EFFECTS OF STIMULUS PULSE DURATION ON COMFORT DURING CONTROLLED MOTOR CONTRACTIONS

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ABSTRACT

Previous work has established that pulse duration can affect comfort during functional electrical stimulation. This study expanded previous work by determining the most comfortable range of pulse duration between 12 and 800 microseconds (μs) on 12 normal females during stimulation of the quadriceps. In addition, tests were conducted which documented how much the stimulus amplitude could be increased and therefore how much greater torque could be generated using the most comfortable pulse duration before it was no longer more comfortable than other durations. This study was conducted using a microprocessor based stimulator which allowed stimulation parameters to be modified between pulses during a pulse train. Results from this study indicated that the most preferred pulse duration within the range tested is near 300 μs and the least preferred pulse duration is near 12 μs. The most preferred pulse duration could produce an average of at least 170% more torque when compared with the least preferred pulse duration.

INTRODUCTION

The potential of functional electrical stimulation (FES) as a therapeutic aid and as a functional assist in the field of rehabilitation has been firmly established. Weak muscles can be strengthened and strong muscles maintained through therapeutic programs. In addition, deficiencies in range of motion of a joint can be decreased or functional range maintained and voluntary control enhanced. Functional electrical stimulation can serve as an orthotic aid allowing ambulation which would be impossible without FES or can allow enhancement of functional use of the upper extremity.

Although transcutaneous FES is rapidly expanding throughout the world, a major limitation in its use is the unpleasant sensation that often accompanies it.(1-6) The impact of this limitation is twofold:

1. Some patients receiving benefit from FES are unable to tolerate stimulus amplitudes, treatment durations, or total time of functional use to as great an extent as is desirable because of discomfort. Many of these patients would be able to attain a higher functional level if electrical stimulation were more comfortable.

2. Some patients reject FES altogether or are unable to tolerate stimulus amplitudes, treatment durations, or total time of use to the extent of being beneficial at all. Many of these patients could receive significant benefit from FES if it were more comfortable.

BACKGROUND

A number of studies have attempted to determine parameters of stimulation that can reduce discomfort.(7-11) In 1965, Vodovnik (7) and in 1975, Gracanin and Trnkoczy (8) studied the effects of different tetanizing currents on comfort. A pulse duration of 300 µs was preferred over one of 1000 µs and regulated voltage pulses were preferred over regulated current pulses. Details as to methodology used to control the torque produced by the electrical stimulus and how preferences were made is not available.

More recently studies conducted by Bowman and Baker (9) verified that stimulation parameters can make a significant difference on comfort during torque-controlled muscular contractions. An average of 88% of 385 responses favored 300 µs pulses over 50 µs pulses at amplitudes necessary to produce 20 ft. lbs. torque about the knee regardless of whether capacitance coupled monophasic or symmetrical biphasic pulses were used or whether regulated current or regulated voltage pulses were used. In contrast, an average of only 7% of the responses favored the 50 µs pulses. Additionally, 76% of the responses favored symmetrical biphasic waveforms over capacitance coupled monophasic while only 12% favored the capacitance coupled monophasic waveform. No significant difference in preferences were recorded between regulated voltage and regulated current sources.

Another study (10) compared three commercial stimulator waveforms at equivalent torque levels about the knee. These included symmetrical 300 µs biphasic pulses, high voltage paired spikes, and 100 Hz sine wave modulated 4000 Hz sinusoidal voltage. Of nearly 100 responses for each pair of combinations, 88% favored the pulsatile over the high voltage spikes while only 4% favored high voltage spikes over the pulsatile. Over 82% of the responses favored pulsatile over modulated sine wave while 14% favored the modulated sine wave over pulsatile. Additionally, 64% of the responses favored the modulated sine wave over the high voltage spikes.

The most significant conclusion that can be drawn from these studies is that electrical stimulation parameters can affect comfort even when compared while carefully controlling amplitudes so that equivalent torques are generated. What is not known is what specific parameters of stimulation offer the <u>least</u> discomfort and how much of a difference parameters make in allowing subjects to tolerate strong contraction levels.

This study was conducted to look at the effects of pulse duration on comfort in more depth than previously reported and to document how much difference one pulse duration makes in terms of generating torque about the knee compared with other pulse durations at equivalent comfort levels.

METHODS

Computer Controlled Laboratory

Objective measures of relative comfort of various stimulation parameters in the generation of muscle force can only be made if all factors influencing sensation are controlled and only the stimulation parameters allowed to vary. A computer controlled laboratory was developed to provide an automated means of obtaining reliable, repeatable results much quicker than has been possible in the past.

Based on previous comfort comparison studies (9) symmetrical biphasic rectangular current-source pulses were used at a fixed pulse repetition rate of 30 pps. The pulse duration was varied (Figure 1) and the stimulus amplitude adjusted for each pulse duration used to produce 15% of the subject's maximum voluntary torque about the knee.

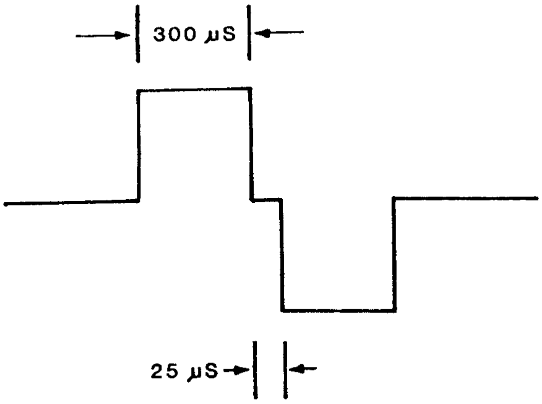


FIGURE 1. SYMETRICAL BIPHASIC WAVEFORM.

The above stimulus parameters were produced by a microprocessor based stimulator which was controlled by a DEC MINC-11/23 computer. The overall system developed is shown in Figure 2.

The DEC MINC-1i/23 computer was the host controller of the entire data collection and analysis procedure. In addition, it communicated with the microprocessor system in controlling the stimulation and in retrieving subject data. The MINC prompted the investigator in the running of the study and was able to detect error situations and take corrective measures to ensure subject safety and the correct operation of equipment.

The stimulator output current was directly proportional to a control voltage supplied by a 12 bit Digital to Analog Converter providing a bipolar resolution of 1 in 2048. The stimulator output waveforms were controlled by a programmable timer which generated variable duty cycle square waves with a resolution of one microsecond.

Due to the very large dynamic current range of the stimulator output stage required to cover pulse durations from 12 to 800 us, two independent output stages were designed. The short duration output stage covered 12-100 us with current capability of ±600 ma at ±300 v and a maximum pulse rise time of 3 μs. The long duration stage covered 101-800 μs with current capability of ±100 ma at ±150 v and a maximum pulse rise time of 10 μs. Either output stage could be selected between pulses under microprocessor control.

The subject was able to see 5 light emitting diodes indicating which relative set of parameters he/she was currently receiving and had 5 buttons with which to select the most comfortable and 5 buttons to select the least comfortable set of parameters following each run. The torque responses were sampled by a 12 bit Analog to Digital Converter and transferred to the MINC.

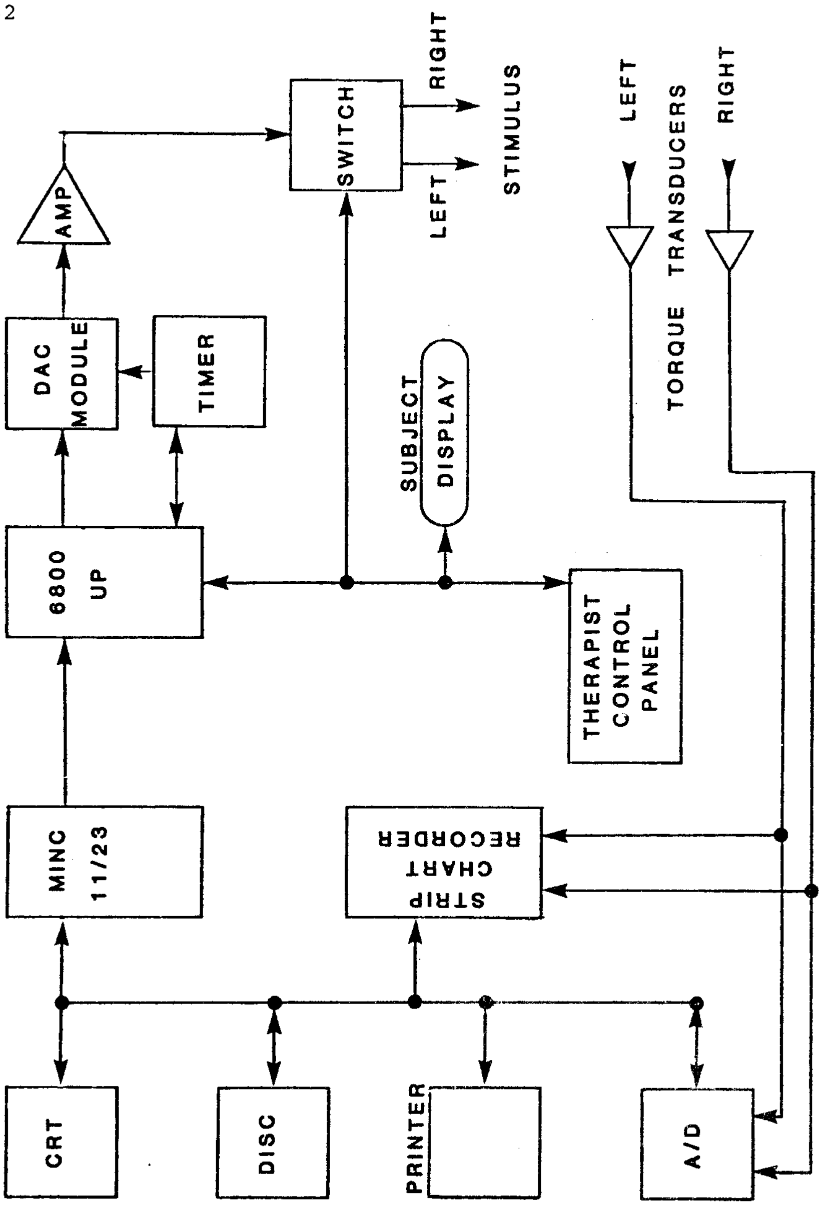


FIGURE 2. BLOCK DIAGRAM OF STIMULUS SYSTEM

Procedures

Twelve female subjects with no known orthopaedic problems of their right knee were included in this study. Four sessions each conducted on a separate day were used to establish a preferred comfort range for pulse durations 12-800 µs and assess how much greater torque could be generated using a pulse duration preferred over one which was not preferred. Females were chosen because of availability (USC School of Physical Therapy and Rancho Los Amigos Hospital Staff Therapists).

Session 1 -- Establishing Torque/Amplitude Curves

Subjects were seated and strapped at the hip in a testing chair with a movable back allowing the hip angle to be set to 120 degrees of flexion. The torque transducer arm was locked at an angle fixing the right knee at 60 degrees of flexion.

The subject was asked to perform three maximal knee extension efforts four seconds long with two minutes rest between efforts. The peak torque generated each effort was automatically sampled and stored in the computer. The torque equal to 15% of the subject's maximal voluntary torque (MVT) was displayed and stored as that subject's operating torque level. Fifteen percent of maximal voluntary torque was established on the basis of previous studies to be a level most subjects could easily tolerate during electrically stimulated contractions and at the same time is within the range of torque necessary during gait.

Motor points of the right quadriceps were located using the computer controlled stimulator set to a pulse repetition rate of 2 pulses per second, pulse duration of 300 µs and using symmetrical biphasic regulated current square waves. Two standard size 5 cm x 10 cm commercially available carbonized rubber electrodes were used with Spectra 360 conductive gel. One electrode was placed 5 cm proximal to the superior border of the right patella. The second electrode was moved over the anterior thigh until a location was found resulting in the greatest twitch torque at a constant stimulus amplitude. The proximal electrode was then fixed and the same procedure used to locate a distal position yielding the greatest torque. Electrode outlines were marked using indelible ink for relocating electrodes on subsequent testing days.

A series of approximately six two-second long runs each at a higher amplitude separated by 30 seconds rest was applied for each of the five pulse durations tested (12, 30, 100, 300, 800 µs) using amplitudes resulting in 10 to 20% of the subject's maximum voluntary torque. These series defined the current-torque relationship centered around the subject's operating torque (15% MVT) for each pulse duration.

Session 2 -- Identify Most and Least Comfortable Pulse Durations

Electrodes were relocated in the same position as marked the first session. A series of twelve six-second long runs were conducted with 1 minute separating runs. Each six-second run was divided into six, one-second segments of electrical stimulation. The first segment applied stimulation using a 100 us pulse duration (the middle of the range of pulse durations investigated) at the predetermined amplitude necessary to produce 15% MVT. The second through sixth segments applied either an increasing order of pulse durations (12, 30, 100, 300, 800 µs) or a reverse order.

Each segment amplitude automatically switched to the amplitude predetermined to yield 15% MVT at that pulse duration (Figure 3). Torque samples were automatically taken and stored in the computer just prior to each switch of pulse duration and amplitude.

During the series of runs, a "parameter indicator display board" was in view of the subject consisting of five lights lettered A-E. Following the first one-second stimulation period (used to develop 15% MVT prior to actual parameter comparisons) the lights lit sequentially at the start of each one-second stimulation period and thereby indicated to the subject that a different parameter was being applied. The subject was asked to identify which parameter A-E felt the most comfortable and which felt the least comfortable.

Stimulus amplitudes were adjusted following each run to minimize differences in torques during the six-second long contractions. The five runs showing the greatest consistency in torque produced throughout the six-second run (selected runs) were used for determining preference.

Sessions 3 and 4 — Assessment of How Much More Torque Can Be Produced When a Preferred Pulse Duration is Used Over a Less Preferred

A series of up to 20 comparisons was made between pairs of pulse durations representing the most comfortable and the least comfortable pulse duration from Session 2. In addition, if the least comfortable pulse duration was at one end of the spectrum of pulse durations tested, comparisons were also made with the opposite end of the spectrum. The order of the pairs was randomized and each pulse duration in the pair was applied for two seconds with one second rest between the pair of contractions and 45 seconds rest between pairs.

In each run, the amplitude of the least comfortable pulse duration was fixed at that which produced 15% MVT. The amplitude of the most comfortable pulse duration was also initially set to that which produced 15% MVT but with each subsequent run that amplitude was increased. Subjects were asked to either express a preference for one of the contractions in the pair or express no preference between one or the other. The series of runs was terminated when the least comfortable pulse duration became preferred (due to the increased amplitude of the most comfortable pulse duration) for three consecutive runs.

This data provided a measure of how much more torque could be produced by the optimum pulse duration before it was no longer preferred and indicated the relative importance of optimizing pulse duration.

RESULTS

Twelve females completed the four day testing protocol with one additional subject being discontinued after Session 2 secondary to an inability to tolerate stimulation producing 15% MVT. Data from two of the subjects who completed the testing protocol were not incorporated into the data analysis. One subject was unable to tolerate stimulation producing 15% MVT at a 800 us pulse duration during one testing session possibly due to a high impedance electrode which was not immediately noted. Data from another subject demonstrated a preference which was dependent upon the order of the stimulus pair regardless of the torque difference or pulse duration.

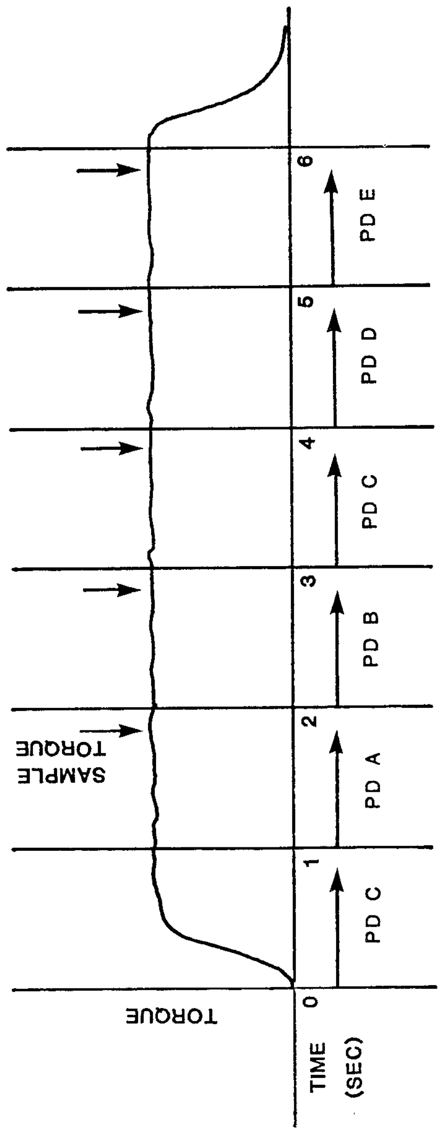

TORQUE
SAMPLE TORQUE
TIME (SEC)
0
1
2
3
4
5
6
PD C
PD A
PD B
PD C
PD D
PD E

FIGURE 3.

Session 1

The mean MVT achieved with the left leg of the ten remaining subjects was 108.6 ft-lbs. with a standard deviation of 32.2 ft-lbs. The range of torque was from 55.33 to 152.1 ft-lbs.

Strength-duration curves established from the operating levels determined the following average current necessary to produce 15% MVT: 12 μs -- 479 ma ($\pm$66 ma); 30 μs -- 196 ma ($\pm$24 ma); 100 μs -- 76 ma ($\pm$11 ma); 300 μs -- 38 ma ($\pm$7.6 ma); and 800 μs -- 29.4 ma ($\pm$6.0 ma).

Session 2

From the five runs with the least variance of torque, the ten subjects ranked their pulse duration preference resulting in fifty responses as to most and least preferred pulse duration. The longer pulse duration, 800 μs, was chosen as most preferred 19 times, 300 μs 14 times, 100 μs 11 times, 30 μs 5 times and 12 μs 1 time (Figure 4). Both ends of the spectrum were chosen as the least preferred pulse duration, however, the shortest pulse duration was chosen 66% and the longest duration 26% of the responses. Twelve μs was selected 33 times as least preferred, 30 μs 3 times, 100 μs 1 time, 300 μs 0 times, and 800 μs 13 times. Based on consideration of both the number of responses for most and least preferred, 300 μs would have to be considered the most desirable duration tested.

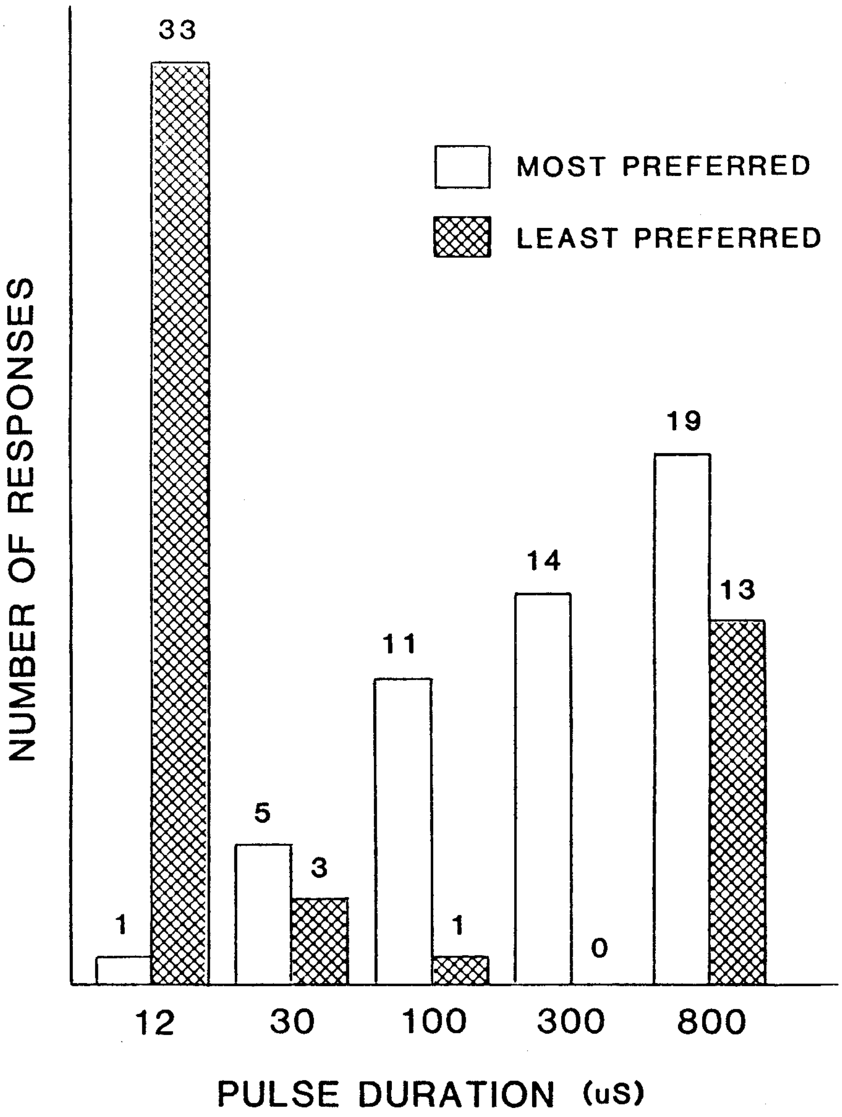
Sessions 3 and 4

A slight shift in preferred pulse duration was observed using the Day 3/4 protocol when compared to the Day 2 protocol. A 300 μs pulse was chosen as the most preferred pulse duration in 6 of the 10 subjects. For these subjects, 300 μs was also compared with 800 and 12 μs. All six subjects chose 12 μs as least preferred. Three subjects chose 800 μs as the most preferred pulse duration. For these subjects, 800 μs was compared with 300 μs and 12 μs. Only one subject chose 100 μs as the most preferred pulse duration. It was paired with itself and all other tested pulse durations.

An example of how torque differences between pulse durations were determined is shown in Figure 5. Runs were ranked in increasing order of torque differences between the preferred and nonpreferred pulse durations. Each run, the amplitude of the most preferred duration was increased. At the point where the first switch in preference occurred a "low" cut-off was established as being the minimum percent increase in torque obtained using the preferred duration before it was no longer preferred (see Figure 5). Further increases in amplitude typically resulted in inconsistent responses of pulse duration preference. At the point where responses became consistently in favor of the previously less preferred duration a "high" cut-off was established. The area between these two cut-offs was considered the "gray" area.

Comparing the most preferred pulse duration (300 μs) with the least preferred pulse duration (12 μs), an average of 211% greater torque (center of "gray" area) was tolerated when using 300 μs than when using 12 μs (Figure 5). When the preference was 800 μs, an average of 216% greater torque was tolerated when using 800 μs than when using 12 μs.

Comparing 300 μs to 800 μs, six subjects preferred 300 μs and



33
MOST PREFERRED
LEAST PREFERRED
NUMBER OF RESPONSES
19
14
13
11
5
3
1
1
0
12
30
100
300
800
PULSE DURATION (uS)

FIGURE 4

tolerated an average of 77% greater torque when using 300 µs. Three subjects preferred 800 µs when compared with 300 µs and tolerated an average of 26% greater torque when using 800 µs.

Increased Torque Obtained Using Initially Preferred Duration (%)	Pulse Duration Preference	
17	300 us	
19	300 us	
50	300 us	
109	300 us	LOW
185	12 us	
191	300 us	GRAY
289	300 us	
322	12 us	HIGH
345	12 us	
352	12 us	
355	12 us	
401	12 us	

Figure 5.

Subjective descriptions as to why one pulse duration was chosen over another varied slightly but general trends were noted. The most preferred pulse durations (300 µs or 800 µs) were generally described as "spread and more dispersed", "a deep strong contraction", and "a vibration". The less preferred (12 µs) was described as "a concentrated point source", "grabbing and pulling", and "burning, stinging and sharp".

This study demonstrates that a significantly greater amount of torque can be generated in the quadriceps when a 300 µs pulse duration is used when compared to short pulse durations. Those subjects preferring 300 µs to 800 µs were able to tolerate substantially greater torques than when using 800 µs. On the other hand, those subjects preferring 800 µs to 300 µs tolerated only minimally greater torques than when using 300 µs. Consequently it is concluded that overall, 300 µs was the preferred duration of those tested.

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ACKNOWLEDGEMENT

The authors would like to acknowledge the valuable input of Lucinda Baker, M.S., R.P.T. and the assistance of Susan Goldman, M.S., R.P.T. and Nora Kubota, M.S., R.P.T. in data collection and analysis. Appreciation is also given to the Physical Therapy Department, University of Southern California, for their support.

This study was supported by Grant No. G008200045, National Institute of Handicapped Research.