An investigation of fatigue phenomenon in the upper limb muscle due to short duration pulses in an FES system.

Jannatul Naeem¹, Amelia Wong Azman¹, Sheroz Khan¹ and Yasir Mohd Mustafah²
¹Department of Electrical and Computer Engineering, International Islamic University of Malaysia, Gombak, 53100, Malaysia
²Department of Mechatronics, International Islamic University of Malaysia, Gombak, 53100, Malaysia

E-mail: naeem_088@yahoo.com

Abstract: Functional Electrical Stimulation (FES) is a method of artificially stimulating muscles or nerves in order to result in contraction or relaxation of muscles. Many studies have shown that FES system has helped patients to live a better lives especially those who are suffering from physical mobility. Unfortunately, one of the main limitations of an FES system besides of its high cost is largely due to muscle fatigue. Muscle fatigue will affect the training duration which could delay patients’ recovery rate. In this paper, we analyzed the occurrence of this fatigue phenomenon in terms of stimulator parameters such as amplitude, frequency, pulse width and pulse shape. The objective of this investigation is to identify other key features of the FES system parameters in order to prolong the training duration among patients. The experiment has been done on a healthy person for the duration of one minute and later the muscles response will be observed. Resultant muscle response is recorded as force using force resistive sensor. The experimental results show muscles will get fatigue at a different rate as the frequency increases. The experiment also shows that the duty cycle is reciprocal to the resultant force.

1. Introduction
The human nervous system is a complex part of body in which actions are controlled by the human brain. The nervous system is meant to make us respond to involuntary and voluntary actions such as grabbing a glass, restraining body movement due to hazardous circumstances, maintaining balance during walking and many more. The two major parts of the nervous system are Central Nervous System (CNS) and Peripheral Nervous System (PNS). The former is made of spinal cord and brain, while the latter consists of receptors (sensing impulses) and effectors (taking actions in response to impulses) [1]. CNS is the body’s main control system which interprets and receives all nerve impulses from body parts and suggests to the muscles what appropriate actions needs to be taken. PNS on the other hand are all the nerve cells outside the brain and spinal cord.
Figure 1 illustrates a structure of a neuron cell. The human body is constantly responding to changes from the outside environment as well as to changes within the body to maintain equilibrium. An electro-chemical signal or the neuron from the brain passed on to and from the nerve pathways are resulted from the activation of sensory inputs from either internal or external sources. When this happened, a potential difference is created between axon and its surroundings which acted like a tiny battery. As a result of that, a muscle would either contracts or relaxes.

Functional Electrical Stimulation (FES) could interrupt the equilibrium within a human body. This is by artificially introducing short electrical pulses to stimulate the muscles which will result to involuntary movements. These muscle contractions can be adjusted by stimulating one or more muscles that will create torque at the joint of the muscle. When the electrical stimulation is used to enhance the muscle functions such as standing, grasping, rowing and gait pattern, this electrical stimulation is known as the Functional Electrical Stimulation (FES). For this reason, FES has been widely used around the world as part of a rehabilitation program to stimulate the contractions of muscles among patients with paralysis condition. Thus, it is not surprising to see many research works in designing effective FES devices over the years.

In the process of designing an FES system, there are some important parameters that need to be considered. Among the main parameters are the voltage and current level, pulse shape, pulse width and pulse frequency. The amplitude of the current defines the strength of stimulation or how strong is the force generated to the muscle. The stimulation frequency mainly controls twitching of the muscle. As the frequency increases, the stimulated muscle will get fatigue fasters which inadvertently limit the muscle training duration.

In [2], the authors stimulate muscles by inserting modulated pulse at a range of 0-200µs, under a constant current of 20mA fixed at 12Hz frequency. The muscle fatigue is measured using equation (1).

$$\text{Fatigue Index} = \frac{\text{Muscle Tension [Newtons]}}{\text{M-wave Parameter [Volts.seconds]}}$$ (1)

In the equation above, the muscle tension represent as force muscle output unit in Newton. The M-wave constraint is in quantitative measure that could be articulated in volts, seconds or volts-seconds depending on the choice of M-wave parameter. In selecting M-wave parameter, there are two important criteria. Firstly, when the muscle is either in fatigue or non-fatigue state, the parameters must reflect the degree of muscle unit recruitment during electrical stimulation. Secondly, the parameters should be kept constant in the duration of constant stimulation. However, in this research, only a single waveform has been used.
In another technique elaborated in [3], the strength of the muscle contraction can be changed by modulating the stimulation parameters such as waveforms, intensity, inter pulse interval and frequency of stimulation for signals applied to different electrodes. These fundamental parameters changes are done for an effective FES control system. For a specific stimulus waveform, it depends on the intensity of the physiological effect and the type of electrode used. In restoring motor unit function it is necessary to use a frequency controlled FES system. The frequency of stimuli signal of an FES system is commonly reported as the main cause of rapid muscle fatigue during muscle recruitment. Muscle recruitment is the number of motor unit that is required for a specific function, a process with its utility determined by the stimulation intensity. Muscle contractions induced by FES tend to result in rapid muscle fatigue, which greatly limits activities such as FES-assisted standing and walking [4]. In [4], a study was conducted to show the effects of randomly modulating the parameters of FES signals on muscles activity. However, the study does not provide any conclusion on the effect of signal modulation on muscle fatigue but only suggest that parameters such lowering the stimulation frequency might be a helpful parameter in reducing fatigue.

In [5], M. Sahin and Y. Tie presented the effects of the traditional square wave together with seven different pulse shapes. The waveforms that they have used include rectangular, linear increase and decrease, exponential increase and decrease, Gaussian, and sinusoidal waveform. Using computational stimulation model, they found that non rectangular pulses are more energy efficient than rectangular waveform and the chronaxie time was longer with all the non rectangular waveform. Linearly decreasing ramp provided the best charge injection for all pulse widths when compared with other waveforms. The experimental results also show that Linear, exponential decrease, and Gaussian pulses to be more efficient than the traditional square wave.

There has also been research on proposing closed loop control system towards next generation FES systems [5, 6].

Most of the available FES systems are current controlled and have utilized the square waves pulse shape. Interestingly, recent studies also have shown that not only tradition mono-phasic or bi-phasic square wave can be used in an FES system but also other pulse shape such as the triangular, exponentially increase, exponentially decreased and raising ramp [7]. Different pulse shape has different energy delivering manner therefore the muscle contraction also be different. The pulse width parameter is closely related to the pulse shape. The pulse width defines the effective stimulation time given to the nerve. This paper studies the muscle fatigue with respect to these different stimulation parameters. From our literature review, the current available off-the-shelf FES systems not only are limited in its functionality, they are mostly very expensive and bulky. Hence, another point to be considered is the total cost in designing and developing an FES system.

The use of stimulation parameters in improving stimulation results has been discussed in view of ultimately producing a programmable stimulator implant for minimizing tissue damage [7]. The authors in [7] have studied and analyzed the effects of pulse width and frequency of stimulation signals by measuring the charge delivered and the energy efficiency. A circuit schematic for a portable functional electrical stimulator is suggested in [8] suggesting improvement in gait and muscle strength. Once again, the parameters that were analyzed are limited to pulse amplitude, pulse-width and pulse duration.

Recently, Sabut [9] combined the effects of FES with the conventional rehabilitation program (CRP) to improve better in gait and muscle recovery as well as sub-acute than chronic stroke patient. While the results show significance change in walking velocity among the chronic strokes patients, the FES parameters that is put to the test is only limited to amplitude variations. At the end of 2011, Dongchul Lee [10] patented a multi waveform circuitry for electrical stimulation to be used as therapy level. He described that different shapes have different characteristics of energy delivered to the tissues. Unfortunately, the work did not come with any analysis to suggest that his proposed waveforms will work better for an FES system. To the best of our knowledge, none of the stated researches have experimented on the effect of stimulation parameters on muscle fatigue.
Therefore, one of the main aims of this research is to study the effects of different stimuli parameters on muscle fatigue. The results from this investigation will help physician to make better decision in providing efficient treatment to the patients.

The remaining of this paper will be as the following; Section 2 is detailed the FES circuit that is used in this research followed by the description on the experimental setup in Section 3. Section 4 will discuss on the results and finally the paper will be concluded in Section 5.

2. FES Circuit Design
In this work, we have adopted the circuit design proposed by Cheng et al. [11]. In the work, they introduced a 9V battery powered FES system that replaces the use of a transformer with a resonant circuit to produce stimulus pulses. The stimulus parameters are frequency, pulse width and amplitude. Pulse frequency is controlled by the Q1 and Q2 gate duty cycle. Pulse width is controlled by Q2 and Q1 current amplitude ranged by R.

![Resonant transformer less FES circuit](image)

Figure 2. Resonant transformer less FES circuit

Unfortunately, the paper only presented a simulation results that shows that the circuit can achieve up to 100mA. Our work extends this work by implementing and validating the circuit in Figure 2 and to study the effect of varying parameters against muscle fatigue.

3. Experiment Setup
The experiment was on the upper limb muscle of a healthy person. At this stage of the research work, electrodes were placed on the biceps muscle since the biceps have larger muscle group area as shown in Figure 3 to obtained better stimulation outcome. It was noticed that the effectiveness stimulation for muscle activation depends greatly on the placement of the electrodes which would require in depth understanding on the full upper limb anatomy.

![Placement of electrodes on the biceps muscle](image)

Figure 3. Placement of electrodes on the biceps muscle

In order to measure the muscle fatigue as previously stated by equation 1, the force must first be obtained. To do this, this experiment had utilized the force-sensing resistor (FSR) sensors. An FSR
sensor work like a variable resistor. When short electrical pulses from the FES circuit are exerted to the biceps muscle, it was resulted to an involuntary hand motion. This involuntary hand motion was exert force to the surface of the FSR sensors. As the force increases on the calibrated FSR sensors surface, the resistance value of the FSR sensors was decreased. The output from the FSR sensors were then is converted to analogue voltages which were connected to the input pins (pin A0-A5) of an Arduino microcontroller. The voltage change detected from the analogue pins is the equivalent force monitored by the Arduino serial monitor. The following is the pseudocode for the algorithm in the Arduino.

Procedure Muscle fatigue force detection (signal)
Signal ← Square wave with the 100mA amplitude
Force ← resultant muscle response measure in force value by force sensitive resistor sensor
SensorValue ← Analogue value reading from sensor
Weight ← consider the analogue value changes linearly according to sensor output of the graph
Force: = weight* acceleration 9.8m/s²

while (device on)
    weight = analogue value/10
    force = weight*9.8
    display (force)
end while

end procedure

Experiments are conducted for one minute on a healthy volunteer. In the first part of the experiment, an initial frequency was set to 1Hz with constant amplitude at 100mA and pulse duty cycle 50 percent. The frequency will later be increased slowly and any changes will be recorded. The second part of the experiment is to vary the duty cycle from 50% to 85%-15%. Variance in the outcome will also be recorded. It needs to be highlighted that the volunteer is given enough time to rest his muscles in between experiments.

4. Result and Discussion

Figure 4 shows a graph of the muscle response with regards to the changes in the stimuli parameters. For the first part of the experiment i.e. varying frequency, there was no activity of muscle contraction observed at 1Hz. The earliest muscle response observed was at the 5Hz frequency. After 1 minute stimulation duration, the muscle begins to show signs of fatigue. As illustrated in Figure 4, the first recorded muscle response was at its highest at 0.38 Newton and slowly decreases over time. As the frequency increases to 10Hz, the first recorded force is at 0.3 Newton. Although there is a slight drop in the force, the experiment shows that the muscle twitched at a faster rate. Unfortunately, because the motor neuron does not have enough time to release the neurotransmitter quickly, hence, the muscles get fatigue at a faster rate as shown in Figure 4.
Figure 4. Muscle response with stimuli parameters of current 100mA, Frequency 5Hz, 10Hz and duty cycle 50%, 85%

In the second part of the experiment i.e. changing the duty cycle, the experiment recorded low force at the first reading for both 5Hz and 10Hz as illustrated in Figure 4 at 0.2 Newton and 0.13 Newton respectively. Interestingly, the muscle does not get fatigue quicker when compared with the results from the first part of the experiment. The results also show that there is only a small variation in the force throughout the experiment.

5. Conclusions
This work presents an investigation on the effect of FES parameters that has been linked to muscle fatigue. One of the objectives of this work is to gives clinician a better understanding on the effect of stimuli parameters to increase the training duration when using FES devices among patients. Results shows, frequency and stimulation time greatly affects on the muscle fatigue. Duty cycle pattern of the stimulation has shows active stimulation time of a cycle, which also effect on the muscle fatigue. A transformerless based FES circuit has been built and tested on a neurological intact person. From this work, we have validated the circuit presented in [11]. The results of this work concluded that the muscle fatigue varies depending on the pulse frequency and the stimulation time and exerted force is related to the pulse amplitude.
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