LEADING ARTICLE

Sports Med 2007; 37 (1): 1-14
0112-1642/07/0001-0001/$44.95/0

Cross Education

Possible Mechanisms for the Contralateral Effects of Unilateral Resistance Training

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Abstract

Resistance training can be defined as the act of repeated voluntary muscle contractions against a resistance greater than those normally encountered in activities of daily living. Training of this kind is known to increase strength via adaptations in both the muscular and nervous systems. While the physiology of muscular adaptations following resistance training is well understood, the nature of neural adaptations is less clear. One piece of indirect evidence to indicate that neural adaptations accompany resistance training comes from the phenomenon of 'cross education', which describes the strength gain in the opposite, untrained limb following unilateral resistance training. Since its discovery in 1894, subsequent studies have confirmed the existence of cross education in contexts involving voluntary, imagined and electrically stimulated contractions. The cross-education effect is specific to the contralateral homologous muscle but not restricted to particular muscle groups, ages or genders. A recent meta-analysis determined that the magnitude of cross education is ≈7.8% of the initial strength of the untrained limb. While many features of cross education have been established, the underlying mechanisms are unknown.

This article provides an overview of cross education and presents plausible hypotheses for its mechanisms. Two hypotheses are outlined that represent the most viable explanations for cross education. These hypotheses are distinct but not necessarily mutually exclusive. They are derived from evidence that high-force, unilateral, voluntary contractions can have an acute and potent effect on the efficacy of neural elements controlling the opposite limb. It is possible that with training, long-lasting adaptations may be induced in neural circuits mediating these crossed effects. The first hypothesis suggests that unilateral resistance training may activate neural circuits that chronically modify the efficacy of motor pathways that project to the opposite untrained limb. This may subsequently lead to an increased capacity to drive the untrained muscles and thus result in increased strength. A number of spinal and cortical circuits that exhibit the potential for this type of adaptation are considered. The second hypothesis suggests that unilateral resistance training induces adaptations in motor areas that are primarily involved

in the control of movements of the trained limb. The opposite untrained limb may access these modified neural circuits during maximal voluntary contractions in ways that are analogous to motor learning. A better understanding of the mechanisms underlying cross education may potentially contribute to more effective use of resistance training protocols that exploit these cross-limb effects to improve the recovery of patients with movement disorders that predominantly affect one side of the body.

1. Background

1.1 Resistance Training

Resistance training, also commonly known as 'weight training' or 'strength training', involves brief, repeated execution of voluntary muscle contractions against a load that is greater than those normally encountered in activities of daily living. Resistance training is one of the most potent tools currently available to increase muscle strength. The load required to provide an effective training stimulus is variable and dependent on the individual's physical capability. Weighted equipment such as dumbbells or barbells may provide an ideal resistance for healthy adults or elite athletes. On the other hand, for the frail elderly or injured workers, resistance of no more than bodyweight may be sufficient. Given that muscle weakness is a common cause of poor functional recovery after injury and disease, it is not surprising that resistance training is now considered an integral part of rehabilitation and health promotion programmes in a wide range of clinical and community settings.

It is well known that resistance training can cause adaptive changes in the muscles and the nervous system and that both contribute to increases in strength.[1-3] While the physiology of many types of muscular adaptations that underlie strength gains is well understood,[4,5] our knowledge regarding the adaptations that occur in the nervous system is rudimentary. The precise location of neural adaptation induced by resistance training has seldom been investigated experimentally. As a consequence, the mechanisms of neural adaptations in response to resistance training are currently unknown. In this article, we will examine the phenomenon of 'cross education', which is perhaps one of the strongest pieces of indirect evidence that neural adaptations contribute to the strength gains that are induced by resistance training.

1.2 Cross Education

'Cross education' or the 'cross-training effect' is an inter-limb phenomenon first reported by Scripture et al.[6] in 1894. It describes the increase in voluntary force-generating capacity of the opposite untrained limb that occurs as a result of unilateral resistance training.[6] Since then, cross education has been examined extensively in the literature.[1,7-16] The main characteristics of cross education can be summarised as follows:

- Cross education can occur in both upper and lower limb muscles from small intrinsic muscles of the hand,[13,17,18] to large antigravity, ambulatory leg muscles such as quadriceps and soleus muscles.[15,19-22] That is, cross education is not specifically observed in one muscle group nor does it appear dependent on relatively direct or indirect corticospinal projections.
- Cross education is not gender or age specific.[16]
- Cross education can occur with training accomplished by voluntary effort, electrical stimulation of muscles[22,23] or mental practice of unilateral contractions.[18,24]

- Cross education can occur with various training modalities (isometric or dynamic) and is governed by the principles of training specificity. In other words, the strength gain is confined to the homologous muscle of the opposite untrained limb, and the increase in strength is the greatest during the same movement task performed by the trained limb.[3,14,16,23]
- Cross education occurs in the absence of substantial muscle activity in the untrained muscles during unilateral exercise[14,21,24,25] and when there is also no muscle hypertrophy in the untrained limb.[20,26]

1.2.1 Why Study Cross Education?

Cross education has potential clinical relevance in exercise rehabilitation for patients who have conditions that prevent them from exercising one limb. These may include acute injuries of the extremities, post-surgical limb immobilisation and certain neurological disorders with predominantly unilateral muscle weakness. If exercising the healthy limb can strengthen the injured or diseased limb, this will potentially minimise complications caused by disuse and maximise the effectiveness of rehabilitation after the injury has healed. Although it is reasonable to raise the possibility that cross education may have some potential clinical application, we are hesitant to make recommendation regarding its specific role in exercise rehabilitation because the underlying mechanism for the effect is unknown. In order to maximise the potential therapeutic benefits of cross education, it is vital that we understand the mechanisms underlying this effect.

1.2.2 Scope and Purpose of the Review

Despite its clinical and scientific relevance, the underlying physiological mechanisms mediating cross education are poorly understood. In order to maximise the potential therapeutic benefits of cross education in clinical rehabilitation, it is important to have a better understanding of the underlying mechanisms. This article examines evidence that implicates a role for neural adaptation in cross education. Furthermore, we outline two viable hypotheses that could explain this inter-limb phenomenon. We describe a number of neurophysiological mechanisms that could contribute to each hypothesis. It is not the purpose of this article to speculate on clinical applications of cross education or to implicate the role of specific cellular mechanisms such as long-term potentiation and long-term depression as the bases of plastic changes mediating strength gain.

1.2.3 Is Cross Education Real?

Despite numerous reports documenting cross education, the validity of many of these studies has recently been questioned for methodological reasons.[27] The first criticism arises from inadequate use of a control group. For example, many studies that have demonstrated cross education employed the contralateral untrained limb of trained subjects as the control group. Results from these studies invite the possibility that the strength gain in the contralateral untrained limb may be due to familiarisation of the testing protocol and training environment.[27-29] Secondly, the criteria for valid measurement of maximal voluntary force identified by Gandevia[30] were rarely fulfilled. These included standardised verbal encouragement, practice, feedback and elimination of perceived submaximal efforts by the subjects.[27,30] Non-fulfillment of these criteria will affect the magnitude of cross education observed.

To critically examine the existence and magnitude of cross education, Munn et al.[27] conducted a meta-analysis of the entire available literature. Only randomised, controlled studies with clearly designated control (subjects who did not train) and training groups that used a training intensity of >50% for >2 weeks were included in the analysis. It was concluded that, on average, unilateral resistance training increases strength of the contralateral untrained limb by 7.8% (of the initial strength of the

untrained side). This corresponds to 35% of strength gain on the ipsilateral trained side.[27] The effects of training type (isometric or dynamic) on cross education could not be confidently identified. The magnitude of cross education, as determined by the meta-analysis corresponds well with the results of a carefully executed, randomised study with a large sample size involving the elbow flexors muscle.[31] Thus, cross education is a genuine physiological phenomenon resulting from unilateral resistance training. However, there is no direct evidence regarding the underlying mechanisms mediating this effect.

2. Mechanisms of Cross Education?

2.1 Adaptations in Muscles

Resistance training is known to induce adaptive changes in the exercised muscles such as hypertrophy, increases in muscle enzyme activities, changes in fibre type and orientation of muscle fibres (for reviews see Abernethy et al.[4] and Baldwin and Haddad[5]). These muscular hypertrophy-related factors are likely to significantly influence the torque-producing capacity.[4]

It is conceivable that muscular adaptations that increase the force-generating capacity of the muscles on the contralateral, untrained side are mechanism for cross education. However, there are several lines of evidence that render this an unlikely possibility:

- Magnetic resonance imaging studies did not detect significant changes in cross-sectional surface area of the untrained leg exhibiting cross education,[20,26] nor was measurable change in girth found in the contralateral untrained limb following unilateral resistance training.[9]
- Biopsy studies revealed no change in muscle enzyme activities or fibre types in the unexercised muscle.[11,20]
- Electromyographic recordings have demonstrated that the untrained limb remains virtually quiescent during resistance training of its contralateral counterpart.[14,21,24,25] Therefore, the untrained limb is unlikely to receive sufficient training stimulus to induce muscular adaptation.

Increases in strength in the absence of direct training and without concomitant adaptive changes in muscle morphology strongly suggest alterations in neural control. However, other non-muscular adaptations may also contribute. Yasuda and Miyamura[12] reported vascular changes and strength gains in the contralateral untrained forearm after 6 weeks of unilateral gripping training (to fatigue). Maximal grip strength, muscle endurance (number of grip contractions before exhaustion) and peak blood flow increased not only in the trained limb, but also in the untrained limb.[12] The authors suggested that the increase in peak blood flow in the untrained forearm may be secondary to the release of neurogenic or metabolic vasodilators in response to exercise.[32,33] It was argued that the increase in peripheral blood flow in the contralateral untrained limb may be partly responsible for the cross transfer of strength and endurance. However, an increase in peripheral vasculature is unlikely to directly influence maximal voluntary contraction (MVC) force since ischaemia is known to occur in the contracting muscles during MVCs. In fact, fatiguing exercise is more likely to have an effect on the nervous system. It has been shown that during and after fatiguing exercise, cortical output and voluntary activation of the exercising muscles are progressively reduced.[30,34,35] This 'central fatigue'[30] reduces force output because the CNS is unable to drive the motoneurons optimally.[30] With repeated bouts of fatiguing exercise, it is possible that adaptations could occur in the CNS that serves to reduce the extent of central fatigue, and that these adaptations also have the capacity to influence strength. Other lines of evidence to suggest cross education is the result of

neural adaptation are the specificity of this effect, i.e. strength gain is only observed in the contralateral homologous muscle. If the mechanism mediating cross education is systemic in origin, then strength gains should be observed in other muscle groups as well. In summary, in the absence of detectable morphological changes in the contralateral untrained muscle, modifications in neural control are likely to explain the phenomenon of cross education following unilateral resistance training.

2.2 Hypotheses: Sites of Neural Adaptation Leading to Cross Education

When performed unilaterally, high-force voluntary contractions have been shown to have an acute and potent affect on the efficacy of neural elements controlling the exercised limb as well as the opposite, resting limb.[36-45] It is conceivable, that with repeated contractions over time (i.e. resistance training), more permanent, functional changes may occur in these neural elements and subsequently change the way the contralateral limb is controlled. For example, Muellbacher et al.[46,47] have shown that practice of simple repeated voluntary contractions can induce short-term plastic changes in the primary motor cortex (M1). We suspect that unilateral resistance training may chronically affect synaptic connectivity within specific neural circuits that contribute to the ability to generate force. Although it is possible that cellular mechanisms such as long-term potentiation and long-term depression may also be involved in cross education, it is beyond the scope of this review to discuss them in detail. As will be discussed in the following sections, the site of neural adaptations that mediate cross education could reside in neural elements located ipsilateral and/or contralateral to the trained limb. However, these hypotheses are not mutually exclusive, that is, both can occur simultaneously.

The first hypothesis presented is that resistance training causes task-specific changes in the organisation of motor pathways projecting to the contralateral homologous muscle. More specifically, re-organisations in the contralateral 'untrained' motor pathways could lead to more efficient neural drive to the untrained muscles, which would result in an increase in strength. This hypothesis is based on evidence that unilateral voluntary contractions can acutely alter the excitability of spinal[36-39] and cortical[36,40-45] motor pathways that project to the contralateral side. It is possible that with repeated voluntary contractions, long-term functional re-organisation in these contralateral pathways may occur.

The second hypothesis is that resistance training induces adaptations in motor areas that are predominately responsible for the control and execution of movements of the trained limb. The opposite hemisphere may access these modified circuits during voluntary contraction of the opposite untrained limb to enhance force output. This paradigm has been examined within the context of 'motor learning', where it has been shown that certain types of unilateral skill training can improve performance of the same skill by the opposite, untrained limb.[48-50] At first glance, the applicability of concepts relevant for motor learning to resistance training may seem questionable. However, it has been suggested that resistance training may be regarded as a form of motor learning,[51] such that individuals learn to replicate the specific patterns of muscle recruitment that produce optimal results in a given task (e.g. produce maximal force in particular movement context).[51,52] Strength may be increased by learning to inhibit the antagonists[19] or improve coordination of synergists.[52,53] It is therefore possible that resistance training may induce functional changes in the organisation of the nervous system in ways that are analogous to motor learning.[51]

2.3 Hypothesis 1: Modification of Contralateral Motor Pathways

2.3.1 Modifications in Cortical Motor Pathways

Unilateral voluntary contractions can bring about complex changes in the state of cortical motor pathways controlling the contralateral homologous muscle. Motor-evoked potentials (MEPs) elicited by transcranial magnetic stimulation (TMS) are facilitated by moderate to high force voluntary contractions (>40% MVC) of the contralateral homologous muscle.[36,41-44,54] In contrast, MEP amplitudes tend to be suppressed during small phasic (but not tonic) contralateral muscle contractions (1–2% MVC).[44] High-force unilateral contractions are also known to affect the efficacy of transcallosal inhibition between the two hemispheres. Transcallosal pathways can be studied in conscious human subjects by monitoring the effects of a conditioning stimulus delivered over the motor cortex of one hemisphere on the size of an MEP induced by a second test stimulus over the opposite hemisphere.[55] Studies using this 'paired-pulse' technique have shown that a conditioning cortical stimulation can induce both an excitatory and inhibitory effect on the MEP elicited by a second test stimulation over the motor cortex of the opposite hemisphere.[40,55-59] When small conditioning and test stimuli (just above threshold for active muscle) are applied over a focal area of the cortex at an inter-stimulus interval of 4–5ms, a small, early facilitation of MEP can occur.[57,58] This facilitation occurs in strictly homotopic areas of the contralateral cortex[40,58] and tends to be masked by late inhibitory volleys when large stimuli are applied.[58] Similar excitatory connections between homotopic areas of the motor cortices have been demonstrated in animals.[60,61]

Motor responses evoked by the test TMS are suppressed if they are preceded by a conditioning stimulus applied 6–50ms before[55-57,62] with peak inhibition occurring at inter-stimulus intervals between 7 and 12ms.[55,62] This is compatible with the interhemispheric conduction time through the corpus callosum.[57,63] Interhemispheric inhibition is evident when the test muscle is both active (contracted at low intensity, ≈5% MVC) and relaxed[55] and the degree of inhibition is positively correlated with intensity of the conditioning stimulus.[57,62]

Muellbacher et al.[41] have shown that the marked interhemispheric inhibition produced by an earlier conditioning TMS on the test MEP is almost completely abolished (i.e. becomes facilitated) when the contralateral homologous muscle is contracting at high force (>50% MVC). Using imaging techniques, Dettmers et al.[45] showed that activity of the ipsilateral cortex (measured by regional cerebral blood flow) increases with the level of force required performing a unilateral key-tapping task. These results suggest that high-force contractions (such as those used in conventional resistance training programmes) may excite the ipsilateral cortex. We speculate that repeated high-force contractions might induce more permanent changes in these motor pathways and thereby alter the neural control system for the contralateral muscles.

2.3.2 Modifications in Spinal Pathways

High-force unilateral voluntary contractions are also known to affect the excitability of spinal motor pathways that project to the contralateral side. For example, Hortobagyi et al.[36] showed that the H-reflex in human wrist flexors (flexor carpi radialis [FCR]) is depressed by strong unilateral flexion and extension of the contralateral wrist, but unaffected by small contractions.[36,38] This depression of the FCR H-reflex is long-lasting and can persist for up to 30 seconds after the end of the contraction.[36] Although the mechanisms mediating this long-lasting depression could not be identified with the methods used, the authors speculated that presynaptic inhibition of 1a afferent motoneuron synapse may be partially responsible for this contralateral effect.[36] In the only study to date that has assessed

long-term changes in spinal circuits projecting to a limb in which strength has increased via cross education, Lagerquist et al.[64] found no change in H-reflex amplitude in the untrained soleus after 5 weeks of unilateral plantar-flexion resistance training, even though H-reflex amplitude increased significantly in the trained leg. This suggests that adaptations in the stretch reflex circuit do not underlie cross education, but does not preclude the involvement of other spinal circuits as mechanisms for the effect.

2.3.3 Influence of Contralateral Muscular Afferents on Ipsilateral Reciprocal Inhibition

Activation of Ia afferents via voluntary contractions or muscle stretch can induce an inhibitory effect on the motoneuron supplying its antagonist through a process known as reciprocal inhibition. Reciprocal inhibition is mediated via specific interneurons (Ia inhibitory interneurons) located in the ventral horn[65,66] that receive inputs from both segmental and supraspinal centres,[67] and act as an integrative centre in the spinal control of voluntary movements. These interneurons are facilitated by Ia afferents arising from the agonist muscle and exert a short-lasting inhibition on the antagonist motoneuron and the Ia inhibitory interneuron fed by the antagonist motoneuron. On the other hand, they are inhibited by Ia inhibitory interneurons that originate from the antagonist motoneuron[65] and by Renshaw cells that stem from the agonist motoneuron[68,69] (see also figure 1). In a pair of mutually antagonistic muscles, reciprocal inhibition is thought to play an important role in the control of fine movements by reducing antagonist activation.[70]

Intracellular recording from motoneurons in cats has demonstrated that the ipsilateral Ia inhibitory interneuron receives facilitatory inputs from the contralateral homologous group I muscle afferents.[71] Delwaide and Pepin[72] and Sabatino et al.[39,73] also showed in human wrist muscles that the gain of the ipsilateral reciprocal inhibitory pathway is modulated by activation of the corresponding contralateral Ia afferents. Reciprocal inhibition of the motoneurons on the ipsilateral side is enhanced by sub-threshold stimulation of the nerve projecting to the contralateral antagonist but depressed by sub-threshold stimulation of the contralateral agonist nerve.[72,73] However, stimulation of purely cutaneous nerve branches on the contralateral side does not have an affect on reciprocal inhibition on the ipsilateral side. When the contralateral stimulus intensity is increased, the degree of ipsilateral reciprocal inhibition becomes less pronounced, i.e. reciprocal inhibition is suppressed by high-intensity stimulation of the contralateral antagonist nerve, but enhanced by high-intensity stimulation of the contralateral agonist nerve.[72]

At threshold stimulus intensity, activation of the contralateral large diameter afferents is likely to contribute to the crossed spinal effect.[72,73] Since the amplitude of the ipsilateral H-reflexes is not significantly altered by stimulation of the contralateral nerves, the authors suggested that the contralateral afferents exert their effect indirectly via Ia inhibitory interneurons.[72,73] At higher stimulus intensity, structures other than Ia afferents could also be activated in the contralateral arm and therefore could contribute to the crossed effect. These include Ib and group II afferents, as well as direct activation of motoneurons and sensory receptors such as skin and joint proprioceptors. This is supported by the observations that both passive (assisted) and active (small contractions) movements of the contralateral wrist enhance ipsilateral reciprocal inhibition.[38,39] The effects of large voluntary contractions (similar to those used in resistance training) on the efficacy of the contralateral Ia inhibitory pathways await further investigation.

Direct action of Renshaw cells on the opposite homologous motoneurons may also contribute to the contralateral effects observed with supra-threshold stimulation. There is some evidence from morpho-

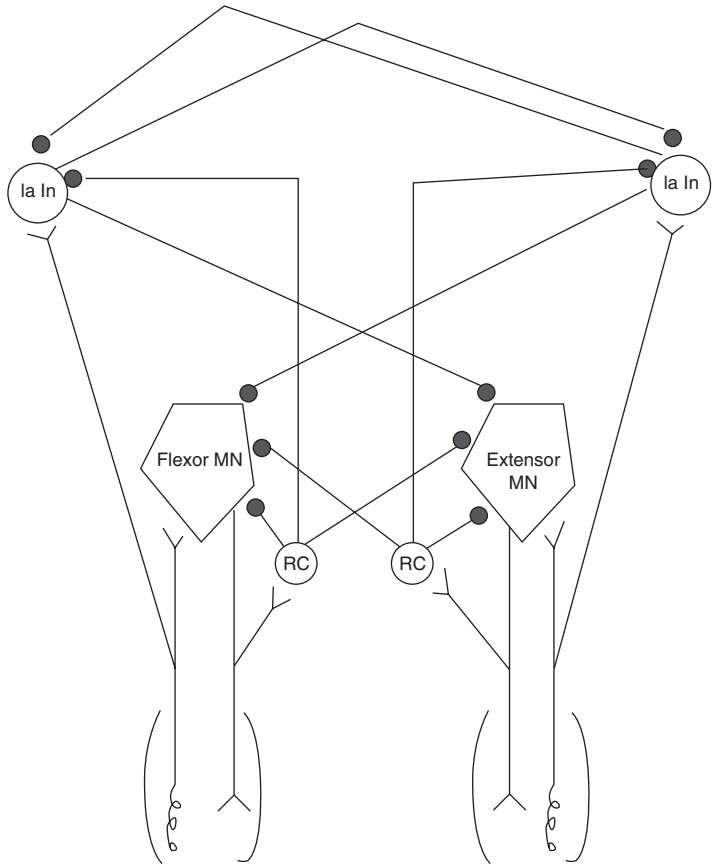

Fig. 1. Schematic representation of the connections between the wrist flexor and extensor muscles in humans. Small filled circles represent inhibition. **Ia In** = Ia inhibitory interneurons; **MN** = motoneuron; **RC** = Renshaw cells.

logical studies in the cat spinal cord to suggest that Renshaw cells project contralaterally;[74] however, bilateral projection of Renshaw cells has not yet been established in humans.

In summary, there exists preliminary evidence to suggest that artificial activation of the contralateral Ia afferents and movements of the contralateral limb can acutely alter ipsilateral spinal circuits (e.g. reciprocal inhibition). Adaptations in these spinal circuits could potentially affect the ability to generate force. For example, in a pair of strictly antagonistic muscles, the agonist may be able to exert more force if it can inhibit its antagonist more effectively during contraction. Inhibition of Renshaw cells could also increase force-generating capacity because Renshaw cells are known to inhibit motoneurons (via the recurrent pathway) and Ia inhibitory interneurons projecting to the antagonistic motoneurons.[68,69] Therefore, attenuation of Renshaw cells may indirectly facilitate more efficient reciprocal Ia inhibition.[75] However, there currently exists no experimental evidence on the adaptability of Renshaw cells or other spinal interneurons in response to resistance training. Much remains to be established regarding the mechanisms mediating bilateral interactions within the spinal circuits and their functional significance. It is tempting to speculate that such bilateral neural interactions could undergo long-

term changes with training and thereby play a role in cross education.

2.4 Hypothesis 2: Cross Education and Motor Learning

As an alternative hypothesis, neural adaptations that lead to cross education may reside in supraspinal areas that are predominantly involved in the control of movements of the trained limb (i.e. adaptations occur in the cerebral hemisphere contralateral to the trained limb). These modified neural circuits may be accessed during voluntary contractions of the opposite, untrained limb in such a way as to optimise the descending command signals from the untrained hemisphere, and thereby facilitate force output during maximal voluntary contractions.

A recent study by Strens et al.[76] provides preliminary evidence that has direct relevance to this hypothesis. These authors showed that the ipsilateral M1 is capable of compensating for a reduction in excitability of the opposite M1 in a functional manner. The excitability of M1 can be depressed by low frequency repetitive TMS (rTMS) applied at above resting motor threshold.[77] This depression of cortical excitability often outlasts the duration of the stimulus.[77,78] Using this technique, Strens et al.[76] showed that when the excitability of M1 in one hemisphere is compromised by rTMS, the opposite M1 could compensate by maintaining force output during a unilateral repetitive finger-tapping task. With bilateral stimulation, the facilitatory function of the ipsilateral M1 was impaired and there was a significant decrease in the ability to maintain force output. The ability of the M1 on one side of the brain to facilitate the opposite M1 during unilateral voluntary movement in this context raises the possibility that the benefits of unilateral resistance training may be accessible to the opposite, untrained hemisphere during maximal voluntary contractions. The site of this of neural interaction may reside in higher cortical centres upstream of the primary motor cortex.[76]

Within the context of 'motor learning', it is well known that practicing a given motor task with one limb can improve the performance of the same task when executed by the opposite homologous limb. This bilateral or 'interlateral' transfer of motor learning[48,79] has been demonstrated in various skill tasks such as drawing and writing,[80,81] pursuit tracking,[82] mirror tracing,[79] ball catching,[83] pointing tasks under distorted vision,[84,85] tactile acuity[86] and skillful operation of an upper-limb prosthetic stimulator.[50] Bilateral transfer of learning may be complete, partial or asymmetrical depending on the nature of the task. Asymmetrical transfer describes unidirectional transfer of learning either from the dominant to non-dominant limb or *vice versa*.[80] In general, relatively simple unilateral tasks such as grasping or lifting small objects usually have a higher index of transfer.[87] Simple anticipatory timing tasks (e.g. button pressing) have been shown to transfer almost completely and symmetrically.[49] From these results, it can be inferred that the neural circuits controlling motor behaviour of anticipatory timing can be used by brain centres controlling either limb independent of the effector system used in the skill acquisition.

Partial or incomplete transfer of learning may occur with more complex or novel tasks such as reaching with force perturbation[88] or catching a weighted ball.[83] Furthermore, in most instances, interlateral transfer of learning is usually asymmetrical. Taken together, these studies suggest that bilateral transfer of learning is to some extent dependent on the effector system used and the nature of the motor task.

We have previously argued that resistance training may be regarded as a form of motor learning as the ability to maximally activate all motor units of the contracting muscle in a particular movement context may be considered a novel skill.[51] If we consider maximal voluntary force as a transferable component of motor behaviour, cross education

therefore represents an incomplete interlateral transfer of strength as only approximately 35% of the strength gain in the trained limb is transferred to the opposite untrained limb.[27] A recent study on cross education has documented asymmetry of transfer. Farthing et al.[89] found a positive cross transfer of strength (39.2%) only from the dominant to non-dominant hand in right-handed subjects. Those who trained with their non-dominant (left) hand did not show a significant cross-education effect when compared with the untrained (control) group. The training task chosen in this study was a relatively unfamiliar movement of maximal isometric gripping and ulnar deviation of the wrist.

The characteristics of interlateral transfer of maximal strength (cross education) bear resemblance to that of a complex or novel motor task. In other words, the nature of interlateral transfer of maximal strength and certain novel motor tasks are both incomplete and asymmetrical. It is possible that the mechanisms mediating cross education of strength would be similar to those dictating cross education of certain motor skills.[79,89] That is, with training, the brain may create an internal representation of the appropriate motor output necessary to produce maximal force involving the specific effector system. Once consolidated, this information may be stored in neural circuits that can be accessed by both hemispheres to modify motor output of an alternative effector system (such as the opposite limb) to increase force.

2.4.1 Potential Sites and Mechanisms of Neural Adaptation

Many regions of the brain are known to participate in motor learning. These include the primary motor cortex,[47] prefrontal cortex,[90-93] the pre-motor, posterior parietal and cerebellar cortices,[93,94] as well as the basal ganglia.[95] Neural adaptations mediating cross education may occur in any of these cortical regions of the trained hemisphere, for which the benefits of training are accessible to the opposite hemisphere during maximal voluntary contractions to increase force produced by the untrained limb. Brain regions with strong bilateral cortical projections such as M1 and supplementary motor areas (SMAs) are likely candidates for this type of neural adaptation. Resistance training may also modify callosal synaptic connections between homologous regions of the brain, thereby allowing the trained hemisphere to facilitate the opposite hemisphere during maximal voluntary contractions.

The corpus callosum provides an anatomical connection between the two hemispheres,[60,96] which is thought to play an important role in interhemispheric transfer of sensory and cognitive information as well as coordinating motor planning and control.[97,98] Transcallosal pathways may provide a direct route by which information regarding motor learning from the trained hemisphere can be utilised by the opposite hemisphere during unilateral motor tasks. Furthermore, since high-force unilateral voluntary contractions can acutely decrease transcallosal inhibition between M1 (see section 2.3.1), it is possible that repeated high-force contractions over time (i.e. resistance training) could result in lasting modifications to the efficacy of transcallosal inhibitory pathways in such a way as to enable the untrained hemisphere to access the contralateral circuits during unilateral voluntary contractions to maximise force output. Alternatively, cortical modifications due to learning in the trained hemisphere may be transmitted to the untrained side more efficiently via the corpus callosum if there is less active transcallosal inhibition.

Interhemispheric connections between cortical centres other than M1 could also facilitate one cerebral hemisphere to access contralateral neural circuit. For example, anatomical studies have shown that interhemispheric connections between the SMAs are comparatively denser than the fibres connecting the two M1.[99,100] It is therefore likely that the SMA is an important cortical locus of neural

interactions between limbs.[101] Other evidence to suggest that the sites of neural adaptation in cross education may reside in higher cortical centres comes from two mental training studies showing that mental rehearsal of unilateral, maximal contractions can lead to cross education.[18,24] However, some authors did not observe cross education using similar mental rehearsal training protocols.[28] Although the design of these studies did not allow for identification of the precise mediating mechanisms, it is possible that adaptations in the higher cortical centres such as M1 and SMA, and indeed other cortical regions known to participate in motor learning and planning (e.g. premotor cortex, prefrontal cortex, basal ganglia and the cerebellum) may contribute to cross education.

3. Conclusions

Despite numerous studies documenting cross education, the sites of adaptation underlying the effect have seldom been investigated experimentally. Consequently, our understanding about the mechanisms mediating this bilateral effect remains speculative. A better understanding of how the benefits of unilateral resistance training can be transferred to the untrained side may ultimately contribute to more effective utilisation of resistance training protocols for a broad range of musculoskeletal and neuromuscular disorders.

In the current article, we have outlined two distinct (but not mutually exclusive) hypotheses to explain cross education based on the current literature and we have presented a number of viable mechanisms by which these adaptations could be mediated. Many of these potential mechanisms can be tested using techniques that are currently available. Research of this kind will not only advance our knowledge in human motor control, it will also generate practical information with direct relevance for exercise rehabilitation.

Acknowledgements

This work is funded by the Australian Research Council. The authors thank Professors Simon Gandevia and Richard Carson for valuable comments on the review. The authors have no conflicts of interest that are directly relevant to the content of this review.

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