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Muscle Fatigue of Quadriceps in Paraplegics: Comparison between Single vs. Multi-pad Electrode Surface Stimulation

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Abstract — **We hypothesize that the asynchronous low frequency stimulation of pads within multi-pad electrode will be less fatiguing compared to the conventional stimulation (two single pad electrodes) when generating comparable large forces of paralyzed human muscles. The experiments to verify the hypothesis were conducted on quadriceps of six individuals with chronic spinal cord injury (ASIA score A) who had not participated in any electrical stimulation program. The following stimulation protocols were compared: stimulation with a self adhesive 7 cm x 10 cm Pals Platinum cathode positioned over the top of the quadriceps (f = 40 Hz), and four oval 4 cm x 6 cm cathodes positioned over the proximal upper leg (f = 16 Hz). The anode in both cases was the 7 cm x 10 cm Pals Platinum electrode positioned over the distal part of the quadriceps. We measured the knee joint torque vs. time with a custom made apparatus, and estimated the interval before the knee joint torque decreased to 70% of the maximum. Mean fatigue interval increase for the four-pad stimulation protocol vs. single-pad stimulation protocol was 153.18%. This suggests that the use of multi-pad electrodes is favorable in cases where a prolonged stimulation of muscles is required.**

Keywords—**fatigue, functional electrical stimulation, multi-pad electrode, quadriceps**

I. Introduction

FUNCTIONAL ELECTRICAL STIMULATION (FES) applied by surface or implanted electrodes can generate contraction of a paralyzed innervated muscle. FES can assist individuals with spinal cord injuries or stroke to restore grasping [1], and limited standing or walking [2]. FES was proven to have some therapeutic effects [3, 4], and can be used as a method for exercise of paraplegics and tetraplegics (e.g., rowing [5] or cycling [6]). Two major problems in translating FES to a common rehabilitation method are: 1) muscle fatigue caused by a non-physiological activation, and 2) inadequate control. Here, we present the potential solution for slowing down the fast occurring muscle fatigue in applications requiring prolonged stimulation sequences (e.g., standing).

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The central nervous system controls the skeletal muscle force output by varying both, the number of activated motor units (recruitment) and firing rate (rate coding). Motor unit recruitment pattern in voluntary contractions is described by the Henneman's size principle. This means that motor units are activated progressively, from small and slow to large and fast. The rate of activation during voluntary contractions is low (f ≈ 5 Hz), yet the net effect of the asynchronous activity of many axons is a fused, smooth muscle force.

FES activates the motoneurons synchronously by sending bursts of charge pulses. A minimum frequency that will result in a fused muscle contraction of skeletal muscles varies between different muscles in the body. A smooth contraction of quadriceps can be generated at a minimum of 20 to 25 Hz [7]. However, stronger contraction can be reached only at higher frequencies; therefore, in many applications 35 to 50 Hz are selected. The consequence is that in FES muscle fatigue occurs more rapidly than during voluntary contractions [8, 9]. FES recruits motor units in a nonselective, spatially fixed, and temporally synchronous pattern [8, 10].

Several research studies addressed the muscle fatigue problem. In order to imitate natural patterns of recruitment and rate coding, it was proposed to stochastically modulate stimulation frequency, current amplitude or pulse duration [11 -13]. A promising idea was the doublet stimulation, based on the catch-like property of the muscles. If a doublet (two pulses separated by a very short interval) followed by a train of pulses is applied to a motoneuron, the result will be a much stronger contraction compared to that obtained by a train of pulses [14 -17].

The method that we tested differs from the listed suggestions. Namely, we hypothesized that the asynchronous low frequency activation of pads within a multi-pad electrode positioned over the human quadriceps muscle, resulting in a strong fused contraction comparable to the force elicited with a single large electrode activated at a higher frequency, would be less fatigable.

II. Materials and Methods

A. Subjects

The experiments included 6 individuals (age, 39 ± 17): 5 chronic paraplegics and one with incomplete tetraplegia (ASIA score A). Subjects had no voluntary movement in lower limbs. The exclusion criteria were orthopedic problems, recent contractures, epilepsy and bypass or any other implanted electrical stimulation devices. Four of six subjects did not use any medication against spasticity (Table 1).

Study subjects never received FES before this study.

TABLE I
DEMOGRAPHICS OF STUDY GROUP

Subject	Age	Injury	ASIA	Time	Spast.med.
1	56	T9/T10	A	9 m	yes
2	34	T11/T12	A	7 m	no
3	22	T7/T8	A	6 m	no
4	28	C6/C7	A	9 m	no
5	28	T11/L1	A	5 m	no
6	40	T11/T12	A	7m	yes

All subjects signed informed consent approved by the local ethics committee.

B. *Apparatus and setup*

Subjects were seated in the chair specially designed for the estimation of knee joint torque. Their torso was fixed to the backrest of the chair by a lumbar belt. Subjects' thigh was securely fixed to the custom made socket. The knee angle was fixed at 90 degrees. The knee joint torque was measured at the subjects' ankle strapped by the bracket that was coupled to the force transducer. Measurement apparatus was designed for both, left and right leg torque measurements (Fig. 1.).

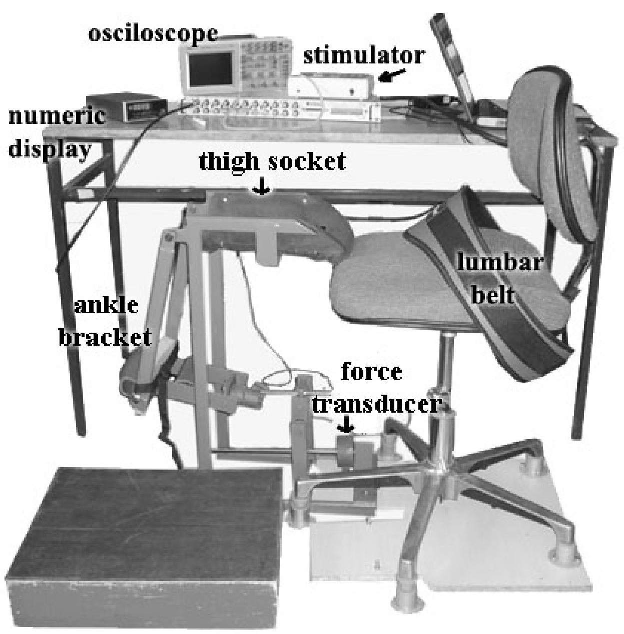

Fig. 1. Experimental setup.

Lebow 3397 force transducer was used for the isometric force/torque measurement. The isometric force data were acquired by A/D card PCI6062 and displayed on the oscilloscope screen for indication. Custom made real time program in Matlab (MathWorks R2006b) was created for determining turn-off time for the stimulation, when the torque drops below 70% of maximal value. For the electrical stimulation we used UNA-FET 4-channel stimulator with self adhesive Pals Platinum electrodes. The stimulator is current regulated, with a safety voltage limit of 150 V. If the voltage limit is not reached due to a high tissue impedance, the maximum current that can be delivered is 150 mA.

C. *Experimental protocol*

Two stimulation protocols were compared: stimulation via two Pals Platinum, 7 cm x 10 cm square electrodes positioned over the top of the quadriceps (cathode) and the anode positioned at the distal part of the quadriceps at 40 Hz (Fig.2, top panel), and four oval Pals Platinum electrodes, 4 cm x 6 cm (cathodes) distributed over the proximal upper leg and one anode (7 cm x 10 cm), at 16 Hz (Fig. 2, bottom panel). Using four cathodes in the second protocol was convenient because their size allowed us to cover most of the quadriceps muscle area in the subjects. It also allowed us to apply the stimulation of relatively low frequency (16 Hz) while still producing fused contraction. 16 Hz was chosen as minimal frequency that produced a smooth force on every subject in the experiment, though on some subjects frequencies as low as 12 Hz could have been used.

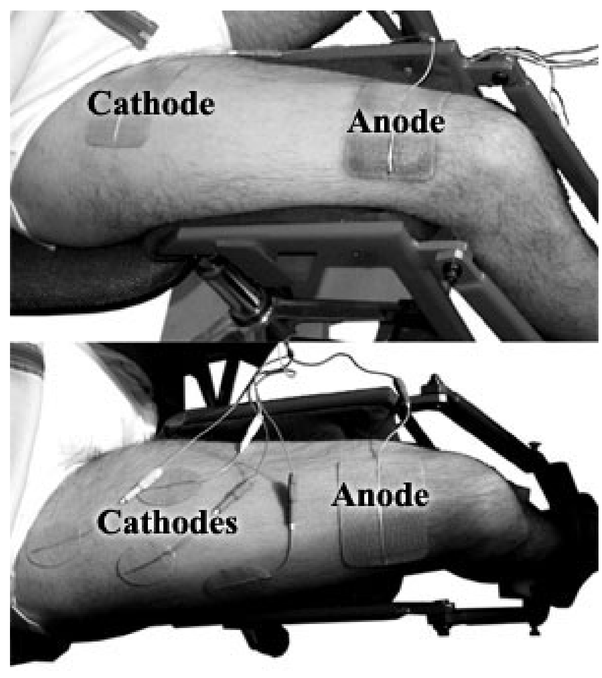

Fig. 2. Electrode positioning (top panel - setup 1, bottom panel – setup 2).

Both protocols consisted of two steps. In first step of protocol 1 we adjusted the intensity of stimulation (current amplitude) to produce maximum joint torque. In first step of protocol 2 we adjusted the intensity of stimulation to produce similar joint torque as in protocol 1. Second step was same for both protocols. It comprised three series of measurements of knee joint torque resulting from continuous electrical stimulation with two rests. The rests between the stimulations series were 5 minutes. We determined the

TABLE 2
FATIGUE INTERVALS

	Time duration (s), 1 cathode			Time duration (s), 4 cathodes		
Subject	1. measurement	2. measurement	3. measurement	1. measurement	2. measurement	3. measurement
1	15.677	9.110	13.641	30.978	26.098	30.533
2	17.095	16.981	13.477	35.551	27.206	34.825
3	7.373	17.063	13.137	31.524	48.479	36.745
4	11.919	8.021	10.919	17.058	22.947	11.422
5	10,896	9,052	8,324	38,074	34,968	27,420
6	4,289	3,787	3,477	26,624	19,256	19,748

interval between the start of stimulation and the instant when the joint torque declined bellow 70% of the maximum torque. In these measurements we applied current amplitude determined in the first step.

Time between two successive protocols was 24h, in order to allow muscles to recover.

We used biphasic stimulation pulses with exponential compensation, pulse duration of 500 µs and 15 and 7 pulses rise and fall for protocol 1 and protocol 2, respectively.

For protocol 2, stimulation was delivered through four asynchronous channels delayed by 25% of one channel stimulation period (Fig. 3).

Currents intensities were 88 ± 37 mA, with maximum current of 125 mA.

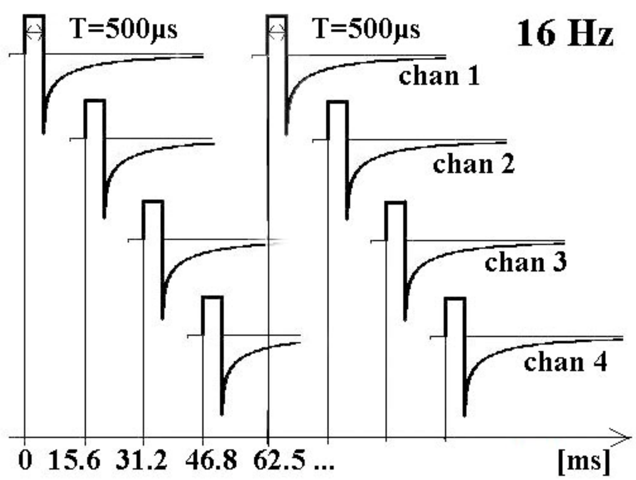

Fig. 3. Protocol 2 stimulation pulses.

III. RESULTS

Data from the torque measurement apparatus were collected for all six subjects. The parameters that we extracted from the recorded data were the maximal torque and time interval during which torque declined from 100% to 70%. The interval values are shown in Table 2.

Subject 6 produced very week and short contraction in protocol 1, while reaching 5-6 times larger values in protocol 2. Therefore, we will consider this case separately, and these results will be excluded from further analysis.

For five subjects (subjects 1-5) included in statistical analysis, the fatigue interval increase when using the protocol with four cathodes in comparison with the protocol with only one cathode was between 66.7% and 255.34%. Mean increase for all four subjects was 153.18%. It was calculated by averaging fatigue interval for all three measurements with one-cathode protocol and comparing the result with the average fatigue interval from the four-cathode protocol.

During measurements we tried to maintain the same maximal torques for both protocols by adjusting the current intensities. The experiments showed that this could be achieved by applying 30% lower current intensities in protocol 2 compared to protocol 1. Mean peak torque variation between the two protocols was less than 20%. There were noticeable intersubject differences in torques, varying between 5 and 30 Nm in protocol 1, and 5 and 40 Nm in protocol 2. For all three measurements, in both protocols, peak torque showed a declining trend. The trend line was comparable for both protocols.

Knee joint torques for subject 2, from the first measurements for both protocols are shown in Fig.4.

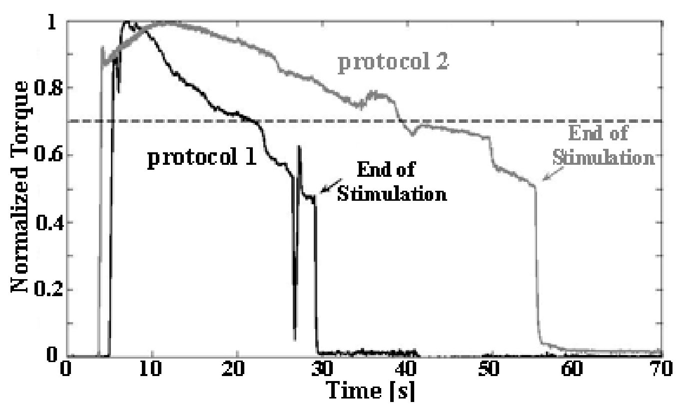

Fig. 4. Normalized knee joint torques for subject 2.

For each protocol torques are normalized with respect to their maximal values. This example shows more than 100% increase in fatigue resistance. Torque twitch in setup 1, around 27 s, is a result of a muscle spasm.

IV. DISCUSSION

We investigated muscle fatigue for paraplegic individuals during FES. Two stimulation protocols were compared: setup with one cathode and stimulation frequency of 40 Hz, and setup with four cathodes and stimulation frequency of 16

Hz. The second protocol proved to be more resistant to fatigue. For the same initial torque values, in protocol 2 large forces were maintained for longer time. The average fatigue interval prolongation was 153.18%.

Two of the subjects produced very low knee joint torques (around 5 Nm). This low torque is likely to be due to the muscle atrophy, or even partial muscle denervation. Another reason could have been that the increased tissue impedance prevented the current to be delivered to the motoneurons owing to the voltage limit of the stimulator applied in this study.

In the case of subject 6, very low values of torques and fatigue intervals were obtained in protocol 1. In protocol 2, these values increased their mean values from: 3 Nm to 10 Nm, and from 3.85s to 21.87 s. We assume that the reason for such a result could be wrong electrode positioning in protocol 1. Also, if the muscle is partly denervated, when using multiple cathode protocol the probability of stimulating some of the remaining operational motoneurons is much higher.

Commonly used stimulation frequency of 40 Hz was applied in protocol 1. We could have selected a lower frequency since fused contractions can be produced at about 25 to 30 Hz. This could have influenced the degree of difference between the results of the two protocols.

V. Conclusion

By lowering stimulation frequency we achieved a better resistance to muscle fatigue of paralyzed muscles. The overall muscle force is a result of summation of the forces produced by all stimulated muscle units. If different muscle units are stimulated asynchronously (in our case each cathode is delivering pulses with time delay of 25% of the stimulation period) the net results will be a fused contraction. The multiple-electrode stimulation was shown to be advantageous over two-electrode stimulation owing to electrode positioning.

In the experiments described we used four cathodes and set the stimulation frequency to 16 Hz. A further decrease of frequency (e.g., 5 to 8 Hz) could be considered with the application of textile multi-pad electrodes with more than four contacts.

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