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Design and Development of a Multi-sensor Monitoring Device for Arm Rehabilitation

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Abstract: A continuous monitoring process for arm rehabilitation activities are important to provide information of rehabilitation results to be analyzed by therapist. The purpose of monitoring is to help them to improve rehabilitation process. Moreover, a portable and simple home-based rehabilitation device can help patients to improve daily rehabilitation activity. Some previous studies regarding home-based rehabilitation process have shown improvement in promoting human movement recovery. But existing rehabilitation devices are expensive and need to be supervised by physical therapist. Some devices are not so efficient to be used at home due to large size and complex system. In this current work, flex sensor, force sensitive resistors and accelerometer were assessed in order to be implemented as a sensory unit for a portable arm rehabilitation device. Analog signal from the sensors will be conveyed to an Arduino microcontroller for data processing and logging. The results of rehabilitation activity can be used for further monitoring and analysis. Experiments were carried out to determine the feasibility of each sensor towards the design of the new rehabilitation monitoring device. The experiments demonstrate the capabilities of the sensors to produce extended information regarding arm movement activity which can be implemented in the design. A liquid crystal display (LCD) monitor will show to the user the achievement of their exercise activity on daily basis.

Keywords: Arduino, arm rehabilitation, assisting device, monitoring device

1. Introduction

Rehabilitation process due to stroke or accident related injuries are based on clinical assessment tools which can be executed by self-report (home-based) and observer-rated (done at rehabilitation centre) [1]. Observer-rated by caregivers can be time consuming and patients require to have repeated observations at rehabilitation centre which can be costly. However, early home-based rehabilitation proved to promote a better physical health because it appeared to permit motor and functional gains that occurred with natural recovery and satisfaction with community integration [2].

Continuous monitoring of physical activity is an important subject in the area of rehabilitation. The results obtained from these observations can be used to determine the progress and effectiveness of a rehabilitation program. How to effectively motivate patients to do the regular physical activity is an important research topic [3~4].

Enormous researches have been done focusing on lower limbs rehabilitation. However, there are not too many researchers done on arm rehabilitation. Majority of the arm rehabilitation researches involved the usage of exoskeleton type devices which, although can maintain correct movement form and can produce force inputs for therapy, but due to its large and complex built, it is not suitable for home-based rehabilitation device [5~9].

Assistive devices are another alternative which incorporate many high-tech systems into rehabilitation. These systems involve attaching devices to the affected human limbs in order to monitor patient's physical activity.

Miniaturized sensors such as accelerometers, flex sensors and force sensitive resistors are widely used in developing assistive devices [10~14]. Accelerometer is a device which measures acceleration indirectly through inertial force. These can be converted into analog/digital voltage signals. Due to this ability, accelerometers have been used to track motion of human [10~12]. Flex sensor can effectively measure movement and flexibility of muscle [13~14]. Force sensitive resistor can detect flexion and extension of individual muscles [15~16]. These sensors proved effective to measure various physical activities parameters. However, there are no attempt on combining all of these sensors.

Therefore, the work described in this paper evolved from the above stated researchers involving the application of several sensors and the development of simple data logging method in the design and development of monitoring device for arm rehabilitation. Data logging enables clinician to do remote monitoring

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and provide organized sets of data on daily basis every time the user do rehabilitation workout at home.

2. Materials

2.1 Hardware

In this study, the developed device consists of 2 units: main unit and sensory unit. The main unit consists of an Arduino Duemilanove microcontroller, a tactile push button and a 16x2 RT1602C LCD display. While the sensory unit consists of a flex sensor, 2 pieces of force sensitive resistor sensors (FSRs) and accelerometer.

2.2 Flexible sensors

Flexible sensor or flex sensor is a type of resistor which actually composed of tiny patches of carbon that can change resistance values when bending from convex to concave shapes. It is known as an ideal input device for controlling limb-like mechanisms due to its ease of positioning when attached to finger or elbow to track movement.

In this project we used flex sensor produced by Spectra Symbol. Resistance value of the sensor is about 8,000 Ω (8K) at 0˚. The resistance will gradually increase if the flex sensor as being bent inward. At 90˚, the resistance value is about 10-14K Ω. The flex sensor may be bent greater than 360˚ depending upon the radius of the curve, this will further increase the resistance value to increase more further. Its life cycle is more than 1 million bend [16].

2.3 Force Sensitive Resistors (FSRs)

A force sensitive resistor (FSR) is also another type of resistor which is composed of polymer thick film. Its resistance changes when physical pressure applied to the active surface. Fig. 1 shows the relation between FSR's resistivity against physical force on its active surface. When there is no pressure, the sensor looks like an infinite resistor (larger than 1MΩ), while the resistance may reduce to several kΩ when the pressure on the active surface increases. FSR as shown on Fig. 2 is very ideal for body-worn sensors since it require less power and easy interface, very lightweight and relatively sensitive to small physical force. Moreover, Oliver Amft et al proves that FSRs can be easily integrated into clothing to detect the contractions of arm muscles which can provide important information for activity recognition [15].

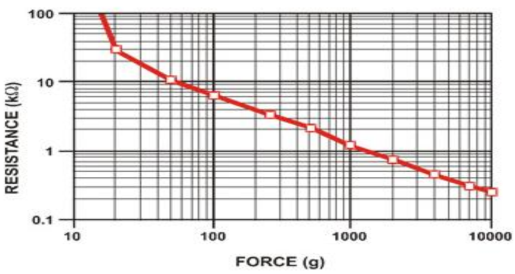


Fig. 1 Resistance against force [17]

Fig. 2 Force sensitive resistor (FSR) [17]

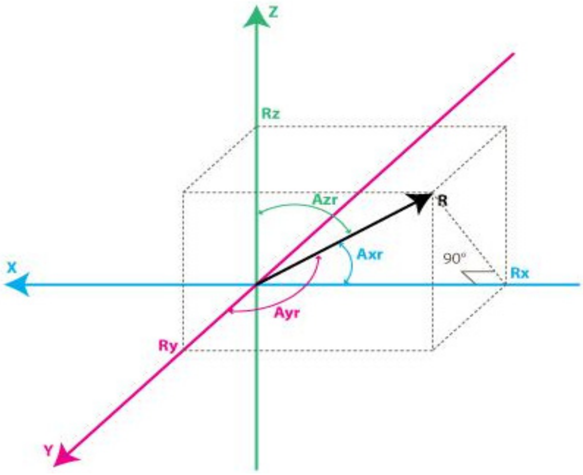


Fig. 3 A model of accelerometer axes and its correspond force vectors (Rx,Ry,Rz) and angles (Axr, Axy and Axz)[16].

2.4 Accelerometer

In this study, an accelerometer (Analog device, ADXL335 ± 3 g) was fixed on the wrist using Velcro strap. This accelerometer is a thin, low power and small 3-axis accelerometer which can give analog voltage output. Accelerometer works by detecting inertial force that is directed in the opposite direction from the acceleration vector. So, it measures acceleration indirectly through an applied force. In short, the output voltage of accelerometer is directly proportional to the acceleration. Even better, accelerometer also can monitor the vertical inclination of body parts relative to ground in ambulatory studies [10]. Fig. 3 shows a simple model of an accelerometer axes and it correspond force vectors Rx, Ry and Rz. Arduino will output analog value in the range of 0 ~1023 from its own built-in 10-bit ADC module. The example of the 3 accelerometer axes values logged into the PC are 586,630,561 (= Adc_X, Adc_Y, Adc_Z). To convert 10-bit ADC value to voltage, the following formula was used :

$$VoltsX = \frac{\left((Adc\_x * Vref)/1024\right) - V\_zeroG}{Sensitivity} \quad (1)$$

In equation (1), Vref is ADC reference voltage, 3.3V. V_zeroG is accelerometer zero-g voltage level which needed in order to get a signed voltage value. As in equation (2), by dividing with accelerometer's sensitivity value (mV/g), we can express voltage value into force value, g.

$$Rx = \frac{((Adc\_x * Vref)/1023) - V\_zeroG}{Sensitivity} \tag{2}$$

By applying this formula to the rest axes, we should be able to have accelerometer readings in force (g) or acceleration (force value (g) *9.8ms^2) for each of them.

In conclusion, with so many advantages in using accelerometer, it is clearly an ideal sensor to measure lower arm movement progress in term of movement acceleration and lower arm inclination relative to ground.

2.5 Arduino Duemilanove

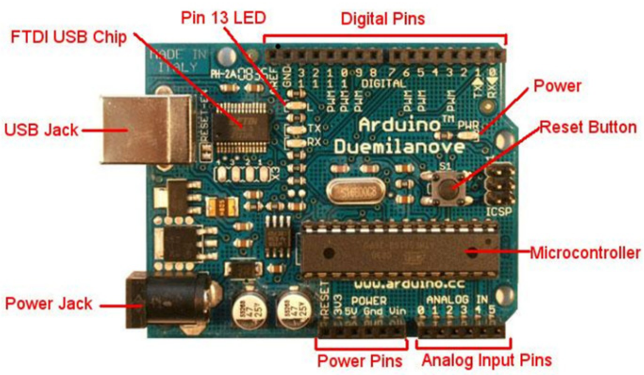


Fig. 4 Arduino circuitry board [13]

Until this paper is produced, PIC microcontrollers are the only choice to be used in final year projects by students in UTHM. This paper took a different approach by using an inexpensive and less hassle microcontroller. To use PIC microcontroller, one have to decide types of board, circuitry, language, compiler for the language, hardware programmer and etc. Arduino Duemilanove provides a complete, flexible, easy-to-use hardware and software platform that is widely used by artists, designers and even hobbyists. Arduino's software is free open source which includes full development environment that can be easily downloaded from the internet. Fig. 4 shows an Arduino development board which utilizes an Atmega 328 microcontroller chip designed by Atmel.

Arduino has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with an AC-to-DC adapter or battery to get started. One of the main advantage of this board is it does not use the FTDI USB-to-serial driver chip. Instead, it features the Atmega8U2 programmed as a USB-to-serial converter.

2.6 Software

Arduino is programmed in C/C++ language based on Arduino IDE (Integrated Development Environment), which is a free software, that enables users to program the Arduino board. The IDE which is available for Windows OS and Linux systems enables the user to design a computer program, to be uploaded into Arduino. The Atmega 328 chips inside the Arduino board will process the programs and interact with external peripherals.

2.7 Data logging

As a monitoring system, this device is equipped with real-time achievement report. Each time arm is bent, the flex sensor will detect the movement and LCD will display achievement of the movement done by the user. Initially, the microcontroller will process the analog data from flex sensor to become output for LCD display and data logging system.

For online real-time PC monitoring, data from flex sensor, FSRs and accelerometer are logged into PC as a .txt format through Microsoft Windows HyperTerminal tool. The .txt files can be further processed by a macro configured Microsoft Excel file to create graphs which can clearly show the characteristics of lower arm movement by all sensors.

3. Experimental Method

3.1 Experimental setup

Literature reviews gave general information on sensors ability which can be applied as a sensory function on this rehabilitation device. Flexion and extension detection ability by flex sensor suited the function of detecting arm bend movements of the device. Sensitive force detecting ability of FSRs is suitable to detect individual muscle movement ability. While accelerometers can sense force generated from movements.

However, experiments were carried out to further verify these characteristics in order to develop a system which can produce quantified results. To do this, we incorporated it into actual physical activities in rehabilitation process. Physical activities that were carried out in the experiments were designed based on information gathered from UTHM health center. The center provides rehabilitation therapy using basic rehabilitation devices such as dumb bells, arm skateboard and arm pulley.

3.2 Flex sensor characteristics

In this first experiment, by using a multi-meter we simply verified the characteristics of flex sensor by monitoring the value of the resistance when the flex sensor is bent. During our early studies, we proved that the more it is bent, the more resistive value will be shown

[16]. Next, we determined the analog voltage value of the flex sensor at certain angle. We proposed the use of these angles as indication for arm bending state to monitor arm bending movement progress.

3.3 FSR characteristics

In this second experiment, two FSRs were attached to the lower arm onto two muscles which are known to be active during isometric activity (strain against resistance): Medial brachioradialis and Medial extensor carpi radialis [15]. The muscle activity of the lower right arm is recorded through 2 distinctive actions as below:

i. Grasping activity (opening and closing hand) – subject was sitting on the chair with right arm relaxing vertical to the subject's chest level. The arm is in flexion position 90˚ to the upper arm. It was known that at this position, the Medial extensor carpi radialis can produce maximum strength [15]. By imitating hand grasping activity, the hand was opened and closed for about 10 repetitions.
ii. Lifting heavy object – Initial position is same as point i. Subject lifted an object located in front of him about for about 10 repetitions.

These actions should enable the FSRs sensors to read muscle activity. As a comparison, two EMG electrodes from a standard EMG device were attached on the lower arm as shown on Fig. 7.

3.4 Accelerometer characteristics

In this final experiment, we used accelerometer attached on the back of the wrist to verify arm movement characteristics by monitoring lower arm inclination and force value of the x,y and z-axis analog value through 2 distinctive action as below :

i. Object lifting – subject was sitting on the chair with right arm pointed towards the floor. Subject will be asked to lift dumbbells weighing 250gram, 2kg and 3kg respectively. Each dumbbell will be lifted 5 repetitions by the subject. For this test, we will not consider Z-axis movement. Subject lifted object about 90˚ from initial arm position, then return to initial position.
ii. Object reaching – subject was sitting on the chair with right arm relaxing on a table vertical to the subject's chest level. An object is located in front of subject within the right arm reach. Arm movement recording was done by reaching the object and move the arm back to initial condition. 10 repetitions were done.

These actions should enable the accelerometer to read arm movement and differentiate each axis according to its force vector.

4. Results and Discussions

4.1 Flex sensor

From the experiment, resistance value against the flex sensor bending angle can be plotted as shown on Fig. 5. The experiment shows that when flex sensor is bend inward, resistance value increased significantly as the angle of flex sensor is bend further. However, when it is bent outward, the resistance value decreased gradually. These preliminary finding suggest that flex sensor is clearly suitable to detect bending angle by utilizing inward bend of the flex sensor [16].

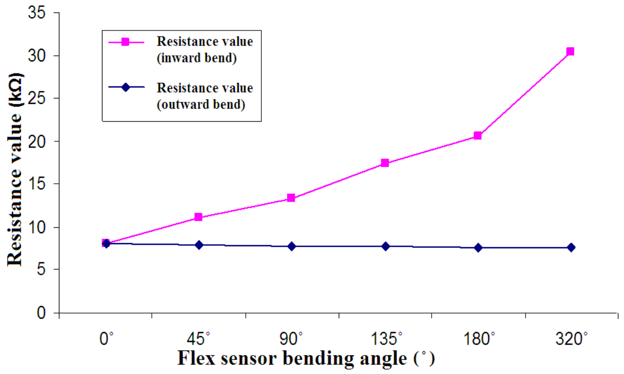


Fig. 5 Resistance value against flex sensor bending angle.

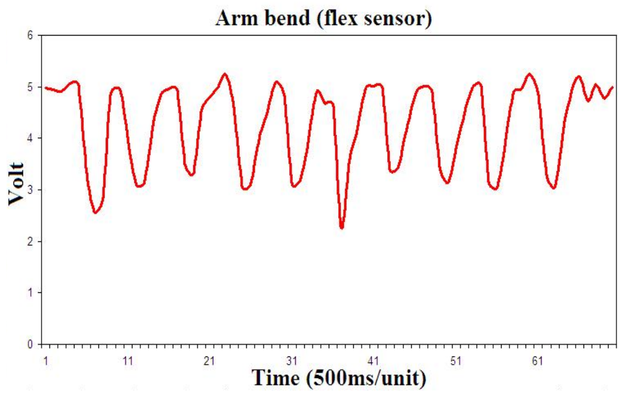


Fig. 6 Flex sensor voltage value due to arm bending movement.

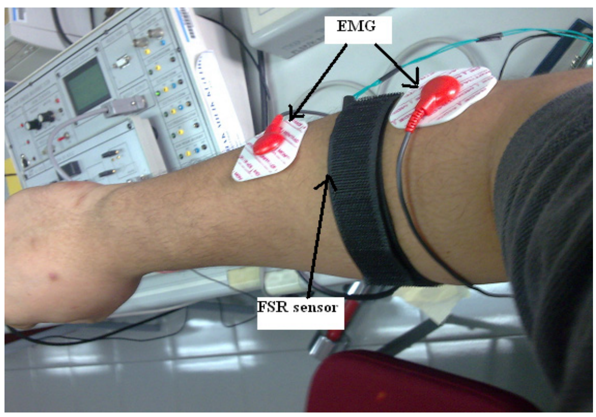


Fig. 7 Location of EMG and FSR targeted medial extensor carpi radialis on the lower arm.

We attached the flex sensor to below part of the elbow guard in order to easily detect arm bending activities. We converted the analog values into voltage values using the formula below :

$$Volt = \frac{Ana\log Data * Vref}{1024} \tag{3}$$

Where, Vref is ADC reference voltage, 5V. 1024 is the total unit of the analog value, as Arduino will output analog value in the range of 0 ~1023 from its own built-in 10-bit ADC module. Fig. 6 shows the result of attaching flex sensor on the tip of subject's elbow. The result clearly shows 10 repetition of arm bending movement. From the data collected above, we applied it as an indicator for arm bending movement to be displayed on LCD monitor which will be shown later in this paper.

4.2 Force Sensitive Resistors

In this experiment, the characteristic of FSRs sensor have been recorded. Two types of distinctive movement have been done to verify the characteristics. The sensors were attached on medial extensor carpi radialis and medial brachioradialis. Voltage value readings can be obtained from FSR sensors. We compared this value with the results taken from two EMG electrodes through a standard EMG analysis device (KL-71001 Biomedical measurement system device). Fig. 7 shows the location of two EMG electrode and a FSR targeted medial extensor carpi radialis.

Fig. 8 shows the result of EMG measurement from both EMG electrodes. While Fig. 9 shows the result of voltage values for both FSRs. based on 10 repetitions of hand grasping activity. From both of these results, it shows similarity in term of detecting muscle movements. Fig. 9 shows that during hand grasping, external carpi radialis muscle are the most active, providing the proof for previous finding [15].

Fig. 10 shows the result of voltage values for both FSRs based on object lifting activity. This activity also gave a clear result of the subject completed 10 repetition workout with once again external carpi radialis muscle gave a significant larger value than medial brachioradialis. By comparing both of these results with the EMG amplitude results, we confirmed that the FSRs can properly detect muscle activations. So, we can conclude that FSR can be used to monitor individual muscles which also confirmed the findings on previous study [15].

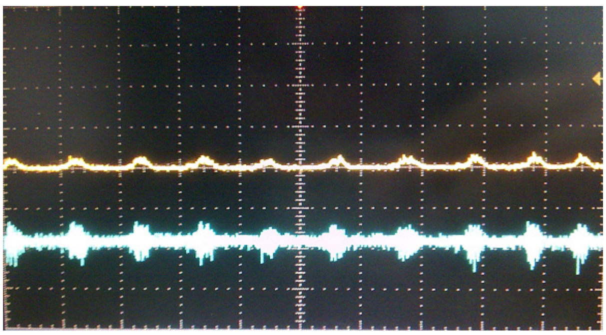


Fig. 8 EMG test result on M. extensor carpi radialis muscles based on hand grasping activity (10 repetitions).

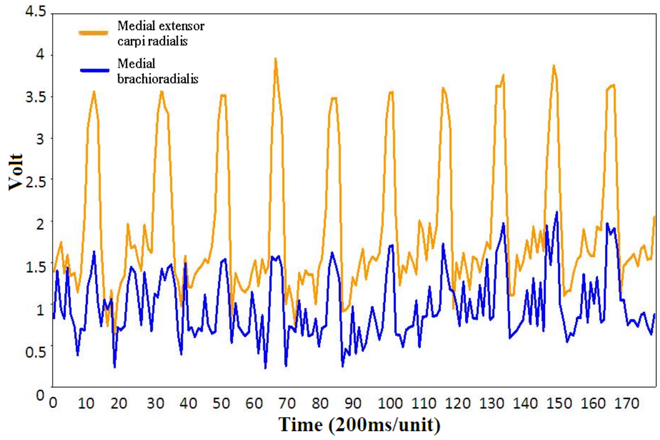


Fig. 9 Force sensitive resistor's voltage results based on hand grasping activity.

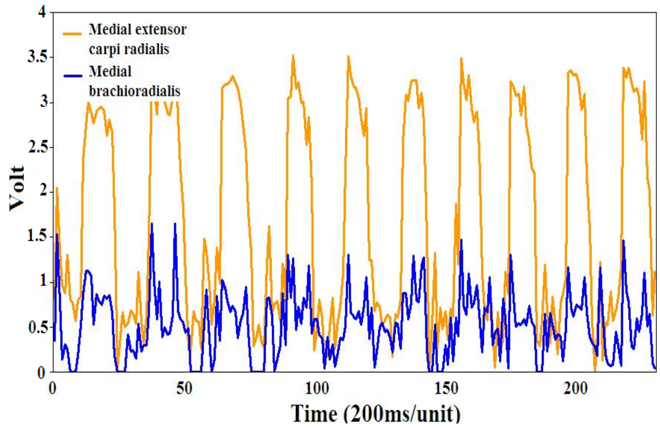


Fig. 10 Force sensitive resistor's voltage results based on object lifting activity.

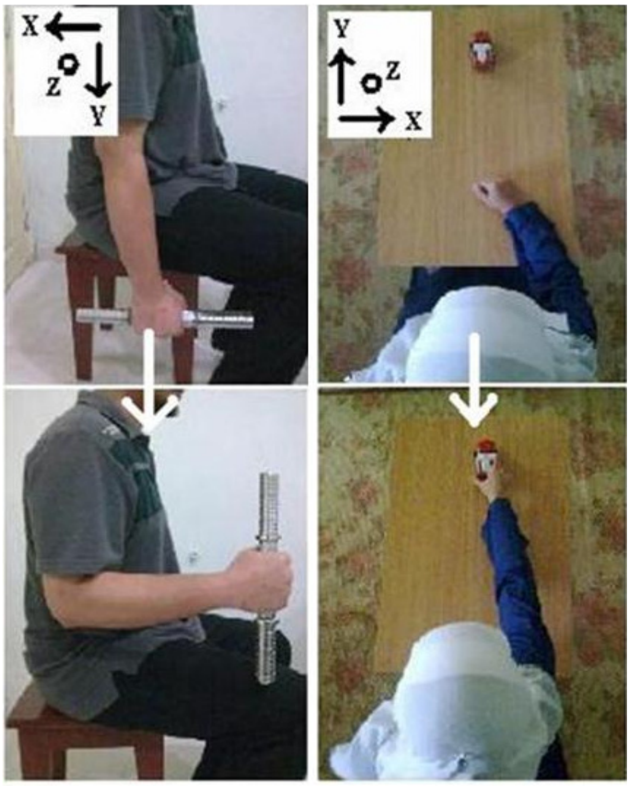
4.3 Accelerometer

Through two different arm movements shown on Fig. 11, the force distribution among X,Y,Z of the accelerometer have been recorded.

As shown on Fig.12, the object lifting activity (Fig. 11(a)) started after 5 second. Each test shows about the similar output. But, if we focused on the output from the workout involved 3kg dumbbell, the amount of time taken to complete a repetition are much more long than the others. While using less heavy dumbbells, the time taken to complete a repetition is less than 2 seconds, however, it is the opposite when using a 3kg dumbbell. This shows that the lower arm, especially the muscles, had to make adjustment on maintaining and balancing the load in order to be able to do the exact movement which is needed. This adjustment may have taken few seconds which is why heavier loads needed more time to complete a repetition in this test. Moreover, even with the less heavy load, if the repetitions are extended to more than 5 repetitions, the results maybe similar to the 3kg. This is because, logically, when the workout intensity increases, the muscle will produce lactic acid which may lower the performance of the muscles. This may resulting to a much longer time needed for the arm to complete a workout even a simple arm bending activity.

For the activity to reach an object (Fig. 11(b)), the movement of the arm was on the positive y direction from initial position. This can be seen on Fig. 13, where about 0.4g force towards positive Y direction was recorded at the first repetition. Then, as the arm returned back to initial position, 0.5g force towards negative Y direction was recorded. This pattern was continually recorded for approximately 10 times. Although the movement was directed towards Y axis, small amount of force excited towards X axis due to untrained subjects and also the tendency of the right hand to react naturally to the right side. Much smaller readings found on Z axis. This was predicted due to the subject's arm movements did not supported by any mechanism from beneath the arm.

From these two experiment results, we can conclude that by using accelerometer, we can monitor the number of force generated towards a certain X, Y or Z direction. The quantified results such as forces generated during certain workout could be useful in estimating fatigue condition of subject due to certain repetitive workout.



(a) (b)

Fig. 11 Two arm movement for accelerometer measurement activity. Top-left are the axes positions of accelerometer during each activity

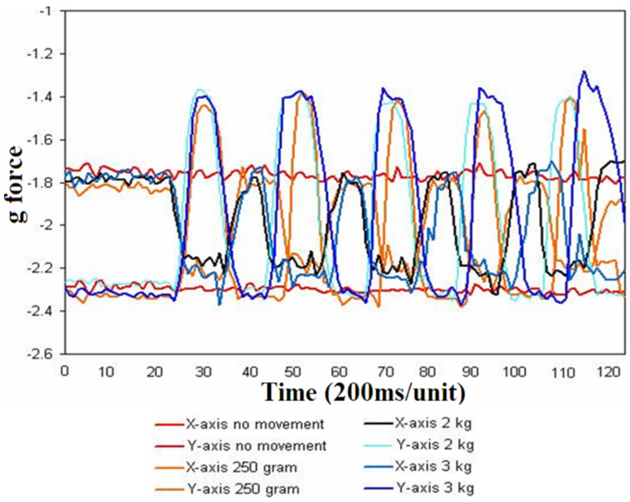


Fig. 12 Voltage output from accelerometer based on different weight during object lifting activity.

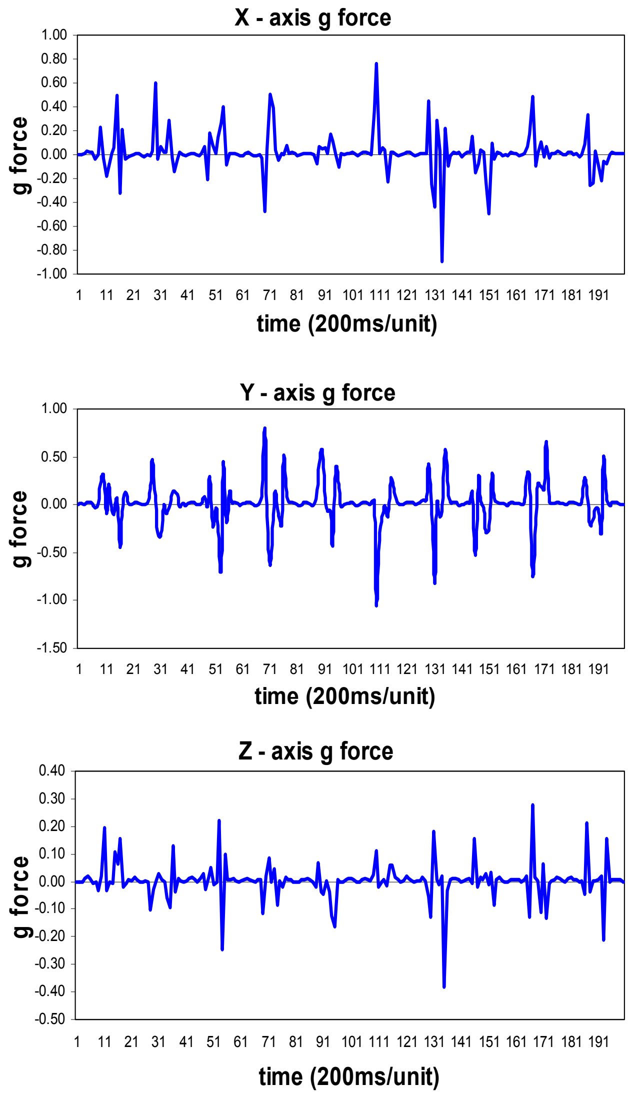


Fig. 13 Signals from accelerometer for object reaching activity.

4.4 Device development

In order for the device to start working, a sketch contains full instruction for the device to operate is downloaded into Arduino board. This arm rehabilitation monitoring device works when analog signal from sensory system is detected due to arm bending, sudden arm acceleration and muscle movement activity. The signals will be sent to the microcontroller and then, processed to be transmitted to PC via USB connection for data.

Fig. 14 shows the overall hardware setup diagram. In this project, we proposed a wearable arm rehabilitation monitoring device based on flex sensor, FSRs and accelerometer. We proposed to use an elbow guard which can be bought in local pharmacy. A single flex sensor is attached on the below part of the elbow guard in order to detect easily the arm bending activities. Fig. 15 (a) shows an initial setup of flex sensor on the elbow guard. Fig. 15 (b) shows the FSRs sensors and accelerometer position. All sensors are connected to Arduino for analog voltage signal detection. Then, the analog signal is transmitted to the built-in 10 bit AD converter (analog to digital) for data processing. Fig. 16(a) shows the actual circuitry of the main unit. Fig. 16(b) shows the main unit with its custom built box. Fig. 17 shows 3 sensors attached on Velcro straps which are being used in the sensory unit.

Basically the device can be powered by 12v adaptor power supply and 9v battery, but due to online data logging purpose, USB connection to PC is needed. Thus, it is powered by 5v power supply from USB connection to PC. When power is ON, the device will display initializing process information on LCD monitor. Sensory unit will start to work by pressing Start/Stop button. At this state, sensory systems will start to send data. Any movements due to arm bending, sudden arm acceleration and muscle movement activity will be detected and sent to Arduino microcontroller and processed to be transmitted to PC via USB connection for online real-time data logging or SD card data logging (non-USB connection). The device will stop working when the button is pressed once again.

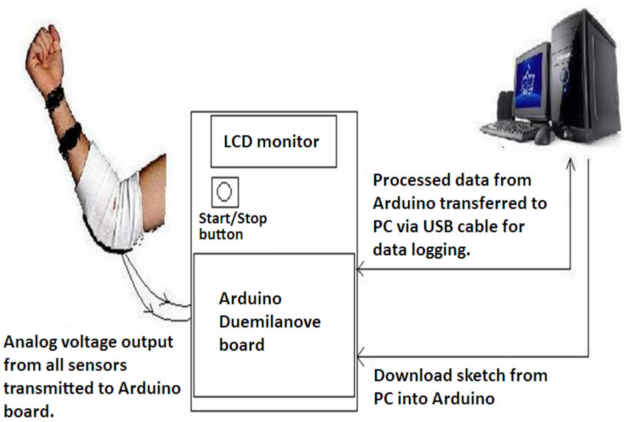
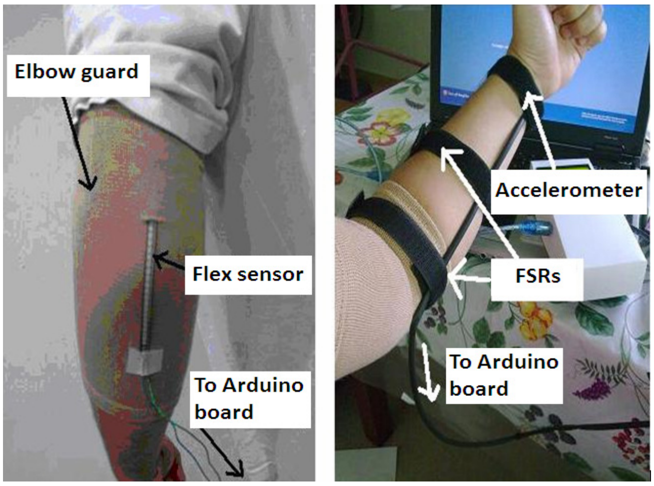


Fig. 14 Overall hardware setup diagram



(a) (b)

Fig. 15 (a) Elbow guard attached with flex sensor, (b) Location of the other sensors.

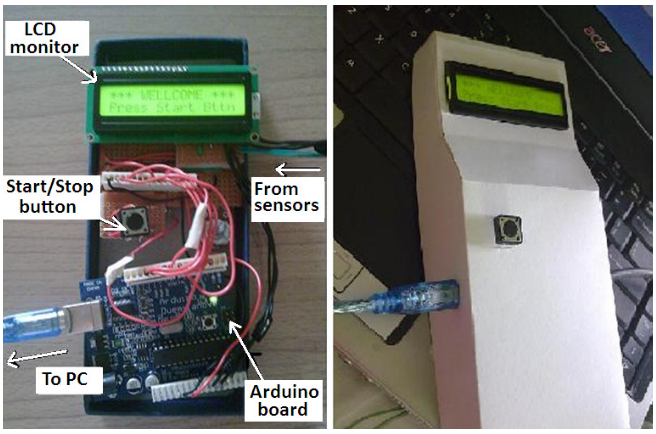


Fig. 16 Hardware setup of the main unit for the monitoring device.(a) actual main unit circuitry (b) main unit with custom built box.

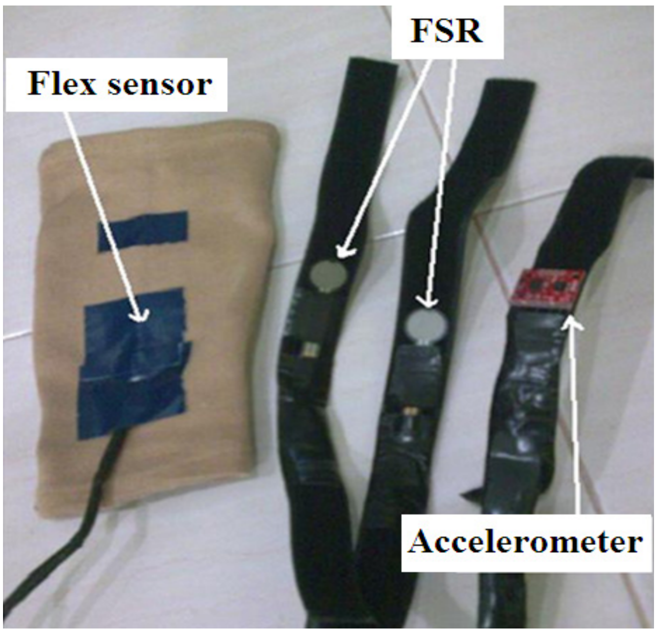


Fig. 17 Picture of sensory unit with Velcro strap.

5. Conclusion

In this paper we proposed a wearable arm rehabilitation device equipped with monitoring system for post-stroke rehabilitation. The device consists of a main unit and sensory unit that utilize a flex sensor, two force sensitive resistors and an accelerometer. It is equipped with real-time monitoring (LCD monitor) and data logging functions (online real-time data logging via USB). The designed system is low cost, compact and does not restrict movement during usage. The proposed system is easy to be attached onto arm with minimal external assistance. It has data logging systems which can store data into PC for certain period of time that can be used by physical therapist for further analysis. By using this device, doctors and physiotherapists do not have to assists patient in home-based rehabilitation.

Our future work will focus on further enhancing the capability of sensory unit by designing a portable data logging unit using secure digital (SD) card. We also hope to use a 2-axis gyro sensor. By using 2-axis gyro sensor, we predict to be able to improve the rehabilitation process which can be determined by measuring arm joints rotational motion which can give more accurate analysis such as subject's performance and limitation towards any specific rehabilitation workout.

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