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# INCREASED CROSS-EDUCATION OF MUSCLE STRENGTH AND REDUCED CORTICOSPINAL INHIBITION FOLLOWING ECCENTRIC STRENGTH TRAINING

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**Abstract—*Aim:* Strength training of one limb results in a substantial increase in the strength of the untrained limb, however, it remains unknown what the corticospinal responses are following either eccentric or concentric strength training and how this relates to the cross-education of strength. The aim of this study was to determine if eccentric or concentric unilateral strength training differentially modulates corticospinal excitability, inhibition and the cross-transfer of strength. *Methods:* Changes in contralateral (left limb) concentric strength, eccentric strength, motor-evoked potentials, short-interval intracortical inhibition and silent period durations were analyzed in groups of young adults who exercised the right wrist flexors with either eccentric ($N = 9$) or concentric ($N = 9$) contractions for 12 sessions over 4 weeks. Control subjects ($N = 9$) did not train. *Results:* Following training, both groups exhibited a significant strength gain in the trained limb (concentric group increased concentric strength by 64% and eccentric group increased eccentric strength by 62%) and the extent of the cross-transfer of strength was 28% and 47% for the concentric and eccentric group, respectively, which was different between groups ($P = 0.031$). Transcranial magnetic stimulation revealed that eccentric training reduced intracortical inhibition (37%), silent period duration (15–27%) and increased corticospinal excitability (51%) compared to concentric training for the untrained limb ($P = 0.033$). There was no change in the control group. *Conclusion:* The results show that eccentric training uniquely modulates corticospinal excitability and inhibition of the untrained limb to a greater extent than concentric training. These findings suggest that unilateral eccentric contractions provide a greater stimulus in cross-education paradigms and should be an integral part of the rehabilitative process following unilateral injury to maximize the response.**

**Key words: corticospinal inhibition, cross-activation, cross-transfer, ipsilateral motor cortex, strength, recovery.**

## INTRODUCTION

The potential to increase muscle strength following resistance training is well-documented and overloading skeletal muscle with eccentric strength training has been shown to be superior compared to concentric strength training for increasing muscle strength (Hortobágyi et al., 1996). An interesting observation, originally described by Scripture et al. (1894), is the phenomena of cross-education, whereby strength training of a single limb was found to increase the strength of the untrained limb. Since this initial report, several studies have provided evidence to support the existence of cross-education using concentric, eccentric and isometric strength training (Cannon and Cafarelli, 1987; Brown et al., 1990; Munn et al., 2005; Lee et al., 2009). Interestingly eccentric training produces the largest changes in strength compared to concentric and isometric (Enoka, 1996; Hortobágyi et al., 1997, 1999). However, the mechanism that modulates the greater cross-education effect following eccentric training remains unknown and untested.

Given lack of muscle hypertrophy in the untrained limb (Farthing et al., 2003), along with reports of increased corticospinal excitability (Kidgell et al., 2011; Goodwill et al., 2012), reduced corticospinal inhibition (Latella et al., 2012), reduced interhemispheric inhibition (IHI) (Hortobágyi et al., 2011) and increased voluntary activation (Lee et al., 2009), cross-education is believed to occur as a result of neural adaptations. While direct evidence to substantiate such claims is increasing, the exact mechanisms and specific locus of adaptation for the cross-education of strength remain unresolved (Carroll et al., 2006; Ruddy and Carson, 2013).

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*Abbreviations:* ANOVA, analysis of variance; FCR, flexor carpi radialis; $GABA_A$, γ-aminobutyric acid; ICI, intracortical inhibition; IHI, interhemsipheric inhibition; iM1, ipsilateral primary motor cortex; ISI, inter-stimulus interval; MEP amplitude, motor-evoked potential; $M_{MAX}$, maximum compound wave; MVIC, maximal voluntary isometric contraction force; rmsEMG, root mean square electromyography; RMT/AMT, resting and active motor thresholds; sEMG, surface electromyography; SICI, short-interval intracortical inhibition; SP, silent period; TMS, transcranial magnetic stimulation..

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Two theories for the potential mechanism underpinning cross-education have been presented (Ruddy and Carson, 2013 for detailed review). Firstly, the 'bilateral-access' hypothesis involves the development of motor engrams (i.e. reorganization of movement representations within the M1) following unilateral practice, that can be accessed not only by the trained limb, but also by the untrained limb. The second 'cross-activation' hypothesis is based on the concept of unilateral contractions being driven by bilateral cortical activity in both the contralateral M1 and the ipsilateral primary motor cortex (iM1), producing lasting neuroplastic changes in both cortices. Certainly, transcranial magnetic stimulation (TMS) studies have shown that bilateral corticospinal excitability is facilitated by high-force contractions, with the scale of ipsilateral corticospinal effects being relative to the level of force gradation (Dettmers et al., 1995; Muellbacher et al., 2000; Hortobágyi et al., 2003). However, the neural adaptation underpinning cross-education following unilateral eccentric training remains unknown.

The corticospinal control of eccentric contractions are organized differently to concentric contractions (Enoka, 1996; Sekiguchi et al., 2003; Gruber et al., 2009; Howatson et al., 2011), with the duration of the silent period (SP) being reduced during eccentric contractions compared to concentric (Sekiguchi et al., 2003), intracortical inhibition (ICI) is significantly reduced, while intracortical facilitation (ICF) is increased during forceful eccentric contractions, but not during concentric contractions (Howatson et al., 2011). Cortical excitability of the iM1 is facilitated during eccentric contractions of the right wrist flexors compared to concentric contractions (Howatson et al., 2011). Taken together, compared to concentric contractions, cortical excitability is facilitated in both contralateral and iM1's during eccentric contractions and the neural networks involved in ICI and IHI appear to be influenced by the type of contraction. On this basis ICI and IHI might be the primary mechanism underpinning the cross-education effects following eccentric training compared to concentric, however, this remains to be tested.

Cross-education has gained scientific and clinical interest, primarily for the potential to minimise strength loss and enhance recovery in patients that are unable to perform training due to single limb injury or impairment (Farthing et al., 2009). Unilateral training of the free limb has been found to maintain strength, attenuate muscle atrophy and function of the untrained limb following periods of immobilization (Farthing et al., 2009; Magnus et al., 2010) and fracture (Magnus et al., 2013). Given the clinical relevance of cross-education, the purpose of the present study was to determine whether the TMS responses following eccentric or concentric cross-education training are different and whether this difference may explain the change in strength of the untrained limb. We hypothesized that unilateral eccentric training would provide a greater stimulus to the non-exercising limb than concentric training and these behavioral changes in strength would be accompanied with modulation in neurophysiological indices associated with cross-education.

## EXPERIMENTAL PROCEDURES

### Participants

Twenty-seven participants (15 males aged 25 ± 1 years and 12 females aged 27 ± 2 years) were selected on a voluntary basis. All volunteers provided written informed consent prior to participation in the study, which was approved by the Human Research Ethics Committee in accordance to the standards established by the Declaration of Helsinki. All participants were right-hand dominant as determined by the Edinburgh Handedness Inventory (Oldfield, 1971), had not participated in strength training for at least 12 months, and were free from any known history of peripheral or neurological impairment. Prior to the experiment, all participants completed the adult safety screening questionnaire to determine their suitability for TMS (Keel et al., 2001).

### Experimental approach

Fig. 1 outlines the organization of the study. Participants were required to attend a familiarization session that involved performing five eccentric, concentric and isometric contractions of the right and left wrist flexors along with exposure to single-pulse TMS. Following the familiarization session, participants were randomly (based strength) allocated to a control, eccentric training or concentric training group. All participants underwent TMS, ultrasonography, and maximum strength testing (isometric, eccentric and concentric) before and after a 4-week supervised strength-training program; however control participants only undertook pre- and post-testing. Post-testing was carried out between 36 and 48 h after the final training session.

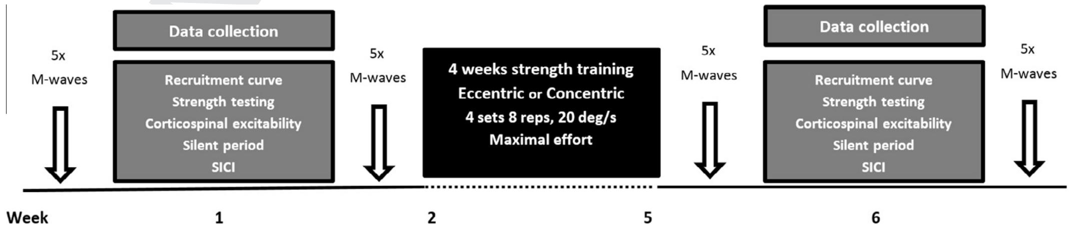

**Fig. 1.** Schematic representation of the experimental design with measures obtained pre and following 4 weeks of maximal unilateral eccentric or concentric strength training of right wrist flexors. Pre and post measures included assessment of peripheral muscle excitability (M-waves), corticospinal excitability and inhibition recruitment curves, short interval intracortical inhibition (SICI) and muscle strength.

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