Cross-Education and contralateral irradiation

by
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Cross-Education is characterized as the improvement in strength of the contralateral homologous muscle after unilateral practice. One potential mechanism to explain this phenomenon is that a unilateral maximal voluntary contraction (MVC) induces an involuntary irradiation of the contralateral homologous muscles. The purpose of the present two studies was to determine if contralateral irradiation is a potential mechanism to explain effects of cross-education. Contralateral irradiation was measured as the EMG co-activation in the homologous unpracticed arm. In Study 1 a unilateral dynamic extension/flexion arm movement was used to activate the triceps. The results indicated that unilateral practice induced a contralateral co-activation on the unpracticed arm. The same result can be reported for an isometric contraction (Study 2). The two studies provided empirical evidence that unilateral MVC did induce an involuntary muscle co-activity on the contralateral homologous muscles with increasing practice time in one testing session.

Key Words: *spill-over, strength, EMG, performance, involuntary irradiation*

Introduction

Athletes and coaches are interested in rehabilitation programs to prevent strength loss after unilateral injuries and to accelerate the process of recovery. One interesting question is if strength exercises with the healthy contralateral limb induce positive effects on the injured limb. The manner in which practice did not only increase the strength of the muscle of the practiced limb but also of the contralateral homologous muscle of the unpracticed side has garnered a great deal of experimental and theoretical attention for more than 100 years (e.g. Carroll et al., 2006; Davies, 1942; Lee & Carroll, 2007; Mühlbauer et al., 2007; Munn et al., 2004; Panzer et all., 2010; Scripture et al., 1894; Zhou, 2003). This type of contralateral transfer is defined as cross-education or spill-over.

Research on cross-education and spill-over has provided strong evidence for the contralateral transfer effect (e.g. Darcus & Salter, 1955; Hellebrandt, 1951, 1955; Rube & Secher, 1991). At an average, the increase of strength at the

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Authors submitted their contribution of the article to the editorial board.
Accepted for printing in Journal of Human Kinetics vol. 27/2011 on March 2011.

contralateral unpracticed homologous muscle group is about 7% to 8% after 4 to 12 weeks of unilateral training (Carroll et al., 2006). In addition, effects of cross-education have been observed in different muscles (large muscle groups, small muscle groups), in different sets of training (static, dynamic), at different tasks (complex vs. simple, upper vs. lower extremities) and in the dominant or non-dominant limb. These conclusions were drawn using an inter-manual transfer paradigm. However, while the research on cross-education received a good bit of experimental attention, there is still a debate on the underlying mechanism of cross-education (Farthing, 2009).

A number of theoretical perspectives have argued that unilateral strength practice resulted in a process analogous to motor learning (Farthing et al., 2007). Practice induced facilitation of stored efferent muscle activation patterns and neural pathway, as well as mediates the unpracticed homologous muscle (Lee & Carroll, 2007). Zijdewind and Kernell (2001) proposed an alternative idea based on a bilateral interaction during the maximal contraction between muscle groups to explain effects of cross-education (Mayston et al., 1994). The basic assumption is that maximal voluntary contractions (MVC) in one muscle group induced involuntary co-activation in the contralateral homologous muscle.

The involuntary co-activation is not related to a motor learning processes. The contralateral irradiation of muscle activity is also observed by Davis (1942). He reports that an increasing amount of intermittent contractions in one muscle group induced a higher muscle activity in the contralateral muscles (see also Dimitrejevic et al., 1992).

Using sub maximal and MVC of the index finger in a within-subject design with five periodic measurements scheduled over one week, Zijdewind and Kernell (2001) provided some empirical evidence that unilateral force generation induced an increase in co-activation on the contralateral finger. This finding supports the idea of the bilateral interaction hypothesis where unilateral MVCs irradiate to the contralateral side.

The within subject design might have the weakness (a) that subjects get familiarized with the testing procedure and the apparatus and (b) learning effects occur. Results may be potentially confounded by the repeating testing procedure (Carroll et al., 2006). The purposes of the present two studies were to determine if involuntary co-activation in the contralateral homologous muscle can be observed during unilateral MVCs in one testing session or without additional strength training. If the bilateral interactions and associated processing mechanisms of irradiation are involuntary during MVC, one would expect that during unilateral voluntary contraction the contralateral homologous muscle is also active. However, it is not clear that irradiation during unilateral practice co-activates the homologous contralateal muscle alone. Although, it appears that subjects activate motor centers and learning processes during unilateral strength practice and at least minimal exposure to physical practice is required. If this is the case, the proposed learning hypothesis predominantly explains the phenomenon of cross-education. A finding of this type may help explain why in some experiments unilateral strength practice results in an increase of strength in the unpracticed contralateral muscle, while in other experiments contralateral transfer is less effective.

In Study 1, we applied a dynamic arm movement task with intermittent contractions, while in Study 2, a static isometric task was used. The study of cross-education is important for practical and theoretical reasons. For practical reasons, it is importantly related to retraining and training protocols designed to increment re-learning when one limb is constrained because of injury and disease with movement disorders (e.g. Schabowsky et al., 2007). From a theoretical standpoint, it is important because the bilateral interaction hypothesis provides a potential mechanism to explain the phenomenon of cross-education. Note, the primary goal of Study 1 was to determine the pattern of bilateral interaction in the triceps brachii in using a dynamic extension/flexion task in one testing session. Previous research with this kind of training set (Davies, 1942) demonstrated that involuntary contralateral muscle activity occurred with an increase of the amount of voluntary unilateral contraction during rehearsed training sessions. The difference between the current and previous studies is that we apply one testing session while the others used rehearsed training sessions. The main objective of Study 2 was to determine the impact of a static training set on the bilateral interaction scheme. It is entirely possible that different training sets (dynamic vs. static) induce a different pattern of irradiation on the contralateral unloaded muscle.

Methods

Subjects

Subjects involved in Study 1 were undergraduate students (N=10) of Sportsciences (age: range: 23-29 years; 3 female, 5 male). In Study 2, subjects were also undergraduate students (N=10) of Sportsciences (age: range: 22-27 years; 2 female, 8 male). Note that they did not participate in study 1. All subjects participated in the studies for course credit. The subjects had no prior experience with the experimental tasks and were not aware of the specific purpose of the study. All of them had no physical activity during the test day. Each subject completed a consent form prior to completing the study. The study was carried out in agreement with legal requirements and international norms, and in line with the standards defined by a local ethics committee. All subjects were right-hand dominant as determined by the Edinburgh Handedness Inventory (Oldfield, 1971) prior to the study.

Methods and protocols used in Study 1

Task, Apparatus and Procedure

After entering the laboratory, subjects were asked about their experience with load on dumb-bells for exercising the triceps. Subjects were presented a written instruction. Then subjects were positioned supinely on the treatment table and the apparatus was adjusted for unilateral practice. The elbow of the practiced arm was fixed. They were instructed to move the dumb-bell with their right and left arm either (order counter balanced). Between testing right or left arm in a second test, a rest interval of 30 minutes was introduced to the subjects to avoid fatigue. The task was to move the dumb-bell from a 90° position between the upper and lower arm in a 180° position as quickly as possible and to return slowly to the starting position (dynamical extension/flexion task). Subjects were instructed to extend and flex until subjective exhaustion. To control the 90° and the 180° position, a cord was strained at both positions. Before the study, subjects were asked about the weight of the dumb-bell they thought they could handle to induce a high load of effort. This load was fixed at the dumb-bell. The unpracticed arm lay on a table beside in a relaxed, horizontal position.

Bipolar surface electromyography (SEMG) (5 – 700 Hz; Biovision, Wehrheim, Germany) was taken from two arm muscles, simultaneously from both sides: triceps brachii (long head) and triceps brachii (lateral head) muscles. Electrodes were fixed before testing. Electrode positions were chosen according international established recommendations (Hermens et al.,, 1999; Ng, Kippers & Richardson, 1998). For starting posture of the biceps brachii, subjects were asked to sit on a chair with their elbow flexed at 90° and the dorsal side of the forearm in a horizontal downwards position (palm of the hand pointing upwards).The electrodes were placed on the line between the medial acromion and the fossa cubit at 1/3 from the fossa cubit in the direction of that line. Additionally of the starting posture triceps brachii (long head), subjects were asked to sit with the shoulder at approximately 90° abduction with the elbow 90° flexed and the palm of the hand pointing downwards. The electrodes were placed at 50% on the line between the posterior crista of the acromion and the olecranon at 2 finger widths medial to that line. For the triceps brachii (lateral head), the electrodes were placed at 50% on the line between the posterior crista of the acromion and the olecranon at 2 finger widths lateral to that line. The reference electrode was attached to the collar bone. Disposable Ag–AgCl electrodes (H93SG, Arbo®, Germany) with a circular uptake area of 1 cm diameter and an interelectrode distance of 2.5 cm were used. Data were stored on a computer for offline analysis (AD-conversion at 1000/s, Superlogics, PCM12 Card: 12 Bit). Before starting the testing session, electrodes were fixed and a baseline SEMG was recorded from left and right triceps brachii. Muscular activity was recorded during the whole testing procedure from the practiced and unpracticed arm. Co-activation is defined as the difference between the baseline and the muscular activity of the homologous muscle at the unpracticed limb during unilateral contractions of the contralateral limb.

EMG-Data Analysis

The analysis of the SEMG data was performed using Matlab (Mathworks, Natick, MA).Raw SEMG was centered and band-pass filtered (2^{nd} order Butterworth filter,20-500 Hz). To create the linear envelope of SEMG signal the moving average was calculated subsequently using a window of 100 ms (Basmajian & de Luca, 1985).

Methods and protocols used in Study 2

Task, Apparatus and Procedure

The task, apparatus and procedure of Study 2 were slightly changed to these applied in Study 1 in a few respects. Upon entering the laboratory, subjects were instructed to sit in front of the table on a height adjustable chair, so that their right or left back of the hand can be positioned on a force plate (60x40cm) fixed on the table. The area on the force plate where subjects had to fix the hand was marked. The angle of the elbow was approximately at 140°. Subjects were instructed to induce a MVC for the triceps by pressing the back hand as hard as possible against the force plate for 30 s. Data collection for the force was controlled by using a Kistler force plate (Type 9286AA, sample frequency 1000Hz). The unpracticed arm lay on an adjacent table in a relaxed horizontal position. MVC is defined as the maximum value of the produced force for the 30 s. The EMG data collection was identical to that in Study 1. For the analysis of the increase of co-activation, the mean of 1000 values of the difference between the baseline and unpracticed limb were calculated and defined as a block.

Statistics for Study 1 and Study 2

For both studies, the analyses of variance were computed using the Greenhouse-Geisser corrections when the epsilon value was smaller than 1. All significant effects are reported at $p < .05$, with additional effect size computed by η^2_p. A posteriori comparisons of the means were computed using t-tests'. Post hoc comparisons of the means were computed using the Scheffé technique for between subject comparison and Duncan's new multiple range technique for within comparisons.

Results

Results of Study 1

Examples of rectified EMG variables from one subject are provided in Figures 1A to 1D. Two subjects were excluded from the study because EMG data recording failed. As calculated, the mean frequency of extension flexion movements between the right (11.91 +/- 5.05) and left (10.92 +/- 6.1) practiced arm did not differ. To analyze the EMG data, a two-way repeated measure 2 (Arm: right, left) by 3 (Test: practiced, unpracticed, baseline) Analysis of Variance (ANOVA) with repeated measures on the arm and the test were applied.

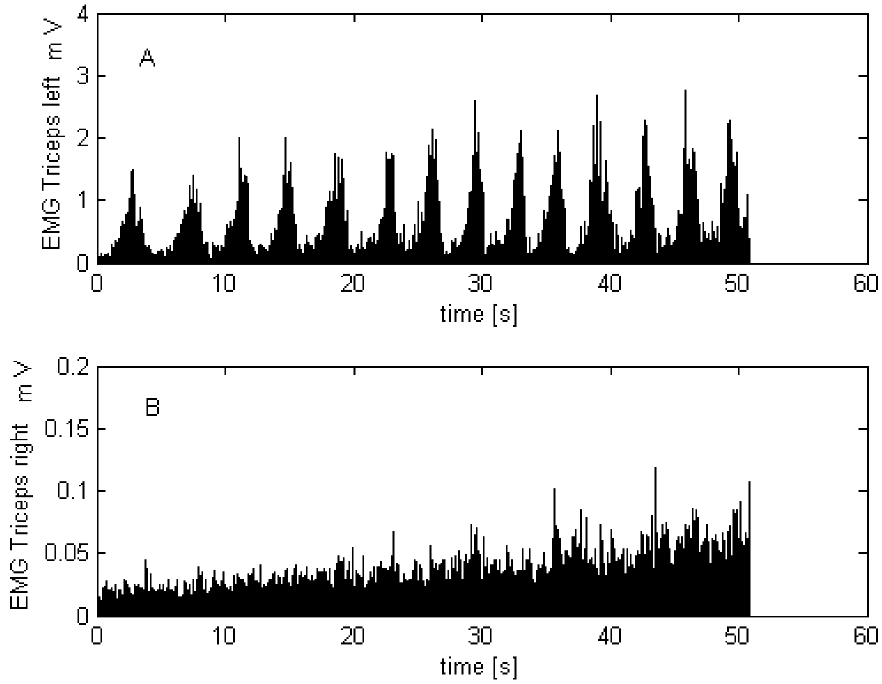

Figure 1 A, B

Example of EMG activity from subject (HMG) of left and right triceps brachii. 1A illustrates the activation co-activation pattern when the left triceps is active.

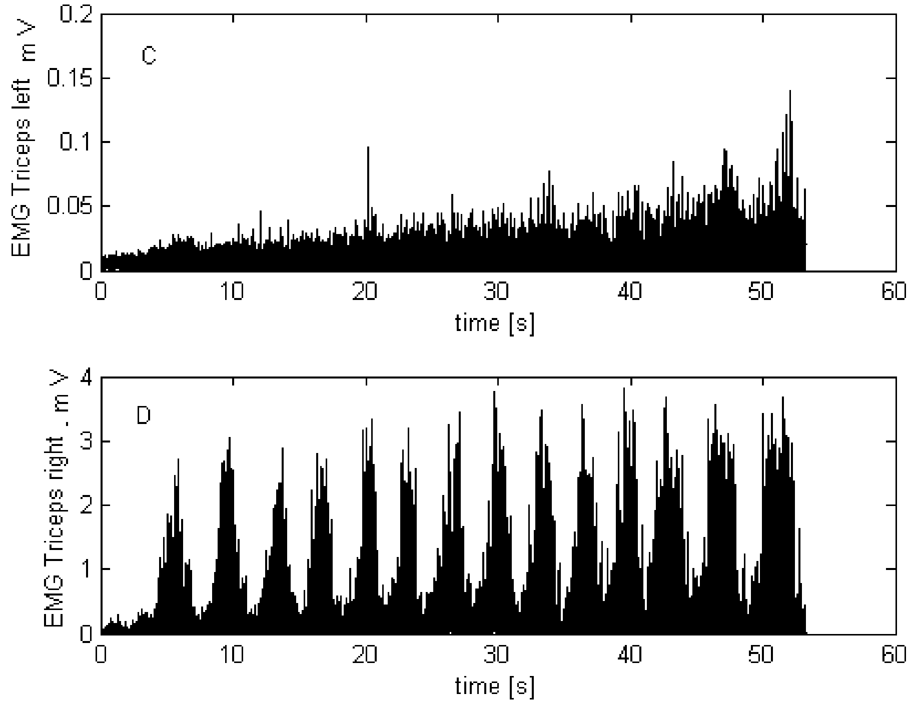

Figure 1C, D

Example of EMG activity from subject (HMG) of left and right triceps brachii. 1D illustrates the activation co-activation pattern when the right triceps is active.

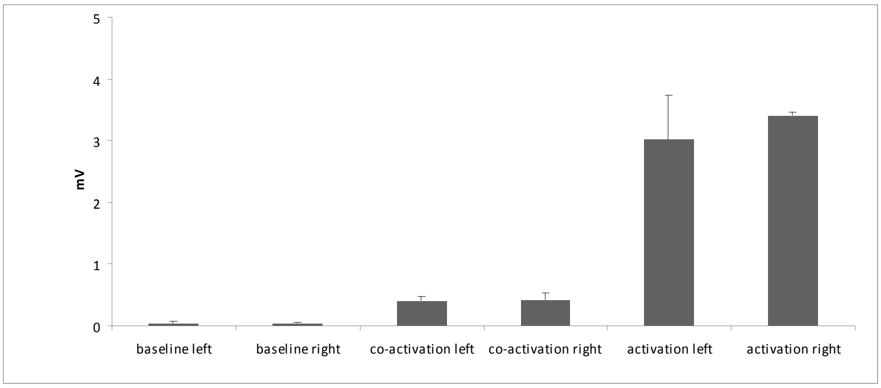

Figure 2

Mean EMG activity and standard deviation of left and right triceps brachii

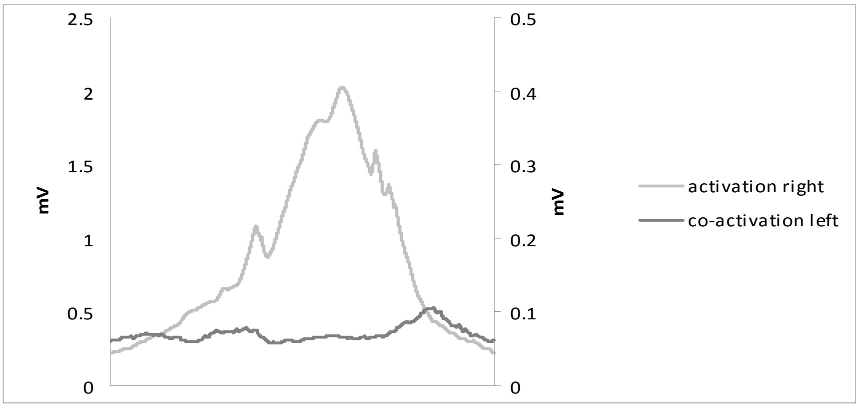

Figure 3

Example of the rectified superimposed and from that the median EMG calculated signal for the practiced and un-practiced limb

The mean EMG data and the SE of the activated and the co-activated muscles are provided in Figure 2.

The analysis indicated a main effect test $F(2,14) = 58.03$, $p<.01$, $\eta^2_p = .89$. The interaction Arm x Test $F(1,14) = 1.66$, $p>.05$ and the main effect arm $F(1,7) = 1.71$, $p>.05$ failed to reach significance. Scheffé post-hoc comparisons for the main effect of test indicated differences between all three tests. The most important difference is between the baseline and the unpracticed limb ($p<.05$). This indicates that measure of co-activation is higher as that for the baseline for both arms. Even though, a significant difference between a baseline and co-activation can be shown, as an example of the rectified median EMG signal calculated from all contraction of one subject. Co-activation in the left limb, when the right is active, is only 2.5%.

The example is provided in Figure 3.

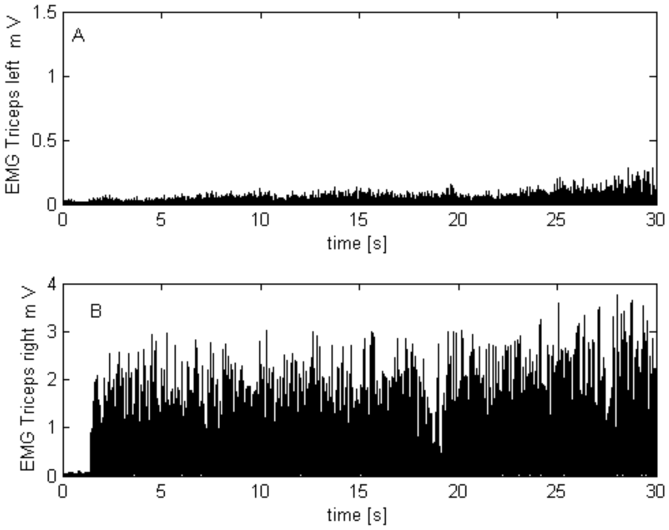

Figure 4A, B

Example of EMG activity from subject (CCS) of left and right triceps brachii. 4A illustrates the activation co-activation pattern when the left triceps is active.

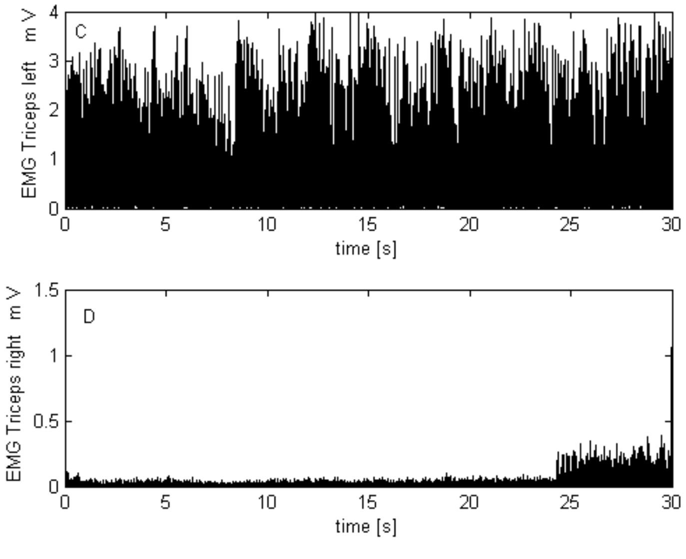

Figure 4C, D

Example of EMG activity from subject (CCS) of left and right triceps brachii 4D illustrates the activation co-activation pattern when the right triceps is active.

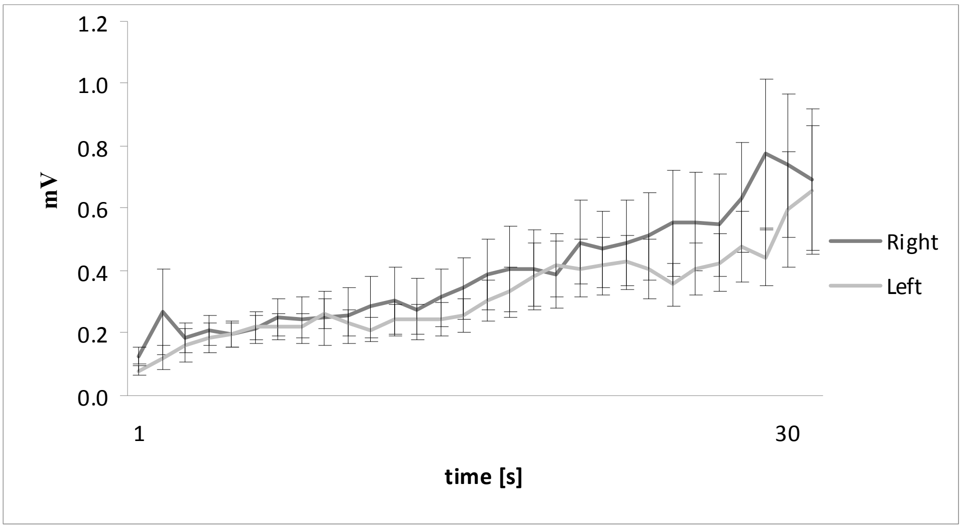

Figure 5

Mean EMG co-activity and standard deviation of left and right triceps brachii during unilateral MVC.

Results of Study 2

Examples of force data and the EMG variables from one subject are provided in Figures 4A to 4D. One subject was excluded from the study because he was not identified as a dominant right hander. The mean MVC for the dominant right (m = 106.65N, SD = 49.03N) and non-dominant left arm (m = 102.85N, SD = 27.43N) was not statistically different, $t(1,8) = .25$, $p>.05$.

As in Study 1, the EMG data were analyzed by a two-way, repeated measures 2 (Arm: right, left) and 3 (Test: practiced, unpracticed, baseline) ANOVA with repeated measures on arm and test. The main effect of test $F(2,16) = 25.24$, $p<.01$, $\eta^2_P = .76$ reached significance. The interaction Arm x Test $F(2,16) = 0.32$, $p>.05$ and the main effect arm $F(1,8) = 0.36$, $p>.05$ failed to reach significance. Scheffé post-hoc comparisons for the main effect of the test revealed significant differences between all three tests. Again, as in Study 1, this indicates

that the measure of co-activation is higher as that of the baseline for both arms. Based on previous results from Study 1, we additionally analyzed the increase of co-activation of the contralateral unpracticed limb during unilateral practice.

In Figure 5, mean blocked co-activation of the contralateral unpracticed limb during unilateral MVC is illustrated. To analyze the increase in co-activation during unilateral MVC, a two-way, repeated measure Block (Block: 1-30) and Limb (Limb: right unpracticed, left unpracticed) Analysis of Variance (ANOVA) with repeated measures on block and limb was conducted.

The analysis indicated a main effect of block, $F(1,29)=4.41$, $p<.05$, $\eta^2_p=.38$. The main effect of limb and the interaction Limb x Block failed to reach significance. Duncan's new multiple range test revealed an increase of co-activation of the unpracticed contralateral triceps throughout unilateral MVC.

Discussion

The primary purpose of the present two studies was to determine the influence which a unilateral MVC exerted on the involuntary co-activation of the contralateral homologous muscle. In terms of the bilateral interactions and the associated processing mechanisms of contralateral irradiation, we hypothesized that during a unilateral MVC the contralateral homologous muscle was involuntarily co-activated. Co-activation is defined as the difference between the baseline and the muscle activity of the unpracticed arm. Taken together, the results of the present two studies produced three main findings. First, unilateral strength practice induces an involuntary co-activation of the contralateral homologous muscle during one testing session. Second, co-activation increases with increasing unilateral contraction. Third, this finding is observed in a dynamic and a static set of training.

These results are consistent with the theoretical perspective of bilateral interactions proposed by Zijdewind and Kernell (2001); their perspective maintains that high efforts (e.g. MVC's) of one muscle are not restricted to the practiced muscle but also irradiate to the other contralateral unpracticed muscle. This involuntary co-activation of the contralateral homologous muscle is discussed as a potential mechanism for the phenomenon of cross-education (see Davies, 1942, Dimitrijevic, et al., 1992).

Discussion of the Results from Study 1

In Study 1, we examined if unilateral contractions induced involuntary muscle activity in the contralateral homologous muscle. A dynamic arm movement task was applied. For this reason, we measured the muscle activity of the tricpes brachii on the left and right practiced and unpracticed arm. The subjects performed the extension/flexion movement similarly with their dominant right and their non-dominant left arm. No asymmetry between the limbs could be observed. The analysis of the EMG data indicated an increase and decrease activation of the active triceps which performed with the additional load. This rhythmical, iterative pattern of muscle activity is associated with the extension flexion movement of the arm (see Figures 1A and 1D). However, in the unpracticed arm, a pattern of muscle activation could be observed. This pattern of muscle activation is similar to that of the practiced arm. The activation of the unpracticed triceps brachii is statistically different from the baseline. This can be characterized as co-activation. The co-activation can be observed for the left and the right arm. The present finding is in line with the expectation based on earlier findings reported by Davies (1942) and Dimitrijevic et al. (1992), that unilateral contraction induced a co-activation on the contralateral unpracticed muscle. However, compared to the active limb the co-activation of the unpracticed limb is around 2.5% (see Figure 3). There can be some doubt that this low co-activation has an effect on the strength in the contralateral unpracticed limb. Based on a more qualitative observation, the increase of co-activation is associated with the increase of the amount of unilateral contractions (see Figure 1B and 1C).

This observation is in line with the results reported by Davies (1942) where subjects had to perform a flexion/extension movement of the wrist and they had to move different loads several times. The present results provided some evidence that in a dynamic set of training unilateral contractions induced a co-activation of the homologous contralateral muscle. This suggests that irradiation at unilateral strength training appears in one testing session.

Discussion of the Results from Study 2

The analysis of the data from Study 2 indicated that subjects perform a similar MVC with their dominant right and their non-dominant left limb in a static testing set, where they had to perform an isometric contraction for 30 s. This is in line with the previous finding from Study 1, where subjects had to perform a dynamic extension flexion movement. As in Study 1, the mean EMG data analysis indicated that unilateral isometric contraction of the triceps brachii induced a higher muscle activity compared to the baseline. The finding that an isometric unilateral contraction induced a co-activation of the homologous muscle is in line with the formulated expectations. In the isometric contraction, activation of the muscle had to be maintained for a time period of 30 s. A qualitative inspection of the EMG data of one subject, which are illustrated in Figures 4A and 4D, provided some evidence that after 20 s of isometric contraction the activation of the contralateral homologous muscle increases for the right and left triceps. Quantitative analysis of the mean recorded EMG signals provided evidence that co-activation increase with the increase of time for unilateral isometric contraction. This finding is in line with previous results reported by Dimtirjevic and colleagues (1992). They demonstrated that by increasing the activation time of the exercised muscle co-activation of the contralateral homologous muscle increase over several testing sessions, while in the current study the increase can be observed during one testing session.

General Discussion and Conclusions

In the present two studies, the general pattern of the finding that unilateral strength practice resulted in a co-activation of the contralateral homologous muscle is similar for dynamic and static sets of training. This suggests that in both sets of training bilateral interaction occurred.

This observation is interesting because in the dynamic set of training an intermittent contraction had to be performed, while in the static set of training a contraction had to be held for 30 s. In contrast to other studies where repeated testing sessions were applied, the current findings provide, as far as we know, for the first time empirical evidence that the involuntary contralateral co-activation appears without additional exercise. This may suggest that contralateral irradiation is one potential processing mechanism to explain the phenomenon of cross-education, and that co-activation of the contralateral homologous muscle is involuntary in terms of reflexes (Sherrington, 1906).

The interesting observation (see Figure 5) in both sets of training that with increasing time of practice muscle activity of the unpracticed limb increases suggests that voluntary unilateral contractions try to inhibit first the involuntary activation at the unpracticed limb. But with increasing time of unilateral contraction the inhibition process seems to level off and is associated with a higher co-activation (Carroll et al., 2006, Zijdewind & Kernell, 2001) in the right and left limb. Control processes of inhibition are degraded by increasing time of unilateral contractions.

Of course contralateral irradiation is one processing mechanism to explain effects of cross-education. Independent of the task or muscle groups, practice seems essential to improve strength at the practiced and unpracticed contralateral limb and other mechanisms could modulate effects of cross-education (Carroll et al., 2007 for an overview; see also Hortobàgyi et al., 2003). But contralateral irradiation can support effects of cross-education. It may be stated that motor control processes have an impact very early in practice and later learning processes evoke cross-education. Both processes act together to induce cross-education.

Practical Implications

Finally, our findings indicate the need to develop clinical training protocols for patients or sports athletes following unilateral injuries and diseases that can enhance their ability to practice their injured limb by contralateral exercises. Two potential training protocols come to mind. First, effects of contralateral irradiation can be applied immediately to induce co-activation of the contralateral limb. Second, in static and dynamic sets of training, co-activation increases with the increase of the amount of contractions or the increase of time to perform MVC with the unilateral muscle. An effective method for enhancing co-activation in the contralateral homologous muscle is to threshold MVCs as long as possible. Perhaps these types of training protocols could assist patients or injured athletes in adopting muscular strength at the injured contralateral limb.

Acknowledgements

This work was supported by a grant from the German Research Foundation (PA 774/10-1).

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