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Integration of Flex Sensor with Finger Exoskeleton for Stroke Patient Rehabilitation

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ABSTRACT

Mirror Therapy is a medical therapy used in stroke patient rehabilitation with upper limb injuries which trick the brain into thinking their affected limb can move without pain through mirror reflection. This research is undertaken to introduce a system integration of flex sensor from Arduino circuit with orthosis, namely finger exoskeleton, for stroke patient rehabilitation via Mirror Therapy. Orthosis is an externally applied device used to statically support an injured limb by restricting or assisting limb movement during rehabilitation process. Flex sensor is a variable resistor used to measure resistance produced from sensor bending. In the system, unaffected fingers movement will manage the flex sensors (master) which control the finger exoskeleton movement (slave). This project consists of fabrication of exoskeletons for index, middle and ring fingers to be worn on the patient hands. A successful system integration of fabricated finger exoskeleton and flex sensor from Arduino circuit enables the evaluation of delay time through angle and speed of finger exoskeleton motion. The use of orthosis in Mirror Therapy rehabilitation provides a two-way feedback between the brain and affected hand which will improve both Mirror Therapy and Neuroplasticity effectiveness leading to decrease of time recovery while providing affordable orthosis.

Keywords: *Stroke; Neuroplasticity; Mirror Therapy; Orthosis; Hand Anatomy.*

Introduction

Stroke is one of the diseases that can lead to high disability of the body parts and end with death to unlucky people. Stroke is caused by either blood clotting or blood vessels rupturing inside the brain. Although stroke patients can recover, they require a long-term period of medical care [1]. Figure 1 shows the examples of stroke patient rehabilitation intervention such as Mirror Therapy [2] and Robotic Therapy [3].

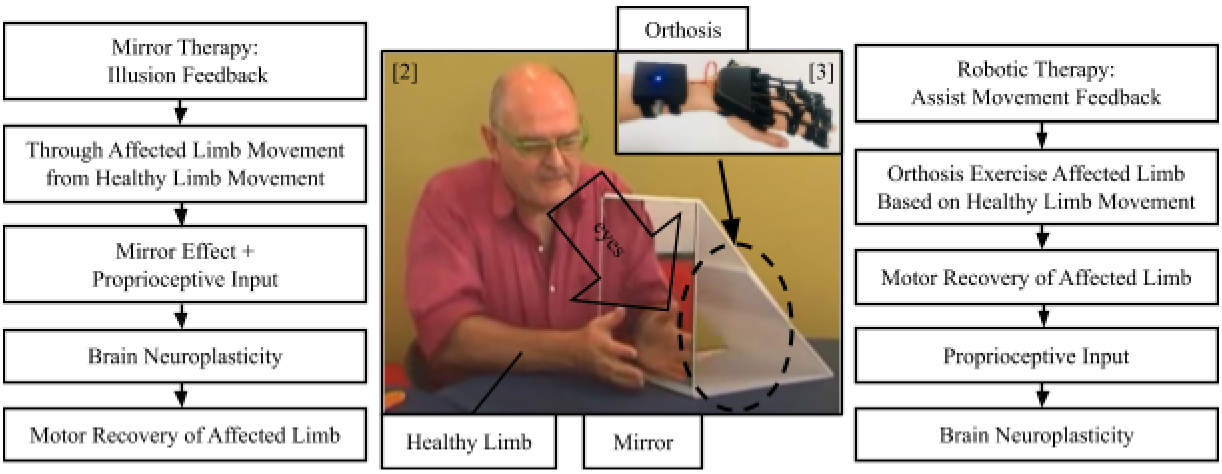


Figure 1: Two-way feedback for mirror therapy and orthosis in robotic therapy [2, 3].

Mirror Therapy is a medical therapy which uses illusion feedback to trick the brain into thinking their affected limb is able to move without pain through mirror reflection of healthy limb movement. This feedback provides mirror effect and proprioceptive input to the brain neuroplasticity to create or repair the neural connection between the brain and affected limb. This neural connection will help in motor recovery of affected limbs to regain their affected limb movement back.

Neuroplasticity is important to stroke patient rehabilitation as the brain is able to modify and change itself by forming new neural connections while removing old and damaged connections [4]. Mirror Therapy can only provide one-way feedback from the brain to the phantom limb. Therefore, orthosis is added into the tool system so that there will be a two-way feedback between brain and affected limb which will increase the effectiveness of Mirror Therapy and reduce stroke patient recovery time.

Orthosis is an externally applied device such as brace, splint or exoskeleton which provide the same characteristic and fundamental of the upper limb to support the affected limb. Orthosis is commonly used in Robotic Therapy to assist movement feedback when the orthosis exercises the affected limb based on the healthy limb movement. This feedback provokes the motor plasticity in the patient's brain which helps in motor recovery of the affected limb. This feedback also provides proprioceptive input to the brain neuroplasticity to create or repair the neural connection between the brain and affected limb, thus regaining their affected limb movement back.

Basic hand anatomy knowledge needs to be learned in order to design a functional exoskeleton to support and enable the affected limb movement without causing any injury to the patient. The finger exoskeleton designed must be able to follow the hand movements such as flexion, extension, abduction, adduction and opposition [5]. The exoskeleton design also needs to be suitable for the size of finger bone in order to create a smooth hand movement. The finger bone has three phalanges such as distal (the bone on the fingertip), middle and proximal (the bone at the finger base) phalanx [5].

The main purpose of this project is to increase the effectiveness of Mirror Therapy by combining Mirror Therapy with finger exoskeleton systems. Currently Mirror Therapy only focuses on providing a one-way feedback from brain to phantom limb which can take a long time to recover. The design and fabrication of 3D printed finger exoskeleton will provide another one-way feedback from phantom limb to brain. In other words, a two-way feedback can be produced from the combination of Mirror Therapy and finger exoskeleton system.

According to the World Health Organization, stroke is known as one of the top causes of death for people in all ages [6]. Data obtained from medical researchers state that approximately 70 to 80 percent of the stroke survivors require long-term medical care [1] and live a poor quality of life [7]. Hence, the development of finger exoskeleton in Mirror Therapy session can act as a stepping stone toward orthosis technology improvement in the medical field.

There are several problem statements found during the development of Mirror Therapy combined with 3D printed finger exoskeleton which use flex sensors as motion controllers. Firstly, determining the necessary parts for Arduino circuit design involved flex sensor and suitable finger exoskeleton design to ensure the user safety during Mirror Therapy. Next, understanding how to integrate an Arduino circuit with flex sensors and finger exoskeleton as a complete system in Mirror Therapy. Lastly, analysing the output produced in the system integration of Arduino circuit with flex sensor and finger exoskeletons which can be used to improve Mirror Therapy.

The objectives of the project related to problem statements are to design and fabricate both Arduino circuit and finger exoskeletons. Besides, to integrate Arduino circuits with flex sensors (Master controller) with 3D printed finger exoskeletons (Slave controller) into one complete system. Finally, to evaluate the angle and speed of finger exoskeletons and whether the delay time is sufficient to be used for rehabilitation purposes.

There are several scopes of the project regarding the development of 3D printed finger exoskeleton using flex sensor. Firstly, the project focuses only on index, middle and ring fingers while limits only on flexion and extension motion of the fingers. Besides, the finger exoskeletons are only made of 3D printer plastic filament and clothing fasteners. Furthermore, the programming software used is Arduino IDE software and electronic components used are Arduino. Next, the design software used is CATIA version 5.20. In addition, the project uses only conductive ink-based flex sensors as motion sensors and attached to the left hand while finger exoskeleton is only attached to the right hand. Lastly, the study focuses only on the stroke patient from Hospital Sungai Buloh.

Flex Sensor Calibration

Flex sensor calibration is a phase where every flex sensor involved in this project needs to be tested through data collection. The objectives of this phase are to check for hysteresis in the sensor and to find the suitable resistor to be applied in the circuit. The resistors used for this project are 5.1 kΩ, 6.8 kΩ, 10 kΩ, 20 kΩ and 47 kΩ. Hysteresis is a time-based dependence of a system output on present and past inputs. When there is a huge amount of hysteresis present on the flex sensor, the present inputs will have a large difference with past inputs. This will cause the flex sensor to be labelled as bad working condition and needs to be replaced with a new flex sensor to prevent any differences of input in further research. Sensitive flex sensors with no or small amount of hysteresis are the ideal sensors to be used for this project.

The ADC formula derived in Figure 2 below is used to calculate the analog voltage produced by the flex sensors. Analog value of 1023 is known to equal to 5V while ADC reading over analog voltage measured is a constant.

$$\frac{1023}{5} = \frac{ADC\ Reading}{Analog\ Voltage\ Measured}$$

Figure 2: Analog digital conversion formula for flex sensor [8].

When flex sensor calibration program code has been successfully uploaded into the microcontroller, ADC Reading and analog voltage results can be seen in the serial monitor for every 1 second. Jigs with angles of 0°, 10°, 30°, 50°, 70° and 90° are created by using a 3D printer to securely hold flex sensors as shown in Figure 3, thus more accurate data can be obtained without any movement during flex sensor bending.

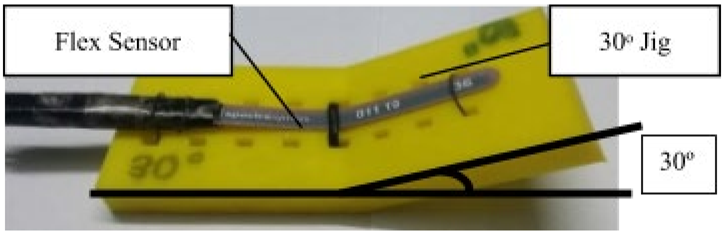


Figure 3: Flex sensor bends 30º.

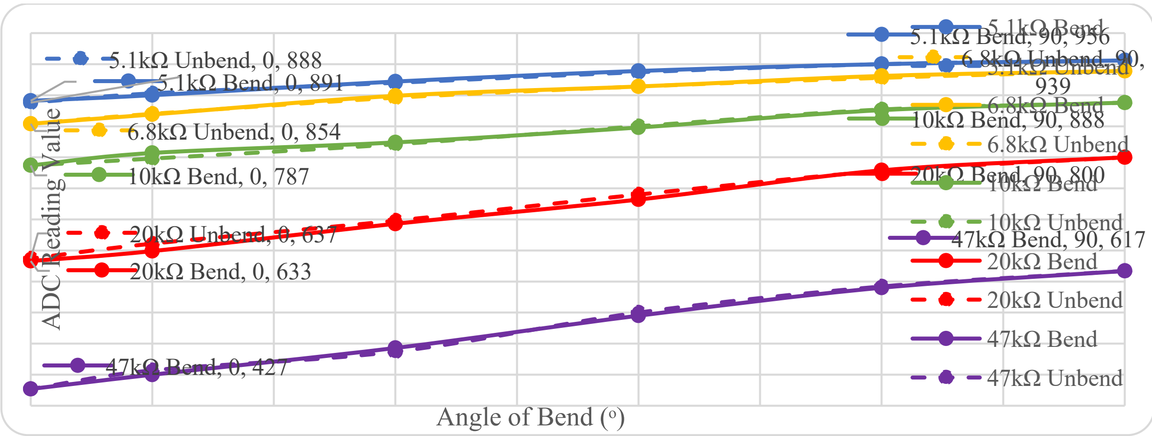


Figure 4: Data obtained from flex sensor using different resistors to compare hysteresis in adc reading value (top).

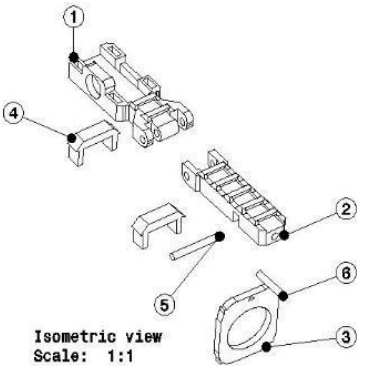
Based on Figure 4 above, flex sensors with 5.1 kΩ resistor have the highest ADC reading value while flex sensors with 47 kΩ resistor have the lowest ADC reading value with the value of 956 and 617 respectively at 90º. This reveals that resistance value will influence ADC reading value of flex sensor as the resistor and flex sensor are arranged in voltage divider rule circuit.

Next, the figure exhibits that the flex sensor with 47 kΩ resistor has the largest ADC reading value difference with the value of 190 while the flex sensor with 5.1 kΩ resistor has the smallest ADC reading value difference with the value of 190 and 68 respectively. This shows that resistance value will affect the sensitivity of the flex sensor as the larger the resistance value applied in the circuit, the lower the flex sensor sensitivity to change 1º angle.

Finally, the figure displays that the flex sensor 1 with 20 kΩ and 40 kΩ resistor have a higher amount of hysteresis compared to other resistors. This indicates that high resistance value will increase the amount of hysteresis which increases the difference value between past and present inputs. In conclusion, 5.1 kΩ resistor should be selected and applied with flex sensor 1 in this project as the resistor provides higher sensitivity and lower amount of hysteresis compared to other resistors.

Finger Exoskeleton Design

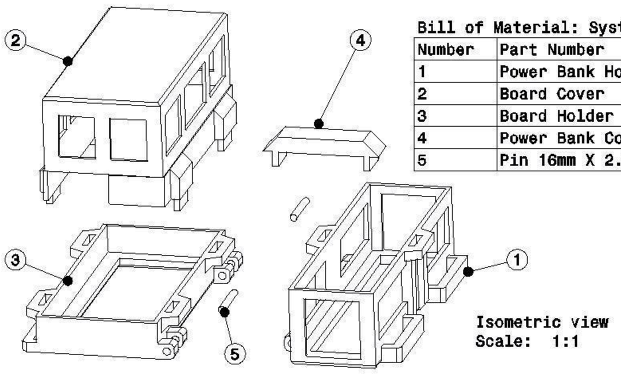
Computer-aid design model of finger exoskeleton can be done by using CATIA version 5.20 software. Each exoskeleton part will be designed and assembled based on the initial design sketch. There are 3 exoskeleton products which are assembled from total 24 different parts in this project such as flex holder, system holder and right-hand exoskeleton designs as shown in Figures 5(a), 5(b) and 5(c) respectively.



Bill of Material: Flex Holder Product

Number	Part Number	Quantity
1	Flex Holder A	1
2	Flex Holder B	1
3	Flex Holder Ring	1
4	Flex Holder Cover	2
5	Pin 19mm X 2.25mm	1
6	Pin 12.5mm X 2.25mm	1

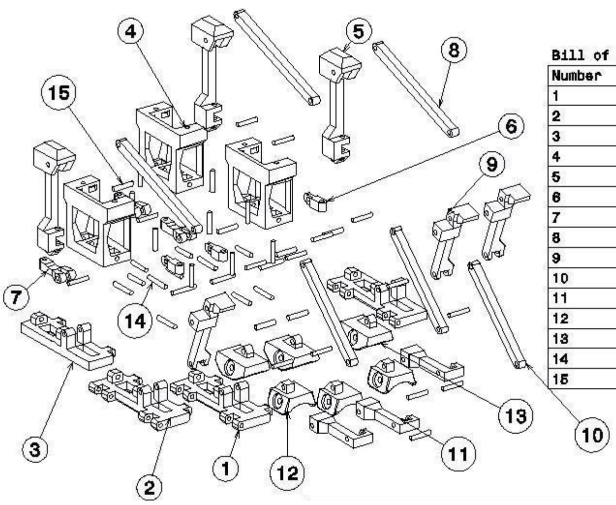
Figure 5(a): Flex holder in exploded view with bill of material.



Bill of Material: System Holder

Number	Part Number	Quantity
1	Power Bank Holder	1
2	Board Cover	1
3	Board Holder	1
4	Power Bank Cover	1
5	Pin 16mm X 2.25mm	2

Figure 5(b). System holder in exploded view with bill of material.



Bill of Material: Right Hand Exoskeleton

Number	Part Number	Quantity
1	Back Hand Middle Bottom	2
2	Back Hand Left Side Bottom	1
3	Back Hand Right Side Bottom	1
4	Back Hand Top	3
5	Back Hand Extension	3
6	Servo To Back Hand Bar	3
7	Servo Extension	3
8	Back Hand To Proximal Bar	3
9	Proximal Extension	3
10	Proximal To Middle Bar	3
11	Middle Extension	3
12	Middle Phalanges Holder	3
13	Proximal Phalanges Holder	3
14	Pin 16mm X 2.25mm	9
15	Pin 12.5mm X 2.25mm	36

Figure 5(c): Right hand exoskeleton in exploded view with bill of material.

Finger Exoskeleton Fabrication

When the exoskeleton part and product design are completed, the exoskeleton parts can be fabricated by using a 3D printer provided by the project supervisor. The 3D printer used to fabricate exoskeleton parts during this project is Creality 3D Ender 3 3D printer and the material used is polylactic acid, PLA filament. The exoskeleton parts need to be saved in stereolithography, STL file format first before transferring the exoskeleton file into 3D printer software. The 3D printer software used in this project is Ultimaker Cura version 4.5.0 where the exoskeleton parts can be virtually arranged on the printer heating bed.

When the exoskeleton parts have completely arranged, the software can convert the part arrangements into G-code where the 3D printer can read the code and fabricate the parts on the printer heating bed in real time. When the exoskeleton parts have fabricated, the parts are removed from the heating bed by using a scraper and assembled into one complete product. Figures 6(a), 6(b) and 6(c) show the fabricated exoskeleton parts involved in each product and assembled on Master and Slave hand.

The functions of flex holders in Figure 6(a) are to control the flex sensor to only bend 0 to 90º angle, prevent the sensor from bending toward the strip which can damage the sensor [9] and prevent any damage on the flex sensor strip. The functions of system holders in Figure 6(b) are to secure Arduino circuit on breadboard and power bank inside a casing to be worn on both patient hands and provide protection against any disturbance that can disrupt the circuit. The functions of right-hand exoskeleton in Figure 6(c) are to provide support on the patient finger and assist the patient finger movement.

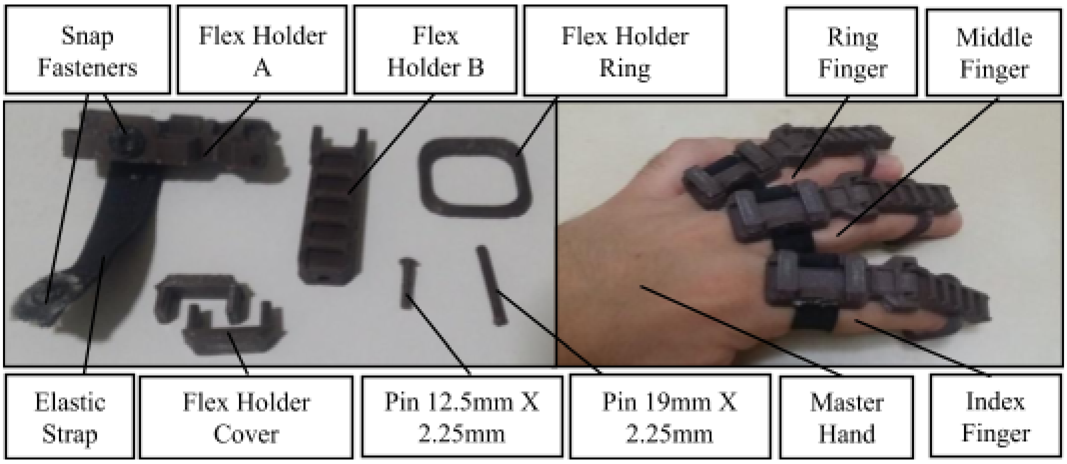


Figure 6(a): Flex holder fabricated parts (left) and flex holder assembly on master hand (right).

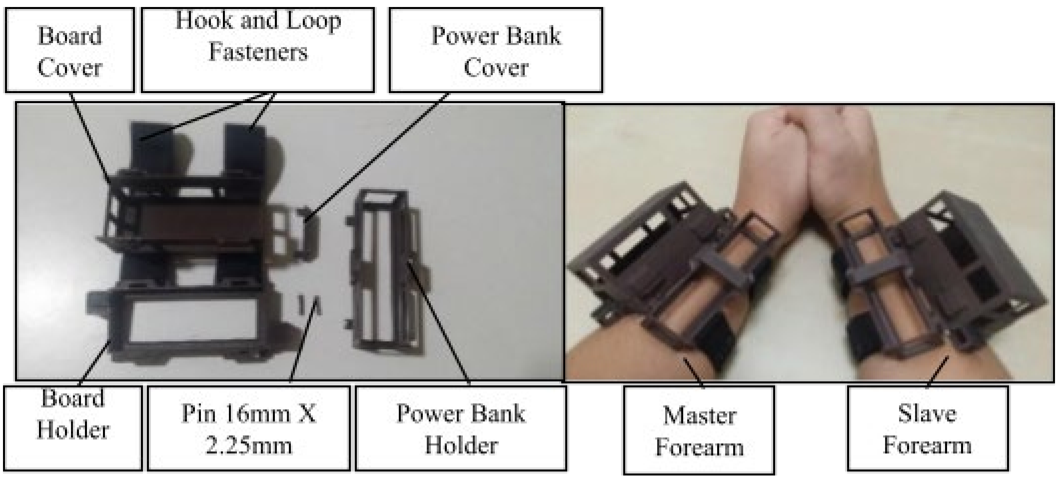


Figure 6(b): System holder fabricated parts (left) and system holder assembly on master and slave forearms (right).

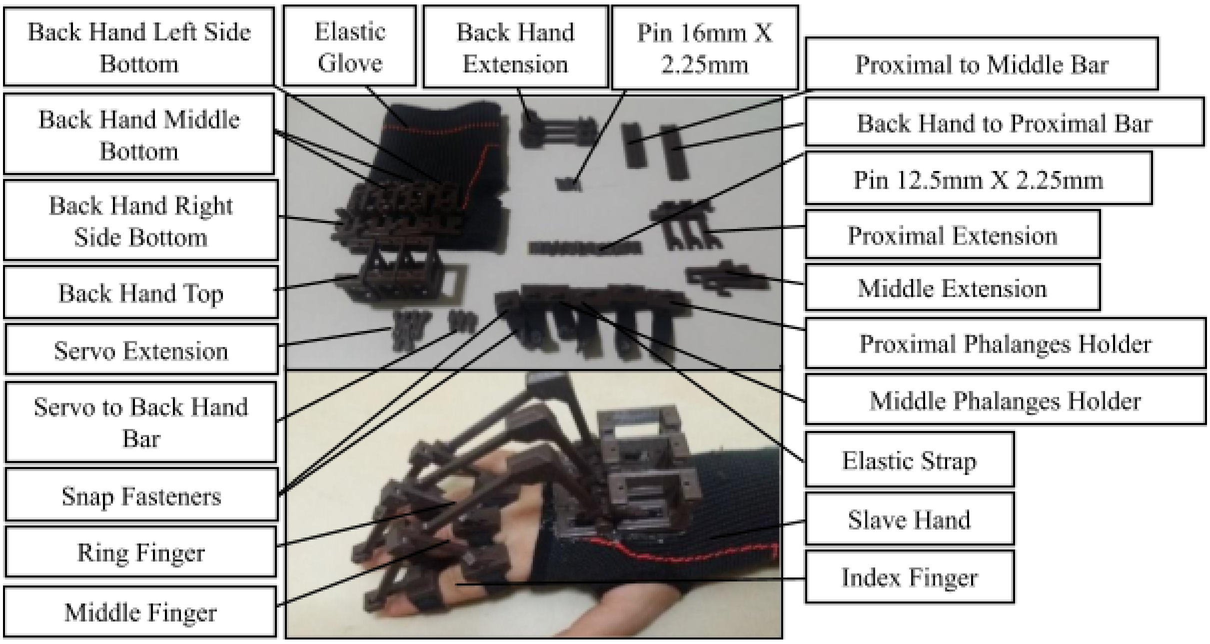


Figure 6(c): Right hand exoskeleton fabricated parts (left) and right-hand exoskeleton assembly on slave hand (right).

System Integration Test Run

System integration test run phase is one of the most crucial phases in this project as the Arduino circuit and finger exoskeleton design have undergone several modifications in order to successfully integrate both designs into one functional system in Mirror Therapy. Figure 7 shows the system integration of flex sensors from Arduino circuit and finger exoskeletons in Mirror Therapy.

Figure 7: System integration of flex sensor from arduino circuit and fabricated finger exoskeleton in mirror therapy.

After Master and Slave circuit program code are uploaded into the microcontrollers, flex sensors are straightened on the flex holders to record the minimum ADC reading values for 0º position in the serial monitor. Then, the sensors are bend to the maximum angle of flex holders which is 90^{o} to record the maximum ADC reading values for 90º position. When the range of ADC reading values are obtained for each finger, Master program code is updated with the latest ADC values. As the program code is updated, servo motor angle can be seen in the serial monitor and finger exoskeleton are pushed by the servo motor. The position and angle of middle and proximal phalanges can be obtained through Kinovea software version 0.8.27 as shown in Figure 8.

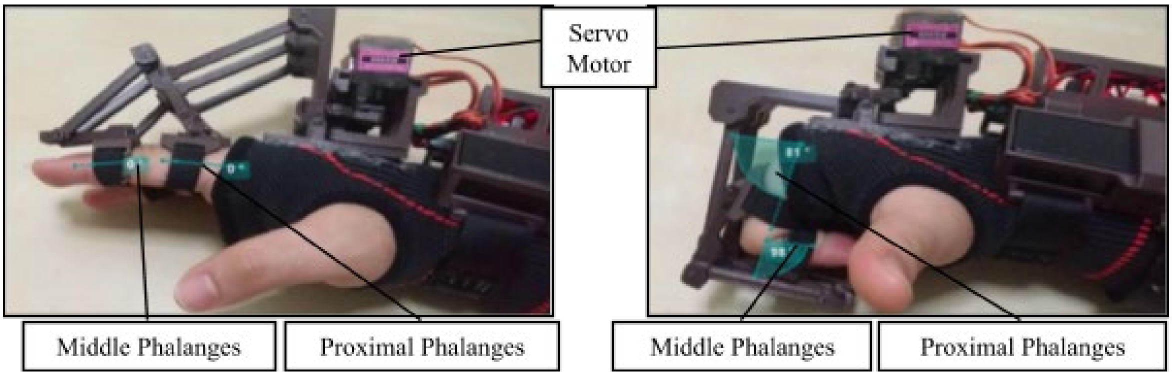


Figure 8: Angle and position of middle and proximal phalanges in finger exoskeleton when servo motor turns 0º (left) and 180º (right).

During modification, hook and loop fasteners are used in system holder assembly in Figure 6(b) as they can provide firm grip and adjustable strap which can be worn by the patients with different forearm sizes. Snap fasteners and elastic straps are used in flex holder assembly in Figure 6(a) and right-hand exoskeleton assembly in Figure 6(c) to ensure the patient fingers are breathable while preventing any interruption of blood flow and are easy to wear by the patients with stroke fingers. Elastic glove is used in right hand exoskeleton assembly in Figure 6(c) to ensure the exoskeleton remains stationary at the back hand as the exoskeletons tend to move around when the patient fingers undergo movement.

Real Time System Evaluation

After the integration of Arduino circuit and finger exoskeleton design were completed, the connection between Master and Slave hands needed to be evaluated so that the connection ran smoothly. An experiment was conducted to investigate the connection between Master and Slave hands by recording a video of both hands undergoing the same animation such as flat position, in between flat to clench position, clench position, in between clench to flat position and back to flat position. The video was imported to Kinovea software so that the both hands animation can be deeply investigated.

Master and Slave hand movement animations are firstly recorded three times for each index, middle and ring fingers and the videos are played in the software. The software then curbs the videos frame by frame and the user is able to easily pinpoint the position and angle produced by both Master and Slave hands for every animation respected based on the real time as shown in Figure 9. During the evaluation, it can be seen that the Slave hand had a slight delay time to imitate every Master hand movement done in one animation.

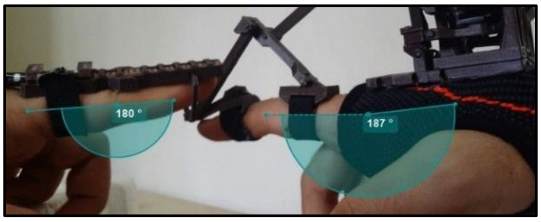


Figure 9: Angle comparison between master and slave index finger.

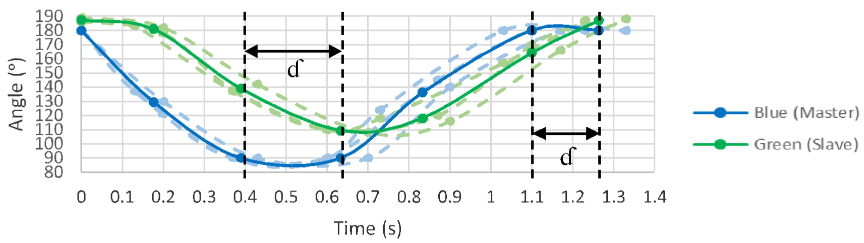


Figure 10(a): Angle comparison between master and slave index finger through time.

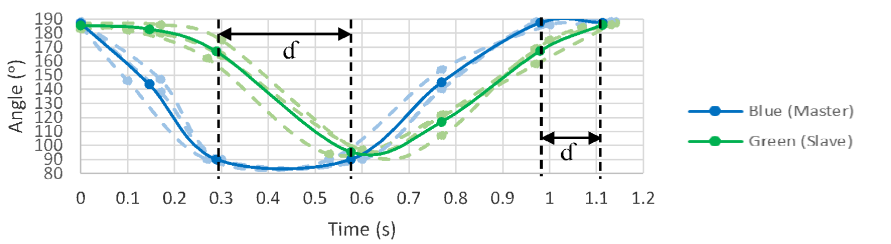


Figure 10(b): Angle comparison between master and slave middle finger through time.

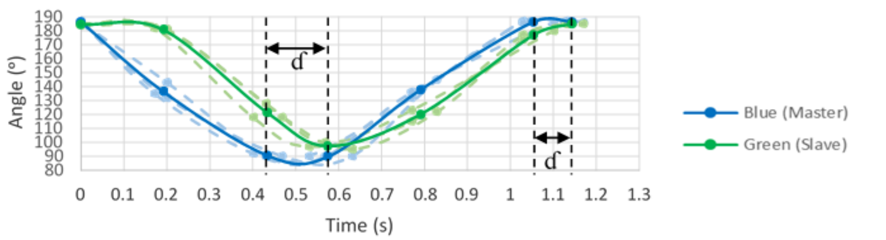


Figure 10(c): Angle comparison between master and slave ring finger through time.

After 3 animations are recorded for each finger and the results are obtained from Kinovea software, there are delay times presented in Figures 10(a), 10(b) and 10(c). Delay time, ɗ can be measured by calculating the time difference when both hands are in clench position and flat position where the hands return to their initial position. As the delay times are completely measured, index, middle and ring have delay time of 400 ms, 420 ms and 240 ms respectively. The robotic hand is considered usable if the delay time is located below 300 to 400ms [10], therefore index and ring finger can be considered as acceptable while the middle finger cannot.

There are several factors that can increase the delay time during design and fabrication for this project. Firstly, a rough finishing surface of a 3D printed part can produce unnecessary friction between two parts which interfere with the movement of parts, thus increasing the delay time. Next, the breadboard is meant to be used as a temporary connection between Arduino parts. A slight disturbance on the breadboard can cause disruption on the circuit voltage which can change the flex sensor value and servo motor angle, thus increasing the delay time. Lastly, servo motors with small maximum stall torque cannot fully control finger movement. Every finger contains their own mass and weight which influence the force and torque required for the exoskeleton to move the finger. If the required force and torque to move the finger exceed the maximum stall torque of MG90S servo motor which is 2.2 kg/cm [11], the finger movement will be slow, thus increasing the delay time.

Conclusion and Recommendations

This research has fulfilled the project objectives. The first objective is achieved where Arduino circuits for flex sensor and finger exoskeleton for each finger have been successfully designed to provide free mobility to patients while undergoing Mirror Therapy session. The drafting for all finger exoskeleton parts can be obtained in Appendices.

The second project objective is settled where the Arduino circuit with flex sensor and finger exoskeleton have been successfully integrated with one another to produce one complete system. The system integration has undergone several tests run in order to provide continuous connection of ADC reading and angle value between Master hand and Slave hand. Finger exoskeleton design has gone through several modifications to be suitable for various finger sizes and can be worn with ease to the patient's hands in a Mirror Therapy session.

The final project objective has been achieved where finger exoskeleton angle and speed have been successfully evaluated by measuring the delay time between Master hand and Slave hand. Delay time in one animation for both hands can be obtained within Kinovea software. As the researchers claimed that robotic hands can be considered usable if the delay time is below 300 to 400 ms [10], index and ring finger exoskeleton are acceptable except for the middle finger.

While undertaking the research, there are several problems encountered during the evaluation which increase the delay time in the integration system. Firstly, rough finishing surfaces of 3D printed parts produce unnecessary friction between two parts which interfere with the movement of parts. Next, breadboards can only provide temporary connection between Arduino parts as any disturbance can change the flex sensor value and servo motor angle in the system. Lastly, insufficient torque of the chosen servo motor is unable to completely control and support the movement of the patient finger.

There are recommendations to improve and decrease the delay time in the integration system. Firstly, a good finishing surface and easy removal of 3D printed parts can be obtained by changing the stock heated bed to glass heated bed. Next, the breadboard can be changed to a permanent circuit board so that circuit connection cannot be easily disrupted by minor disturbance. Lastly, selection of servo motors with higher maximum stall torque can be used to provide more sufficient mobility and control on patient fingers.

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