Portable Therapeutic Guided Wrist Flexion Exerciser Device for Recovery Monitoring

Nur Anida Jumadi[1], Mack Donald Sangkah Kinatu[1] and Mohammad Fairuz Mohd Nasir[2]
[1]*Department of Electronics Engineering, Faculty of Electrical & Electronics Engineering, Universiti Tun Hussein Onn Malaysia, 86400, Batu Pahat, Johor*
[2]*Public Works Department, Maintenance Division, Kementerian Kerja Raya*
anida@uthm.edu.my

***Abstract*— Wrist pain and stiffness is a common complaint for many people. This problem is triggered by many factors such as injuries caused by sudden impact, an activity that involves repetitive wrist motions as well as outstretched hand during falling forward. Based on the key rehabilitation engineering principles as well as ergonomics principles, this paper discusses the development of wrist flexion rehabilitation device for recovery monitoring. The user will be guided throughout wrist-flexion exercise session where the Arduino Mega has been utilized to control the whole operating system. Several sensors have been employed to gather all necessary inputs required for training counting system and determination of bending degree. Furthermore, rapid prototyping technique using 3D technology has been implemented for fabricating wrist flexion assembly parts. Besides that, this device is also equipped with data logging system where the physiotherapist is able to use the stored data for monitoring the recovery process. Data from mock training revealed that the developed device is able to guide the user throughout the rehabilitation process.**

***Index Terms*— Arduino; Ergonomics Principles; Rapid Prototyping; Rehabilitation Engineering; Wrist Flexion Device.**

I. INTRODUCTION

The objective of rehabilitation is to enable the once injured body to regain at least minimum potential for conducting normal daily activities. By definition, rehabilitation engineering is the use of engineering science and principles to develop technological solutions and devices to assist individuals with disabilities and to aid the recovery of physical and cognitive functions lost because of injury and disease [1]. The human hand and wrist are complex structures and they are capable of performing various movements for manipulating objects and tools [2][3]. Therefore, many studies have been conducted regarding hand and wrist especially in product design, ergonomics and rehabilitation fields.

The wrist is made up of eight small bones. These small bones which also known as carpals are functioned to support the carpal tunnel that runs through the wrist [4] The anatomical movements of the wrist are known as flexion-extension and abduction-adduction. Figure 1 depicts an example of flexion and extension movement. The flexion and extension are moving that occur in the sagittal plane. During flexion, the palm goes towards the lower surface of the forearm whereas for an extension, the dorsal surface of the palm goes towards the upper surface of the forearm [5]. Abduction and adduction are two terms that are used to describe movements towards or away from the midline of the body. Abduction is a movement away from the midline whereas adduction is a movement towards the midline [6].

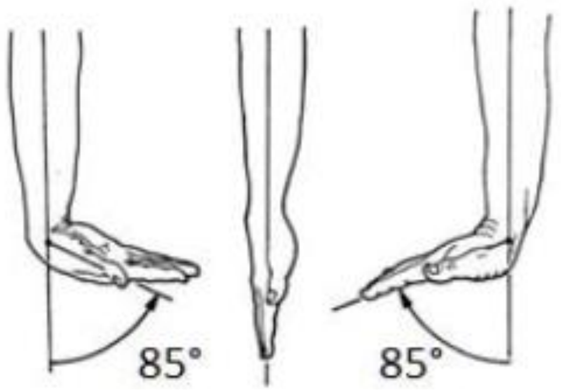


Figure 1: (a) flexion at 85 degrees; (b) anatomic position at 0degress and (c) extension at 85 degrees. [5]

Wrist pain can lead to functional disabilities and can be occurred from repetitive motions that can be triggered by everyday activities such as typing and sewing as well as from sports activities [7]. Wrist pain with bruising and swelling can be a sign of injury. Examples of manual wrist rehabilitation device in the current market are pinch grip, rolling machine, twisting machine and hand strengthens.

However, the limitation of current wrist rehabilitation device is it can only be operated manually. In other words, any patients using this device will not follow the proper routine training. As a result, there is a high tendency for the end-user to carry out the exercise until getting tired, loss of interest or even worst, will feel demotivated. The rehabilitation process requires constant monitoring of the patient in order to track down the progress as well as treatment effectiveness. However, the recovery stage is difficult to tell since the current device does not provide any information on the recovery improvement. Therefore, the end-user will never know the recovery performance of the wrist. For that reason, this research has been proposed with the aim to develop a wrist-flexion exerciser personal monitoring and training system for assisting and guiding proper routine training. The proposed system is equipped with data logging capabilities, which enables the physiotherapist to monitor and analyze the data for offline processing.

This paper is organized as follows. In section 2, a brief explanation of key engineering and ergonomic considerations are given. In section 3, the design and implementation of the prototype are presented. The experimental results are shown and discussed in section 4. Finally, the whole work of this research is summarized in the last section.

II. ENGINEERING AND ERGONOMIC CONSIDERATION

Engineering design considerations usually involve problem analysis, synthesis, evaluation, decision and finally implementation. In general, some of the key engineering design steps that need to be taken into account are the mechanical design of the grip holder and arm body, fabrication of these custom parts, electronics sensors that are applicable to use, the assembly and testing of the design as well as evaluation of the prototype [8].

On the other hand, ergonomic or human factors play an important part in rehabilitation design and such examples of ergonomic consideration involves the principle of proper positioning, anatomical control site and display suitability [9]. In this research, stiffness during wrist flexion movements characterizes wrist flexion difficulty. Therefore, the lack of wrist flexion rehabilitation may unduly limit the use of upper limb extremity especially involving hand gripping. In terms of proper positioning and anatomical control site, the best site to be chosen is the finger to control the wrist flexion movement by placing a handle to be gripped by fingers. This is because the fingers are the only body part that the user has reliable control in terms of speed and dependability. Regarding the display suitability, this project chooses auditory and visual forms for display presentation. The proposed system utilizes the LCD and LED to inform the user about training steps as well as current exercise count whereas the buzzer is used to alert the user during a specific training session.

III. DESIGN AND IMPLEMENTATION OF WRIST FLEXION PROTOTYPE DEVICE

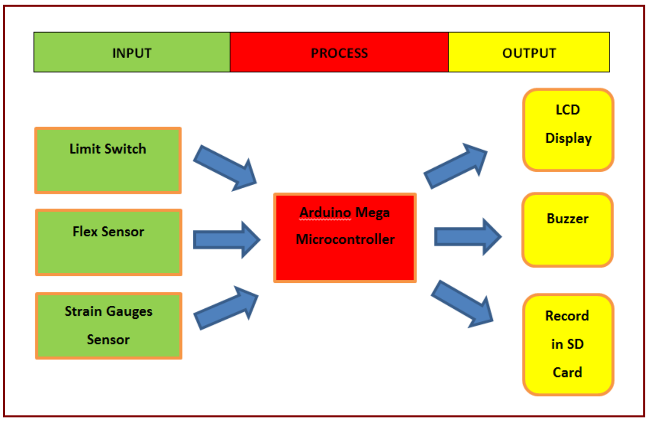


Figure 2: Overall block diagram of the proposed wrist flexion prototype device

The overall block diagram of the proposed system is shown in Figure 2. There are three main sections namely as input, process and output. The flex sensor, limit switch and load cell are the sensors used to acquire the input signal. The Arduino ATMega2560 microcontroller has been selected as data interfacing and acquisition tools with main functions are to receive and process the inputs from multiple sensors as well as to produce the required output [10]. Besides known as an inexpensive microcontroller, the advantages of using Arduino Mega are it provides more inputs and output pins whereas the Arduino IDE software provides an easy-to-code environment since the software is an open source code [10]. Finally, the LCD as well as the buzzer will be used to display the output signals to the end-user whereas the Secure Digital (SD) card is used to save the exercise record.

Briefly, there are four (4) phases involved in this project, which include the development of the circuit sensors, development of training counting system and wrist flexing measurement, development of the wrist prototype using 3D printing technology and finally, displaying the training instructions as well as saving the exercise record.

A. Phase 1: Sensors Selection, Circuit Connection and Data Acquisition

As mentioned previously, there are three main sensors that have been chosen namely as limit switch, flexible sensor and strain gauge load cell. In this project, the limit switch as well as flexible sensor is bought from Cytron, Malaysia whereas the load cell is bought from Mybotic, Malaysia. The details function of each sensor is described in the following section.

i. Limit switch

As shown in Figure 2, the limit switch acts as a sensor to detect the mechanical movement of the grip holder. As the user pull it downward, the limit switch will be pressed and hence, producing an input counting to be fed into the microcontroller. The microcontroller will use this data to count how many times the grip holder has been pulled.

ii. Flexible sensor

The second sensor is the flexible sensor, which is used to measure the bending or flexing degree of the wrist. The flexible sensor is the sensor that can measure the changes in the resistance proportional to changes in its form [11]. The flexible sensor is an analog resistor and therefore can be designed to work as a variable analog voltage divider. As the grip holder of the device is pulled, the flexible sensor will be deformed accordingly and thus, causing the conductive particles inside it to further apart. As a result, the resistance reading will be increased. The ADC in the microcontroller will convert the resistance value into voltage reading by using the voltage divider principle. For this implementation, any suitable resistor value must be placed between the flexible sensor pin and the microcontroller pin. In this project, a 10kΩ resistor has been used as the voltage divider resistor.

iii. Strain gauge micro load cell

The third sensor is the implementation of the strain gauge micro load cell circuit to measure the wrist force [12]. In this research, the 5 kg strain gauge load cell is used to convert the load acting on it into a measurable electrical output (mV/V). The formula as stated in (1) is used to convert the load cell output into the measured force. In this project, the output unit for measured force is in grams.

$$\text{Measured Force}\,(g) = 5\times \text{Measured Output}\,(mV/V) + A \quad (1)$$

$$A = 0 - \left(5\times \text{Measured Output}\,(mV/V)\right) \quad (2)$$

where A is the offset value of the load cell when the load cell is measured with no force on it. The measured output (without load) is then fed into the Equation (2) to obtain the required offset value.

iv. Circuit connection and data acquisition

Figure 3 below illustrates the circuit connection between the limit switch, flexible sensor as well as a load cell and the ATmega2560 microcontroller. The limit switch and flexible sensor are connected to digital pin 8 and analog pin 0, respectively. Meanwhile, the two output pins of the load cell sensor are connected to digital pin 2 and 3.

Besides that, not showing here is the connection of the LCD to the microcontroller. A variable resistor is used to adjust the LCD screen brightness and is connected to analog pin 3 whereas the data output from the LCD is connected to analog pin 4 until pin 7. In addition to that, the Register/Select and enable pins of the LCD are connected to analog pin 12 and 11, respectively. Meanwhile, the auditory (buzzer) and LED indicators are connected to digital pin 38 and 39, respectively. The whole circuit is drawn using Proteus software and the printed circuit board (PCB) is designed to place the circuit components.

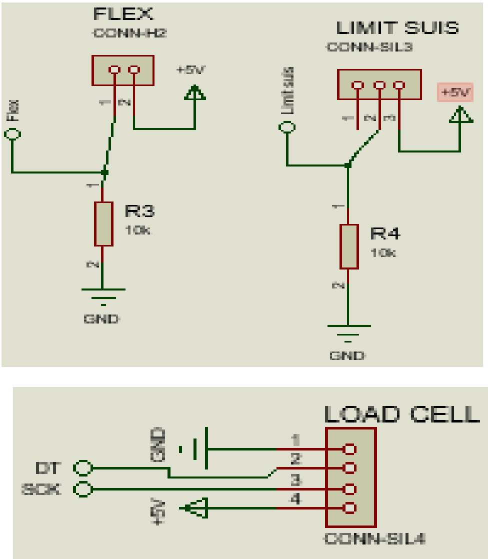


Figure 3: Schematic diagram of the limit switch, flexible sensor and load cell circuits.

B. Phase 2: Programming C++ in Arduino IDE platform

The second phase involves the programming development of training counting system as well as measurement of wrist flexing which is done using C++ language in the Arduino IDE platform. In this project, the training counting system is developed in order to guide the user to follow the common three-twelve (3-12) wrist exercise routine. Briefly, the user must complete twelve (12) cycles of exercise where one cycle of exercise is consist of flexing the wrist three (3) times following five (5) seconds rest. The flow chart of the proposed training counting system for wrist exercise routine can be referred to Figure 4.

Meanwhile, in order to measure the bending degrees, not only the measured voltage of Arduino 5V line as well as resistor value used to construct the voltage divider circuit must be correct, but the resistance values of the flexible sensor during straight and 90-degree bending have to be accurate as well. These four important data will be used to map or estimate the wrist-bending angle.

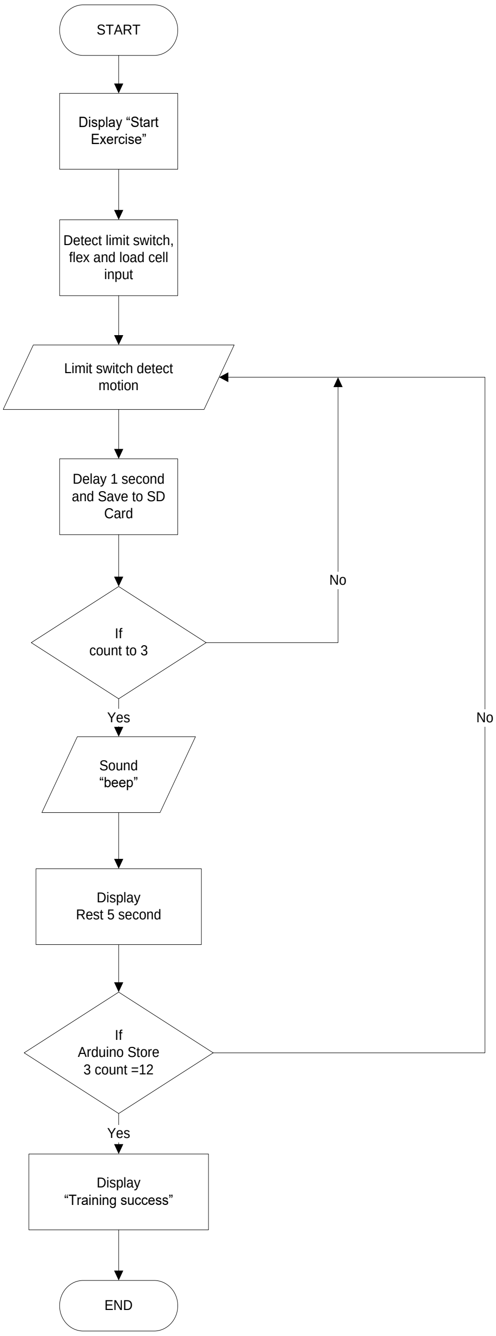
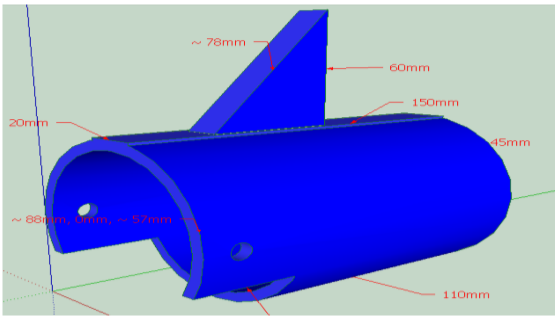


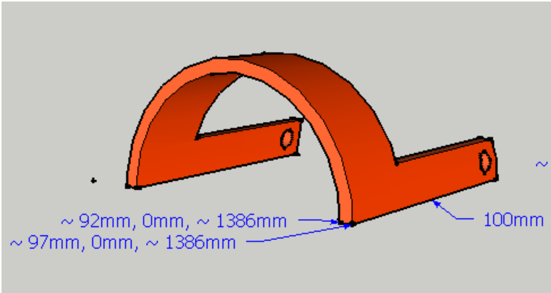
Figure 4: The flow chart of training counting system

C. Phase 3: Mechanical Design of Prototype Pieces

Google SketchUp is a useful 3D modeling program, which can be applied to architectural, civil, and mechanical design. Figure 5(a) and 5(b) illustrate the proposed design of grip holder piece and arm body piece of the wrist flexion exerciser device; respectively. The diameter of the grip holder is 9.2 cm whereas the length of the tubular arm body is around 11 cm. These measurements are basically following the second author's wrist and arm size. He has a normal body mass index (BMI) of 20 kg/m^2.



(a)



(b)

Figure 5: The design of a) tubular arm body of wrist exerciser device and b) grip holder

D. Phase 4: Data Logging

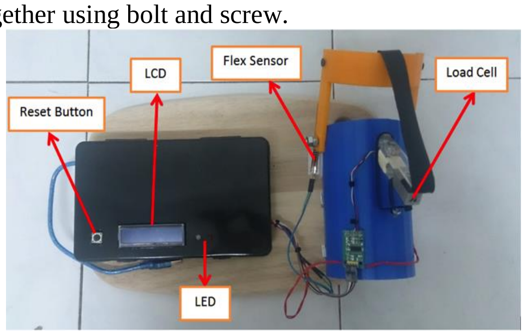
The SD card is used to record three important information which is: number of exercises that have been done by the user, the strength of the wrist to pull the grip holder as well as the wrist bending degrees. The SD card reader has four pins that are connected to digital pin 50 until pin 53 of the microcontroller. The physiotherapist or the patient can use the saved data to analyze the recovery process.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

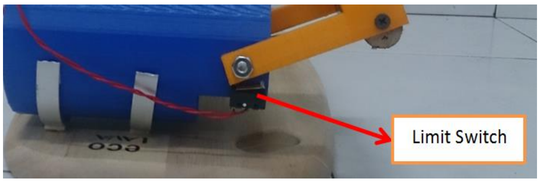
There are four main results to be discussed in this section. The first one to be discussed is the completed assembly of the wrist exerciser, which has been prototyped using 3D printing technology and Google SketchUp software. After that, the selected sensors underwent function ability experiments in order to ensure that the sensors are able to produce a desirable outcome. Then, an evaluation study is conducted based on the mock training session to assess the programming outcome and finally, how the SD card saved the training data to be used for further analysis is presented here.

A. Wrist exerciser prototype device

The completed assembly of the prototype with several different views such as top, left and front views are presented in Figure 6(a), 6(b) and 6(c), respectively. The position of the limit switch underneath the grip holder can be seen clearly in Figure 6(b). The grip holder and arm body are fastened together using bolt and screw.



(a)



(b)

Figure 6: The top (a) and right view (b) of wrist flexion exerciser prototype with the corresponding labeled of main components

B. Sensors testing

Before the system can be implemented in the real application, several testing experiments are conducted on the chosen sensors to ensure that the sensors are not only able to function as expected but can also give desired outcomes.

i. Limit switch test result

Figure 7: Result of the limit switch

The first experiment is to test the programming for limit switch whether it is able to count the wrist flexion or not. As can be seen in Figure 7, the display in the LCD manages to show how many training sets have been successfully achieved. Each recorded set indicates that the user has successfully bent the wrist three times.

ii. Flexible sensor test result

Table 1
Flexible Sensor Reading

Sensor Position in Degree	Test 1 (°)	Test 2 (°)	Test 3 (°)	Average (°)	Average Error (%)
Straight (unflexed)= 0°	1	0	2	1	Offset value
15°	14	15	15	14.7	2.00
30°	31	30	31	30.7	2.33
45°	45	45	46	45.3	0.67

Table 1 tabulates the flexible sensor reading during 0° and 45° that have been successfully measured using Arduino Mega. For each sensor position, three repeatable tests have been conducted and the error percentage for each position has been calculated. From the table, it is found that the largest average error is 2.33% at 30° bending. Though, the wrist is able to flex up to 85°, the experiment for 85° flexion could not be carried out since the structure of the grip holder can be easily broken due to full force effect.

iii. Strain gauge load cell test result

Table 2
Load cell reading

Load Ballast (g)	Test 1 (g)	Test 2 (g)	Test 3 (g)	Average (g)	Average Error (%)
0	1	0	1	0.67	Offset value
50	51	50	49	50	0
500	500	505	500	501.7	0.34
1000	995	1005	990	996.7	0.33

Table 2 presents the load cell reading captured using Arduino Mega. It can be seen that the load cell has an offset value of 0.67 g. This value is then fed into equation (2) above for calibration purpose. Up to 1000 g testing, the highest average error is 0.34 % only which was occurred during 500 g load ballast.

C. *Data Collection Protocol and Prototype Evaluation*

Figure 8: Wrist flexion exerciser prototype during a mock training session

For assessing the programming training, one mock training session has been carried out. Figure 8 above shows how the wrist exerciser prototype is used during the evaluation process. It can be seen that the subject's hand is gripping the hand holder of the developed wrist exerciser. This device can be operated either by connecting it to the battery or power bank through the USB 5V connector.

i. *Data Collection Protocol*

Following are the data collection protocol one should adhere to data collection procedures. First, the user or patient should comfortably sit on a chair. Once the weak wrist slotted into the device, the fingers must firmly grip the designated holder. After powering up the device, the user can start the training by following the instructions as displayed on the LCD (See Prototype Evaluation). Finally, once the training set is completed, the exercise records that have been previously saved in the SD card can be viewed by the user or physiotherapist for further evaluation.

ii. *Prototype Evaluation*

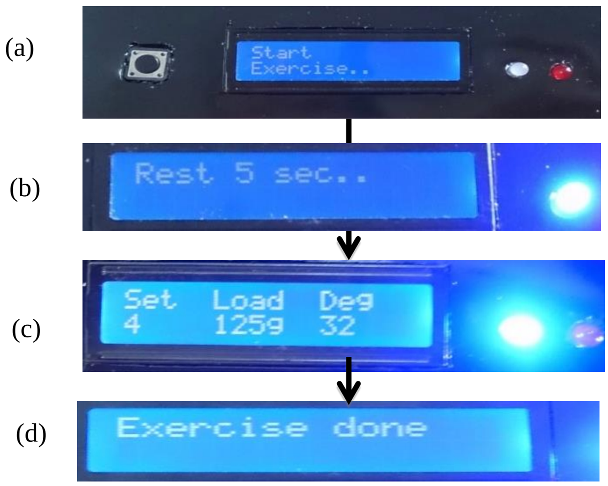


Figure 9: LCD is displaying the sequence of training instructions during the mock session.

For better understanding, Figure 9 describes the sequence instructions in the form of pictures flow during a mock training session. When the device is powered up, the LCD display will show the 'Start Exercise' caption indicating that the user or patient can start the training by pulling the grip holder downward (Figure 9(a)). Next, in Figure 9(b), the LCD displays three important information which are the current count set, the wrist force value after successfully pulling the grip holder as well as how far the wrist is able to flex. Then, after completing the three times counts, the patient is instructed to take 5 seconds rest via the LCD display as shown in Figure 9(c). At the same time, the beep from the buzzer as well as the lights up from the red LED will alert the user to take 5 seconds rest immediately. Once the training is completed in 12 sets, the programming system will notify the user that the exercise has been successfully completed (Figure 9(d)).

D. *SD Card Output*

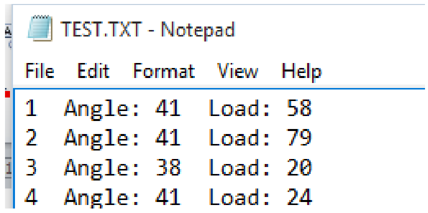


Figure 10: Data recorded in SD card

Figure 10 above shows the example of how the data during a training session is recorded in the SD card. It can be seen clearly that the first, second and third columns are the training count obtain from the limit switch, the wrist bending degrees from the flexible sensor as well as the wrist force recorded from the strain gauge load cell. This recorded information will be beneficial for the user or physiotherapist to evaluate the recovery performance.

E. *Further Discussion*

During evaluation of mock experiment, we noticed that when the limit switch was pressed, the reading of the flexible sensor would continually record even though the wrist was still in flexing position. This will cause the reading of flexible sensor to be inaccurate. Therefore, to overcome this problem, the delay time of 1 second was included in the programming. Besides that, the grip holder was broken several times when testing the wrist flexion more than 45°. The reason why this happened is due to the limited source of suitable ink materials to produce a firm structure for the grip holder plus extra forces enforce during this session.

Meanwhile, from the point of ergonomics view, this developed prototype is meant to be used by an average adult who needs to rehabilitate the wrist in flexion movement. This is mainly because the grip holder as well as the prototype body has been designed to be fitted by the average size of adult's hands. Children have a smaller size of hands and therefore, this prototype is not recommended for children as it will not be as effective as it should be.

V. CONCLUSIONS

In conclusion, the prototype of the portable therapeutic wrist flexion exerciser guided device has been successfully developed. The developed prototype caters the wrist flexion rehabilitation and therefore is suitable for those who experience the wrist stiffness or weak wrist due to injury caused by repetitive movements. The system guided the user to do proper training and at the same time saving the recorded training to be used for later analysis. The guiding system is fully automated and controlled by Arduino Mega based on the information received from the analog sensors namely as a limit switch, flexible sensor and load cell sensor. The mechanical design of the grip holder as well as the body has been designed using Google SketchUp and later is printed using the 3D printing technology. These two pieces items are then fastened together by using bolt and screw. In the future, we plan to replace the flexible sensor with a variable resistor in order to obtain a more accurate wrist flexion degree. Most importantly is the mechanical design of the wrist flexion device. For the adult use, suitable materials required to form the wrist flexion structure particularly at the grip handle so that it will not easily break.Besides that, the whole prototype can be redesigned to fit the children's hand. For a better wrist force flexion, the use of load cell sensor can be replaced with springs.

ACKNOWLEDGMENT

Authors would like to express deep gratitude to Registrar Office UTHM and Research, Innovation, Commercialization and Consultancy Office (ORICC), Universiti Tun Hussein Onn Malaysia for funding the conferences and travel fees.

REFERENCES

[1] M. Atlihan, E. Akdoǐan, and M. S. Arslan, "Development of a therapeutic exercise robot for wrist and forearm rehabilitation," in 2014 19th International Conference on Methods and Models in Automation and Robotics, MMAR 2014, 2014, no. 111, pp. 52–57.

[2] A. R. Tilley, The Measure of Man and Woman: Human Factors in Design. New York: Whitney Library of Design, 1993.

[3] D. J. Williams, H. I. Krebs, and N. Hogan, "A robot for wrist rehabilitation," in 2001 Conference Proceedings of the 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2001, vol. 2, pp. 5–8.

[4] B. R. Wang, J. Reed, and J. Leone, "A Systematic Approach To A Painful Wrist," Can. J. Diagnosis, vol. 1, no. August, pp. 86–97, 2001.

[5] A. M. Barbosa, L. a O. Rodrigues, S. S. Dos Santos, and R. S. Gonçalves, "Comparison of a mechanical and biomechanical system applied in the human wrist rehabilitation using a cable-based system," in Proceedings - 2012 Brazilian Robotics Symposium and Latin American Robotics Symposium, SBR-LARS 2012, 2012, pp. 120–124.

[6] M. Gonzalo, A. Jarrín, P. Gabriela, and M. Cáceres, "Functional elbow and wrist rehabilitation prototype controlled by computer," in 2014 XIX Symposium on Image, Signal Processing and Artificial Vision, 2014, pp. 1–5.

[7] A. J. Mcdaid, "No Title," in 2015 IEEE International Conference on Rehabilitation Robotics (ICORR), 2015, pp. 434–439.

[8] M. R. Sajadi, A. Nasr, S. A. a Moosavian, and H. Zohoor, "Mechanical Design , Fabrication , Kinematics and Dynamics Modeling , Multiple Impedance Control of a Wrist Rehabilitation Robot," in 2015 3rd RSI International Conference on Robotics and Mechatronics (ICROM), 2015, pp. 290–295.

[9] D. Dauria, F. Persia, and B. Siciliano, "Human-Computer Interaction in Healthcare: How to Support Patients during Their Wrist Rehabilitation," in Proceedings - 2016 IEEE 10th International Conference on Semantic Computing, ICSC 2016, 2016, pp. 325–328.

[10] Arduino, "Aurduino mega 2560 Datasheet," 2013. [Online]. Available: http://www.mantech.co.za/datasheets/products/A000047.pdf. [Accessed: 03-Jan-2017].

[11] Sparkfun, "Flex Sensor Datasheet," 2014. [Online]. Available: https://www.sparkfun.com/datasheets/Sensors/Flex/flex22.pdf. [Accessed: 05-Dec-2016].

[12] Robotshop, "Datasheet," 2011. [Online]. Available: http://www.robotshop.com/media/files/pdf/datasheet-3133.pdf. [Accessed: 12-Dec-2016].