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SHORT COMMUNICATION

Does cross-education of strength depend on limb dominance? Testing baseline strength differences as moderator

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Cross-education of strength refers to strength gains in the opposite untrained limb. It was previously proposed that the magnitude of cross-education effect may be contingent upon how much stronger the dominant limb is relative to the non-dominant limb before training.

Objective: To examine whether the magnitude of cross-education depends on the baseline strength difference between the dominant and non-dominant arm, as well as individuals' preference for using their dominant arm in daily activities.

Design: Retrospective analyses.

Methods: 73 untrained individuals were randomly assigned to either a time-matched non-exercise control group or a training group. The training group performed unilateral elbow flexion exercise with the dominant arm (x3/week for 6 weeks). Maximum strength of the non-dominant was measured before and after the intervention. Moderation analyses were conducted with baseline strength difference and handedness score as moderators.

Results: No significant group by baseline strength difference interaction was found for strength changes of the non-dominant arm (i.e., cross-education of strength) [b = 0.255, CI = (-0.259, 0.769), SE 0.257, p = 0.325]. Similarly, there was no statistically significant group by handedness score interaction for strength changes of the non-dominant arm [b = -0.028, CI = (-0.117, 0.062), SE 0.045, p = 0.537].

Conclusions: Six weeks of unilateral high-load resistance training induced a cross-education effect, however, its magnitude was not dependent on baseline strength differences between limbs. The limited variability in handedness in the present sample may have restricted the ability to fully evaluate its potential moderating role, and thus, further research is warranted.

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Keywords: ■ contralateral transfer ■ handedness ■ interlimb transfer ■ resistance training ■ unilateral training.

INTRODUCTION

Cross-education of strength refers to a phenomenon in which unilateral resistance training of one limb results in strength gain in the contralateral untrained limb.[1,2] Previously, it was proposed that the magnitude of cross-education effect is asymmetrical, whereby a greater magnitude of cross-education of strength is observed from the dominant to the non-dominant limb (i.e., by training the dominant limb).[3] This theoretical model is based on one early study that observed a greater cross-education of strength for the group that trained their dominant hand with unilateral isometric ulnar deviation exercise compared to the group that trained the non-dominant hand.[4] However, more recent studies have reported that the magnitude of cross-education effect was similar between the dominant and non-dominant limbs.[5-7] The reasons for this discrepancy remain unclear, though one potential explanation may relate to limb proficiency in strength tasks.[3,5] For example, it has been proposed that the cross-education of strength is similar to the cross-education of skills, where learning a task using the more proficient system (e.g., dominant limb or side of brain for that task) creates a better-stored motor engram for the contralateral limb.[3] In other words, if the dominant limb is more proficient at executing the strength task (i.e., stronger) than the non-dominant limb at baseline,[4] training with the dominant limb may provide a better stored motor engram for maximum force production which can be subsequently accessed by the opposite untrained hemisphere[3].

In the context of this model, it has been suggested that the magnitude of the cross-education effect may be contingent upon how much stronger the dominant limb is relative to the non-dominant limb before training.[3] If this is true, it would then make conceptual sense that individuals who have greater strength difference between the dominant and non-dominant limbs at baseline may result in a greater cross-education effect. The present analyses aimed to retrospectively investigate whether the magnitude of cross-education effect following 6-weeks of unilateral resistance exercise depended on the baseline strength difference between the dominant and non-

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dominant arms. As a follow up to this, we sought to determine whether the magnitude of the cross-education of strength depends on individuals' preference for using their dominant arm over their non-dominant arm in daily activities (i.e., handedness). It was previously suggested the magnitude of the cross-education of skills may depend on the individual's handedness.[3] If similar mechanisms underlie the cross-education of strength, then handedness may moderate its magnitude.

METHODS

The present study involved retrospective analyses of data obtained from a trial, in which one-repetition maximum (1RM) strength of the elbow flexors was measured before and after 6 weeks of unilateral elbow flexion resistance training.[2,5]

Participants

The current analyses were conducted on data from 73 non-resistance trained right-handed individuals who were between the ages of 18–35 years, did not regularly use tobacco products, and did not have any orthopedic injuries that prevented from performing elbow flexion exercise. Only right-handed individuals were included in the present study to align with the previous study,[4] which served as the basis for the previous theoretical model[3]. In that study, only right-handed individuals were included and greater cross-education of strength was observed when the dominant (right) arm was trained, compared to training the non-dominant (left) arm.[4] Prior to each testing visits (pre- and post-test), participants were instructed to refrain from consuming alcohol and engaging in any type of exercise for 24 hours, caffein intake for 8 hours, and food consumption for 2 hours. All participants provided written informed consent to participate in the study.

Procedures

Following the first (pre-testing) visit, participants were randomly assigned to one of four groups: (1) time-matched non-exercise control (Control); (2) dominant arm training (D-Only); (3) non-dominant arm training (ND-Only); and (4) dominant and non-dominant arm training (D+ND). Of note, data from the D+ND were not included in this analysis since it was not relevant to our research questions. Data from the ND-Only group were also excluded because the primary purpose of the present analysis was to test the specific hypothesis proposed by Farthing et al.[3] that the magnitude of cross-education following dominant-arm training depends on the baseline strength difference between the dominant and non-dominant limbs. Accordingly, analyses were limited to the D-Only and Control groups. The post-testing visit for reassessment of 1RM strength was completed between two to five days after the final training visit, at a similar time of the day (± 1 hour) as the pre-testing visit. Participants in the training group visited the laboratory on 20 separate occasions (i.e., 1 pre-testing, 1 post-testing, and 18 training visits). The participants in Control group only visited the laboratory for the pre- and post-testing visits.

Training protocols

A detailed description of the training protocol is available elsewhere.[2,5] Briefly, the training visits occurred three times per week for six weeks (18 total supervised sessions) on non-consecutive days. Each training session involved unilateral dumbbell elbow flexion exercise completed on the dominant (D-Only), with back and heels against the wall to maintain proper form. During each training session, participants performed up to, but no more than five heavy single repetitions, followed by four sets of high-load exercise. The first attempt of the heavy single repetitions began at around 80–85% 1RM and the load was progressively increased to meet or exceed the participant's previous 1RM. If participants failed on any of the attempts or completed all five attempts, then the heavy single training was concluded for that training session. The subsequent bout of high-load exercise involved completing four sets of 8-12RM (i.e., reaching volitional failure within 8-12 repetitions).

One-repetition maximum (1RM) strength

1RM strength (i.e., the heaviest weight that can be lifted one time) of the individual's arms were tested using the elbow flexion exercise with dumbbells. The 1RM was completed in its entirety in the non-dominant arm, before transitioning to the dominant arm. All 1RM attempts were separated by 90 seconds of rest, and were performed with the individuals' back and heels against the wall (i.e., to ensure strict form). All 1RM attempts were measured to the nearest 0.2 kg. Verbal encouragement was provided by researchers throughout the test.

Handedness score

Handedness scores were used to assess individuals' preference for using their dominant arm over their non-dominant arm in daily activities. Handedness score was calculated by using the Edinburgh Handedness Inventory, a validated tool for assessing handedness preference (8). Participants indicated their hand preference for the following activities: (1) writing, (2) throwing, (3) using a toothbrush, and (4) using a spoon. The handedness score was calculated using the standard formula,[8] yielding values ranging from -100 to 100, with higher positive scores indicating stronger right-handedness, lower negative scores indicating stronger left-handedness, and values near zero suggesting ambidexterity. Of note, all participants in the present study were right-handed, and all handedness scores were positive (i.e., > 0).

Statistical analysis

Retrospective, exploratory moderation analyses using the "PROCESS" macro in SPSS 30.0 were conducted to investigate whether the magnitude of cross-education is dependent on the arm proficiency (i.e., strength difference at baseline and handedness). More specifically, two separate models were run to examine whether the effect of training (X = D-Only vs. Control) on the magnitude of cross-education of strength (Y = 1RM strength changes of the non-dominant arm) depends on the 1RM strength difference between dominant and non-dominant arm at baseline (*W1*) and handedness score (*W2*). Irrespective of the model, sex (male or female) was included as a covariate, and regression coefficients (*b*) were reported along with 95% confidence interval (CI), standard error (SE), and *p*-value. Statistical significance was set at $p < 0.05$, and all data are presented as mean (standard deviation, SD) unless otherwise stated.

RESULTS

Participants

The demographics for each group's age, height, and body mass, respectively, were as follows: D-Only (n = 35): 21.1 (3.0) years, 167.6 (9.3) cm, and 69.2 (18.2) kg; and Control (n = 38): 21.3 (3.5) years, 169.1 (9.3) cm, and 74.7 (24.0) kg. Baseline strength difference and handedness score, respectively, were: D-Only: 0.81 (0.79) kg and 99.18 (4.82); and Control: 0.88 (1.22) kg and 97.84 (7.48). Changes in 1RM strength of the non-dominant (untrained) arm were 1.38 (1.10) kg for the D-Only and -0.19 (1.03) kg for the Control group. As previously reported (5), there was evidence that the changes in strength of the non-dominant arm were greater in the D-Only group than in the Control group, indicating the presence of a cross-education effect.

Moderation analyses

For the D-Only compared to the Control (Figure 1A), there was no statistically significant group by baseline 1RM strength difference interaction for 1RM strength changes in the non-dominant arm (i.e., magnitude of cross-education) [b = 0.255, CI = (-0.259, 0.769), SE 0.257, p = 0.325] when controlling for sex (Table 1). The results were robust and remained unchanged when the covariate (i.e., sex) was removed from each model (data not shown).

For the D-Only compared to the Control (Figure 1B), there was no statistically significant group by handedness score interaction for 1RM strength changes in the non-dominant arm (i.e., magnitude of cross-education) [b = -0.028, CI = (-0.117, 0.062), SE 0.045, p = 0.537] when controlling for sex (Table 1). The results were robust and remained unchanged when the covariate (i.e., sex) was removed from each model (data not shown).

DISCUSSION

Six weeks of unilateral high-load resistance training increased strength in the contralateral untrained arm, demonstrating a cross-education of strength.[5] The main finding of the present study was that the magnitude of cross-education effect did not depend on the baseline strength difference between the dominant and non-dominant arm. For hand preference in daily activities, the present study showed limited variability in handedness scores, which may have limited the ability to fully examine its potential moderating role in the cross-education response.

A previous study reported a greater cross-education of strength in the group that trained their dominant hand with unilateral isometric ulnar deviation exercise compared to the group that trained the non-dominant hand.[4] To explain this finding, it was proposed that the cross-education of strength is similar to cross-education of skills, where the magnitude of cross-education effect is greater by training the dominant limb compared to the non-dominant limb.[3] This theoretical model suggests that training the stronger (i.e., more proficient) limb at baseline would provide a better-stored motor

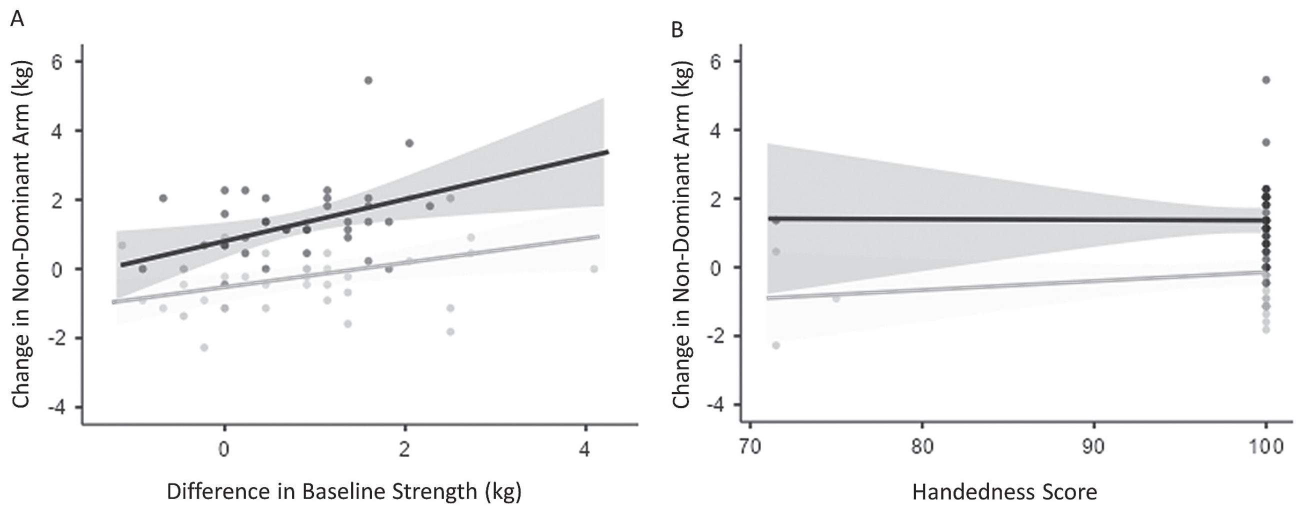

FIGURE 1. (A) The relationship between group (D-Only vs. Control) and maximum strength changes of the non-dominant arm (cross-education of strength) across different baseline strength difference values. (B) The relationship between group (D-Only vs. Control) and maximum strength changes of the non-dominant arm (cross-education of strength) across different handedness score values. Black lines and dots represent the D-Only group and grey line and dots represent the Control group.

TABLE 1. Results of the moderation analyses using baseline strength difference and handedness score as moderators.

Moderator (*W*)	R^2		b	95% CI	p value
Baseline Strength Difference (Diff)	0.463				
		Group	1.38	0.75, 2.01	< 0.001
		Strength Diff	0.35	0.08, 0.63	0.0131
		Group x Strength Diff	0.26	-0.26, 0.77	0.325
		Sex	0.52	0.01, 1.03	0.0465
		Constant	-0.80	-1.33, -0.27	0.0037
Handedness Score (Handedness)	0.374				
		Group	4.29	-4.56, 13.14	0.3371
		Handedness	0.03	-0.02, 0.08	0.2881
		Group x Handedness	-0.03	-0.12, 0.06	0.5372
		Sex	0.10	-0.43, 0.63	0.6994
		Constant	-2.80	-7.49, 1.89	0.2382

engram, thereby leading to greater cross-education of strength.[3] More specifically, it was suggested that the magnitude of cross-education effect may depend on how much stronger the dominant limb is than the non-dominant limb before training (i.e., the greater the strength difference, the greater the cross-education effect).[3] However, in contrast to the previous theoretical model, the results of the present study showed that the cross-education of strength did not differ based on individuals' baseline strength difference between dominant and non-dominant arm, indicating that the magnitude of cross-education effect does not depend on how much stronger the dominant arm is before training. Our findings suggest that because the dominant arm is stronger than the non-dominant arm at baseline, this does not necessarily indicate that training the dominant arm will provide a better-stored motor engram (if this is indeed a mechanism of cross-education of strength). Of note, the findings of the present study are based on strength measures only and do not allow direct inference regarding underlying neural mechanisms. Although previous work using the same dataset showed no changes in muscle thickness in the untrained arm[2], this finding does not provide direct evidence for neural mechanisms underlying cross-education. Thus, further research incorporating neural and/or neuromuscular measures is needed to clarify whether training the dominant arm results in a better-stored engram as previously proposed. Furthermore, it should be noted that it remains unknown whether the absence of a moderating effect of baseline strength difference on cross-education would be consistent across different exercise tasks. For example, Farthing et al.[4] employed an ulnar deviation exercise, which has been suggested to be relatively novel, whereas the present study involved elbow flexion. Although it is difficult to establish clear criteria for defining exercise novelty, further research is needed to clarify whether task characteristics influence the potential moderating effect of baseline strength differences on cross-education.

The results of the moderation analysis also indicated that the magnitude of cross-education of strength did not vary based on the dominant arm preference in daily activities. A previous study reported that the dominant limb is typically stronger than the non-dominant limb, and this strength asymmetry may be affected by individuals' preference for using their dominant limb in daily activities and manual tasks.[9,10] Furthermore, the magnitude of cross-education of skills has been suggested to depend on handedness.[3] Although a preference for the dominant arm in daily activities may contribute to greater strength and cross-education of skills, our results suggest that this does not necessarily lead to a greater cross-education of strength. Of note, however, the majority of participants had a handedness score of 100, indicating a strong preference for their dominant hand in daily activities. This limited variability may have hindered the ability to fully assess the moderating role of handedness in the cross-education of strength, and thus requires caution when interpreting the results.

CONCLUSION

It was previously proposed that the magnitude of cross-education effect may depend on how much stronger the dominant limb is relative to the non-dominant limb at baseline.[3] However, the findings from the present study do not support this theoretical model, as the magnitude of cross-education of strength was not dependent on the baseline strength difference. A lack of variability in handedness scores limited the ability to fully examine the potential moderating role of arm preference in daily activities, and thus, further research is warranted.

CONFLICT OF INTEREST

The authors report there are no competing interests to declare.

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AUTHORS' CONTRIBUTION

All authors read and approved the final version of the manuscript.

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