Effect of Frequency Modulation versus Pulse Duration Modulation of Low Frequency Current on Muscle Torque

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ABSTRACT

Background: *Electrical stimulation is used extensively throughout the world to augment muscle strength. Therefore investigating the parameters that could maximize torque output is a key element to the application of electrical stimulation. The purpose of the study was to investigate the effect of different electrical stimulation protocols on the peak isokinetic quadriceps muscle torque for healthy subjects.* ***Materials and Methods:*** *Forty healthy male subjects participated in this study with a mean age of (19.8±0.72) years. They were assigned randomly into two equal groups. Group I received the frequency-modulation protocol and group II received pulse duration modulation protocol. Isokinetic concentric peak torque of the non dominant quadriceps muscle was evaluated before and after training in the four weeks. Training was administered at low velocity (60^0/sec) in the functional range from 90 degree knee flexion up to 0 extensions while electrical stimulation was administered for 10 minutes, three times a week, in alternative days.* ***Results:*** *Frequency modulation protocol had a high significant increase in the quadriceps muscle isokinetic peak torque than the pulse duration modulation protocol. Peak torque increased post training from 158.1 ±38.62 to 190.1±33.55 for group I and from156.82±35.0 to 166.64±34.92 for group II.* ***Conclusion:*** *Frequency modulation protocol produced augmentation of peak torque of the quadriceps muscle than the pulse duration modulation protocol. It was an effective electrical stimulation strategy that can be followed for muscle strengthening than traditional approaches that uses constant frequency.*

Key words: *Frequency modulation –pulse duration modulation- muscle torque.*

INTRODUCTION

Electrical stimulation (ES) is used extensively throughout the world to augment muscle strength[21]. It has been shown to be effective in improving quadriceps femoris (QF) muscle torque production in healthy subjects[1].

Low frequency pulsed current (LFPC) stimulators are commonly used in clinical practice by physical therapists to improve torque production of the quadriceps femoris muscle. LFPC stimulators typically deliver biphasic or monophasic pulses at frequencies ranging between 1 and 150 Hz and the pulse duration between 50 and 450 µs[24,29].

The pulse parameters that most commonly adjusted to maximize torque output include the amplitude of the current, pulse duration (PD) and frequency of the pulses. These parameters characterize the features of a single pulse. The PD and current amplitude of the individual stimulation pulses influences the recruitment of the nerves which can be recruited by many different combinations of these two parameters[2,25].

Increasing PD from 150 to 450 microseconds (µs) has recently been shown to increase motor unit recruitment and evoked more torque[14]. Also increasing the current amplitude results in proportional increase in the torque produced of the stimulated muscle but it was limited by the participant tolerance to the stimulation[12].

Frequency of the pulse has been studied extensively because of its important role in determining the torque development and controlling muscle fatigue[6,26].

Increasing the frequency leads to increase in torque production but concurrently accelerates muscle fatigue. Recently researchers showed that progressively increasing the stimulation frequency resulted in better isometric performance than constant frequency or intensity[14,17].

Within the available literature, there is no recent prospective study has systematically investigated the accumulative training effects of ES following repeated sessions over weeks using different stimulation protocols of frequency and pulse duration modulations. So, the purpose of the study was to investigate the effect different electrical stimulation protocols on the peak isokinetic quadriceps muscle torque. This could provide physical therapists with effective protocols concerning augmentation of muscle strength and could be used for musculoskeletal and neuromuscular disorders.

SUBJECTS, MATERIALS AND METHODS

Forty healthy male volunteers were recruited for the study from the Faculty of Physical Therapy, Cairo University students and employees. Their age were ranged from (18 – 30) years old. Subjects were randomly assigned into two equal groups. Each group was consisted of twenty male subjects.

Subjects were excluded if they had any contraindication for electrical stimulation or received any beverages containing caffeine regularly or missed two sessions.

Instrumentations

1- Bio-Trac Plus: It is the device that was used to deliver neuromuscular stimulation. It is a small hand-held battery powered (9 volts) unit for single or dual-channels operation with independent output control, with asymmetric biphasic pulse, frequency ranges from (2 to 100) Hz, pulse duration ranges from (50 to 450) µsec, work / rest ranges from (1 to20) seconds, treatment time ranges from (0 to 30) minutes and amplitude ranges from (0 to 80) mA. The device manufactured by EMS Physio. Ltd. England. The portable stimulators have been used in many studies. Researchers found that portable stimulators produced comparable levels of peak torque at comparable levels of discomfort to those produced by clinical stimulators[19,20,22].

2- Biodex system III isokinetic dynamometer: It is the device that was used to measure the isokinetic concentric peak torque of non dominant quadriceps femoris (QF) muscle before and after training. The system has visual and auditory biofeedback, which aided concentration when working hard physically. The system provided with computer system (IBM compatible) that collects, displays, stores the isokinetic test data and controls the movements of dynamometer. It has been widely used in research, clinical setting and rehabilitation to objectively assess factors of muscle performance. The validity and reliability of the Biodex isokinetic dynamometer has been investigated under static and dynamic conditions with satisfactory results[8].

Procedures

All evaluating and training procedures were done at Faculty of Physical Therapy, Cairo University. After signing a written consent form, all subjects underwent the same evaluation procedures included:

- Subjects' ages were recorded and their height and weight were measured.
- The non dominant lower extremity was determined by asking the subject to kick a ball in front of him. The limb that was used to kick the ball is considered to be the dominant one while the other limb is considered to be the non dominant one.
- Isokinetic concentric peak torque of the non dominant QF muscle was assessed before and after training at lower velocity (60^0/sec) in the functional range from 90 degree knee flexion up to 0 extensions as it more representatives for dynamic muscle performance[7,9]. Each subject was allowed to do first unrecorded three light trial repetitions of knee extension and flexion before the test as warm up and to familiarize with the system then the subject did maximum five repetitions of knee extension with angular velocity 60°/sec[11]. The subject asked to sit on the dynamometer's chair with the tested knee at 90^o Flexion; the back support was adjusted to allow hip angle 110^o to the horizontal. This test position had been shown to be reliable for yielding maximal knee torques[5]. The resistance pad placed at the lower leg, two centimeters above the medial malleolus. A thigh strap, waist strap, and 2 chest straps were then secured to stabilize the subject in the dynamometer chair (figure 1 a). The dynamometer's axis of rotation was aligned with the lateral femoral epicondyle, and the knee was extended from 90 degrees to 0 degrees to ensure that the axis of rotation of the knee is aligned with the axis of rotation of the

dynamometer. The knee was then positioned in 90 degrees of flexion. The speed of the dynamometer was set at 60^{o}/sec. Gravity correction was performed throughout the test. The subjects was instructed to hold the sides of the padded seat for added stabilization and maximally contract their non dominant QF muscle following the command pull (figure 1 b). The highest torque reading of the five trials was accepted as the peak torque[11].


(a) (b)

Fig. (1): Starting position of the test, with knee flexed 90 (a). Final position of the test, with full extension of the knee (b).

Training procedures

Subjects in group I received constant pulse-duration (450 µsec) and progressive increases in frequency (30 Hz for the first week, 40 Hz for the second week, 50 Hz for the third week and 60 Hz for the fourth week) (Frequency-modulation protocol). While subjects in group II received constant frequency (50 Hz) and progressive increases in pulse duration (150 µsec for the first week, 250 µsec for the second week, 350 µsec for the third week and 450 µsec for the fourth week) (Pulse-duration-modulation protocol). For both groups duty cycle was set at 4 seconds on and 16 seconds off (duty cycle of 20%) and the intensity of the stimulator will be adjusted to the current that could be maximally tolerated by each subject for 10 minutes. Electrical stimulation was administered three times a week, in alternative days, for four weeks[18,28].

Electrical stimulation was administered to the non dominant QF muscle. The proximal electrode was placed over the upper thigh covering the proximal portion of rectus femoris and vastus lateralis muscles (15 cm distal to anterior superior iliac spine). The distal electrode was placed over the lower aspect of the thigh covering distal bulk of vastus medialis (figure 2)[17]. Prior to application of electrodes the skin over the electrode placement site was cleaned with alcohol swabs and to ensure consistent electrode placement for the next sessions a clear plastic sheets was placed over the subject's thigh or using permanent marker according to subject's preference[20]. The intensity was increased gradually until the subject could not tolerate further increase in intensity after a short periods habituation to the stimulus was occurred the subject was asked again (can you tolerate further increase in intensity?) at this level maximum tolerable intensity was recorded for each subject[18].

Fig. (2): Position of the subject and electrodes placement during application of electrical stimulation.

Statistical Analysis

Descriptive statistics including the mean and standard deviation was used to describe ages, weights and heights of participants. Student t test was used was used to determine significant differences in peak torques between both groups and to compare between pre and post test values of the peak torque within each group. The P-value < 0.05 was taken as significant.

RESULTS

Demographic characteristics of both groups presented in (table 1). There were no significant differences between both groups regarding age, weight and height (P>0.05).

Table (1): Demographic data of the subjects in both groups (I and II).

General Characteristics	Group (I)		Group (II)		Comparison	
	Mean	±SD	Mean	±SD	P-value	S
Age (year)	19.8	± 0.69	19.75	± 0.63	0.8	NS
Weight (Kg)	77.6	± 5.62	75.85	± 10.34	0.78	NS
Height (cm)	176.3	± 4.66	177.25	± 6.23	0.68	NS

*SD: standard deviation, P: probability, S: significant, NS: non-significant

The results revealed that there was a significant increase in the peak torque for both groups as P value was (0.01). The mean values of peak torque increased post training from 158.1 ±38.62 to 190.1±33.55 for group I and from156.82±35.0 to 166.64±34.92 for group II as shown in table (2) and figure (3).

Table (2): Comparisons between mean values of peak torque Pre and Post training for both groups.

Variable	Group	Pre training		Post training		t- Value	P - Value
		Mean	SD	Mean	SD		
Peak torque	I	158.1	38.62	190.1	33.55	10.1	0.0001*
	II	156.82	35.0	166.64	34.92	8.99	0.0001*

* Significance at P<0.05. SD= standard deviation

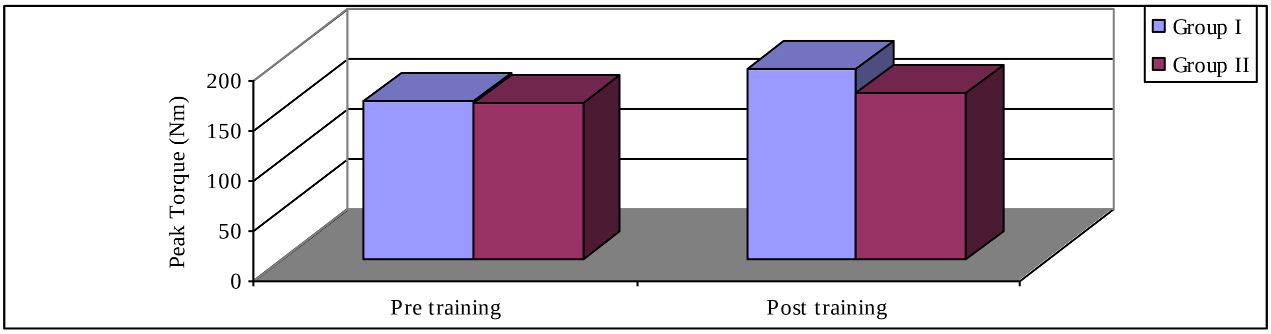

Fig. (3): Mean values of peak torque pre and post training for both groups.

Table (3): Percentage of improvement in the mean values of the peak torque between both groups.

	Group I	Group II
Percentage of improvement	20.24%	6.26%

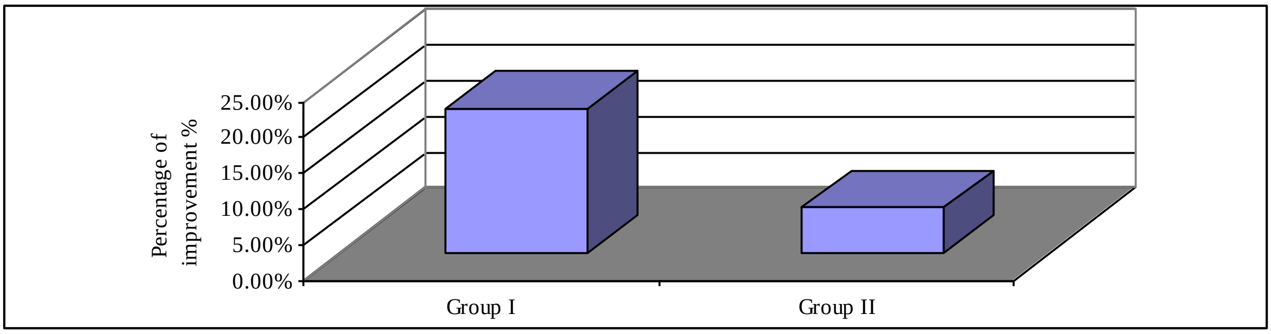

Fig. (4): Percentage of improvement in peak torque post training.

DISSCUSION

The purpose of this study was to investigate the effect of different electrical stimulation protocols on the peak isokinetic quadriceps muscle torque. This helped set a protocol for electrical stimulation that can be followed by physical therapists.

The principal findings of this study support that there were a significant differences between the effects of the different electrical stimulation protocols used in this study in the magnitude of the peak isokinetic quadriceps muscle torque. Electrical stimulation protocol which progressively increased frequency produced better performance in peak torque than protocol which progressively increased PD.

These findings were in agreement with (Kesar et al., 2008)[17] who suggested that frequency modulation strategies produced better performance in peak forces in response to the fatiguing trains than PD modulation or no modulation i.e. (constant frequency and PD) strategies[17].

Based on the literatures, during voluntary contraction the CNS controls skeletal muscle force output by varying both the activation frequency (firing rate of activated motor unit or rate coding) and the number of activated motor units (recruitment). When the recruitment is completed at sub-maximal force levels, higher forces are achieved by using progressively higher activation rates of previously recruited motor units[27]. So that muscle force can be controlled by varying the ES frequency and intensity[6].

When LFPC applied, the nerve fiber firing frequency will be equal the pulse frequency provided that the pulse intensity is sufficiently above threshold[29]. The stimulation intensity can be modulated by adjusting either the current amplitude or pulse duration of the stimulus which is easier to control and provide more consistent force response from the muscle compared to stimulation amplitude[16]. The possible physiological mechanisms that could contribute to the findings of the current study include:

1- Force generation by each muscle fiber:

During the pulse duration modulation protocol, the frequency was maintained at 50 Hz throughout the protocol and the pulse duration was modulated from (150 to 450 microseconds). Thus, a smaller fraction of the motor unit pool was recruited initially. Then, the pulse duration was progressively increased to recruit more motor units. Motor units that were recruited earlier in the protocol continued to be activated throughout the protocol. Thus, motor units that were recruited early were activated for a longer period of time compared with the motor units that were recruited later in the protocol[23].

In contrast, during the frequency modulation protocol, the pulse duration was maintained at 450 microseconds throughout the protocol and the frequency was modulated from (30 to 60 Hz). Increased pulse duration to 450 microseconds increased the activated area of the stimulated muscle and recruited more motor units[13]. Thus a maximum number of motor units were recruited throughout the frequency modulation protocol. This allowed the sharing of force generation among a greater number of muscle fibers throughout the protocol. The amount of adenosine triphosphate (ATP) utilized by actin-mysoin adenosine triphosphatase (ATPase) is proportional to the force generated by each fiber[23].

Thus, greater ATP utilization by the actin-myosin ATPase per muscle fiber occurred during the pulse duration modulation protocol compared with during the frequency modulation protocol. We, therefore, believe that the frequency modulation protocol produced less fatigue in the recruited motor unit population because of greater motor unit recruitment at the commencement of the protocol, resulting in lower ATP consumption per active muscle fiber by actin-myosin ATPase and consequently improving muscle performance[6].

2- The number of stimulation pulses:

It also may have contributed to the large difference between the frequency modulation and pulse duration modulation protocols. During the pulse duration modulation protocol, when all of the motor units were always activated at a high frequency of 50 Hz, a greater number of stimulation pulses were delivered to the muscle compared with during the frequency modulation protocol, in which stimulation frequency was progressively increased from (30 to 60 Hz). The calcium ATPase and sodium-potassium ATPase reactions in response to each action potential contribute to ATP utilization during muscle force generation[15].

Because relatively fewer pulses were delivered during the frequency modulation protocol compared with the pulse duration modulation protocol, less ATP was utilized by the calcium ATPase and sodium-potassium ATPase during the frequency modulation protocol[10].

Muscle fatigue is related to metabolic demand. Higher stimulation frequencies contribute to more rapid muscle fatigue. Thus, the frequency modulation protocol might be less fatiguing than the pulse duration modulation protocol because it delivers fewer pulses to the muscles[3]. The frequency modulation protocol appeared to be less fatiguing due to less metabolic demand per recruited muscle fiber by greater motor unit recruitment at the commencement of the protocol and by delivering fewer stimulation pulses, which resulted in better muscle performance than the pulse duration modulation protocol at the end of training with ES[6].

3- The available range for frequency modulation

It can also be used to explain the differences in performance. There is a direct relationship between stimulation frequency and muscle force production, with near-maximal forces produced at approximately 60 Hz[4]. A 30 Hz frequency was the best starting stimulation frequency for quadriceps femoris muscle activation because it can prevent low frequency fatigue and retained a large capacity to increase force during frequency modulation[6].

Conclusion

Frequency modulation protocol produced augmentation of the peak torque of the QF muscle than the PD modulation protocol. It was an effective ES strategy that can be followed for muscle strengthening than traditional approaches that uses constant frequency.

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الملخص العربي

تأثير التردد المتغير مقابل النبضة الزمنية المتغيرة للتيار منخفض التردد على عزم العضلة

يستخدم التنبيه الكهربائي بصورة شائعة في العالم لزيادة قوة العضلات . ولذلك فإن دراسة معايير التنبيه الكهربائي التي نستطيع من خلالها زيادة قوة العضلات مطلوبة لتطبيق التنبيه الكهربائي . وتهدف هذه الدراسة إلى بحث تأثير البروتوكولات المختلفة للتنبيه الكهربائي على أقصى عزم للعضلة الرباعية والتي يمكن من خلالها وضع بروتوكول للتنبيه الكهربائي يمكن إتباعه بواسطة أخصائي العلاج الطبيعي لزيادة القوة العضلية . ولقد أجريت هذه الدراسة على أربعين شخص من الأصحاء من الذكور متوسط أعمارهم (19.8±0.72) وتم تقسيمهم عشوائيا إلى مجموعتين متساويتين. المجموعة الأولى (بروتوكول التردد المتغير) ، المجموعة الثانية (بروتوكول النبضة الزمنية المتغير) . ولقد تم التنبيه الكهربائي لمدة عشر دقائق ، ثلاث مرات أسبوعيا لمدة أربع أسابيع . وقد تم تقييم أقصى عزم للعضلة الرباعية . وقد أظهرت النتائج : أنه هناك زيادة مؤثرة في العزم الأقصى للعضلة الرباعية بعد استخدام بروتوكول التردد المتغير بالمقارنة بالبروتوكول المغير للنبضة الزمنية . ويستخلص من البحث الآتي : أن بروتوكول التنبيه الكهربائي المغير للتردد نتج عنه أداء أفضل في العزم الأقصى للعضلة الرباعية من بروتوكول النبضة الزمنية المتغير. كما أنه إستراتيجية تنبيه كهربائي فعالة لتقوية العضلات أفضل من البروتوكولات التقليدية التي تستخدم تردد ثابت .