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EFFECTS OF UNILATERAL VOLUNTARY AND ELECTROMYOSTIMULATION TRAINING ON MUSCULAR STRENGTH OF THE CONTRALTERAL LIMB

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Abstract

This study investigated the effects of unilateral electromyostimulation (EMS) versus voluntary isometric strength (VIM) training on knee extension strength of the contralateral limb, a phenomenon termed cross education, in previously untrained healthy young adults. Subjects in EMS (n=10) and VIM (n=10) groups trained with 40 voluntary or evoked isometric knee extensions, at an intensity of 65% of maximum voluntary contraction force (MVC), three sessions per week for four weeks. Before and after training, both legs were tested for MVC on an isokinetic dynamometer, at 0 deg.s\(^{-1}\) (isometric), 60 and 180 deg.s\(^{-1}\) velocities. The results showed that the EMS and VIM training induced similar strength improvement in the trained limb (P<0.05), as well as cross-education effects (EMS +21.1% and VIM +21.4% in the contralateral limb, both P<0.05) in isometric MVC, but no cross education was found for isokinetic performance. Analysis of integrated EMG showed a trend, but not statistically significant, of increase in the trained groups. No significant variation in knee extension strength, neither in EMG, was found in a control group (n=10). The mechanism of cross education in response to the EMS training, and the application significance of cross education in exercise rehabilitation are of the interests in further studies.

KEY WORDS: cross education, electromyostimulation, unilateral training, iEMG, knee extension.
INTRODUCTION

It is well known that muscular strength increases in response to repeated overloading, and the adaptation showing specificity to the overloading. However, it has been reported that chronic unilateral motor activities could affect the function of the unpracticed contralateral limb, a phenomenon known as cross education (alternatively cross transfer or cross training. Enoka, 1988). Cross education occurs during both the learning of skills and the improvement in strength (Hellebrandt, 1951; Hortobágyi et al., 1999; Yue and Cole, 1992). Muscular strength gains in the contralateral limb of from 10% to 70% have been reported, depending upon the training program and pre-training status of the subjects (see review of Zhou, 2000). It has been speculated that this phenomenon is due to neural mechanisms, because no evidence of muscle hypertrophy or other structural changes have been reported in the contralateral limb (Enoka, 1988; Zhou, 2000). However, the exact neural mechanisms involved are still not clear. How this phenomenon is related to the overloading and specificity principles of strength training, and whether it can be used as a neuromuscular intervention in rehabilitation, have been attracting research interests for many years (Devine, 1981; Kannus et al., 1992; Moritani and deVries, 1979; Hortobágyi et al., 1999).

Both voluntary isometric contraction (VIM) and electromyostimulation (EMS) have been regarded as valid means of strength training for improving muscular strength and/or facilitating rehabilitation (Hortobágyi et al., 1997; Morrissey, 1988), whilst the mechanisms involved in these training methods are different. The EMS can be delivered directly to the muscle and/or the motor nerve endings, while the voluntary training involves higher levels in the nervous system including the motor-sensory cortex. Interestingly, it has been shown that EMS training can also produce cross-education effects (Cabric and Appell, 1987; Hortobágyi et al., 1999; Tachino et al., 1989) although contradictory reports also exist in the literature (Davies et al., 1985; Singer et al., 1986). These discrepancies may be related to differences in research design and intensities of EMS and voluntary training utilized in those studies.

This study was designed to provide further evidence in EMS induced cross-education effect. The aims of the study were to investigate whether an EMS training of similar intensity as that in a voluntary training program would induce similar cross education and to discuss the potential mechanisms of the cross education.
METHOD

Subjects. Thirty male subjects, who were habitually active but not specifically trained in a sport, volunteered to participate in the study. Ten subjects were arbitrarily assigned to each of the three groups for VIM training, EMS training, or control without training (CON). The physical characteristics of the subjects are summarized in Table 1.

Training. Each training group completed three sessions per week for four weeks, of unilateral isometric knee extension training on the dominant leg (which was defined as the leg normally used in kicking a ball). The training was performed in a laboratory under supervision. For all strength testing subjects were sat in the testing chair of a Cybex II isokinetic dynamometer (Lumex Corp., Bayshore, New York) with knee and hip joint angles both at 90 degrees, and the lower leg strapped to lever brackets using a velcro belt. The contraction force was shown on a computer monitor which was linked to Cybex II dynamometer to provide visual feedback. In each training session, the VIM group performed five sets of eight voluntary isometric contractions (ie. $5 \times 8 = 40$ repetitions), at an intensity of 65% MVC (McDonagh and Davies, 1984) as predetermined from the pre-training test. For each repetition, subject was asked to produce and maintain the required level of force for five seconds, followed by five seconds of rest. A two-minute recovery period was allowed after each set. The required level of force was adjusted after two weeks of training according to the improvement in strength.

In EMS training, the same setting of the dynamometer as in the VIM training was used. The electrical stimulation was delivered using a two-channel battery-powered electrical neuromuscular stimulator (R-STIM II, American Imex, Irvine California, USA) via two pairs of self-adhesive electrodes coated with conductive gel (Dermatrode, American Imex, Irvine California, USA). The size of each electrode was 100 mm $\times$ 50 mm. As validated in a pilot study, a transverse distal and proximal thigh electrode placement was selected for the anode (+) and cathode (-), respectively. The stimulation pulses were delivered at 100 Hz with a fixed pulse width of 250 microseconds, and the electrical current was tuned to produce a force that was equivalent to 65% MVC. In each training session, the subject produced 40 EMS isometric contractions, each contraction lasted five seconds followed by 20 seconds of rest.

Testing. Subjects participated in a familiarization trial one week before formal testing. All subjects were tested for their maximal voluntary isometric (MVIM) and isokinetic (MVIK) knee extension torque prior to the
training, after two weeks of training (for adjustment of training intensity), and within two days after four weeks of training to evaluate the effects. Prior to all testing, subjects were asked not to perform any strenuous exercise for at least 48 hrs to minimize possible residual fatigue effect.

All strength testing was performed on a KIN-COM isokinetic dynamometer (Kinetic communicator 500-H, Chattanooga Group Inc., Chattecx, TN, USA), linked to an AMLAB system (v2.0, Associated Measurement Laboratories International, Lane Cove, NSW, Australia). The initial angles at the knee and hip joints were both 90 degrees. Force in Newtons (N), torque in Newton-meters (Nm), and force/position data were determined from the original data through an AMLAB schematic circuit. All force data was sampled at a rate of 100 Hz.

During voluntary contractions surface electromyogram (EMG) signal was collected from the rectus femoris (RF), vastus lateralis (VL) and vastus medialis (VM) muscles via the AMLAB system. The system had differential amplifiers with features of CMRR >120 dB and input impedance >10^{12} \Omega. The EMG signal was band-pass filtered (20 to 3000 Hz), and A/D converted at a sampling rate of 1000 Hz. Each recording electrode had an Ag-AgCl surface of 10 mm in diameter, and the distance between the two electrodes was 20 mm. The recording electrodes and the reference electrode together with the pre-amplifier were pre-packed in a small box and firmly attached to the skin using self-adhesive sticker and tapes. The electrodes were placed on the muscle belly according to the recommendation of Delagi et al. (1981). The skin was shaved, carefully cleansed with alcohol swabs and abraded using fine grade garnet paper. Electrode gel was used to improve conduction. The original EMG signal was then rectified and integrated (iEMG) which was expressed as the area under the curve (mV.s). The iEMG was calculated for 5 s for MVIM, 1.5 s for MVIK at 60°.s\(^{-1}\) and 0.5 s for MVIK at 180°.s\(^{-1}\).

For warming-up, subject performed five minutes stationary cycling at 100 watts, followed by a series of standardized lower body stretching, then a series of submaximal isometric (0°.s\(^{-1}\)) contractions on the KIN-COM dynamometer. Following a two-minute rest subject was then required to exert a maximal effort in knee extension for a period of five seconds. The peak force over the five seconds period was recorded. Three contractions were performed with a two-minute rest between repetitions. Following a five-minute recovery from the MVIM, subject performed MVIK at velocities of 60°.s\(^{-1}\) and 180°.s\(^{-1}\) through the range of motion of 90° to 180°. Three trials were performed separated by a two-minute recovery period. Five minutes were allowed between the tests of different velocities.
**Data analysis.** For each testing condition, the two highest peak force/torque values among three trials were averaged for further statistical analysis. The relative variation to pre-training in measured variables was also calculated. Analysis of variance (ANOVA) with repeated measures was used to evaluate strength changes in response to training. Sheffe post-hoc comparisons were performed to identify at which testing occasion the difference occurred.

The experimental procedures were approved by the Human Research Ethics Committee of Southern Cross University, Australia. Written consent was obtained from each subject prior to the experiment.

**RESULTS**

Significant improvement in knee extension strength of the trained limb, in both MVIM and MVIK, were found in the VIM and EMS groups (P<0.05) after the four weeks of training (Table 2), whilst no significant differences were found among the three groups prior to training.

Both VIM and EMS groups showed significant (P<0.05) and similar level of cross education in MVIM strength, whilst no such changes were found in the control group. However, no strength gain in MVIK tests was found in the contralateral limb (Figure 1).

The analysis of integrated EMG (sum of three muscles) showed a trend of increment in both trained and contraleteral limbs in both training groups (Figure 2), although these did not reach statistical significance (P >0.05).

**DISCUSSION**

This study investigated whether the EMS intervention would induce similar cross education as voluntary exercise. The four weeks of voluntary and EMS isometric training resulted in similar increments in maximal voluntary isometric force of both the trained limb (+24.5% in VIM, +21.1% in EMS) and the contralateral limb (+21.4% in VIM, +21.1% in EMS). The magnitude of cross education was in a similar range of what have been
reported in the literature. In a summary of ~40 relevant studies, the trained limb demonstrates an average (±SD) strength gain of 25±12%, whilst the contralateral limb shows 15±10% cross education, after 4 to 20 weeks of unilateral training (see review of Zhou, 2000). In addition to a confirmation of previous findings in respect of cross education phenomenon, it should be emphasized that the present study utilized the same submaximal training intensity (~65%MVC) in both VIM and EMS groups, with the EMS training induced similar cross education effect as the voluntary training.

One problem with previous EMS training studies has been that the stimulation intensity is often limited by subject’s level of tolerance to the discomfort associated with the percutaneous stimulation (Delitto and Snyder-Mackler, 1990). This limitation makes it difficult to control the level of overloading or to directly compare the effects between voluntary and EMS training. The present study was the first to utilize an EMS intensity that was normalized and similar to that of the voluntary training group. The significant contralateral strength gain after the unilateral EMS training is interesting as previously cross-education effects have been reported repeatedly for voluntary unilateral isotonic, isokinetic or isometric training (Moritani and deVeres, 1979; Kannus et al., 1992; Hortobágyi et al., 1997; Rutherford and Jones, 1986; Weir et al., 1997), but few studies have found that EMS training could result in similar cross education. The discrepancies may be partly due to various muscle groups, subject characteristics, training intensity and testing protocols utilized in different studies (Cabric and Appell, 1987; Davies et al., 1985; Hortobágyi et al., 1999; Singer et al., 1986; Tachino et al., 1989). The present study utilized the same intensity and repetitions in both VIM and EMS training, therefore provided more concrete evidence for the EMS induced cross education.

A few interesting aspects deserve further discussion or investigation in respect of cross education. One of them is the potential mechanisms of cross education. The major physiological factors that determine muscular strength include neural activation of the muscle and the size of the muscle (Sale, 1988). It has been speculated that the neural adaptation plays a major role in cross education because no evidence of muscle size change (ie. hypertrophy) is found in the untrained limb.

Several candidate neural mechanisms for cross education have been proposed in the literature, with most of them focused on supra-spinal levels. Cross education has only been shown in homologous muscle pairs in the limbs. Hellebrandt (1951) speculated that there might be diffusion of impulses between the two motor cortexes.
during unilateral activities. More recently, Kristeva et al. (1991) analyzed the movement related cortical magnetic fields accompanying left and right unilateral and bilateral finger flexion, and suggested that the unilateral voluntary movement appears to involve the contralateral cortex. The finding that even unilateral training with imagined contractions of the abductor muscle of the fifth finger can induce a strength gain of 11% in the homologous muscle of the other hand further underscores the potential cortical contribution to cross education (Yue and Cole, 1992), although this effect has not been replicated in other muscles (Herbert et al., 1998). From an anatomy point of view, Carr et al. (1994) suggested that it might be due to bilateral central drive to the homologous muscles, because there is about 10% of the corticospinal fibres that enter the lateral and anterior corticospinal tract of the ipsilateral side while the remaining fibres cross to the contralateral side (Nyberg-Hansen and Rinvik, 1963).

Some authors have used surface EMG as an indicator of neural effect on the contralateral muscle. Hortobágyi et al. (1997) found that there is a certain level of EMG activity in the contralateral limb during unilateral activities, and speculated on the effect of postural stabilization required during such activities. However, the EMG activity (~15% of that during MVC) seems not substantial enough to be accounted for overloading and strength gain in the contralateral limb (up to 104% increment, Hortobágyi et al., 1999). Coactivation of agonist and antagonist muscles may also affect the strength in the contralateral limb thereby contributing to cross education. Carolan and Cafarelli (1992) reported a 16% strength gain in the knee extensor muscles and a reduction of 13% in coactivation of the hamstring muscles, while there was no significant change in integrated EMG activity of the vastus lateralis, in the unpracticed contralateral limb. Because the decrease in hamstring activity reduces the opposing force to the contracting quadriceps femoris, the decline in coactivation is manifested as an increase in knee extension strength. Few studies on cross education have recorded EMG from both the agonist and antagonist muscles, so it is difficult to assess the generality of this finding. Furthermore, the small but significant decrease in EMG activity of the hamstring muscle as reported by Carolan and Cafarelli (1992) was limited to the first week of training, while the strength of the unpracticed limb continued to increase in the subsequent two weeks. This dissociation suggests that other mechanisms must contribute to the cross education.

The above mentioned mechanisms are all related to the supra-spinal function of the CNS. However, the cross education induced by EMS training cannot be solely explained by these mechanisms, because EMS might have by-passed these supra-spinal levels (Delitto and Snyder-Mackler, 1990). Hortobágyi and colleagues (1999)
suggested that the spinal and supra-spinal adaptations were uncoupled with EMS training and testing, and proposed three reasons for the speculation that the site of cross education likely resides at the spinal level. First, the magnitude of EMG activity recorded from the contralateral quadriceps muscle during training was not proportional to the magnitude of the strength gain, as mentioned above (Hortobágyi et al., 1999). Secondly, voluntary training was less effective (37% strength gain) compared with EMS training (104%). This suggests that EMS training is able to access mechanisms that are not accessible by central drive during voluntary training. Thirdly, the greater strength gain achieved by EMS training cannot be fully explained by the accommodation to the discomfort associated with transcutaneous stimulation. It is possible that the noxious sensations associated with EMS may activate supra-spinal mechanisms, which subsequently affect the contralateral muscle activity. To verify this possibility, the authors (Hortobágyi et al., 1999) applied electrical stimulation at a remote location to the muscle during voluntary training, and found that the cross education under this treatment was much less (+66%) compared to that achieved by direct EMS training (+104%). The results of the present study demonstrated that with the same intensity and repetitions EMS training can induce similar levels of cross education as voluntary training, that provides further evidence for the possible spinal mechanisms.

Another interesting aspect is that the cross-education effect showed specificity. It is well known that neuromuscular adaptations to strength training exhibit specificity, that is, the functional and structural adaptations are confined to the organs and systems that are subjected to the exercise stress, and the greatest training effect is normally found when the testing routine matches the training exercise. It has been shown that cross education is specific to the homologous muscle in the contralateral limb (Hortobágyi et al., 1999) and to the mode of training/testing (Hortobágyi et al., 1997; Weir et al., 1997). It was interesting that similar specificity was observed after voluntary training compare to EMS training as found in the present study. Only isometric strength was increased, but no significant change in isokinetic performance was observed in the contralateral limb. It seems the specific adaptation may occur at the spinal level as evidenced in the EMS group, although whether the higher nerve centres are involved and the exact mechanisms are still not clear.

A further aspect is that if muscular strength can be improved without a noticeable hypertrophy, it would indicate existence of an activation deficit prior to training, so that an increased muscle activation capacity manifests an improved strength. Whether humans can maximally activate a muscle is not the focus of this study. However,
from the literature available to us, few studies have provided data on muscle activation pre-post training in relation to cross education. As mentioned above, some authors have used EMG as an indicator of muscle activation, and reported an increased EMG in both limbs after unilateral training (Hortobágyi et al., 1997; 1999). These could be explained as either that the subjects are capable of accessing motor units that were not accessible prior to training during maximal voluntary contractions, or the firing frequencies of the recruited motor units are increased (Moritani and deVries, 1979; Häkkinen, 1989). The EMG technique has been criticized as not sensitive enough to evaluate muscle activation changes (Cafarelli and Fowler, 1993; Herbert et al, 1998). It has been suggested that twitch interpolation technique may be a better option to assess muscle activation. Most studies on cross education recruited subjects who had no previous experience in strength training. Whether humans can maximally activate muscles, and whether training can alter the capacity of muscle activation, are still debatable because contradictory evidence is reported from studies in which different testing techniques are used (Allen et al., 1995; Garfinkel and Cafarelli, 1992; Häkkinen et al., 1989; Moritani and deVries, 1979; Shield and Zhou, 1999). Subsequently whether cross education can be observed in previously well trained subjects is unknown.

Finally, it has been repeatedly suggested that unilateral training would be beneficial to those with injuries or operations on one limb, because the cross education may assist in prevention of muscle atrophy and/or deterioration of neuromuscular function of the affected limb due to immobilization (Hellebrandt, 1951; Devine et al., 1981; Kannus et al., 1992). However, to the knowledge of the authors, there have been not many well controlled clinical studies to evaluate the validity and efficacy of cross education (Gibson et al., 1988; McCartney et al., 1988; Mills and Quintana, 1985; Stromberg, 1986). Further investigations are very much needed in this field.

REFERENCES


Table 1. Subject characteristics.

<table>
<thead>
<tr>
<th>Group (n=30)</th>
<th>Age (yrs)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>22.6 ± 3.0</td>
<td>1.755 ± 0.075</td>
<td>76.8 ± 9.9</td>
</tr>
<tr>
<td>VIM (n=10)</td>
<td>22.9 ± 4.7</td>
<td>1.749 ± 0.077</td>
<td>75.6 ± 4.7</td>
</tr>
<tr>
<td>EMS (n=10)</td>
<td>22.3 ± 3.8</td>
<td>1.757 ± 0.076</td>
<td>78.9 ± 12.0</td>
</tr>
<tr>
<td>CON (n=10)</td>
<td>22.6 ± 3.6</td>
<td>1.758 ± 0.072</td>
<td>76.9 ± 13.2</td>
</tr>
</tbody>
</table>

Table 2. Variation in knee extension strength of the trained leg pre and post four weeks of training. (*P<0.05, compared to pre-training)

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<thead>
<tr>
<th></th>
<th>IM</th>
<th>EMS</th>
<th>CON</th>
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<tbody>
<tr>
<td>MVIM (N)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>1045 ±260</td>
<td>986 ±128</td>
<td>1023 ±176</td>
</tr>
<tr>
<td>Post</td>
<td>1301 ±276*</td>
<td>1195 ±153*</td>
<td>1019 ±164*</td>
</tr>
<tr>
<td>MVIK (Nm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60 °•s⁻¹</td>
<td>773 ±177</td>
<td>853 ±105</td>
<td>811 ±125</td>
</tr>
<tr>
<td>Pre</td>
<td>945 ±225*</td>
<td>1038 ±139*</td>
<td>797 ±165</td>
</tr>
<tr>
<td>Post</td>
<td>552 ±171</td>
<td>635 ±75</td>
<td>528 ±96</td>
</tr>
<tr>
<td>180 °•s⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>644 ±196*</td>
<td>734 ±77*</td>
<td>537 ±94*</td>
</tr>
<tr>
<td>Post</td>
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</table>
Figure 1. Variations (relative to pre-training) in maximal voluntary isometric (MVIM) and isokinetic (MVIK, at 60 s\(^{-1}\) and 180 s\(^{-1}\)) knee extension strength in the trained and contralateral limbs of the VIM, EMS and CON groups after four weeks of training.
Figure 2. Variations in integrated EMG (relative to pre-training, sum of vastus lateralis, rectus femoris and vastus medialis) of the trained and contralateral limbs during maximal voluntary isometric contraction after four weeks of unilateral training.