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Effect of Electrode Size, Shape, and Placement on Electrical Current and Subject Comfort During Electrical Stimulation

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Effect of Electrode Size, Shape, and Placement on

Electrical Current and Subject Comfort During Electrical Stimulation

by

Bonnie J. Forrester

A Publishable Paper in Lieu of a Thesis in Partial
Fulfillment of the Requirements for the
Degree Doctor of Physical Therapy Science

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Each person whose signature appears below certifies that this publishable paper in his/her opinion is adequate, in scope and quality, as a publishable paper in lieu of a thesis for the degree Doctor of Physical Therapy Science.

_____

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Abstract

Effect of Electrode Size, Shape, and Placement on Electrical Current and Subject

Comfort During Electrical Stimulation.

Bonnie J. Forrester

Six healthy subjects were studied to determine the optimal size, shape and placement of

stimulating electrodes during the application of electrical stimulation (ES) to the biceps,

quadriceps, and tibialis anterior muscles. Subjects were recruited to allow for diversity in

age, sex, and skin pigmentation. Subjects sat in a custom designed multi-positional chair,

which allowed precise positioning of each extremity. After determining the maximal

voluntary contraction (MVC) of the muscle and careful determination of the motor point,

ES, with a biphasic square wave of 300 ms duration and a frequency of 30 Hz, was used

to bring the muscle to 10% MVC. Subject tolerance to ES was recorded using a visual

analogue pain scale (VAS) and autonomic measures of heart rate, blood flow, galvanic

skin resistance, and skin temperature. The electrical current required (ES_I) and VAS pain

scores were analyzed using a repeated measure ANOVA. Autonomic measures were

correlated with VAS pain scores using Pearson's correlation coefficients. The analysis

revealed significant increases in ES_I and VAS scores for placements away from the motor

point, but no significant differences in ES_I and VAS scores with electrode size and shape.

Specifically, there was a significant increase in ES_I and or pain values when the electrode

was moved medially and laterally on the biceps, distally and medially on the quadriceps,

and distally and laterally on the TA. Autonomic functions showed no significant

correlations with current requirements or VAS scores. This data supports the importance

of determining the motor point before placing the stimulating electrode pad for the

administration of ES.

Electrical stimulation (ES) is used as an adjunct in rehabilitation therapy for direct or indirect strengthening of skeletal muscle (Petrofsky 1991a, 1992; Petrofsky et al. 2001, 2002, Selkowitz 1985), selective muscle retraining (Laughman et al.1982; Currier and Mann 1983), motor learning (Carmick 1997), spasticity reduction (Carmick 1997; Seib et al.1994, Robinson et al. 1988, Alfieri 1982), and minimizing immobilization muscle atrophy (Delitto et al.1988; Draper and Ballard 1991; Snyder-Mackler et al. 1994). Patients, who do not have diminished sensation, frequently have difficulty tolerating the discomfort associated with ES, especially with the amount of current required to achieve a muscle contraction strong enough for strength training. Tolerance is highly associated with the individual's coping style and perceived control over the event and may be linked to both the sensory stimulation and motor contractions (Delitto et al.1992).

Autonomic nervous system (ANS) reactions to pain may impact the effectiveness of ES. Patients often sweat and experience an increased heart rate during electrically stimulated muscular contractions. ANS reactions can be life threatening when using ES to increase strength and reduce spasticity in patients who have a spinal cord injury. Patients with neurological lesions of the spinal cord above T6 are susceptible to autonomic dysreflexia when type II and IV neurons are incidentally stimulated (Ashley et al. 1993, Matthews et al. 1997). In addition, these patients typically have insensate skin, which puts them at high risk of burns under the stimulating electrode (Petrofsky 1991a). Therefore, therapists must keep the current as low as possible when applying ES, in order to minimize or prevent these complications. One factor that has been implicated in determining the effectiveness of stimulation is tissue impedance.

High tissue impedance translates to high voltages needed to drive current into skeletal muscle. But it is not muscle that is key. Muscles are stimulated indirectly, that is through their motor point, by ES. Therefore, the closer the electrode is to the motor point, the less current it takes to stimulate the muscle through its nerve. Coincidentally, the motor point has the greatest density of sodium channels and therefore the lowest impedance (Reichel et al. 2002). By moving an impedance probe over a muscle, the point where the motor nerve enters the muscle can be easily found. Electrical impedance units, however, are rarely used in the clinic for finding the MP. Clinicians have the option of using anatomical motor point charts or searching for the MP with the active electrode. MP charts show typical areas where motor points are found on superficial muscles, but the exact points can vary with the individual. Texts on the use of ES (Hayes 1993, Nelson and Currier 1991) recommend finding the MP by searching in the general motor point area with the active electrode until there is a strong contraction. Some clinicians find the MP by putting the active electrode on their finger, then touching around the muscle to look for the strongest response. Empirically, ES is deemed to be most effective and tolerable when the active electrode is placed directly over the MP. If the pad is placed incorrectly, patient comfort will be compromised and the benefits of ES not achieved.

Electrode size is another important consideration. Alon et al. (1985, 1994) studied the effect of electrode size on subject tolerance of ES. From their selection of pad sizes, they found that a 4.5 x 4.5 cm pad was most tolerated on the gastrocnemius (1994), while a 9 x 9 cm pad gave highest tolerance on the quadriceps (1985). The larger the pads, the lower the current density, and hence, less pain. While large electrodes are

perceived as being more comfortable by the patient, they can cause unwanted stimulation of neighboring muscles or may not deliver enough current density to get the desired response. The size of the quadriceps in an adult may merit use of a large electrode, but when selective control of smaller muscles or direct stimulation of a denervated muscle is desired, a smaller pad size is required. For example, when applying ES to the closely spaced muscles of the forearm, use of smaller electrodes and careful placement is required to avoid unwanted contractions in neighboring muscles (Reed 1997). Children's muscles have smaller surface areas, which require smaller pads. As a guideline for the pediatric population, Carmick (1997) advises that a child's muscle should be large enough for use of an active electrode that is no smaller than one inch, in order to avoid pain and overflow to nearby muscles. Smaller electrode pads may also be needed for direct contraction of denervated muscle, in order to provide denser current delivery.

Limited studies have been published on the effect of pad shape during the delivery of ES. Alon (1985) found no difference in force production or subject tolerance when comparing square and rectangular electrodes of the same surface area. Square and rectangular electrodes have a straight leading edge, which only varies in length depending on the orientation of the pad. Patients often state they feel the most discomfort at the leading edge of the electrode (personal communication). No studies have examined pad shape, with variations in the leading edge, in relation to the amount of current required (ES_I) to reach a set muscle force.

This study was conducted to look at the effect of electrode size, shape, and placement on the amount of ES_I and pain perceived during an electrically induced contraction of the biceps brachii (biceps), quadriceps femoris (quadriceps), and tibialis

anterior (TA). Level of electrically induced force was 10% of the muscles maximal voluntary contraction (MVC). While some studies have looked at pad size, the sizes were much larger than electrodes typically used in therapy. Therefore, this study used standard, off the shelf, electrodes commercially available to the therapist. Additionally, VAS pain scores and autonomic reactions to the ES were recorded and analyzed for indications of subject tolerance.

METHODS

Subjects

Three males and three 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), were recruited. Subjects skin pigmentation ranged from very light to very dark. All subjects were within one standard deviation of their ideal body weight and had no known medical disability. Skin pigmentation ranged from very light to very dark. (See Table 1 for anthropometric values). All subjects were told of the purpose, procedure, and risks of the experiments and that they could stop the procedure at any time. Subjects signed an informed consent form approved by the LLU Review Board. Subjects were assigned an identification number, which was recorded on their data collection sheet.

Measurement of strength

Strength was measured using the following devices. Isolation of the line of force for each muscle was achieved through the use of a custom designed multi-positional chair with attached motor drives, which allowed precise positioning of each subject's 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 four strain gauges arranged in a Wheatstone bridge. Force produced by an isometric contraction of the muscle was measured using an isometric strain gauge device with a ratio of force to bending of the bar of: 100 kg of force bends the steel bar $5/10^{6}$ of an inch. Output was amplified using a Biopac strain gauge amplifier with a gain of 5000. An A-D converter digitized the electric signal with a 16 bit resolution at 200 samples per second.

Electrical stimulation

Electrical stimulation was applied using the Challenge CH8000A, powered muscle stimulator, (MPTS, Inc.) with a biphasic square wave of 300 ms duration and a frequency of 30 Hz. Amplitude of current was controlled in the ranges of 0-100 milliamps. Stimulus current was measured through a 10 Ohm resistor in series with the electrode. Voltage drop across the resistor was measured on a Hewlett Packard digital oscilloscope to calculate the current going through the skin. Current was measured using Ohms law (F=V/R). During each experiment the current required to reach 10% MVC was determined by reading that preset value off the panel meter.

Carbon rubberized electrodes (Unipatch, part #625) were used for the stimulating and collecting pads. Stimulating electrode sizes were 13.4, 19.4 and 25.8 cm^{2}; shapes were square, round, and square with a serrated edge, with a similar surface area of 25.8 cm^{2}; and placements were at 2 and 4 cm, proximal, distal, medial, and lateral from the MP, using the 13.4 cm^{2} stimulating pad. The collecting pad was 25.8 cm^{2} and held stationary at the musculotendinous junction, except on the biceps where moving the stimulating electrode distally caused overlap of the two pads. On the biceps the

collecting 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.

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 s 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.

Autonomic parameters

EMG was measured using a Biopac EMG amplifier with a gain of 5000, bandwidth DC to 500 Hz and digitized through an A-D converter with a 16-bit resolution at 200 samples per second. Electrodes were 0.5 cm^2 carbonized, hydrogel electrolite pads (5500 Q-Trace Gold, Model #30807732, Graphics Controls Corp., Buffalo, N.Y.). 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 a

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 of the electrical signals were digitized in an A/D converter, with a 16 bit resolution, at 200 samples per second. Data was managed with the AcKnowledge 4.0 computer program, displayed on a 20 inch monitor, and stored on disc for later analysis.

Procedures

Subjects were seated in a specifically designed motorized chair with the joints proximal and distal to the muscle being stimulated positioned at 90°. For the quadriceps femoris muscle, the hip and knees were positioned at 90°, 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. Procedure for testing the tibialis anterior was similar, with the exception that the foot was supported at 90°. For the biceps brachii, the shoulder and elbow were positioned at 90°, the wrist was secured with a leather cuff attached in line with a force transducer, and the hand was allowed to hang free. If there was excessive hair on the overlying skin, it was shaved. 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 min before the beginning of ES. Room temperature during the experimental days ranged from $21.7-25^o$ C. Subjects were asked to perform two maximal muscle contractions of 2 s durations, with a 1 min 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 then set on a Weston panel meter 1971 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 and 4 cm placements 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. The devices to measure autonomic reactions were positioned: EMG pads were placed on the contralateral muscle; thermister probes were applied over the contralateral muscle and on the forehead; electrodermal finger electrodes were placed on the left ring finger; and a plethysmogram was placed on the left middle finger. The electrical stimulator was set to a biphasic square wave of 300 μs duration with a frequency of 30 Hz. Subjects were given two trials with the electrical stimulator to acclimate them to the procedure. Subjects 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 min rest between runs, during which the subjects were asked to rate their pain on the VAS. Their previous VAS ratings were keep from view to prevent bias. Devices were removed from the subject between muscle protocols and they were instructed to move about.

Data analysis

ES$_I$ values recorded by the investigator, pain ratings from subject VAS scores, autonomic nervous system data retrieved from the Acknowledge 4.0 software, and manually recorded anthropometrical measures were entered into the SPSS statistical

package (SPSS 1966) for statistical analysis. ES_I and pain values were compared for differences among the shapes placed on the MP, the sizes placed on the MP and for differences in placement values from the MP using repeated measures ANOVA with the Bonferroni adjustment for multiple comparisons. ANS values for skin temperature (forehead & opposite extremity), galvanic skin resistance, heart rate and blood flow were collected from the Acknowledge 4.0 program at the following time frames: baseline, beginning (1s), 10s and 20s. EMG changes in the contralateral muscle were additionally collected at 5s and 15s intervals. Calculating the mean change from their baseline value and converting to a percentage [value – baseline value)/baseline value] normalized ANS values. The mean of the two runs per trial were calculated. VAS scores were normalized by calculating their difference from the value at the MP. Means and standard deviations (SD) were calculated for the group for each of these variables. A Pearson correlation coefficient was calculated between mean normalized VAS scores at each placement and the ANS normalized values at beginning and 20s time frames. The level of significance used in all statistical tests was $\alpha=0.05$.

RESULTS

Subjects completed all the testing sequences with the following exceptions. One subject, who had good tolerance of ES to the biceps and TA, 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 brevis (peroneals) when the stimulating electrode was moved 4 cm lateral from the motor point (MP) of the tibialis anterior (TA). When this occurred, stimulation was stopped and no data was 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 in any of the three muscles, and corresponding VAS pain values were not significantly different from each other. As muscle size increased greater ES_I was required to reach 10% MVC. Interestingly, pain scores did not increase in the same proportions. When testing pad shape (Table 2), lowest values for ES_I were required for the TA (18.3 to 19.6 mA), moderate ES_I for the biceps (24.1 to 31.7mA), and highest ES_I values were required for the quadriceps (48.5 to 51.4 mA). Mean VAS scores were lowest for the TA (2.5 to 3.0) whereas the biceps and quadriceps had similar ranges (5.5 to 6.9and 6.4 to 7.1 respectively). When testing pad size, a similar trend was seen (Table 3), with the TA requiring the least ES_I (17.0 to 18.3mA); biceps requiring moderate ES_I (24.1 to 25.3 mA); and quadriceps requiring the most ES_I (37.8 to 51.8 mA). Mean pain scores for the TA were low (2.4 to 3.2), but were large 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. 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 TA. Electrode placement in several directions showed significantly larger ES_I and VAS pain scores concurrently (Table 4). Specific analysis by muscle reveals the following:

Biceps. Mean ES_I of 24 ±14.6 mA on the MP elicited 10% MVC, with the largest increases occurring laterally; 33 ±14 mA at 2 cm and 31 ±11 mA at 4 cm. A significant increase was found at the 2 cm location (p=.00). The meanVAS pain score was 6.3 ±1.7 at the MP, with a significant increase to 7.8 ±1.3 mA occurring at 4 cm medially

(p=.005). There were no significant differences at proximal or distal distances in ES_I or VAS ratings.

Quadriceps. Mean ES_I of 38 ±8 mA elicited 10% MVC on the MP, with significant increases occurring 2 cm medially 54 ±10 mA (p=.03) and 2 cm distally 51 ±11) mA (p=.03). There were no significant differences when moving proximally and laterally. VAS pain scores averaged 6.1 ±1.6 at the MP, with significant increase to 7.9 ±0.4 at 2 cm distally (p=.03) and 8.8 ±0.9 at 4 cm distally (p=.046).

Tibialis Anterior. Mean ES_I of 17 ±6 mA elicited 10% MVC on the MP, with significant increases occurring 4 cm laterally 28 ±4 mA (p=.003) and 2 cm distally 21 ±9 mA (p=.006). There were no significant differences when moving proximally and medially. Mean VAS pain scores were 2.7 ±2 at the MP, with a significant increase to 5.4 ±3.6 4 cm laterally (p=.04).

Autonomic reaction values for contralateral 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

The effect of electrode size, shape, and placement on achieving a set force in three muscles was examined in six subjects. The main result found in this study is that placement of the electrode pad off of the MP during the application of ES can cause an increase in the amount of current required to achieve a set muscle force, with concurrent increases in subject discomfort.

Electrode placement was studied due to the contention of experienced clinicians that not enough care is taken clinically to find the actual MP (personal communications).

Results from this study support the contention that sloppy placement of the electrode pad can cause increased ES_I and pain during the application of ES. In terms of which direction off the MP causes the most difficulty, our results are not consistent among the three muscles, but there is a trend. Moving proximally, away from the MP caused no significant increase in ES_I or VAS scores for any of the muscles tested. All of the muscles tested have a longitudinal muscle fiber arrangement. Brooks et al. (1990) contend that muscle tissue is more conductive in the longitudinal direction of their fibers than in the transverse direction. This may account for our finding of no significant effect when moving off the MP in a proximal direction.

This longitudinal effect did not hold true when moving the electrode distally because moving in this direction closed the distance between the electrodes. Subjects immediately commented on the painful effect. The interelectrode distance affects the depth and density of current flow between the electrodes. When placed close together current will flow superficially with increased density; while placing them farther apart allows deeper current flow, but diminishes the current density in the intervening tissues (Nelson and Currier 1991). Perhaps this superficial, dense flow of current activates more cutaneous nerve fibers. This effect was statistically significant on the TA (2 cm distal) and quadriceps (2 and 4 cm distal), but not on the biceps. The limited length of the biceps did not allow us to move the stimulating pad very far distally because the electrodes would have overlapped; therefore, we moved the collecting pad medially during that data collection. Most likely this is the reason there is no statistically significant pain scores in this direction on the biceps. On the quadriceps, we placed the collecting pad above the patella, near the musculotendinous junction. Closing the

interelectrode distance on the quadriceps consistently caused significant ES_I and VAS pain score increases. The TA has a long tendon of insertion, which allowed us to place the collecting pad at a distance from the muscle belly, but closing the interelectrode distance still caused a significant ES_I and VAS pain score increases in this direction.

Significantly more current was required when moving the pad transversely across the muscle (i.e., laterally on the biceps and TA and medially on the quadriceps). Moving the pad laterally on the biceps (2 cm) took it away from the motor nerve, which enters the biceps superiomedially. Moving laterally (4cm) from the MP of the TA caused excitement of the peroneals and we stopped the experiment on two of the subjects due to full contraction of these muscles.

Subjects scored the lowest mean VAS pain values when the electrode was placed on the MP. Nearly all placements away from the MP caused a mean increase in pain values, but significance was not found at all locations. Moving the pad proximally caused no significant increases in VAS scores. Again, the lack of effect when moving proximally may be due to longitudinal muscle fiber arrangement or it may be due to the entry orientation of the motor nerve. The motor nerve enters the biceps, quadriceps, and TA from a proximal to distal direction, therefore, when moving the pad proximally it may maintain a close relationship with the nerve, keeping ES_I and painful values nearly the same as those found at the MP. As discussed previously, moving distally closed the interelectrode space, which gave a significantly more painful effect.

Moving transversely caused significant pain on the biceps and TA. When moving medially on the biceps, subjects had to be cautioned to hold their arm away from their body to prevent the stimulation from jumping over onto the chest wall. The risk of this

effect may have contributed to their perception of pain. Moving medially on the TA caused the pad to be off the muscle belly and onto the bone for two subjects, due to their thinner body type. This proved to be quite painful, yet surprisingly, this direction showed no statistical difference in pain from values recorded on the MP. Moving laterally caused significant pain increases in the TA, which may be due to the added contraction of the peroneals.

Longitudinal versus transverse placement of the electrode may make a difference in ES_I. Brooks et al. (1990) found that a longitudinal orientation of rectangular electrodes produced significantly more torque than a transverse orientation (using a bipolar pad placement), and speculates that longitudinal placement enhances conductivity along the longitudinal bias of the muscle fibers. In our study, the pad was consistently applied transverse to the muscle fibers because this placement allowed the connecting wires to be directly in line with the ES machine. Also, during the placement series, square pads were used, which most likely minimized pad conductivity bias.

Significant pain increases did not always correlate with significant ES_I increases (Figure 2). Significant pain increases were reported at 4 cm medially on the biceps and 4 cm distally on the quadriceps without concurrent ES_I increases. Significant pain increases mirrored significant ES_I increases in two locations, 2 cm distal on the quadriceps and 4 cm lateral on the TA. Cutaneous nerve distribution may account for these patterns of pain.

Anatomical texts (Rohen et al. 2002, Moore 2000) show typical cutaneous nerve innervation patterns. On the biceps, sensory nerve branching from larger nerve trunks comes in medially. Moving the electrode 4 cm medially on the biceps placed the ES

closer to this branching pattern. Cutaneous sensory innervation of the TA arrives from a proximal-lateral direction, which is the direction of increased pain (4 cm lateral) on this muscle. Sensory nerve fibers that innervate the quadriceps arrive at the MP from a proximal-medial direction, which is well superior to the medial area off the MP. Significant pain increases were not found in this area. While there is no specific representation of increased branching or cutaneous sensory nerve density in these locations, further studies may find density differences.

While no statistical differences were found in either ES_I or pain values for pad size, other studies, using larger pad sizes, have shown that pad size does affect subject tolerance of ES. In one aspect of their studies, Alon et al. (1985, 1994) compared the effect of electrode size and shape on the strongest motor nerve excitation level that could be tolerated by the subjects. Within their parameters, they found certain pad size optimizations for two muscles. In their 1985 study, they found the largest electrodes, each with a surface area of 81 cm^2, gave highest tolerance on the quadriceps while their third largest pad size, a 4.5 x 4.5 pad, was most tolerated on the gastrocnemius in their 1994 study. These are both large, antigravity, postural muscles that can accommodate a large pad size. Electrodes of this size are rarely used in the clinic.

The pads we chose to compare were sizes typically used in a rehabilitation clinic. They are readily available and can be conveniently cut to smaller sizes (Unipatch catalogue). Also, the pads were tested on muscles of varying size and we did not want to overcome the boundaries of these muscles. The pads did not differ in size from each other by a large amount. Using pads of 13.4, 19.4 and 25.8 cm^2 they differed step-wise by approximately 50%. This may account for a lack of statistical difference due to pad

size, along with our small subject number and large variability of results. In Alon's 1985 study, their smallest pad size was 9 cm^2, which was compared with pads that were approximately 200 to 400% larger. In 1994 his smallest pad was 2.25 cm^2 and sizes increased by 100, 200 and 300%. In the earlier study the larger size pads (81 cm^2) were most comfortable for the quadriceps, but in the later study the third largest size (20.25 cm^2) proved most comfortable on the gastrocnemius. Muscle size most likely accounts for differences in optimization of pad size. The goal is to balance pad and muscle size so that current density is sufficient to cause an isometric contraction of the muscle with tolerable pain levels.

Patients state they feel pain and discomfort along the leading edge of the pad (personal communications). In this study, changing the shape of the pad edge did not alter perceptions of pain. In regards to pad shape, Alon (1985) tested square versus rectangular shaped pads, each with a total surface area of 81 cm^2, and found no significant difference in subject tolerance. They reached their stimulators' maximal electrical output, which they speculate limited the results for the rectangular electrode. In terms of leading edge, these pads most likely differed only in the length of their straight edge.

Typical electrode shapes available for use in the clinic are square, rectangular and oval (Unipatch catalogue). Larger electrodes and non-typical pad shapes are available at higher cost, but are not typically used for ES in the clinic. Results from this study support the use of readily available electrode pads, in that small differences in electrode size and shape, when carefully placed on the muscles motor point, do not make a significant difference in the amount of ES$_I$ to reach a set force.

Lastly, in this study an impedance device was used to locate the site of lowest electrical impedance, which is known to be over the nerve's motor endpoints. Impedance devices are not commonly used in the clinic. As discussed in the introduction, utilizing MP charts or using the active electrode to look for strongest contraction sites are both imprecise methods for locating the MP. Using an impedance device to find the specific motor point on an individual muscle is a precise, non-painful method of increasing patient comfort during the application of ES.

In summary, results from this study indicate the stimulating electrode should be placed directly over the muscles MP before the application of ES. Additionally, small differences in size and shape of clinically available electrodes do not appear to make significant differences in patient tolerance of ES. These findings can be added to numerous other studies looking for ES delivery parameters that will minimize discomfort and increase patient tolerance of ES in the clinic (Baker et al. 1988, Laufer et al. 2001, Bennie et al. 2002, Delitto and Rose 1986, Alon et al. 1985, 1994, Carmick 1997, Nolan 1991, Brooks et al. 1990, Lieber and Kelly 1991, Selkowitz 1985). This previous body of knowledge reveals several telling comments. Alon (1985), while advocating the use of larger electrode pads for non-painful excitation, never the less states that during muscle reeducation, painful ES may be needed to obtain adequate muscle torque. Selkowitz (1985) 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 (1991) suggest "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".

Likely, information gained from ES parameter studies can be used to establish guidelines in the clinic, but it may ultimately come down to the individual and how much discomfort they can accommodate in order to achieve the perceived benefits of ES.

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Appendix I

Figures and Tables

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

Figure 2. Surface area tracings of the biceps brachii, quadriceps femoris and tibialis anterior, respectively, with locations of significant increases (p ≤ 0.05) in electrical stimulation intensity (E) and pain scores (P). **X** = motor point (MP). • = 2 & 4 cm locations. Not drawn to scale.

Proximal

Lateral

Medial

Distal
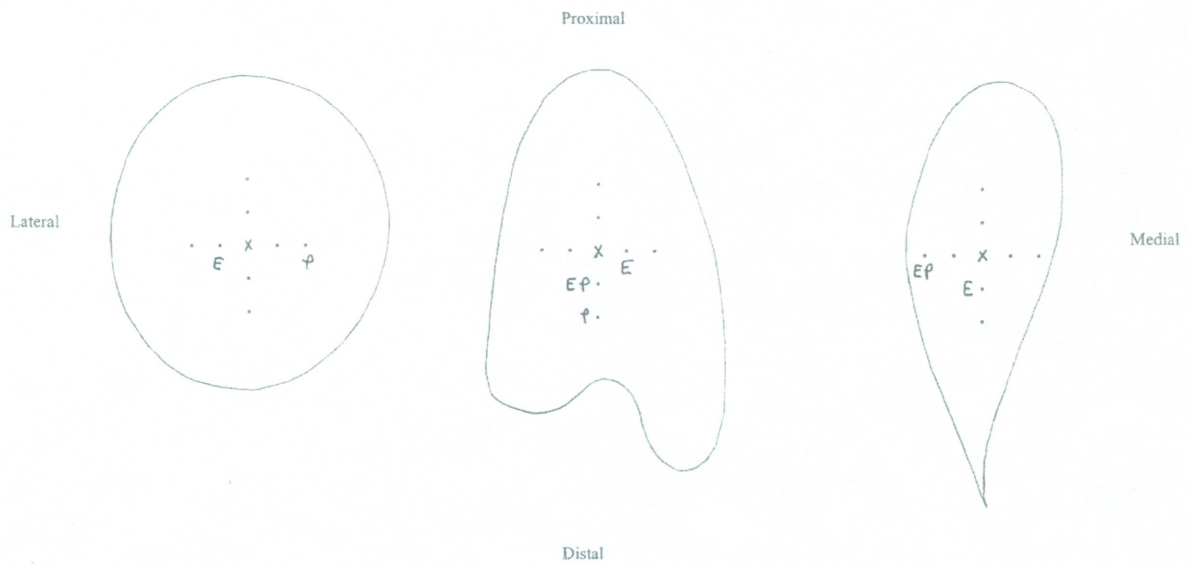
Table 1. General characteristics of the subjects.

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*

Table 2. ES_I (mA) and pain (VAS) values by shape.*

	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

*No values of $p \leq 0.05$.

Table 3. ES_I (mA) and pain (VAS) values by size.*

	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

*No values of $p \leq 0.05$.

Table 4. ES_I (mA) and pain (VAS) values by placement.*

	MP		2 cm Proximal		2 cm Medial		2 cm Distal		2 cm Lateral		4 cm Proximal		4 cm Medial		4 cm Distal		4 cm Lateral	
Current	Mean	SD	Mean	SD	Mean	SD	Mean	SD	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	p32.7	14.5	28.5	10.6	28.0	5.7	27.3	11.8	31.0	11.7
Quad	37.8	7.4	44.7	9.7	p53.7	12.1	p50.6	14.1	48.8	10.0	45.6	15.4	55.9	18.1	65.7	28.0	47.3	14.0
TA	17.0	6.0	16.7	6.7	15.7	5.6	p21.4	9.5	21.7	6.7	18.5	5.8	17.8	11.2	24.6	13.9	p27.9	3.8
Pain	Mean	SD	Mean	SD	Mean	SD	Mean	SD	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	p7.4	3.0	7.5	1.9	7.8	1.3	7.9	2.0	7.6	2.6
Quad	6.1	1.6	5.8	1.4	7.5	0.5	p7.9	0.4	6.3	1.0	7.3	0.6	8.0	1.1	p8.8	0.9	7.3	1.7
TA	2.7	2.0	2.8	2.3	4.0	2.7	3.6	2.8	4.3	2.9	4.8	2.8	6.1	2.6	3.5	3.7	p5.4	3.6

* p = significance of 0.05 or smaller.

Appendix II

Literature Review

Electrical Stimulation: Description, Clinical Uses, and Parameters of Application.

Electrical stimulation (ES) uses an electrical current to induce action potentials in peripheral nerves and skeletal muscles. It is used in biological systems, such as man, to stimulate muscle contraction through alpha motor neurons or to block the transmission of nociceptive input through sensory neurons (Nelson and Currier 1991). This is usually accomplished by stimulating action potentials in peripheral nerves through electrodes placed on the skin and is technically called transcutaneous electrical stimulation. Axons in peripheral nerves respond to the excitatory input of ES depending on their diameter and function (Alon 1985). Excitation of large sensory neurons causes a sensation of tingling and is called sensory stimulation. Excitation of large motor neurons causes either twitch or tetanic muscle contractions and is known as motor stimulation. If the smaller sensory neurons are stimulated, pain is perceived (Burke 1975).

Since motor nerves are more reactive to ES, they respond to stimulation well before the muscle, itself. Stimulation of these motor nerves causes them to develop action potentials, which travel to the muscle and cause contraction of their motor units. This is the order of occurrence in an intact system. To obtain isometric or isotonic skeletal muscle contractions, stimulation must occur at a rate high enough to achieve tetany. Stimulation at less than 10 pulses per second (pps) causes the muscle cells to twitch asynchronously, but, at 35-50 pps, the muscle cells display tetany and recruitment of muscle fibers increases rapidly thereafter.

ES does not follow the natural order of motor unit recruitment. Voluntary contractions have asynchronous recruitment patterns, which limit metabolic demand and minimize fatigue of the muscle; ES causes synchronous motor unit recruitment, causing a marked metabolic demand and rapid muscle fatigue (Adams and Harris 1993). Smaller motor units and those with slow-twitch oxidative fibers (type I) have the lowest threshold for voluntary activation. Increasingly forceful contractions are achieved by recruitment of progressively larger motor units and those with fast-twitch glycolytic fibers (type II) (Hayes 1993). ES recruits motor units in the reverse order as progressively more current is given in order to achieve the desired muscle contraction force (Nelson and Currier 1991). This contributes to the fatiguing effect of ES, which must be compensated for by increasing the on/off ratio of delivery. Additionally, surface ES is thought to activate only relatively superficial portions of the muscle, but using MRI mapping of ES, researchers found individual differences in the depth of stimulus penetration in various portions of the quadriceps (Adams and Harris 1993).

ES of peripheral nerves also stimulates 1st order sensory neurons. Again, ES does not replicate the natural activation patterns of the sensory receptors. Tapping sensations are felt at less than 10 pps which increase to a tingling feeling at pps greater than 35. This feeling spreads in the area between the electrodes and into deeper tissues. When the smaller diameter (type IV) nociceptors are activated, it is perceived as pain and can limit tolerance of ES procedures.

Clinical Application of ES

Electrical stimulation (ES) has many useful clinical applications. Of interest in this review is its use as an adjunct in rehabilitation therapy for strengthening of skeletal

muscle, delaying development of disuse atrophy, selective muscle retraining, motor learning, spasticity reduction, and wound healing.

Strengthening.   Several investigators have studied the ability of ES to strengthen healthy quadriceps muscles by comparing non-exercised control groups with groups performing voluntary isometric contractions, ES only isometric contractions or ES assisted voluntary contractions (Currier and Mann 1983, Laughman et al. 1983, McMiken et al.1983, Selkowitz 1985).   They found all three-exercise protocols could achieve a significant change in quadriceps muscle strength, when compared to non-exercising control groups.   Selkowitz (1985) argues that the quadriceps is easy to strengthen and increases in isometric strength using only ES most likely depends on the ability of the subjects to tolerate longer and more forceful contractions.   Additionally, Laughman (83) confirms a cross education effect in the contralateral, non-exercised quadriceps, which he speculates is due to a central motor learning enhancement of the maximal level of motor unit recruitment, even in contralateral muscles that are not directly exercised.

When using ES to strengthen skeletal muscle, complete activation of motor units is not always possible. Belanger and McComas (1981) found complete motor unit activation was possible using ES to the tibialis anterior, but could not activate all the motor units of the gastrocnemius. This may make a difference in the strengthening effects that can be achieved in certain muscles.

Additionally, there may be a difference between males and females in achieving increased skeletal muscle strength with ES. Alon et al. (1999) found that plantar flexion force elicited by ES was significantly lower in females than in males and speculates that females may require longer conditioning periods to achieve therapeutic levels of muscle

contraction. Laufer et al. (2001) found means of maximally tolerated ES induced contractions were smaller in women than in men, but conceded their subjects showed great variability. These results suggest that the ability of ES to generate muscle contraction forces may be sex dependent. Various biological and socio-psychological differences between the sexes have been offered to explain this effect (Alon et al. 1999, Jensen et al. 1994, Laufer et al. 2001), but further research is needed to substantiate these findings.

Clinicians have found ES highly effective when strengthening the quadriceps after surgical interventions about the knee. By necessity, surgery to a joint requires the limb to be immobilized for a period of time, while it heals. Disuse atrophy sets in quickly, but can be slowed with the use of ES. Gould et al. (1982) used ES to exercise normal healthy muscles immobilized in a cast for two weeks and found 50% less muscle atrophy than in both a non-exercised control group and an isometric exercise group. Delitto et al. (1988) found ES induced isometric co-contractions of the quadriceps and hamstrings following posterior cruciate ligament surgery produce greater isometric strength gains than a voluntary exercise program. Draper and Ballard (1991) found that both an ES/voluntary isometric contraction (VIC) protocol and a biofeedback/VIC protocol are effective following anterior cruciate ligament repair. When comparing high-intensity ES, low-intensity ES, and battery-powered stimulators, Snyder-Mackler et al. (1994) found high-intensity ES produces the greatest increase in quadriceps force production during the early post-surgical days following anterior cruciate ligament repairs. These studies agree that ES protocols produce minimal joint stress and are a safe means of strengthening during early recovery from these surgeries.

Denervated muscles have lost input from their peripheral nerve. These muscles experience Wallerian degeneration, which causes the muscle to experience a significant amount of fiber loss. Clinically, a muscle is considered denervated when needle EMG recordings show fibrillation potentials and, in addition, do not respond to ES delivered at 30 Hz (Petrofsky 1991a). Denervated muscle is less excitable and requires ES directly in order to achieve a strengthening contraction. Investigators have been testing for optimal stimulation parameters for direct stimulation of denervated muscle. Kosman, et al. (1947) used a biphasic waveform with frequencies of 5 to 25 Hz and were able to produce strong contractions with little discomfort. Petrofsky (1991) found a biphasic sine wave with a 25 milliseconds pulse width applied with a frequency of 10 Hz reduced longstanding atrophy in the quadriceps of paraplegics with an L1 injury.

Patients with a significant amount of atrophic muscle mass, such as those with spinal cord injury (SCI), are at risk of developing serious health problems, including cardiovascular deconditioning, renal failure, pressure sores, and bone fractures. This atrophy can be minimized through use of an ES facilitated exercise program. A well-designed ES program is tolerated by individuals with spinal cord paralysis and can dramatically lower the incidence of secondary medical problems in this population (Petrofsky et al. 1991b, 1992, 2000).

ES can be used for specific isometric/isokinetic exercise of the paralyzed limb (Figoni et al. 1991) to build and maintain muscle bulk with the goal of increasing padding around bony prominences, increasing blood circulation, and strengthening bone, thereby helping to prevent pressure sores and fractures. A leg cycling program promotes cardiovascular conditioning in both quadriplegic and paraplegic patients with SCI

(Mutton et al. 1997, Faghri et al. 1994, Hooker et al. 1990). A method of ES delivery called functional electrical stimulation (FES) allows standing and walking exercise programs (Petrofsky et al. 1991b, 1992, Gordon and Mao 1994, Graupe and Kohn 1998). Contemporary FES programs typically use transcutaneous non-invasive, microcomputerized ES systems with Walkman-size units, controlled by finger-touch buttons mounted on the handbars of a walker, that stimulate in a synchronous fashion (Brissot el al. 2000, Graupe and Kohn 1998). While this type of walking is impractical as a means of daily mobility, it can help people with thoracic level SCI keep physically and psychologically fit by increasing their physical activity level and promoting reentry into their community (Petrofski 1992).

Autonomic dysreflexia (AD) needs to be considered when applying ES to patients with SCI above T6. AD occurs because the splanchnic nerve outflow of the sympathetic nervous system (SNS) in the thoracic spinal cord is cut off from central control. This lack of central input allows the SNS to discharge spontaneously with subsequent loss of control of heart rate and blood pressure. ES delivery to these patients must be carefully monitored because cutaneous sensory nerve stimulation may activate SNS outflow from the spinal cord, causing an AD response. Matthews et al. (1997) tried to obstruct the AD reaction during the application of FES by applying a topical anesthetic cream under the electrode pads to block nociceptor input to the spinal cord, but found this approach did not block cardiovascular and hormonal AD responses. Keeping current levels as low as possible may help prevent the AD response. Careful placement of the stimulating electrodes directly over the motor points of the muscles can help to minimize the amount of current required to achieve a muscle contraction (Ashley et al.1993).

Strengthening and Motor Learning. Patients with upper motor neuron (UMN) damage experience difficulty with voluntary activation of their muscles, weakness, and spasticity. These impairments impede their ability to regain independent function. Physical therapy for this population typically involves use of motor learning techniques, with the goal of helping the patient relearn efficient muscle activation synergies (Cozean et al. 1988, Carmick 1997). ES can be used as an adjunct during motor learning therapy.

A cerebrovascular accident (CVA), commonly called a stroke, frequently leaves the patient with an UMN hemiparalysis on the side of the body opposite the site of cerebral damage. The use of ES in this population typically attempts to improve the patient's ability to walk or use the involved hand. Cozean et al. (1988) found a combined protocol of ES and biofeedback training produced significant improvements in gait parameters, even in patients with long standing impairments. Bofataj et al. (1989) used multichannel ES to gain numerous gait improvements in severely impaired patients during an intensive three-week training session. Cauraugh et al. (2000) used ES in conjunction with traditional therapy protocols to significantly improve isometric extension force in the wrist extensors of stroke patients.

Physical therapy for children with UMN disorders, such as cerebral palsy (CP), typically attempts to improve motor skills by using the therapists' hands to block unwanted movements and facilitate desired movement strategies. Emphasis is frequently on improving gait and facilitating bilateral hand use. Therapists frequently state they do not have enough hands to provide needed input and cannot spend enough time with the child. ES can be used to provide additional input of the desired muscle activation patterns and can be applied at home. In two separate articles, Carmick (1993a.b.) reports

the use of a task-oriented model of motor learning supplemented with ES facilitation to improve crawling, bilateral hand use, and symmetrical walking in children with a hemiplegic type of CP. The youngest (1.6 years old) showed the greatest improvement, but the older ones also had beneficial gains. Comeaux (1997) found significant improvement of dorsiflexion at heelstrike in children with hemiplegic or quadriplegic spastic type cerebral palsy after using a protocol of ES to the gastrocnemius or to both the gastrocnemius and tibialis anterior. Dubowitz et al. (1988) used ES on the TA of two children with hemiplegia and found improvements in maximum voluntary contraction of their ankle dorsiflexors, with subsequent functional improvement of their gait. Regarding improved hand use, Carmack (1997) used a combination of ES, wrist splint stabilization, and motor learning activities to teach a child with hemiplegic type CP to use both hands to tie his shoelaces.

Spasticity Reduction. Spasticity, a pathological state of muscle hypertonia, is a sign of damage to the UMN. Spasticity can be both a help and a hindrance to function. For example, it can be used for weight bearing during transfers, but can also interfere with comfort and proper positioning in bed or in the wheelchair. Whether or not spasticity levels should be reduced is ultimately up to the patient. When making that decision, it is helpful to try temporary measures of reduction in order to assess the effectiveness of doing so.

ES has been used for the temporary reduction of spasticity. Alfieri (1982) used ES to stimulate the antagonists of spastic muscles in order to activate reciprocal inhibition to the spastic agonist and found the technique could significantly reduce spasticity. The effect was short-lived, with the spasticity returning to natural levels

within one hour. Alfieri thought spasticity would increase if ES was allowed to overflow into the spastic muscle, but Carmack (1997) found that ES strengthening of spastic finger flexors in a child increased function without increasing his spasticity. Robinson et al. (1988) used ES for fatiguing exercise of the quadriceps with SCI patients to temporarily decrease spasticity. They found no carryover 24 hours later. Seib et al. (1994) depressed ankle "stiffness" in brain injured and SCI patients for up to 24 hours by using ES to their tibialis anterior muscles.

Wound Healing. Maintaining skin integrity is a constant concern for those with UMN or spinal cord injuries. Patients who have impaired circulation, diminished cutaneous sensation, or are unable to move themselves independently to achieve pressure relief in bed or in the wheelchair are at risk of developing decubitis ulcers. Frequently, decubitis ulcers are slow to heal and cause a grave health risk in this population. Facilitating closure of resistant decubitis ulcers improves the length and quality of life for those who suffer from them and reduces the cost of providing medical care (Petrofsky et al. 2000).

ES can be used to facilitate the closure of decubitis ulcers, which is especially important when the ulcers are resistant to healing. Various protocols have been reported in the literature for promoting wound healing. High voltage galvanic stimulation increased the rate of closure for healing resistant open wounds in a study by Akers and Gabrielson (1984). Carley and Wainapel (1985) found the use of a low intensity direct current in the range of 200 to 800 microamps to be an effective, convenient, and reproducible method for healing chronic open wounds. Both direct microcurrent DC stimulation and high voltage galvanic stimulation were found to be effective by Franek

(1999). Feedar et al. (1992) used monophasic pulsed ES with good results. Petrofsky (2000) used a monophasic square wave stimulator set at 500 microseconds to heal chronic pressure sores on patients with SCI, showing that high voltage is not necessary. This is important because low voltage ES delivery decreases the risk of burns, soft tissue injuries, and bone fractures that can be caused by the strong muscle contractions which occur when using high voltage ES with these patients.

The effect of electrical stimulation on ulcerations may be due to an inhibitory effect on bacterial growth or enhancement of natural healing processes. The polarizing effect of a DC current is required to achieve these effects (Nelson and Currier 1991). ES has been shown to inhibit bacterial growth in vitro, whether using low-intensity DC (Rowley et al. 1974a,b), or high-voltage DC (Kincaid and Lavoie 1989). DC current has been shown to enhance leukocyte proliferation and collagen synthesis, as well as to accelerate epithelialization (Carley and Wainpapel 1985), increase circulation and blood flow (Currier et al. 1986) and influence macrophage and fibroblast motility (Orida and Feldman 1982, Erickson and Nuccitelli 1984), all of which may increase the bodys own natural healing ability. When applying ES in the clinic, a through knowledge of effective and safe application is required.

Parameters of ES Application

Clinically, ES is delivered using stimulation machines from competing manufacturers. ES machines consist of three basic elements: a power source that relies on 'household' current or batteries, an oscillator circuit that generates a repetitive signal, and an output amplifier that provides for amplitude regulation of the waveform and delivery of a constant current or voltage. ES units used in the field of rehabilitation can

be classified as either direct current (DC), alternating current (AC), or pulsed current and differ only in their ability to provide a variety of waveforms (Nelson and Currier 1991).

Waveforms. Waveform indicates the shape taken by different parameters of pulse duration and current modulations when plotted on a graph. The goal is to find a waveform that will excite the peripheral nerve with the least amount of current, in order to minimize pain, muscle fatigue, and risk for soft tissue effects, such as burns. Baker et al. (1988) found a high frequency symmetric balanced biphasic square waveform most comfortable on the large quadriceps and an asymmetric version most comfortable on the smaller muscles of the forearm, but found a small subset of subjects who preferred a medium frequency (2500 Hz) waveform on both muscles. He suggests a medium frequency waveform should be tried for those having difficulty adapting to ES. Laufer et al. (2001) found monophasic and biphasic waveforms give better subject tolerance than a polyphasic waveform for production of maximal muscle torque with minimal fatigue, provided phase duration and stimulation frequency are held constant. Their polyphasic waveform resulted in rapid muscle fatigue and weaker ES induced contractions of the quadriceps muscle. Bennie et al. (2002) compared rectangular, sine, interferential, and Russian waveforms and found the sine waveform had the highest subject tolerance, while requiring the least stimulus current to produce a set contraction force of the quadriceps. Delitto and Rose (1986) tested the comfort level of sinusoidal, sawtooth, and square waveforms, which they delivered to the quadriceps with identical current characteristics. No one waveform was found to be most or least comfortable, leading the authors to conclude that individual preferences exist for different waveforms.

Electrodes. After waveform, the next consideration for delivery of ES is electrode type, size, and placement. Early electrodes were made from silicone rubber impregnated with carbon particles. They required a coupling agent and tape to hold them in place. Contemporary electrodes use polymers as the coupling medium and many are prepackaged with hypoallergenic adhesive agents or are self-adhering. They may be designed for one use or for multiple uses. Electrodes vary in their conductive properties and can cause skin irritation and dermatological reactions, either due to mechanical shearing of the electrodes and tape, or reactions to coupling agents and adhesive materials (Nelson and Currier 1991).   The amount of current being delivered through the electrode can also cause a range of reactions, such as mild inflammatory responses and small burns in areas of high current density under the electrode. Factors that increase the risk for burns are delivery of too much current (DiVincenti 69) and insensate skin (Hooker 95).

Electrode Size, Shape, and Impedance. Electrode size is an important consideration due to its effect on current density. Alon et al. (1985, 1994) studied the effect of electrode size on maximally tolerated motor nerve excitation. Of the sizes they studied, a 4.5 x 4.5 cm pad was most tolerated on the gastrocnemius (1994) and a 9 x 9 cm pad gave highest tolerance on the quadriceps (1988). While larger electrodes require greater voltage output, they develop less pulse-charge density per unit area than smaller ones. This is perceived as more comfortable by the patient; but large electrode pads can cause unwanted stimulation of neighboring muscles. While the size of the quadriceps in an adult may merit use of a large electrode, smaller muscles require a smaller size pad, which increases the current density unless current delivery is turned down. When selective control of smaller muscles or direct stimulation of a denervated muscle is

desired, a smaller pad size may be required. For example, when applying ES to the closely spaced muscles of the forearm, use of smaller electrodes and careful placement is required to avoid unwanted contractions in neighboring muscles (Reed 1997). Also, children's muscles have smaller surface areas, which require smaller pads. As a guideline for the pediatric population, Carmick (1997) advises that a child's muscle should be large enough for use of an active electrode that is no smaller than one inch, in order to avoid pain and overflow to nearby muscles. Smaller electrode pads may also be needed for direct contraction of a denervated muscle, in order to provide enough current delivery.

Electrode shape has been given little consideration, but may also influence patient comfort during ES. Alon (1985) used square and rectangular electrodes of the same surface area and found both shapes gave equal tolerance. Clinically, patients often state they feel the most discomfort around the edge of the electrode (Petrofsky, personal communication). The shape of the leading edge of an electrode is usually straight. Altering the edge of the electrode by serration or rounding it may alter this discomfort.

Another issue to consider when choosing an electrode is the amount of impedance it will contribute to the ES delivery system. Impedance, measured in Ohms, is the resistance of an object to current flow and varies according to the composition of the object. Resistance impedes the direct flow of current, making it necessary to increase the current in order to obtain the desired effect. When applying ES to the human body, several factors affect the impedance of the system. Electrode impedance varies among different types and brands, according to their size and composition (Nolan 1991). In regard to size, small electrodes in Nolan's study offered the highest impedance, whereas

the carbon-rubber composition electrodes offered low impedance when compared to metal electrodes. Nolan also found that electrodes of the same brand differ in impedance, which he speculates accounts for some of the impedance variations in his study. Also, impedance of electrodes varies within the same pad. Most electrodes have their lowest impedance at the point where the tip of the lead wire inserts into the electrode (Nelson and Currier 1991). Build up of dirt and oil in reusable pads increases pad impedance. Cleaning pads properly after each use will prevent this increase.

Other factors that affect impedance are the interelectrode distance and orientation of the electrodes. The distance between electrodes affects the depth of current flow between them. When placed close together, current will flow superficially, while placing them farther apart allows the current to flow deeper, but diminishes the current density in the intervening tissues (Nelson and Currier 1991). Orientation of the electrodes can have an effect on torque production. Brooks et al. (1990) contends that muscle tissue is nearly four times more conductive in the longitudinal direction of its fibers than in the transverse direction and they found that a longitudinal orientation of the electrode produces significantly more torque than a transverse orientation.

Impedance is affected by the composition of the various biological tissue types in the segment being stimulated. The water and ion content of the tissues are important factors that affect its impedance. Blood, nerve, and muscle have high water content and therefore have the lowest electrical impedance, whereas fat, skin (epidermis), and bone have low water content and high electrical impedance (Nelson and Currier 1991). Surface electrodes, by necessity, are placed on skin, which offers high impedance. In order to lower its resistance, skin is usually shaved (if hair removal is necessary) and cleaned with

alcohol to remove dirt, oil, and dead skin before application of the electrode. McMiken et al. (1983) uses a hot, wet towel on the skin for five minutes to reduce skin resistance before applying ES. Hayes (1993) states that the keratin layer of the skin offers the highest impedance and abrading the skin slightly before application of ES decreases its resistance by 50-100%. She also states that tissue resistance may decrease as an effect of ongoing ES. The size and density of the tissue under the skin, overlying the muscle, also gives impedance to the flow of current. Fat and water content in this region varies within subjects and among subjects due to differences in body types. Empirically, this also affects tolerance and delivery of ES.

Patient tolerance of ES may come down to choosing waveforms and electrodes that agree with the individual's ability to tolerate the sensations produced. Lieber and Kelly (1991) studied various electrodes to determine if any one type was most efficient in producing quadriceps torque. They concluded the most important factor in determining torque generation level is the quadriceps muscle's intrinsic ability to be activated, as opposed to electrode size, current, current density, or skin impedance. This suggests that tolerance and efficacy of ES may be primarily determined by intrinsic tissue properties of the individual muscle and the patient's perception of the stimulus parameters.

Electrode Placement and Motor Point Determination. Electrode placement is an important consideration when applying surface ES, because impedance varies over the surface of the muscle being stimulated. Studies have shown that areas in the body with the greatest density of sodium channels in the cell membranes have the lowest resistance to electrical activity (Reichel et al. 2002). Therefore, the measurement of electrical impedance, which is a measure of tissue electrical resistance, has proven useful since the

lowest surface impedance of the skin is located above motor nerves. By moving an impedance probe over a muscle, the point where the motor nerve enters the muscle can be found easily. Electrical impedance units are rarely used in the clinic. Clinicians have the options of using anatomical motor point charts or searching for the motor points with the active electrode. Motor point charts show typical areas where motor points are found on superficial muscles, but the exact points vary with the individual. Training manuals (Hayes 1993, Nelson and Currier 1991) recommend finding the motor point by searching in the general motor point area with the active electrode until the contraction is strongest. Some clinicians find the motor point by putting the active electrode on their finger and touching around the muscle looking for the strongest response. Empirically, ES is deemed to be most effective and tolerable when the active electrode is placed directly over the motor point.

Tolerance, Compliance, and Pain. Transcutaneous stimulation of neuromuscular structures always results in activation of sensory receptors on the surface of the skin. This sensation interferes with the effectiveness of ES because it frequently causes patient discomfort and anxiety. Pain perception involves more than just the direct stimulation of sensory fibers. It also involves the individuals coping style, perceived control over the event causing the pain, and other cognitive-behavioral aspects of pain perception. Delitto et al. (1992) found that behavioral styles appear to affect how subjects characterize the discomfort associated with ES and that the involuntary muscle contractions, themselves, also contribute to discomfort. They recommend using interventions tailored to the patient's preferred coping style as a means of increasing patient tolerance.

Patient's who have experienced damage to their nervous system present with a more complex picture. UMN injury of cerebral origin frequently leaves patients with spasticity, which can cause them to be hypersensitive to cutaneous stimulation (Carmack 1997). Children, in general, are less able to tolerate ES than adults, and those with UMN damage are even less tolerant (Carmack1997, Reed 1997). This can impact the ability of this population to tolerate the sensory input of ES.

Pain is a complex variable to measure, due to the emotional, autonomic, and subjective components. These reaction components affect the subject's judgment of pain. Even with controlled electrically delivered stimulus intensity, the meaning of pain to the subject makes it difficult to obtain objective measurements. Revel et al. (1976) states, "A measure of pain is nevertheless useful, even though it must be accepted as a composite of the effects of the pain stimulus and the subject's preparedness to report that pain".

Pain measurement. The widely used Verbal Rating Scale (VRS) uses 5-7 word categories such as no-mild-moderate-severe-unbearable pain, thereby transferring the subject's continuous feelings onto a verbal scale (Ohnhaus and Adler 1975). These words, and the intervals between the words, do not mean the same thing to all people. Verbal scales have been used successfully to test for cerebral hemispheric differences and male/female differences in dealing with pain. Using a verbal measurement scale, Neri and Agazzani (1984) found pain thresholds and tolerance for a noxious stimulation were lower on the right side of the body. They speculate that right limb sensory input and verbal output are both processed in the left cerebral hemisphere, therefore, there may be quicker reaction times and a more specific limb representation on the right side of the body. They found no differences between males and females, but did find that subjects

older than sixty had higher pain and sensory thresholds. While a verbal scale was able to pick up these differences, it lacks sensitivity for picking up relatively small changes in pain.

Numerical rating scales are reported to give improved discrimination for smaller changes in pain (Ohnhaus and Adler 1975). The Visual Analogue Scale (VAS) is a numerical rating scale, which conventionally utilizes a 10 cm line with one end (L) signifying 'no pain' and the other end (R) signifying 'unbearable pain'. It is a continuous line, thereby eliminating the intervals of a verbal scale. The VAS is able to assess the subject's actual change in pain intensity (Ohnhaus and Adler 1975). Downie et al. (1978) studied four different numerical rating scales, including the VAS, in both horizontal and vertical orientations and found good correlations among them in terms of their ability to measure the same underlying pain variables. He felt a continuous line may be confusing and found evidence for including demarcations. Revill et al. (1976) used lines of various lengths to test the effect of a certain drug on pain during childbirth. They found that a 5 cm line was ineffective compared to 10, 15, or 20 cm lines, which were equally sensitive in their ability to detect distinct differences in pain expression. He concludes that "the linear analogue rating of a constant pain stimulus is reproducible and changes in rating are likely to be real changes of opinion", even for recalled pain events. Price et al. (1983) confirms the validity of the VAS to measure and compare chronic and experimental pain.

Warning patients concerning aversive procedures may prepare them for dealing with the pain and may affect their autonomic reactions. Mittwoch et al. (1990) found that 5 or 30 second warnings gave lower pain scale ratings than 60 or 180 second warnings.

Sosnowski (1983) found the ambiguity of not knowing for sure when an electric shock was coming resulted in a pronounced effect on skin resistance, but not on heart rate.

Males and females may have differences in their perception of pain, but the evidence is conflicting. In a Swedish study, Jensen (1993) found sex differences in coping with chronic pain among men and women who work outside the home, and speculates that women may attach more emotion to pain than men do. Physiologically, Lautenbacher and Rollman (1993) found women had less tolerance for ES induced pain, especially during menstrual cycles. Alon et al. (99) found lower overall ES tolerance in females, but his data showed great variability.

Autonomic Correlations

The autonomic nervous system (ANS) responds to many types of sensory input. Noxious stimuli activate the sympathetic division of the ANS, which is responsible for autonomic reactions to pain such as local vasoconstriction, increased heart rate and strength of contraction, and activation of the sweat glands (Kendal et al 2000). Local vasoconstriction helps reduce bleeding when the skin is compromised, and an increased heart rate and blood pressure helps protect arterial perfusion pressure. Skin temperature in the body may go down as a side effect of the vasoconstriction. Sweat glands may be activated due to the arousal effect of a noxious stimulus.

Measuring autonomic parameters may give clues to the patient's unconscious reaction to the painful effects of ES. Skin temperature has been shown to increase under the stimulating electrode as a consequence of current application (Bennie el al. 2002), but no studies have looked at remote skin temperatures to see if there is an ANS effect. Initial skin temperature itself may have an effect on pain thresholds. In a study by

Washington et al. (2000), cold-water immersion of the hand before ES significantly increased pain thresholds (an analgesic response), with thresholds returning to baseline within one hour. The influence of skin temperature was small, requiring cooling below 20° C before the pain threshold began to increase significantly.

Other considerations are the effect of heat and moisture on the skin. Studies suggest heating or hydrating the skin before placement of the electrode pad will lower skin resistance (McMiken et al.1985, Kirno et al. 1992). Many patients sweat during the application of ES, which will lower skin resistance under the electrode. Skin resistance can be measured by testing galvanic skin resistance (GSR), a measure of activation of the sweat glands. Bennie et al. (2002) found that delivery of ES with the Russian waveform gave the greatest increase in galvanic skin resistance (GSR) of the contralateral extremity, which decreased significantly after cessation of the stimulation. Of interest, Ohman et al. (1975) found most ANS responses, such as heart rate, diminish with repeated exposure to a noxious stimulus, but GSR does not. Sosnowski (1983) showed that ambiguity, that is, not knowing for sure when a shock was coming during the experiment, resulted in a pronounced effect on skin resistance but not on heart rate. For subjects in the shock group, the effect of repetition of trials was found to have a habituation effect for heart rate but a dishabituation effect for skin resistance.

ES to a muscle has been shown to have a crossed effect in the contralateral extremity. Laughman et al. (1983) found a crossed education effect in the contralateral quadriceps during their ES study and compared this finding with that of Rose et al. (1957), who found increased strength without hypertrophy of the contralateral quadriceps during their exercise protocol. Both of these authors attribute this effect to motor

learning, that is, the central command center's learned ability to activate larger numbers of motor units, which overflows to the contralateral muscle.

Additionally, Paquet et al. (1996) found that body position has an effect on flexion and crossed extension reflexes. Excitability of extensor muscles (quadriceps and soleus) on both sides was enhanced in standing, whereas the flexion reflex in the TA had a significantly smaller responsive area in sitting. This supports theories of situational reflex adaptability in the nervous system (Kendal et al. 2000).

In summary, ES is a beneficial adjunct during the rehabilitation of musculoskeletal and neurological disorders. One of the factors limiting its widespread use is patient complaint of discomfort during current application. This review has looked at numerous studies pertaining to comfortable, effective delivery of ES. Three revealing thoughts come out of this body of knowledge:

1) Alon (1985), while advocating the use of larger electrode pads for non-painful excitation of the muscle, states that during muscle reeducation, "muscle contraction without pain results in less muscle torque than muscle contraction accompanied by painful stimulation"; 2) Selkowitz (1985) proposes that "the relative increase in isometric strength using only ES, may be determined by the ability of the subjects to tolerate longer and more forceful contractions"; and 3) Lieber and Kelly (1991) suggest that ES "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". These remarks suggest that, while information gained from numerous studies can be used to establish guidelines for the delivery of ES, it may ultimately come down to the

individual and how much discomfort they can accommodate in order to achieve the

perceived benefits of ES.

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Appendix I

Figures and Tables

METHODS

Subjects

Subjects were recruited from the faculty and staff at Loma Linda University for a sample variety of sex, age and skin pigmentation. Three males and three females were used who had a mean age of 46 years ($\pm$7), mean height of 166.1 cm ($\pm$13.3) and mean body mass of 75.4 kg ($\pm$9.9). All subjects were within one standard deviation of their ideal body weight and had no known medical disability. Skin pigmentation ranged from very light to very dark. Arm, thigh and leg length averaged 30.2, 42.4 and 36.3 cm (11.9, 16.7, and 14.3 inches) respectively. (See Table 1 for anthropometric values). All subjects were told of the purpose, procedure and risks of the experiments and that they could stop the procedure at any time. Subjects signed an informed consent form. The Institutional Review Board approved all of the procedures. Subjects were assigned an identification number, which was recorded on their data collection sheet.

Measurement of Subject Characteristics

Each subject was weighed using a standard, calibrated medical step-on scale. Their height was measured using a marked system on the wall. Their birth date was recorded on their data sheet and they were assigned a subject identification number. Extremity segment lengths and circumferences were determined using a flexible cloth tape measure. Muscle surface area was determined by drawing the peripheral outline of the muscle on a lightweight muslin material, which was cut out and weighted on Monobloc scale (Mettler Corp. Toledo #PB 153-S). One cm^2 of this fabric weighs .004 gram; therefore this ratio was used to determine the surface area of the fabric muscle outline.

Measurement of strength

Measurement of strength was calculated using a custom designed multi-positional chair with attached motor drives, which allowed precise positioning of each subjects 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 consists of four strain gauges arranged in a Wheatstone bridge. Force produced by an isometric contraction of the muscle was measured using the isometric strain gauge device with a ratio of force to bending of the bar of: 100 kg of force bends the steel bar $5/10^6$ of an inch. Output was amplified using a Biopac strain gauge amplifier with a gain of 5000. An A-D converter digitized the electric signal with a 16 bit resolution at 200 samples per second.

Motor point determination

Electrical impedance was measured at 200 cycles per second, with the points of lowest impedance being determined as the MP.

Electrical stimulation

Electrical stimulation was applied using the Challenge CH8000A, powered muscle stimulator, (MPTS, Inc.) with a biphasic square wave of 300 ms duration and a frequency of 30 Hz. Amplitude of current was controlled in the ranges of 0-100 milliamps. Stimulus current was measured through a 10 Ohm resistor in series with the electrode. Voltage drop across the resistor was measured on a Hewlett Packard digital oscilloscope to calculate the current going through the skin. Current was measured using Ohms law (F=V/R). During each experiment the current required to reach 10% MVC was determined by reading that preset value off the panel meter.

Carbon rubberized electrodes (Unipatch , part #625) were used for the stimulating and collecting pads. Stimulating electrode sizes were 13.4, 19.4 and 25.8 cm^2; shapes were square, round and serrated, with a similar surface area of 25.8 cm^2; and placements were at 2 and 4 cm, proximal, distal, medial and lateral from the MP, using the 13.4 cm^2 stimulating pad. The collecting pad was 25.8 cm^2 and held stationary at the musculotendinous junction.

Measurement of pain

A visual analogue scale (VAS), consisting of a 10 cm line, with a dot at each cm marking, was used to measure the subjects discomfort after each 20 s contraction. Subjects were instructed to place a mark on the 10 cm line that represented their perception of discomfort, with the left end of the line representing no pain and the right end representing unbearable pain.

Autonomic parameters

EMG was measured using a Biopac EMG amplifier with a gain of 5000, bandwidth DC to 500 hertz and digitized through an A-D converter with a 16-bit resolution at 200 samples per second. Electrodes were 0.5 cm^2 carbonized, hydrogel electrolite pads (5500 Q-Trace Gold, Model #30807732, Graphics Controls Corp., Buffalo, N.Y.).

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 a 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 of the electrical signals were digitized in an A/D converter, with a 16 bit resolution, at 200 samples per second. Data was managed with the AcKnowledge 4.0 computer program, displayed on a 20 inch monitor, and stored on disc for later analysis.

PROCEDURES

Subjects were seated in a specifically designed motorized chair with the joints proximal and distal to the muscle being stimulated positioned at $90^{o.}$ For the quadriceps femoris muscle, the hip and knees were positioned at 90°, 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 freely, with no contact on the floor. This procedure was similar for testing the tibialis anterior, with the exception that the foot was supported in a 90°, neutral, position. For the biceps brachii, the shoulder and elbow were positioned at 90°, the wrist was secured with a leather cuff attached in line with a force transducer and the hand was allowed to hang free. If there was excessive hair on the overlying skin, it was shaved. The skin was wiped with alcohol to clean it of oil and dirt. A surface area tracing of each muscle was

drawn on lightweight muslin material, using a felt marker. The subjects were instructed how to use the visual analogue scale (VAS). During the set-up, subjects acclimated to the room temperature for 20 min before the beginning of ES. Room temperature during the experimental days ranged from 21.7-25° C. Subjects were asked to perform two maximal muscle contractions of 2 s durations, with a 1 min rest between contractions. The average of the two contractions were used to calculate 10% maximal voluntary contraction (10% MVC) for that muscle. This force was then set on a Weston panel meter 1971 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 and 4 cm placements 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: EMG pads were placed on the contralateral muscle; thermister probes were applied over the contralateral muscle and on the forehead; electrodermal finger electrodes were placed on the left ring finger and a plethysmogram was placed on the left middle finger. The electrical stimulator was set to a biphasic square wave of 300 ms duration with a frequency of 30 Hz. Subjects were given two trials with the electrical stimulator to acclimate them to the procedure. Subjects 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, using computer generated data collection sheets as a guide. Each parameter was collected twice. Muscles were given a 1 min 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 the subject between muscle protocols and they were instructed to
move about.

Appendix IV

Forms

*Have AcKnowledge program ready
*Have Aerosport calibrated and running
Date and Time:
Room Temperature:
Basic Intake and Set-up #1
1. Read informed consent & sign.
2. Subject identifier:
3. Age
4. Weight: LB.   KG (Lb/2.2)
5. Height: INCHES   CM (2.54 cm/inch)
6. **Adjust chair** to support extremity & fasten strain gauge **strap**.
* Let extremity hang free - notice if current gauge is at zero
7. **Measure extremity length and circumference**.
8. Make **surface area tracing** of target muscle.
10. **Calculate 10% of maximal** muscle isometric force and record.
(Do 2x and use peak measurement)
11. **Use impedance device** to locate motor point (MP) of target muscle.
12. **Mark MP** with ink pen.
13. **Apply EMG pads** on contralateral muscle.
(One on MP, second one 1 cm away and reference on lateral thigh)
14. Test if operational.
15. **Apply thermister** probes to forehead and left thigh. (skin temp)
16. Test if operational.
17. **Apply plethysmogram transducer** to finger (HR & O2 sat)
18. Test if operational
19. **Apply electrodermal activity electrodes** to finger. (galvanic resistance)
20. Test if operational
21. Apply **slow flow pneumotach** and instruct subject in use
22. Test if operational
23. **Set Challenge stimulator (battery operated)** to biphasic square wave,   300 microsec duration & 30 cycles/second.
Length & Circumferences:
Thigh (Femur)
Length (Gr Tro - Lat Cond) =
Circum at 1/2 length =
Leg (Tibia)
Length (Tib tub - Med Mall) =
Circum at 1/2 length =
Arm (Humerus)
Length (Gr Tub - Lat Cond) =
Circum at 1/2 length =

	Code*
Subject ID #:	
Date & time:	
Electrode Placement Sequence A (2 square inch pads)	
Muscle:	
1. **Check stimulator parameters**: biphasic square wave, 300 microsec duration and 30 cycles/second.	
2. **Apply electrode pads on MP** & other on distal MT Jct	
3. **Apply current** to reach 10% Fmax hold for 20 sec.	
4. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
5. **Apply current** to reach 10% Fmax hold for 20 sec.	
6. **Input data** to AcKnowledge and Aerograph & save to disc.	
7. **Apply same size/shape pad at distance 1: 2 cm Proximal**	
8. **Apply current** to reach 10% Fmax hold for 20 sec.	
9. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
10. **Apply current** to reach 10% Fmax hold for 20 sec.	
11. **Input data** to AcKnowledge and Aerograph & save to disc.	
12. Apply pad & record at **distance 2: 2 cm Lateral**	
13. **Apply current** to reach 10% Fmax hold for 20 sec.	
14. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
15. **Apply current** to reach 10% Fmax hold for 20 sec.	
16. **Input data** to AcKnowledge and Aerograph & save to disc.	
17. Apply pad & record at **distance 3: 2 cm Distal**	
18. **Apply current** to reach 10% Fmax hold for 20 sec.	
19. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
20. **Apply current** to reach 10% Fmax hold for 20 sec.	
21. **Input data** to AcKnowledge and Aerograph & save to disc.	
22. Apply pad & record at **distance 4: 2 cm Medial**	
23. **Apply current** to reach 10% Fmax hold for 20 sec.	
24. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
25. **Apply current** to reach 10% Fmax hold for 20 sec.	
26. **Input data** to AcKnowledge and Aerograph & save to disc.	
27. Apply pad & record at **distance 5: 4 cm Proximal**	
28. **Apply current** to reach 10% Fmax hold for 20 sec.	
29. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
30. **Apply current** to reach 10% Fmax hold for 20 sec.	
31. **Input data** to AcKnowledge and Aerograph & save to disc.	
32. Apply pad & record at **distance 6: 4 cm Lateral**	
33. **Apply current** to reach 10% Fmax hold for 20 sec.	
34. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
35. **Apply current** to reach 10% Fmax hold for 20 sec.	
36. **Input data** to AcKnowledge and Aerograph & save to disc.	
37. Apply pad & record at **distance 7: 4 cm Distal**	
38. **Apply current** to reach 10% Fmax hold for 20 sec.	
39. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
40. **Apply current** to reach 10% Fmax hold for 20 sec.	
41. **Input data** to AcKnowledge and Aerograph & save to disc.	
42. Apply pad & record at **distance 8: 4 cm Medial**	
43. **Apply current** to reach 10% Fmax hold for 20 sec.	
44. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
45. **Apply current** to reach 10% Fmax hold for 20 sec.	
46. **Input data** to AcKnowledge and Aerograph & save to disc.	
*Code = Subject #: placement:	
Placements = MP, 2cmP, 2cmL, 2cmD, 2cmM, 4cmP, 4cmL, 4cmD, 4cmM	

	Code*
Subject ID #:	
Date & time:	
Electrode Placement Sequence B (2 square square)	
Muscle:	
1. **Check stimulator parameters**: biphasic square wave, 300 microsec duration and 30 cycles/second.	
2. **Apply electrode pads on MP** & other on distal MT Jct	
3. **Apply current** to reach 10% Fmax hold for 20 sec.	
4. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
5. **Apply current** to reach 10% Fmax hold for 20 sec.	
6. **Input data** to AcKnowledge and Aerograph & save to disc.	
7. **Apply same size/shape pad at distance 1: 2 cm Distal**	
8. **Apply current** to reach 10% Fmax hold for 20 sec.	
9. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
10. **Apply current** to reach 10% Fmax hold for 20 sec.	
11. **Input data** to AcKnowledge and Aerograph & save to disc.	
12. Apply pad & record at **distance 2: 2 cm Medial**	
13. **Apply current** to reach 10% Fmax hold for 20 sec.	
14. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
15. **Apply current** to reach 10% Fmax hold for 20 sec.	
16. **Input data** to AcKnowledge and Aerograph & save to disc.	
17. Apply pad & record at **distance 3: 2 cm Proximal**	
18. **Apply current** to reach 10% Fmax hold for 20 sec.	
19. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
20. **Apply current** to reach 10% Fmax hold for 20 sec.	
21. **Input data** to AcKnowledge and Aerograph & save to disc.	
22. Apply pad & record at **distance 4: 2 cm Lateral**	
23. **Apply current** to reach 10% Fmax hold for 20 sec.	
24. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
25. **Apply current** to reach 10% Fmax hold for 20 sec.	
26. **Input data** to AcKnowledge and Aerograph & save to disc.	
27. Apply pad & record at **distance 5: 4 cm Distal**	
28. **Apply current** to reach 10% Fmax hold for 20 sec.	
29. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
30. **Apply current** to reach 10% Fmax hold for 20 sec.	
31. **Input data** to AcKnowledge and Aerograph & save to disc.	
32. Apply pad & record at **distance 6: 4 cm Medial**	
33. **Apply current** to reach 10% Fmax hold for 20 sec.	
34. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
35. **Apply current** to reach 10% Fmax hold for 20 sec.	
36. **Input data** to AcKnowledge and Aerograph & save to disc.	
37. Apply pad & record at **distance 7: 4 cm Proximal**	
38. **Apply current** to reach 10% Fmax hold for 20 sec.	
39. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
40. **Apply current** to reach 10% Fmax hold for 20 sec.	
41. **Input data** to AcKnowledge and Aerograph & save to disc.	
42. Apply pad & record at **distance 8: 4 cm Lateral**	
43. **Apply current** to reach 10% Fmax hold for 20 sec.	
44. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
45. **Apply current** to reach 10% Fmax hold for 20 sec.	
46. **Input data** to AcKnowledge and Aerograph & save to disc.	
*Code = Subject #: placement:	
Placements = MP, 2cmD, 2cmM, 2cmP, 2cmL, 4cmD, 4cmM, 4cmP, 4cmL	

	Code*
Subject ID #:	
Date & time:	
Electrode Placement Sequence C (2 square inch pads)	
Muscle:	
1. **Check stimulator parameters**: biphasic square wave, 300 microsec duration and 30 cycles/second.	
2. **Apply electrode pads on MP** & other on distal MT Jct	
3. **Apply current** to reach 10% Fmax hold for 20 sec.	
4. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
5. **Apply current** to reach 10% Fmax hold for 20 sec.	
6. **Input data** to AcKnowledge and Aerograph & save to disc.	
7. **Apply same size/shape pad at distance 1: 4 cm Proximal**	
8. **Apply current** to reach 10% Fmax hold for 20 sec.	
9. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
10. **Apply current** to reach 10% Fmax hold for 20 sec.	
11. **Input data** to AcKnowledge and Aerograph & save to disc.	
12. Apply pad & record at **distance 2: 4 cm Lateral**	
13. **Apply current** to reach 10% Fmax hold for 20 sec.	
14. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
15. **Apply current** to reach 10% Fmax hold for 20 sec.	
16. **Input data** to AcKnowledge and Aerograph & save to disc.	
17. Apply pad & record at **distance 3: 4 cm Distal**	
18. **Apply current** to reach 10% Fmax hold for 20 sec.	
19. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
20. **Apply current** to reach 10% Fmax hold for 20 sec.	
21. **Input data** to AcKnowledge and Aerograph & save to disc.	
22. Apply pad & record at **distance 4: 4 cm Medial**	
23. **Apply current** to reach 10% Fmax hold for 20 sec.	
24. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
25. **Apply current** to reach 10% Fmax hold for 20 sec.	
26. **Input data** to AcKnowledge and Aerograph & save to disc.	
27. Apply pad & record at **distance 5: 2 cm Proximal**	
28. **Apply current** to reach 10% Fmax hold for 20 sec.	
29. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
30. **Apply current** to reach 10% Fmax hold for 20 sec.	
31. **Input data** to AcKnowledge and Aerograph & save to disc.	
32. Apply pad & record at **distance 6: 2 cm Lateral**	
33. **Apply current** to reach 10% Fmax hold for 20 sec.	
34. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
35. **Apply current** to reach 10% Fmax hold for 20 sec.	
36. **Input data** to AcKnowledge and Aerograph & save to disc.	
37. Apply pad & record at **distance 7: 2 cm Distal**	
38. **Apply current** to reach 10% Fmax hold for 20 sec.	
39. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
40. **Apply current** to reach 10% Fmax hold for 20 sec.	
41. **Input data** to AcKnowledge and Aerograph & save to disc.	
42. Apply pad & record at **distance 8: 2 cm Medial**	
43. **Apply current** to reach 10% Fmax hold for 20 sec.	
44. **Input data** to AcKnowledge and Aerograph & save to disc.	
Rest 1 min	
45. **Apply current** to reach 10% Fmax hold for 20 sec.	
46. **Input data** to AcKnowledge and Aerograph & save to disc.	
*Code = Subject #: placement:	
Placements = MP, 4cmP, 4cmL, 4cmD, 4cmM, 2cmP, 2cmL, 2cmD, 2cmM	

	Code*
Subject ID #:	
Date & time:	
Electrode Shape Sequence A (Sq, Serr, R)	
Muscle:	
1. **Apply 1st electrode pad shape: SQUARE**	
(One on MP and other on distal musculotendinous jct.)	
2. **Measure distance** between edges.	
3. **Check Challenge stimulator parameters**: biphasic square wave, 300 microsec duration & 30 cycles/sec.	
4. **Apply current** to reach 10% Fmax hold for 20 sec.	
5. **Input data** to AcKnowledge and Aerograph.	
6. Rest 1 minute	
7. **Apply current** to reach 10% Fmax hold for 20 sec.	
8. **Input data** to AcKnowledge and Aerograph.	
9. **Apply 2nd pad shape: Square SERRATED**	
10. **Apply current** to reach 10% Fmax hold for 20 sec.	
11. **Input data** to AcKnowledge and Aerograph.	
12. Rest 1 minute	
13. **Apply current** to reach 10% Fmax hold for 20 sec.	
14. **Input data** to AcKnowledge and Aerograph.	
15. **Apply 3d pad shape: ROUND**	
16. **Apply current** to reach 10% Fmax hold for 20 sec.	
17. **Input data** to AcKnowledge and Aerograph.	
18. **Apply current** to reach 10% Fmax hold for 20 sec.	
19. **Input data** to AcKnowledge and Aerograph.	
*Code: Subject #; shape	
Shapes = Sq, Serr. R	

	Code*
Subject ID #:	
Date & time:	
Electrode Shape Sequence B (Serr, R, Sq)	
Muscle:	
1. **Apply 1st electrode pad shape: Square SERRATED**	
(One on MP and other on distal musculotendinous jct.)	
2. **Measure distance** between edges.	
3. **Check Challenge stimulator parameters**: biphasic square wave,	
300 microsec duration & 30 cycles/sec.	
4. **Apply current** to reach 10% Fmax hold for 20 sec.	
5. **Input data** to AcKnowledge and Aerograph.	
6. Rest 1 minute	
7. **Apply current** to reach 10% Fmax hold for 20 sec.	
8. **Input data** to AcKnowledge and Aerograph.	
9. **Apply 2nd pad shape**: **ROUND**	
10. **Apply current** to reach 10% Fmax hold for 20 sec.	
11. **Input data** to AcKnowledge and Aerograph.	
12. Rest 1 minute	
13. **Apply current** to reach 10% Fmax hold for 20 sec.	
14. **Input data** to AcKnowledge and Aerograph.	
15. **Apply 3d pad shape: SQUARE**	
16. **Apply current** to reach 10% Fmax hold for 20 sec.	
17. **Input data** to AcKnowledge and Aerograph.	
18. **Apply current** to reach 10% Fmax hold for 20 sec.	
19. **Input data** to AcKnowledge and Aerograph.	
*Code: Subject #; shape	
Shapes = Sq, Serr. R	

	Code*
Date & time:	
Electrode Shape Sequence C (R, Sq, Serr)	
Muscle:	
1. **Apply 1st electrode pad shape: ROUND**	
(One on MP and other on distal musculotendinous jct.)	
2. **Measure distance** between edges.	
3. **Check Challenge stimulator parameters**: biphasic square wave, 300 microsec duration & 30 cycles/sec.	
4. **Apply current** to reach 10% Fmax hold for 20 sec.	
5. **Input data** to AcKnowledge and Aerograph.	
6. Rest 1 minute	
7. **Apply current** to reach 10% Fmax hold for 20 sec.	
8. **Input data** to AcKnowledge and Aerograph.	
9. **Apply 2nd pad shape: SQUARE**	
10. **Apply current** to reach 10% Fmax hold for 20 sec.	
11. **Input data** to AcKnowledge and Aerograph.	
12. Rest 1 minute	
13. **Apply current** to reach 10% Fmax hold for 20 sec.	
14. **Input data** to AcKnowledge and Aerograph.	
15. **Apply 3d pad shape: Square SERRATED**	
16. **Apply current** to reach 10% Fmax hold for 20 sec.	
17. **Input data** to AcKnowledge and Aerograph.	
18. **Apply current** to reach 10% Fmax hold for 20 sec.	
19. **Input data** to AcKnowledge and Aerograph.	
*Code: Subject #; shape	
Shapes = Sq, Serr. R	

Subject ID #:	Code*
Date & time:	
Electrode Size Sequence A (2,3,4)	
Muscle:	
1. **Apply 1st size electrode pads:** *2 square inches (1.44" per side)*	Same as 1st placement size
(One on MP and other on distal musculotendinous jct.)	
2. **Apply current** to reach 10% Fmax; hold 20 seconds.	
3. Input data to AcKnowledge and Aerograph & **save** to disc.	
4. Rest 1 minute.	
5. **Apply current** to reach 10% Fmax; hold 20 seconds.	
6. Input data to AcKnowledge and Aerograph & **save** to disc.	
7. **Apply 2nd size electrode pads:** *3 square inches (1.73 per side)*	
(One on MP; other on distal musculotendinous jct.)	
8. **Apply current** to reach 10% Fmax; hold 20 seconds.	
9. Input data to AcKnowledge and Aerograph & **save** to disc.	
10. Rest 1 minute.	
11. **Apply current** to reach 10% Fmax; hold 20 seconds.	
12. Input data to AcKnowledge and Aerograph & **save** to disc.	
13. **Apply 3nd size electrode pads:** *4 square inches (2" per side)*	Same as square shape size
(One on MP; other on distal musculotendinous jct.)	
14. **Apply current** to reach 10% Fmax; hold 20 seconds.	
15. Input data to AcKnowledge and Aerograph & **save** to disc.	
16. Rest 1 minute.	
17. **Apply current** to reach 10% Fmax; hold 20 seconds.	
18. Input data to AcKnowledge and Aerograph and **save** to disc.	
*Code: Subject #: Size	
Size: 2,3, 4 square inch	

	Code*
Subject ID #:	
Date & time:	
Electrode Size Sequence C (4,2,3)	
Muscle:	
1. **Apply 1st size electrode pads: 4** *square inch (2" side)*	Same as square shape size
(One on MP and other on distal musculotendinous jct.)	
2. **Apply current** to reach 10% Fmax; hold 20 seconds.	
3. Input data to AcKnowledge and Aerograph & **save** to disc.	
4. Rest 1 minute.	
5. **Apply current** to reach 10% Fmax; hold 20 seconds.	
6. Input data to AcKnowledge and Aerograph & **save** to disc.	
7. **Apply 2nd size electrode pads: 2** *inch square (1.44 side)*	Same as 1st placement size
(One on MP; other on distal musculotendinous jct.)	
8. **Apply current** to reach 10% Fmax; hold 20 seconds.	
9. Input data to AcKnowledge and Aerograph & **save** to disc.	
10. Rest 1 minute.	
11. **Apply current** to reach 10% Fmax; hold 20 seconds.	
12. Input data to AcKnowledge and Aerograph & **save** to disc.	
13. **Apply 3nd size electrode pads: 3 inch square** (1.73 side)	
(One on MP; other on distal musculotendinous jct.)	
14. **Apply current** to reach 10% Fmax; hold 20 seconds.	
15. Input data to AcKnowledge and Aerograph & **save** to disc.	
16. Rest 1 minute.	
17. **Apply current** to reach 10% Fmax; hold 20 seconds.	
18. Input data to AcKnowledge and Aerograph and **save** to disc.	
*Code: Subject #: Size	
Size: 2, 3, 4 square inch	

	Code*
Subject ID #:	
Date & time:	
Electrode Size Sequence B (3,4,2)	
Muscle:	
1. **Apply 1st size electrode pads: 3** *square inch (1.73 side)*	
(One on MP and other on distal musculotendinous jct.)	
2. **Apply current** to reach 10% Fmax; hold 20 seconds.	
3. Input data to AcKnowledge and Aerograph & **save** to disc.	
4. Rest 1 minute.	
5. **Apply current** to reach 10% Fmax; hold 20 seconds.	
6. Input data to AcKnowledge and Aerograph & **save** to disc.	
7. **Apply 2nd size electrode pads: 4** *square inch (2" side)*	Same as square shape size
(One on MP; other on distal musculotendinous jct.)	
8. **Apply current** to reach 10% Fmax; hold 20 seconds.	
9. Input data to AcKnowledge and Aerograph & **save** to disc.	
10. Rest 1 minute.	
11. **Apply current** to reach 10% Fmax; hold 20 seconds.	
12. Input data to AcKnowledge and Aerograph & **save** to disc.	
13. **Apply 3nd size electrode pads: 2 square inch (1.44 side)**	Same as 1st placement size
(One on MP; other on distal musculotendinous jct.)	
14. **Apply current** to reach 10% Fmax; hold 20 seconds.	
15. Input data to AcKnowledge and Aerograph & **save** to disc.	
16. Rest 1 minute.	
17. **Apply current** to reach 10% Fmax; hold 20 seconds.	
18. Input data to AcKnowledge and Aerograph and **save** to disc.	
*Code: Subject #: Size	
Size: 2, 3, 4 square inch	

Subject ID # _____   **Series** _____

                                                      Step # _____

Intolerable _____ **No Discomfort**

Intolerable _____ **No Discomfort**

Intolerable _____ **No Discomfort**

Intolerable _____ **No Discomfort**

Intolerable _____ **No Discomfort**

Intolerable _____ **No Discomfort**

Intolerable _____ **No Discomfort**

Intolerable _____ **No Discomfort**