Electromyographic biofeedback in the neuromuscular reeducation of a quadriplegic: Training, response generalization and long term control

Carl Frederick Coolbaugh

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ELECTROMYOGRAPHIC BIOFEEDBACK IN THE NEUROMUSCULAR REEDUCATION
OF A QUADRIPLEGIC: TRAINING, RESPONSE
GENERALIZATION AND LONG TERM CONTROL

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A Thesis
Presented to the
Faculty of
California State College,
San Bernardino

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In Partial Fulfillment
of the Requirements for the Degree
Master of Arts
in
Psychology

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by
Carl Frederick Coolbaugh
April 1982
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Approved by:

Chairman

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ABSTRACT

This study explores the degree of voluntary muscular control obtained by a severely injured quadriplegic subject utilizing EMG Biofeedback from left and right triceps brachii. Generalization effects to left and right flexor carpi radialis muscles, as well as arm range of motion, were examined. The subject was a male, age 25, diagnosed as having a C-5, C-6 comminuted cervical vertebral fracture. Nine, twenty-five minute baseline sessions were run over a three week period with left and right muscle groups monitored during moderate and maximum effort extensions. Twenty-four, twenty-five minute sessions were run over an eight week period in which left and right tricep feedback was given during alternate ten second extension periods followed by twenty second rest periods. EMG signals were filtered, integrated and digitally quantified. Feedback training resulted in large percent increases in both frequency and amplitude of tricep EMG over baselines. Flexor carpi radialis EMG scores yielded increases over baseline suggesting generalization. Following training, immediate unsustained extension of the elbow was replaced by some sustained extension, in both arms, indicating a gain of tricep strength. A three month follow-up study was conducted over three weeks. Follow-up baseline percent in-
crease were recorded over all initial baseline levels. Follow-up feedback training sessions consisted of three sessions of moderate effort extension followed by three sessions of maximum effort extension. Follow-up percent increases in frequency and filtered integrated triceps levels above previous therapy levels indicated long term effects were maintained. Follow-up unfiltered integrated triceps feedback levels fell below initial feedback levels. Integrated flexor carpi radialis levels fell below previous therapy levels suggesting that some long term generalization was maintained. The results of this study demonstrate the utility of EMG biofeedback as a method for enhancing muscular control in a case of severe muscular dysfunction.
# TABLE OF CONTENTS

**LIST OF FIGURES** ................................................................. vi

**ACKNOWLEDGEMENTS** ............................................................ viii

**INTRODUCTION** ........................................................................... 1

  Origins of Electrophysiologic Muscle Study ................................ 1
  Motor Function and Physiological Aspects of Muscles ...................... 2
  Biofeedback Paradigm .................................................................. 4
  Electromyographic Biofeedback, Neuromuscular Reeducation and Response Generalization ......................... 4
  Statement of the Problem ................................................................ 14

**METHOD** .................................................................................. 17

  Subject ....................................................................................... 17
  Apparatus ................................................................................... 17
  Procedure .................................................................................... 20

**RESULTS** .................................................................................. 24

  Initial study (Part One) ............................................................... 24
  Three Month Follow-Up (Part Two) .............................................. 32

**DISCUSSION** ............................................................................. 40

**REFERENCES** ............................................................................. 47
LIST OF FIGURES

1. Flow diagram of data acquisition system which traces the input signals from amplification to feedback and quantification. Components are arranged in terms of signal processing order

2. Filtered quantified triceps brachii mean proportional frequency counts for three weeks baseline verses the last three weeks of feedback

3. Filtered quantified triceps brachii proportional frequency counts averaged each week across feedback training. Week zero indicates baseline levels averaged over two weeks

4. Filtered quantified triceps brachii mean proportional frequency counts averaged over one week baseline and the last week of feedback training during maximum effort extensions

5. Filtered integrated triceps brachii mean microvolt levels averaged over three weeks baseline verses the last three weeks of feedback training

6. Unfiltered integrated triceps brachii mean microvolt levels averaged over three weeks baseline verses the last three weeks of feedback training

7. Unfiltered integrated flexor carpi radialis mean microvolt levels averaged over three weeks baseline verses the last three weeks of triceps brachii feedback

8. Filtered quantified triceps brachii mean proportional frequency counts averaged over three weeks initial baseline verses last two weeks follow-up with feedback

9. Filtered integrated triceps brachii mean microvolt levels averaged over three weeks initial baseline verses last two weeks follow-up with feedback

10. Unfiltered integrated triceps brachii mean microvolt levels averaged over three weeks initial baseline verses last two weeks follow-up with feedback
11. Unfiltered integrated flexor carpi radialis mean microvolt levels averaged over three weeks initial baseline verses last two weeks follow-up during triceps brachii feedback.
ACKNOWLEDGEMENTS

I would like to thank Dr. FrederickNewton for serving as the chair of my thesis committee. His close supervision, guidance and excellent advice was most appreciated. I would also like to thank Drs. Stuart Ellins and Nikolai Khokhlov for serving on my thesis committee. Their suggestions were very helpful in the completion of this thesis.

I would like to thank Cornel Ormsby, who works in the psychology laboratory, for the custom electronic equipment he designed and built for me. I wish to thank President Pfau for the financial support which enabled me to present this work at two psychology conventions.

Finally I would like to thank my sister for all of her proofreading of this manuscript and my mother and father for their continuing support and encouragement throughout my graduate school experience.
Origins of Electrophysiologic muscle study

In 1786 Luigi Galvani observed, by chance, that electricity could produce twitching in a dead frog's leg. This event inspired Galvani to perform a number of experiments in which he demonstrated that the introduction of electric current into the body yields a muscular response and also that changes in electrical activity occur in normal muscle movement. Galvani believed he had discovered the essential life force which he called "animal electricity" (Hassett, 1978). In the mid nineteenth century Helmholtz, was the first physician to study the transmission time of electrical signals from nerve to muscle in a human subject (Yanof, 1965). About the same time G.B.A. Duchenne, used electricity in his study of the dynamics of intact skeletal muscles. Duchenne studied the movements of muscles stimulated by electricity through the skin, and has been called the father of medical electrophysiology (Basmajian, 1978). In 1841, Carlo Matteucci demonstrated that current flowed from the surface of a muscle to a wound in the muscle. On the basis of Matteucci's work du Bois-Reymond conceived a theory of the polarization of animal tissue and confirmed Matteucci's work. Du Bois-Reymond also recorded the first human electromyogram (EMG), from the contracting arm of a man by using liquid electrode jars (Goldstein, 1972). Although many other scientists have contributed to this field since
these early pioneers, it has only been in recent years that
electrophysiologic methods, for studying the function of
nerve and muscle, have come to be used in a broad clinical
context. This development has resulted largely from
advances in technology which has also permitted the
development of more refined techniques.

Motor Function and Physiological Aspects of Muscles

Voluntary motor function is dependent on the
transmission of neural impulses. These impulses originate
in the brain and are transmitted through the upper motor
neurons which innervate the anterior horn cells. Axons of
the anterior horn cells, lower motor neurons, lead to
various groups of muscles they innervate. Neural impulses
generate electrical waves called motor unit potentials or
motor action potentials (MAPS). Normal MAPS usually range
from 3 to 5 msec in duration and up to around 3 mv in
amplitude (Cohen and Brumlik, 1968). The motor unit is the
ultimate unit of voluntary function and under normal
circumstances depends upon the activity of the nerve and
muscle (Marinacci, 1968). The motor unit refers to a
single lower motor neuron and the muscle fibers it
innervates. This includes the lower motor neuron's cell
body, which is located in the spinal cord, its axon which
exits the spinal cord becoming first a nerve root and
finally a peripheral nerve, its terminal arborizations,
neuromuscular junctions and all the muscle fibers it innervates (Aminoff, 1978).

A typical muscle is a mass of tissue which is made up of millions of individual muscle fibers held together by a layer of connecting tissue (Goldstein, 1972). The muscle fiber is the structural unit of contraction, and contracts as a result of a propagated action potential. An individual muscle fiber is a fine thread about 0.1mm wide and can be up to 30cm in length (Basmajian, 1978). During contraction the muscle fibers will shorten to roughly 57 percent of their resting length and an apparent smooth contraction of the entire muscle is the result of the summation of asynchronous twitching of these fibers (Basmajian, 1972).

Trauma or disease can change the nerve and or muscle resulting in an attenuation of voluntary function. A subject who has suffered partial severance of the spinal cord will typically display a large reduction of voluntary function. The reduction will usually occur at and below the spinal cord level of the trauma. Types of paralysis or paresis are based on location. The most commonly encountered types are: hemiplegia, a spastic or flaccid paralysis of one side of the body and extremities limited by the ventral and dorsal median lines, paraplegia, a symmetrical paralysis of the lower extremities and quadriplegia, a paralysis of all four extremities (Chusid
Biofeedback Paradigm

Biofeedback refers to a process whereby a physiological response is brought under control through volitional means. The response may or may not be ordinarily under voluntary control and control may be attenuated or absent due to trauma, disease or disuse atrophy. Usually the response is not readily apparent to the subject and must be amplified by electronic means. Amplified, the physiological signal can produce feedback for the subject usually through visual or auditory modes. It is important that the feedback be given to the subject continuously and on a relatively immediate basis since as time elapses, between the occurrence of the physiological response and the feedback, the ability to control the response diminishes or is lost.

Electromyographic Biofeedback, Neuromuscular Reeducation and Response Generalization

Prior to 1960, the usual methods of physical therapy and exercise were employed in an attempt to rehabilitate diseased or traumatized nerve and or muscle conditions. However, many subjects were unable to benefit from the commonly used therapies and new methods were examined.

The major goal in neuromuscular reeducation is the
reinitiation and maintenance of functional neural transmission. Biofeedback has been used to accomplish this goal and may encompass several different results: the reduction of muscular output, as in the spasticity of hyperactive muscles, in cases of torticollis (Brudny, Grynbaum and Korein, 1974), or dystonia (Bird and Cataldo, 1978). To produce coordinated movement of a group of muscles that by themselves have sufficient tone but not the ability to produce integrated movement (Olton and Noonberg, 1980), and to increase the output of muscles suffering from paralysis, paresis and or disuse atrophy, as in subjects who have sustained spinal cord damage (Seymour and Bassler, 1977), or cerebral vascular accidents (Johnson and Garton, 1973).

Although the term biofeedback did not come into widespread use until 1969 (Blanchard and Epstein, 1978) the components and result of EMG biofeedback were recorded by Marinacci and Horande (1960). They noticed that motor units increased in frequency and amplitude due to increased transmission of neural impulses facilitated by EMG output. Marinacci and Horande successfully used EMG biofeedback in treating a sixty-four year old male who had suffered thrombosis of the right middle cerebral artery resulting in left hemiplegia. A needle electrode was inserted into the left deltoid and no voluntary motor unit activity was detected. The electrode was then inserted into the normal
right deltoid and the subject was instructed how to generate motor unit activity by listening to auditory feedback. The subject was able to accomplish this task with ease. The electrode was then placed into the left deltoid and the subject immediately generated 10 to 15 percent of the motor units in this location. The triceps, extensors and flexors and the muscles of the left hand were also treated resulting in a 20 percent functioning of the muscles of the left upper extremity within one hour. Although they called this treatment method "audio-neuromuscular re-education", Marinacci and Horande may be considered the fathers of electromyographic biofeedback. Thus, although the electromyogram has been used as a diagnostic and prognostic procedure for fifty years it was not until the 1960's that it was studied as a therapeutic tool (Owen, Toomim and Taylor, 1975).

Even though Marinacci and Horande's technique showed promise few practitioners reported on its use, apparently indicating that employment of the new procedure was minimal. Four years later Andrews (1964) reported that visual and auditory EMG feedback was used in the treatment of twenty hemiplegic subjects whose conditions ranged from one to fourteen years poststroke and had remained unchanged in response to conventional therapy. All of these subjects had no voluntary movement of their biceps and triceps on their involved side. Needle electrodes were inserted into
the subject's normal muscle to acquaint them with the feedback, oscilloscope readout, auditory tone and specific mental effort needed to produce the voluntary contraction. The electrodes were then inserted into the involved muscles and the subjects were instructed to contract them. If no EMG potentials occurred, the joints activated by the muscles were passively put through their range of motion. The subjects were instructed to try and voluntarily complete the movement. If action potentials were seen on the oscilloscope the subjects were asked to watch them and try to repeat whatever they did to produce them. All subjects were allowed five minutes to obtain good function of their muscles under study or they were considered to have failed therapy. Seventeen of the twenty subjects were successful in producing voluntary motor unit action potentials which produced voluntary, controlled action of their muscles.

Mroczek, Halpern and Mc Hugh (1978) compared EMG feedback with physical therapy for effectiveness in training hemiplegic subjects to increase motor activity. The subjects, two females and seven males, ranged in age from 50 to 75 years. Two subjects suffered left hemiparesis and seven subjects right hemiparesis, ranging from one to ten years poststroke. The goal was increased muscle contraction in the wrist extensors in seven subjects, increased muscle contraction of the biceps in one
subject and inhibition of the biceps in another. The subjects were divided into two groups. Both groups received baseline recordings twice weekly for two weeks. Next the first group, five subjects, received four weeks, three sessions per week, of EMG training followed by four weeks, three sessions per week, of physical therapy. The second group, four subjects, received therapy in the reverse order. Biofeedback and physical therapy sessions were 30 min long. Subjects received visual and auditory EMG feedback and were instructed to increase or decrease appropriate muscle activity. EMG output and range of motion increased under both biofeedback and physical therapy conditions. However, the group receiving biofeedback prior to physical therapy demonstrated a larger increase in EMG output but not range of motion than did the group which received physical therapy first.

EMG biofeedback has also been utilized to treat paraplegic subjects. Toomim and Johnson (1974) successfully used EMG biofeedback to treat a 54 year old female paraplegic subject who was injured in an auto accident and had sustained spinal cord damage at the T11-12 level. The subject, who was ten years post trauma, reported that she had regained some function of the waist and hip muscles, during the previous five years and could demonstrate limited ability to abduct both legs and extend them backward when standing with braces in bars. The
subject could walk and flex her hips using leg braces and crutches.

During the first eight sessions several active motor units were found in the gastrocnemius, tibialis anterior and biceps femoris. During the ninth session nearly complete control of the motor units in the left biceps femoris was obtained during the second half hour of therapy. After four months of therapy the subject demonstrated bilateral plantar flexion of the feet. The gastrocnemius and tibialis anterior also showed increased activity. However, the subject could not clearly differentiate muscle activity in these areas. During month five the subject was able to stand in braces without arm support. In the eighth month the subject began riding an exercise bike and by the ninth month she was riding three times a week.

During fourteen months of therapy, strengthening of the quadriceps, gluteal muscles, hip adductors and abductors and hip flexors took place. Motor unit activity was also discovered at the proximal end of the rectus femoris and vastus intermedius muscle. The subject was able to extend her legs, lock the knees and walk with short leg braces and a jump walker.

Seymour and Bassler (1977) used EMG biofeedback in conjunction with physical therapy training to treat a 25 year old female paraplegic subject. The subject had
undergone a thoracic laminectomy and as a result of this surgery became paraplegic at the T-8 level on the left side and on the right side at the T-5 level. Biofeedback sessions lasted an average of 30 min during which two or three sets of muscles were exercised. Muscles treated bilaterally were the gluteus maximus, gluteus medius, quadriceps, hamstrings, tibialis anterior and gastrocnemius. Various muscles were contracted in groups such that a particular movement would exercise several muscles simultaneously. Muscles monitored in group exercise demonstrated an increase in amplitude when compared to their output on an individual basis.

Biofeedback training was discontinued, during group exercise, on muscles that attained a muscle grade of poor or if no amplitude increase was noted for two weeks.

After two months of therapy the subject demonstrated a muscle strength of poor in the quadriceps and tibialis anterior and started ambulating while supported by parallel bars. Ambulation exercises included side stepping, foot placement, resistive and backward ambulation. Biofeedback training was included with these exercises for muscles still demonstrating output increases or muscles that had not reached a strength of poor. Biofeedback was completely discontinued on all muscles that demonstrated no further improvement for up to three weeks.

After four months of treatment the subject could
ambulate, at the clinic, with the help of a reciprocal walker and a bilateral metal ankle-foot orthoses. Five months after initial treatment the subject could ambulate at home, up to 350 feet without tiring, utilizing the same supportive equipment.

The authors of this case study believe that since the subject had not been able to ambulate for approximately three years, her improved condition was, in large part, due to a high level of motivation and the combination of EMG biofeedback with exercise and gait training. The subject's improved condition was reported unchanged after a one year follow-up.

Response generalization, in the EMG biofeedback literature, has usually referred to concomitant increases or decreases in one or more non-target muscles as a result of increases or decreases in a target muscle facilitated by EMG biofeedback.

Negative findings of muscle tension generalization have been reported in the literature. Alexander (1975) found no generalization of muscle tension reduction between trained frontalis target muscles and untrained forearm extensor non-target muscles. Shedivy and Kleinman (1977) trained eight subjects to successively increase and decrease frontalis muscle activity for five consecutive days. Sternomastoid EMG activity was recorded from four subjects and from the semispinalis and splenius muscles in
the other four subjects. A significant increase and
decrease of frontalis EMG activity was recorded during
appropriate periods. However, sternomastoid EMG levels did
not significantly change during either increase or decrease
frontalis periods. Semispinalis and splenius EMG levels
demonstrated no change during frontalis increase periods
but significantly increased during frontalis decrease
periods. The authors conclude that their findings support
Alexander (1975) i.e., that frontalis EMG changes do not
generalize to other somatic muscles.

Glaus and Kotses (1979) take a rather unconventional
view in examining response generalization in the EMG
biofeedback literature. They propose that response
generalization should decrease since in the traditional
operant conditioning paradigm non-target responses diminish
with concomitant contingent reinforcement of the target
response. However, they point out that the idea of
response covariation, whereby covariation in two or more
muscles changes in response to manipulation of one of the
muscles, has evolved in the EMG biofeedback literature.
Furthermore, tension covariation between trained and
untrained muscles is expected to increase with additional
training. Glaus and Kotses examined covariation between
facial and forearm EMG levels during facial EMG
biofeedback. Thirty male undergraduate students between
18-21 yrs were equally assigned to either a frontalis
increase group, a frontalis decrease group or a frontalis noncontingent group. All subjects participated in 20 min conditioning sessions during three consecutive days. A comparison of facial EMG measures demonstrated some covariation between forearm and facial EMG for all groups. However, results of covariation across sessions demonstrated decreased covariation for the groups which received facial muscle training whereas the noncontingent feedback group remained stable thus supporting the concept of response generalization, defined by them, but not muscle tension generalization as used in EMG biofeedback.

Evidence of successful response generalization has also been reported in the EMG biofeedback literature. Freedman and Papsdorf (1976) examined the efficacy of conditioning low EMG levels to produce whole-body relaxation. They simultaneously monitored masseter and forearm extensor muscle groups of three male and three female insomniacs during frontal EMG biofeedback training. The subjects received six half-hour sessions of EMG biofeedback during which one min periods were recorded for baseline, midsession and end of session. Maximum raw peak-to-peak signals were analyzed using a three-way analyses of variance with specific comparisons. The analyses demonstrated that frontal muscle training generalized to the masseter muscle within and across sessions but not to the forearm extensors.
Brudny, Korein, Levidow, Grynbaum, Lieberman and Friedmann (1974) have reported a remarkable case of response generalization. They treated a 28 year old male subject with a C-5, C-6 vertebrae fracture dislocation. The subject was diagnosed as a paraplegic with marked weakness of both upper extremities. The subject had received conventional physical therapy for three years. Sessions typically lasted 30 min, three times a week. Both visual and auditory feedback was provided which indicated amplitude and frequency of muscle output. Two specific goals were set for the subject: reduction of activity in the right spastic biceps and pronation of the forearm for use of a wrist-driven splint. The subject achieved both goals within two weeks. The same two goals were reached concurrently in the left untrained arm which had not received EMG biofeedback. A two year follow-up examination showed that the subject had retained these functions and was able to feed and groom himself, drive an electric wheelchair and type.

Statement of the Problem

Lack of documentation and description is a major problem in many of the existing EMG biofeedback case studies. Thus the nature, range of improvements and degree that EMG biofeedback treatment may have contributed to the improvement are impossible to determine (Fernando and
Basmajian, 1978).

Most neuromuscular reeducation EMG biofeedback studies have been attempts either to reduce spasticity (Cleeland, 1973; Swaan, Van Wieringen and Fokkema, 1974; Brudny, Grynbaum and Korein, 1974; Brudny, Korein, Levidow, Grynbaum, Lieberman and Friedmann, 1974; Brudny, Korein, Grynbaum, Friedmann, Weinstein, Sachs-Frankel and Belandres, 1976) or to increase muscular output. Of the latter of these types most of the studies have been concerned with either hemiplegia (Mroczek et al. 1978; Marinacci and Horande, 1960; Andrews, 1964) or paraplegia (Toomim and Johnson, 1974; Seymour and Bassler, 1977). However, the possibility of training a quadriplegic subject to increase tricep muscle output utilizing EMG biofeedback has not been systematically explored.

The purpose of this study was to determine the degree of voluntary muscular control that could be obtained by a quadriplegic subject utilizing only contingent EMG biofeedback. Based upon the assessment of clinical problems and the degree of involvement, the right and left triceps brachii were chosen as the target muscles for therapy. Range of motion which is an index of clinical improvement was also examined.

The examination of muscle tension generalization was specifically concerned with whether or not non-target muscles, flexor carpi radialii, would demonstrate a
corresponding change in amplitude in the same direction as the target muscles which received contingent EMG biofeedback to increase amplitude.
METHODS

Subject

The subject was a male, age 25, diagnosed as having a C-5, C-6 comminuted cervical vertebral fracture with post traumatic neuropathy and resultant quadriplegia. The injury occurred in 1973 and was the result of a diving accident. Since that time, the subject has been confined to a wheelchair and has undergone frequent physical therapy sessions with minimal improvement only to the biceps brachii, deltoideus and dorsi-extensors of the wrist.

Apparatus

All recordings were made with two reference and one ground 11mm silver-silver chloride surface disk electrodes. Surface electrodes record subdermal potentials that represent a sum of individual potentials produced by many nerve or muscle fibers which are activated (Aminof, 1978). Presented in Figure 1 is a flow diagram of the data acquisition system. Muscle leads were sent to two Narco NB-132 preamplifiers which were connected to Narco NB-122 EMG active bandpass filter modules which had variable gains set at 54. The filter gain was determined to provide, along with a calibrated input, the most compatible output range which approximated the expected muscle output. The low and high pass filters were set at 500 and 100 Hz.
Figure 1. Flow diagram of data acquisition system which traces the input signals from amplification to feedback and quantification. Components are arranged in terms of signal processing order.
respectively. These bandpass filters are essentially flat between the cut-off frequencies and have a 46dB attenuation within the first octave. Filtered output was sent to an amplitude bandwidth selector (ABS) which set threshold and ceiling amplitudes. Threshold was set at zero microvolts and the ceiling was set at 995 microvolts. The ABS had a millisecond reset rate which was set at 50 to suppress artifacts which were contaminating electric signals produced by movement from any muscles other than those under study or from external electrical sources. Artifacts add to the electrical output thus making it appear higher than it actually is. A quantifier (Bio-Feedback Systems, Inc., DQ-1) displayed a digital readout which represented a sum of the periods of the input signal and was proportional to the filtered frequency of the muscle output. This provided visual feedback along with a visual display light (Narco NB-151) which changed in intensity proportional to the amplitude of the filtered EMG. In addition to the two types of visual feedback, a variable pitch audio feedback module (Narco NB-141) provided a mean frequency modulated signal that increased or decreased with input signal level changes. Three cumulating, resetting integrators (Coulbourn Instruments, S76-22) and two high speed electronic counters (Coulbourn Instruments, R11-25) recorded filtered and unfiltered muscle activity. The integrators were set to accumulate 100 millivolt
(thousandths of a volt) seconds of time integrated signal, reset, then send an output pulse to the counters.

One integrated digital count sum was recorded per session for each left and right filtered triceps, unfiltered triceps and unfiltered flexor carpi radialis muscles. Each of these sums multiplied times 100 millivolt seconds represented a total electrical output over time (area under the curve) across trials for each session. This permitted evaluation of time differences in the amount of EMG signal between baseline and feedback conditions. A formula was derived for converting these integrated scores into voltages. The integrated sum was divided by session time seconds. The result was divided by the preamplifier and amplifier gain then converted into microvolts (millionths of a volt). This permitted evaluation of voltage differences between baseline and feedback conditions.

Procedure

The subject underwent neurological and musculo-skeletal evaluation by an orthopaedic surgeon who concurred with previous neurological and physical therapy reports made after the accident.

The subject served as his own control and left and right muscle groups were alternated such that each session began with the opposite side from the previous session.
This provided counterbalancing of treatment.

The electrode sites were approximated such that they were centered over the belly of the muscles (Blakiston, 1951; Quiring and Warfel, 1960; Owen et al., 1975). Silver nitrate was used to mark the electrode sites to insure replication from session to session. Prior to each session the subject's skin was cleaned with acetone, to remove grease and dirt, then rubbed briskly to remove some of the dead, scaly portion of epidermal or outer layer of skin. This insured optimal recording conditions by lowering skin impedance to around 5000 ohms. An electrically conductive paste was used which facilitates electrode contact. A small amount of the paste was placed in the electrode cups before the electrodes were attached to the skin.

During each session the subject was seated in a wheelchair, arm extended forward and elbow bent, with palm flat in the neutral position. The subject placed his elbow on the back of a chair located next to and forward to him. The subject would make a practice extension of his arm to insure that the equipment was functioning properly or so that final adjustments could be made. All integrator counters were manually reset immediately prior to the beginning of the session. The quantifier was electronically reset at the sound of it's built-in buzzer/timer which also signaled the beginning of each
trial. The quantifier's buzzer/timer was set to sound and reset every ten seconds.

The instructions to the subject, for each session, were to extend his tricep during the first 10 sec, rest the next 10 sec with arm extended, and at the beginning of the third 10 sec period, return his arm to the starting position and rest until the buzzer sounded indicating the beginning of the next trial. This sequence was repeated 25 times for each arm. Baseline and feedback sessions were divided into moderate and maximum extension sessions for comparative purposes. The first two weeks of the study, week one and two of baseline (six sessions) and weeks four through ten of the study, weeks one through seven of feedback training (21 sessions) were "moderate effort" extension sessions. During moderate extensions the subject was instructed to try to exert himself but not to over exert himself. Week three of the study, week three of baseline (three sessions) and week eleven of the study, week eight of feedback training (three sessions) were "maximum effort" extension sessions. The subject was instructed to exert all possible strength during these contractions. The subject was requested to restrict his movement except for the desired muscle extension to help reduce artifacts.

During all baseline recordings, data was recorded without the subject being able to view the written record
of the data. During feedback training the subject was informed, at the beginning of each session, of his previous high and rough average quantified frequencies. At the end of each session he was informed of the filtered integrated voltage levels.

A three month follow-up study was conducted in which baseline and feedback conditions were examined and compared to the initial phase of the study.
RESULTS

Initial Study (Part One)

A summary of filtered digital quantifier scores indicate increases over the eight weeks of feedback training. Mean tricep EMG values of digital quantifier scores were calculated for the nine initial baseline (three weeks) and last nine feedback (three weeks) training sessions. Presented in Figure 2 are percent changes from initial baseline for left and right triceps. Analysis of these scores, which represent numbers proportional to the frequency of muscle output activity, indicates a 168% left and a 205% right tricep increase above averaged initial baseline.

The results of frequency increases across trials for left and right triceps are presented in Figure 3. This figure represents means averaged across three sessions for each of seven weeks of feedback training with week zero representing a six session (two week) initial baseline mean. Analysis of these feedback training sessions indicates a strong trials effect with frequency of EMG output levels yielding large percentage increases at the end of training compared to the first day of training. Gradual increases over training days for left and right triceps were indicated by increases in digital quantifier values. A comparison of maximum effort extension trials
Figure 2. Filtered quantified tricep brachii mean proportional frequency counts for three weeks baseline verses the last three weeks of feedback.
Figure 3. Filtered quantified tricep brachii proportional frequency counts averaged each week across feedback training. Week zero indicates baseline levels averaged over two weeks.
made at the end of feedback training to those made during initial baseline (Figure 4) indicates a 87% left and a 117% right increase in digital quantifier scores.

A summary of filtered and unfiltered integrated triceps brachii and flexor carpi radialis (FCR) scores, which represent muscle voltage output levels, indicates increases during initial EMG feedback training. All integrated scores were averaged over the nine initial baseline sessions (three weeks) and last nine feedback sessions (three weeks).

Mean microvolt (peak to peak) levels were calculated for all integrated scores. Figure 5 represents filtered integrated triceps levels which indicates a 50.74 left and a 8.16 right mean microvolt increase above initial baseline. These levels represent a 136% left and a 52% right triceps increase above initial baseline. Unfiltered integrated triceps levels are presented in Figure 6 which indicates a 65.63 left and a 12.01 right mean microvolt increase above initial baseline. These levels represent a 54% left and a 17% right triceps increase above initial baseline. Unfiltered integrated FCR levels (Figure 7) indicate a 119.05 left and a 58.74 right mean microvolt increase above initial baseline. These levels represent a 32% left and a 41% right increase over initial baseline.

The clinical goals, noticeable increased triceps strength and range of motion, were partially realized. The
Figure 4. Filtered quantified triceps brachii mean proportional frequency counts averaged over one week baseline and the last week of feedback training during maximum effort extensions.
Figure 5. Filtered integrated triceps brachii mean microvolt levels averaged over three weeks baseline verses the last three weeks of feedback training.
Figure 6. Unfiltered integrated triceps brachii mean microvolt levels averaged over three weeks baseline versus the last three weeks of feedback training.
Figure 7. Unfiltered integrated flexor carpi radialis mean microvolt levels averaged over three weeks baseline verses the last three weeks of triceps brachii feedback.
subject made no height improvement when attempting extension of the elbow with the shoulder at 180 degrees abduction-elevation. During pre-feedback training the subject would voluntarily elevate the upper extremities, with the elbow extended, to a position of 180 degrees abduction-elevation at the shoulder joint whereupon immediate unsustained extension of the elbow with sudden dropping into a flexed position would occur. During post feedback training the subject demonstrated that immediate unsustained extension of the elbow was replaced by some sustained extension, in both arms, indicating a gain in tricep strength.

Three Month Follow-Up (Part Two)
Mean EMG baseline values were calculated representing three sessions (one week) of moderate effort extension follow-up baseline. These values were compared to initial (part one) baseline means representing three sessions (one week) of moderate effort extension. Filtered digital quantifier follow-up baseline means yielded a 137% left and a 255% right tricep frequency increase above initial baseline. Mean microvolt levels were calculated for all integrated scores. Filtered integrated tricep follow-up baseline means yielded a 4.90 left and a 3.57 right mean microvolt increase above initial baseline. These levels represent a 18% left and a 25% right tricep voltage
increase above initial baseline. Unfiltered integrated tricep follow-up baseline means yielded a 29.82 left and a 41.77 right mean microvolt increase above initial baseline. These levels represent a 28% left and a 77% right tricep voltage increase above initial baseline. Unfiltered integrated FCR follow-up baseline means yielded a 5.65 left and a 69.89 right mean microvolt increase above initial baseline. These levels represent a 2% left and a 49% right FCR voltage increase above initial baseline.

Mean EMG feedback values of filtered digitally quantified triceps, filtered and unfiltered integrated triceps and unfiltered integrated FCR scores were calculated representing three sessions (one week) of moderate effort extension with feedback and three sessions (one week) of maximum effort extension with feedback. These values were compared to averaged initial (part one) baseline and feedback training levels. Filtered digital quantifier means yielded a 179% left and a 247% right tricep frequency increase over initial baseline (Figure 8) and a 4% left, 14% right increase over initial feedback training levels.

Mean microvolt levels were calculated for each follow-up feedback integrated condition. These data indicate that follow-up filtered integrated tricep feedback levels yielded higher voltage levels compared to initial (part one) tricep feedback training levels. However,
Figure 8. Filtered quantified triceps brachii mean proportional frequency counts averaged over three weeks initial baseline verses last two weeks follow-up with feedback.
follow-up unfiltered integrated tricep feedback levels decreased from initial (part one) unfiltered integrated tricep feedback levels and follow-up FCR levels decreased from initial tricep feedback training FCR levels.

Filtered integrated tricep feedback levels yielded a 61.30 left and a 21.61 right mean microvolt increase above initial baseline (Figure 9). This represents a 164% left and a 136% right increase in voltage above initial baseline. These levels also represent a 10.57 left and a 13.45 right mean microvolt increase which is equal to a 12% left and a 56% right increase over initial feedback training levels. Unfiltered integrated tricep feedback levels yielded a 61.95 left and a 10.57 right mean microvolt increase above initial baseline (Figure 10). This represents a 51% left and a 15% right increase in voltage above initial baseline. These levels also represent a 3.68 left and a 1.44 right mean microvolt decrease which is equal to a 2% left and a 2% right decrease from initial feedback training levels. Unfiltered integrated FCR levels yielded a 89.96 left and a 30.57 right mean microvolt increase above initial baseline (Figure 11). This represents a 24% left and a 21% right increase in voltage above initial baseline. These levels also represent a 29.10 left and a 28.18 right mean microvolt decrease which is equal to a 6% left and a 14% right decrease from initial tricep feedback training
Figure 9. Filtered integrated triceps brachii mean microvolt levels averaged over three weeks initial baseline verses last two weeks follow-up with feedback.
Figure 10. Unfiltered integrated triceps brachii mean microvolt levels averaged over three weeks initial baseline verses last two weeks follow-up with feedback.
Figure 11. Unfiltered integrated flexor carpi radialis mean microvolt levels averaged over three weeks initial baseline verses last two weeks follow-up during triceps brachii feedback.
levels.

The clinical results remained unchanged from the end of initial (part one) feedback training. The subject made no height improvement when attempting extension of the elbow with the shoulder at 180 degrees abduction-elevation. However, the subject maintained his ability to demonstrate some sustained extension, in both arms, when attempting to resist sudden dropping into a flexed position as a result of voluntarily elevating the upper extremities, with the elbow extended, to a position of 180 degrees abduction-elevation at the shoulder joint.
DISCUSSION

The results of this study indicated that voluntary muscular control of the triceps brachii in a quadriplegic subject was enhanced by increasing EMG output, utilizing EMG biofeedback. This finding is particularly significant since to date no prior EMG biofeedback controlled studies demonstrating increased output of the triceps brachii in a quadriplegic subject have been reported.

The most consistent finding in this study was the increase in EMG activity from target muscles during and following feedback training. This result appears highly reliable because EMG increases were found for each method of data analyses: integrated filtered and unfiltered EMG (amplitude); digital quantification of EMG (frequency).

The subject participated in a hospital rehabilitation program in 1973 and a three month exercise program in 1975. However, he had not participated in any exercise program since that time. The subject has used a manual wheelchair for the past seven years. Although the arm movement necessary to move the wheelchair includes extension of the elbow, the subject reports that he also uses his shoulder in this action. Therefore the biceps, deltoid and supraspinatus muscles most likely contribute to the motion. Although the subject had been exercising these muscles for this period of time, in this manner, he had not recognized
any noticeable clinical improvement. During the present study the subject did no home muscle practice or other therapy outside of our experimental setting. Thus the increases in frequency, amplitude and the clinical results of resistance to gravity are thought to be entirely due to the biofeedback therapy.

Increase in voltage and frequency of muscle potentials is most probably due to overuse which causes a hypertrophy or enlargement of the muscles. Additionally the ability of the terminal axons of the lower motor neuron cells to grow new connections on adjoining denervated muscle fibers contributes to this outcome. This process of budding or sprouting for re-innervation is a natural tendency of normal functional motor nerve fibers. It has been hypothesized that denervated fibrillating muscle activates sprouting to effect re-innervation as a means of self-survival and that this process is common in diseases which result in large quantities of denervated muscle fibers (Marinacci, 1968).

When extensive damage occurs and many nerve fibers are permanently injured, the undamaged nerves may participate in the development of giant motor or macromotor units by assuming control of more muscle fibers, through sprouting-re-innervation, than they originally innervated. Giant motor unit formation may be considered a repairing of the neuromuscular mechanism and is an example of a
regenerative process which compensates for the inadequate number of motor unit cells. A single giant motor unit can generate the same power as fifty normal ones. However, it fatigues rapidly and does not possess the ability to execute fine movement (Marinacci, 1968; Guyton, 1976). This is the most likely reason that the subject generally appeared fatigued by the end of each session, acting as if he had expended a large amount of energy.

Although EMG output is not a direct measure of muscle tension (Goldstein, 1972) correlations as high as 0.95 have been reported between these two variables i.e., between the force of muscle pull and integrated EMG (Wilcott and Beenken, 1957). The EMG output is a recording of motor unit firing. The electrical activity from the motor unit occurs prior to the contraction of the muscle, which is a mechanical event (Thompson, Lindsley and Eason, 1966). De Luca (1978) states that a motor unit action potential is accompanied by a twitch of muscle fibers which is delayed 2 to 3 msec and that motor units have to be repeatedly activated to sustain muscle contraction. This succession of MAPS has been designated the motor unit action potential train (MUAPT). De Luca has proposed a model of the EMG signal as a linear, spatial and temporal summation of the MUAPTs recorded by the electrode. However, the total EMG signal probably contains a complex algebraic summation of electrical output produced by various properties of the
muscle itself added along with the MAP output.

Prior to the start of the study, the subject informed me that his right arm was considerably weaker than his left arm. Post initial baseline sessions, it was noted that his left tricep mean microvolt output level was 138% greater than his right tricep mean microvolt output level. It is a considerable accomplishment that, at the conclusion of the three month follow-up, the subject could produce a slightly higher right tricep mean microvolt output level over the initial (part one) left tricep mean baseline level.

During the initial stages of biofeedback therapy the subject would make tricep extensions which produced little frequency and amplitude output. As therapy progressed output increased but occasionally the subject would make several extensions in which frequency and amplitude were minimal. This would surprise the subject and several times he asked me if I was sure the equipment was working properly. I would remind him that we tested the equipment prior to the beginning of the session. He accepted that the lack of output was due to his muscles. He would concentrate on producing higher output and was usually successful within a few additional trials. Toward the final weeks of biofeedback therapy, if a decreased output occurred, the subject would say out loud to himself "no that's not right, I did not do it like I am supposed to". He would then increase his muscular output within a few
trials. It appeared that he became cognitively aware of his proprioceptive cues, which occurred over the course of the biofeedback therapy, that enabled him to switch into an operational mode that permitted conscious control over his muscles.

The subject was highly motivated to participate in the study and this factor most likely helped to facilitate the increases in muscular output obtained. The subject maintained his motivated state throughout the study and he was very pleased with the outcome, stating that he would be willing to participate in future therapy.

The increase in FCR voltage output during the initial phase of the study indicated that muscle tension generalization did occur to a limited extent. Although only a 32% left and a 41% right increase in voltage output was realized, this increase must be viewed in the appropriate perspective. Since the subject's condition was of such a severe nature, with limited initial muscle output, the muscle tension generalization that was realized most likely represents a broader range of improvement than the percentages demonstrated reflect.

Some studies that have reported negative muscle tension generalization results have done so utilizing seemingly unrelated pairs of muscles; e.g., Glaus and Kotses (1979) compared facial and forearm EMG, Freedman and Papsdorf (1976) compared frontal and forearm EMG, Alexander
(1975) compared frontalis to forearm and leg EMG. It may be more reasonable to expect muscles that are either in close proximity or are related synergistically, to produce certain movements, to be more suitable candidates to achieve muscle tension generalization. It may indeed be naive, both physiologically and psychologically to look for muscle tension reduction generalization or increased output muscle tension generalization in unrelated muscles.

The decrease in unfiltered triceps and FCR output voltage recorded during the three month follow-up tends to support Glaus and Kotses (1979); i.e., that response generalization, defined by them, should lessen with continued reinforcement of the target response and concomitant nonreinforcement of related responses. However, it may indicate that muscle tension generalization takes a longer time to be fully realized and when it does occur extinction of the response may take place at faster rates than for target responses. Since the unfiltered tricep voltage decreased less compared to the unfiltered FCR voltage, it may be that the more related the candidate generalization muscle is to the target muscle, the greater the generalization response and the more resistant the response will be to extinction. Additional research may address these possibilities.

A suggested improvement on the present procedure of muscle extension was provided by Wolf (Note 3) who
recommended placing the medial side of the elbow on the back of the chair with the forearm and hand placed horizontally, on a plane parallel to the floor, in an attempt to eliminate gravity on the force of elbow extension. Although the force of gravity was obviously held constant in the present study it is certainly more desirable to eliminate outside influences as much as possible.

In conclusion, the results of this study demonstrate that EMG biofeedback can be an important tool to successively increase tricep brachii muscle frequency and voltage output in a quadriplegic subject. Additionally muscles synergistically related, to produce movement, were successful in demonstrating increased amplitude muscle tension generalization. Although the results may be small and take time to become evident, EMG biofeedback appears to be a viable therapeutic method for subjects with severe muscular dysfunction.
References


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Reference Notes

