

Autotuned Electrical Muscle Stimulator with Electromyogram Biofeedback

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Abstract: This paper discusses on the implementation of electromyogram sensor as the biofeedback of the improvised electrical muscle stimulation technology to improve the muscle strength. The paper explains some fundamental of muscle behavior followed by the muscle weakness issues. The techniques of muscle stimulation and the innovative solutions to overcome the problems encountered by the current muscle stimulation techniques are discussed. The project methodology is explained with proper circuit configurations and programming technique. Preliminary works and validation process on the wrist extensor muscle are presented. Finally, the project functionality is examined based on the simulation results that show the system behavior with respect to the muscle contraction reading.

Keywords: electrical muscle stimulator, muscle strengthening, electromyogram.

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1. INTRODUCTION

A survey conducted by National Health and Morbidity Survey (NHMS) in 2011 shows that the level of poor self-rated health among Malaysians were significantly greater compare to Japans, Canadians, and Americans with 20.1% prevalence [1]. As reported, the number of musculoskeletal disorder was increased rapidly in Malaysia, especially among labor workers. A study was conducted in Selangor to investigate the prevalence of work-related musculoskeletal disorder showed 77.3% of non-healthcare working population suffered this problem [2]. This proved that the number of people having muscle weaknesses was high. The most crucial issue regarding the musculoskeletal disorder is the chronic injuries that led to paralyze. These paralysis patients are unable to do the daily activities due to the muscle weaknesses. As to improve their muscle strength, physiotherapists would advise patients to do many exercises. However, the active treatments like weight lifting, running, light sports activities and the other exercises are impossible to be done by an individual with weaker muscle strength. For patients with muscle grade less than 2 based on the Muscle Strength Grading Chart of the Sultan Ismail Hospital (HSI), Johor Bahru, Malaysia where these patients will have difficulties to move their limbs against gravitational force which therefore active treatments are impossible. Therefore, the experts introduce the muscle stimulation technique as a passive treatment for the paralysis.

The Electrical Muscle Stimulation (EMS) is the new method to improve the muscle weakness suffered by most of the chronic disease patients such as stroke, spinal cord injury and severe accidents. This technology applies certain current intensity upon the weak muscle to trigger the muscle to move or response. The muscle contracts

once the current is applied across the origin point and the insertion point of the muscle; just like how the brain signal works to initiate movements. However, the EMS technology nowadays is an open loop system without any feedback. Therefore, the physiotherapist needs to adjust the current intensity applied on the treatment muscle manually based on their experiences. This trial and error method is subjective and inaccurate tuning could results in less effective treatment.

The main goal of this project is to control the intensity of the current EMS device automatically by analyzing the biofeedback of muscle condition. This project integrated an electromyogram sensor as the biofeedback for the current EMS system. This sensor is used to measure the muscle strength. In this project, the current intensity tuning of the EMS to stimulate the muscle is controlled automatically by a microcontroller, Arduino through MATLAB Simulink application based on the biofeedback measurement. This proposed system is tested on the wrist extensor muscle for feasibility and functionality tests. The reason of choosing this muscle activity is due to the body mechanics criteria and as wrist is one of the lighter body parts.

2. THEORETHICAL

2.1 Physiology of Muscle

In every human body, there are three different muscles tissues with their respective functions; namely as skeletal muscles, cardiac muscles and smooth muscles. All these muscle tissues have the ability to contract and relax, initiate a motion, provide stabilization and generate heat. This project focuses on the skeletal muscles as these muscles such as human limbs move when these muscles contracted. The contractions of skeletal muscles support the movement of skeleton as these muscles are attached

to the bone [3]. All the skeletal muscles are placed opposing with the other skeletal muscles. In order to move a limb, the respected skeletal muscle must be contracted while the opposite muscle relaxed or sometimes stretched [4].

The contractions of a muscle are depending on the impulses of motor neurons that transmitted to the muscle fibers. This transmission produces an electric field due to the depolarization of the muscle fibers. With sufficient electric current propagates across the muscles, muscle will able to contract and initiate movements [3]. The muscle strength can be improved by alternately contract and retract the muscle during the active exercises. Nevertheless, the sustained activities of muscles can cause fatigue once it reaches the limits. Muscle fatigue is known as the gradual decreases in muscle force due to the repeated contractions. The definition of muscle fatigue has been focused as an exercise-induced reduction in the production of muscle force during the sustained activities [5, 6]. Muscle fatigue must be avoided in any muscle treatment; otherwise, the stimulation treatment will fail due to the decreases of muscle movement force. It will take some times for the muscle to recover gradually. With this condition, the muscle fatigue is justified as not the reason of any treatment failure [7].

In Malaysia, most reported cases involving musculoskeletal disorder that are related with work activities in awkward posture [8]. This results in weakening of the muscle among these populations. Without appropriate exercises, the muscles will be weakening. The worst cases may lead to paralyze. Clinically, the muscle can be strengthening by appropriate stimulation technique. One has proved that the electrical stimulation can improve the muscle strength, increase the motion range, reduce pain and heal the muscle tissue [9]. One of the modern stimulation techniques is by applying the electrical current across the muscle. This technique is known as the Electrical Muscle Stimulation.

2.2 Electrical Muscle Stimulation

The primary study of electrical stimulations has done by Michael Faraday in 1831 after he observed the active movement once the current is applied across a nerve [10]. The electrical stimulation earlier application was to relieve muscle pain [11], but it has now been commonly used to treat weak muscle [12]. The concept is by applying a transcutaneous electrical current across the muscle to produce muscle contractions [13]. The repetitions in the muscle contractions helped to strengthening the muscle as a passive treatment.

However, the disadvantages of EMS have shown that it may lead to muscle fatigue when overstimulate if the delivery of the treatment are not well-customized [9]. Barbara M. Doucet, A.L., and Lisa Griffinb (2012) had discussed the important parameters that must be considered during the stimulation. The most important parameter is the current intensity and the pulses frequency of the EMS device. Appropriate applied current intensity is essential to improve the muscle strength [14]. Meanwhile the pulses frequency are said to be at constant lower level so that the muscle contracted smoothly at lower force [15]. However, there is none information or monitoring system to check the condition

of the muscle whether it is getting fatigue or under stimulate. Therefore, the system needs a suitable sensor to monitor the muscle capability in order to fine tune the stimulate parameters.

2.3 Biofeedback Instruments

Sinkjaer et al. in 2003 proposed the implementations of electromyogram (EMG) sensor, electroneurogram (ENG) sensor and electroencephalogram (EEG) sensor in the development of EMS technology [16]. The EMG sensor was used to obtain the biopotential reading of the skeletal muscle. Meanwhile, the ENG sensor and EEG sensor are used to record the nerve signal and brain signal respectively [17]. There are also several instruments that can measure the electric potentials and magnetic fields through the surface of human body. These instruments are measuring the electric fields produced from the depolarization of muscle membranes and the conduction of nerve impulses that can be obtained through body skin [18]. This paper proposed the integration of EMG sensor as the biofeedback in order to measure the skeletal muscle behavior.

Electromyography is a study on the measurement of skeletal muscle biopotentials. It measures the electric potential on the skin through the electrode. Every skeletal muscle is contracted under the voluntary control once instigated by the neurons impulse. These motor neurons are producing the electrical potentials known as motor unit action potentials (MUAPs) [4]. As the muscle tissue conduct these MUAPs, the electrical potential can be obtained by placing the electrode onto the respective muscle tissue. In short, the electromyography measures the presence MUAPs in the superficial muscle tissue that can be easily obtained on the body surfaces.

The EMG readings are having a lot of noises because the electrode is contacted on a single motor unit with many muscle fibers. Therefore, the EMG measures a combination of MUAPs when muscle is contracted [19]. Since the raw EMG signal consists of electric noises, an appropriate signal conditioning technique is implemented in the development of EMG sensor. The earlier research has introduced the technique to obtain the enveloped EMG signal for better measurement with the implementation of the rectifier, the amplifications and the filters [20, 21]. This project implements a smart EMG sensor as the biofeedback sensor with integrated signal conditioning circuits.

3. METHODOLOGY

The project proposes to control the current intensity of the EMS device automatically by sensing the muscle strength. The Arduino UNO R3 is used as the microcontroller of the system programmed using MATLAB Simulink. This tool also used as the user interface with the dashboards libraries. Therefore, the physiotherapist or end user can observe the treatment behavior through this application.

3.1 Project Design

In order to ensure the reliability of the system, the current EMS device, BioMed 2000 XL, was modified to integrate the sensor module as the biofeedback for the parameters tuning. The current EMS devices come with knob tuning

potentiometer to adjust the current intensity. In this project, the potentiometer is replaced with a digital potentiometer, MCP4161 from Microchip Technology Inc. The microcontroller is programmed to control this digital potentiometer through Serial Peripheral Interface (SPI) communication to achieve desired current intensity of EMS.

The tuning of the current intensity of the modified EMS device depends on the patient's muscle strength condition. The electromyogram sensor, MyoWare, is integrated in the EMS device that works as an input for system. This sensor measures the muscle strength of the patient and work as biofeedback of the EMS device to create a closed-loop system.

The MATLAB Simulink toolbox is used to control the output of the system. A few dashboard components in this application are used as the user interface. The user can control the system through this Simulink application Graphical User Interface (GUI) as shown in Figure. 1.

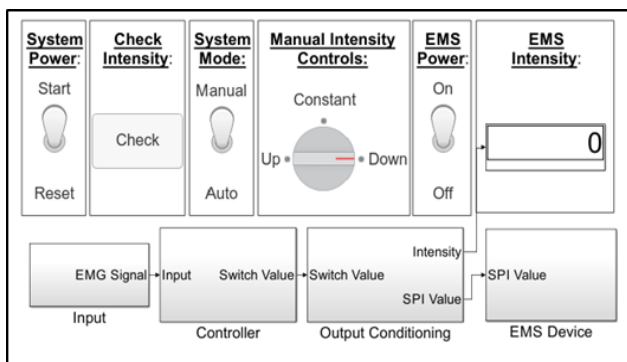


Figure 1. Simulink Application Graphical User Interface

3.2 Research Procedure

The project begins by studying the muscle strength. The muscle strength is measured in order to identify suitable technique to retrieve the muscle strength measurement using the MyoWare sensor. The best signal conditioning technique with optimum sampling time that is compatible with MATLAB Simulink program is determined. Subsequently, the EMS device was tested to investigate the EMS parameters where each of the tunable components was analyzed. Since the optimum setting of the frequency and pulse width parameter are fixed and unchanged throughout treatment, therefore these two potentiometers are adjusted and remain at a suitable resistance value. The only parameter that needs to be controlled is the current intensity of the EMS device. Once the circuit of the EMS device is studied, the project continues with the development of electronic circuits. The Arduino microcontroller is connected to the MyoWare sensor as the analog input and the digital potentiometer as the output via SPI communication. This digital potentiometer is then replacing the actual potentiometer for the current intensity controller. Another connection between the Arduino microcontroller and the EMS device is to switch on and off the device digitally via the Arduino microcontroller. The last part of the system development is the Simulink programming to acquire and process the obtained measurement from the sensor. The detail of the Simulink block diagram is shown in Figure 2.

The important components are listed as follow:

- **Arduino Input:** This block retrieves the analog input from the Arduino pin A5. The signal is converted into double format and mapped to the range of 0 to 5.
- **Maximum:** This block finds the maximum of the input signal to check if the EMS device has reach its suitable intensity. This block can be reset by the constant block 'Reset' that controlled by the 'Check Intensity' dashboard button.
- **Controller Switch:** This block is used to switch intensity either increase the SPI value by 5 or 0.
- **Saturation:** This block saturates the SPI value from 0 to 255 as to control the EMS intensity.
- **Output Conditioning Switch:** This block checks the constant block 'Mode' value controlled by the dashboard toggle button 'System Mode' to set the mode of the system between manual and automatic.
- **Arduino Digital Output:** This block is connected to Arduino pin D8 as the switch of EMS device. The toggle button 'EMS Switch' controls this block.
- **Arduino SPI WriteRead:** This block reads the input array and write into the Arduino SPI slave select pin 10 to control the EMS intensity.

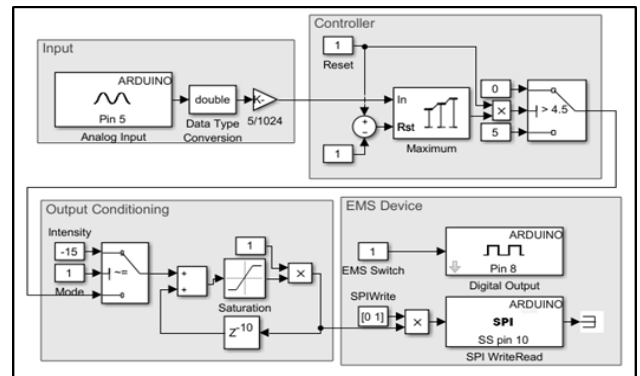


Figure 2. Details of the Simulink block diagram of the system.

3.3 Functionality Test

Once the circuit development completed with programming, the system is tested for the functionality validation. This experiment is conducted towards the human wrist extensor muscle as the subject shown in Figure 3. Two electrode pads of the electromyogram are placed onto the mid muscle while the reference electrode pad of the electromyogram is placed on the other muscle that not contracts when the wrist is extend.

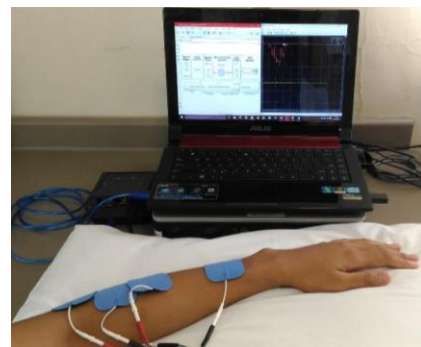


Figure 3. Electromyogram electrode pads on human wrist extensor muscle

The MyoWare sensor measures the electric potential properties of the muscle and provides inputs to the system accurately. In the other hand, the output of the system in terms of current intensity is delivered across the muscle by placing both electrodes at the origin and the insertion point of the muscle respectively.

To test the system, toggle button ‘System Power’ is turned once the muscle is completely relaxed. The system mode is switched to “Auto” in order to allow the EMS device tune automatically to the suitable intensity based on the biofeedback. Nevertheless, the user can simply press the ‘Check’ button if the intensity is not at par to their desired value.

4. RESULTS AND DISCUSSIONS

The results of this experiment recorded from the Simulink graph is shown in Figure 4. The signal indicates the desired muscle contraction during the EMS treatment. After several investigation, the repeatability of the results prove that the sensor can record the muscle contraction with the implementation of Simulink block diagram as in the subsystem Input as shown in Figure 2.

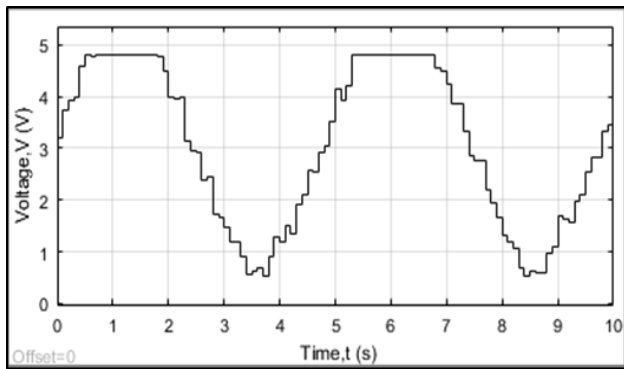


Figure 4. Output signal represents the desired muscle contraction during the EMS treatment.

At the same time, the resistance of potentiometer for each parameters used in producing the desired signal are investigated. It is proven that the potentiometers of pulse width tuning and frequency tuning can be fixed at 5kΩ to obtain the desired signal. However, the resistance of potentiometer used to determine the amplitude of the signal must be tunable in the range of 0Ω to 5kΩ. It needs to be adjusted according to the muscle strength.

4.1 Simulations Results

The finished project is tested onto the subject muscle to shown the functionality of the system. The simulation is carried out in about 100 seconds. Figure 5 shows the results when the system is tested towards the actual wrist extensor muscle.

All the dashboard components are simulated and the observed output is recorded in Table 1.

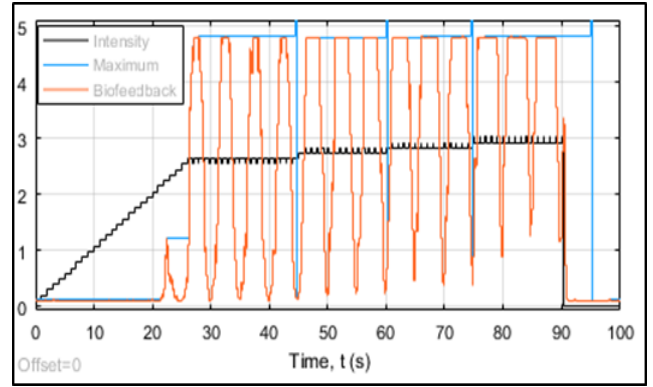


Figure 5. Stimulation output of the improvised EMS device

Table 1. Dashboard Component Outputs

Component	State	Output
System Power (Toggle Button)	Start	Enable the intensity to increase from zero.
	Reset	Turn down intensity to zero.
Check Intensity (Push Button)	Released	Do nothing.
	Pressed	Reset the maximum of input signal to find the new suitable intensity.
System Mode (Toggle Button)	Manual	Enable the manual tuning of EMS device.
	Auto	Enable the automatic tuning of EMS device.
Manual Intensity Control (Knob)	Up	Increase the intensity by 15 of 255.
	Constant	Maintain the intensity at current value.
	Down	Decrease the intensity by 15 of 255.
EMS Power (Toggle Button)	On	Switch on the EMS device.
	Off	Switch off the EMS device.

These results prove that the system can be used safely without overstimulation that may cause muscle fatigue. At $t=27s$, the controller of the system stop increasing the current intensity when the muscle contraction reading is more than 4.5V, which is much lower than the maximum capability of muscle contractions. However, if the user did not satisfy with the lower intensity, the system can find another higher suitable intensity by pressing the ‘Check’ button as shown at $t=45s$, $t=60s$, $t=75s$ and $t=95s$. Nevertheless, if the user feels that the current intensity is high, by toggling button ‘System Power’ to ‘Reset’ will help in turning down the intensity to zero as what happen at $t=90s$. Besides, the system enable user to choose between manual tuning stimulation and automatic tuning stimulation mode. It takes less than 51 seconds to achieve the desired signal.

4.2 Project Limitations

There are several limitations of the current design of the

system. The memory of the microcontroller is important in order to ensure smooth loading of code for the data acquisition and also control of the EMS device. To ensure no lagging and accurate in the control of the tuning the memory within the microcontroller need to be sufficient and fast.

As the device is tuned based on the biofeedback readings, if the muscle is not relax or there are body movements, this will affect the contraction of wrist extensor muscle. These small contractions are amplified in the MyoWare sensor and cause fluctuations in the input signal of the system. The fluctuation of signal above 4.5V will immediately halt the tuning of the current intensity. Therefore, it is difficult to obtain the desired signal of EMS treatment. However, the 'Check' button can be used to reset the maximum value.

5. CONCLUSION

In conclusion, the modified closed-loop EMS device can be used to treat weak muscle with automatic tuning function for current intensity. The project verified that the proposed EMS device able to produce the same output signal for muscle stimulation. This project has improved the passive treatment of EMS to be measurable and the integrated automatic tuning system can avoid under or overstimulation of the muscle due to the error in the setting of current intensity of the EMS device. In addition, the progress of the treatment also can be observed through the simple user interface.

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