The Effect of Different Electro-Motor Stimulation Training Intensities on Strength Improvement

The effect of different training intensities of electro-motor stimulation (EMS) on strength gains produced in the quadriceps femoris muscle group was investigated. Twenty-four subjects were randomly assigned to one of three groups: Control (C), Low Intensity (LI) trained at 25% of their maximum voluntary isometric contraction (MVIC), and High Intensity (HI) trained at 50% of MVIC. Results indicated a significant strength improvement in both training groups ($p<0.01$) following a three-week EMS training program. The HI group showed significantly greater strength gains (48.5%) than the LI group (24.2%) ($p<0.01$). A significant carry-over effect was also demonstrated in a three-week follow-up period, specifically in the HI group. Positive isokinetic strength changes in the concentric mode were observed in both training groups. In addition, a significant cross transfer effect was demonstrated in the contralateral homologous muscle group ($p<0.01$) for both HI and LI groups.

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This paper is based on a thesis presented as part of the requirements for the degree of Master of Applied Science, in the School of Physiotherapy, Curtin University of Technology. It stems from an on-going research program on muscle stimulation which is being undertaken in the Centre of Applied Research in Exercise Science and Rehabilitation in the School of Physiotherapy at Curtin University of Technology.

Electrical stimulation has been used for centuries by the medical profession for therapeutic and diagnostic purposes (see Stillwell 1983 and Geddes 1984 for extensive reviews). In the rehabilitation setting, electro-motor stimulation (EMS) has been utilized by physiotherapists to re-educate muscle action (Williams and Street 1976, Benton *et al* 1981), retard muscle atrophy (Gould *et al* 1983, Morrissey *et al* 1985), decrease spasticity (Alferi 1982, Bajd *et al* 1985) and enhance muscle performance (Benton *et al* 1981, Stillwell 1983). In the treatment of weak or atrophied muscle, it is frequently used as an adjunct to voluntary resisted exercise to improve muscle function (Eriksson and Haggmark 1979, Lainey *et al* 1983).

In recent years a number of studies have investigated the effects of EMS on muscle strength (see Kramer and Mendryk 1982, Lloyd *et al* 1986 for reviews). Many of these studies have focused on the relative effectiveness of EMS and voluntary exercise in increasing muscle strength. Both normal healthy muscle and weak atrophic muscle have been studied in these investigations, and varying degrees of success have been reported in the use of EMS to improve strength.

The interest in using EMS to strengthen normal healthy muscle was heightened when Dr. Yakov Kots, a Russian researcher, reported his results in 1977. Kots claimed that there were rapid and dramatic isometric strength gains (up to 40%), increased velocity of muscle contraction, and better endurance performance of muscle following EMS training in highly trained athletes (cited in Halbach and Straus 1980 and Kramer and Mendryk 1982). Since then, a considerable number of researchers have attempted to duplicate the success of Kots' study. Thus far, very few studies have been able to produce results comparable to Kots' study (see Lloyd *et al* 1986 for a review).

It has been very difficult to compare the results of different studies directly due particularly to the lack of standardization and the tremendous variations which exist in the method of EMS application, training and testing protocols (Singer *et al* 1987). One of the major factors that makes comparison of studies difficult is the control of the EMS training intensity.

The training intensity of EMS can be defined as the amount of muscle force produced by the electrically induced contractions during the training program. In EMS training studies, the relationship between EMS training intensity and strength gains has been poorly documented and has not been systematically investigated.

Many EMS studies have utilized the maximum tolerated isometric contraction (MTIC) as the training intensity (see Table 1 in Lloyd *et al* 1986). The MTIC reflects the maximum intensity of current that can be tolerated by a subject in producing a tetanic contraction of the stimulated muscle. The MTIC is highly variable, depending on the individual's compliance and pain tolerance. A large variation in the training intensity is implied because of this factor. The use of the MTIC as a means of standardizing the training intensity is therefore questionable and probably not the optimal method of controlling the induced force levels, during a training session.

Some studies have measured the training intensity in terms of EMS induced torque (Laughman *et al* 1983, Currier and Mann 1983, Kramer *et al* 1984, Walmsley *et al* 1984, Selkowitz 1985, Mohr *et al* 1986, Kubiak *et al* 1987). The EMS induced torque is usually expressed as a percentage of the maximum voluntary isometric contraction (MVIC), and the pre-test MVIC measurement is most often used as the baseline reference for measuring training intensity.

The method of calculating the training intensity has been inconsistent in the literature. Studies have measured a single contraction in a single training session (Owens and Malone 1983), or a single contraction in each daily session (Laughman *et al* 1983). Considering current accommodation and variation in individual tolerance, the EMS induced torque can vary significantly from one contraction to another. Thus it may not be valid to estimate the overall mean training intensity by measuring only a few contraction torques during the course of EMS training.

Other authors (Currier and Mann 1983, Selkowitz 1985, Kubiak *et al* 1987) have consistently measured the torque values of each EMS contraction for the calculation of the overall mean training intensity. Selkowitz (1985) reported a wide range of 'training contraction intensities' from 29.98% to 164.8% of pre-test MVIC, confirming the variability of the MTIC. The mean training intensity in his study was 91% of pre-test MVIC with a resultant strength gain of 44% of pre-test MVIC. Currier and Mann (1983) reported a training intensity of 67% for the EMS group and a strength gain of 14%. Laughman *et al* (1983) trained the EMS group at 33% and reported a 22% strength gain. Stefanovska and Vodovnik (1985) trained subjects at an exceptionally low intensity of 5% of pre-test MVIC and produced 13% and 25% strength increases in the two EMS groups. Kubiak *et al* (1987) trained subjects at a minimum intensity of 45% of pre-test MVIC and produced 33% of isometric strength gains. They concluded that there was no consistent correlation between stimulus intensity and the amount of indicated muscle tension. The discrepancies in the above results suggest the need for further research focusing on the relationship between training intensity and strength gains.

De Domenico and Strauss (1987) suggested that the peak intensity of the EMS stimulus was the main determinant of induced muscle force. Thus it may be argued that higher stimulus intensity levels, producing higher contraction forces, might be required in order to achieve effective training results. Some authors have suggested that a minimum contraction force, ranging from 35% (Muller 1957), 60% (Walmsley *et al* 1984) to 65% (Owens and Malone 1983), is required for muscle strengthening. There is no agreement in the literature on the relative force level which produces optimal strength gains from EMS training.

There has not been sufficient research investigating the effect of training intensity on the resultant strength gains from EMS training. Furthermore, quantifying the training intensity would facilitate comparison of the training effects of EMS with other strength training methods such as isometric exercise. At present, many of the investigations comparing EMS with isometric exercise have not equated the training intensities of the various training modes. Currier and Mann (1983) recorded mean training efforts of 119.1% of pre-test MVIC for an exercise group, 66.7% for an EMS group and 88.4% for a combined group. Laughman *et al* (1983) compared EMS at 33% training intensity with voluntary exercise at 78%, and concluded that electrical stimulation was equally effective as isometric exercise. Their results may reflect the differences in the training intensity, rather than the relative efficiency of EMS versus voluntary exercise.

The primary purpose of this study was to examine the effects of different pre-determined EMS training intensities, on strength gains produced in the quadriceps femoris muscle group.

The study addressed the following research questions:

(a) Does EMS training produce significant strength gains when compared to a control group (no training)?
(b) Does a high EMS-induced training force level produce a greater strength gain than that produced by a low EMS-induced training force level?
(c) Is the strength gain produced by EMS specific to the mode of muscle contraction (isometric versus isokinetic)?
(d) Does EMS training produce strength gains in the contralateral homologous muscle group (a cross transfer effect)?
(e) Can the strength gain from EMS training be maintained following the completion of the training program (a carry-over effect)?
(f) Does the MTIC change during the course of training and is it related to the training intensity?

Methodology

Research Design

This study utilized a control group and two experimental groups. The low intensity experimental group (LI) received stimulation to produce a force equal to 25% of MVIC. The high intensity experimental group (HI) received stimulation to produce a force equal to 50% of MVIC. The control group (C) underwent testing procedures only (they received no EMS training).

The two EMS training groups underwent a three-week training period of five daily sessions per week, or fifteen sessions altogether. Each group received a total of 450 individual contractions, receiving approximately 2,250 seconds of stimulation (5s per contraction). The subjects in all three groups were compared for pre- and post-test strength changes in isometric and isokinetic knee extension torques. Following EMS training there was a three-week follow-up period to evaluate any carry-over effects in the training groups. The entire study was conducted over a nine-week period. The research design is summarised in Figure 1.

Subjects

Twenty-four volunteer university students (12 males and 12 females) participated in this study. The subjects were distinguished on the basis of gender and then randomly assigned into one of three groups as follows:

1. Control group (C), (N = 8, 4 males and 4 females; mean age = 23.3, SD = 3.38)
2. Low intensity group (LI), (N = 8, 4 m and 4 f; mean age = 24.8, SD = 3.42)
3. High intensity group (HI), (N = 8, 4 m and 4 f; mean age = 26.8, SD = 3.37)

The main criteria for subject selection were:

- no present or previous history of neurological or orthopaedic impairment of the lower limbs;
- no involvement in any form of lower extremity strengthening program for at least one month prior to the study, and up to the completion of the entire study;
- an ability to tolerate the assigned EMS stimulation intensity.

Informed consent was obtained in writing from each subject after reading a document explaining the purpose and procedures of the experiment.

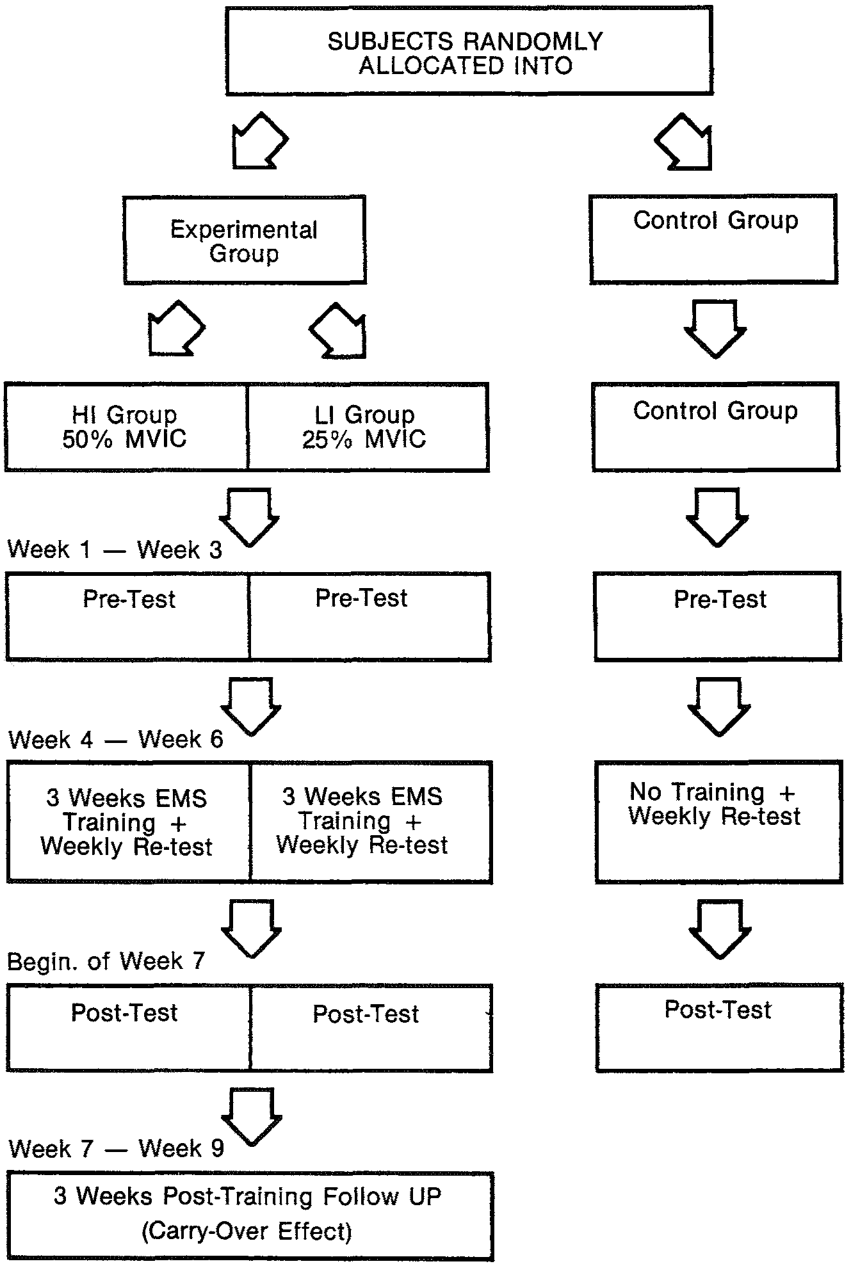


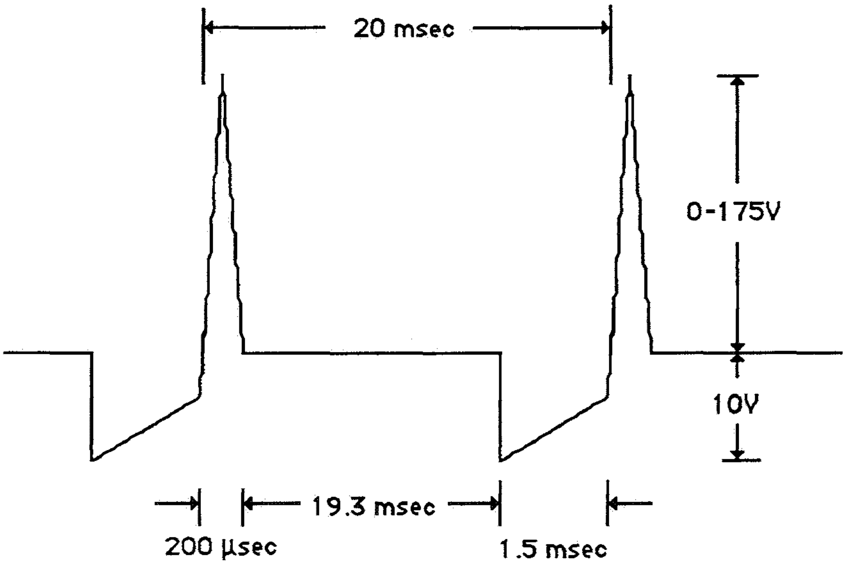
Figure 1: Summary of the research design

Instrumentation and Measurement Procedures

Electrical stimulation was provided by a MINIDYNE III (Electro-Medical Supplies Ltd., U.K.), delivering a current with a frequency of 50 Hz and waveform as shown in Figure 2.

The electrodes used, and the subject's, positioning were as described by De Domenico and Strauss (1986) for the electrical stimulation of the quadriceps femoris muscle group.

A robotic dynamometer (Kinetic Communicator [KIN/COM] Chattecx Corp., U.S.A.) was used to measure and analyse all muscle force productions.



The stimulus characteristics are as follows:

Stimulator	Minidyne III
Waveshape	Biphasic Asymetrical Spike
Frequency	50 Hz
Pulse Width	200 microsec
Interpulse (peak-peak)	20 msec
Surge Period	1-5 sec ON, 1-5 sec OFF

Figure 2: Diagram showing the current waveform and stimulus characteristics of the Minidyne III electrical stimulator

Pre-Test Procedures

Prior to EMS training all subjects participated in three sessions of pre-test measurements; once a week for three consecutive weeks. The first session was used for familiarization and no data were recorded. The subsequent sessions were used to determine the pre-test MVIC strength for both limbs. The pre-test MVIC values of the non-dominant limb were then used to calculate the training intensities of the LI and HI groups at 25% and 50% MVIC respectively. The pre-test MTIC in the non-dominant limb was recorded at the beginning of the first EMS training session. Each subject was seated with the pelvis and thigh of the non-dominant limb secured by two webbing straps. The hip was maintained at 60 degrees of flexion from neutral, by reclining the subject at 30 degrees from the vertical. The arms were crossed in front of the chest, with the back reclining against a back support (De Domenico and Strauss 1986).

In isometric strength testing, the knee was positioned 60 degrees from full extension. Each subject performed two sub-maximal warm-up trials, and then three maximum isometric knee extensions to determine the MVIC strength. The subjects were instructed to push as hard as possible against the leg pad for five seconds until the force output line reached a plateau. A two-minute rest period followed each contraction. All the testing procedures were repeated on the dominant limb.

For isokinetic testing, the range of movement was measured by the dynamometer from full extension to 90 degrees of knee flexion. The velocity of movement was set at 60 degrees per second. The subjects again performed two sub-maximal warm-up trials prior to the actual testing. Three measurements of maximum concentric and eccentric muscle force were recorded. The measurements were then repeated on the knee extensors of the contralateral limb.

Training Procedures

Each subject in the experimental groups received five consecutive, daily sessions of training per week for three weeks. Each session consisted of three sets of ten contractions (5s on and 5s off per contraction) with a rest period of one minute between each set of contractions.

Each subject was positioned on the dynamometer plinth in a similar position to the isometric testing procedure. The left thigh of each subject was cleaned with warm water and soap to reduce the surface resistance. The two surface electrodes were encased in sponge pads which were previously soaked in a hot 5% Savlon solution. The electrodes were covered by a plastic sheet and then a towel in order to keep the skin surface warm and moist. The plastic sheet and the electrodes were fastened in place with Nylatex straps (Chattanooga Corp.). The thigh and pelvis were held by two webbing straps, and the lower leg was secured onto the leg pad with a Nylatex strap.

The experimenter was responsible for adjusting the controls of the stimulator (Minidyne III). Current intensity was adjusted until the contractile force reached the appropriate training intensity (25% or 50% MVIC), as indicated by the torque readings on the computer monitor. The experimenter monitored the torque readings continuously and adjusted the current intensity to maintain the appropriate level of force output.

The MVIC of each subject was retested at the beginning of the first training session of the second and third weeks of training. Subsequently, the training intensity was adjusted according to the new MVIC measurement. In the last training session of each week, the MTIC of each subject was re-tested. When testing the MTIC value, the experimenter was responsible for gradually increasing the current amplitude until the subject indicated his/her maximum tolerance. The subject was asked to tolerate one more contraction at this current intensity before the current was discontinued. Subjects were asked to avoid changing their normal activities during the entire nine-week period.

Post-Test Procedures

When EMS training was completed, all subjects including the control group were re-tested for both isometric and isokinetic torque measurements in both limbs.

In the subsequent three-week period following post-test measurement, the subjects in the experimental groups were re-tested once a week to determine any carry-over effects from EMS training. Only the MVIC of the trained quadriceps femoris muscle was re-tested in this procedure.

Data Handling and Analysis

In order to allow a direct comparison between each group, the absolute torque values for the performance of each subject were normalized with reference to their pre-test measurements. The pre-test values were taken as 100% and subsequent measurements were expressed in porportion to this value.

Raw data obtained were tested by multivariate analysis of variance (MANOVA) to compare the strength improvement within groups and between groups. A repeated measure with one factor fixed design was used. The difference between pre- and post-test, and left and right sides and two genders were evaluated. The interaction of left and right sides, by pre- and post-test measurements were also examined. A $p<0.05$ significance level was accepted as the minimum level of significance in the statistical analysis.

Results

In general terms, the results indicated a significant strength improvement in the HI and LI groups ($p<0.01$), whereas the control group did not show any significant strength improvement. This improvement in the two experimental groups declined in the follow-up period.

Table 1:
Summary of the mean absolute MVIC strength changes in the trained and untrained limbs (* denotes significant change)

MVIC Strength	*Pre-Test*	*Post-test*	*% Change*	*Significance*
Trained Limb				
HI	159.7 (50.4)	232.9 (59.2)	48.49 (17.8)	$p<0.001$*
LI	172.0 (48.4)	214.9 (66.3)	24.6 (13.8)	$p<0.005$*
Control	166.6 (42.9)	188.5 (49.7)	0.69 (7.09)	$p>0.710$
Untrained Limb				
HI	158.5 (41.9)	198.5 (61.7)	24.1 (11.2)	$p<0.002$*
LI	165.1 (36.2)	194.3 (64.3)	18.1 (17.9)	$p<0.029$*
Control	175.7 (40.5)	180.2 (37.8)	3.29 (9.5)	$p<0.040$*

Comparing the HI and LI groups, the strength gains were significantly greater in the HI group ($p<0.01$). This indicates a positive relationship between the training intensity and strength gains. The MVIC changes of the three groups during the EMS training period and the three-week follow-up period are summarised in Figure 3. The data on force production for each subject have been normalized to their pre-test measurements (pre-test measurements equal 100%). This allows a direct comparison between subjects and between groups.

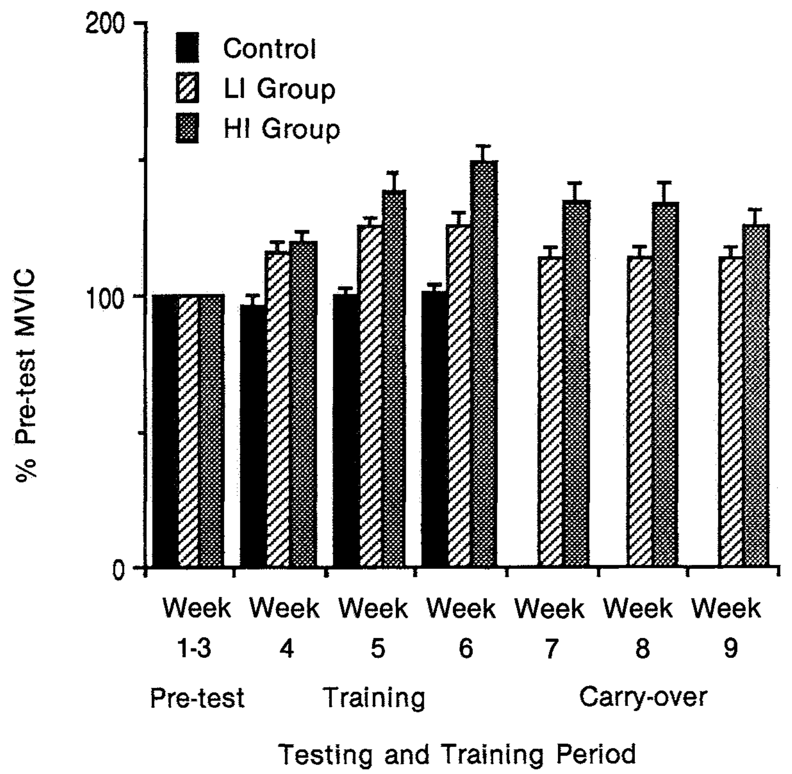
Isometric Strength Changes in the Trained Limb

Both training groups demonstrated a significant improvement in MVIC strength (at 60 degrees of knee flexion) over the three-week training period ($p<0.01$). No significant strength improvement was observed in the control group. A mean increase of 48.5% was noted in the HI group, and 24.2% in the LI group, while the control group showed no strength change. The mean increase in post-test MVIC of the HI group was significantly greater than the LI group ($p<0.05$). While the HI group demonstrated consistent increases from week to week, the LI group showed a significant increase from week one to week two ($p<0.05$), but almost plateaued by week three.

The results are depicted in Figure 3 together with a summary table of the MANOVA. The absolute isometric strength changes after three weeks of EMS training are summarised in Table 1.

The Carry-over Effect after EMS Training

Both the HI and LI groups were retested for MVIC of the training limb once a week for three weeks following the completion of EMS training. The isometric strength gain of the HI group dropped from 48.5% to 24.8% of MVIC by the end of the three-week



Source of Variation	SS	DF	MS	F	Sig. of F
Group	1048.89	2	524.44	0.14	0.868
Sex	94304.54	1	94304.54	25.69	0.000*
Prepost	4531.97	1	4531.97	13.96	0.002*
Group by Sex	19384.93	2	9692.47	2.64	0.099
Group by Prepost	1263.03	2	631.51	1.95	0.172
Sex by Prepost	1086.03	1	1086.03	3.35	0.084
Group by Sex by Prepost	589.25	2	294.62	0.91	0.421

Figure 3: Summary of the changes in MVIC strength in the trained limb, and a summary of the MANOVA (* denotes significant change)

follow-up period. This was still significantly greater than the pre-test MVIC value ($p<0.05$). During the same period, the strength gain of the LI group decreased from 24.2% to 12.8% which was not significantly greater than the pre-test value. Thus the HI group showed better strength retention than the LI group in the three-week follow-up period. The results are depicted in Figure 4 together with a summary table of the MANOVA.

The Cross Transfer Effect

The HI and LI groups demonstrated significant strength improvements in the post-test isometric strength of the untrained limb compared to the pre-test measurements ($p<0.01$). The control group did not show any significant strength improvement in the untrained limb. There were no significant differences between the two training groups, where mean increases of 24.1% in the HI group and 18.1% in the LI group were recorded. The results are reported in Figure 5. The pre- and post-test values for maximum isometric strength in the untrained, contralateral quadriceps muscle are summarized in Table 1.

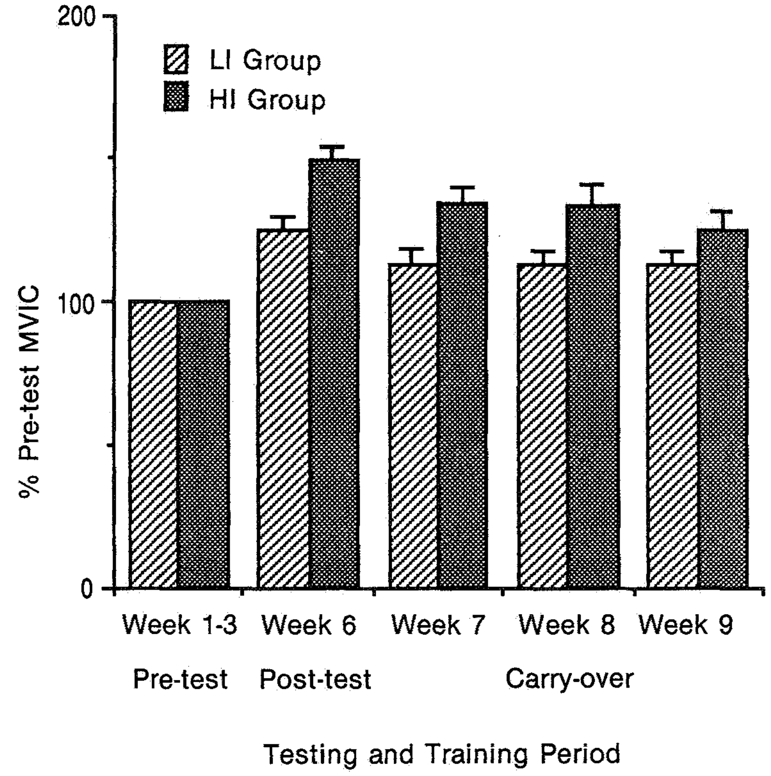
Isokinetic Strength Improvement

Isokinetic strength was measured as the work performed during maximal concentric (CON) and eccentric (ECC) muscle actions. Work is the area under each of the concentric and eccentric strength curves. There were significant differences between the pre- and post-test concentric muscle work of the trained limb in the HI and LI groups ($p<0.01$). No significant concentric strength improvement was observed in the control group. The HI and LI groups showed a 22.2% and a 12.3% increase in concentric muscle strength respectively. For the untrained limb, there were no significant changes in concentric muscle strength for all three groups.

For eccentric muscle strength, there were no significant differences between the pre-test values, in either the trained or untrained limbs of all three groups. The results are demonstrated in Figure 6.

Changes in the MTIC During Training

The maximum tolerated isometric contraction (MTIC) was measured at pre-test and weekly intervals during the three-week training period. The MTIC measurement was expressed as a percentage of the MVIC strength of that particular training week. This was to take into account the strength gain resulting from EMS training of each week. The MANOVA statistics showed that there were significant increases in the MTIC strength in the two training groups after three weeks of EMS training ($p<0.01$). The mean MTIC increased from 56.6% of pre-test MVIC to 72.7% at post-test in the HI group, and from 43.4% to 60.5% in the LI group. The HI group consistently produced a higher MTIC than the LI group throughout the training. The results are depicted in Figure 7.



Source of Variation	SS	DF	MS	F	Sig. of F
MWithin Group (1)	1622317.28	1	1622317.28	106.16	0.000*
MWithin Group (2)	1485909.76	1	1485909.76	97.24	0.000*
Group	1497.32	1	1497.32	0.10	0.761
Week	28516.17	4	26516.17	25.18	0.000*
Week by Group	2395.80	4	598.95	2.12	0.092

Figure 4: Summary of changes in MVIC strength in the trained limb over a three-week follow up period and a summary of the MANOVA (* denotes significant change)

Discussion

The results of the present study clearly showed that EMS training produced significant strength gains in normal healthy muscle. They further demonstrated that higher EMS training intensities produced significantly greater strength gains than lower training intensities. In addition, significant strength gains were seen in the non-exercised corresponding muscle group of the opposite limb.

Training Intensity and Isometric Strength Gains

The HI training group had a significantly higher mean increase in MVIC (48.5%) from pre-test to post-test, than the mean MVIC of the LI group, which increased by 24.2% ($p<0.01$). Thus the results indicate that higher training force levels produce greater strength gains in EMS training.

The study reported by Selkowitz (1985) was one of the few studies to provide evidence for a relationship between training intensity and strength gains. The present study, however, is one of the first studies that has compared two different training intensities while other factors were controlled. Thus the difference in strength gains between the HI and LI groups can be mainly attributed to the training intensity. The results suggest a strong relationship between training intensity and strength gain, *ie* that a higher training intensity produces a higher strength gain. It is possible that training intensities greater than 50% of MVIC could produce even higher strength gains. However, it is not clear at this point if further increases would produce any greater strength gain. It is possible, for example, that a plateau of improvement may be reached.

The magnitude of strength gains from the HI group (mean = 48.5%) are more comparable to Kot's study of 40% strength gain, and Selkowitz's study (1985) of 44% isometric strength gains. However, it is relatively high, compared to some of the studies reported in the literature.

Laughman *et al* (1983) utilized 33% MVIC training intensity and reported a 22% mean increase in MVIC from the EMS training group. Currier and Mann (1983) utilized 60% MVIC training intensity and recorded a mean 14% improvement. Kubiak *et al* (1987) trained the EMS group at more than 45% of MVIC and recorded 33% mean increase in strength. In contrast, Stefanovska and Vodovnik (1985) used an exceptionally low training intensity of 5% of pre-test MVIC, and reported 13% and 25% mean improvement in the two EMS groups. Their results are difficult to explain in view of the findings from this and other studies.

The discrepancy in the results between studies can be accounted for by differences in a variety of factors. These include the control and calculation of the training intensity, the number and the duration of contractions and various aspects of the training and stimulation parameters.

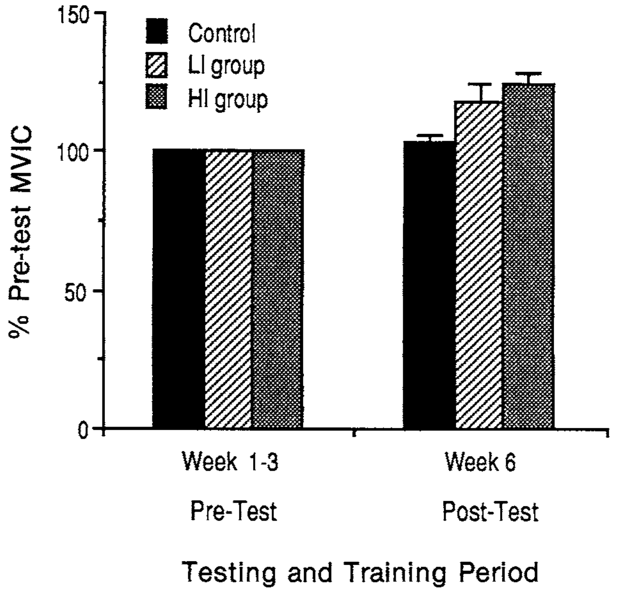


Figure 5: Summary of changes in MVIC strength in the untrained limb (cross-transfer effect)

In studies that have quantified training intensity, the calculation of training intensity was mainly based on the pre-test MVIC measurement, and did not take into account the concomitant increase in the MVIC as training progressed. This may account for some of the higher values of training intensity reported in the literature (Currier and Mann 1983, Selkowitz 1985).

Another important consideration is the total number of contractions and total stimulation time. Each subject in the study by Selkowitz (1985) received 1,200 seconds of stimulation, whilst in the present study the total stimulation time was 2,250 seconds. Thus the training protocol in Selkowitz's study consisted of a shorter stimulation time and somewhat higher average training intensity. Currier and Mann (1983) utilized a similar stimulation time as the present study and yet produced only a 14% strength gain. Cabric and Appell (1987) utilized a 21 consecutive day training program and the number and duration of contractions were progressed during the course of training. It is not clear how much of their resultant strength gains were affected by these factors. Methodological differences in the application of stimulation parameters may also have contributed to the discrepancies in results between the various studies.

Carry-over Effect

The HI group maintained a significant mean strength improvement (24.8% of MVIC) up to three weeks following the completion of EMS training. Thus the mean strength gain of the HI group declined by 13.7% from the 48.5% improvement recorded at the post-test. The mean strength gain of the LI group declined by 11.4% from the 24.2% measured at post-test, to 12.8% at the end of the three-week follow-up period, which was not significantly greater than the pre-test strength level. Thus, the HI group

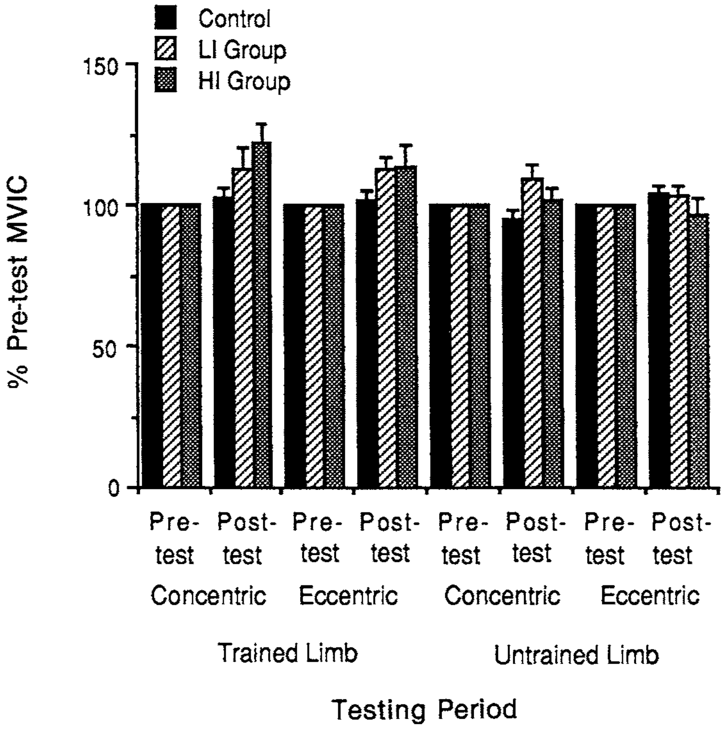
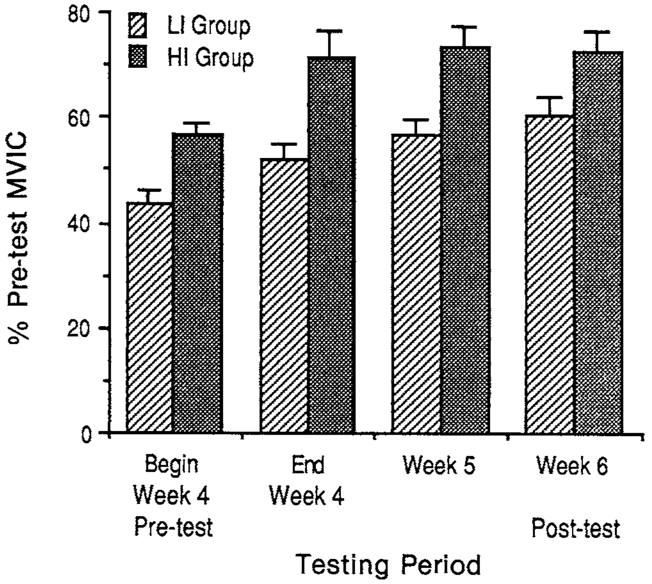


Figure 6: Summary of the changes in isokinetic strength (Work) in both limbs for all three groups



Source of Variation	SS	DF	MS	F	Sig. of F
MWithin Group (1)	150726.58	1	150726.58	553.53	0.000*
MWithin Group (2)	92248.01	1	92248.01	338.77	0.000*
Group	3571.11	1	3571.11	13.11	0.003*
Week	2392.06	3	797.35	17.09	0.000*
Week by Group	183.76	3	61.25	1.31	0.283

Figure 7: Summary of the mean changes in the MTIC for the HI and LI groups throughout the training period and a summary of MANOVA (* denotes significant change)

demonstrated a significant carry-over effect and the LI group did not, in the three-week follow-up period following EMS training.

Very few studies have addressed the issue of whether strength training from EMS has any long lasting effect. Boutelle *et al* (1985) reported one of the few studies that present favourable results in this area. They reported a mean strength improvement of 32.0% MVIC at post-test, and this was maintained to a mean strength gain of 27.8% of MVIC, one month later. Thus, the mean strength gain fell by only 4.2% over a period of one month without further stimulation. The authors attributed the carry-over effect to underlying neuromuscular adaptations.

In the period following voluntary exercise training during which strength changes were monitored (detraining), a decrease in both the integrated electromyographic (EMG) activity and motor unit synchronization have been reported (Sale *et al* 1982, Komi 1986). Komi (1986) suggested a reversal of mechanisms during 'detraining' following voluntary exercise — that initially strength loss was due to a reduction in maximal neural activity, followed by an increasing contribution due to muscular atrophy.

The results of the HI group, showing significant carry-over of strength gains after a period of three weeks, suggested that the increased neural activation was not significantly reduced. It is not clear if the neural adaptations can be maintained past the three-week post-training period. The question of whether there will be a complete reversal of neural adaptations calls for further investigation.

Cross Transfer Effect

The isometric strength of the contralateral limb showed significant improvement in both the HI and LI groups ($p<0.01$). Although the HI group produced a higher mean strength increase of 24.1%, it was not significantly higher than that of the LI group at 18.1%. The similarity of the strength gains between the HI and LI groups suggests the influence of neutral factors, irrespective of the magnitude of stimulation. This finding supports the work of Laughman *et al* (1983) and Singer (1986) who reported significant increases of isometric strength in the contralateral limb following EMS training. Laughman *et al* (1983) and Singer (1986) utilized different training intensities in their studies, and obtained similar magnitudes of strength gain in the contralateral limbs (15% and 14% respectively). This further suggests that the cross transfer effect may be independent of the training intensity.

Moritani and deVries (1979) suggested that in voluntary exercise training, neural factors acting via increased facilitation or disinhibition at various levels of the nervous system, were solely responsible for the cross transfer effect, and that muscular hypertrophy was not a significant factor. Whilst there are a variety of theories to account for the cross transfer effect during voluntarily induced movements or exercises, these theories are not appropriate to explain the cross transfer effect produced by EMS training, in which muscle contractions are electrically induced in an otherwise passive subject.

The present study shows that a lower

EMS training intensity may be adequate if the cross transfer effect is the desired outcome. It is not clear if there is a threshold intensity for producing significant cross-transfer of strength gains. It would be interesting, for example, to determine if a 5% or 10% of MVIC training intensity would produce similar results as those obtained in the present study.

The cross transfer effect from EMS training appeared to be limited to isometric strength only. No significant isokinetic strength gains were demonstrated in the contralateral limb of any of the three groups. More research is required to investigate the precise mechanism and extent of the cross transfer phenomenon.

Isokinetic Strength Changes

The present results showed a significant improvement in the concentric muscle strength of the HI and LI groups at a velocity of 60 degrees per second, but not in the control group. No significant strength changes were produced in the eccentric mode at the same velocity of movement. Thus the present study provides evidence that EMS training in the isometric mode can produce a limited (22.2% in HI group and 12.3% in the LI group) improvement in concentric isokinetic strength.

Previous studies have reported conflicting results with isokinetic strength changes resulting from EMS training. Some studies have reported no significant isokinetic strength gains following EMS training (Currier and Mann 1983, Boutelle *et al* 1985). Other studies have reported some isokinetic strength gains at the low velocity movement of 30 degrees per second (Romero *et al* 1982, Singer *et al* 1983, Nobbs and Rhodes 1986). Romero *et al* (1982) and Boutelle *et al* (1985) measured isokinetic torque at 60 degrees per second and both reported no significant strength gain from EMS training.

The present study demonstrated a significant mean concentric strength gain of 22.2% in the HI group at 60 degrees per second but no improvement in the eccentric muscle strength was recorded. It is not clear why concentric strength was selectively improved.

Change in MTIC During EMS Training

The increase in the maximum tolerated isometric contraction (MTIC) induced by EMS is an important consideration. Although both experimental groups showed signficant increases of MTIC during each week, the torque production of MTIC was consistently lower than the MVIC of each particular week ($p<0.01$). In general terms, the MTIC has always been shown to be less than the MVIC (Kramer *et al* 1984, Walmsley *et al* 1984, De Domenico and Strauss 1986).

The increase of MTIC with EMS training can be attributed to current accommodation and decreased discomfort experienced by the subjects (Boutelle *et al* 1985). De Domenico and Strauss (1986) concluded that the subjects' pain tolerance, or experience of discomfort from stimulation, was one of the most important factors determining the magnitude of the MTIC, especially for low-frequency stimulators. In the present study, the HI group generated a mean MTIC of 72.7% of MVIC, which corresponded closely to the figure of 74.2% of MVIC elicited with a similar stimulator (Minidyne II) reported by De Domenico and Strauss (1986).

Some of the subjects in the HI group reported considerable discomfort during training at 50% of MVIC. The complaint usually involved either sensory discomfort or marked muscle soreness which lasted from a few minutes to up to forty eight hours. Unless the discomfort can be reduced, training at higher intensities will not be tolerated by some subjects. Indeed, the painful sensation and muscle soreness associated with EMS are perhaps the main limiting factors for its application to human muscles at the present time.

Possible Neural Mechanisms in EMS Training

The strength gains resulting from three weeks of EMS training may be largely attributed to neural factors. It has been shown that significant strength changes can be produced with 3-5 weeks of voluntary exercise training without significant morphological changes such as muscular hypertrophy (Moritani and deVries 1979). Moritani and deVries (1979) proposed that short-term strength changes following 2-4 weeks of training were essentially the result of neural adaptations. A possible difficulty with the results of their study lies in the use of circumferential measurements to determine the changes in muscle girth. These are known to be unreliable and technically imprecise (Stokes 1985, De Koning *et al* 1986). A more recent study by Luthi *et al* (1986) utilized computed tomography, which is a more precise and objective approach, to study the morphological changes in muscle following a six-week program of resisted exercise training and found no changes in muscle cross-sectional area.

Singer and Breidahl (1987) demonstrated that there were no significant 'gross' morphological changes using computed tomography, following a four-week programme of EMS training, in subjects with a previous history of knee problems. As the present study involved EMS training in a relatively short period (three weeks), it is unlikely that there would have been any significant morphological changes. Based on the results of Luthi *et al* (1986) and Singer and Briedahl (1987), it is probable that neural adaptations were the predominant contributor to the strength changes seen in the present study.

Luff (1987) suggested that long term changes in the activation of skeletal muscle were produced primarily by neural influences mediated via the nerve; and less importantly by hormonal influences. Evidence for neural influences was demonstrated in cross-reinnervation studies, in which the nerves between a fast and a slow muscle were transposed and after some time usually several months — the muscles started to reverse their morphological profile and contractile properties as influenced by the new nerve supply (Sreter *et al* 1975, Luff 1984).

Examination of the trend of strength increases during the three-week training period provides further evidence to support the effect of neural factors. Significant strength increases were demonstrated from the first week of EMS training, especially in the HI group, and this initial period would not be expected to be associated with changes in muscle size. Further evidence using EMG analysis and computed tomography is required to investigate this concept.

Since EMS training should not involve active voluntary contraction, the neural mechanisms involved in voluntary exercise training cannot be directly applied to EMS training. The concepts of long-term potentiation (Bliss and Lomo 1973), enhanced motor unit synchronization (Milner-Brown *et al* 1975) and reversal of normal motor unit activation patterns (Garnett and Stephens 1981), may possibly account for the strength training effect of short-term EMS training programs. The following discussion presents possible neural mechanisms to account for strength changes resulting from EMS training seen in the present study.

As the electrical stimulus activates various parts of the femoral nerve during EMS training to the quadriceps muscle group, both afferent and efferent fibres are stimulated (Benton *et al* 1981). The efferent (motor) fibres then stimulate the muscle to contract. As high force levels were induced in the present EMS training program, massive sensory input through various afferent fibres including those from skin, muscle and tendon would have been produced. The primary muscle spindle afferent (Ia) fibres convey the stimulus impulse to the spinal cord, where a monosynaptic reflex (H reflex) is induced and a second efferent impulse is generated (Clamann *et al* 1974).

The Hoffmann (H) reflex is a monosynaptic reflex elicited by a single electrical stimulus, and is usually demonstrated via stimulation of the tibial nerve to the calf muscle (see Hugon 1973, Goodgold and Eberstein 1980 for review). The EMG signal of this reflex can be displayed as an H wave. There is probably a strong facilitation of spinal motoneuron pools during the H reflex, due to increased input from Ia afferent fibres. In the cat, Mendell and Henneman (1971) have shown that all, or nearly all of the Ia afferent fibres make direct connections with each of the motor cells within a given motoneuron pool. Such connections might also lead to increased afferent input to inter-segmental and higher spinocortical pathways; which may be translated into descending efferent output to the appropriate spinal motoneuron pools. This may result in a raised central level of excitation in the spinal motoneuron pools, these becoming more receptive to stimulation. Although the H reflex may be easily demonstrated with a single stimulus, it is possible that with repeated electrical stimulation there may be a widespread facilitatory effect on the spinal motoneuron pools and the relevant cortical centres above.

Long-term potentiation (LTP) is a phenomenon in which tetanic stimulation of a set of input fibres potentiates synaptic transmission in a particular pathway (see Dolphin 1985 for a review): LTP can last from a few hours to several weeks, and has been suggested to be an important mechanism in motor learning (Collingridge and Bliss, 1987). This phenomenon has been observed in both the peripheral and central nervous systems, particularly in the hippocampus (Johnston and Brown 1983). Long-term potentiation, resulting in increased neuro-transmitter sensitivity and synaptic efficacy, may be an important mechanism responsible for the increased muscle force development from EMS training.

Additionally, there may possibly be an increased synchronization of motor unit firing patterns, due to increased input from local sensory fibres and from higher motor control centres (Grimby and Hannerz 1968, Milner-Brown *et al* 1975). In voluntary exercise training, it has been suggested that increased alpha motoneuron activation with concomitant motor unit synchronization causes muscle force to increase, as well as serving as a stimulus for hypertrophic factors (Komi 1986). Singer (1986) demonstrated a shift in the EMG power spectra following EMS training, which has been suggested to represent a trend towards enhanced motor unit synchronization. Kramer and Wessel (1985) demonstrated an increase in EMG activity following EMS, and suggested that there was an increased number of motor units activated.

The increase in force production may be partly attributed to a possible change in the recruitment pattern of motor units. High levels of muscle tension are produced by the activation of large, fast-twitch, fast-fatiguing motor units (type II), supported by a background of smaller, slow-twitch, fatigue-resistant motor units (type I) (Burke 1980). In electrical stimulation, it has been postulated that the fast-twitch motor units are selectively activated, and are responsible for the strength gains from EMS training (Kramer and Wessel 1985).

The size principle of motor unit recruitment, a concept which is currently under review (Enoka and Stuart 1984), states that the critical firing level and activation of motor units follows a rank order of activation according to their sizes (Henneman *et al* 1965). Thus the smaller motor units will be activated first, with the gradual recruitment of the larger units as contraction force develops. In the present study, especially in the HI group, the stimulus intensity produced a peak tension towards the end of each contraction. The production of high peak tension seems most appropriate for the recruitment of the large motor units (type II) (Burke 1980). The higher training force level may possibly lead to the selective activation of these large motor units. Conversely, the lower training force level (25% MVIC) in the LI group, may not have favoured the recruitment of the larger type II fibres, as the level of tension was submaximal. This may possibly account for the difference in strength increases between the two training intensities.

Moritani *et al* (1985) pointed out that the extent of motor unit activation was differentially affected by fatigue, depending on the muscle fibre type. The proportion of muscle fibre types varies among individuals and among different muscle groups, and is influenced largely by genetic factors and to a smaller extent, by training or de-training (Burke 1980, Howald 1982, Komi 1986). Muscle fatigue leads to a reduction in tension and reduced firing rates of motoneurons (Green 1986). Muscle fatigue has been demonstrated to be a significant factor in electrical stimulation within the range of 50 to 80 Hz, producing marked force reduction (Jones *et al* 1979). Stimulation with a lower frequency (20 Hz or less) has produced a somewhat different fatigue pattern which is more long-lasting (Edwards *et al* 1977). Muscle fatigue is one of the reasons why the stimulus intensity has to be adjusted in order to maintain the same training force production. Rapid muscle fatigue is also an indication that the fast-twitch fibres are discharging at a maximum frequency (Stefanovska and Vodovink 1985). Edwards (1981) has proposed a number of possible causes for the fatigue phenomenon in the fast-twich motor units including central inhibition, neuromuscular junction block, and an impaired excitation of the sarcolemma.

Howald (1982) pointed out that conversion of type II to type I fibres was demonstrated with prolonged, intensive endurance training, whereas transformation of type I to II fibres has been difficult to achieve. Therefore, in the present experiment involving only short-term strength training, the transformation of fibre type would not be expected to play a role and the strength training effect is likely to be the result of increased activation (neural adaptation) of the type II units from the relevant motoneuron pool for the quadriceps muscle group.

The significant findings in the contralateral limb provides further evidence for the involvement of neural factors. It supports bilateral facilitatory influences on the neural circuits from unilateral stimulation of the quadriceps (Laughman *et al* 1983, Singer 1986). Possibly, the 'spino-bulbo-spinal' pathway suggested by Shimamura and Livingstone (1963) may be the link between the peripheral contractile apparatus and the central nervous system, mediating the response to electrical stimulation. Further experimental work, both on animals and humans, will be essential to provide evidence on the exact neural mechanisms involved.

The gradual loss of the strength training effect in both the HI and LI groups (carry-over) suggests that some of the neural adaptations are not long lasting. It has been suggested that the decline in strength gains following voluntary exercise training is due to a reversal of neural mechanisms (see Komi 1986 for review). A similar mechanism may be at work in EMS training (Boutelle *et al* 1985). However, the rate and extent of the decline in strength has not been thoroughly investigated. This area has significant implications for the use of EMS as a rehabilitation tool and warrants further research.

In summary, a number of possible neural mechanisms have been suggested to account for the strength training effect of electro-motor stimulation in the present investigation. Electro-motor stimulation is known to activate both efferent and afferent pathways in peripheral nerves, eliciting a strong tetanic contraction as well as the H reflex. The facilitation of the H reflex pathway, as well as inter-segmental and higher spinocortical pathways, may lead to increased activation of the spinal motoneuron pools controlling muscle force development in both limbs. Other mechanisms that may be involved include, long term potentiation, increased sychronization of motor unit activation and selective recruitment of the fast-twitch, fast-fatiguing muscle fibres. These mechanisms may have contributed to the increased muscle force development following EMS training. Further research is necessary to demonstrate the precise mechanisms mediating strength gains from EMS training.

Summary and Conclusions

A three week EMS training program produced significant strength gains in the quadriceps femoris muscle group. The higher training intensity (50% MVIC) produced significantly greater isometric and isokinetic strength gains than the lower training intensity of 25% MVIC. A significant carry-over effect was demonstrated in the HI group in the three week follow-up period. Significant isometric strength gains were also observed in the contralateral homologous muscle group. The strength training effect of EMS was attributed to neural adaptations elicited by electrical stimulation.

The findings of this investigation have significant implications for future research and the clinical application of EMS. A higher training intensity is advocated during EMS training to achieve an immediate, large strength gain. Future research may utilize the present findings in selecting an appropriate training intensity, especially when EMS is compared with submaximal and maximal voluntary exercise.

On the basis of the findings from the present study, the following conclusions can be drawn:

1. A three week EMS training program produced significant isometric strength gains in the HI (48.5%) and LI (24.2%) groups. No significant changes were seen in the control group.

2. A high training force level (50% MVIC) produced significantly greater isometric strength gains than a low training force level (25% MVIC).
3. Significant isokinetic strength gains at 60 degrees per second were demonstrated in both HI (22.2%) and LI(12.3%) groups but only in the concentric mode.
4. A significant cross transfer effect was demonstrated in the contralateral limb for both HI (24.1%) and LI (18.1%) groups. There was no significant difference in the cross transfer effect between the two groups. There were no significant changes in isokinetic strength in the contralateral muscle group.
5. A significant carry-over effect (24.8% of pre-test MVIC) was demonstrated by the HI group at the end of the three week follow-up period. The strength gains in the LI group declined considerably in the same period, and was not significantly different from the pre-test value.
6. The MTIC measurement changed significantly during the course of training in both HI and LI groups, suggesting increased tolerance to electrical stimulation as training progressed.

References

Alferi V (1982), Electrical treatment of spasticity, *Scandinavian Journal of Rehabilitation Medicine,* **14,** 177-182.

Bajd T, Gregoric M, Vodovnik L and Benko H (1985), Electrical stimulation in treating spasticity resulting from spinal cord injury, *Archives of Physical Medicine and Rehabilitation,* **66,** 515-517.

Benton LA, Baker LL, Bowman BR and Waters RL (1981), *Functional Electrical Stimulation — A Practical Clinical Guide,* 2nd edition, Rancho Los Amigos, California.

Bliss TVP and Lomo T (1973), Long-lasting potentiation of synaptic transmission in the dentate area of the anaesthetized rabbit following stimulation of the perforant path, *Journal of Physiology (London),* **232,** 331-357.

Boutelle D, Smith B and Malone T (1985), A strength study utilizing the Electro-Stim 180, *The Journal of Orthopaedic and Sports Physical Therapy,* **7** (2), 50-53.

Burke RE (1980), Motor unit types: Functional specialisations in motor control, *Trends in Neuroscience,* **XX,** 255-258.

Cabric M and Appell HJ (1987), Effect of electrical stimulation of high and low frequency on maximum isometric force and some morphological characteristics in Man, *International Journal of Sports Medicine,* **8,** 256-260.

Clamann HP, Gillies JD, Skinner RD and Hennemann E (1974), Quantitative meausres of output of a motoneuron pool during monosynaptic reflexes, *Journal of Neurophysiology,* **37,** 1328-1337.

Collingridge GL and Bliss TVP (1987), NMDA receptors — their role in 'long-term potentiation', *Trends in Neuroscience,* **10** (7), 288-293.

Currier DP and Mann R (1983), Muscular strength development by electrical stimulation in healthy individuals, *Physical Therapy,* **63** (6), 915-921.

De Domenico G and Strauss GR (1986), Maximum torque production in the quadriceps femoris muscle group using a variety of electrical stimulators, *The Australian Journal of Physiotherapy,* **32** (1), 51-56.

De Domenico G and Strauss GR (1987), Muscle force production induced by electrical stimulation of motor nerve, *Proceedings of the Xth Congress of the World Confederation of Physiotherapy,* Sydney, 356-360.

De Koning FL, Binkhorst RA, Kauer JMG and Thijssen HOM (1986), Accuracy of an anthropometric estimate of the muscle and bone area in a tranversal cross-section of the arm, *International Journal of Sports Medicine,* **7,** 246-249.

Dolphin AC (1985), Long-term potentiation at peripheral synapses, *Trends in Neuroscience,* **8,** 376-378.

Edwards RHT, Hill DK, Jones DA and Merton PA (1977), Fatigue of long duration in human skeletal musclafter exercise, *Journal of Physiology (London),* **251** (2), 303-315.

Edwards RHT (1981), Human muscle function and fatigue in R Porter and J Whelan (Eds.), *Human Muscle Fatigue: Physiological Mechanisms,* pp. 1-18, Pitman Medical, London.

Enoka RM and Stuart DG (1984), Henneman's 'size principle': current issues. *Trends in Neuroscience,* **7,** 226-228.

Eriksson E and Haggmark T (1979), Comparison of isometric muscle training and electrical stimulation supplementing isometric muscle training in the recovery after major knee ligament surgery, *American Journal of Sports Medicine,* **7,** 169-171.

Garnett R and Stephens JA (1981), Changes in the recruitment threshold of motor units produced by cutaneous stimulation in man, *Journal of Physiology (London),* **311,** 463-473.

Geddes LA (1984), A short history of the electrical stimulation of excitable issue, including electrotherapeutic application. *A Supplement to the Physiologist,* **27** (1), American Physiological Society, Bethsaida.

Goodgold J and Eberstein A (1980), The blink, H, and tonic vibration reflexes in *Electrodiagnosis of Neuromuscular Disease,* 3rd edition, Williams and Wilkins, Baltimore, pp 258-279.

Gould N, Donnermeyer D, Gammon GG, Pope M and Ashikaga T (1983), Transcutaneous muscle stimulation to retard disuse atropy after open menisectomy, *Clinical Orthopaedics and Related Research,* **178,** 190-197.

Green HJ (1986), Muscle power: Fibre type recruitment, metabolism and fatigue, in NL Jones, N McCartney and AJ McComas (Eds), *Human Muscle Power,* Human Kinetics, Champaign, Illinois, pp 65-75.

Grimby L and Hannerz J (1974), Differences in recruitment order and discharge pattern of motor units in early and late reflex components in man, *Acta Physiologica Scandinavica,* **90,** 555-564.

Halbach JW and Straus D (1980), Comparison of electro-myostimulation to isokinetic training in increasing power of the knee extensor mechanism, *The Journal of Orthopaedic and Sports Physical Therapy,* **2** (1), 20-24.

Henneman E, Somjen G and Carpenter DO (1965), Functional significance of cell size in spinal motoneurons, *Journal of Neurophysiology,* **28,** 560.

Howald H (1982), Training-induced morphological and functional changes in skeletal muscle, *International Journal of Sports Medicine,* **3,** 1-12.

Hugon M (1973), Methodology of the Hoffmann Reflex in man, in JE Desmedt (Ed), *New Developments in Electro-myography and Clinical Neurophysiology,* **3,** 277-293.

Johnston D and Brown TH (1983), Giant synaptic potential hypothesis for epileptiform activity, *Science,* **211,** 294-297.

Jones DA, Bigland-Richie B and Edwards HT (1979), Excitation frequency and muscle fatigue: Mechanical responses during voluntary and stimulated contractions, *Experimental Neurology,* **64,** 401-413.

Komi PV (1986), Training of muscle strength and power: Interaction of neuromotoric, hypertrophic, and mechanical Factors, *International Journal of Sports Medicine,* **7,** 10-15.

Kramer J and Mendryk SW (1982), Electrical stimulation as strength improvement technique: a review, *The Journal of Orthopaedic and Sports Physical Therapy,* **4** (2), 91-98.

Kramer J, Lindsay D, Magee D, Mendryk SW and Wall T (1984), Comparison of voluntary and electrical stimulation contraction torques, *The Journal of Orthopaedic and Sports Physical Therapy,* **5** (6), 324-331.

Kramer JF and Wessel J (1985), Electrical activity and torque following electrical stimulation and voluntary contractions of quadriceps, *Physiotherapy Canada,* **37** (5), 283-287.

Kubiak RJ, Whitman KM and Johnston RM (1987), Changes in quadriceps femoris muscle strength using isometric exercise versus electrical stimulation, *The Journal of Orthopaedic and Sports Physical Therapy,* **8** (11), 537-541.

Lainey CG, Walmsley RP and Andrew GM (1983), Effectiveness of exercise alone versus exercise plus electrical stimulation in strengthening the quadriceps muscle, *Physiotherapy Canada,* **35** (1), 5-11.

Laughman RK, Youdas JW, Garrett TR and Chao EYS (1983), Strength changes in the normal quadriceps femoris muscle as a result of electrical stimulation, *Physical Therapy,* **63** (4), 494-499.

Lloyd T, De Domenico G, Strauss GR and Singer KP (1986), A review of the use of electro-motor stimulation in human muscle, *The Australian Journal of Physiotherapy,* **32** (1), 18-30.

Luff AR (1984), Contractile properties of cross-reinnervated cat muscle during transformation, *Proceedings of the Australian Physiological and Pharmacological Society,* **15,** 7P.

Luff AR (1987), Plasticity of muscle activation, *Proceedings of The Australian Physiological and Pharmacological Society,* **18** (2), 124-128.

Luthi JM, Howard H, Claassen H, Rosler K, Vock P and Hoppler H (1986), Structural changes in skeletal muscle tissue with heavy-resistance exercise, *International Journal of Sports Medicine*, **7**, 123-127.

Mendell, LM and Henneman E (1971). Terminals of single Ia fibres: location, density, and distribution within a pool of 300 homonymous motoneurons. *Journal of Neurophysiology*, **34**, 171-187.

Milner-Brown HS, Stein RB and Lee RG (1975), Synchronisation of human motor units: possible roles of exercise and supraspinal reflexes, *Electroencephalography and Clinical Neurophysiology*, **38**, 245-254.

Mohr T, Danzl L, Akers TK and Landry R (1986), The effect of high volt galvanic stimulation on quadriceps femoris muscle torque, *The Journal of Orthopaedic and Sports Physical Therapy*, **7** (6), 314-318.

Moritani T and de Vries HA (1979), Neural factors versus hypertrophy in the time course of muscle strength gain, *American Journal of Physical Medicine*, **58** (3), 115-130.

Moritani T, Muro M and Kijima A (1985), Electromechanical changes during electrically induced and maximal voluntary contractions: electrophysiologic responses of different muscle fibres types during stimulated contractions, *Experimental Neurology*, **88**, 471-483.

Morrissey MC, Brewster CE, Shields CL and Brown M (1985), The effects of electrical stimulation on the quadriceps during postoperative knee immobilisation, *The American Journal of Sports Medicine*, **13** (1), 40-45.

Muller EA (1957), The regulation of muscular strength, *Journal of the Association for Physical and Mental Rehabilitation*, **11**, 41-47.

Nobbs LA and Rhodes EC (1986), The effect of electrical stimulation and isokinetic exercise on muscular power of the quadriceps femoris, *The Journal of Orthopaedic and Sports Physical Therapy*, **8**(5), 260-268.

Owens J and Malone T (1983), Treatment parameters of high frequency electrical stimulation as established on Electro-stim 180, *The Journal of Orthopaedic and Sports Physical Therapy*, **4** (3), 162-168.

Romero JA, Sanford TL, Schroeder RV and Fahey TD (1982), The effect of electrical stimulation of normal quadriceps on strength and girth, *Medicine and Science in Sports and Exercise*, **14**, 194-197.

Sale DG, McComas AJ, MacDougall JD and Upton ARM (1982), Neuromuscular adaptation in human thenar muscles following strength training and immobilisation, *Journal of Applied Physiology*, **53**, 419-424.

Selkowitz DM (1985), Improvement in isometric strength of the quadriceps femoris muscle after training with electrical stimulation, *Physical Therapy*, **65**, (2), 186-196.

Shimamura M and Livingstone RB (1963), Longitudinal conduction systems serving spinal and brainstem coordination, *Journal of Neurophysiology*, **26**, 258-272.

Singer KP, Gow PJ, Otway WF and Williams M (1983), A comparison of electrical muscle stimulation, isometric, isotonic and isokinetic strength training programmes, *The New Zealand Journal of Sports Medicine*, **11** (3), 61-63.

Singer KP (1986), The influence of unilateral electrical muscle stimulation on motor unit activity patterns in atrophic human quadriceps, *The Australian Journal of Physiotherapy*, **32** (1), 31-37.

Singer KP and Breidahl P (1987), The use of computed tomography in assessing muscle cross-sectional area, and the relationship between cross-sectional area and strength, *The Australian Journal of Physiotherapy*, **33** (2), 75-82.

Singer KP, De Domenico G and Strauss G (1987), Electro-motor stimulation research methodology and reporting: a need for standardization, *The Australian Journal of Physiotherapy*, **33**(1), 43-48.

Sreter FA, Luff AR and Gregely J (1975), Effects of cross-reinnervation on physiological parameters and on properties of myosin and sacroplasmic reticulum of fast and slow muscle of the rabbit. *Journal of General Physiology*, **66**, 811-821.

Stefanovska A and Vodovnik L (1985), Change in muscle force following electrical stimulation, dependence on stimulation waveform and frequency, *Scandinavian Journal of Rehabilitation Medicine*, **17**, 141-146.

Stillwell KG (1983), *Therapeutic Electricity and Ultraviolet Radiation*, 3rd edition, Williams and Wilkins, Baltimore.

Stokes M (1985), Reliability and repeatability of methods for measuring muscle in physiotherapy, *Physiotherapy Practice*, **1**, 71-76.

Walmsley RP, Letts G and Vooys J (1984), A comparison of torque generated by knee extension with a maximal voluntary muscle contraction vis-a-vis electrical stimulation, *The Journal of Orthopaedic and Sports Physical Therapy*, **6** (1), 10-17.

Williams JGP and Street M (1976), Sequential faradism in quadriceps rehabilitation, *Physiotherapy*, **62** (8), 252-254.