

CHANGE IN MUSCLE FORCE FOLLOWING ELECTRICAL STIMULATION

Dependence on Stimulation Waveform and Frequency

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ABSTRACT. Change in muscle force in healthy subjects due to electrical stimulation was accomplished with rectangular and sinusoidal currents. The pulse width of rectangular stimuli was 0.3 ms and repetition frequency was 25 Hz. The frequency of sinusoidal stimuli was 2500 Hz, chopped by a 25 Hz rectangular signal. Thirteen healthy subjects were involved in the study and divided into three groups. The first group (A) had stimulation with rectangular impulses, the second (B) with sinusoidal impulses and the third (C) was a control group. The quadriceps muscle was stimulated daily for 10 minutes for 3 weeks. The maximal voluntary isometric torque increased for 25 % in group A and 13 % in group B, while there was no significant difference in group C. Different patterns of fatigue occurred with different stimuli. The presence of fatigue during the high frequency sinusoidal stimulation diminished the strengthening effects.

Key words: electrical stimulation, muscle contraction, muscle strength

Electrical activation of the neuromuscular system produces therapeutic effects and is a useful method in restoration of lost or impaired motor function (19, 29). With electrical stimulation it is possible to increase muscle activity: to influence their morphological, physiological and biochemical properties, resulting in an improvement of muscle strength in healthy subjects (6, 13, 15-18), or recovery of atrophied musculature due to inactivity (10, 11, 30).

The choice of adequate parameters is relevant in the application of electrical stimulation (12, 28). The modification of muscle force is related to the physical conditions of contraction obtained by electrical stimulation. Munsat et al. (20) demonstrated that isometric muscle contraction resulted in an increased proportion of red fibres. The metabolic characteristics as well as contractile properties of muscle fibres can be altered by different patterns of muscle activity influenced by stimulation repetition

frequency (3, 14, 21, 23-27). Bajd et al. (2) reported the muscle fatigue dependence on the ratio of stimulation train and subsequent pause. Low stimulation frequency lessened muscle fatigue during the strengthening program of knee extensors in paraplegic patients (1, 2).

Two controversial opinions regarding the role of frequency and stimulation waveforms in increasing the muscle force appear from literature. Stimulation signals used in rehabilitation practice are mostly rectangular and monophasic with the frequencies up to 50 Hz. These frequencies correspond to some extent to the discharge rates of motoneurons during the repetitive activity. The phasic motoneurons exhibit a higher frequency of discharge than the tonic ones, 30-60 as against 10-20 Hz being the usual frequencies, though tonic motoneurons could discharge at the frequency as high as 40 Hz (4, 5, 9). On the other hand, high frequency sinusoidal pulses can be found in applications of stimulation directed toward achieving better muscle properties in healthy subjects and sportsmen (7, 8, 17). Kots and Divieti found that the maximal isometric contraction due to stimulation of muscle motor end-plate occurs at 2500 Hz. Kots's experiments involved the frequency range from 100 Hz to 5 kHz, whereas Divieti investigated the range between 1 kHz and 5 kHz.

The purpose of our study was to compare changes in muscle force in healthy subjects due to long-term electrical stimulation performed with two types of stimulus:

- rectangular, monophasic and low repetition frequency stimulation pulses,
- sinusoidal high-frequency signal modulated by low-frequency rectangular stimuli.

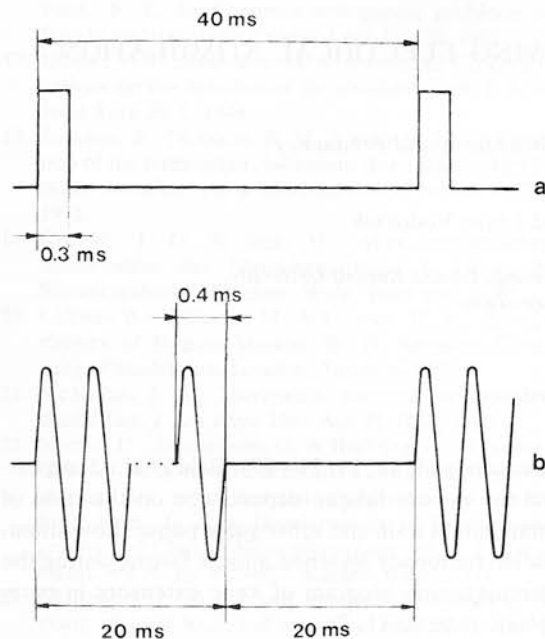


Fig. 1. Current stimuli used for electrical stimulation.

METHODS

Stimulation

The repetition frequency of rectangular stimuli was 25 Hz and the pulse width was 0.3 ms (Fig. 1a). The frequency of sinusoidal stimuli was 2500 Hz. The modulation frequency of sinusoidal waveform was also 25 Hz (Fig. 1b). The purpose of stimulation was to affect the quadriceps muscle force only, while maintaining its contractile properties unaltered. In this way the frequency close to the discharge frequency on n.femoralis (22) innervating m. quadriceps was chosen. In order to avoid the muscle fatigue a 50 s pause followed each 10 s stimulation train. Surface electrical stimulation of knee extensor muscles was delivered through large (90×50 mm) stainless steel sheet-metal electrodes covered with water-soaked foam rubber. The proximal electrode was placed over muscles rectus femoris and vastus lateralis, while the distal over muscles rectus femoris, vastus lateralis and vastus medialis. The stimulated quadriceps muscle was contracting isometrically, with knee flexed at 60°.

Measurements

The isometric knee joint torque was assessed by a measuring system transforming the torque into voltage via the strain-gauge transducers. The device, into which the lower limb was firmly fixed, enabled adjustments of knee flexion angle. The fixation point was 40 cm from approximate centre of rotation of the knee joint. During measurements, the subjects were in the sitting position, and the knee was flexed in the same position as during the stimulation.

Evaluation of long-term strengthening effects

Thirteen healthy subjects (20–25 years) were involved in the experiment. They were divided into three groups. Five subjects of the first group (group A) were stimulated with rectangular stimuli, while 5 subjects in the second group (group B) received sinusoidal stimulation. The third group (group C) with 3 subjects was the control group.

The variability of the knee joint torque during the voluntary contraction was determined from the measurements performed in subjects from the third group. The experiment lasted for 4 weeks. In the first week, three control measurements of torque produced at the maximal voluntary isometric contraction were carried out in all subjects. During the subsequent 3 weeks, subjects from A and B groups were stimulated for 10 min every day. Before and after stimulation, maximal voluntary isometric contraction was measured. The stimulation current amplitude was adjusted to produce only 5% of average isometric torque obtained in the control measurements during the first week. In this way the treatment was made uniform and electrical stimulation did not cause unpleasant feelings in any subject.

Evaluation of short-term strengthening effects

The time course of the isometric torque response during the stimulation was found to be important when explaining the short-term strengthening effects. Thus, two additional measurements were performed in five arbitrarily chosen subjects. First, the isometric torque was measured during 10 min of intermittent stimulation (10 s train, 50 s pause). Second, continuous stimulation for one minute was applied. To obtain the difference in the muscle fatigue, rectangular and high-frequency sinusoidal stimuli were applied in the same subject on 2 different days. On both occasions the amplitude of stimulation current was adjusted to the value which produced the same initial isometric torque.

RESULTS

Maximal isometric torque values measured before and after the stimulation during the strengthening program are presented by the help of linear regression analysis. The results are shown in Table 1. No significant differences in muscle strength can be observed from standard deviations appertaining to the results of control measurements on subjects from group C. The daily measurements consisted of five maximal contractions lasting approximately one second. The measured and fitted data for 2 subjects, one belonging to the first group and the other belonging to the second group, are given in Fig. 2. It is important to note that multiple correlation coefficient is much higher for group A. This means that results obtained with the long-term stimulation consisting of rectangular stimuli, dem-

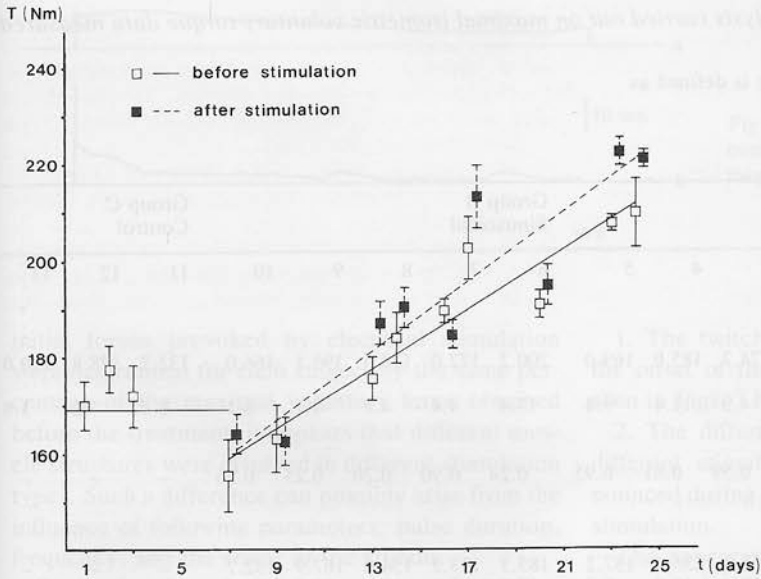


Fig. 2. (a) Values of maximal voluntary isometric torque obtained in subject 5 (Table I) from group A. □, ■, Data with standard deviations of five maximal contractions. The rising lines show data calculated by regression analysis; the horizontal line represents an average value of control data.

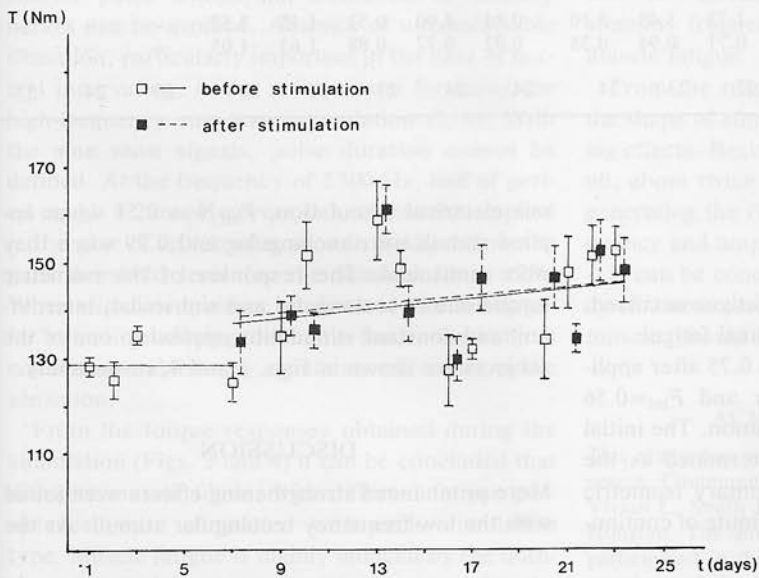


Fig. 2. (b) Values of maximal voluntary isometric torque obtained in subject 8 (Table I) from group B.

onstrated a fairly constant rate of increase. The measure for a change in torque was defined as a difference between the value of regression line at the last day of experiment and the average value of control measurements performed during the first week (Table I, Fig. 2). The average change in maximal voluntary isometric torque was 25.3% for group A, and 13.2% for group B. The average value of stimulation current was 43.12 ± 7.1 mA for group

A and 73.1 ± 17.0 mA peak-to-peak amplitude for group B.

The analysis of the torque response measured during electrical stimulation offers a better explanation of the results obtained. The persistence of muscle contraction can be quantified by a factor of muscle fatigue (F_{mf}). It is defined as a ratio of the mean value of isometric torque (T_0) and its initial value (T_s):

Table I. Results of regression analysis carried out on maximal isometric voluntary torque data measured before stimulation

The percentage change in muscle force is defined as

$$\frac{T_c + NT_i - T_a}{T_a} \cdot 100 [\%]$$

Stimulus waveform	Group A Rectangular					Group B Sinusoidal					Group C Control		
	1	2	3	4	5	6	7	8	9	10	11	12	13
Subject													
Average value of control measurement data (T_c); Nm	146.1	144.0	174.2	185.0	169.0	200.2	172.0	128.5	195.1	166.0	132.2	178.8	120.0
Standard deviation; Nm	11.0	11.0	4.9	11.4	9.4	13.4	4.4	4.5	8.1	6.1	6.5	7.8	5.8
Multiple correlation coefficient	0.86	0.81	0.59	0.81	0.95	0.24	0.90	0.20	0.25	0.76	-	-	-
Constant regression coefficient (T_c); Nm	139.9	122.9	158.8	155.4	137.2	185.3	113.5	134.0	167.9	132.7	-	-	-
SE; Nm	6.9	8.4	10.4	12.8	5.3	17.9	12.0	12.0	25.9	13.6	-	-	-
Independent regression coefficient (T_i); Nm/day	2.32	2.30	1.75	3.48	3.10	0.84	4.00	0.52	1.15	3.52	-	-	-
SE; Nm/day	0.51	0.58	0.71	0.94	0.38	0.92	0.77	0.88	1.63	1.05	-	-	-
Number of days (N)	21	26	27	23	24	24	24	23	26	22	20	24	22

$$F_{mf} = \frac{T_0}{T_s}; 0 \leq F_{mf} \leq 1,$$

where $F_{mf}=1$ would mean that no fatigue occurred, while $F_{mf}=0$ would represent maximal fatigue.

The factor of muscle fatigue was 0.75 after application of intermittent rectangular and $F_{mf}=0.56$ after intermittent sinusoidal stimulation. The initial value of isometric torque was determined as the same percent of the maximal voluntary isometric torque in each subject. After one minute of continu-

ous electrical stimulation, F_{mf} was 0.51 when applied stimuli were rectangular and 0.29 when they were sinusoidal. The responses of the isometric torque due to rectangular and sinusoidal, intermittent and constant stimulation applied to one of the subjects are shown in Figs. 3 and 4, respectively.

DISCUSSION

More pronounced strengthening effects were found with the low-frequency rectangular stimuli. As the

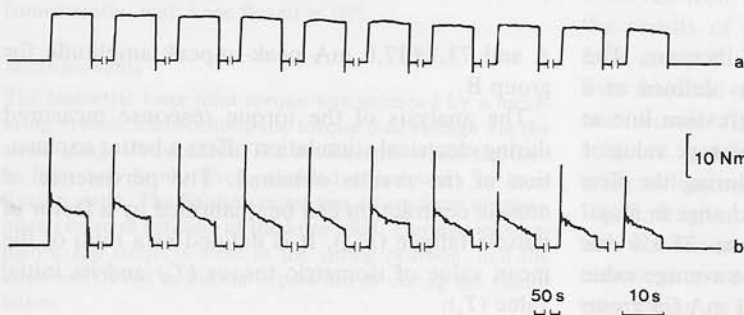


Fig. 3. Isometric torque response during 10 min of intermittent stimulation performed with rectangular stimuli (a), and sinusoidal stimuli (b). Note that the initial torque values were the same in both cases (the initial spike (b) was not considered).

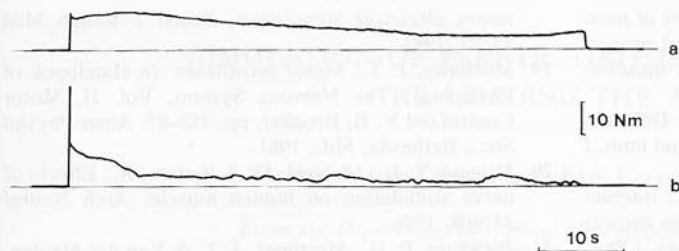


Fig. 4. Isometric torque response during continuous stimulation performed with rectangular (a) and sinusoidal stimuli (b).

initial forces provoked by electrical stimulation were determined for each subject by the same percentage of the maximal voluntary force obtained before the treatment, it appears that different muscle structures were involved in different stimulation types. Such a difference can possibly arise from the influence of following parameters: pulse duration, frequency, and the shape of the stimuli.

By varying the pulse duration, one may selectively stimulate fibres of different diameters. At the shorter pulse widths, an excitation of sensory nerves can be avoided. Absence of uncomfortable sensation, particularly important in the case of normal innervation, is the main reason for using the high-frequency sine wave stimulation (7, 8). With the sine wave signals, pulse duration cannot be defined. At the frequency of 2500 Hz, half of period equals 0.2 ms. However, 0.3 ms duration applied in the case of rectangular stimuli, is also below the pain threshold level for the sensory fibres (28). When stimulated, either by sinusoidal or rectangular stimuli producing the same force, the subject could not establish any significant difference in the sensation.

From the torque responses obtained during the stimulation (Figs. 3 and 4) it can be concluded that different muscle fibres, with different fatigue persistence, were stimulated with each stimulation type. Muscle fatigue is mainly induced by the duration of muscle activity, and is increased by the stimulation frequency. Due to low repetitive frequency, rectangular impulses produced contraction of slow twitch and slow fatiguable muscle fibers (Figs. 3a and 4a). High-frequency sinusoidal stimuli caused rapid fatigue of the stimulated muscle (Figs. 3b and 4b). This is an indication that the motoneurons innervating the oxidative fibres discharged at the maximal possible frequency. Furthermore, there are two observations also indicating the prevalent activation of the fast fatigable muscle fibres (either glycolytic or oxidative):

1. The twitch torque response appears only at the onset of the electrical stimulation, as can be seen in Figs. 3b and 4b.

2. The differing patterns of fatigue due to two different stimulation waveforms were more pronounced during continuous than during intermittent stimulation.

The appearance of fatigue during the high frequency sinusoidal stimulation diminishes the strengthening effects. Thus, the difference in results is a direct consequence of the difference in stimulus frequency, causing differing degrees of muscle fatigue.

From the results obtained it is not evident that the shape of stimuli influenced the final strengthening effects. Besides, to generate the sine wave stimuli, about twice as much energy is required as for generating the rectangular stimuli of the same frequency and amplitude.

It can be concluded, therefore, that the frequency of stimuli, used with the aim of strengthening the muscle, should be close to its fusion frequency.

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