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Effects of Variation in Rest Interval and Electrode Placement on Isometric Torques Induced by Electrical Stimulation

by

Ann M. Cox

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF Master of Science

Department of Physical Education and Sport Studies

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Effects of Variation in Rest Interval and Electrode Placement on Isometric Torques Induced by Electrical Stimulation submitted by Ann M. Cox in partial fulfilment of the requirements for the degree of Master of Science.

S.W. Mendryk

Supervisor

Jack C. Kramer

S. Hunka

Date August 10, 1984

ABSTRACT

Electrical muscle stimulation (EMS) is a useful modality in the rehabilitation of injured muscles and traumatized joints. The present study investigated the effect of varying the rest period between isometric, electrically induced contractions of the knee extensor muscles. Rest intervals of 35, 50 and 65s were selected. The present investigation also compared the torques produced by two indirect methods of electrode pad placement. A faradic current generated by the TECA SP5/T stimulator was used in this study.

Thirty healthy university-aged males were randomly assigned to one of two indirect methods of pad placement. Group 1 received the electric current via the lumbo-sacral plexus and the femoral nerve while group 2 received the stimulation via the femoral nerve and the motor points of the quadriceps. In the three test sessions, the subjects were required to produce 10 consecutive stimulated knee extension torques. No voluntary effort on the part of the subject was desired. For each test session the subjects performed the task with a different rest interval interspersed between the consecutive torques. All subjects were randomly assigned a sequence order of rest intervals prior to testing. Maximal isometric torques for the 10 consecutive stimulated contractions of knee extension were measured by a Cybex II isokinetic dynamometer at 60 degrees of knee flexion.

A two-way analysis of variance (2-way ANOVA) with repeated measures on rest interval was used to examine the mean torque decrements, mean torques and peak torques. The results of the study showed that the 50s and 65s rest intervals produced less torque decrement than was produced with the 35s interval ($p \leq 0.05$ and $p \leq 0.01$ respectively). Additionally, the 65s rest interval produced a greater mean torque than was produced with the 35s rest interval ($p \leq 0.05$). Comparing the torques produced by the two pad placements revealed that pad placement group 1 produced greater torque decrement and greater peak torque than were produced by pad placement group 2 ($p \leq 0.01$ and $p \leq 0.05$ respectively). This study also observed that the average torques of the initial three and five stimulations were greater than the average torques of the final three and five stimulations respectively ($p \leq 0.001$).

The conclusions drawn from the present study were: i) the 50s and 65s rest intervals interspersed between the 10 consecutive 10s stimulated contractions provided the best stimulus for improving muscular strength as these intervals provided greater mean torques and less torque decrements when compared to the 35s rest interval; and ii) pad placement group 1 provided a more optimal strength training stimulus as this placement generated greater peak torques and greater torque decrements than those generated by pad placement group 2.

DEDICATION

To my parents, Marg and Bill, who have been so supportive throughout my years of education.

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Chapter I

INTRODUCTION

Electrical stimulation of the nervous system is inherently unnatural. However, its use, no matter how crude, dates back almost 2000 years. As early as 46 A.D. the first form of electrical stimulation was used for medical purposes.[50] A special organ of the torpedo fish produced an electric charge which was used to shock prey and deter predators. The electrical discharge of this fish was suggested for the treatment of pain, and specifically for headache and gout.[41] This practice has been documented in the works of the first Roman physician, Scribonius Largus, who prescribed the following treatment for headache:

> Headache, even if it is chronic and unbearable, is taken away and remedied forever by a live black torpedo placed on the spot which is in pain, until the pain ceases. As soon as the numbness has been felt the remedy should be removed lest the ability to feel be taken from the part.[41]

Since that time the therapeutic use of electrical stimulation has grown immensely to include treatment of angina pectoris, constipation, epilepsy, hemiplegia, paralysis, sciatica, scoliosis, and spasticity.[5 41 81] The method of application has also progressed greatly. By the early eighteen hundreds, electrical acupunture and hydroelectric baths had become popular. Implantations of electrical devices in the form of pacemakers were marketed in the mid-twentieth century.[41]

Today electricity continues to be invaluable in the treatment of disease. Surface electrical stimulation has been used very successfully in the rehabilitation of muscle atrophy in recent years.[24 30 35 48] Weakness and pain often makes it impossible for a voluntary contraction to occur. Increasing the strength and bulk of a weakened, painful muscle as well as re-educating a muscle action, increasing blood supply, improving venous and lymphatic drainage and preventing and loosening adhesions all have been common conditions treated with modern electrical apparatus.[77 81]

The latest applications of electric current have focused on the strengthening of healthy muscle. Athletes are now adopting electrical muscle stimulation (EMS) as a new method of training in an attempt to gain an advantage over their competitors.[45] [81] No longer is it the sole responsibility of physiotherapists and rehabilitation specialists to understand and discover the potential of EMS. Physical educators are faced with the challenge of evaluating the potential for using electricity to their advantage in the field of athletics.

Much of the purported success of EMS as a means of enhancing athletic performance can be traced to the work conducted by Kots,[52] [53] a Russian neurologist. Kots[52] has reported that up to 30% greater isometric force can be produced during an electrically induced muscular contraction, and that a 30-40% increase in muscular strength has occurred following as few as 20 sessions of EMS. The basis for this claim is that electrically induced muscular contractions can recruit more of the muscle fibers in a muscle than can be achieved by a maximal voluntary contraction (MVC), resulting in a higher tension being developed within the muscle.[52] [53]

To produce muscular strength increases of this magnitude, Kots has utilized what is now termed, the "Russian Technique" of EMS. This technique consists of stimulating the muscle for 10 seconds (s) duration causing a maximal isometric contraction. Ten seconds was reported by Kots to be the appropriate duration for the stimulation, as a maximally stimulated isometric contraction can be maintained for 12.5s (±1.8) before the muscle begins to lose tension - that is fatigue.[53] Ten electrically stimulated contractions interrupted by 50s rest periods, constitute a single treatment session. Fifty seconds rest interval, according to Kots,[52] was an adequate interval between contractions to allow subsequent contractions to be maximal for the full 10s. The "10/50/10" protocol, therefore, represented the maximal workload that a muscle could tolerate in one treatment - 10 maximal efforts, each of 10s duration, could only be completed if a 50s rest interval was between efforts.[52]

In North America, little research has been conducted to examine Kots' unprecedented mode of training. Difficulty in verifying the Russian results mainly arises from the limited information made available regarding the criteria specified by Kots. Details concerning exact properties of the electrical current and method of electrode pad placement used by the Russian researchers have not been published on this continent. It is thought that a high frequency (1600-2500 cycles per second or cps) stimulator producing a sinusoidal current interrupted for 10 milliseconds (ms) every 20ms was used to cause the muscular contractions[24] and that both the direct and indirect method of pad placement were used.[52] Exact placement of the electrodes, however, is unclear, as are many other treatment details.

The researchers in North America who have attempted to duplicate the Russian Technique in their studies cannot be certain of doing so due to this insufficient documentation of Kots' work. The importance of Kots' work lies in the identification of a potentially useful strength improvement technique. Further investigation is required to better understand the potential of EMS as a method of strength training.

A. STATEMENT OF THE PROBLEM

With increasing numbers of people becoming involved in the fitness movement, more demand is being placed on physicians to diagnose their subsequent ailments and on therapists to treat them. To keep abreast of the increase in patient number, these professionals must be concerned about efficiency in their therapeutic practices.

An area in which the physiotherapist or the athletic therapist can strive to become more efficient, is the length of treatment time when using various modalities. If a therapist is able to complete a treatment in a shorter period of time, but still obtain the desired physiological responses from the body tissues, then he or she will be able to treat more patients and patients can return to activity sooner.

The purpose of this study was to address this problem directly, using electrical muscle stimulation (EMS) as a model. EMS is considered to be a useful modality in the rehabilitation of injured muscle or traumatized joints. This study investigated the effect of varying the rest period between isometric electrically induced contractions of the knee extensor muscles. Rest periods of 35, 50 and 65s were examined to determine the minimal time required to permit 10 maximal contractions each of 10s duration.

B. SUBPROBLEM

A variety of techniques are popularly used in the application of an electrical current to the target muscle or muscle group. Some factors which may dictate the method utilized include the presence of a cast, the presence of an open sore or swelling, the position and mobility of the patient, and the comfort of the patient in terms of the current sensation.

Two conventional techniques of electrical current application are the direct and the indirect technique.[77] [81] The present study examined two indirect methods of applying a commonly used form of faradic current (continuous, asymetrical, biphasic square wave produced by the TECA SP5/T stimulator) employed by clinicians.

C. HYPOTHESES

The three null hypotheses tested in this study were:

1. no significant difference in mean torque decrement, mean torque or peak torque existed between the three rest intervals when averaged over method of electrode pad placement $(p \leq 0.05)$
2. no significant difference in mean torque decrement, mean torque or peak torque existed between the two methods of electrode pad placement when averaged over rest interval $(p \leq 0.05)$
3. no mean torque decrement, mean torque or peak torque for any combination of method of electrode pad placement and rest interval differed significantly from any other combination $(p \leq 0.05)$

D. DELIMITATIONS

The delimitations of this study included:

1. the use of 30 normal, healthy, male university-aged volunteers, with no history of right knee or hip pathology or injury
2. the use of a clinically, unmodified (TECA SP5/T) electrotherapeutic stimulator
3. the testing of isometric right knee extension contractions with the joint angle of the knee fixed at 60 degrees flexion
4. the intensity of the EMS machine controlled by the subject and restricted to the subject's maximally tolerated level
5. the size and placement of the two surface electrodes
6. the three rest intervals of 35, 50 and 65s between the 10s contractions
7. the subject consciously relaxing the quadriceps (and hamstrings) throughout all contractions

E. LIMITATIONS

The limitations of this study included:

1. the inability to ensure that the subject's tolerance was indeed his maximal tolerance
2. the inability to ensure that the subject was not voluntarily contracting his muscles either with the stimulation (ie. the quadriceps) or against the stimulation (ie. the hamstrings)

3. the use of an external apparatus measuring maximal resistance torque, to represent contractile force within a muscle
4. the daily variation of the subject's tolerance, skin resistance and motivation

F. EXPLANATION OF TERMS

ISOMETRIC CONTRACTION: An isometric contraction is a contraction where the muscle develops tension, but does not shorten, appreciably, in length. During an isometric contraction, the muscular tension varies, but the muscle length and angle of the joint at which the contraction takes place remain constant.

MAXIMAL TOLERANCE: During each session, the subject was requested to stimulate his quadricep muscle to his maximal level of tolerance. The intensity dial was turned up by the subject to the point where the subject was taking as much current as he could tolerate within the limits of discomfort. Allowing the subject to control the intensity dial enabled the subject to turn down the intensity should he consider it necessary. As well, this control of the intensity dial may have decreased the subject's apprehension.

MEAN TORQUE: Mean torque was the average torque produced by the 10 stimulated contractions within one session.

MUSCULAR FATIGUE: Muscular fatigue was the decrease in the muscle's ability to attain or maintain tension during repeated bouts of electrical stimulation. In the present study, fatigue was measured by the decrease in torque that the quadriceps were able to produce during one session.

MUSCULAR STRENGTH: Muscular strength is the tension-building capacity of a muscle. Unfortunately the tension developed in a muscle during a contraction cannot be assessed directly by measuring the intramuscular tension developed between the muscle's boney insertions. Instead, an external apparatus measures a force representing the contractile tension of the muscle. In this particular study, a dynamometer (Cybex II dynamometer) measured the resulting torque produced by contraction of the quadriceps.

PAD PLACEMENT: The electrical current was transmitted from the electrical muscle stimulator (TECA SP5/T stimulator) to the skin via insulated wire leads and two electrodes. To ensure a firm and consistent contact between the electrodes and the skin, the lead electrodes were secured to the skin by an elastic tensor. Skin provides a high resistance to the electrical current due to the small number of ions located in its thick, dry, epidermis layer. By uniformily moistening a folded piece of cotton cloth with warm water and placing it between the skin and the electrode, the skin resistance was reduced. The damp intermediate cloth softened the dehydrated layer and provided ions to propagate the electrical current transcutaneously.[77]

The current was applied by utilizing two indirect techniques. For group 1, the experimenter, placed the distal electrode over the femoral nerve (the main nerve supply of the quadriceps) and the proximal pad over the lumbo-sacral area. Group 2 received the stimulation through a distal pad over the motor points of the three superficial quadriceps and a proximal electrode over the femoral nerve in the groin area.

PEAK TORQUE: Peak torque was the highest torque produced in one session. Three peak torques were identified per subject, each peak torque representing a 10s stimulated contraction.

REST INTERVAL: The rest interval was the period of time in between the ten 10s stimulated contractions. In this study, the three rest intervals used were 35, 50 and 65s. Within one session the rest interval was constant. For each session, however, the subject experienced a different rest interval which was randomly assigned prior to testing. During all rest intervals, the subject was instructed to remain seated in the testing chair with his legs relaxed.

SCORE: A score was an average of the initial or final stimulated torques. For Data 1, one score represented the average torque of the first [illegible] stimulations and another score represented the average torque of the last three stimulations. The average torque of the first five stimulations and the average torque of the last five stimulations described the scores of Data 2.

SESSION: One session consisted of ten 10s stimulated contractions interspersed by a rest interval of either 35, 50 or 65s. Within one session, the rest interval was consistent; however, different sessions had different rest periods.

STIMULATED CONTRACTION: The recorded torques represented muscular contractions which were elicited by electrical stimulation only. Voluntary effort on the part of the subject was not required nor desired.

TORQUE: Torque is a turning effect produced by a force acting about an axis of rotation. Mathematically, torque is equivalent to the force multiplied by the perpendicular distance from the line of action that the force acts and the fulcrum.[17]

In this particular study, torque, measured in foot-pounds (ft-lb), was recorded for knee extension. The axis of rotation at the knee was an imaginary line drawn through the femoral condyles in the saggital plane.[49] The lever arm associated with knee extension was the distance between the axis of rotation and the padded resistant block of the lever arm positioned just proximal to the level of the malleoli.

TORQUE DECREMENT: Torque decrement was the difference between the average torque of the initial stimulations and the average torque of the final stimulations recorded within one session. In this study, the torque decrement was defined in two ways: i) the average torque of the first three stimulations (ie. stimulations 1, 2 and 3) minus the average torque of the last three stimulations (ie. stimulations 8, 9 and 10), and ii) the average torque of the first five stimulations (ie. stimulations 1, 2, 3, 4 and 5) minus the average torque of the last five stimulations (ie. stimulations 6, 7, 8, 9 and 10).

Chapter II

REVIEW OF LITERATURE

The aim of electrotherapy is to obtain a contraction of the muscle being stimulated. The three qualities of the stimulating current necessary to cause the desired response of the muscle are: i) the current must be of a minimum intensity; ii) the current must be of a minimum duration; and iii) the current must reach its maximum intensity with an adequate speed of rise.[10, 14]

If a stimulus is inadequate to induce a response from excitable tissue, it is said to be a "subliminal" stimulus.[11] If it is just adequate to induce a response it is "minimal".[11] A minimal stimulus is produced from a single nerve or motor fiber. As the stimulus strength is gradually increased more and more motor units are recruited.[69] The lowest stimulus that excites all of the fibers of a given group of nerve or muscle fibers is a "maximal" stimulus. Any stimulus greater than this is "supramaximal".[11]

INTENSITY

The intensity of current is measured in milliamps. The level of intensity (or the number of milliamps) that a current must reach to cause the muscle to suddenly respond with a contraction, or a nerve to suddenly respond with a propagation of impulses is termed threshold.[10] For different motor and nerve fibers, the threshold is not the same.[10]

When stimulating a single motor fiber or a single nerve fiber, the fiber will not respond until the stimulus reaches threshold, and will not increase any further with increased current.[10] This "all-or-none" response may appear to defy the observed phenomenon of a muscle contraction gradually increasing in strength with enhanced EMS or with greater voluntary effort. However, because different motor and nerve fibers have different thresholds, as the stimulation intensity increases, more fibers will be excited until, at a certain level of current intensity, all of the muscle fibers are active resulting in a maximal contraction.[10] The summation of fiber activity within muscle accounts for the smooth transition from a just discernible contraction to a well defined maximal contraction.

The current intensity must be great enough to produce a greater than normal contraction of the target muscle or muscle group in order to improve strength.[52] Edwards et al.[21] found that stimulating the quadriceps at a frequency of 50cps or more, could produce a force up to 60% of that obtained during MVC. Bigland and Lippold[7] reported that stimulating the ulnar nerve at 40cps yielded a muscular contraction equal in strength to MVC. Kots[52, 53] claimed that 10-30% greater torques could be generated with EMS than with MVC. Despite the discrepancy in the percentage of MVC that can be obtained with EMS, there is general agreement that the greater the intensity, the greater the penetration of current.[45, 53] Having to penetrate the superficial adipose tissue as well as the skin, the current must be of sufficient intensity to excite the motor nerves of the underlying musculature.[45] In that context, the deeper the muscle fibers of the muscle, the greater the intensity of stimulation necessary to activate its motor neurons. [84] The more muscle fibers that are stimulated by the penetrating current, the greater the resultant tension.[53]

The level of stimulation intensity tolerated varies immensely between individuals. As the current passes transcutaneously to the muscle, many of the sensory (pain) nerve endings, which are numerous in the skin, become irritated.[84] Increasing the current intensity, increases the irritation. As a result, the magnitude of contraction, which is proportional to the stimulating intensity for a fixed frequency, is limited by the individual's ability to tolerate what is often perceived as an unpleasant sensation.[84]

In the literature, EMS studies report to employ a wide range of training intensities. Several studies stated to have used maximally tolerated EMS.[30, 35, 48, 54, 60, 79] In two studies involving a post-surgical immobilization period, Eriksson and Haggmark[31] and Stanish et al.,[79] found that in comparison to a control group, EMS retarded the deterioration of muscle function and metabolic potential, and lessened muscle atrophy which confronts a muscle after disuse. Godfrey et al.[35] also studying post-surgical knees, observed a superiority of EMS over voluntary isometric exercise or dynamic torque. However, this might be partially explained by the fact that the electrically stimulated group trained at maximal tolerance while the isometrically exercised group worked at 75% MVC. Johnson et al.[41] reported 25-200% improvement in strength of atrophied quadriceps of patients suffering from varying degrees of chondromalacia patella after 20 treatments of maximally tolerated EMS. With healthy subjects, Kramer and Semple[54] observed no difference in strength gains among groups exercised voluntarily, artifically or a combination of both despite differences in the percentage of MVC that the groups were trained (108% MVC, 87% MVC, and 107% MVC respectively). Massey et al.[60] found that training with maximally tolerated stimulation was no more effective than training with the traditional methods of progressive dynamic weight-training or isometric training.

Other studies involving normal subjects have reported amazingly similar results despite using EMS intensities ranging from 33% - 80% MVC. Laughman et al.[55] found no difference between groups isometrically exercised and groups electrically stimulated in final strength, despite the average torque monitored on the seventh contraction being 78% and 33% MVC respectively. In fact, the stimulated group had a slightly larger observed strength improvement (22%) than the voluntarily exercised group (18%). This appears to be contradictory to Knuttgen's minimal 'stimulus recommendation' of 50% MVC to increase strength, and suggestion that the closer to 100% MVC, the faster the development of strength.[51]

Currier and Mann[23] examined three isometrically trained groups: group 1 completed voluntary exercise at 119%MVC; group 2 completed electrical stimulation based exercise at 67%MVC; and group 3 completed superimposed exercise (EMS superimposed onto MVC) at 88%MVC. In an earlier study Currier et al.,[22] in examining isometric exercise superimposed with EMS and isometric exercise alone, did not specify the training workload but did report that the intensity of EMS was adjusted for the subjects' variable tolerance. In both studies,[22 23] it was concluded that EMS alone or EMS superimposed on voluntary effort was no more effective than the conventional isometric training. McMiken et al.,[62] using EMS not exceeding 80% and isometric contraction of "near maximum", support the results reported by Currier and

Mann [23] and Currier et al.. [22]

Using intensities varying from 33-108% MVC, it appears that repeated cutaneous electrical stimulation is comparable in effectiveness to common strengthening methods of static and dynamic exercise in healthy subjects. [23 54 55 60 62] In studies involving patients, it has been reported that EMS was actually superior to traditional rehabilitation techniques with no undersirable side effects. [30 35 41 79]

DURATION

The duration of currents used in stimulation ranges from 0.01-3,000 ms. [20] The minimal duration of an effective stimulus for nerve tissue is 0.03ms while that for muscle tissue is approximately one ms. [11] Currents over 10ms are classified as long duration and those 10ms or less in length are short duration currents. [20] Long duration currents are primarily used to stimulate denervated muscle while short duration currents are used for innervated muscle. [20]

Impulses of long duration cause uncomfortable stabbing sensations. [77] With impulses of 1ms or less, this discomfort is reduced to a mild, prickling feeling under the electrode which is more bearable. [77] The body receives minimal insult with impulses of even shorter duration (i.e. 0.03-0.1ms) due to the least amount of stimulus toxicity associated with this length of impulse. [14]

If the duration of an effective current is shortened without altering the intensity, there is a time when the current is no longer effective as a stimulus even though the intensity has not been altered. Wise (as reported by Cummings [20]) presented some insight into the phenomenon.

> After a motor nerve has been stimulated, there is a very brief refractory period (recovery period) when the nerve cannot be depolarized (send a message) at this point again. After a brief contraction, the fibers of a motor unit also go through a refractory period. These refractory periods in a nerve and muscle pass very quickly with muscle fiber being the slower to recover. For an individual muscle fiber the refractory period is at least 10ms long.

It is possible to compensate for this lack of duration by increasing the intensity. In other words, if the duration is decreased to the point of ineffectiveness, the effectiveness of the current can be restored by an increase in intensity. [10] The shorter the duration, and correspondingly the higher the frequency, of the current, the greater the intensity required to maintain an effective stimulus.[10] Kots[53] used the 10ms duration, as was cited by Wise, and stated that a modulated current of 10ms on, 10ms off, produced a maximal contraction with the least required intensity.

A shorter pulse duration, demanding higher current may cause technical problems clinically. A patient may be unable to tolerate the current required for a particular pulse duration to be effective. Similarly, the stimulator may not be able to produce adequate current for a particular pulse duration.

SPEED OF RISE

The speed of rise, the speed with which the current reaches its maximal intensity, is the third major factor which influences the response obtained from muscle fibers.[10] [20] It has been observed that when a current is of a constant intensity, the nerve adapts itself by a process called accomodation. Consequently, the stimulus is ineffective in initiating an impulse. When the intensity rapidly changes, by either rising or falling, the current is more effective for stimulation than a slowly changing intensity since it does not allow for accomodation.[20]

If the speed of the rise or fall of an effective stimulus is slowed down without altering the intensity, there is a point when the current is no longer effective as a stimulus even though the intensity has not been altered. The effectiveness of this current can be restored by increasing the intensity.[10] Therefore, the slower the rise, and similarly the lower the frequency, of current the greater the intensity must be for the current to be effective. In observing wave forms, one can appreciate that a rectangular wave changes more suddenly than a sinusoidal wave, which, in turn, changes more suddenly than a triangular wave.[77] The former two types of waveforms, therefore, are more effective than the latter waveform at a lower intensity. Slower rising currents such as the triangular wave form are referred to as selective currents and are found to be more conducive in stimulating denervated muscle than innervated muscle.[10] [77]

FREQUENCY

Pulse frequency which is partly determined by the duration of impulse and primarily dependent upon the length of rest between impulses,[20] has a less significant influence on muscle response than current intensity, pulse duration or speed of rise.[34] In fact, increasing the frequency from 40 to 100cps has little, if any, effect on the strength of an isometric contraction.[34] Frequency, however, is directly related to two of these factors; pulse duration and speed of rise.

Each muscle fiber has an optimum frequency where the threshold for excitation is lowest.[10] Above the optimum frequency, the threshold rises because with increasing frequency, the duration of the stimulus becomes progressively shorter. Below the optimum frequency, the threshold again rises, the rise in this instance, being due to inadequate rise speed of current.[10] Since frequency is directly related to rise time, the lower the frequency, the slower the rise time.

In normal innervated tissue, the natural frequency of excitation for a maximal voluntary contraction is usually 50-100cps,[20] [27] [34] with the threshold frequency of each individual muscle decreasing as the contraction force is reduced.[34] To produce a strong contraction utililizing EMS, a frequency of at least 50cps is required to produce a tetanically fused muscle contraction.[20] [24] [29] [3] Below this frequency, the tetanic contraction degenerates to a level where, at approximately 20cps, only a tremor (incomplete tetany) is visible.[24] [29] [34] At extremely low frequencies (less than 10cps[10]), the muscle activity decays into individual twitch responses.[24] [34]

It has been observed in humans, that muscle fibers are selective in choosing the frequency to which they respond. High frequency impulses (100cps or more) stimulate the fast twitch (FT) muscle fibers, while the low frequency impulses (30cps or less) activate the slow twitch (ST) muscle fibers.[20] [53] The goal of the training program, therefore, will often dictate the frequency of stimulation. If an increase in power and mass is desired, stimulation of FT fibers will achieve the effects most rapidly while stimulating the ST fibers will improve the endurance capabilities of the muscle.[20]

Frequency has been suggested to be related to pain.[24] [33] [52] It has been observed that with increasing frequency, the pain threshold rises much more than the motor threshold, the difference being very pronounced above 1000cps.[10] [33] On this basis, it has been claimed that using a frequency greater than 1000cps gives the best muscular response with the least amount of pain.[52] Kots[52] has reported that a modulated high frequency, interrupted sinusoidal current has an anesthetic quality. This type of current has been proclaimed as having the ability to block the small afferent (sensory) nerves in the area being stimulated and activate the large efferent (motor) nerves which cause the muscle to contract.[52] The 2500cps frequency current thought to be used by Kots,[24] however, is a carrier wave which is modified by interruptions of 10ms duration between continuous current periods of 10ms. As a result, it is a 50cps current which actually provides the motor stimulation.[16] In North American clinics, a 50cps (faradic) current is commonly used [20, 19] which is reported only to produce a mild prickling sensation due to stimulation of superficial nerve endings.[34]

PHYSIOLOGY OF NERVE CONDUCTION

The next few sections will provide a brief review of the fundamental neurophysiology of nerve and muscle excitation, outlining the processes which occur during voluntary and electricaally stimulated contractions.

The excitability of nerve and muscle tissue provides the basis for the therapeutic use of electrical stimulation. Both nerve and muscle cells are capable of transmitting electrochemical impulses along their membranes. An electrolytic fluid is found inside and outside the cells. A slight excess of anions (negative ions) accumulate along the inner surface of the cell membrane and an equal number of cations (positive ions) oppose on the outside of the membrane creating a membrane potential.[31] The resting membrane potential (i.e., when no electrical impulses are being propagated) is approximately 85 millivolts (mv).[25, 38]

The resting membrane potential can be disturbed by a chemical, mechanical, thermal, or electrical change which alters the permeability of the membrane.[38] The sequence of events resulting in rapid changes in the membrane potential followed by an immediate return of the membrane potential to its resting value is called and action potential (AP).[38]

Although not clearly understood, an AP is initiated by changes in the membrane properties that allow an increase in sodium permeability causing an influx of cations inside the cell membrane.[25] Not only does inflow of sodium ions neutralize the normal electronegativity inside the fiber, but also it creates a positive charge inside the membrane. This is called a reversal potential and for large, myelinated nerve fibers it can be approximately +45mv.[31]

Almost immediately following depolarization, the membrane again becomes almost totally impermeable to sodium ions. In addition, the membrane's permeability of potassium ions increases causing an outward flow of cations. These two events cause the membrane to return to normal resting potential. The ions are then actively transported across the membrane to their original locations (i.e., sodium on the outside; potassium on the inside) by sodium and potassium pumps, respectively.[31] This process of returning to the normal resting state is called repolarization.[31]

The two stages of an action potential, depolarization and repolarization, take less than a millisecond.[31] A second AP, however, cannot occur in an excitable fiber as long as the membrane is still depolarized from the first AP. The interval where the nerve is inexcitable is termed the refractory period. The refractory period of a large, myelinated nerve fiber is about 1/2500s. A nerve fiber, therefore, can carry a maximum of approximately 2500 pulses per second (pps).[31]

MUSCLE BIOENERGETICS

A muscle contraction involves the transformation of chemical energy into mechanical energy.[61] The two major energy systems of the body, the aerobic and anaerobic systems, provide the necessary energy for muscular work. The system which is utilized by the muscle depends upon the type of activity in which the muscle is engaged. For submaximal, endurance-type efforts, the muscle attains its energy primarily from the aerobic system. Conversely, if the muscle is involved in short intense bouts of work, the muscle is fueled predominantly by the energy from the anaerobic system.[61] Due to the short intense nature of the contractions examined in the present study, the latter system will be detailed.

The anaerobic system is comprised of two pathways; the adenosine triphosphate-phosphocreatine (ATP-PC) pathway and the lactic acid (LA) pathway.[61] Both pathways provide a method of replenishing ATP, the fuel for muscular activity. The ATP-PC system is the least complicated of the body's energy systems and provides the most rapidly available source of ATP to be utilized by the muscle. The LA system is slower in becoming activated but is able to provide approximately twice as much ATP as that which is obtained from the ATP-PC system.[61] Neither pathway requires oxygen to function.

The immediate source of energy for muscular contraction is the adenosine triphosphate (ATP) molecule which is stored in all muscle cells.[34, 61, 69] Every molecule of ATP consists of two high-energy phosphate bonds, each containing approximately 8000 calories of energy per mole of ATP.[34, 61] When the phosphate bonds are broken, the energy liberated supplies a source of energy for the muscle cell.

To replenish ATP stores quickly (within 10s of the commencement of an intense muscular effort),[61] another high-energy molecule, also stored in the muscle cells, is necessary. Phosphocreatine (PC), like ATP, liberates a large amount of energy when the bond between the creatine and phosphate is broken.[27, 61] This energy is used directly to resynthesize ATP. Ironically, the only means by which PC can be re-formed is from the energy released during the breakdown of ATP. These two interdependent reactions are referred to as "coupled reactions" as the energy released from one series of reactions is linked with the energy needs of the other series.[61] That is, the energy liberated from the breakdown of PC is used to resynthesize ATP, and the energy released from the breakdown of ATP is utilized to resynthesize PC.

The second anaerobic pathway to restore the ATP supply is the LA system, or more commonly referred to as glycolysis. Glycolysis, meaning the "dissolving of sugar", uses glucose (sugar) to manufacture ATP.[61] In the absence of oxygen, carbohydrates (glycogen and glucose), are incompletely broken down, leaving the by-product lactic acid within the muscle cell. Accumulation of high levels of lactic acid indicates depletion of glucose stores thereby causing muscular fatigue and limiting the anaerobic capacity of ATP production. The LA system, however, is capable of providing the muscle with ATP during maximal exercise lasting om 10s to two or three minutes prior to the onset of the aerobic system.[61]

PHYSIOLOGY OF MUSCLE CONTRACTION

The skeletal (voluntary) muscles of the human body constitute approximately 40% of the total body weight.[27] Each muscle is composed of many thousands of individual contractile fibers. These muscle fibers, or muscle cells, are the organizational unit of the muscle. Groups of muscle fibers are contained within a sheath of connective tissue to form muscle bundles. In turn, these bundles are bound together by connective tissue. The entire muscle is encased in yet another connective tissue sheath.[61]

Skeletal muscle is sometimes referred to as striated or striped muscle due to the visible alternating light and dark striations under a microscopic view of a myofibril. Myofibrils are the basic structural and functional component of a muscle cell.[2] [61] The regularity of the alternating light and dark bands is caused by a geometric arrangement of protein filaments.[61] The light areas are referred to as "I" (isotropic) bands while the dark areas are called "A" (anisotropic) bands.[69] The "I" band is bisected by a dark "Z" line. The portion of the fiber lying between the two "Z" lines is called a sarcomere, the basic contractile unit of the muscle cell.[47] [69]

These light and dark bands are composed of two different protein filaments; a thinner actin filament and a thicker myosin filament.[61] [69] The "I" band is composed entriely of the thinner actin filament. The "A" band, however, is composed mainly of the thicker myosin filament with only a small amount of actin.[61]

SARCOTUBULAR SYSTEM

The sarcotubular system consists of two distinct tubular systems; the transverse tubule system (T-system) and the sarcoplasmic reticulum (SR). These two systems are responsible for uniting the excitatory process and the mechanical contraction within a muscle.[69]

The T-system consists of tubules leading from, and continuous with, the sarcolemma which is a membrane that surrounds the striated muscle fiber.[69] The tubules also run crossways through the fiber reaching deep into the fiber.[47] In man, the transverse tubules run across the fibers at the junctin of the "A" and "I" bands. Thus, there are two networks of traversally running tubules per sarcomere.[69] With the membranous walls of the transverse tubules being continuous with the sarcolemma, an action potential passes along the T-tubules and around each fibril. The sarcolemma, therefore, has the capacity to propagate an action potential.[47 69]

The SR is a special endoplasmic reticulum which forms an irregular longitudinal arrangement around each of the fibrils and between the T-tubules.[69] The portion of the SR adjacent to the T-tubule is oriented in a transverse direction and forms a large lateral sac running beside the T-tubule. This lateral sac is called a terminal cistern.[69] The cross sectional view of this arrangement with a T-tubule surrounded on both sides by terminal cisternae is referred to as a "triad".[61]

The primary functions of the terminal cisternae are to bind to and store calcium ions.[69] The terminal cisternae release the calcium ions in response to electrical activity spreading inward along the T-tubules. The enhanced sarcoplasmic calcium concentration then initiates and sustains the contraction until the calcium is reabsorbed by the SR. Thus, the SR is not only the source of calcium to initiate contraction but also the "relaxing factor" in muscle.[69]

THE CONTRACTILE APPARATUS

The extraordinary property of a muscle cell is its ability to contract. Regulated by calcium, the interaction of thick and thin myofilaments produce this phenomenon.

The thick myofilament is composed almost entirely of myosin molecules.[34 69] Tiny protein projections extend laterally from its central core. These lateral protrusions or "cross-bridges" have the capacity to bind with actin.[61 69]

Actin is one of several important proteins comprising the thin myofilament of the muscle fibril. Actin consists of a double helix of globular molecules which forms the backbone of the actin filament.[35] Spiraling around the double helix is tropomyosin, a long, thin molecule.[61] The ends of the tropomyosin molecules are enclosed within the globular molecules of troponin. This third protein associated with the thin myofilament has a high affinity to calcium ions.[38] Troponin does not bind directly to the actin protein but binds indirectly through its attachment to tropomyosin.[69] The presence of the troponin-tropomyosin complex prevents the binding of myosin and actin.[38]

THE SLIDING FILAMENT THEORY

The occurrence of a muscular contraction is explained by the sliding filament theory which suggests that one set of filaments slide over the other causing the muscle to shorten. The sliding filament theory has been described as:

> . . .a mechanism somewhat analogous to the way in which a telescope shortens, i.e., the overall length of the telescope (muscle) decreases as one section (actin) slides over the other (myosin), with neither section itself shortening.[61]

The precise manner in which the sliding process occurs is not completely understood. However, it is thought that the cross-bridges of the thick filaments form a type of chemical bond with the active sites on the on the thin filaments.[61]

EXCITATION

Each muscle fiber is innervated by a motor neuron.[2] The site of innervation, the neuromuscular junction, is located near the middle of the muscle fiber. Contraction of the muscle cell is initiated by an AP transmitted by a motor neuron to the muscle fiber via the neuromuscular junction.[69] With this junction being centrally situated, the AP can spread from the centre of the fiber towards its two ends allowing all of the sarcomeres to contract almost simultaneously.[38]

The transmitted impulses cause a release of acetylcholine (ACh) which is stored in the synaptic vesicles of the nerve terminal.[2] [69] The liberated chemical diffuses across the neuromuscular junction and binds to a specific site on the motor end plate of the sarcolemma.[2]

The presence of ACh on the motor end plate results in changes in the permeability of the motor end plate's membranes. The membrane threshold potential is lowered to cause an increased influx of sodium ions. The altered potential is called an end-plate potential which is capable of producing a single AP in the sarcolemma.[2] [69]

EXCITATION-CONTRACTION COUPLING

The propagation of action potentials along the T-tubules causes calcium ions to be released from the terminal cisternae of the SR.[47] [69] The "freed" calcium ions bind immediately to the troponin molecules on the actin filaments which, in an unknown manner, removes the inhibitory effect of the troponin-tropomyosin complex on the actin filament.[47] In the presence of calcium,the myosin cross-bridges are able to interact with the actin filament.[47] Biochemically, this linkage is referred to as actomyosin.[69] The formation of actomyosin activates an enzyme component of the thick filament called andenosine triphosphatase (ATPase).[61] This enzyme causes the breakdown of ATP which liberates large amounts of energy. The released energy enables the cross-bridges to move in such a way that the actin filament slides over the myosin filament towards the centre of the sarcomere.[61] [69] In a shortened state, the sarcomere's banding changes. With a contraction, the "I" band narrows while the width of the "A" band remains constant.[2] [69]

In order to account for the degree of shortening that is observed in a muscle, the cross-bridges must be able to attach, move, and detach at different actin sites in a cyclic manner.[38] This series of actions, termed the "rowing motion of the lateral projections",[69] requires a large source of ATP as a single myosin cross-bridge may "make and break" with active sites on actin filament hundreds of times in a one second contraction.[61] The ATP utilized for a muscular contraction is primarily produced within the mitochondria of the sarcoplasm.[38] [47] The rate and extent of ATP resynthesis depends upon the availability of ADP in the cell and the oxygen supply from the blood, although a small amount of ATP resynthesis can occur in the cytoplasm via anaerobic glycolysis.[34]

RELAXATION

Following the passage of an electrical impulse through the T-tubules, the calcium ions are actively pumped out of the sarcoplasm by the entire SR.[47] [69] The calcium is stored in the terminal cistern until the next AP is transmitted. In the absence of calcium, the myosin and actin interaction terminates producing muscular relaxation.[69]

By way of summary, calcium initiates and terminates a muscular contraction. If calcium ions are released from the terminal cisternae of the SR, the muscle contracts. If the calcium ions are reabsorbed by the SR, the muscle relaxes.

RECRUITMENT ORDER OF MOTOR UNITS

A motor unit consists of a group of muscle fibers activated by a single nerve.[19] Each motor unit is active at a characteristic level of tension and ceases to discharge when tension falls below this critical level. In this way, motor units can be described by referring to the percentage of maximal muscular tension at which it is active.[42]

In humans, the muscle fibers of a motor unit can be of two basic types; the slow twitch (ST) fiber and the fast twitch (FT) fiber. Slow twitch fibers are innervated by small, lightly myelinated, low excitation frequency (30cps) motor neurons which cause the contraction and relaxation times to be slow.[37] [45] [84] It is estimated that the peak tension of ST fibers is attained within 100ms.[85] Characterized by high mitochondrial and capillary densities, ST fibers rely on the aerobic energy system.[45] [82] Being highly resistant to fatigue, ST fibers are best suited for endurance activities.[69] [84]

Fast twitch fibers, unlike the aerobic ST fibers, have low mitochondrial and capillary densities making FT fibers susceptible to fatigue.[82] Deriving energy from the anaerobic system, FT fibers have high glycolytic and myofibrillar ATPase activity.[45] [69] Large, high excitation frequency (30-100cps or more) motor neurons innervate the FT fibers. These heavily myelinated neurons cause high conduction velocities which generate quick, strong muscular contraction.[37] [45] [84] Fast twitch fibers reach peak tension in approximately 10ms.[85]

Based on these physiological capabilities and on the fact that FT motor units innervate a large number of fibers while ST motor units have a low innervation ratio, FT muscle fibers are primarily responsible for producing short duration power and strength activities,whereas ST fibers are associated with long sustained contractions at low tensions.[20] [69] [70]

In order to minimize the amount of fatigue produced during a muscle contraction, the proportion of each fiber type's contribution towards the contraction varies depending on the magnitude of effort.[27] In turn, the amount of the tension generated is directly dependant upon the electrical activity of the motor unit.[7] Therefore, even with maximal contraction, new muscle fibers are being recruited.

This was demonstrated by Gollnick et al.[36] who examined the muscle fiber type that was recruited at different tensions relative to the MVC of the knee extensors. At low tensions, the ST fibers were predominantly active while at higher tensions the FT muscle fibers were preferentially recruited. The critical tension was determined to be 20% MVC. With sustained contractions less than 20% MVC, there was a major reliance on aerobic ST fibers while above this level there was a dependence upon anaerobic FT fibers. It was suggested that restriction of blood flow and thus the availability of oxygen at tensions greater than 20% MVC may partially explain the recruitment order of muscle fibers.

Although the magnitude of the contraction dictates the type of muscle fiber that is activated, the amount of tension generated is directly dependent upon the electrical activity of the motor unit.[7] The excitability of the motor units is determined by the size of the cell body. This size controls the recruitment order of the muscle fibers. The ST fibers which are associated with small cell body neurons are recruited first. Conversely, FT neurons with the large cell bodies are the first units to be inhibited.[42 66 70]

The recruitment order of muscle fibers during EMS is opposite to the "normal" voluntary sequence. This can be explained by the fact that electrical threshold of a muscle fiber during EMS is inversely proportional to axon diameter.[84] Consequently, for a small, electrically stimulated contraction, the large FT fibers are recruited first.[20 84] In addition, FT fibers are superficially located in the muscle.[84] As a result of these two facts, the FT fibers, which are most prone to fatigue, are stimulated prior to ST fibers during EMS.

Munsat and his associates,[67] while treating patients with implanted stimulation of the femoral nerve to attempt to correct knee flexion contractures, found that recruitment of a particular muscle fiber did not solely depend upon the frequency of current. When a muscle was stimulated to contract isometrically in a lengthened state against resistance, an increased proportion of recruitment of ST fibers was noted along with an increased size of both ST and FT fibers. On the other hand, when the muscle contracted isometrically in a shortened length and with less resistance, the ST fibers decreased in number and in size compared to the FT fibers. This lends support to the reverse recruitment order of EMS when contrasted to the voluntary sequence.

Voluntary and artificial muscular contractions differ fundamentally in another respect. During a volitionary effort, the excitation of muscle fibers is alternated asynchronously so as to minimize the metabolic fatigue experienced by the fibers during contraction.[62] It appears that with cutaneous electrical stimulation, all motor units are activated synchronously precipitating early fatigue.[62]

The significant differences between voluntary and stimulated contractions must be recognized and understood. Knowledge of dissimilarities in recruitment order and time over which similar fibers act can help explain the occurence of physiological adaptations which may otherwise be unexpected.

MUSCULAR FATIGUE

Physical fatigue has long been recognized as a deterent of productivity whether it is at a fish-packaging plant or at a high school track meet. Unfortunately, fatigue has been poorly understood for about as long as it has been known to exist.

Muscular fatigue is characterized by the decrease in ability of a muscle to continue to exert its previous level of tension.[17] It is not known for certain whether the force that can be exerted by a muscle is limited by: the capacity of the nervous centers and conducting pathways to deliver the motor impulses to the muscle fiber; or the efficiency of the circulating system to transport needed substances into the muscle or to transport unwanted metabolites out of the muscle; or the intrinsic contractile properties of the fibers themselves.[64 78] Much of the research on muscular fatigue that has been done is concerned with determining the primary site causing the reduced muscular function. The two popular theories of muscular fatigue are the "central" fatigue theory and the "peripheral" fatigue theory.

EVIDENCE FOR CENTRAL FATIGUE

Support for the central fatigue theory was evident as early as the late 1920's. Reid[72] observed the response of muscle to voluntary contractions and to artificially stimulated contractions. The middle finger, resisting 1/2-5 kilograms (kg), was voluntarily contracted at a frequency of 12-160 per minute (/min). The artificial stimulation, applied both indirectly and directly, consisted of short (1/5-3/5s) duration faradic stimulation at rates of 12-80 pulses per minute (ppm). The initial contraction height of maximum voluntary effort and indirect stimulation was identical. After complete voluntary fatigue at a fast rate of contractions, indirect as well as direct stimulation produced sizeable contractions, though smaller than the initial amplitude. During a slow rate of voluntary contractions (12-80/min) carried to the point of fatigue, the response of the muscle to indirect and direct stimulation was practically unimpaired. Similarly, after fatiguing the muscle isometrically, it still responded strongly to direct electrical stimulation. As a results of his work, Reid claimed that the central nervous system (CNS) is the primary site for fatigue, but he also recognized that neuromuscular and contractile fatigue are contributing factors.[72]

Asmussen and Mazin[3] were also able to lend support to the central fatigue theory. Five subjects engaged in arm/finger isotonic work to exhaustion with two minute rest periods interspersed between work bouts. All the odd numbered work bouts were conducted with the subjects' eyes opened. All the even numbered work bouts were conducted with the subjects' eyes closed. After exhaustion had been reached with the eyes closed, it was found that 15-30% more work could be accomplished when the eyes were opened. When subjects worked to exhaustion with their eyes opened, none of the subjects were able to produce a measureable increase in the amount of work when their eyes were closed.

From this work it appears as though increased arousal of the CNS caused by the opening of the eyes, actually increased the average mechanical responses of the patellar tendon tap by 93-168% when compared to the subjects when their eyes were closed. Having the eyes of the subjects opened, therefore, appeared to increase the amount of work performed by the muscles being tested as well as increase the central excitatory state, as manifested by the increased responsiveness of the patellar reflexes.

The "diverting activity" (i.e. the eyes being opened) is explained by an increased facilitation of neural/motor systems which, in fatigue, is inhibited centrally through afferents from receptors in the fatigued muscle.[3]

Bigland-Richie et al.[8] provided further evidence for the central fatigue theory. The force of the quadriceps produced by a supramaximal stimulation via the femoral nerve (50cps) and by a maximal voluntary effort were compared over a 60s period. During the first 30s, the contraction force during both conditions fell similarly suggesting that the inability to maintain force was due to failure at or distal to the neuromuscular junction. After 45s, however, the voluntary force fell faster than the artificially stimulated force indicating that the later period of strength decrement was due to a decrease in the central neural drive.[8]

EVIDENCE FOR PERIPHERAL FATIGUE

The central fatigue theory was not seriously challenged until Merton[64] who initiated the peripheral fatigue theory. Merton compared the maximal voluntary tension with the maximal electrically stimulated tension developed in the adductor pollicis muscle. In man, this muscle is the only ulnar supplied muscle acting on the thumb and, in addition, is the only muscle used in voluntary adduction of the thumb.[64] The voluntary force and the artificially stimulated force, therfore, can be compared with reasonable certainty that the same muscle mass produced both forces.

Merton stimulated the ulnar nerve at a frequency of 50cps and a duration of one second which produced a contraction identical to the MVC produced by an unfatigued adductor pollicis muscle[64]. After voluntarily fatiguing the muscle, however, this stimulation format could not elicit a mechanical response. Furthermore, Merton observed that recovery did not occur until circulation was restored. This phenomenon was attributed to biochemical changes in the contraction mechanism which could be overcome by eliminating the occlusion.

The work of Merton is contrary to Reid's observations. Merton argued that if fatigue occured centrally, then strength should begin to recover when the muscular effort ceased as there was no interference with the circulation to the central structures. The discrepency between Reid's and Merton's results may be accounted for by the difference in the rate and/or the strength of contractions. Reid employed a series of repetitive submaximal contractions while Merton utilized a sustained maximal contraction. [13]

Similar to Merton, Naess and Storm-Mathiesen (as reported by Simonson[78]), after voluntarily fatiguing the adductor pollicis muscle, were unable to restore the strength of the muscle using indirect electrical stimulation of the ulnar nerve. These investigators supported Merton's conclusion that the site of fatigue was peripheral.

In contrast to Merton, however, Naess and Storm-Mathiesen credited the presence of fatigue to a failure in the neuromuscular junction. Naess and his associate found a decrease in the action potential height when the fatigued adductor pollicis muscle was indirectly stimulated. Transmission fatigue was, therefore, observed as the limiting factor in a muscular contraction.

Transmission fatigue has long been accepted in neuromuscular physiology.[78] Immediately after complete fatigue by indirect stimulation of the motor nerve, the muscle responds to direct stimulation.[78]

Stephens and Taylor[80] suggested that both peripheral components contribute to fatigue. In the initial stage of force decrement, fatigue of the sustained maximal contraction of the first dorsal interosseous muscle was attributed to failure at the neuromuscular junction as the action potential of the ulnar nerve was relatively unchanged when compared to the significant decrease in force. As the force generated fell to approximately 25% in the second stage, however, fatigue was then attributed to failure within the contractile mechanism. At high levels of force the presence of artificial occlusion (arterial cuff) made no difference in the progression of fatigue but in the second stage of fatigue, the cuff prevented the plateauing that occurred normally when the force was diminished to approximately 25% MVC. The force produced by the muscle which had the blood supply impaired, decreased to a level well below the 25% MVC.[10]

It is evident that muscular fatigue is complex. It is probably most accurate to state that this phenomenon is a result of a combination of central, neuromuscular and contractile fatigue and that the site of fatigue depends upon the type of activity. It is speculated that neuromuscular fatigue is most marked during intense muscular contractions and that contractile fatigue is more prominent during low tension efforts.[10] Central fatigue has been commonly viewed as a safety device to protect the muscles from injury.[13]

BLOOD FLOW AND FATIGUE

The rate of fatigue is directly related to the intensity of the contraction.[32] At low tension levels up to approximately 10-15% MVC, a steady state is reached whereby the metabolic requirements needed for the contraction are sufficient to maintain the contraction.[56] In this state, fatique is not reached.[56] At tensions greater than 15% MVC, the metabolic requirements become less sufficient for the needs of the contraction. When the supply and demands of energy sources are not in balance, fatigue is inevitable.

Muscular contraction of higher intensities cause impairment of blood flow.[8 26 32] The greater the force of contraction, the greater the force of mechanical compression exerted by the muscle fibers on the blood vessels.[32] The exact percentage of MVC at which blood occlusion occurs during an isometric contraction is not agreed upon. Some investigators have suggested that a force as low as 20% MVC is capable of interrupting the blood supply to the active muscle.[1 28] Most, however, agree that a contraction ranging from 30-60% MVC causes the internal muscular pressure to be equivalent to the blood pressure.[16 51 64 75] Still others have proposed that blood flow is not interrupted during an isometric contraction until 70% MVC is obtained.[12 32]

Regardless of the %MVC that blood occlusion occurs, it is well known that a sustained isometric contraction causes a depletion of high energy phosphates (ATP and PC) compounds which are immediately available for the maintenance of muscular contraction.[17] [61] In addition, without circulating blood, the removal of accumulated metabolites is impaired. With the depletion/replenishment system inoperative during blood impedment, the force of the sustained contraction decreases. [50] The rate of force degradation is directly related to the intensity of the contraction. [17] A maintained contraction reduces in strength until the tension falls to the critical level (20-70% MVC, depending on the reference) at which point the fatigue curve flattens. This plateau represents the re-establishment of steady state as blood flow is restored and the faitgue rate is reduced.[64] [75]

DURATION OF ISOMETRIC CONTRACTION

The amount of force exerted and the duration for which this tension can be sustained without fatiguing are inversely related.[34] When an isometric contraction is below 15-20% MVC, the muscle cannot reach a state of fatigue regardless of the duration of contraction.[4] [36] This can be explained by the fact that the muscle is able to produce the energy required for maintaining the static contraction at a rate equivalent to the rate at which energy is expended.[34] In this instance, a steady state is attained. For an isometric contraction which is greater than 15-20% MVC, however, the muscle expends (entirely in the form of heat)[9] at a faster rate than the rate at which energy is regenerated.[36] [69] With a static contraction greater than 15-20% MVC, therefore, a gradual depletion of stored energy must result and fatigue is inevitable. The time required for fatigue to develop is indirectly related to the tension exerted.

When developing a training program, the energy system(s) utilized must be identified. The energy system that is involved is directly dependant upon the duration of activity.[61] Activities of long duration (i.e., exceeding five minutes) rely predominantly on energy derived from the oxygen system. Exercises of short duration (five minutes or less) obtain energy primarily from the ATP-PC and LA systems.[61]

A training program designed for improving muscular strength involves exercise bouts of short duration and of near maximal effort. With intense, heavy muscular activity, the ATP-PC system will provide the necessary energy.[61 83] This immediate anaerobic energy source, however, can be depleted, in man, within 10s. [61 83]

The duration of a muscular contraction which is claimed most effective for the purpose of strength training, varies from six to 15s. Hettinger and Muller (as reported by Rose et al.[74] and Fardy[32]) stated that maximal strength improvements could be obtained with an isometric contraction held for six seconds. Kots[52 53] and others[51] have suggested that a 10s muscular contraction was the optimum length for a maximal effort. Royce[75] reported that an isometric MVC could be maintained for 15s at which time the tension produced by the muscle began to fall.

In the literature, strength training studies have utilized various lengths of contractions. Many studies[11 35 40 48 54 60 62] have employed the 10s contraction as proposed by Kots for improving muscular strength. Several[22 30, 31 58 74] have chosen the six seconds as suggested by Hettinger and Muller. Still others[23 24 55 61] have allowed for a 15s contraction (five seconds to reach peak tension with the remaining 10s maintained at the maximal level of intensity).

REPEATED MUSCULAR CONTRACTIONS

There are two major criteria for improving muscular strength, both of which employ the overload principle.[50] A muscle must contract against a resistance of an adequate load, a sufficient number of times in order to increase its strength.[77] Since the first factor of training at a high intensity has been discussed, the number of repetitions will be reviewed presently.

The evolution of the number of repetitive actions within one strength training workout is intriquing. In the early 1950's, Hettinger and Muller (as reported by Rose et al.[74] and by Fardy[32]) claimed that strength could increase at a rate of five percent per week just by isometrically contracting a muscle, or muscle group, for six seconds at two-thirds maximal tension, once daily, five times per week. These results were supported a few years later when

Rarick and Larsen[71] duplicated Hettinger and Muller's study, concluding that brief periods of isometric tension (one six-second bout of isometric exercise daily at two-thirds MVC) proved to be as effective for strength development as more frequently repeated (up to eight per day) exercise bouts at higher levels of tension (up to 80% MVC).

In the early 1960's, Muller (reviewed by Matthews and Fox[61]) claimed that maximal strength could be developed best by training five day a week with each training session consisting of five to 10 maximal contractions held for five seconds each. The length of the rest interval dispersed between the series of contractions was not indicated. Berger[6] stated that the optimum number of repetitions for increasing the tensile strength of a muscle is between three and nine repetitions in one set and that this format should be repeated for 12 weeks to produce an increase in strength.

Hislop (as reported by Hood and Forward[44]) expressed the importance of the rest interval when he stated: "If a maximal effort has been executed, the tension reached can't be repeated or exceeded by a second contraction in a short interval of time". With this in mind, Kots[52] designed an experiment to determine the optimal rest interval which enabled a second maximal isometric contraction of 10s (induced by electrical stimulation) to be equivalent in strength to the first contraction of the same duration. Using intervals of 10, 20, 30, 40 and 50s, Kots found the 40 and 50s rest period to be superior. Proceeding one step further, Kots examined which of these two rest intervals would permit a series of 10 consecutive, maximal isometric contractions each of 10s in duration. It was reported that the 50s rest interval allowed each of the contractions to be maximal. With the 40s rest period between each of the 10 efforts, the last contractions were submaximal.

Today, a routine including two to five bouts (sets) of six to 10 repetitions daily, or every other day, is practiced commonly as this is thought to produce the greatest strength increase in the least amount of time. Studies[24 59 79] utilizing this protocol for increasing strength have reported greater resting concentrations of energy stores, such as muscle creatine and adenosine, suggesting the capacity of the ATP-PC system has been enhanced. Since this system is used for intense maximal efforts, the ability of muscle to improve its strength is increased.

RECOVERY FROM REPEATED MUSCULAR CONTRACTIONS

In order to perform multiple contractions, the intercontraction rest interval must be of sufficient length. During this period, the energy stores which have been depleted through muscular activity are restored so as to be available when needed by the next effort. The recovery period, as it is termed, is functionally the opposite process of fatigue.[77]

The amount of recovery that occurs during an intercontraction rest interval depends on two factors; the length of the recovery period and the degree of strength degradation.[12] These factors appear to have a paradoxical relationship. This paradox was illustrated by Caldwell[12] who observed the amount of recovery that occurred during a series of contractions. Each session consisted of ten 12.5s isometric contractions separated by intertrial intervals of 12.5, 25, 50, 100 and 200s, with intervals being constant within a given session. It was observed that with short intercontraction intervals, recovery tended to increase with successive rest periods but with long relief intervals there was a tendency for recovery to decrease with repeated rests. The explanation to this seemingly unrealistic condition is that the amount of recovery is not only determined by the length of recovery period but also by the degree to which the muscle has been degraded by prior efforts. Contractions occurring more frequently accumulate more metabolites and deplete local energy sources to a greater degree than contractions with longer intercontraction intervals. The shorter intervals, therefore, are inadequate to permit complete recovery of contraction strength.

In a later study, Caldwell and Lyddan[13] conducted a similar study, however, each session in this instance, included ten 25s isometric contractions separated by intercontraction periods of 25, 50 and 100s. Although supporting the conclusions of the earlier study with regard to the recovery tending to increase with shorter rest intervals and decrease with long rest periods, Caldwell and his associate were unable to define a clear relationship between decrement and recovery. The shorter intercontraction interval displayed a slight inverse relationship between decrement and recovery but for the 50 and 100s rest, both decrement and recovery tended to decrease with trials.

Since recovery patterns, like fatigue curves, are a function of the exercise intensity, it seems reasonable that muscles must be fatigued to the same level of strength before making a comparison of the relative effects of two or more exercise programs on recovery.[17] In a study by Clarke[14], this factor was not controlled. There was an apparently greater recovery following static exercise. This difference, however, may not have been due to the fact that the muscle was fatigued isometrically, rather than isotonically, but that the isometric exercise was more fatiguing as was evidenced by the significantly lower final strength scores (32.2 kilogram, or kg, for the isotonic group and 19.9kg for the isometric group).

Conducting a study similar in design to Clarke's earlier study, Clarke and Stull[17] exercised the forearm flexors of 31 adult males for three minutes isotonically, maximally contracting once every two seconds. One week following, the same group isometrically exercised their forearm flexors, not for a particular duration as in Clarke's[14] study, but to the level of strength decrement equivalent to that which this muscle group attained the week prior. After both testing sessions, the subject rested for 60s before maximally contracting the forearm flexors. This sequence of 60s rest followed by MVC was repeated for 10 minutes (min) following the two exercise bouts.

Unlike the previous study, Clarke and Stull[17] failed to conclude that the recovery is faster following isometric exercise. Instead, these investigators observed that the strength recovery curve has two components; a fast component initially followed by a slow component. The advantage in recovery of one mode of exercise over the other changes depending upon the phase of recovery.

For both exercise conditions, the initial phase of recovery lasting up to two minutes is characterized by a fast component. After two minutes of recovery, the slow component dominates. When muscle strength is depressed to the same level, the isotonically exercised muscle recovers quicker during the initial stage of recovery.[17] This advantage subsides and thereafter recovery is 35% faster following isometric exercise.[17] One must be cautious, however, of interpretation. The 35% faster recovery in the second phase following isometric exercise may not be advantageous if one wishes to recover as much strength as possible in the first couple of minutes of recuperation.

Clarke and Stull[17] have suggested that the two components of the recovery curve parallel the normal recovery blood flow curves. The initial phase is associated with reactive hyperemia while the second phase accounts for normal blood flow debt. In recovery blood flow curves, the first stage is much faster than the second stage.

In attempting to define the relationship between chemical recovery in muscle and the recovery of muscle performance, Harris et al.[43] found that occlusion of circulation (artificially) during recovery prevented resynthesis of energy stores thereby inhibiting muscle strength recovery. Under normal conditions, however, it was observed that PC resynthesis occurred in a biphasic manner, exhibiting a fast and then a slow recovery component. Since the replenishment of PC relies on the presence of oxygen,[78] the biphasic resynthesis of PC must be related directly to the biphasic blood flow curves.

QUADRICEPS FUNCTION

The quadriceps is very important for everyday physical activity. Originating above the knee joint and inserting onto the tibia below the knee, the quadriceps muscle group extends the knee. Due to their internal attachments, the force that the muscle produces cannot be measured directly. The muscular tension generated, therefore, is tested externally via their levers systems.[88]

Being easy to position and stabilize, tha quadriceps group is a good muscle for testing. As a result, it is a common muscle used in investigations, making comparisons with other studies possible.

In studies observing muscular strength of the quadriceps, it has been commomly agreed that the maximum isometric contraction of the quadriceps can be obtained at 50-70 degrees of flexion.[11 21 39 46 57 61 76] At this angle, the quadriceps (specifically the vasti) is in the lengthened position. Being a two-joint muscle, however, the angle at the hip is also important to consider.

While a subject is in a sitting position with the knee flexed at 60 degrees, it has been suggested that the hip should be extended to 110-135 degrees in order for the heavy resistive exercise of the knee extensor muscles to be performed effectively.[21] This angle places the rectus femoris in a lengthened position. With the knee flexed to 60 degrees and the hip extended 110 degrees, all muscles of the quadriceps, therefore, are in a lengthened state enabling the muscle to exert the greatest extensor force at the knee.[21] A strong contraction results because the sarcomeres are lengthened which places the cross bridges in a more effective position for formation.[17]

To accurately measure the strength of the quadriceps mechanism, one must stabilize the rest of the body (i.e. the hips and trunk) to restrict extraneous movements of the subject during testing. A subject will be unable to exert maximum force of the muscle group being tested unless other muscle groups of the body contract to provide as firm a base as possible from which to pull. [63] The stabilizing force must be at least equal to the maximal force that the muscle being tested is able to exert.[63] If the stabilization is inadequate, the measured force of the muscle will represent a submaximal effort.

Mendler[63] demonstrated that the force of the knee extension increases as stabilization of the body is increased. Compared to no stabilization, other than the weight of the body while in a sitting position, the maximal torque produced by the quadriceps at 60 degrees knee flexion could be increased by 20% with the hands grasping the sides of the chair and by a further 10% with thigh and back stabilization. Using the same knee flexion while in a seated position, Richards and Currier,[73] confirmed that grasping the sides of the chair and using a backboard increased the torque of knee extensors. Without supporting the back, the rectus femoris of the quadriceps group was recruited to assist in stabilzing the hip and, therfore, could not contribute its full effort to knee extension.

SURFACE ELECTRODES FOR STIMULATION

Electrodes represent "the interface between the technical and biological systems."[84] Two electrodes are necessary; one to introduce the electrical current and one to allow the electrical current to exit from the patient thus completing the circuit. Although electrodes vary considerably in size, shape and type, they should share common characteristics. Electrodes should be simple, inexpensive, and flexible to conform to the body contours.[65]

Surface electrodes are usually made of metal (lead, stainless steel, aluminum, brass or tin) plates covered with a soft material such as several layers of gauze or cloth moistened with warm saline or tap water[20] [65] [77] [84]

The size of the electrode varies substantially depending upon the area and the tissue being stimulated as well as the desired effect. Generally, the electrode size is proportional to the area to be treated. A large muscle requires a larger electrode than a nerve. Covering more surface area, a larger electrode decreases the current density and, hence, increases the threshold.[15] [20] This is desirable when the aim is to prevent contraction of muscles other than those being treated, and in particular the antagonists to the muscle being stimulated.[77] In addition, less current density minimizes the discomfort of the patient due to fewer surface pain receptors being excited.[20] [77] [84] Contrarily, a smaller electrode pad increases the current density, lowers the threshold required for excitation and increases the pain level.[20] [77]

The size difference between the two electrodes is more important when applying direct current rather than alternating current. With direct current there is a distinct positive (anode) and negative (cathode) electrode. The cathode is the active electrode and is usually smaller than the anode or dispersive electrode.[5] [77] The difference in dimensions causes a higher current density under the active electrode thereby depolarizing the nerve fiber at a lower threshold.[84] With alternating current both electrodes become "active" during the alternate phases of each stimulating cycle, therefore, minimizing the desirability and effectiveness of using electrodes of significantly different sizes.

The distance between the electrodes is another factor which influences the adequacy of the stimulating current. In general, the further apart the two electrodes are placed, the deeper the penetration of current.[5] Conversely, as the distance between the electrodes decreases, the more superficial the effect of the stimulation. Applying the current by the direct technique produces superficial contraction[52] which may be partly explained by the proximity of the electrodes which are usually closer than those of the indirect technique.

APPLICATION TECHNIQUE

The two main methods used in the placement of surface electrodes are the indirect and the direct technique. The indirect (or unipolar) technique is used most frequently and involves the placement of one electrode pad over the motor point(s) of the muscle(s), or over the main nerve trunk supplying the muscle or muscle group, and the other pad on another part of the body.[10] The motor point of a muscle is the point where the major nerve enters the muscle that it innervates. It is at this point that the nerve is most superficial and, therefore, most sensative to the current.[10] [77] With the indirect method usually the electrode over the motor point(s) is smaller than the other electrode.[10] The larger electrode can be placed over the nerve trunk supplying the muscle which will stimulate all the muscles supplied by that nerve trunk.[77]

The direct (or bipolar) technique places both electrodes of equal dimensions directly over the muscle belly[20] along its longitudinal axis.[14] The density of current when using this technique is almost exclusively located in the target muscle, with only a slight possibility of the current strength spreading to other muscles or muscle groups not directly involved.[10]

The preference of the indirect method clinically can be explained, at least partly, by the difference in the excitation range of nerve and muscle tissue. The excitation range is the ratio between the current strength required for a maximal contraction and the current strength required for a minimal contraction.[10] For nerve tissue the excitation range is considerably smaller than that of muscle.[10] In stimulating a muscle through its nerve, a slight increase in current will increase the magnitude of the contraction markedly. However, to obtain the same increase in contraction force by stimulating the muscle directly, a much greater increase in current is required.[10] Due to stimulation of sensory receptors with the increased intensity, the magnitude of contraction may be limited by pain in the latter case.

ELECTRICAL MUSCLE STIMULATION STUDIES

Several recent studies have attempted to duplicate the Russian protocol.[23 31 55 79] Curwin et al.,[24] in a biochemical study, examined the effects of EMS in the rehabilitation of post-surgical knees. All patients were immobilized for six weeks following anterior cruciate ligament reconstructive surgery. Serial muscle biopsies were made during the immobilization period and for 12 weeks after removal of the cast. The patients were divided into two groups; one group received physiotherapy involving no EMS and the other group received physiotheraphy including EMS. A high frequency (2500cps) electrostimulator provided the external stimulus for the EMS group. The current, modulated by interruptions of 10ms every 20ms (that is, 10ms on followed by 10ms off), was applied to the patients using a 15/50/10 protocol. The results show that there was no significant difference in glycogen concentration between the two groups. However, there was an increase in myofibrillar ATPase in the EMS group as compared to a decrease in the other (control) group. It was not reported whether or not this difference was significant. Stanish et al.,[79] conducting a similar study to that of Curwin et al., did report a significant difference between the two groups in regard to myofribrillar ATPase ($p \leq 0.05$). These researchers concluded that immobilization of a muscle for six weeks has a significant detrimental effect on myofibrillar ATPase. It appears that EMS can prevent some of the deteriorating biochemical changes that occur in muscle when it has been immobilized for a period of time.

Laughman et al.[55] and Currier and Mann[23], using similar methodology, evaluated the ability of EMS to increase normal quadriceps strength. Both studies compared a control group, an isometrically exercised group and an electrically stimulated group. A fourth group which received voluntary exercise combined with superimposed electrical stimulation was added to the comparison in Currier and Mann's study. A high frequency (2500cps) stimulator exhibiting a modulated sine wave of 50pps (10ms on, 10ms off) was applied to the quadriceps via the indirect technique for all groups receiving stimulation. A 15/50/10 protocol was utilized for 15-25 sessions over a five week period. It was reported that the isometrically exercised group, the electrically stimulated group and the isometrically exercised group with super-imposed stimulation had significantly higher torque increases than the control group, even after the adjustment was made for initial strength differences. No significant difference in torque was observed between the experimental groups.

Other studies in the literature have utilized the 10/50/10 protocol of the Russian Technique but have used a low frequency faradic current.[30 35 41 54 62] Although all of these studies examined the quadriceps muscle group, the sample population, electrode placement, and treatment frequency was inconsistent.

Johnson et al.[41] applied a low frequency (65cps) faradic current to the quadriceps of patients with varying degrees of chondromalacia patella and muscle atrophy via the indirect technique. With the knee flexed at five degrees, the patient received 20 treatment sessions of maximally tolerated stimulation. The results revealed an increase in quadriceps strength ranging from 25-200% which was directly dependent upon the severity of the patient's condition, and upon the frequency and number of the stimulations. However, this study failed to include a comparison group.

Another study involving a strength improvement program for atrophied quadriceps was conducted by Godfrey et al.[35] Patients sustaining either surgery or injury to the knee were randomly assigned to an isometrically exercised group or an electrically stimulated group. The 10/50/10 sequence was followed by both groups for 12 sessions with the muscle contracting either voluntarily or artificially. A faradic current with a frequency of 60cps was applied via the direct method to the patients in the stimulated group.

Although trained isometrically, the patients were tested for maximum isokinetic torque generated by the quadriceps on a Cybex II dynamometer at angular velocities of 3, 10 and 25 revolutions per minute (rpm). The results showed that the EMS group had a significantly higher average than the isometrically exercised group at 3rpm but not at 10 or 25rpm ($p \leq 0.05$).

Similar to Godfrey et al.,[35] Eriksson and Haggmark[30] conducted a study comparing two groups of patients undergoing quadriceps strengthening. Dissimilar to Godfrey et al., however, the patients in Eriksson and Haggmark's study received a faradic current with a frequency of 200cps, for five to six seconds followed by a five second rest for one hour daily, five days a week for four weeks. The results from the study indicated that there was better muscle function with less atrophy of the quadriceps in the group acquiring stimulation and that there was a significantly higher oxidative enzyme activity (specifically, succinate dehydrogenase) in this group when compared to the non-stimulated group.

In training the quadriceps of healthy subjects utilizing the 10/50/10 protocol, Kramer and Semple[54] studied the effect of EMS on strength gains as compared to traditional methods of training over a period of 10-12 sessions. A control group, an isometrically exercised group, an electrically stimulated group and an isometrically exercised group with superimposed electrical stimulation were examined with a faradic, alternating current (assymetrical, biphasic rectangular wave pulse of 1.0ms at 100cps) providing the stimulus for the stimulated groups. No significant difference was reported between the trained groups. A significant increase in strength was noted in the experimental groups, however, when compared to the control group.

A similar study was conducted by McMiken et al..[62] An isometrically exercised group and an electrically stimulated group receiving a faradic current exhibiting a square wave of 0.1ms duration at a frequency of 75cps, when compared for strength gains, showed no significant difference. A control group was not included in the study.

Currier [illegible] al.[22] supported the results of the previous studies.[54] [62] A rectangular wave delivered at 25cps was indirectly applied to normal quadriceps employing a 6/10/6 format. Although Currier and his associates found no significant difference between the isometrically exercised group (19% improvement) and the isometrically exercised group with EMS superimposed (21% improvement), it was revealed that these experimental groups did differ significantly from the control group over 10 sessions.

It appears from these studies that repeated cutaneous electrical stimulation is comparable in effectiveness to common strengthening methods of isometric or dynamic exercise with no undesirable side effects. In studies using patients, EMS was actually reported to be superior to traditional rehabilitation techniques.[23 54 55 60 62] Furthermore, electrical stimulation superimposed on voluntary effort does not enhance strength gains beyond that achieved through voluntary or electrical stimulation only programs in this population.[22 23 54]

Chapter III

METHODOLOGY

A. SUBJECTS

A total of 30 university-aged males (18-31 years) volunteered for this study. The subjects were healthy, having no known pathological condition(s) nor previous surgery of either the right knee or right hip.

Each of the 30 subjects was randomly assigned to one of two indirect methods of electrode placement. On three separate test days the subjects were required to produce 10 consecutive stimulated knee extension torques. During each session the subject performed the task with a different rest interval interspersed between the consecutive torques. The three rest intervals used in the study were: i) 35s, ii) 50s and iii) 65s. Prior to testing, all subjects were randomly assigned a sequence order of these rest intervals.

B. MEASUREMENT APPARATUS

A Cybex II isokinetic dynamometer*, capable of measuring both isometric and isokinetic torques, was used to measure the isometric torques produced by the quadriceps. The dynamometer consisted of a padded chair, a resistant lever arm, various straps to stabilize the body and a speed selector which was adjusted to 0 degrees per second (degrees/s).

A Cybex II Dual - Channel (paper) Recorder simultaneously recorded the torque (measured in ft-lb) and the angle of knee extension on a paper readout. The torque range scale was set at 0-360ft-lb and the paper speed at five millimeters per second (mm/s). The torques recorded on the printout represented the resistant torque that the dynamometer had to produce to counteract the effort torque of the subject.

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* Lumex, Inc, Bay Shore, NY 11706, USA

C. CALIBRATION

Calibration of the Cybex II Dual-Channel Recorder was performed with the lever arm positioned at 30 degrees from the vertical (ie. the testing angle). A Tru-Trac traction machine* was positioned such that it pulled perpendicular to the lever arm. The force of traction was applied to the arm at a distance of 2.33 feet (ft) from the dynamometer's axis of rotation and was measured by a cable tensiometer.** Knowing the force produced and the length of the lever arm, the true torque was calculated. This true torque was compared to the recorded torque registered on the recorder's readout. Each major division on the printout represented a range of 37.2-42.3ft-lb which was calibrated at the beginning of each testing day. The recorder was calibrated throughout the full scale of 0-360ft-lb and in the direction of knee extension, at the angle of testing.

D. ELECTRICAL MUSCLE STIMULATOR

The electrical muscle stimulator used in this study is a common, clinically used stimulator. The TECA SP5/T*** is designed for therapeutic use on normally innervated muscle. The TECA stimulator produces a faradic (alternating) current with an asymetrical square wave form. Its frequency was set at 100cps with the current being on for 1ms and off for 9ms.[107] The electrical stimulator was observed to provide a maximum current of 34.1 milliamperes when passed through a 1000-ohm resistor. The milliamperes of the current was measured via a Beckman 3030 multimeter.**** The current was well tolerated by the subjects.

* TRU-EZE Manufacturing Co, Inc, Temecula, CA 92390, USA

** Pacific Scientific Co, Inc, Los Angeles, CA, USA

*** TECA Corp, Pleasantville, NY 10570, USA

**** Beckman Instruments, Inc, Brea, CA 92621, USA

E. TESTING PROCEDURE

Thirty volunteers were randomly assigned to one of two electrode pad placement groups. The random assignment was to minimize the effects of learning and/or conditioning. All subjects were tested using three rest intervals; i) 35s, ii) 50s and iii) 65s.

Each subject participated in four to six sessions and received similar instructions. The first one to three sessions, depending on the subject, were used to familiarize the subject with the purpose of the study, the testing procedure, the apparatus and the sensation of EMS. If the subject was unable to become comfortable with the sensation of the EMS within three practice sessions, he was eliminated from the study. Two males withdrew from the study for this reason and replaced by two other volunteers. During the first session, informed consent forms (see Appendix 1 on page 72) were signed by each subject.

The practice sessions were followed by three test sessions - one session for each rest period. A minimum of 48 hours was required between any two sessions including the practice sessions.

During all sessions, the subject used the indirect method of pad placement that he had been randomly assigned to. In group 1, the larger (9x14 centimeter or cm) proximal electrode was placed over the lumbo-sacral plexus just to the right of the subject's spinal column. The smaller (7x16cm) distal electrode was positioned over the femoral nerve which is the major nerve supplying the quadriceps. Group 2, using the same electrodes as used by the first group, placed the larger proximal electrode over the femoral nerve in the groin area and the smaller electrode over the motor points of the distal quadriceps. A motor point is the point at which the motor nerve pierces the muscle that it innervates. It is at this point that the nerve is most superficial and therefore most sensitive to the electrical stimulation.

Prior to any session, the subject was requested to perform five minutes (min) of flexibility/warm-up exercises. The subject was then sea[illegible] Cybex chair so that the back of his flexed knee was resting over the edge of the chair. [illegible]ed Cybex seat back supported the subjects back. For shorter subjects, back pads were placed between the subject and the seat back to render support.

To fix the body in place and to prevent other muscles assisting in the action of the quadriceps, the upper body was stabilized by two shoulder straps and the pelvis by a seat belt that was placed around the hips. The right thigh which was supported along its entire length by the horizontal padded seat was secured by a velcro strap placed approximately 10cm above the patella over the thigh. The axis of rotation of the lever arm was adjusted to coincide with the rotational axis of the knee joint (ie. through the femoral condyles).[49 61] The lower right leg was strapped against a padded block at the lower end of the adjustable lever arm. This pad was positioned so that the lower edge of the pad was just proximal to the level of the malleoli. After the lower leg was stabilized, the lever arm was adjusted so as to place the knee at 60 degrees flexion (from the horizontal).

During the first practice session, the exact positioning of the distal electrode was determined by using a small electrode probe. With the respective proximal electrode in place the two groups used the probe as the distal electrode. The stimulator was set to a low frequency pulse rate (10 pulses per minute or ppm) and the intensity to zero. For group 1, the subjects positioned the probe over their mid-groin area to locate the femoral nerve. The intensity was then gradually increased by the subject until a barely visible contraction of the quadriceps was observed. Without increasing the intensity, the probe was moved about this general region. The point which elicited the greatest contraction at this intensity was marked with a felt pen. For group 2, three points on the distal quadricep were located. The same procedure as for the first group was used. For each of the three points, though, the intensity was turned to zero and then increased until a contraction of the respective muscles was just visible. The three muscles involved in this second group were vastus medialis, rectus femoris, and vastus lateralis. The most sensitive spots to EMS represented the motor points of these three muscles which were marked in felt pen. The marks for each groups were to be kept visible by the subject so that the probing would not be necessary each session. The distal electrode pad was then placed over the appropriate area(s). As with the proximal electrode pad, the distal electrode pad was moistened in warm water before being placed on the subject. The cloth pad, one centimeter larger than the electrode on all sides, separated the electrode from the skin. Each electrode and pad were held firmly in place with a tensor bandage.

During the practice session the "10/50/10" (10s of stimulation, 50s of rest, repeated 10 times) sequence was used. This technique was chosen as it was the middle rest interval of the study. As well, this is the most widely used format of EMS in physiotherapy clinics for increasing muscular strength.

The subject, during the practice session, was instructed to turn up the EMS, now set on the continuous mode, until he could see the quadriceps beginning to contract. At this point, the subject gradually increased this contraction up to his maximal tolerance by increasing the current at a moderate speed. The target time for reaching maximum was two seconds. The maximally tolerated contraction was held for approximately eight seconds. Each subject repeated this 10 times with a 50s rest period between each stimulation.

During the test sessions, the same format as was followed in the practice session(s) was implemented. The subjects were requested to tolerate as much current as possible and were reminded to reach their maximal tolerance level within two seconds. Voluntary effort was discouraged. Each testing session would include ten 10s stimulated contractions interrupted by either 35, 50 or 65s rest intervals. The order in which each subject performed the three tests was determined by random assignment prior to the testing sessions.

The practice sessions took approximately 45min while each of the test sessions involved 15min. The maximum total time commitment for the subject, therefore, was three hours.

The recorder was calibrated using a tensiometer (refer to Section C. CALIBRATION on page 43) prior to each testing day throughout the study. The recorder and tensiometer demonstrated validity coefficients ranging from 0.97 to $\geq$0.99 and reliability coefficients ranged from 0.98 to $\geq$0.99.

The error for repeated tests on separate days using the Cybex II dynamometer to measure isometric knee extension torques with the subject's shoulders, pelvis and thigh secured while in a seated position has been estimated to range from 4.1-6.5%.[51]

F. STATISTICAL DESIGN

The independent variables of this study were the three rest intervals and the two methods of pad placement. The dependent variable was the torque produced under the various combinations of independent variables. Each of the six cells contained 15 subjects.

A two-way analysis of variance with repeated measures on one factor, rest interval, was used to examine mean torque decrements, mean torques and peak torques. When a significant F was reported, a Scheffe post hoc test was used to locate the significance. A 0.05 level of significance was used throughout the analysis.

Chapter IV

RESULTS

The isometric, knee extension torques produced during the 10 stimulations were statistically analyzed using a two-way analysis of variance (2-way ANOVA) with repeated measures on one factor (see Appendix 2 on page 76). Groups were defined by the two different placements of electrode pads, and the repeated measures were the rest intervals of 35, 50 and 65s. Four dependent variables were examined: i) the torque decrement derived from the difference between the average torque of the first three stimulations and the average torque of the last three stimulations (Data 1-Table I); ii) the torque decrement derived from the difference between the average torque of the first five stimulations and the average torque of the last five stimulations (Data 2-Table II); iii) the mean torque of the 10 stimulations (Data 3-Table III); and iv) the peak torque of each session (Data 4-Table IV). A visual graphic representation for Data 1 and Data 2 is found in Figure 1 (page 51) and for Data 3 and Data 4 in Figure 2 (page 52). Conversion from ft-lb torque to newton-meter (N-m) torque can be made by multiplying by 1.35.

When observing torque decrement, significant differences were found for the main effects; a significant difference was observed in the rest interval for Data 1 ($p \leq 0.001$) and Data 2 ($p \leq 0.001$), and in pad placement for Data 1 ($p \leq 0.007$) and Data 2 ($p \leq 0.01$). No interaction effects for Data 1 or Data 2, however, were observed.

For Data 3, a significant difference was found on the rest interval factor ($p \leq 0.03$) but not on pad placement. Conversely, for Data 4, a significant difference was found in the pad placement ($p \leq 0.05$) but not in the rest interval. No interaction was observed between rest interval and pad placement for Data 3 or Data 4.

A Scheffe ($p \leq 0.05$) post hoc test was applied to those means for which a factor showed a significant F-ratio (see Appendix 3 on page 79). In both Data 1 and Data 2, the post hoc test revealed that the means of the 50s and 65s rest intervals, when averaged over the pad

TABLE I

TORQUE DECREMENT MEANS (ft-lb) WITH STANDARD DEVIATIONS FOR PAD PLACEMENT (A) AND REST INTERVAL (B) FOR DATA 1

PAD PLACEMENT (A)	REST INTERVAL (B) 35s	50s	65s	
1	46.42 (14.64)	40.02 (11.24)	33.23 (20.01)	39.89 (16.29)
2	36.99 (21.18)	22.18 (14.39)	18.50 (18.72)	25.89 (19.63)
	41.71 (18.52)	31.10 (15.60)	25.87 (20.46)	

TABLE II

TORQUE DECREMENT MEANS (ft-lb) WITH STANDARD DEVIATIONS FOR PAD PLACEMENT (A) AND REST INTERVAL (B) FOR DATA 2

PAD PLACEMENT (A)	REST INTERVAL (B) 35s	50s	65s	
1	32.29 (10.48)	26.55 (8.08)	23.27 (13.25)	27.37 (11.22)
2	25.62 (16.80)	14.73 (11.29)	13.23 (12.70)	17.86 (14.59)
	28.96 (14.17)	20.64 (10.69)	18.25 (13.74)	

TABLE III

MEAN TORQUE MEANS (ft-lb) WITH STANDARD DEVIATIONS FOR PAD PLACEMENT (A) AND REST INTERVAL (B) FOR DATA 3

PAD PLACEMENT (A)	REST INTERVAL (B)			
	35s	50s	65s	
1	172.13 (46.70)	187.37 (57.63)	182.85 (40.28)	180.78 (48.05)
2	151.66 (22.71)	156.19 (35.79)	162.66 (34.77)	156.84 (31.26)
	161.90 (37.55)	171.78 (49.73)	172.76 (38.37)	

TABLE IV

PEAK TORQUE MEANS (ft-lb) WITH STANDARD DEVIATIONS FOR4PAD PLACEMENT (A) AND REST INTERVAL (B) FOR DATA 4

PAD PLACEMENT (A)	REST INTERVAL (B)			
	35s	50s	65s	
1	206.63 (55.21)	216.63 (62.97)	212.68 (44.39)	211.98 (53.63)
2	181.84 (30.74)	176.77 (33.05)	179.41 (37.17)	179.34 (33.05)
	194.24 (45.68)	196.70 (53.41)	196.04 (43.64)	

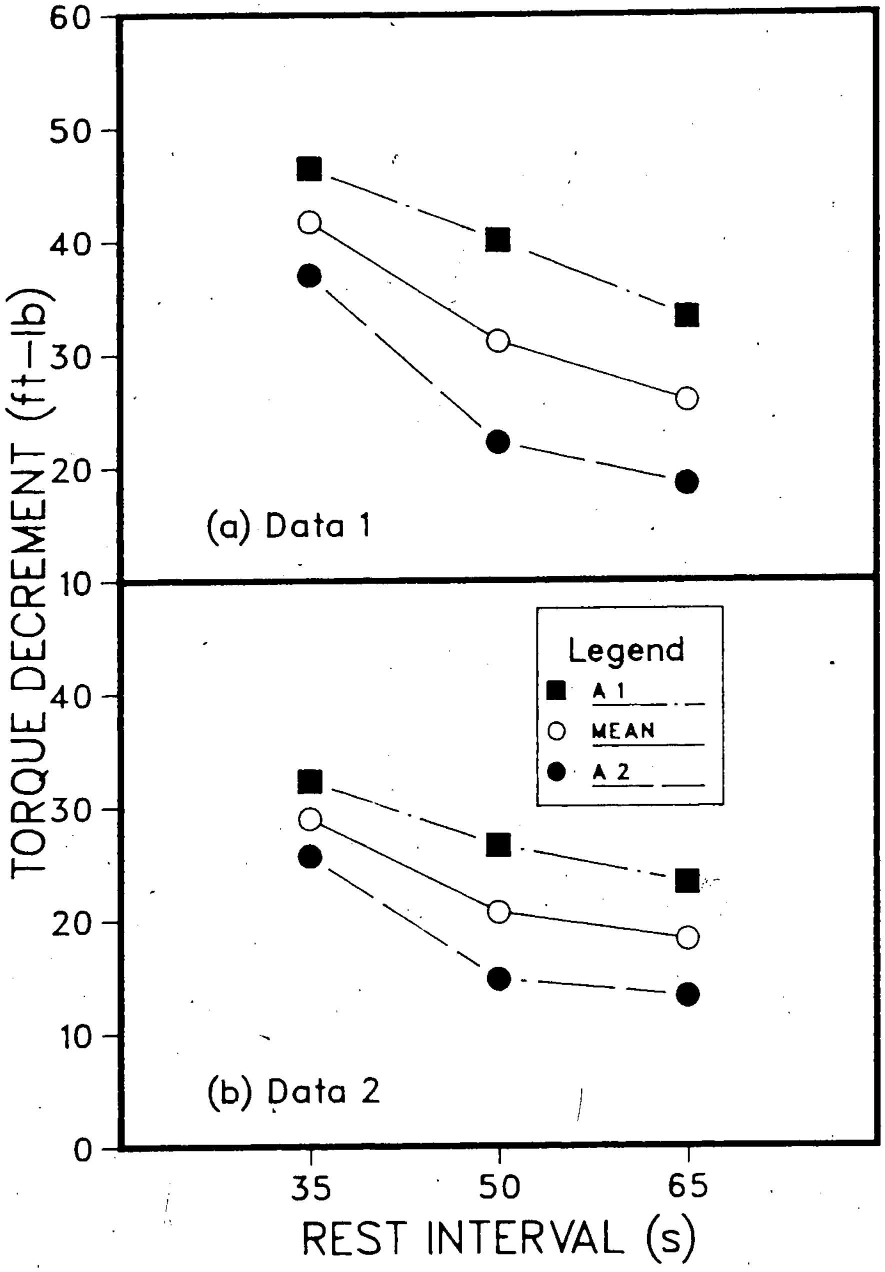

Figure 1: Torque Decrements for Data 1 (a) and Data 2 (b).

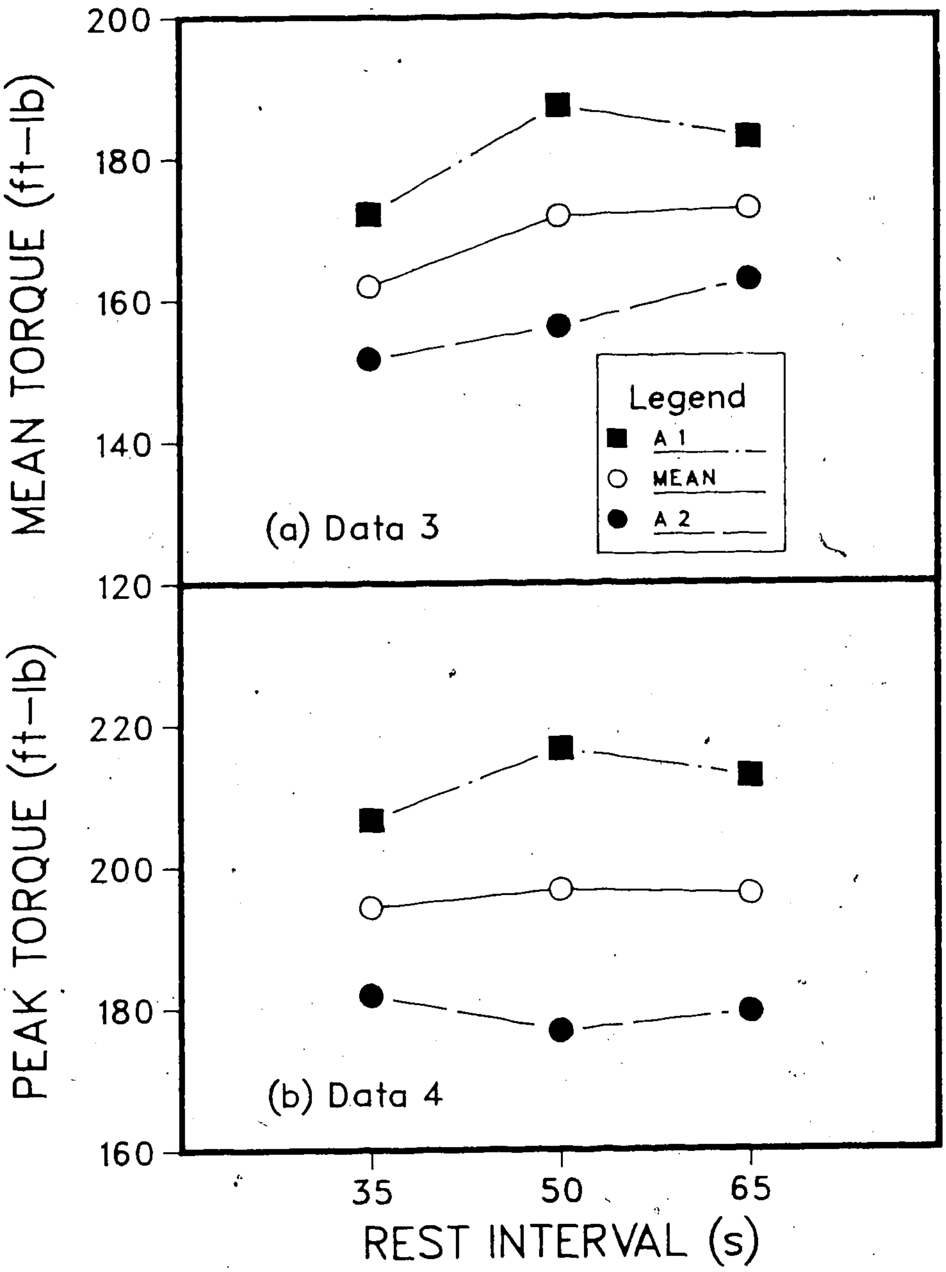

Figure 2: Mean Torques for Data 3 (a) and Peak Torques for Data 4 (b).

placement groups, produced less torque decrements than the mean of the 35s interval ($p \leq 0.05$ and $p \leq 0.01$ respectively). The means of 50s and 65s rest intervals, however, did not demonstrate significantly different torque decrements when averaged over pad placement groups for either Data 1 or Data 2. When averaged over rest intervals, pad placement group 1 produced greater torque decrement than pad placement group 2 for both Data 1 and Data 2 ($p \leq 0.01$).

Although a significant F ratio was revealed on the rest interval factor for Data 3, a Scheffe ($p \leq 0.05$) post hoc test did not reveal a si[illegible]erence between the rest intervals. A less conservative Tukey Test, however, d[illegible] a significant difference between the means of the 35s and 65s rest intervals ($p \leq$ [illegible] but no significant differences were found between either the means of the 35s and 50s intervals or of the 50s and 65s intervals (see Appendix 3 on page 79).

Data 4 revealed that pad placement group 1 produced greater peak torques than did pad placement group 2 ($p \leq 0.05$) when averaged over the time intervals.

Additional 2-way ANOVA's with repeated measures on score were performed on each rest interval for Data 1 (Table V) and for Data 2 (Table VI). A significant difference was found between the scores within the 35s, 50s and 65s rest intervals for Data 1 and Data 2 ($p \leq 0.001$). The initial scores (the average torque of the first three or five stimulations) were significantly higher in torque than the final scores (the average torque of the last three or five stimulations) when averaged over pad placement. Pad placement was not found significant for any of the three rest intervals for either Data 1 or Data 2.

Although interaction was not evident for the 35s rest interval for either Data 1 or Data 2, interaction between pad placement and score was observed for the 50s and 65s rest intervals in Data 1 ($p \leq 0.001$ and $p \leq 0.05$ respectively) and in Data 2 ($p \leq 0.03$ and $p \leq 0.04$ respectively). A Scheffe post hoc test revealed interaction between all of the possible combinations within Data 1 and Data 2 ($p \leq 0.001$).

TABLE V

SCORE MEANS (ft-lb) WITH STANDARD DEVIATIONS FOR PAD PLACEMENT (A) AND REST INTERVAL (B) FOR DATA 1

REST INTERVAL (B)

	35s		
	first 3	last 3	
A1	196.92 (52.60)	150.50 (40.71)	173.71 (51.89)
A2	171.99 (28.48)	135.01 (22.92)	153.50 (31.60)
	184.46 (43.45)	142.75 (33.40)	

	50s		
	first 3	last 3	
A1	208.63 (61.59)	168.61 (54.87)	188.62 (60.82)
A2	167.27 (35.59)	145.09 (35.87)	156.18 (36.88)
	187.95 (53.71)	156.85 (47.09)	

	65s		
	first 3	last 3	
A1	201.20 (41.69)	167.96 (41.39)	184.58 (44.18)
A2	171.25 (35.37)	152.76 (36.26)	162.01 (36.43)
	186.22 (40.93)	160.36 (39.01)	

TABLE VI

SCORE MEANS (ft-lb) WITH STANDARD DEVIATIONS FOR PAD PLACEMENT (A) AND REST INTERVAL (B) FOR DATA 2

REST INTERVAL (B)

	35s		
	first 5	last 5	
A1	188.27 (50.47)	155.98 (43.24)	172.13 (49.01)
A2	164.47 (26.37)	138.85 (21.85)	151.66 (27.13)
	176.37 (41.37)	147.41 (34.77)	

	50s		
	first 5	last 5	
A1	200.64 (59.89)	174.09 (55.58)	187.37 (58.30)
A2	163.56 (35.46)	148.82 (36.99)	156.19 (36.38)
	182.10 (51.91)	161.46 (48.14)	

	65s		
	first 5	last 5	
A1	194.49 (40.81)	171.22 (40.83)	182.85 (41.82)
A2	169.28 (35.05)	156.05 (35.64)	162.66 (35.38)
	181.88 (39.52)	163.63 (38.44)	

Chapter V

DISCUSSION

The subjects who volunteered for this study were highly motivated. As the result of their previous voluntary exercise training, it was believed that these athletes would be more familiar with a maximal effort and the sensation associated with it than the normal population. The same discomfort which may have been interpreted by a non-athletic person as a result of the stimulation may have been identified by an athlete as the feeling that accompanies a maximal contraction. Based on this assumption, it was anticipated that the selected population may have been better able to tolerate the stimulation. This assumption proved to be fairly accurate as only two of 30 subjects were forced to discontinue due to their inability to become accustomed to the stimulus. These two volunteers were replaced to maintain the 30 subject total for this study.

The majority of the subjects tolerated the stimulation so well that 60% (18 out of 30) were able to withstand the maximal intensity output of the stimulator. Of this 60%, 55% (10 subjects) were able to reach the maximum output of the stimulator during the practice sessions. It appears, therefore, that over half of the subjects could have tolerated more current intensity and, as a result, did not achieve a physiologically maximal electrical stimulation based contraction. Whether or not this would have translated into greater torques is beyond the scope of the present investigation.

Comparing pad placement groups, it was noted that nine of the 18 subjects who were able to tolerate the maximal intensity output of the electrical muscle stimulator were from pad placement group 1 and the other nine were from group 2. Six of the 10 subjects who reached the maximal output of the machine during the practice sessions were from group 1 while only four were from group 2. With regard to tolerating the maximal output of the stimulator, it would appear that the two pad placements were equivalent.

TORQUE DECREMENT AND MEAN TORQUE: The results of the statistical analysis revealed that the 50s and 65s rest intervals produced significantly less torque decrement ($p \leq 0.05$ and $p \leq 0.01$ respectively) than the 35s rest interval when averaged over pad placement, regardless of whether the average torque of the last three stimulations was subtracted from the first three stimulations (Data 1 - Table I on page 49) or the average of the last five stimulations was subtracted from the first five stimulations (Data 2 - Table II on page 49). The less torque decrement associated with the two longer rest intervals appears to be reasonable, as one would anticipate that a muscle given more time to recuperate between stimulations would be better able to maintain the initial level of tension than a muscle with a recovery period of shorter duration. With the 35s rest period interspersed between the stimulated contractions, muscular fatigue was more apparent as evident by the greater torque decrement.

When the 10 stimulations per session were averaged and the means compared, it revealed that the 65s rest interval produced significantly greater mean torques ($p \leq 0.05$) than the 35s rest interval (Data 3 - Table III on page 50). It would appear that the longest rest period enabled the muscle to recover from the previous stimulation to a greater degree than the shortest rest interval, thereby, permitting stronger contractions over the 10 stimulations to be generated by the 65s interval.

Since no difference in torque decrement or mean torque was observed between the two longer intervals of rest, it is suggested that the 50s rest between the 10 stimulated contractions of the quadriceps permits a similar strength training stimulus as does the 65s rest. The equal strength improving potential of the 50s and 65s intervals has important clinical significance. A treatment session utilizing the 10/50/10 protocol requires nine minutes and 10s while a 10/65/10 session necessitates 11min and 25s. The 10/50/10 sequence is able to accomplish physiological changes similar to the 10/65/10 protocol but in a shorter period of time. For practical purposes, therefore, the 50s rest interval would be selected over the 65s interval because of the more efficient use of time.

To further emphasize the importance of this finding, a hypothetical situation is proposed. If a therapist, during a seven hour workday, did nothing other than conduct EMS strengthening sessions, he or she would be able to treat just less than 49 (48.8) patients per day using the 10/50/10 protocol, or just less than 37 (36.8) patients per day using the 10/65/10 protocol. In one day, therefore, nine additional patients could receive EMS therapy utilizing the 10/50/10, as opposed to the 10/65/10, protocol.

An additional advantage of using the 10/50/10 sequence is the ease at which the therapist can keep track of the time, as well as, the number of stimulations that have occured within a session. In using a stopwatch, the stimulated contraction commences when the stopwatch is started. The contraction lasts for 10s. With a 50s rest, the muscle receives its second stimulation at one minute. Within each minute of treatment, therefore, the muscle receives stimulation for the first 10s and then relaxes for the remaining 50s. The tenth stimulation commences when nine minutes appears on the stopwatch.

Many of the EMS strength training studies have employed a 50s rest interval between 10 stimulated contractions.[23] [24] [35] [40] [41] [54] [55] [62]. Few studies have advocated the 10/35/10 protocol for improving muscular strength. In prescribing an interval training program, however, Mathews and Fox[61] have suggested that a 10/30/10 protocol repeated five times within one workout is able to train the ATP-PC energy system. It is this system that provides the required energy for maximal efforts of short duration. The inability of the present study to support Mathews and Fox's claim may not depend so much on the rest interval selected, perhaps, as on the mode of training utilized (i.e. EMS vs voluntary effort). More research comparing these two training methods is definitely required.

The results of the present study, thus far, support Kots' claim that a 50s rest interval interspersed between ten 10s stimulated contractions creates a greater strength stimulus than a shorter interspersed rest period.[53] The results of this study, however, do not support Kots' statement that the tenth stimulated contraction of a session is as "maximal" as the first muscular contraction.[53]

Within all three rest intervals, it was found that the average torque of the first three and of the first five stimulations was significantly higher ($p \leq 0.001$) than the average torque of the last three and of the last five stimulations (refer to Table V on page 54 and Table VI on page 55). Within each session, therefore, a significant loss of ability to produce a maximal stimulated contraction was evident. The decrease in torque, however, [illegible] more significant when the overall torque decrement of the 50s and 65s rest interval sessions was compared to the torque decrement of the 35s rest interval session, as was previously discussed.

TORQUE DECREMENT AND PEAK TORQUE: In observing the two indirect methods of electrode pad placement, it was found that pad placement group 1 demonstrated significantly greater torque decrement than pad placement group 2 (refer to Tables I and II on page 49). The larger decrement for group 1 was significant when both the average of the final three torques was subtracted from the initial three torques (Data 1 - $p \leq 0.007$) and when the average of the final five torques was subtracted from the initial five torques (Data 2 - $p \leq 0.01$). Interpreting torque decrement to represent fatigue, pad placement group 1 exhibited more fatigue during a 10 stimulation session than did pad placement group 2.

The greater fatigue experienced by group 1 may be explained by the fact that pad placement group 1 produced significantly higher peak torques ($p \leq 0.05$) than pad placement group 2 (Data 4 - Table IV on page 50). Since strength of a contraction is inversely related to the length of time for which the contraction can be maintained for,[34] a stronger contraction will result in the muscle fatiguing faster. Fatigue occurs due to the accumulation of metabolites and/or the depletion of energy stores. These two processes occur more quickly during muscle contractions of higher torque than contractions of lower torque.

The higher torque produced by pad placement group 1 may be a result of more muscle fibers, and in particular more FT fibers, being recruited than with the pad placement group 2. A possible explanation for the increased recruitment of muscle fibers may be related to the size of the nerve being stimulated. The lumbo-sacral nerve trunk (L3-L4) is larger than is the femoral nerve.[1] With the electrical threshold of a nerve being inversely proportional to the diameter of the nerve's axon during EMS, the lumbo-sacral trunk should be more easily excited than the femoral nerve. For the same intensity level, therefore, more fibers should be recruited in pad placement group 1 than pad placement group 2, which does not involve the lumbo-sacral trunk.

The size of the electrode may also help to explain the torque difference between the two pad placement groups. A small electrode increases the current density per unit area and, hence, decreases the threshold required to stimulate an excitable tissue. The smaller electrode in group 1 being placed over the femoral nerve, which innervates the quadriceps, may stimulate more motor neurons than having the larger electrode over the femoral nerve as in group 2. Stimulating more motor neurons causes a stronger muscular contraction.

A third interpretation of the discrepency in peak torque found between the two pad placements is related to pain. It may be that the location of the two electrodes in group 2 are situated over areas containing more subcutaneous adipose tissue than the placement of the pads in group 1. In order for the current to penetrate the adipose tissue to stimulate the underlying muscle fibers, the intensity must be increased. The increase in intensity causes more superficial nerve endings to be stimulated which increases the pain level. Pain, therefore, may be a limitation of pad placement group 2 to produce large torques.

With FT fibers being responsible for producing strong, short duration contractions, it is possible that the higher torque produced by group 1 is not only a result of the number of muscle fibers recruited but also the type of muscle fiber preferentially selected. In group 1, the electrode pads are in closer proximity to each other than the pads in group 2. As the distance between the electrodes decreases, the more superficial the current becomes. Since FT fibers are more superficially located, it is suggestive that these fibers are predominantly stimulated during EMS using the pad placement of group 1. Electrodes that are spaced further apart, such as those in group 2, facilitate the recruitment of deeper excitable tissue (i.e. ST fibers).

Regardless of the reason, the greater torque produced in group 1 has important clinical significance. In practical terms, the placement of the electrodes used in group 1 is perferable when the motor points of the distal quadriceps are inaccessible as would be the case with the presence of a cast or wound. As well, group 1's electrode placement may be selected if the knee is effused. Swelling in a joint causes the current to spread which decreases the amount of current reaching the target (i.e. motor points).[77]

With regard to training, it appears that the pad placement utilized by group 1 would be beneficial for improving strength as greater tension was produced by the muscle during EMS using this technique. The positioning of the electrodes used in group 2 appear to be preferable when the goal of the EMS sessions is to increase muscular endurance since less fatigue (i.e. less torque decrement) was associated with this group.

PERCENT MVC: The subjects in group 2 were only able to generate 84% of the MVC that the subjects in group 1 were able to produce voluntarily. When contrasting the force produced by the two groups during EMS, however, group 2 averaged slightly higher mean torques than group 1 (88% MVC for group 2 and 85% MVC for group 1). Perhaps the lower voluntary efforts of group 2 could account for their relatively high %MVC with the stimulated contractions.

When the average of the three peak torques for each subject was compared to their respective MVC, 17% (5 out of 30) of the subjects produced greater torques of the quadriceps with stimulation than with voluntary effort. Three of these five subjects were from group 2. It is speculated that perhaps these subjects were unable to reach their physiological maximum in muscular strength voluntarily as they may not participate regularly in heavy resistance training. Details of the subjects' training programs at the time of testing were not recorded by the author.

All of the 30 subjects, however, were able to produce a mean peak torque averaged over the three sessions that was greater than 60% MVC. This percentage was superior to Knuttgen's[51] minimal 50% MVC recommendation necessary to increase the strength of a muscle. All subjects, therefore, were able to generate a stimulated contraction of sufficient intensity to produce a strength training stimulus, at least, at the beginning of the 10 stimulation session (since it was the peak torques that were averaged).

In addition, at muscular tensions of 60% MVC or greater, the blood within the muscle becomes occluded. With the restriction of blood flow, and thus the availability of oxygen, it is postulated that the FT fibers were perferentially recruited since these fibers gain their energy from anaerobic sources. Paradoxically, these are the fibers that are responsible for producing a more intense contraction. Thus, it is the FT fibers which are being stressed at these levels of tension. Since both groups produced high levels of tensions within the muscle, it is speculated that the two groups experienced blood occlusion which would explain, at least partially, the presence of fatigue. No statistical comparison between the two groups with respect to % MVC, however, was conducted.

Chapter VI

SUMMARY AND CONCLUSIONS

Electrical stimulation has been used for centuries as a means of rehabilitating injured tissue. Only recently has it been suggested that electrical stimulation be applied to normal tissue to induce advantageous physiological changes. In the mid 1960's, Kots claimed that electrical muscle stimulation (EMS) can be used to increase the isometric strength of the normal muscle by as much as 30% following 20 treatments using what is referred to as the "Russian Technique". This technique consists of 10 maximally stimulated isometric contractions held for 10s with 50s rest between stimulations. The 10/50/10 protocol is popularly used in North American therapy clinics. To date, however, there is little published data that supports the claim that the 10/50/10 protocol is the optimum stimulus for increasing muscular strength.

The purpose of this study was to investigate the effect on torque of varying the rest period between isometric electrically induced contractions of the knee extensor muscles. A comparison of torque produced using two conventional methods of pad placement was also included in this study. Group 1 received the electric current via a distal electrode pad placed over the femoral nerve and a proximal pad placed over the lumbo-sacral area while group 2 received the stimulation through a distal electrode pad positioned over the motor points of the quadriceps and a proximal pad positioned over the femoral nerve.

The 30 university-aged males who volunteered for this study were randomly assigned to one of the two indirect methods of pad placement. All subjects produced 10 maximally stimulated isometric contractions of the quadriceps per session on a Cybex II dynamometer positioned at 30 degrees from the vertical. For each of the three test sessions, the participants used a different rest interval (35, 50 or 65s) between the 10 stimulations which was randomly assigned prior to testing. Torque decrements between the first three and last three stimulations and between the first five and last five stimulations, as well as, mean torques and peak torques were determined from the 10 stimulations within each session.

Prior to each testing day, the Cybex II dynamometer and paper recorder, which measured and recorded respectively the isometric torques produced by the quadriceps, were calibrated at the testing angle (i.e. 30 degrees from the vertical) using a Tru-Trac traction machine. The force of traction, measured by a cable tensiometer, was applied perpendicular to the lever arm at a distance of 2.33ft from the dynamometer's axis of rotation and in the direction of knee extension. Calibration was performed throughout the full 0-360ft-lb scale utilized during the test sessions.

A 2-way ANOVA with repeated measures on rest interval was used to examine the mean torque decrements, mean torques and peak torques. The results of this study were:

1. the 50s and 65s rest intervals produced less torque decrements than was produced with the 35s interval ($p \leq 0.05$ and $p \leq 0.01$ respectively) but were not significantly different from each other
2. pad placement group 1 produced greater torque decrements than was produced with pad placement group 2 ($p \leq 0.01$)
3. the 65s rest interval produced a greater mean torque than was produced with the 35s rest interval ($p \leq 0.05$)
4. no significant difference in mean torque was found between either the 35s and 50s intervals or the 50s and 65s intervals
5. pad placement group 1 produced greater peak torques than was produced with pad placement group 2 ($p \leq 0.05$)
6. the average torque of the initial three and five stimulations were significantly greater than the average torque of the final three and five stimulations respectively ($p \leq 0.001$)

The results of the present study concur with Kots' statement that a 50s rest interval between 10 consecutive 10s maximally stimulated isometric contractions provides a better strength stimulus than a shorter rest period. The results of this study, however, cannot support Kots' claim that the tenth stimulated torque is of the same intensity of contraction as the first stimulated torque using the 10/50/10 protocol. Within all three (10/35/10, 10/50/10 and 10/65/10) sessions a significant decrease in torque was observed.

On the basis of the results of the present study, it was concluded that the 50s and 65s rest intervals provided the best stimulus for improving muscular strength as these rest intervals produced the greater mean torques and less torque decrements than the 35s rest interval. From a practical consideration, a therapist would select the 50s rest interval over the 65s rest interval during an EMS strengthening session as time is used more efficiently. With regard to pad placement, it was concluded that group 1 was superior to group 2 for increasing muscular strength as the former placement produced greater peak torques and greater torque decrements than the latter placement. It is anticipated that this would lead to a more optimal strength training stimulus.

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APPENDIX 1

INFORMED CONSENT FORM

The University of Alberta

Department of Physical Education

INFORMED CONSENT FORM FOR THE INVESTIGATIVE STUDY: EFFECTS OF VARIATION IN REST INTERVAL AND ELECTRODE PLACEMENT ON ISOMETRIC TORQUES INDUCED BY ELECTRICAL STIMULATION

Outline of Procedures (retained by subject)

For a number of years, electrical stimulation techniques have been used in the rehabilitation of damaged tissues. In more recent years, the effect of electrical stimulation on normal tissue has produced a new interest. Russian researchers, suggesting that electrical stimulation training can enhance muscular strength, have reported up to 30% greater isometric force produced during an electrically induced muscular contraction than during a maximal voluntary contraction, and that 30-40% strength gains have followed an electrical stimulation based training program. The basis for this claim is that electrically induced muscular contractions can activate more of the muscle fibers in a muscle than a maximal voluntary contraction.

The "Russian Technique", an electrical stimulation strength training program, consists of stimulating a specific muscle for a 10 second duration causing a maximal isometric (no movement in the joint) contraction. Ten electrically stimulated efforts interrupted by a 50 second rest period constitutes one treatment session. The Russians suggested that the "10/50/10" protocol (10 seconds of stimulation; 50 seconds rest; repeated 10 times) represents the maximal workload that a muscle can tolerate in a single treatment session. That is; 10 maximal muscular efforts, each 10 seconds in duration, can only be completed [illegible] second rest period is permitted between efforts.

In North America, there is little information reported in the literature explaining the relationship of various rest periods between consecutive muscular efforts and fatigue. To verify the Soviet claims and to better understand the technique itself, researchers on this continent must examine this mode of training more carefully.

The present study will observe one treatment session of ten 10 second electrically induced muscular efforts and, specifically, examine the effects of various rest periods on fatigue. Rest periods of 35, 50 and 65 seconds have been selected. The magnitude of the isometric forces produced in the quadriceps (thigh muscles) will be measured during the 10 stimulations. As the quadriceps tighten, the leg will attempt to straighten, pushing against the padded, immovable lever arm, positioned just above your ankle. No voluntary effort on your part is required.

Each participant of the study will be requested to attend one to three practice sessions and three test sessions. During the practice period(s) you will be given an opportunity to become familiar with the purpose of the study, the testing procedure, and the sensation of electrical stimulation. Depending upon the speed at which you become comfortable with the set-up will determine the number of practice sessions necessary. During the following three test sessions you will be randomly assigned to one of three rest periods (35, 50 or 65 seconds). On each testing day, therefore, you will receive a different rest period. A minimum of 48 hours is required between any of the sessions. You will not be re-tested unless you report zero to minimal muscular stiffness.

The practice session(s) will take 30- minutes while the test sessions will be approximately 20-30 minutes in length each. T total time commitment for each participant, therefore, is between 1 1/2-3 hours over a 1- period.

Each subject will be randomly assig to one of two methods of current application. Group 1 will receive the electrical current via one electrode placed on the lower back and one electrode placed at the top of the thigh in the right groin area. Group 2 will receive the electrical stimulation via one electrode placed over the right groin region and the other electrode over the thigh musculature just above the right knee. The exact position of these electrodes will be determined and marked with a water insoluble pen in the practice session.

Once the electrodes have been positioned, each volunteer will be seated in the testing chair. The upper body, the right thigh, and the right leg will be stabilized by various straps and pads. Throughout the study, the knee will be positioned at a fixed angle (60 degrees of knee -bend).

The electrical stimulator will be to the left of you when you are seated in the testing chair. At all times, you will be in control of the intensity dial which you will gradually turn up as quickly and as high as your tolerance will allow. It is important to note that you will increase the intensity to a level in which you feel that you are accepting a maximally tolerated stimulus intensity. No dosage is assigned by the investigator. The maximal intensity is therefore individually determined. You may turn down or terminate the current at any point during the study.

The first perception of the electrical stimulation will be a prickling sensation on the skin. The prickling will disappear as the intensity is increased, at which point the quadriceps will begin to tighten. At the maximally tolerated current intensity you will feel a very strong muscular contraction which will be similar to that which you have experienced in traditional resisted exercise. To reiterate, it is important that no voluntary effort be used during the electrically stimulated contractions.

The isometric force recording apparatus has been calibrated and will be continually calibrated throughout the study. The electrical muscle stimulator used in this study has been inspected by the Canadian Standards Association. The electrical stimulation techniques utilized in the present study are commonly used in existing physiotherapy clinics and are familiar to the investigator. The danger of electrical shock and/or burn is minimal.

Maximally tolerated intensities of electrical stimulation producing strong muscular contractions may cause some muscle discomfort either during or after the session. If experienced, this will be similar to the muscle soreness/stiffness which may be present during or after hard voluntary workouts. With each of you stretching before the stimulation sessions, the possibility of muscle tears is considered minimal. Muscular damage caused by electrical stimulation has not been reported in the literature to date. In fact, two recent studies conducted at this university with a similar method using maximally tolerated electrical stimulation have reported no complications to the subjects.

In the event of questions please feel free to contact Ms. Ann Cox (484-7824). You have the right to withdraw from participation at any time. No records nor photographs which would permit your identification will be made public or used in any medical article without your written permission.

The University of Alberta

Department of Physical Education

INFORMED CONSENT FORM FOR INVESTIGATIVE STUDY: EFFECTS OF VARIATION IN REST INTERVAL AND ELECTRODE PLACEMENT ON ISOMETRIC TORQUES INDUCED BY ELECTRICAL STIMULATION

Subject Consent (retained by investigator)

I, ______________________________, do hereby agree to participate as a subject in the study entitled "Effects of Variation in Rest Interval and Electrode Placement on Isometric Torques Induced by Electrical Stimulation" conducted by Ms. Ann Cox. I have been requested to obtain a medical prior to my participation in this study. I have not experienced in the past, nor am I experiencing at present, any serious injury to my right knee or right hip which could interfere with, or be affected by, partaking in this study.

The investigator has cautioned me to the potential risks of the study - from minor electrical shock and/or burn to muscle soreness and possible muscle tears. It has also been indicated to me that the method used in this study is a safe, commonly practiced physiotherapy technique and that similar methods utilizing maximally tolerated electrical stimulation have been recently conducted at the university with no complications to the subjects reported. I have been advised that I may withdraw from the study at any time.

______________________________ Subject's Signature

______________ Date

______________________________ Address

______________ Phone Number

I was a witness during the above explanation and to the signature.

______________________________ Witness' Signature

______________ Date

APPENDIX 2

ANOVA TABLES

TWO-WAY ANALYSIS OF VARIANCE SUMMARY TABLE FOR PAD PLACEMENT (A) AND REST INTERVAL (B) FOR DATA 1

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARES	F RATIO	PROBABILITY
A	4411.113	1	4411.113	8.516	0.007*
S-Within	14503.375	28	517.978		
B	3908.848	2	1954.424	10.997	0.001**
AB	270.938	2	135.469	0.762	0.471
BS-Within	9952.250	56	177.719		

[illegible]O-WAY ANALYSIS OF VARIANCE SUMMARY TABLE FOR PAD PLACEMENT (A) AND REST INTERVAL (B) FOR DATA 2

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARES	F RATIO	PROBABILITY
A	2035.562	1	2035.562	7.317	0.011*
S-Within	7789.531	28	278.198		
B	1895.325	2	947.662	10.379	0.001**
AB	102.590	2	51.295	0.562	0.573
BS-Within	5113.332	56	91.309		

*significant at the $p \leq 0.05$ level
**significant at the $p \leq 0.01$ level

TWO-WAY ANALYSIS OF VARIANCE SUMMARY TABLE FOR PAD PLACEMENT (A) AND REST INTERVAL (B) FOR DATA 3

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARES	F RATIO	PROBABILITY
A	12900.938	1	12900.938	2.888	0.100
S-Within	125062.000	28	4466.500		
B	2167.500	2	1083.750	3.662	0.003*
AB	588.750	2	294.375	0.984	0.380
BS-Within	16758.000	56	299.250		

TWO-WAY ANALYSIS OF VARIANCE SUMMARY TABLE FOR PAD PLACEMENT (A) AND REST INTERVAL (B) FOR DATA 4

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARES	F RATIO	PROBABILITY
A	23974.688	1	23974.688	4.303	0.047*
S-Within	155992.000	28	5571.141		
B	97.500	2	48.750	0.155	0.857
AB	855.938	2	427.969	1.358	0.266
BS-Within	17650.000	56	315.178		

* significant at the $p \leq 0.05$ level
** significant at the $p \leq 0.01$ level

APPENDIX 3

POST HOC TESTS

SCHEFFE POST HOC COMPARISON OF TORQUE DECREMENT BETWEEN THE THREE REST INTERVALS

(a) Data 1

	35s	50s	65s
35s		9.501*	21.204**
50s			2.317
65s			

(b) Data 2

	35s	50s	65s
35s		11.372*	18.843**
50s			0.938
65s			

TUKEY POST HOC COMPARISON OF MEAN TORQUE BETWEEN THE THREE REST INTERVALS

Data 3

	35s	50s	65s
35s		4.903	5.923*
50s			0.048
65s			

* significant at the $p \leq 0.05$ level
** significant at the $p \leq 0.01$ level

APPENDIX 4

RISKS OF EMS

RISKS OF EMS

Similar to voluntary efforts, problems can arise from the use of EMS. Muscle strains, patellar dislocations, fractures of brittle bones as well as burns, electrical shock and skin irritations during stimulation treatments have been docummented. [29 52 62] However, the method of applying EMS via large electrode pads used in this study is similar to conventional faradic stimulation techniques employed by physiotherapists which have proved to be both safe and acceptable in terms of pain elicited. Notwithstanding, precautions were taken to reduce the likelihood of problems. The provisions made by the experimentor are outlined below.

SUBJECT'S STATE OF HEALTH: All participating subjects reported (in writing). having no previous nor present trauma, surgery or known pathology to the right hip or knee. which might have predisposed the subject to the potential risks of EMS. Each subject stated (verbally) having no known systemic infection.

COMMUNICATION: Before the subjects committed themselves to the study, detailed instructions were given by the investigator, who conducted all sessions. The possible risks of the study were outlined verbally, as well as written (in the Informed Consent Form). The sensations of EMS at the various intensity levels were described by the investigator and the subjects were encouraged in the practice session(s) to describe their perception of the current as they gradually increased the intensity dial.

WARM-UP: Prior to any session, the subject performed a minimum of five minutes of flexibility and stretching exercises, emphasizing the lower limb. It was important that the muscle was warm to facilitate the response of the muscle to the stimulation. In addition, once the subject was positioned for testing, he performed up to three warm-up trials against resistance in preparation for the experiment's task.

SKIN: It was not deemed necessary to shave any of the subjects' legs or backs. To decrease the high resistance of the skin to electrical current, the electrode pads were soaked in warm water prior to application. The moistened pads, consisting of several layers of cloth, were thick enough to make a good contact between the skin and the electrodes as well as thick enough to absorb any chemicals which might have formed under the electrodes. Care was taken to remove any creases from the folded cloth which would have caused uneven distribution of current and, consequently, discomfort to the subject. The cloth pads were slightly larger on all sides than the electrode thereby reducing the danger of the metal plates coming in contact with the skin causing a concentration of current. Not only would the current concentration cause pain but there was also the possible risk of tissue damage from chemical action. Breaks in the skin likewise could create a concentration of current, as current travels to those tissues with least resistance.[77] Petroleum gel was applied to open wounds for protection.

ELECTRODES: To ensure a good contact between the electrode and the skin, the metal (lead) electrodes were secured by a tensor wrap. The flexible qualities of the electrodes enhanced the contiguity of the two surfaces. The size of the electrodes were large enough to prevent uncomfortable current densities. The corners of the electrodes were rounded to decrease the amount of current concentration that ~~would have~~ occurred if the electrode had become bent.[75] Firm, consistent contact and rounded corners of appropriately sized electrodes, therefore, minimized the discomfort experienced by the subjects while enhancing the force output of the muscle. Furthermore, the two methods of pad placement used in the study are conventional techniques used for improving strength with minimal associated pain.

STIMULATOR: The TECA SP5/T stimulator and the operating procedures followed are comm[illegible]ically. The selected current produced by the stimulator was presented in the alternating current (AC) mode. Due to the biphasic nature of AC, the polarity of the electrodes changed with each phase of current. The ions, therefore, moved in one direction for one phase, and in the opposite direction during the other phase. If these two opposite phases are equal, which is the case with faradic stimulation,[77] the chemicals formed under one electrode during the first phase will be neutralized during the next phase. The danger of toxic substances accumulating under electrodes is that they can cause skin irritation and electrolytic burns to the associated tissues.[20] [77]

Before the subject was connected to the current, the apparatus was thoroughly examined. Prior to the stimulation being turned on, all connections were checked and secured, and the intensity dial was returned to zero. To test the output, the moistened electrode pads were put face to face. As the intensity was increased throughout the entire range, the current needles of the milliampmeter and the voltmeter were observed for their smoothly rising movements. These routine procedures were followed as safeguards against electric shock which could have occurred as a result of a sudden increase in current intensity. Once the subject was set up, further measures of safety were heeded to decrease the risk of shock. The pads were well-soaked and well-secured to the subject to provide a consistent flow of current. Towels were supplied for the subject to dry sweaty palms as it was the subject who controled the intensity dial. In addition, the subject was instructed to turn up the intensity smoothly so as to have no sudden surges in current.

MUSCLE SORENESS: Muscle soreness was the major difficulty experienced by the subject. The severity, though, was reduced by the warm-up period (both general and specific) prior to testing and the required minimum of 48 hours between any two sessions. In addition, because the subject was in control of the intensity dial, he could turn the dial up or down depending upon the sensation he was experiencing.

In conclusion, with the selected current and procedures followed, the subjects of this study were exposed to a minimal degree of physical risk.