applied to the stroke patient. Next, the controller will be preliminary study and design by using the math model.

- **Exoskeleton Mathematical model**

In this paper we will be describe the motion of hand exoskeleton by using MATLAB/Simulink. To model the hand exoskeleton using the 2 link manipulator (with spring and damper to describe) The model depicts below consists of two light rigid rods A and B, and a linear spring-damper in a Newtonian reference frame N. [#] Rod A is connected with frictionless revolute joints to N and B at points O and P ,respectively. Right-handed sets of mutually perpendicular unit vector ni ai and bi (i=1,2,3) are fixed in N ,A, and B ,with n1 vertically downward, a1 directed from O to P, b1 directed from P to Q, and n3=a3=b3 parallel to the axes of the revolute joints. The distance from O to P is LA and the distance from P to Q is LB. The masses of P and Q are denoted as MP and MQ. The spring's natural length is Lo, its spring constant is k, and the damping constant is b. The angle QA and QB characterize the orientation of A and B in N and the motion variable are QA and QB . A damping torque of -c QA and -c QB act on A and B.

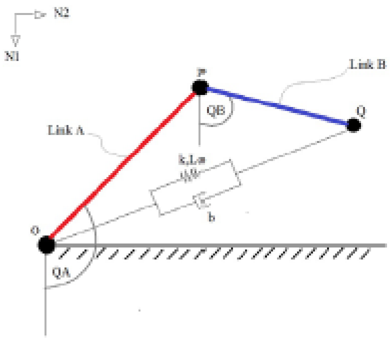

Figure 4 Simplified Hand Exoskeleton Attached on Finger

Find the equations which govern the motion of the system.

$$L_{OQ} = \sqrt{{L_A}^2 + {L_B}^2 + 2L_A L_B cos(QA + QB)} \quad (1)$$

$$S_{LOQ} = L_{OQ} - L_o \quad (2)$$

$$S_{L\dot{O}Q} = \frac{-L_A * L_B \sin(QA - QB) * (\dot{Q}A - \dot{Q}B)}{L_{OQ}} \quad (3)$$

From diagram we will describe the equation of motion of system in state space from in state variable. In system have state variable $x_1 = QA$, $x_2 = \dot{Q}A$, $x_3 = QB$ and $x_4 = \dot{Q}B$

In state space representation form,

$$\dot{x_1} = x_2$$

$$\dot{x}_2 = \left[\frac{1}{L_A L_B M_Q \cos(x_1 - x_3) - \frac{L_A L_B (M_P + M_Q)}{\cos(x_1 - x_3)}}\right]\Bigg[L_A L_B M_Q \sin(x_1 - x_3)\, x_2^2 + \frac{L_B^2 M_Q \sin(x_1 - x_3)\, x_4^2}{\cos(x_1 - x_3)} - \frac{L_A L_B (x_1 - x_3)}{L_{OQ}} - \frac{L_B^2 (k * S_{LOQ} + b * S_{L\dot{O}Q}) \sin(x_1 - x_3)}{L_{OQ} \cos(x_1 - x_3)} - cx_4 + \frac{cx_2 L_B}{L_A \cos(x_1 - x_3)} - gL_B M_Q \sin(x_3) + \frac{gL_B (M_P + M_Q) \sin(x_1)}{\cos(x_1 - x_3)}\Bigg]$$

$$\dot{x_3} = x_4$$

$$\dot{x}_4 = \left[\frac{1}{\frac{L_A L_B (M_P + M_Q)}{\cos(x_1 - x_3)} - L_A L_B M_Q \cos(x_1 - x_3)}\right]$$
$$\left[\frac{L_A^2 (M_P + M_Q)\sin(x_1 - x_3) x_2^2}{cos(x_1 - x_3)} + L_A L_B M_Q sin(x_1 - x_3) x_4^2 - \frac{L_A L_B (k * S_{LOQ} + b * \dot{S_{LOQ}}) sin(x_1 - x_3)}{L_{OQ}} - \frac{L_A^2 (M_P + M_Q)(k * S_{LOQ} + b * \dot{S_{LOQ}}) sin(x_1 - x_3)}{L_{OQ} M_Q cos(x_1 - x_3)} + cx_2 - \frac{cL_A (M_P + M_Q) x_4}{L_B M_Q cos(x_1 - x_3)} + gL_A (M_P + M_Q)\sin(x_1) - \frac{gL_A (M_P + M_Q)\sin(x_4)}{cos(x_1 - x_3)}\right] \quad (4)$$

The mathematical model, equation (4) in state space form, is used to described the dynamic of the hand exoskeleton where the the finger is considered as the mass-spring-damper load. MATLAB/Simulink can be used to simulate the model. The simulation results from the model yield the angle and velocity of each hand exoskeleton joints. We used S-Function Simulink to model it. The initial condition is QA = 95 degree ,QB = 0 degree ,LA = 106mm ,LB = 15mm ,MP = 4g ,MQ = 3g , Lo = 95mm ,k = 1 N/m ,b = 2 N-sec/m ,c = 2 N-sec/m and T = 1 N-m. The results show the fingertip's trajectory that follow the desired trajectory in for the designed controller. The simulation of fingertip result shows in figure 8 that describes the trajectory of fingertip from the start to the end.

- **Pneumatic Mathematical Model**

Pneumatic Modeling is described in spool valve form to to model it. Spoon valve has transfer function to show characteristic of pneumatic valve.

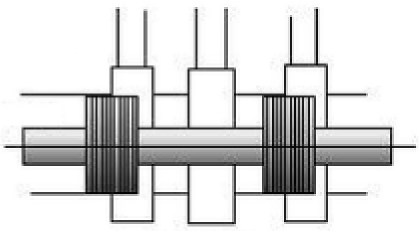

Figure 5 Spoon Valve

$$z = \frac{G_s u - \frac{F_L}{K_s} \pm z_{HVS}}{\left(\frac{D}{\omega_n}\right)^2 + 2\zeta\left(\frac{D}{\omega_n}\right) + 1} \quad (5)$$

where

G_s is static gain, K_s is static stiffness, z_{HVS} is hysteresis in-output, ω_n is natural frequency and ζ is damping ratio

Controller Design

- Trajectory Tracking Controller

Normal form of Dynamic System can be considered as

$$\dot{\eta} = f_0(\eta, \xi) \quad (7)$$

$$\dot{\xi}_i = \xi_{i+1} \qquad \text{for } 1 \leq i \leq \rho - 1 \quad (8)$$

$$\dot{\xi}_\rho = a(\eta, \xi) + b(\eta, \xi)u \quad (9)$$

$$y = \xi_1 \quad (10)$$

Where $\eta \in D_\eta \subset R^{n-\rho}, \xi = col(\xi_1 \dots\dots \xi_\rho) \in D_\xi \subset R^\rho$

We want to design a feedback controller such that

$$\lim_{t\to\infty} [y(t) - r(t) = 0]$$

while ensuring boundedness of all state variables. Reference input, *r(t)* is constant.

We assume that

1. $b(\eta, \xi) \geq b_o \geq 0, \qquad \forall\, \eta \in D_\eta, \xi \in D_\xi$
2. $\dot{\eta} = f_0(\eta, \xi)$ is bounded-input-bounded-state stable over $D_\eta \times D_\xi$

This assumption holds locally if the system is minimum phase and globally if $\dot{\eta} = f_0(\eta, \xi)$ is ISS.

3. *r(t)* and its derivatives up to $r^{(\rho)}(t)$ are bounded for all t $\geq$ 0 and the ρth derivative $r^{(\rho)}(t)$ is a piecewise continuous function of t. Moreover, $\mathcal{R} = col(r, \dot{r}, \dots, r^{(\rho-1)}) \in D_\xi$ for all t $\geq$ 0

For r(t), it can be specified as a given function of time where it is the trajectory path of grasping hand. Main purpose for the trajectory tracking is to minimize error between the desired path trajectory and the actual path trajectory so that error goes to zero as time tends to infinity.

Establishing auxiliary state for the error, in order to perform tracking

$$e_1 = \xi_1 - r, \quad e_2 = \xi_2 - r^{(1)}, \dots, e_p = \xi_p - r^{(\rho-1)}$$

$$\dot{\eta} = f_0(\eta, \xi) \quad (11)$$

$$\dot{e}_i = e_{i+1} \qquad \text{for } 1 \leq i \leq \rho - 1 \quad (12)$$

$$\dot{e}_\rho = a(\eta, \xi) + b(\eta, \xi)u - r^\rho \quad (13)$$

To ensure

$e = col(e_1, \dots\dots, e_\rho) = \xi - \mathcal{R}$ is bounded for all t $\geq$ 0 and converges to zero as t tends to infinity.

r, r^1, ..., r^ρ are available to the controller needed in state feedback control. We specified the region of validity to be a local. Local tracking is achieved for sufficiently small initial states and sufficiently small $\|\mathcal{R}\|$.

We use feedback linearization method to design the controller.

$$u = [-a(\eta, \xi) + r^{(\rho)} + v]/b(\eta, \xi) \quad (14)$$

$$\dot{\eta} = f_0(\eta, \xi), \quad \dot{e} = A_c e + B_c v \quad (15)$$

$$v = Ke, \; A_c - B_c K \text{ is Hurwitz.} \quad (16)$$

Then, $A_c - B_c K$ Hurwitz $\Rightarrow$ $e(t)$ is bounded and $\lim_{t \to 0} e(t) = 0 \Rightarrow \xi = e + \mathcal{R}$ is bounded $\Rightarrow \eta$ is bounded.

Pneumatic Controller Design

Pneumatic actuator is clean, easy to control and cheapest cost of device, chosen. Pneumatic controller has microcontroller to control. The generated signal controls the movement of device. In this device microcontroller will use on/off signal without the feedback control from the finger hand. The microcontroller generates the signal in PWM to control pneumatic solenoid valve and control pneumatic the piston. The device uses one pneumatic piston to control five fingers. Pressure to operate device is 30 PSI.

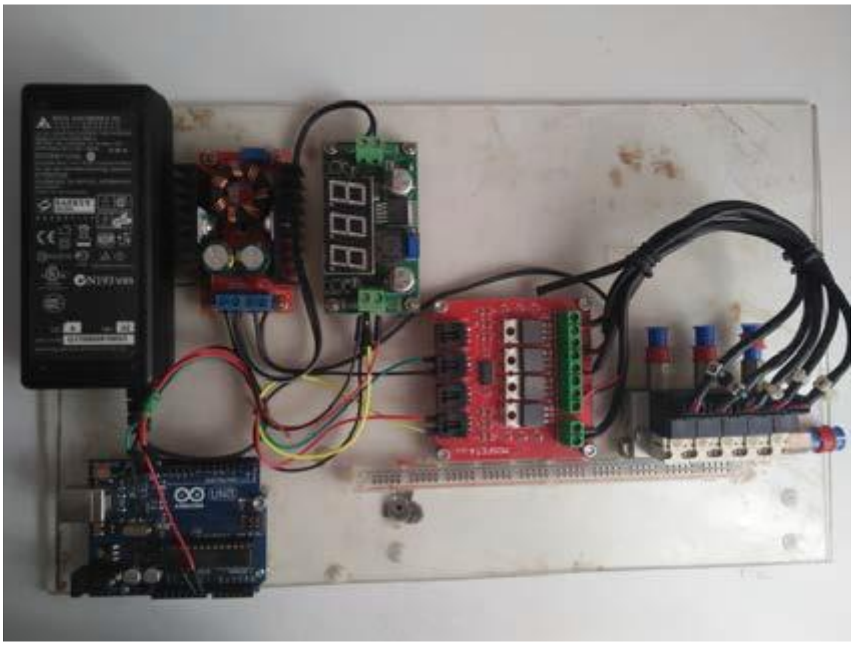

Figure 6 Controller Board

Set up and Test

To testing device we used flex sensor with microcontroller to measure angle of finger for analysis finger trajectory of patient finger. Flex sensor operate resistance in 79 K Ohm in 0 degree to 92 K Ohm in 90 degree. To measurement we install flex sensor on glove and testing with hand exoskeleton. We add glove with flex sensor between patient finger and hand exoskeleton device to test. The device can flexion and extension all finger and operate with pneumatic controller that shown finger trajectory in fig 4.2 to used compare with simulation result in MATLAB.

Figure 7 Flex sensor to measurement

Experimental and Simulation Result

To describe the mathematical model will be used equation (8) and (9) for regenerate in state space form. MATLAB/Simulink can be used in modeling and simulation the mathematical model and derive the angle, and velocity of each hand exoskeleton joint. We used S-Function Simulink to modeling it. The initial condition is QA = 95 degree ,QB = 0 degree ,LA = 106mm ,LB = 15mm ,MP = 4g ,MQ = 3g , Lo = 95mm ,k = 1 N/m ,b = 2 N-sec/m ,c = 2 N-sec/m and T = 1 N-m. The result that shown finger tips trajectory that simulated in condition for design controller.

Result of testing we used computer to collect data and shown tip finger trajectory of the patient. At start finger at rest in horizontal frame when the device operate fingertip move and stop at 90 degree of horizontal reference.

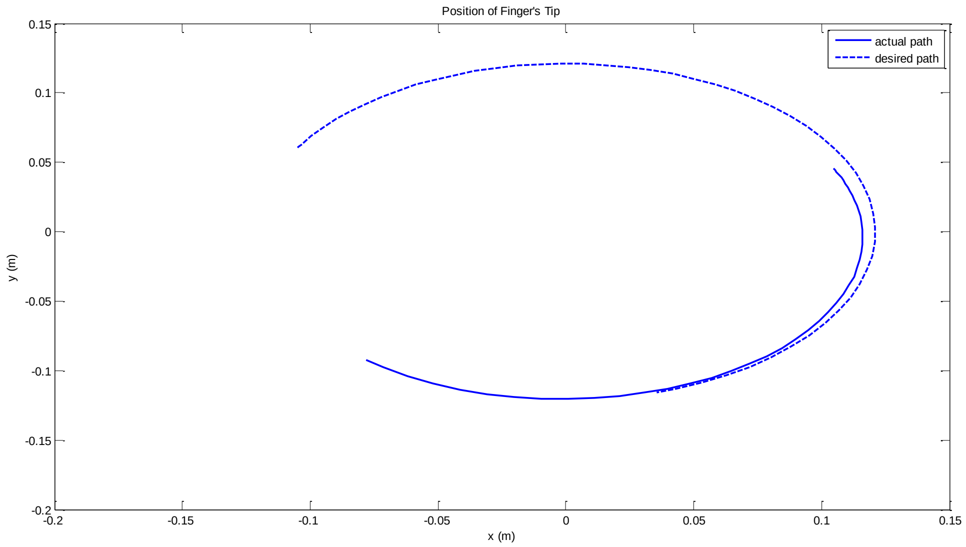

Figure 8 Simulation of Position of Finger's Tip between Controlled Path and Desired Path

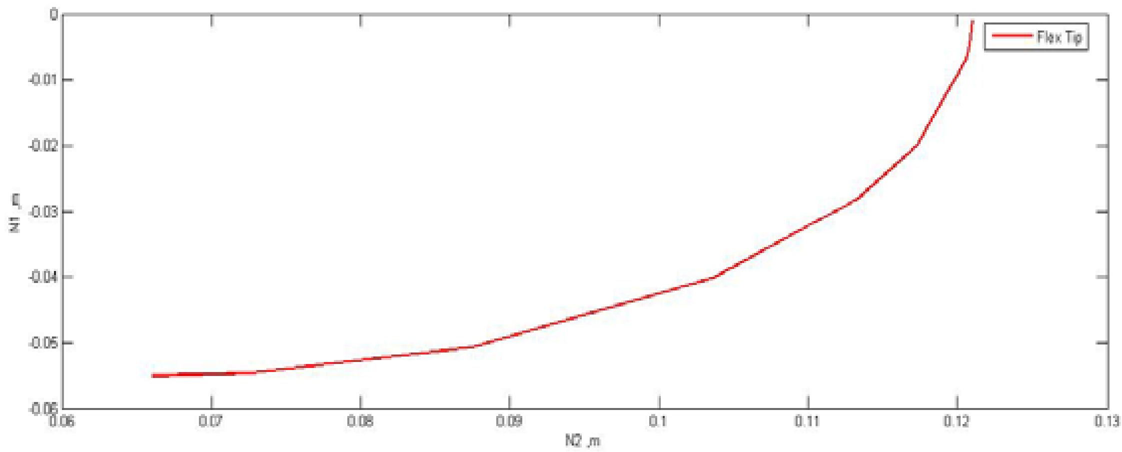

Figure 9 Position of Finger's Tip of flex sensor measurement

To compare result of simulation and testing device of fingertip trajectory we used MATLAB to plot data and shown its in figure 10. The trajectory of fingertip simulation and flex sensor are same trend. We will adjust gain in the controller to control device with pneumatic controller.

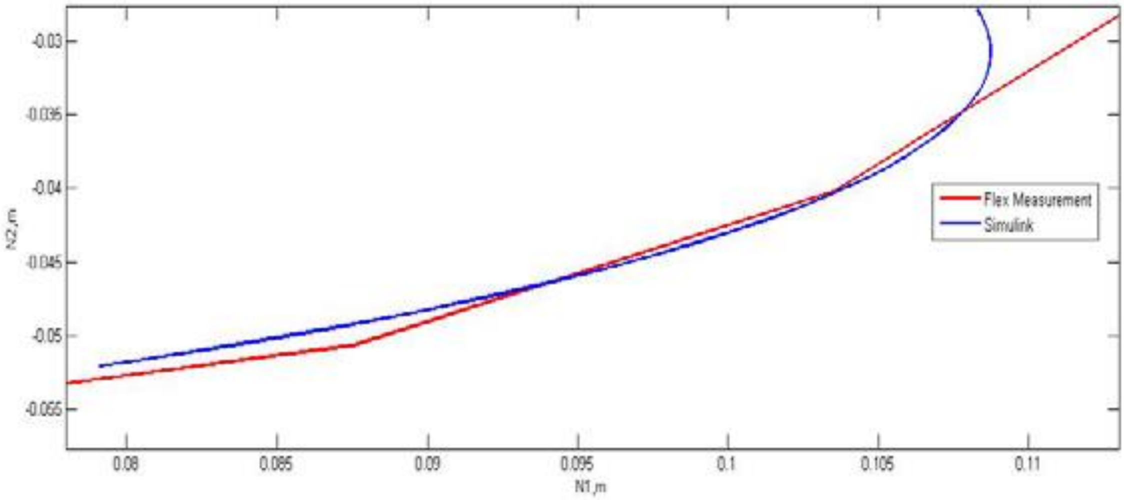

Figure 10 Simulation result and Experimental result comparison.

Conclusion

The hand exoskeleton for rehabilitation patient with stroke can be flexion/extension the all of finger hand of patient. The device is light weight and strong that used ABS Plastic. The device used pneumatic actuator that clean and easy to control. Main concept of device is one pneumatic piston control all fingers and used on-off microcontroller. The mathematical model can be used describe model and used to design controller for device.

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