Effect of Electrode Size, Shape, and Placement During Electrical Stimulation

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ABSTRACT

Objective: The effect of electrode size, shape, and placement during electrical stimulation of the biceps, quadriceps, and tibialis anterior muscles were studied to assess what current is required during current-controlled electrical stimulation (ES_I) to reach a set muscle force, as well as to evaluate patient comfort.

Methods: The electrodes used were round, square, and square with a serrated edge (with similar surface areas of 25.8 cm^2); electrode sizes were 3.66 cm^2, 4.39 cm^2, and 5.08 cm^2. Electrodes were placed at distances from the motor point of 2 cm and 4 cm proximal, distal, medial, and lateral, using a 3.66-cm^2 pad. Associated subject comfort was recorded on a visual analogue pain scale (VAS) and assessed by heart rate, blood flow, galvanic skin resistance, and skin temperature.

Results: Significant increases were found in ES_I and VAS scores for placements away from the motor point, but there were no significant differences in ES_I and VAS scores among the electrode size and shapes. Specifically, there was a statistically significant increase in ES_I and/or pain values when the electrode was moved medially (VAS = 7.1/3.0) and laterally on the biceps (2 cm ES_I = 32.7/14.5; VAS = 7.4/3.0), and distally (2 cm ES_I = 50.6/14.1;VAS = 7.9/0.4:4 cm VAS = 8.8/0.9) and medially on the quadriceps (2 cm ES_I = 53.7/12.1), and distally (2 cm ES_I = 21.4/9.5) and laterally (4 cm ES_I = 7.9/3.8;VAS = 5.4/3.6) on the TA. Autonomic functions showed no significant correlations with current requirements or VAS scores.

Conclusions: These data support the importance of determining the actual motor point before placement of the stimulating electrode pad prior to the administration of ES, but refute the common concept that pad size and shape have any meaningful relationship to tolerance of ES.

INTRODUCTION

This study is one in a series of investigations examining the effect of various parameters that will improve the tolerance of electrical stimulation (ES).[1-5] Numerous publications cite the use of ES as a means of building and maintaining skeletal muscle strength as an adjunct to physical training for sports.[6-10] For example, Maffiuletti et al[10] found that after 4 weeks of training the quadriceps and plantar flexors in volleyball players there was a 20% increase in strength of the knee extensors and a

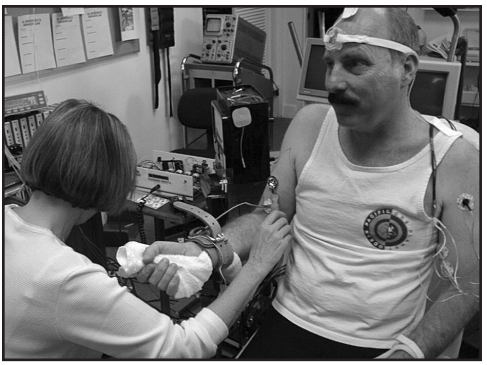

Figure 1. Testing for motor point (MP) location of the biceps brachii, after subject is positioned in the multipositional chair.

13% increase in strength of the plantar flexors, resulting in significantly higher vertical jumps in the ES-treated group. Yanagi et al[11] used ES to strengthen agonist–antagonist muscle pairs to stabilize joints.

ES can also be used for rehabilitation. For example, Delitto et al[12] and Snyder-Mackler et al[13] showed that ES was useful in strengthening thigh musculature after anterior cruciate ligament surgery. Vaes et al[14] used ES to stabilize the ankle during gait and exercise when there was weakness and laxness at the joint. Pengel et al[15] reviewed the use of ES in relieving back pain from athletic and work-related injuries.

ES can be especially useful for maintenance of muscle bulk after a spinal cord injury.[2,3,5,16] However, achieving the beneficial effects of ES is often limited because of the pain and discomfort many individuals experience during its application. While muscle is the target of ES, muscle lies below a layer of insulative fat; in addition, type III and IV sensory neurons are incidentally stimulated first during the application of ES, causing pain and discomfort.[17] Additionally, these neurons can trigger autonomic nervous system reactions to the pain, such as increased heart rate and sweating. There can be significant difficulties even in those who cannot directly feel the stimulation. When using ES in patients with spinal cord problems, those with lesions above T6 are susceptible to autonomic dysreflexia, which can be life threatening.[18-20] In addition, the insensate skin puts them at high risk of burns under the stimulating electrode.[2] Therefore, in order to prevent or minimize these complications, current must be kept as low as possible when applying ES.

Several factors are thought to affect the amount of current required during the delivery of ES, such as tissue impedance, pad placement, and shape and size of the electrode. Muscles are stimulated indirectly, that is, through their motor nerve. The motor nerve is most susceptible to stimulation at the point where it branches to enter the muscle, known as the motor point (MP). Therefore, the closer the electrode is to the MP, the less current it should take to stimulate the muscle through its nerve. Coincidentally, the MP has the greatest density of sodium channels and therefore the lowest impedance.[21] By moving an impedance probe over a muscle, the point where the motor nerve enters the muscle can be easily found. Electrical impedance measurement is rarely used as a way to find the MP. ES texts recommend finding the MP by searching in the general MP area with the active electrode until the strongest contraction is seen.[22,23]

The size and shape of the electrode is thought to affect comfort. Many choices of electrode types are available to increase patient comfort. Alon et al[24,25] contend that larger pads increase tolerance of ES, but large pads can cause unwanted stimulation of neighboring muscles or may not deliver enough current density to get the desired response. Few studies have been published on the effect of pad shape during the delivery of ES. Patients often state that they feel the most discomfort at the leading edge of the electrode. To date, no studies

Table 1. General Characteristics of Subjects

Subject	Gender	Skin Pigmentation	Age (years)	Weight (kg)	Height (cm)
1	M	Very Light	50	73.9	175.3
2	M	Med Dark	48	79.4	167.6
3	M	Med Light	42	93.4	177.8
4	F	Very Light	54	69.4	141.0
5	F	Very Dark	45	66.2	163.8
6	F	Very Light	35	70.3	170.8
		Mean	*46*	*75.4*	*166.1*
		SD	*7*	*9.9*	*13.3*

have examined the effect of variations in the shape of the leading edge of the pad in relation to the amount of current required (ES_I) to reach a set muscle force. This investigation was therefore performed to evaluate the effect of the aforementioned parameters in order to contribute to current knowledge and help increase tolerance of ES.

METHODS

The study subjects included 3 males and 3 females with a mean age of 46 years (± 7), mean height of 166.1 cm (± 13.3), and mean body mass of 75.4 kg (± 9.9). All subjects were within one standard deviation of their ideal body weight and had no known medical disability (Table 1). The university's Institutional Review Board approved all procedures and subjects signed a consent form.

Electrical Stimulation

Electrical stimulation was applied to the biceps brachii (biceps), quadriceps femoris (quads), and tibialis anterior via 2 carbonized rubber electrodes (Unipatch, Wabasha, Minn) using the Challenge CH8000A powered muscle stimulator (MPTS, Inc., Loma Linda, Calif) with a biphasic square wave of 300-millisecond duration followed by a 20-millisecond pause, with a frequency of 30 Hz. Amplitude of current was controlled in the ranges of 0–100 mA. Stimulus current was measured through a 10-Ω resistor in series with the electrode. Voltage drop across the resistor was measured on a Hewlett-Packard (Palo Alto, Calif) digital oscilloscope 7000 to calculate the current passing through the skin. Current was measured using Ohm's law (I = V/R). The current required to reach 10% of the muscles' strength, an amount deemed to be appropriately low to allow subject differentiation of pain thresholds, was determined from a preset value provided by a model 1971 Weston panel meter (St. Louis, Mo). Electrode sizes were 3.66 cm^2, 4.39 cm^2, and 5.08 cm^2; electrode shapes were square, round, and square with a serrated edge, with a similar surface area of 25.8 cm^2. Electrode placements were at 2 cm and 4 cm, proximal, distal, medial, and lateral from the MP, using the 3.66-cm^2 pad so that overflow stimulation was minimized. The distal pad was 5.08 cm^2 and held stationary at the musculotendinous junction, except on the biceps, where moving the proximal electrode distally caused overlap of the two pads. On the biceps the distal pad was moved medially to a point where no overlap would occur during the distal placement testing. After running an electrical impedance probe over the muscle belly to find its point of lowest impedance, the stimulating electrode was placed on the MP. The MP of the rectus femoris was used as the reference point for the quadriceps because it lies superficially and is most assessable.

Table 2. Current-Controlled Electrical Stimulation and Pain Values by Shape of Electrode*

	Electrode Shape					
	Round		Square		Serrated	
Current	Mean	SD	Mean	SD	Mean	SD
Biceps	30.5	19.5	24.1	16.3	31.7	16.0
Quad	51.4	27.6	48.5	23.4	49.4	25.7
TA	19.6	7.6	18.3	6.2	18.5	6.4
Pain	Mean	SD	Mean	SD	Mean	SD
Biceps	6.4	2.4	5.5	2.8	6.9	2.1
Quad	7.1	1.5	6.4	1.2	6.9	1.6
TA	3.0	2.5	3.2	2.7	2.5	2.1

Current controlled electrical stimulation (ES1) units are milliamperes (mA).
*No values of P≤0.05.

Measurement of Strength
Isolation of the line of force for each muscle was achieved through the use of a custom-designed multipositional chair with attached motor drives, which allowed precise positioning of each extremity (Figure 1). Joints proximal and distal to the stimulated muscle were held dependent at 90˚, with the distal joint (ankle or wrist) held stationary using a leather strap attached in line with an isometric strain gauge device, which consisted of 4 strain gauges arranged in a Wheatstone bridge configuration. Force produced by an isometric contraction of the muscle was measured using an isometric strain gauge device. Its ratio of force to bending of the bar was 100 kg:5/10^6 of an inch. Output was amplified using a Biopac strain gauge amplifier with a gain of. An A-D converter (Biopac Systems, Inc. Santa Barbara, Calif) digitized the electric signal with a 16-bit resolution at 200 samples per second.

Measurement of Pain
A visual analogue scale (VAS) consisting of a 10-cm line was used to measure the subject's discomfort after each 20-second contraction. Subjects were instructed to place a mark on the line that represented their perception of discomfort, with the right end of the line representing no discomfort and the left end representing intolerable pain.

Measurement of Autonomic Parameters
Skin temperature was measured on the forehead and opposite extremity using a thermister probe suspended in a Plexiglas cylinder (4-cm diameter x 1 cm high, with four 1.2-cm diameter x 0.5-cm-high circular feet and a 1-cm wide strap) so that it barely touched the skin, allowed good airflow, and caused no circulatory occlusion. Changes in electrical resistance from the thermister were transduced to an electrical output through a Biopac electrical thermister amplifier using a gain of 5000**.** Blood flow and heart rate were measured using a photoelectric plethysmogram transducer. A Biopac DC amplifier, with a gain of 10 amplified the output. Galvanic skin resistance was measured using an Ag/AgCl electrode (Biopac finger electrode transducer TSD103A), which was attached to the middle finger of the left hand. A neutral electrode gel was placed between the electrode and skin. A Biopac electrodermal activity amplifier, with a gain of 10, amplified the output. All electrical signals were digitized in an A/D converter, with a 16-bit resolution, at 200 samples per second. Data were managed with the AcKnowledge 4.0 computer program, displayed on a 20-inch monitor, and stored on disk for later analysis.

Table 3. Current Controlled Electrical Stimulation and Pain Values by Size of Electrode*

	Electrode Size					
	2 inch		3 inch		4 inch	
Current	Mean	SD	Mean	SD	Mean	SD
Biceps	24.3	14.6	25.3	11.0	24.1	16.3
Quad	37.8	7.4	51.8	22.4	48.5	23.4
TA	17.0	6.0	18.0	5.8	18.3	6.2
Pain	Mean	SD	Mean	SD	Mean	SD
Biceps	6.3	1.7	6.4	2.3	5.5	2.8
Quad	6.1	1.6	6.7	1.1	6.4	1.2
TA	2.7	2.0	2.4	2.0	3.2	2.7

Current controlled electrical stimulation (ES1) units are milliamperes (mA).
*No values of P≤0.05.

Procedures

Anthropometric measures were obtained and recorded. Subjects were seated in a specifically designed motorized chair; joints proximal and distal to the muscle being stimulated were positioned at 90º in relation to each other. For the quadriceps femoris muscle, the hip and knees were positioned at 90˚ to each other, a motorized cuff support was positioned under the knee to allow for full thigh contact, and the ankle was secured with a leather cuff attached in line with a force transducer. The foot was allowed to hang free. The procedure for testing the tibialis anterior was similar, with the exception that the foot was supported at 90˚ to the leg. For the biceps brachii, the shoulder and elbow were positioned at 90˚ to each other, the wrist was secured with a leather cuff attached in line with a force transducer, and the hand was allowed to hang free. Prior to ES, excessive hair on the overlying skin was shaved and the skin was wiped with alcohol to clean it of oil and dirt. The subjects were shown how to mark the visual analogue scale (VAS) to indicate their level of pain. During the set-up, subjects acclimated to the room temperature for 20 minutes before the beginning of ES. Room temperature during the experimental days ranged from 21.7˚ to 25˚ C. Subjects were asked to perform two maximal muscle contractions of 2-second duration, with a 1-minute rest between contractions. The mean of the two contractions was used to calculate 10% maximal voluntary contraction (10% MVC) for that muscle. This force was used as a compromise for two reasons. First, for clinical use and pain management, this force and current are higher than that normally used. In contrast, for sports training it is less. Therefore, the current used was a compromise between the two extremes. Second, if high-power stimulation were to have been used, it would be hard to tell on a visual analog scale, exact levels of pain due to saturation of the sensory nerves with stimulation. At lower stimulation levels the level of pain is easier to grade because the sensory nerves can fire over a wider range of response.

This force was then set on the panel meter and was used to determine the amount of current needed to produce 10% MVC. The MP of the target muscle was found using an electrical impedance device and marked using a felt marker. The 2-cm and 4-cm placement points were measured and marked with the same pen. The ES electrode pads were positioned, with one pad over the MP and one near the musculotendinous insertion (MTI). The devices to measure autonomic reactions were positioned thus: thermister probes were applied over the contralateral muscle and on the forehead; electrodermal finger electrodes were placed on the left ring fin-

ger; and a plethysmogram was placed on the left middle finger. The electrical stimulator was set to a biphasic square wave of 300-millilsecond duration, followed by a 20-millisecond pause, with a frequency of 30 Hz. Subjects were given two trials with the electrical stimulator to acclimate them to the procedure. They were instructed to keep the stimulated muscle relaxed and to allow the stimulation to cause the contraction. Each muscle was stimulated in a random order of shapes, sizes, and placements, using computer-generated data collection sheets as a guide. Each parameter was collected twice. Muscles were given a 1-minute rest between runs, during which the subjects were asked to rate their pain on the VAS. Their previous VAS ratings were kept from view to prevent bias. Devices were removed from subjects between muscle protocols and they were instructed to move about.

Data Analysis

Means and standard deviations were analyzed using repeated measures ANOVA with the Bonferroni adjustment for multiple comparisons. The level of significance used in all statistical tests was $P<0.05$. Data were analyzed using the SPSS 10.0 statistical package.[26]

RESULTS

Subjects completed all the testing sequences with the following exceptions. One subject, who had good tolerance of ES to the biceps and tibialis anterior, could not tolerate ES to the quadriceps. This was the last muscle to be stimulated and the testing was stopped. Two subjects experienced activation of the fibularis longus and fibularis brevis when the stimulating electrode was moved 4 cm laterally on the tibialis anterior. When this occurred, stimulation was stopped and no data were recorded.

Tables 2 and 3 list the means and standard deviations for current and VAS pain values for pad shapes and sizes when placed on the MP. Size and shape of the electrode did not significantly change ES_I or VAS pain values in any of the three muscles. As muscle size increased, greater ES_I was required to reach 10% MVC. It is interesting to note that pain scores did not increase in the same proportions. In tests of pad shape (Table 2), lowest values for ES_I were recorded for the tibialis anterior (18.3 mA to 19.6 mA), moderate ES_I for the biceps (24.1 mA to 31.7mA), and highest ES_I values were recorded for the quadriceps (48.5 mA to 51.4 mA). Mean VAS scores were also lowest for the tibialis anterior (2.5 to 3.0), whereas the biceps and quadriceps had similar ranges (5.5 to 6.9 and 6.4 to 7.1, respectively). In tests of pad size, a similar trend was seen (Table 3), with the tibialis anterior requiring the least ES_I (17.0 mA to 18.3mA); biceps requiring moderate ES_I (24.1 mA to 25.3 mA); and quadriceps requiring the most ES_I (37.8 mA to 51.8 mA). Mean pain scores for the tibialis anterior were again low (2.4 to 3.2), but were high for both the biceps (5.5 to 6.4) and quadriceps (6.1 to 6.7).

Lowest mean ES_I and VAS pain scores were found at the MP, with only two exceptions: 2 cm proximately and medially on the tibialis anterior. Significantly higher values were found when moving laterally and medially on the biceps, distally and medially on the quadriceps, and distally and laterally on the tibialis anterior (Table 4).

Autonomic parameters for contralateral electromyelogram (EMG), skin temperature on forehead and contralateral muscle, galvanic skin resistance, heart rate, and blood flow showed no specific pattern of correlation with VAS scores.

DISCUSSION

In the present investigation, placement of the electrode off the MP during the

Table 4. Means and Standard Deviations for Electrode Placement*

			2 cm							
	MP		Proximal		Medical		Distal		Lateral	
Current	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Biceps	24.3	14.6	28.1	13.3	28.7	13.3	26.8	14.4	32.7	14.5
Quad	37.8	7.4	44.7	9.7	53.7	12.1	50.6	14.1	48.8	10.0
TA	17.0	6.0	16.7	6.7	15.7	5.6	21.4	9.5	21.7	6.7
Pain	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Biceps	6.3	1.7	7.3	2.7	7.1	3.0	6.8	3.1	7.4	3.0
Quad	6.1	1.6	5.8	1.4	7.5	0.5	7.9	0.4	6.3	1.0
TA	2.7	2.0	2.8	2.3	4.0	2.7	3.6	2.8	4.3	2.9

*TA: tibialis anterior.

application of ES caused an increase in the amount of current required to achieve a set muscle force, with concurrent increases in subject discomfort. Our results are not consistent among the muscles in terms of which direction off the MP caused statistically significant increases, but trends were noted. Moving proximally, away from the MP, caused no significant increase in ES_I or VAS scores for any of the muscles tested. However, moving in the distal direction closed the distance between the electrodes, and subjects immediately commented on the increased pain on the quadriceps. The interelectrode distance affects the depth and density of current flow between the electrodes,[27] with shorter distances between the pads causing the current to flow more superficially, with increased density.[5] This superficial, dense flow of current may activate the cutaneous nerve fibers and account for increased pain. The limited length of the biceps did not allow us to move the proximal electrode very far distally because the electrodes would have overlapped; therefore, we moved the distal electrode medially during that data collection. The tibialis anterior has a long tendon of insertion, which allowed us to place the distal pad at a distance from the muscle belly.

Moving medially and laterally from the MP did not cause a consistent trend. Moving 2 cm medially on the quadriceps caused significantly increased ES_I values, but moving 4 cm medially on the biceps caused increased pain, and subjects had to be cautioned to hold their arm away from their body to prevent the stimulation from jumping onto the chest wall. Moving medially on the tibialis anterior caused the pad to be off the muscle belly and onto the bone for 2 subjects because of their thinner body types. This proved to be quite painful, yet surprisingly, there was no statistical difference in pain scores. Moving laterally caused significant ES_I increases in the biceps (at 2 cm) and tibialis anterior (at 4 cm), which may be due to added contraction of muscle groups in that direction.

While no statistical differences were found in either ES_I or VAS for pad size, other studies have shown increased subject tolerance using very large pads.[24,25] Electrodes of very large size are rarely used in a clinical setting due to overflow of ES to other muscle groups. The pads we chose to compare were sizes typically used in a rehabilitation clinic and are readily available (Uni-patch Inc., Wabasha, MN). They differed in size from each other by only about 50%, which may account for a lack of statistical difference due to pad size. Changing the shape of the pad or pad edge did not alter perceptions of pain.

One possible explanation for the lack of significant reductions in pain with larger electrode sizes may be the current flow under the electrode itself.

4 cm							
Proximal		Medical		Distal		Lateral	
Mean	SD	Mean	SD	Mean	SD	Mean	SD
28.5	10.6	28.0	5.7	27.3	11.8	31.0	11.7
45.6	15.4	55.9	18.1	65.7	28.0	47.3	14.0
18.5	5.8	17.8	11.2	24.6	13.9	27.9	3.8
Mean	SD	Mean	SD	Mean	SD	Mean	SD
7.5	1.9	7.8	1.3	7.9	2.0	7.6	2.6
7.3	0.6	8.0	1.1	8.8	0.9	7.3	1.7
4.8	2.8	6.1	2.6	3.5	3.7	5.4	3.6

Current flow does not move uniformly across 2 electrodes. In fact, the current density is higher in the middle than the edges, and current flows in arcs called Maxwell lines.[28] Thus a small change in electrode size may not cause enough difference to shift currents in a meaningful way.

Another possibility is that the newer carbon electrodes do not apply uniform current into the skin. With older metal electrodes, current was uniform across the contact area. But carbonized rubber has an electrical resistance of its own and may not provide appreciable current differences with size away from the center, where the leadwire enters the electrode.

In summary, results from this study reinforce the fact that the stimulating electrode should be carefully placed directly over the muscles' MP before application of ES. Additionally, small differences in size and shape of clinically available electrodes do not appear to affect patient tolerance of ES. These findings can be added to numerous other studies that looked for ES delivery parameters that will minimize discomfort and increase patient tolerance of ES in the clinic.[1,8,12,24,25,29-33]

This previous body of knowledge reveals several telling comments. Alon, while advocating the use of larger electrode pads for non-painful excitation, nevertheless states that during muscle reeducation painful ES may be needed to obtain adequate muscle torque.[24] Selkowitz[8] advocates that in order to strengthen skeletal muscle using ES, the relative increase "may be determined by the ability of the subject to tolerate longer and more forceful contractions." Lieber and Kelly [32] suggest that "NMES efficacy is primarily determined by the intrinsic tissue properties of the individual and is not dramatically changeable by using high stimulation currents or large electrode sizes."

Information gained from ES parameter studies such as the present one can likely be used to establish guidelines for the use of ES in the clinical setting, sports medicine, clinical, and exercise training.

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