

Doublet Stimulation to Reduce Fatigue in Electrically Stimulated Muscle During Controlled Leg Lifts

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Abstract—Stimulation trains using doublets, two closely spaced stimulation pulses, are thought to reduce the rapid fatigue seen in electrically stimulated muscle. The purpose of this study was to determine if doublet trains could elicit more leg lifts than conventional singlet trains when using surface stimulation of human quadriceps muscle. Eighteen subjects had singlet and doublet stimulation trains applied to their quadriceps to produce closed-loop, leg lift trajectory cycles. Trials ran until the muscle fatigued. Data was collected from 23 legs. The mean \pm standard deviation of the number of cycles resulting from singlets was 160 ± 105 while the number for doublets was 127 ± 114 . A paired t-test showed this difference to be significant. It is thought that the conflicting reports of doublet performance seen in the literature is due to the different protocols used by each study.

Keywords—Functional electrical stimulation, muscle fatigue, spinal cord injury

I. INTRODUCTION

Functional electrical stimulation (FES) is used to generate contractions in muscles paralyzed or weakened because of spinal cord injury (SCI) or other upper motor neural trauma or disease [1,2,3,4]. An important limitation of practical FES systems to restore grasp, standing or gait is that stimulated muscles exhibit premature fatigue. Several techniques have been used to ameliorate fatigue including exercising paralyzed muscle to convert fibers into slow fatiguing units [5], cyclic stimulation to reduce stimulation frequency [6] and special methods implemented in nerve cuff electrodes to block activation of fast fatiguing units [7].

A potential alternative method to reduce fatigue is patterned stimulation, that is stimulation with non uniform stimulation frequency. There are two rationales driving the use of patterned stimulation. The first is that stimulation with initial doublets or variable frequency more closely mimics how the central nervous system (CNS) activates muscles under voluntary control. The second is that patterned stimulation yields higher muscle forces than uniform stimulation [8] with the thought that the higher forces for equivalent stimulation amplitude can be used to alter fatigue.

Our lab is examining the use of doublet stimulation to affect fatigue of stimulated muscle. A doublet train consists of two closely spaced pulses emitted at a regular frequency, as contrasted with the conventional singlet train (Figure 1). As shown by Karu et. al. [8], doublet pulses can deliver muscle force twitches with a significantly higher torque-

time integral per pulse than singlet stimulation (Figure 3 in [8]).

Studies are inconclusive on whether doublets can indeed reduce fatigue in electrically stimulated human muscle when surface stimulation is used. Karu et. al. [8] showed that doublets led to significant improvement in the ability of stimulated muscle to track a constant force for an extended time when compared to singlets. However, Kebaetse et. al. [9] found that the number of leg lifts achieved by stimulation was the same for singlets and doublets. Bigland-Ritchie et. al. [10] stimulated isometric thenar muscles with conventional trains and trains that had an initial doublet. The trains with doublets resulted in slower rates of force decline. Using the same setup but a different stimulation protocol, Thomas et. al. [11] found that while trains with doublets increased muscle force, they had no impact on fatigue.

The study reported here had a similar purpose, to determine if there is any difference in the fatigue properties of human muscle when stimulated with singlet and doublet stimulation. The hypothesis was that doublet stimulation would result in more leg lifts than singlet stimulation when used in a closed loop, trajectory control system that gradually increased stimulus amplitude to accommodate for fatigue.

II. METHODS

A. Apparatus

Two by four inch, self-adhesive surface electrodes (RE-PLY model #658, UniPatch, www.uni-patch.com) were

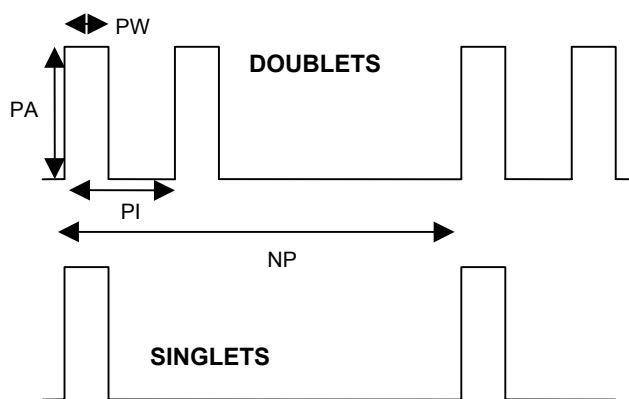


Fig. 1. Definition of doublet waveform parameters.

applied to the skin over the quadriceps. Stimulation was applied with a custom stimulator that delivered uni-polar, controlled current, square wave pulses with a fixed pulse width of 300 microseconds. Pulse amplitude could range from 0 to 120 mA and was manipulated by the closed loop controller. The PI for doublets was 5 ms, and the N-let period was 40 ms for both singlets and doublets (Figure 1). Note that with these settings, doublet trains had twice the number of pulses per time as singlets. The stimulator was controlled by a custom program running on a standard PC. Subjects were fixed in a leg bench with one leg strapped to a beam rotating about a joint that was aligned with the knee. The angle of the beam was measured with a potentiometer whose output was sampled at 25 Hz (the stimulation frequency) by the computer. Weights (All-Pro, model 400, www.allproweights.com), adjustable between 0 and 10 lbs were strapped to the ankle.

B. Trajectory controller

A closed loop, position control system was used to activate the leg. The controller was based on the adaptive neural net controller developed by Abbas [12,13]. The Abbas controller is ideal for cyclic stimulation applications. It contains a set of neurons, one per stimulus pulse delivered over the motion cycle. The output of each neuron is a raised cosine basis function that is shifted in time with respect to neighboring neurons. The output to the stimulator is the weighted sum of all the neurons. The weight of each neuron is adjusted based on tracking errors from the previous cycle. The controller is relatively simple, can adapt to a wide range of reference trajectories, and from our experiments, is always stable. For details on the controller, consult [12,13].

The knee angle reference trajectory for the controller was a raised cosine bell with period 4 s and amplitude of 65 deg with 0 deg defined when the leg was dangling down. The cycle was repeated every 6 s.

C. Subjects

Eighteen able-bodied subjects (12 male, 6 female, mean age 26 ± 6.9) participated. All subjects agreed to participate and signed a consent form approved by the University of Minnesota Institutional Review Board. Each leg was treated separately. Of the 36 total possible legs, 13 were excluded due to joint problems, poor tracking, unable to reach a minimum of 15 cycles, or took excessive time to fatigue. Data was collected from the remaining 23 legs (16 subjects).

D. Protocol

Subjects were positioned in the bench with the thigh anchored and shank fixed to the rotating beam. Active and reference stimulation electrodes were positioned over the quadriceps in roughly the locations specified in [1]. The

active electrode was precisely positioned over the motor point previously found by moving a small wand electrode over the muscle to find the point with the smallest visible stimulation threshold.

The stimulation amplitude was set in the following manner. With the 10 lb ankle weight attached, a continuous singlet train was applied. The stimulation amplitude was gradually raised while monitoring leg position. The goal was to reach 70 deg of extension (90 deg was straight out) with a stimulation amplitude that was tolerated by the subject. If the amplitude was not tolerable, weight was removed and another lift attempted. This was repeated until a liftable weight and tolerable amplitude were found. That weight was used for the trial, and the amplitude recorded as the subject's maximum amplitude. If the lift could not be achieved with the smallest weight of 1 lb, the leg was not used for the study.

A recruitment curve of leg angle versus stimulation amplitude was conducted with amplitude ranging from 0 to the subject's maximum. The curve was used to adjust the initial neuron weights for the trajectory controller. Prior to the recruitment curve and to each data trial, the subject was instructed in relaxation methods to minimize artifacts caused by voluntary contractions.

The cyclic leg lift trial followed immediately after these preparatory steps. The trial consisted of repeated leg lifts, one every 6 s with the network controller applying stimulation to force the leg angle to match the reference trajectory. As the muscle fatigued, the controller adjusted the stimulus amplitude upward to maintain trajectory tracking. The controller was prevented from raising the amplitude above the subject's maximum. A failed cycle was defined as one where the stimulus amplitude was saturated at its maximum for 25% of the reference cycle and the RMS tracking error of the cycle was greater than 25% of the RMS value of the reference trajectory. The trial was terminated after 3 consecutive failed cycles (indicating that the muscle was fatigued), and the number of cycles recorded as the dependent experiment variable.

A second trial using the opposite leg was then conducted, including the preparatory steps of finding the appropriate ankle weight and maximum stimulation amplitude. The subjects returned 3 to 7 days later for trials 3 and 4 with the opposite stimulation wave form. For one half the subjects, day one was right leg singlets followed by left leg doublets whereas day two was right leg doublets followed by left leg singlets. The remaining subjects did their trials in the reverse order.

III. RESULTS

Data from a typical trial is shown in Figure 2 where the left plots are the reference and measured knee angle trajectories, and the right plots the stimulation amplitude.

Row 1 is from cycle 10 and shows reasonable tracking and unsaturated stimulation amplitude of an unfatigued muscle

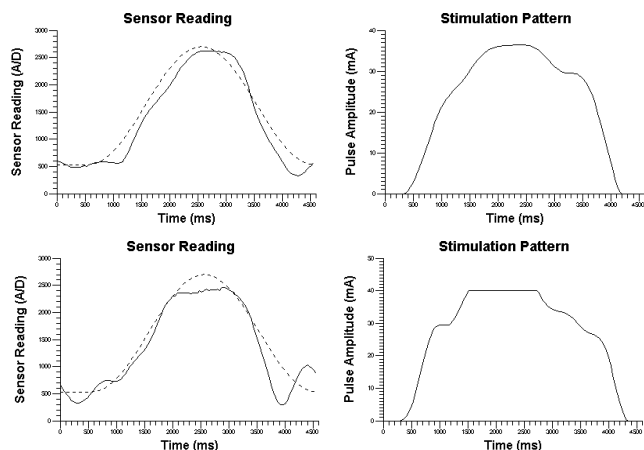


Fig. 2. Data from one trial. Top row is cycle 10, bottom is cycle 119

early in the trial. Row 2 is from cycle 119 and shows the stimulation amplitude at saturation and tracking that was not able to reach the peak of the reference trajectory. Because the tracking error was greater than 25% and the amplitude saturated for more than 1 s, the cycle was flagged as a failure. This trial terminated at cycle 120.

Fifteen of 23 legs had more cycles for singlets. Figure 3 shows the pooled results over all 23 legs for mean and standard deviation of the number of cycles achieved with singlets (160 ± 105) and doublets (127 ± 114). A paired, 2-tailed t-test showed this difference to be significant ($p = .03$). ANOVA showed no significant differences between number of cycles performed on the first experiment day compared to the second, but significant subject-to-subject differences in number of cycles.

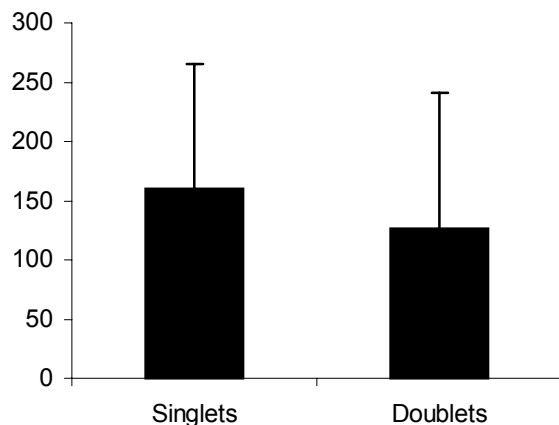


Fig. 3. Number of cycles pooled over all trials. Mean and std. dev.

IV. DISCUSSION

The results showed that for this protocol, stimulation trains containing doublets did worse on fatigue reduction for cyclic leg lifts when compared to conventional stimulation trains containing singlets. On average, singlets led to 33 more cycles than doublets, a difference of 26% of the doublet mean.

Karu et. al. [8] used continuous, isometric stimulation of the quadriceps with a closed loop controller that tracked force and different, optimized NPs for singlet and doublet trains. Kebaetse et. al. [9] used non-isometric, periodic stimulation of the quadriceps to perform knee extension with the stimulus amplitude fixed at a level that induced 20% of maximum voluntary muscle force. Bigland-Ritchie et. al. [10] used isometric stimulation of the thenar muscles with trains of 10 to 13 pulses repeated once every second. Stimulus amplitude was fixed at 20% above that which saturated the EMG response. Our study used a closed loop controller that modulated stimulus amplitude to produce regulated, cyclic leg extensions. Singlet and doublet trains had equal NP which meant there were more pulses per time in the doublet train, but at the same time, the doublet train required a lower stimulus amplitude to extend the knee. Others have used still different protocols. Because the various studies have come to different conclusions on the effectiveness of doublet trains, it is likely that any supposed advantage for doublet stimulation depends on the specific train pattern and the specific experiment protocol. For example, the Karu study had continuous stimulation whereas this study was cyclic which allowed the muscles to reperfuse between stimulus bouts. Perhaps doublets only have an advantage under mildly ischemic conditions.

One limitation of this study is that able-bodied subjects were used. Because FES is intended for those with SCI, the experiment should be repeated in paralyzed muscle. Karu et. al. [8] found approximately the same fatigue effects in paralyzed muscle compared to muscles under voluntary control. Thomas et. al. [11], however, found significant differences in the behavior of paralyzed muscle compared to muscles in non-injured control subjects. Extrapolation of results from able-bodied subjects to subjects with SCI is risky and we make no statements here on the applicability of our findings to practical FES for individuals with SCI.

Another limitation is that comparison trials took place with 3 to 7 days intervening. Although this guaranteed complete muscle recovery from fatigue, it did mean that there was no control over what happened to the muscle and that electrodes were in new locations. The closed loop controller decreases sensitivity to electrode location, but the

assumption must still be made that the same motor unit pool was recruited. An alternative protocol would be to conduct both trials on the same day with a 30 to 90 minute recovery period.

ACKNOWLEDGMENT

The authors wish to thank Andrew Sloan who developed most of the software and constructed the electronics for this study.

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APPENDIX

Number of cycles for all 23 legs, singlets and doublets.

Leg	Singlets	Doublets
1	104	76
2	117	82
3	86	67
4	381	540
5	387	225
6	108	142
7	75	88
8	184	71
9	64	78
10	198	82
11	47	56
12	109	120
13	100	16
14	85	75
15	144	109
16	177	83
17	200	129
18	161	170
19	193	93
20	229	142
21	86	77
22	34	35
23	407	355