Strength and Endurance in Human Skeletal Muscle, Why Electrical Stimulation Usually Fails To Generate the Same Response As During Voluntary Effort

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Abstract

Background- Electrical stimulation has been used to train paralyzed muscle. However, papers often cite that rapid fatigability of muscle compared to voluntary effort. Methods and Procedures; The literature is reviewed over the last 25 years examining the normal recruitment order of motor units, the impact of recruitment order, stimulation frequency and asynchronous recruitment on muscle strength and endurance. Results;

Recruitment order has little impact on muscle endurance. However, synchronous stimulation (where all units are stimulated together, drastically reduces muscle endurance. Stimulation frequency above 20 Hertz also reduces endurance.

Conclusions; Electrical stimulation of muscle in people with paralysis shows poor torque and endurance due to the fact that present electrical stimulators do not mimic the normal recruitment method and frequency of the human body.

Key words electrical stimulation, endurance, recruitment, motor control

Conclusion

Electrical stimulation of human muscle can be used to generate the same tension and with the same fatigue characteristics as is seen with voluntary effort. The limiting factor is not recruitment order by the high frequency of stimulation and the lack of an asynchronous recruitment pattern. This can be simulated with multi-channel electrical stimulation.

Introduction

In 1744 a German scientist whose name was Krueger, wrote "*but what is the usefulness of electricity, for all things must have a usefulness that is certain. Since electricity must have a usefulness and we have seen it cannot be looked for either in theology or in jurisprudence there is nothing left but medicine. The best effect would be found in paralyzed limbs to restore sensation and reestablish the power of motion"* [1]. In this early treatise, Krueger felt that there must be a practical use in medicine for electricity and saw the potential use for moving muscle. Over the years, however, electrical stimulation has evolved as a technique to retrain partially paralyzed muscles after stroke [2], to regain strength after surgical procedures to the knee [3], and conditioning after cardiac surgery [4]. It has been used quite frequently for such modalities as healing difficult bone fractures [5] and has been used for patients with stroke or spinal cord injury to reduce muscle spasticity [6, 7, 8]. Electrical stimulation has been shown to increase the circulation to skin and muscle [10, 11, 12]. Electrical stimulation has been used (1) to increase strength and endurance of muscle, (2) improve range of motion, (3) neuromuscular reeducation [13], (4) pain management, (5) reducing edema [14], and (6) as an aid in the healing of bone fractures and pressure sores. It has been used for peroneal nerve stimulation [15, 16], the restoration of shoulder movement [17], recovery of tendonesis grip [18], in an upper arm prosthesis [19] and for restoring some degree of gait in paraplegics [20, 21, 22].

One limitation often cited with electrical stimulation is that muscles fatigue much more quickly than with voluntary effort [23, 24]. Irrespective of the degree of activation of the muscle with electrical stimulation, peak torque, in most studies, rapidly decreases from muscle fibers [24]. Typically, this has been blamed on differences in recruitment patterns during electrical stimulation versus voluntary activity. Henneman, first published that motor units were first recruited by size from slow-twitch motor units (small neurons) to the large fast-twitch motor units [25]. Since fast-twitch motor units are more susceptible to electrical stimulation, it has been assumed for years that since recruitment order would be reversed with electrical stimulation, and that this would account for the reduction in muscle fatigue[23]. Recently, however, Gregory and Bickel conducted a review of the literature and provided convincing evidence that, with electrical stimulation, due to the anatomy of the muscle and other factors, recruitment order may not be fully reversed and this may not be a major limiting factor in the reduced endurance in muscle [23]. Other factors may have equal bearing, such as, the frequency at which electrical stimulation is applied and how recruitment is accomplished, that is, are all motor units recruited together or are them alternated? This paper reviews the normal neurological recruitment patterns in muscle and examines the effect of altering these by electrical stimulation on strength and endurance in muscle.

Motor Unit Recruitment

Milner-Brown, Stein, and Yemm [26, 27] studied, with fine wire needle electrodes, the recruitment order of motor units in human muscle during voluntary isometric contractions. The results of their experiments showed that motor units were recruited initially at a frequency of about 9 cycles per second and frequency was kept constant until all motor units were recruited. Motor units were recruited asynchronously (activated units were alternated) with an increasing number of motor units recruited until about half of the muscle strength was exerted. At half of the maximum strength of the muscle, motor units were fully recruited and the increase in tension in the muscle was developed by increasing the firing frequency of the motor units. In other words, once a motor unit is recruited, it may drop out of the motor neuron pool after a short period of time and be replaced by another motor unit so that the first motor unit can recover while the second motor unit carries the load. Physiologically, this is due to the fact that with a constant neurological input to an alpha motor neuron, the alpha motor neuron slowly becomes refractory and harder to excite [28]. Thus motor neurons require a stronger excitatory input to maintain their firing rate if firing on a prolonged basis during a constant tension contraction. Figure 1, from Petrofsky et. al. [29] shows that for the human brachioradialis muscle, for low tension isometric contractions, human motor units are recruited at different points in time depending upon the tension exerted in the muscle. However, for tension above 50% of the maximum strength of the muscle, discharge frequency of all the motor units increased.

Typically, however, as a modality, electrical stimulation is accomplished at a constant stimulation level and, with all motor units firing together (synchronously). Further, we typically set electrical stimulators at frequencies between 30-100 cycles/sec (Hertz) to achieve a smooth muscle contraction. This may be the cause of some of the increased fatigability in muscle as shown below.

The effect of synchronous simulation on muscle strength and endurance

In early experiments, by using fast-twitch, slow-twitch and mixed skeletal muscle in a cat, we were able to study the effect of recruitment order and asynchronous versus synchronous electrical stimulation on isometric strength and endurance. Figure 2 illustrates a computer control system for controlling movement in muscle. The computer controls an electrical stimulator with up to 10 different channels of output with electrodes applying a uniform electrical field to different bundles of alpha motor neurons at the L_{6}, L_{7}, and S_{1} ventral roots of the spinal cord. The cat was anesthetized with Ketamine to allow reflexes to remain intact. By either randomly or serially activating the electrodes, the muscle motor units could be stimulated asynchronously or synchronously [30, 31]. The use of an anodal block below the stimulating electrodes could, once motor units are recruited, block the propagation of action potentials to the muscle. A unique property of an anodal block is that when the anodal block is applied, the blocking current first blocks fast-twitch motor units then slow-twitch units [31]. Thus, if all motor units were recruited and the anodal block was at full power, by removing the block, recruitment order would be from slow to fast-twitch motor units. With this basic model then, we are able to study the effect of recruitment order and asynchronous versus synchronous electrical stimulation on strength and endurance.

By providing a sensor on the calcaneous to measure the tension generated by the muscle, and with the appropriate computer software, isometric contractions could be sustained briefly or to fatigue with all motor units firing synchronously or with 3, 5, or 10 groups of motor neurons firing asynchronously. Recruitment order could either obey the Henneman principle of small to large or from large to small. Figure 3 illustrates the effect of frequency of stimulation on tension. Motor units were recruited synchronously at an appropriate stimulus intensity to recruit them in the gastrocnemius muscle at frequencies between 5 and 50 hertz. Contractions were very weak and unfused at 5 hertz. At 10 hertz, contraction tension was still only 20% of the maximum strength of the muscle, and frequencies about 35-50 hertz were necessary to achieve full tension of the muscle. However, if motor units were recruited asynchronously, with either 3, 5, or 10 groups of motor neurons, much greater tension was developed at a frequency of 5 hertz and, greater than 90% of the tension in the muscle was achieved by a frequency of 20 hertz. This was attributed, in these experiments, to removal of the series elastic component in the muscle by asynchronous motor unit firing patterns. Once one motor unit fired and removed the series elastic component, the second motor unit that replaced it in the asynchronous pattern was able to exert its active state directly into the insertion of the muscle, providing more force. Stimulation with electrical stimulation is usually at frequencies of 30-50 hertz or higher. The natural discharge frequency is 9-10 hertz. The question that arose then, was how important is frequency of stimulation in causing muscle fatigue. As shown in figure 4 [35], at a frequency of 200 cycles/sec, tension was reduced by 50% in 1 second and by 10 seconds muscle was almost fully fatigued. In contrast, when frequency was only 25 cycles/sec, after 1 second tension dropped by only 5% and by 10 seconds tension dropped by 20%. At frequencies of 10 cycles/sec, very little muscle fatigue was seen after 10 seconds of stimulation. Thus, as shown in figure 4, the lower the stimulation frequency, the better the endurance characteristics of the muscle fibers. The high fatigue in the muscle fibers at high frequencies has been attributed to neuromuscular failure [35].

Logically then, endurance should be increased if stimulation frequency is reduced. To see if endurance was improved by starting contraction at lower frequency of stimulation, the computer was programmed to elicit fatiguing isometric contractions to mimic human muscle. The initial stimulation frequency was 10 hertz. Recruitment was at first increased to maintain a given tension and, once all motor units were recruited, increasing the frequency of discharge to as high as 40cycles/sec[34]. When this was accomplished, as shown in figure 5, if all motor units fired together (synchronous stimulation) even with a computer program varying recruitment and the frequency of discharge, endurance was very short at low isometric contraction tensions and, by half of the maximum strength, endurance was only a few seconds[30, 31, 32]. In contrast, if the motor neuron pool was broken into 2, 3, 5, or 10 subdivisions and these were stimulated asynchronously, endurance was very long and decreased exponentially with tension as has been observed for human muscle [34]. Using this model then it was possible to study recruitment order.

Recruitment Order

Using 3 asynchronous groups of motor neurons, the impact of recruitment order on isometric endurance is shown in figure 6 [30, 31, 32]. Illustrated here is the endurance in seconds for the cat medial gastrocnemius muscle as a percent of the maximum strength of the muscle for contractions between 10-100% of the muscle's maximum strength. By using the anodal block electrode versus the stimulation electrodes, recruitment order could be conducted in the forward versus the reverse direction. As can be seen in this figure, reversing recruitment order had only a minimal effect on isometric endurance and only at low contraction tensions.

Finally, by using 3 sets of electrodes over the quadriceps muscle in spinal cord injured individuals and firing these 3 sets of electrodes asynchronously and following the program developed on cat muscle, endurance was compared in 6 control subjects during voluntary contraction to 6 paraplegics during isometric contractions elicited by electrical stimulation between 10-100% of their maximum voluntary strength [34]. As shown in figure 7, the endurance at the lowest tension (10%) was significantly less than control subjects during voluntary effort. However, there was no statistical difference between the endurance times above 15% of the muscle's maximum strength.

It would appear then, from the above, that recruitment order was probably never the issue in limiting endurance in paralyzed muscle. Endurance for bicycling [33] and for isometric exercise [34] can be similar to voluntary human contractions. The issue in lower endurance, therefore, is not one of recruitment order but synchronous versus asynchronous electrical stimulation and frequency of stimulation. With synchronous electrical stimulation, intramuscular pressures are high and blood flow is quite limited during the contraction such that muscle fibers fatigue rapidly [35]. Thus the difference between electrical stimulation and voluntary effort is more of the way in which the electrodes are applied to muscle, the frequency of discharge, and the manner in which stimulation is used, and not simply recruitment order. There are electrical stimulators that are on the market today that use asynchronous recruitment patterns (i.e. Challenge 2010, MPTS inc, Irvine, Ca.) but, these are rare and need to be developed in the future.

The electrical stimulator- a more confounding variable

While much research has been done to understand why endurance and peak torque is much shorter during electrical stimulation than during voluntary effort, the one overlooked factor often is the electrical stimulator itself and the electrodes. In recent studies [36, 37], it has been shown that electrode position and electrode size may not be as important as once thought. In these studies, little difference in muscle contraction force and comfort could be found between electrodes differing by as much as 3 fold in size when looking at contraction strength in muscles like the quadriceps muscle. Modern carbonized rubber electrodes seem to disperse more current near the center than around the edges [38] and, if a large muscle group is involved such as the quadriceps, even with large electrodes, only a fraction of the muscle may actually be stimulated. Because of the arrangement of the carbonized rubber wick inserting in the center of the electrode rather than on the edges of the electrode, these electrodes disperse current down the center between the electrodes and current falls off rapidly toward the edges irrespective of manufacturers' claims. Therefore, even if an electrode that was 10 cm wide was placed over the quadriceps to stimulate all four heads of the muscle, most of the current would be in the center of the electrode and not on the edges. Self-adhesive electrodes used today do not provide even current distribution as was seen in previous years with carbonized rubber electrodes where a liquid electrode get was placed under the electrodes [38]. This is another important variable.

Another potential variable is the stimulator itself. Numerous studies have been conducted examining stimulator output in relation to manufacturer's claims. An ideal square wave output for a stimulator is shown in figure 10. In contrast, the average output of 5 different stimulators (Chattanooga) is shown on the same figure. As can be seen, the output is far from the square wave and, there is a charge constant time in which the electrode charges and instead of maintaining a constant output as seen with an ideal square wave, current dissipates during the square wave. Making matters worse, if stimulators are left on for long periods of time (even 20 seconds), the entire output of the stimulator may fall. Recently, Bennie et. al. 2002 and Forrester et. al. 2004 [36, 37] showed that even at full power Chattanooga, and EMPI stimulators had a fall off in muscle current. But the worst case is battery operated stimulators. Battery operated stimulators such as the intellect TENS units, are commonly used for electrical stimulation. When used for electrical stimulation of muscle, the output current of the battery is just not strong enough to provide a continuous strain of impulses from the stimulator. As shown in figure 11, when 5 such TENS units were used and stimulation was applied across the skin over the quadriceps muscle over a period of continuous stimulation at 250 ms pulse width and 50 mA output, stimulus amplitude continually dropped. This was paralleled by a drop in battery voltage from 9 volts to 7.1 volts over the same time period and reduction in muscle force. Thus, in some cases, the reduction in muscle strength associated with stimulation may be related to the stimulator or electrodes and not at all related to physiological phenomena such as recruitment order.

Conclusions:

Electrical stimulation of muscle is at best an artificial process. What the clinician is trying to accomplish is to mimic the normal operation of the nervous system and provide a smooth contraction of skeletal muscle which can be sustained long enough for muscle training. Unfortunately, because of slight differences in recruitment order and principally due to the fact that motor units are recruited asynchronously such that some motor units are allowed to relax while other contract, motor units fatigue much more quickly during electrical stimulation than during voluntary effort. Asynchronous stimulation can be mimicked with multiple electrodes and a computer controlled stimulator, but few stimulators presently available on the market are capable of handling this. Another confounding variable is the stimulator itself. Irrespective of manufacturer's claims, stimulators generally do not provide the current and voltage that is specified by the manufacturer and, for battery operated stimulators, current and voltage rapidly fall while continuous use to do the inability of the battery to provide continuous charge to operate the stimulator.

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Figure Legends

Figure 1. This figure shows the frequency of discharge of individual motor units in the human brachioradialis muscle in relation to the tension exerted by the hand grip muscles as a percent of the maximum strength of the muscle for 5 individual motor units.

Figure 2. This figure shows a representation of a computer controlled system for studying the effect of electrical stimulation on strength and endurance in skeletal muscle. The muscle is connected through the calcaneous to a force transducer providing a feedback to the system, between up to 10 sets of electrodes are controlled by the computer stimulating individual bundles of motor neurons going to the target muscle. Below the stimulator electrode (marked as anodes and cathodes) are parallel plates that form an anodal block.

Figure 3. This figure illustrated here is the relationship between strength in the medial gastrocnemius muscle and frequency of stimulation when all motor units are discharged at the same time (synchronous stimulation, T1) and when stimulation is applied to the motor nerve divided into 3 segments and stimulated asynchronously (T3) 5 different subgroups stimulated asynchronously (T5) and 10 subgroups stimulated asynchronously (T10).

Figure 4. This figure illustrates the tension developed by muscle in the cat medial gastrocnemius muscle at frequencies of stimulation of between 5-200 Hz. 1, 3, and 10 seconds after the onset of stimulation. The results illustrate the mean of 10 experiments ± the appropriate standard deviation.

Figure 5. This figure illustrates the endurance for fatiguing isometric contractions at 10, 15, 20, 30, 40, 55, 70, and 100% of the muscle’s maximum strength for the cat medial gastrocnemius muscle during synchronous stimulation and during stimulation 2, 3, 5, and 10 subgroups of electrodes firing asynchronously. The endurance for the contractions is illustrated on the y-axis whereas tension is illustrated on the x-axis. Muscle strength was maintained at a percent of the muscle’s maximum strength by a computer program whereby recruitment was changed first and motor units were recruited at 9 Hz. and, after all motor units were recruited frequency was increased to as high as 70 Hz.

Figure 6. Illustrated in this figure is the endurance for fatiguing isometric contractions at 10, 15, 20, 30, 40, 55, 70, and 100% of the muscle’s maximum strength for isometric contractions of the medial gastrocnemius muscle in the cat with recruitment order set in the forward versus the reverse direction. This point illustrates the mean of 10 experiments ± the appropriate standard deviation.

Figure 7. This figure illustrates the isometric endurance of the humans for their hand grip muscles (diamonds) at contraction tensions between 10-100% of the muscle’s maximum strength sustained to fatigue. This data is compared in 10 human volunteers (± the appropriate standard deviation) to 10 medial gastrocnemius muscles in cats during electrical stimulation (squares).

Figure 8. This figure shows the stimulus amplitude during a single impulse of a theoretical square wave (diamonds) compared to an actual square wave generated by a Chattanooga electrical stimulator (squares).

Figure 9. This figure shows the reduction in stimulus amplitude from a TENS unit over a period of 20 seconds with stimulus being left on continuously at a current of 50 mA and frequency of 30 Hz. Data illustrates the average of 5 different stimulators ± the appropriate standard deviation.

Figure 1

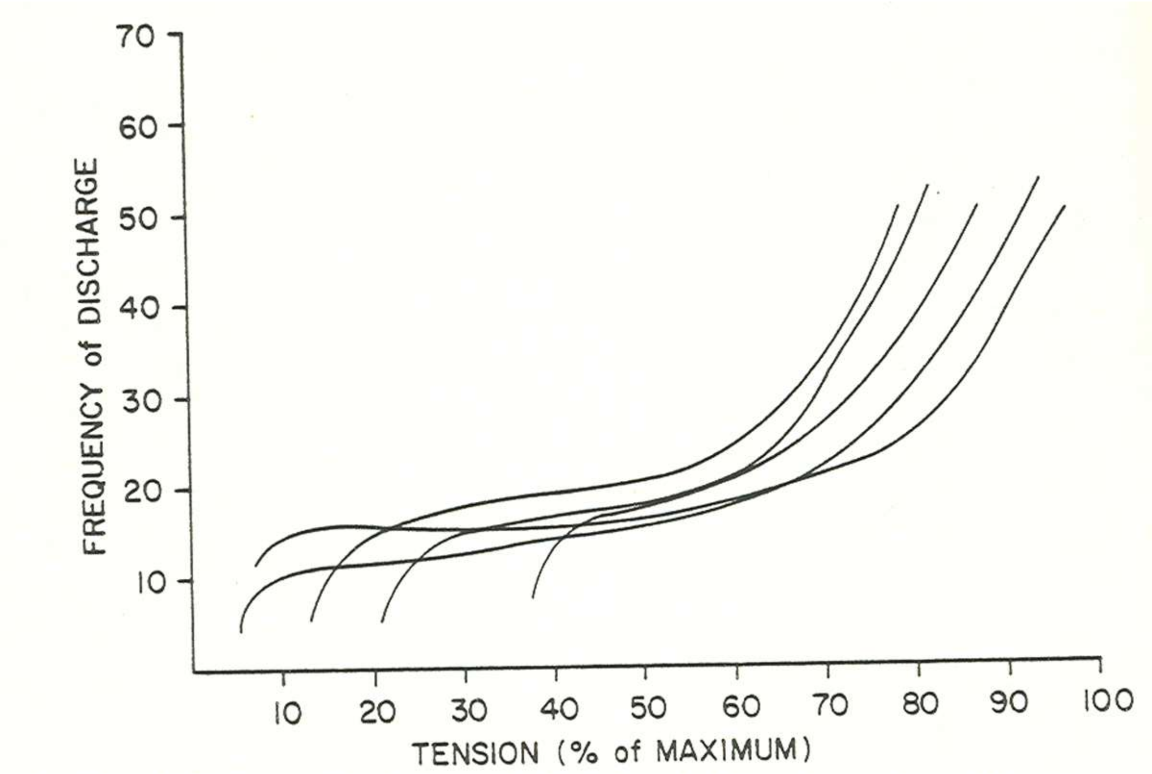

FREQUENCY of DISCHARGE
70
60
50
40
30
20
10
10
20
30
40
50
60
70
80
90
100
TENSION (% of MAXIMUM)

Figure 2

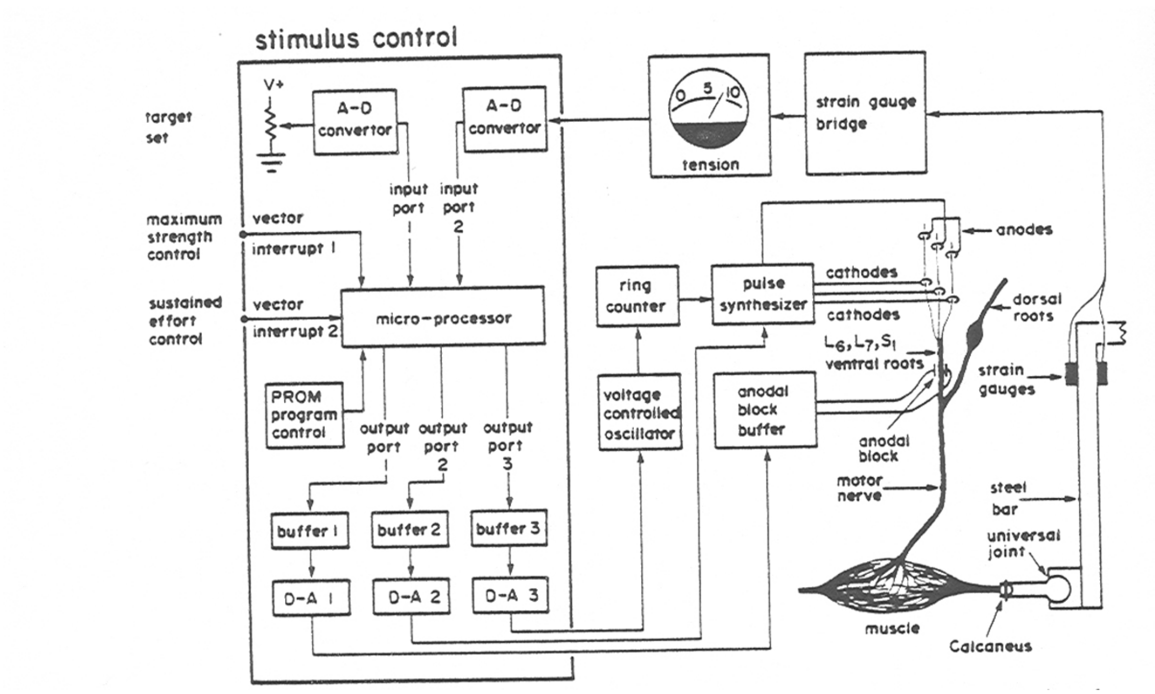

stimulus control
target set
V+
A-D convertor
A-D convertor
tension
0 5 10
strain gauge bridge
input port 1
input port 2
maximum strength control
vector interrupt 1
sustained effort control
vector interrupt 2
micro-processor
PROM program control
output port 1
output port 2
output port 3
buffer 1
buffer 2
buffer 3
D-A 1
D-A 2
D-A 3
ring counter
voltage controlled oscillator
pulse synthesizer
anodal block buffer
anodes
cathodes
cathodes
dorsal roots
L6, L7, S1 ventral roots
anodal block
motor nerve
strain gauges
steel bar
universal joint
muscle
Calcaneus

Figure 3

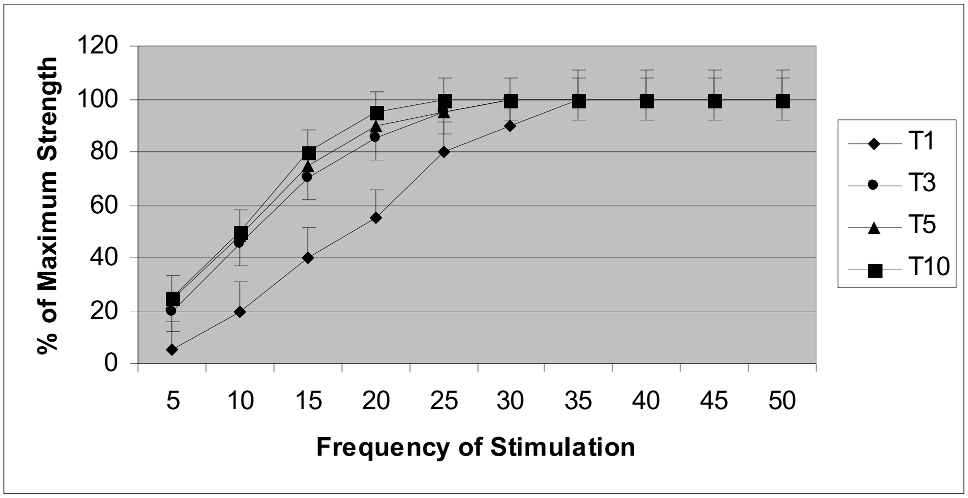

% of Maximum Strength
0
20
40
60
80
100
120
5
10
15
20
25
30
35
40
45
50
Frequency of Stimulation
T1
T3
T5
T10

Figure 4

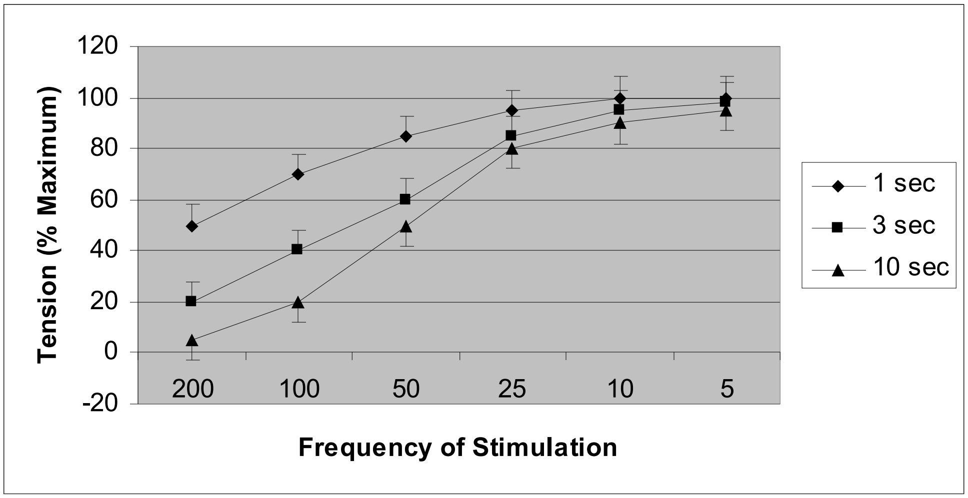
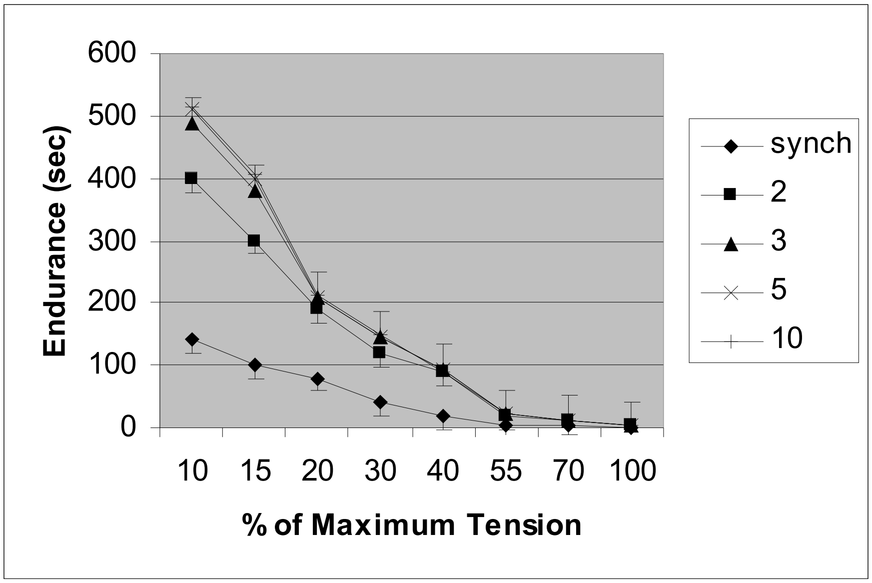
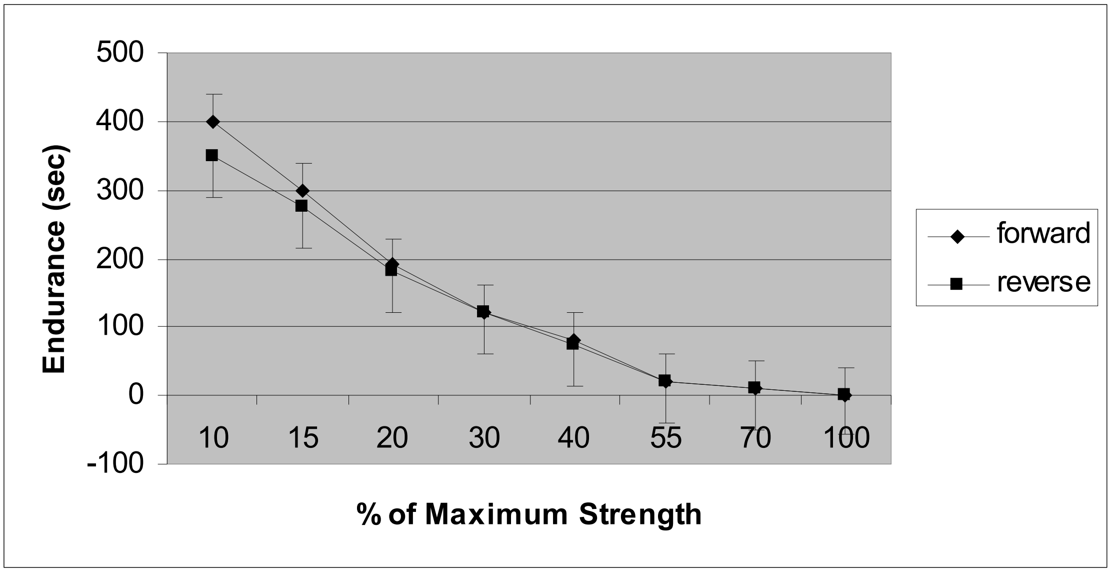

120
100
80
60
40
20
0
-20
Tension (% Maximum)
200
100
50
25
10
5
Frequency of Stimulation
◆ 1 sec
■ 3 sec
▲ 10 sec

Figure 5



Endurance (sec)
600
500
400
300
200
100
0
10
15
20
30
40
55
70
100
% of Maximum Tension
synch
2
3
5
10

Figure 6



500
400
300
200
100
0
-100
Endurance (sec)
10
15
20
30
40
55
70
100
% of Maximum Strength
forward
reverse

Figure 7

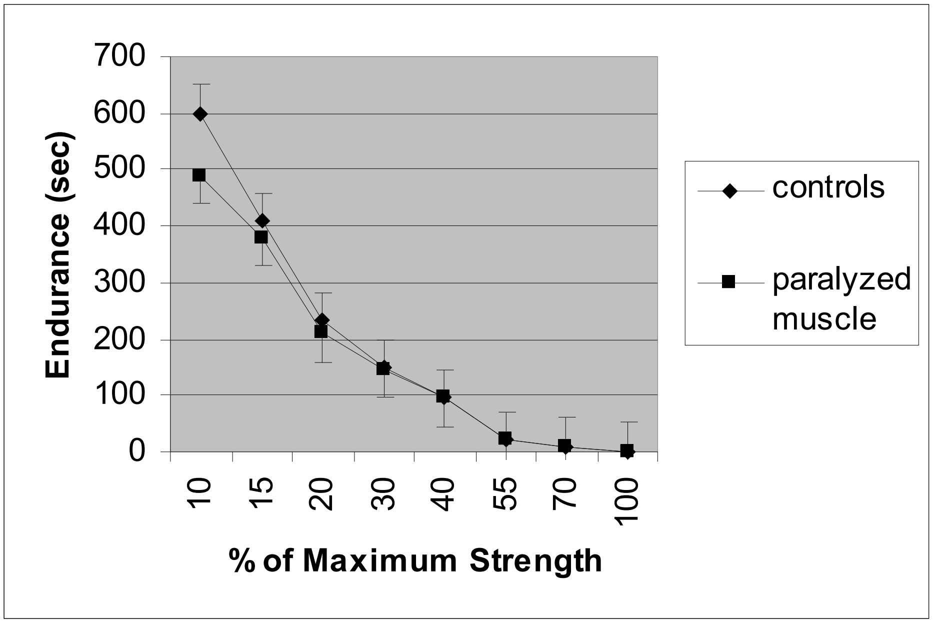
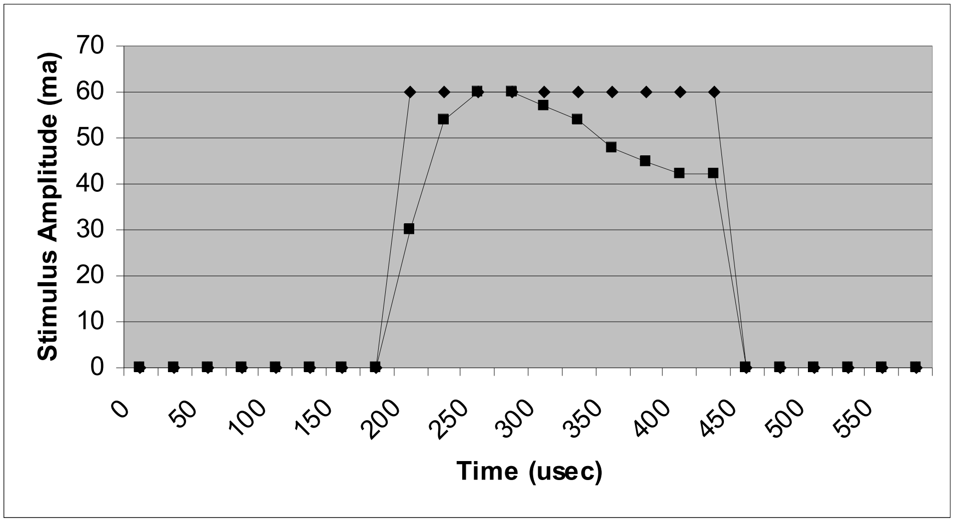
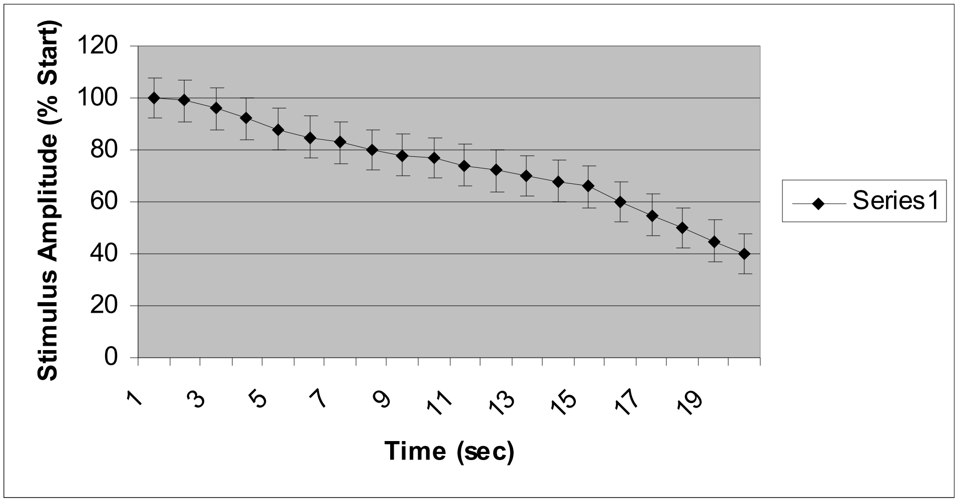

700
600
500
400
300
200
100
0
Endurance (sec)
10
15
20
30
40
55
70
100
% of Maximum Strength
controls
paralyzed muscle

Figure 8



Stimulus Amplitude (ma)
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
350
400
450
500
550
Time (usec)

Figure 9


Stimulus Amplitude (% Start)
120
100
80
60
40
20
0
1
3
5
7
9
11
13
15
17
19
Time (sec)
Series1