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ANALYSIS ON THE EFFECT OF STIMULATOR PARAMETERS IN ELECTRICAL STIMULATION PROCEDURE ON THE HUMAN BICEP MUSCLE

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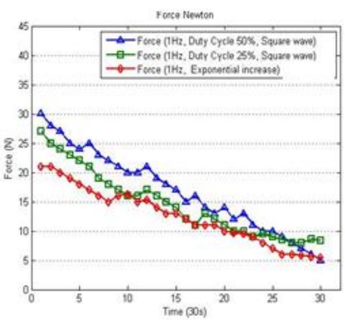
Graphical abstract



Abstract

While electrical stimulation has proven to produce positive outcome among patients, electrical stimulation in post stroke rehabilitation faced one main limitation – muscle fatigue. Muscle fatigue limits the training time, hence, affecting the recovery process. This work analyzes the occurrence of muscle fatigue with respect to the different stimulator parameters; amplitude, pulse shape and frequency. The detection of muscle fatigue will be monitored as force where the force sensitive resistor (FSR) sensors are used to detect the variations of the force exerted by the muscle. In this work, it is assumed that the fatigue in muscle will happen when the force recorded reduces to 60% from its initial force over the stimulation period. The experiment results proof that the stimulator parameters, amplitude, pulse shape and frequency, have different effect to the upper limb muscle with respect to muscle fatigue. The results also show that the exponential waveform can be considered in future rehabilitation program since the onset of muscle fatigue is delayed later in the experiment when compared to the other signals. This allows extended training duration among stroke patients to benefit from the recovery window time frame especially for patients who are still in their early recovering stage.

Keywords: Muscle fatigue, Post stroke rehabilitation, Exponential Waveform

Abstrak

Walaupun Electrical Stimulation (Rangsangan Elektrik) telah terbukti dapat memberi kesan positif dikalangan pesakit, rangsangan elektrik dalam pemulihan selepas strok masih menghadapi satu masalah – kelesuan otot. Kelesuan otot dalam pesakit akan menghadkan masa pemulihan, seterusnya akan melambatkan proses keseluruhan pemulihan. Penyelidikan ini menganalisa bagaimana kejadian kelesuan otot berkait dengan parameter isyarat perangsang yang berbeza; amplitud, bentuk isyarat dan kekerapan. Keletihan otot akan dikesan menggunakan sensor pengesan daya yang akan mengesan variasi daya yang dijana oleh otot. Dalam penyelidikan ini, diandaikan bahawa kelesuan otot berlaku apabila daya yang dicatatkan menurun kepada 60% daripada daya awal semasa tempoh rangsangan. Hasil eksperimen yang telah dijalankan membuktikan bahawa amplitud, bentuk isyarat dan kekerapan isyarat ransangan mempunyai kesan yang berbeza kepada otot lengan dalam menyebabkan kelesuan otot. Hasil eksperimen juga menunjukkan bahawa isyarat ransangan berbentuk eksponen sesuai dipertimbangkan untuk diguna pakai dalam program pemulihan di masa yang akan datang kerana ia dapat melambatkan kelesuan otot berbanding bentuk isyarat ransangan lain. Ini membolehkan tempoh pemulihan di kalangan pesakit strok dapat dipanjangkan sejurusnyanya mempercepatkan proses pemulihan keseluruhan pesakit terutamanya dikalangan pesakit strok yang masih baru.

Kata kunci: Kelesuan Otot, Pemulihan Selepas Strok; Isyarat Ransangan Eksponen

1.0 INTRODUCTION

The use of electrical stimulation for medical purposes has long been established. Since then, the function of electrical stimulation expanded and evolved with the introduction of new applications. In ancient China, it has been reported that electrical pulses has been used alongside with acupuncture as a means to relieve pain on patients [1] as well as restoring health by unblocking chi flow [2, 3]. The introduction of electrical pulses coupled with acupuncture is found out to be more effective and ease the insertion of needles process because the needles are not necessarily accurately inserted on the acupuncture pressure point since the stimulation area between the two acupuncture needles are larger.

On the other end of the continent, some mental health institutions have introduced the use of electrical current on patients who were experiencing psychiatric illness since the early 60s. It was assumed that the electroconvulsive therapy which is formerly known as electrical shock therapy on individual with psychiatric illness can reset the brain signal and correct the behavioural disorder. This direct electrical stimulation via invasive or non-invasive electrode to the human scalp however, has been under scrutiny since there has not been any clear evidence on the efficacy of the therapy on the patients with the most recent public claim in 2014 [4].

A safer and successful application of the electrical stimulation is in the area of restoring loss of muscle functions such as restoring the bowel and bladder control, recovering foot drop movement and improving hand grip function [5]. In this application, electrical pulses are sent to muscle via electrodes placed externally or internally on the muscle under treatment to promote muscle contractions. The main idea behind this is that involuntary movement can be excited when muscle is elicited with electrical pulses at a certain threshold value [5].

In all of the mentioned applications, there are specific settings that need to be followed in order to achieve health benefit outcome from the stimulation treatment as well as for safety purposes among patients during the stimulation procedure. The most common settings in every stimulation procedure involved are related to the correct frequency and amplitude setting of the stimulation signal and in less often occasions would also involve the selection of the pulse shape and the pulse width of the stimulation signal. In the case of electrical stimulation application to promote muscle functions, correct settings in these parameters are important to reduce the effect of muscle fatigue.

One of the earlier papers in reviewing the effect of muscle fatigue was by Toshiki *et al*. [6] in which their paper concluded that intermittent high frequency (100 Hz) pulses of 4-second burst may effect reduction of muscle fatigue.

Since then, there were many more researches investigating solutions in electrical stimulation procedure to delay the onset of muscle fatigue as much as possible. Thrasher *et al*. in their paper [7, 8] investigated the use of random modulation signal as stimulator pulse. From their results, they discovered that the use of random modulation signal is not a solution for fatigue reduction [7]. Other research works in this area include investigating generation of muscle fatigue with respect to the use of single or multiple (localized or distributed) surface electrodes [9,10], single or multiple channel output as well as comparing the effect of synchronous and asynchronous stimulation at varying frequencies to reduce fatigue [10, 11]. Except for [7, 8], the other works have used a 50% duty cycle square wave signal. Therefore, it is the intention of this paper to report the effect of different amplitude and frequency parameters for different pulse shape (25% duty cycle square wave and exponential waveform) in electrical stimulation by reviewing and analyzing it against muscle fatigue assessment which can be useful for stimulation procedure to restore loss of muscle function especially among stroke patients.

2.0 METHODOLOGY

Rehabilitation medicine has established a general recovery window time frame as guideline and information for patients. Post stroke rehabilitation immediately between 24 and 48 hours will have higher chance to regain their lost skills. As described in previous section, electrical stimulation is listed as one of the successful intervention methods in stroke rehabilitation in restoring loss muscle function among stroke patients. The main limitation of electrical stimulation however, is the muscle fatigue condition that could limit the training time, hence, delaying the recovering process. Therefore, it is evident that electrical stimulation procedure should be tailored according to the patient in order to benefit from the recovery window period. In other words, the efficacy of electrical stimulation during training process depends greatly on the number of stimulation that can be done on the affected muscle without adverse effect on the muscle conditions while re-educating the muscle ability. This can be done by setting correct parameters on the stimulator device and personalized it according to a patient's need.

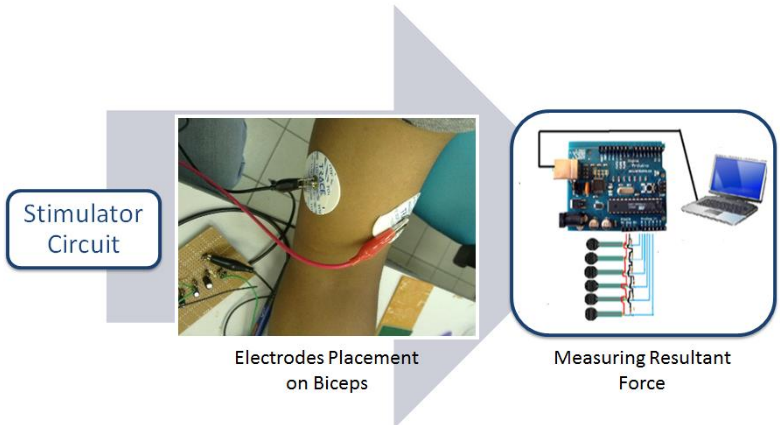


Figure 1 Experimental flow setup

Figure 1 shows the experimental setup to assess muscle fatigue against electrical stimulator parameters. A pair of electrodes is placed on the upper limb bicep of a healthy subject close to where the peripheral nerves are located. The bicep muscles were chosen due to its larger group of nerves, hence, making it easier to stimulate the muscle. Pre-gelled foamed Ag/AgCl surface electrodes of a diameter of 45×42 mm were used in this experiment. Before placing the electrodes, the skin area was cleaned to avoid additional resistance due to dust that could affect measurement. All five subjects were made seated and placed hands on the table close to a force sensor configuration as shown in Figure 2. The amount of resultant force exerted by the muscle is read by the force sensitive resistor (FSR) sensors via a microcontroller.

Stimulation was applied to the muscles for a duration of 30 seconds with five minutes break interval in between experiment. The stimulating current was gradually increased from 50 mA to 70 mA and to a maximum amplitude of 100 mA. The 50 mA is set to be the minimum amplitude value based on our pre-trial setup in which a visible muscle contraction that is able to be detected and recorded by the FSR sensor is at 50mA. In addition to varying current, the effect of varying pulse shape and duty cycle for square wave signal on fatigue was also analysed. The duty cycle was set to at 25% and 50% stimulation. As for the stimulation frequency, the values were set at 1 Hz, 5 Hz, 10 Hz and 15 Hz. Each experiment was repeated three times and the average force value were recorded. In this paper, fatigue was assumed to be detected when the force measured falls below 60% from the maximum force value recorded using the equation (1):

$$Fatigue\ Index = \frac{Muscle\ Tension}{M_{waveparameters}} \quad (1)$$

where $M_{waveparameters}$ constraint is the quantitative measurement represented in volts seconds.

Figure 2 FSR sensors configuration for force measurement

3.0 RESULTS AND DISCUSSIONS

The analysis of muscle fatigue was carried out against four stimuli parameters i.e. the amplitude, frequency, pulse shape (duty cycle) and waveforms (square and exponential) on the bicep muscles of five healthy persons.

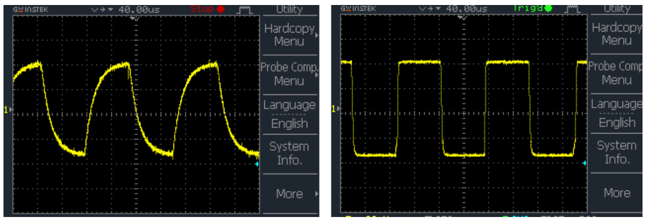
3.1 Hypotheses

While the exact reasons of muscle fatigue are still unknown, it is predicted that muscle fatigue occurs due to synaptic junction mechanisms failure altering neurotransmitters release which limit contractile mechanisms. In [12], it is described that individual who has acute paraplegics less than ten months has higher fatigue resistance than chronic paraplegics. In another article, it was elaborated that slow-twitching muscle became fatigue slower than fast-twitching muscle. Meanwhile, different pulse shapes have different energy levels therefore muscle response will be different. Therefore, the hypotheses of this experiment that will be conducted on healthy subjects are such that, muscle fatigue is faster when using;

i. higher frequency pulse
ii. higher amplitude

iii. pulse width that has stimulation duty cycle greater than 50%
iv. square wave pulse shape when compared to exponentially increase pulse shape

Figure 3 shows the output signals from a stimulator circuit that were used in this experiment.



(a) (b)

Figure 3 Examples:(a) the exponentially increase pulse shape, (b) approximately 50% duty cycle square wave

3.2 Analysis on Stimuli Parameters

To explain the muscle fatigue condition, we have broken this section into three subsections by discussing the output according to the amplitude increment i.e. 50 mA, 70 mA and 100 mA. All other parameters i.e. the frequency, the duty cycle for the square wave (DCS) and the pulse shape will be varied according to the predetermined values.

3.2.1 Muscle stimulation at 50 mA

As shown in Figure 4(a), the highest initial muscle force recorded was 30N for the DCS of 50% which is higher than the other two waveforms, that is, the exponential and the square wave with a duty cycle of 25%. Figure 4(a) shows that at 21s, the fatigue for the 50% duty cycle square wave was first detected. On the other hand, the square wave with 25% and the exponential waveform recorded their fatigue times at 23s and 24s respectively. It can be clearly seen from Figure 4(a) that the DCS of 50% has the highest decreasing rate when compared with the

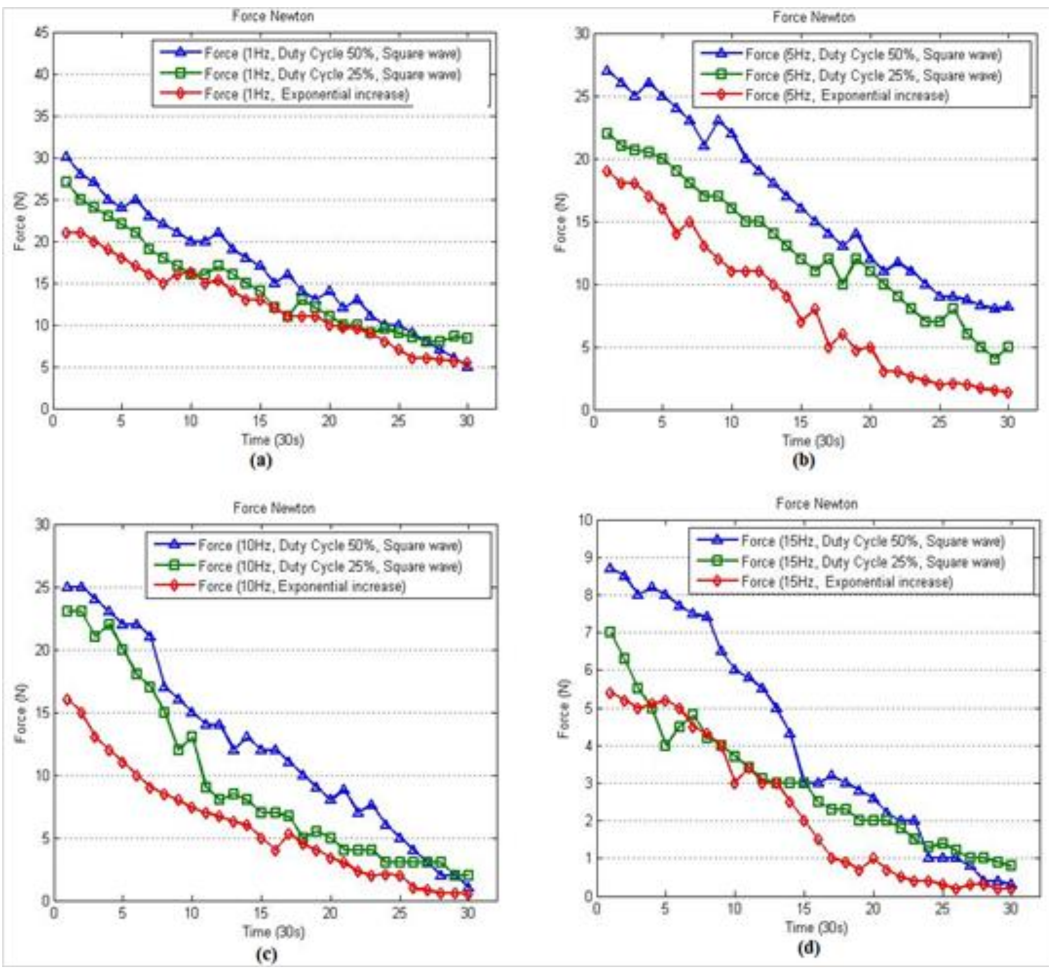


Figure 4 Muscle forces versus time for the frequency (a) 1 Hz, (b) 5 Hz, (c) 10 Hz and (d) 15 Hz for the 50 mA current amplitude

others. At time of 30s, the muscle force dropped to 5N, because of the reason that the DCS at 50% has less rest time in stimulation cycle than 25% of duty cycle while exponential waveform has less energy injection for stimulation, therefore less fatigue time.

From Figure 4(b), it shows that both square wave with duty cycle (25% and 50%) recorded a similar fatigue time at approximately 21s, although the square wave with the 50% duty cycle has a higher initial force of 22N.

Figure 4(c) and 4(d) illustrates the outputs for the frequencies 10 Hz and 15 Hz respectively. During the stimulation period, the DCS of 50% for both 10 Hz and 15 Hz developed muscle fatigue at a faster rate than the other two waveforms. For the 10 Hz, the force value started at 25N and stopped below 1N as shown in Figure 4(c) while for the 15 Hz, the initial force recorded was 9N before dropping to zero as shown in Figure 4(d). In both frequency settings, the remaining two waveforms had lower force readings and continue to decrease at a slower rate. However, compared to both pulses DCS 25%, force falls sharply from 0s - 5s as shown in Figure 4(d). This might be due to motor neuron that could not response quickly to the stimulation.

3.2.2 Muscle Stimulation at 70 mA

In this second part of the experiment, the previous setup for the parameters of the stimulator is the same except that the current intensity has been increased from 50 mA to 70 mA. Our initial hypothesis is that with the increase in the stimulation amplitude, the resultant force by the muscle will be greater than 50 mA.

The hypothesis is confirmed when the initial force started at 41N for the DCS 50% as illustrated in Figure 5(a). This is an increase of 11N compared to the output from the previous experiment, that is, when the current was set to 50 mA. In fact, the same

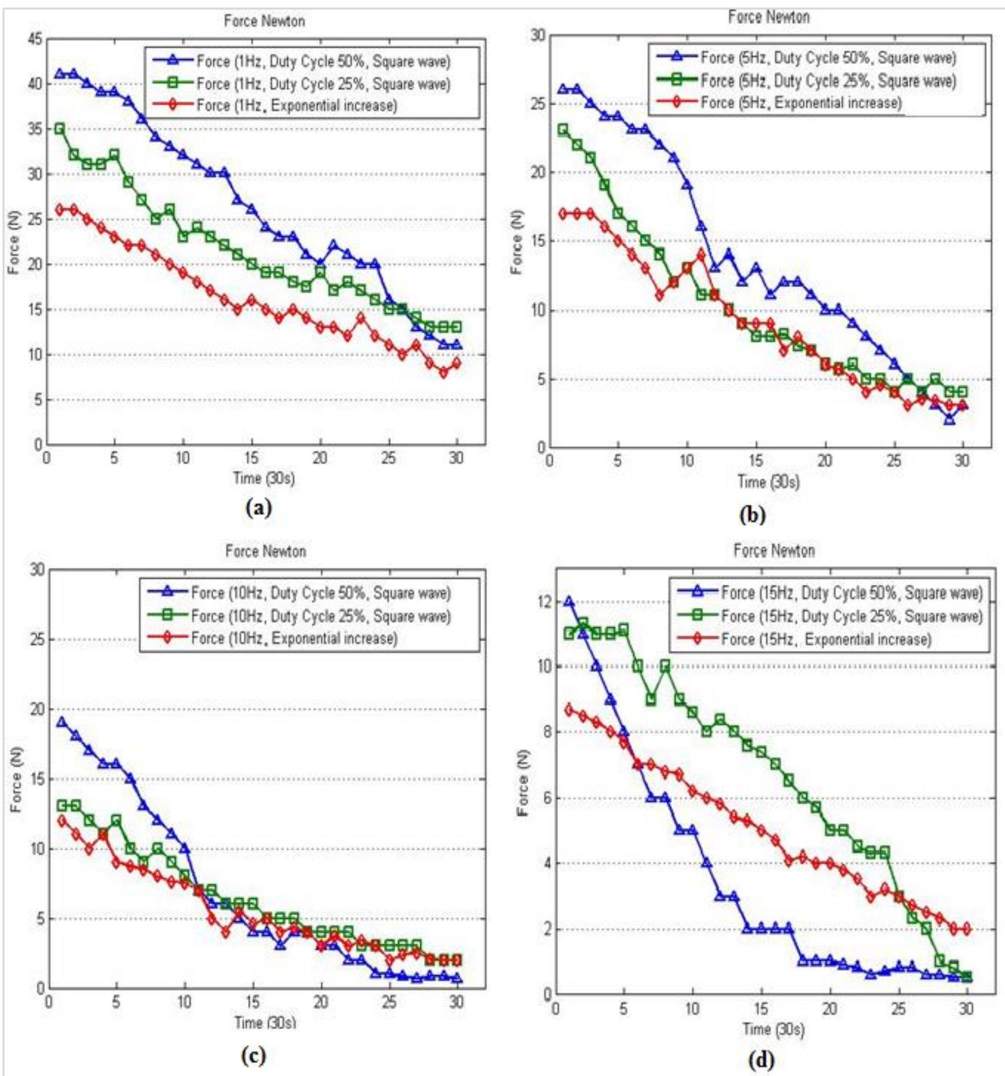


Figure 5 Muscle forces versus time for the frequency (a) 1 Hz, (b) 5 Hz, (c) 10 Hz and (d) 15 Hz for the 70 mA current amplitude

increment pattern at the starting force values could be seen for all categories as shown in Figure 5. In graph of Figure 5(a), the time stamp when force falls below 60% was at the 25th, 26th and 28th second for the 50% DCS, 25% DCS and for the exponential waveform respectively. Based on results it is realized that there is not much difference in the fatigue time for both square wave with 50% and 25% DCS. The exponential waveform is more stable in comparison to other waveforms even though the magnitude of the muscle contraction is small. In Figure 5(b), the maximum muscle force for the DCS 50% is 26N and quickly gets fatigue after 20 seconds. On the other hand, DCS 25% and exponential wave gets fatigued at 20th second and 21st second respectively. However, given that the DCS 50% has the largest drop margin by the end of the stimulation, hence, this determined that it gets fatigue faster in comparison to other waveforms. At 15 Hz frequency, the muscle twitches faster and small muscle contractions occur. Due to continuous stimulation, the muscles will get tired faster and experience a little sensation of discomfort.

In Figure 5(c) and Figure 5(d) the duty cycle 50% get fatigued very quickly and the muscle force is the lowest at the end of the stimulation time. In the Figure 5(c) the force decreases sharply for the both waveforms. For DCS 50% it drops from 19N to 0.8N and for DCS 25%, it decreases from 13N to 2N consequently, showing the fatigue point where it actually started. Interestingly, Figure 5(c) shows that after 14s the muscle force decreases in an approximately similar pattern for all the waveforms. In Figure 5(d), the muscle force falls sharply at the 11th second for DCS 50% in to others i.e. at 20s for DCS 25% and at 21s for the exponential wave.

3.2.3 Muscle Stimulation at 100mA

In the last part of this experiment, 100 mA were set on the stimulator circuit. With the DCS of 50%, muscle force is higher than DCS 25% as well as for the corresponding exponential wave. The initial force for DCS 50% is 61N as shown in Figure 6(a). DCS 25% has less muscle force, starting with force of 51N and decreases slowly in comparison with DCS 50% but not

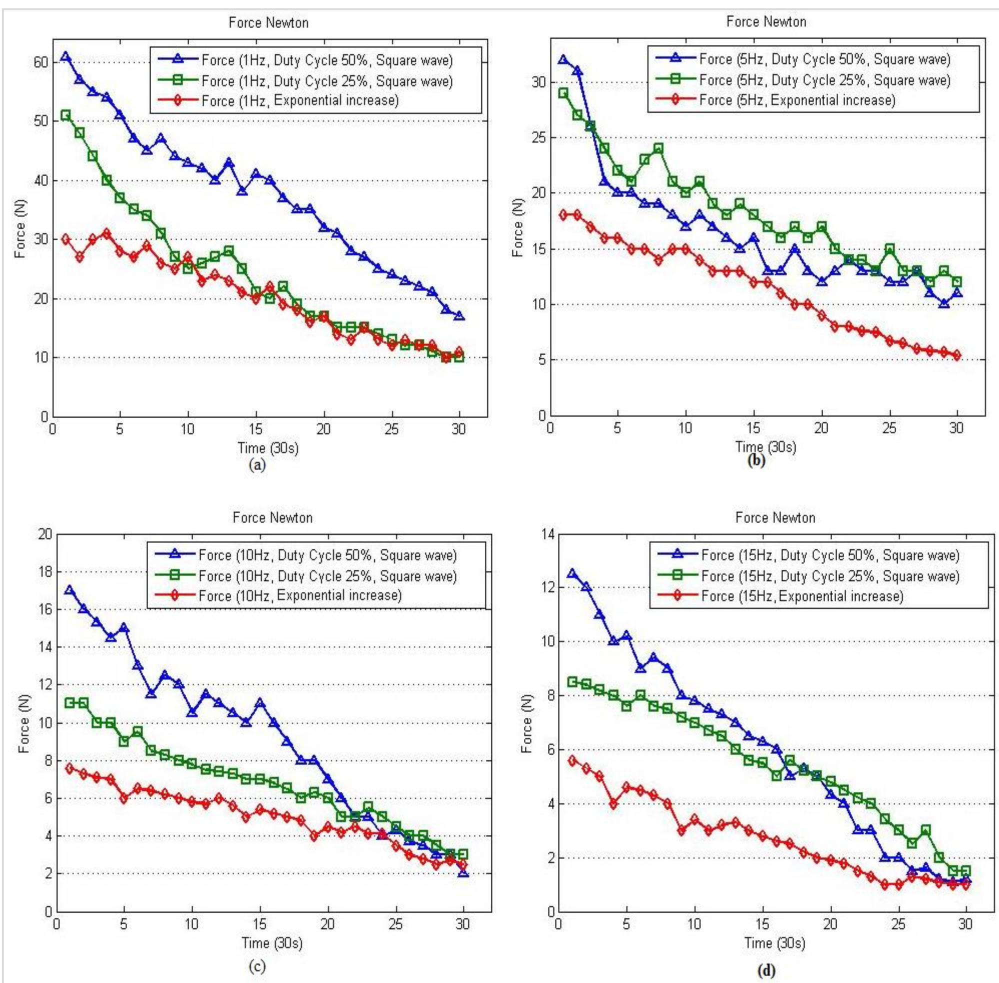


Figure 6 Muscle forces versus time for the frequency (a) 1 Hz, (b) 5 Hz, (c) 10 Hz and (d) 15 Hz for the 100 mA current amplitude

compared to the exponential wave. Exponential waveform shows the smallest contraction in comparison to other waveforms starting with maximum force of 30N. It can be seen from the Figure 6(a) that the muscle fatigue for DCS 50% occur at 24 seconds, as the force decreases by 60% from the initial force of 61N to the new value of 24N. It is because, the muscle activation time in every second is half of the second and rest half is the resting period. Hence, the muscle gets fatigue with higher force resultant. DCS 25% becomes less fatigue because muscle activation time is less and rest time (off) longer. At 15s, the duty cycle 25% and exponential waveform shows similar force value during the stimulation period as shown in Figure 6(a). The exponential wave has lesser energy power in comparison to others. As a result of that, the muscle gets fatigue slower over the stimulation period. The force drops from 30N to 12N i.e. 60% at the 27th second.

Figure 6(b) shows the outcome when the frequency is set to 5 Hz. Muscle twitch faster while increases the frequency. From responses given by volunteers, at 5 Hz, they began to feel a slightly pinch sensation. It is also observe that the muscle gets tired quickly at 5 Hz than 1 Hz frequency. For the DCS 50% square wave, the muscle force decreases dramatically from 32N to 13N at 10th second but later the force falls gradually over the stimulation period. For the DCS 25%, muscle force decreases by 60% i.e. from 29N to 11N after 26th second. Surprisingly, the exponential wave fatigue time starts 2 second earlier than the square wave of 25% duty cycle. This is because the rest time for the exponential waveform was shorter, thus, the muscle gets fatigue quicker in this case.

At the frequency of 10 Hz and 15 Hz, the muscle was stimulates at a faster rate but the responses observed was not as quick. Figure 6(c) and Figure 6(d) demonstrates the muscle force for the 10 Hz and 15 Hz frequency. In each second, there are more than 10 to 15 times for the 10 Hz and 15 Hz respectively of stimulated pulses applied to the nerve. Theoretically, the nerves neurotransmitter cannot restore quickly when stimuli pulse is given at a fast rate. It is therefore, at these two frequencies, more discomfort have been experienced by the volunteers. In the Figure 6(c) for the 10 Hz, the DCS 50% gets fatigued at 21th second, DSC 25% gets fatigued at 25th second and exponential wave at 26th second. As for the stimulation at 15 Hz frequency, the DCS 50% fatigue time starts at 17th second which is quicker than any frequency and waveform, duty cycle 25% fatigue time starts at 24th second and for the exponential wave it starts at 19th second.

Section 3.2.1 to section 3.2.3 described the tabulated data for all three parameters. These data are summarized and grouped in Table 1, Table 2 and Table 3 for 50 mA, 70 mA and 100 mA respectively.

Table 1 Summarized results of fatigue time and muscle force for 0 mA current

Frequency (Hz)	Fatigue time (s)			Muscle force DCS 50%		Muscle force DCS 25%		Muscle force exponential	
	Square wave DCS 50%	Square wave DCS 25%	Exponential wave	Max force (N)	Min force (N)	Max force (N)	Min force (N)	Max force (N)	Min force (N)
1	21	23	24	30	6	26	6	22	9
5	21	21	15	26	2	23	5	19	8
10	10	11	13	25	1	23	1	16	3
15	11	12	12	8.8	0.5	7	1	5.5	0.5

Table 2 Summarized results of fatigue time and muscle force for 70 mA current

Frequency (Hz)	Fatigue time (s)			Muscle force DCS 50%		Muscle force DCS 25%		Muscle force exponential	
	Square wave DCS 50%	Square wave DCS 25%	Exponential wave	Max force (N)	Min force (N)	Max force (N)	Min force (N)	Max force (N)	Min force (N)
1	25	26	28	41	13	35	11	26	9
5	22	20	21	26	3	23	4	16	3
10	11	12	14	19	0.5	13	2	12	2
15	9	11	15	12	0.4	11	0.4	8	2

Table 3 Summarized results of fatigue time and muscle force for 100 mA current

Frequency (Hz)	Fatigue time (s)			Muscle force DCS 50%		Muscle force DCS 25%		Muscle force exponential	
	Square wave DCS 50%	Square wave DCS 25%	Exponential wave	Max force (N)	Min force (N)	Max force (N)	Min force (N)	Max force (N)	Min force (N)
1	24	20	26	61	17	51	10	30	10
5	20	19	24	32	12	29	11	17	5
10	20	20	23	17	2	11	3	8	2.2
15	17	18	21	12.5	0.8	8.5	1.5	5.8	0.8

4.0 CONCLUSION

Based on our experimental results, it can be summarized that the effect of stimulator parameters on muscle fatigue are as the following:

i. The stimulation current intensity is proportional to the strength of muscle contraction. As the current intensity increases, the muscle contraction will also become higher.

ii. The effect of the duty cycle on muscle fatigue is also proportional in nature. As the duty cycle increases, the muscle fatigue becomes fatigue at faster rate.

iii. The stimulation frequency is also proportional to the occurrence of muscle fatigue. The higher the frequency, the quicker the muscle will become fatigue.

iv. The pulse shape has also a direct effect on the muscle fatigue. The exponential wave produces less fatigue when compared to the square wave.

Square wave is the best for strong muscle contraction while exponential wave performs better in fatigue, considering all the cases respectively. Having said that, our results show that the muscle becomes fatigue at a slower rate when stimulated with the exponential wave. While modern simulators mostly use the square wave signal to achieve better muscles contraction as described in the literature review, based on the results, it is believe that there are rooms for different waveforms to be used in future rehabilitation program. Since the exponential waveform produce later muscle fatigue, this means that it can extend the training duration among stroke patients to benefit from the recovery window time frame especially for patients who are still in their early recovering stage.

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