Game Nexus

The Cross-Education Effect of Unilateral Arm Training on Contralateral Muscle Strength and EMG Activity: The Modulatory Roles of tDCS and Practical BFR

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ABSTRACT

Cross-education refers to strength gains in the untrained limb following unilateral training. Blood flow restriction (BFR) and transcranial direct current stimulation (tDCS) are known to induce peripheral and neural adaptations, respectively. This study investigated whether combining unilateral BFR and tDCS enhances cross-education effects in the untrained arm. Thirty-eight healthy young men were randomly assigned to four groups: tDCS-pBFR, Sham-pBFR, tDCS, and Control. Over four weeks, participants performed unilateral dumbbell curl training (30% 1RM, 3 sessions/week). The primary outcomes for the untrained arm were one-repetition maximum (1RM), arm muscle circumference (AMC), and electromyography (EMG) activity. ANCOVA with pre-test as covariate was used for statistical analysis. Strength of the untrained arm (1RM) increased significantly in tDCS-pBFR and Sham-pBFR groups compared with control ($p < 0.05$), while AMC changes were significant only in Sham-pBFR. EMG activity did not differ significantly among groups. No significant difference was observed between tDCS-pBFR and Sham-pBFR groups. Unilateral BFR training, with or without tDCS, produces cross-education effects in the contralateral untrained arm. Strength improvements appear to be primarily mediated by neural adaptations, with limited changes in muscle size or EMG activity. These findings support the use of BFR and neuromodulatory interventions to enhance contralateral strength, particularly in rehabilitation settings.

Keywords: Cross-education, Blood flow restriction, tDCS, Strength, Neural adaptation

Introduction

The enhancement of muscular strength can arise from both morphological changes within the muscle and neural adaptations within the central nervous system. Conventional resistance training programs typically employ moderate to high loading intensities to stimulate hypertrophy and neural drive, thereby producing substantial strength gains (1, 2). While such programs are highly effective, they may be contraindicated in certain populations due to the mechanical stress placed on joints and connective tissue (3). For this reason, alternative methods that reduce loading requirements yet still promote meaningful improvements in performance have gained attention in recent years.

One of the most prominent of these methods is blood flow restriction (BFR) training, where low-intensity exercise is combined with partial vascular occlusion. BFR can elicit hypertrophic and strength adaptations comparable to high-load protocols, even when external loads are only 20–30% of one-repetition maximum (4, 5). Nevertheless, adaptations induced by BFR appear to be predominantly peripheral, with limited evidence for robust neural contributions compared to traditional resistance training (6). This limitation has motivated interest in pairing BFR with neuromodulatory interventions capable of directly enhancing cortical excitability.

Among such interventions, transcranial direct current stimulation (tDCS) has attracted considerable research interest. Anodal stimulation over the primary motor cortex is known to facilitate neuronal excitability, modulate corticospinal output, and in some cases augment voluntary force production (7-9). Evidence also suggests that combining brain stimulation with physical training may potentiate the effectiveness of both approaches (10).

A particularly intriguing context for these combined strategies is the phenomenon of cross-education. Cross-education refers to the strength gain observed in the contralateral, untrained limb following unilateral resistance exercise (11, 12). This effect is believed to arise primarily through neural mechanisms, including interhemispheric communication and cortical plasticity (13). Importantly, both BFR and tDCS target different aspects of adaptation—peripheral and neural, respectively—suggesting their combination may amplify cross-education effects. Indeed, recent studies have speculated that neuromodulation could reinforce the transfer of training-induced adaptations to the untrained side (14). In our previous study, we demonstrated that combining pBFR with tDCS can influence local muscular adaptations (15). The present investigation was therefore designed as a logical extension of that work, focusing specifically on cross-education outcomes in the untrained limb.

The present study is designed to investigate this possibility by combining unilateral BFR training with anodal tDCS. Specifically, we aim to determine whether this dual intervention, applied during four weeks of unilateral dumbbell curl training, augments not only local muscular hypertrophy and strength but also enhances strength and EMG activity in the untrained arm. We hypothesize that participants receiving both BFR and tDCS will demonstrate greater cross-education effects compared to those receiving either intervention alone.

Methods and Materials

Study design and Subjects

This study employed a randomized design. Random allocation sequences were generated in SPSS software (SPSS Inc., USA), sealed in opaque envelopes, and numbered consecutively to ensure allocation concealment. Participants were assigned to one of four groups: tDCS + pBFR, Sham-tDCS + pBFR, tDCS only, or control. Group assignment was revealed only after confirming eligibility criteria. A total of 44 healthy young men volunteered for the study and successfully met the inclusion requirements. Recruitment was conducted from the student population of the University of Mazandaran. Prior to baseline assessments, participants attended a familiarization session, which included instructions and practice with the tDCS procedure, EMG recordings, maximal voluntary contraction (MVC) testing, and the unilateral biceps curl exercise protocol.

To minimize confounding factors, participants were instructed to:maintain their normal daily routines,avoid nutritional supplements or additional training throughout the study, abstain from alcohol, caffeine, and strenuous physical activity for 48 hours before both pre- and post-tests.All subjects signed written informed consent prior to participation. The research protocol was approved by the University of Mazandaran Research Ethics Committee (IR.UMZ.REC.1403.001).

Transcranial Direct Current Stimulation (tDCS)

Stimulation was delivered using a Neurostim 2 device (MedinaTeb, Iran), capable of producing direct current intensities between 0.1–2 mA with a maximum voltage of ±30 V. To target the primary motor cortex (M1), the anodal electrode was positioned over the C3 site of the 10–20 EEG system, while the cathodal electrode was placed over the contralateral C4 region. Electrode placement was determined by standardized measurements between the nasion, inion, and preauricular landmarks (16). During the experimental sessions, a constant current of 1.5 mA was applied for 15 minutes using saline-soaked carbon electrodes (5 × 5 cm). A trained researcher, independent of subsequent data analysis, administered all stimulation procedures. Participants were blinded to the stimulation condition, and those in the sham-tDCS group received the same setup, but the current was gradually reduced after an initial brief ramp-up period, ensuring successful blinding (12). (Fig. 1)

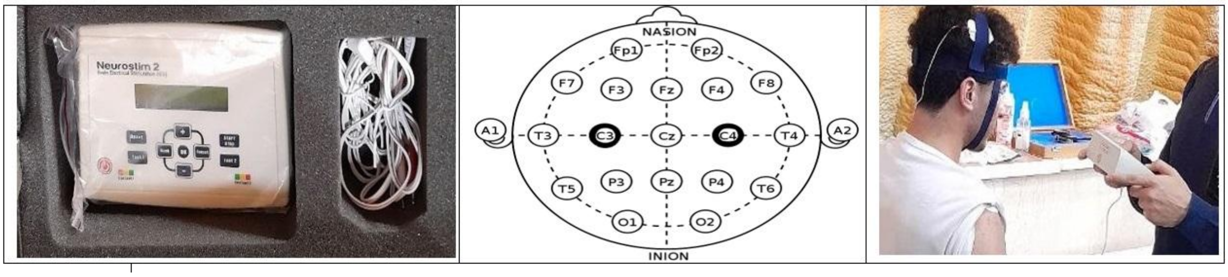

Figure 1. anodal tDCS stimulation for 15 minutes using a 5cm x 5cm carbon pad dipped in conductive gel. anode electrode was placed over C3. Cathode electrode was placed on the C4.

Practical Blood Flow Restriction (pBFR)

Blood flow restriction was applied using elastic sports bands designed to partially occlude circulation in the trained limb. The bands measured 5 × 94 cm, with markings every 2 cm to allow participants to adjust pressure consistently during the unilateral biceps dumbbell curl sessions. The wraps were positioned on the proximal upper arm, just above the biceps and below the deltoid.

During training, participants performed curls at 30% of 1RM, following a protocol of one set of 30 repetitions and three sets of 15 repetitions (17, 18). The elastic wraps were placed at the start of each set and removed upon completion. This procedure followed the method described by Wilson et al. (19).

To ensure consistent application, participants were familiarized with a 0–10 perceived pressure scale, where 0 indicated no pressure, 7 corresponded to moderate pressure without pain, and 10 indicated maximal pressure with pain. For all training sets, participants were instructed to maintain a pressure corresponding to 7 out of 10, ensuring both safety and effectiveness of pBFR (Fig. 2).

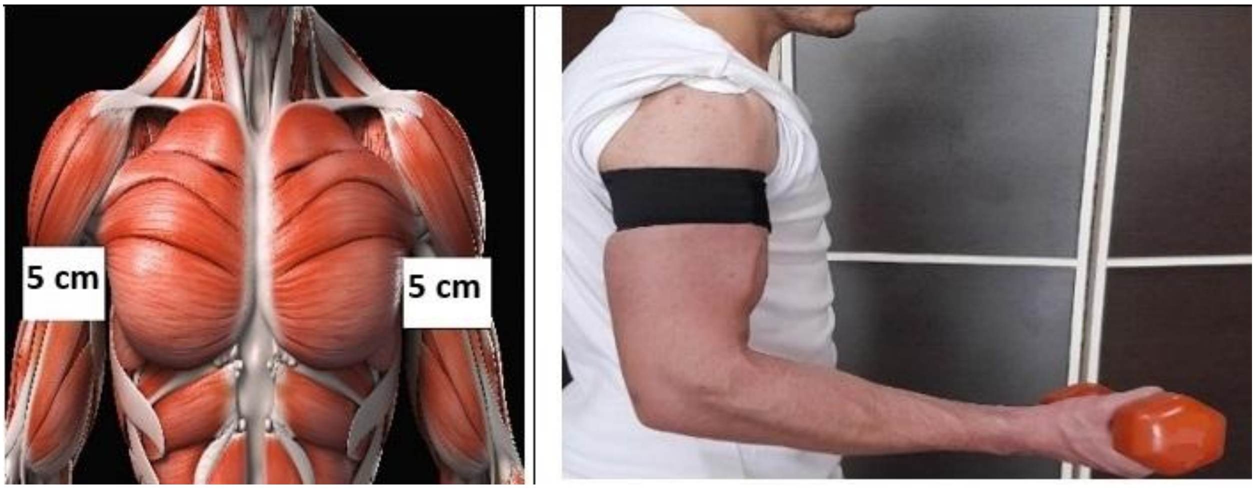

Figure. 2. Practical blood flow restriction (pBFR). 5cm BFR wrap. The wraps were applied to the proximal end of the upper limb.

Electromyography

Electromyographic activity was measured using the MegaWin Muscle Tester ME 6000 (Mega Electronics Ltd., Finland). Surface electrodes (Skintact, Innsbruck, Austria) were positioned over the biceps brachii muscle belly according to SENIAM guidelines to ensure standardized placement. Prior to electrode application, the skin was shaved and cleaned with cotton and rubbing alcohol to minimize impedance and improve signal quality. Electrodes were secured with adhesive tape to reduce movement artifacts during testing. Signals were recorded at a sampling rate of 2000 Hz using MegaWin software (version 3.1). Data were bandpass filtered between 10–500 Hz, and a 50 Hz notch filter was applied to remove power-line interference. To account for inter-subject variability and possible differences in electrode placement between pre- and post-tests, EMG signals were normalized to Maximum Voluntary Isometric Contraction (MVIC). RMS values quantified muscle activation, allowing assessment of cross-education effects in the untrained arm.

One-repetition maximum (1RM)

Maximal strength was assessed using a one-repetition maximum (1RM) test, following the protocol described by Brzycki (1993) (20). Participants performed repetitions at a controlled speed and through a full range of motion until momentary muscular failure.

The procedure began with a general warm-up, followed by a set of 10 repetitions using a light warm-up load. The load was then progressively increased until participants could perform only 4–6 repetitions to failure. The 1RM was then calculated using Brzycki's equation, providing an indirect measure of strength gains via cross-education. (20), providing an estimate of maximal voluntary strength for each participant.

Circumferences

The untrained arm was measured to estimate muscle size. The distance between the acromion and olecranon was measured, and a mark placed at 50% of this distance (21, 22). AMC was calculated as:

$AMC = c - (T * \pi)$

where c is arm circumference and T is triceps skinfold thickness (21, 22). This provided an index of muscle volume changes in the untrained limb resulting from cross-education.

Training Protocols and Groups

Participants were assigned to one of four groups, each receiving a distinct combination of interventions:

tDCS + pBFR Group: Individuals in this group received anodal tDCS at 1.5 mA for 15 minutes, immediately followed by a general and specific 5-minute warm-up. They then performed practical blood flow restriction (pBFR) exercises targeting the dominant arm, while the untrained contralateral arm was monitored for cross-education effects. Training consisted of four consecutive sets: the first set of 30 repetitions, followed by three sets of 15 repetitions at 30% 1RM, with 45-second rest intervals between sets. Sessions were conducted three times per week, with at least one day of rest between sessions, for a total duration of four weeks (4–7 pm) in the Health Laboratory of the University of Mazandaran.

Sham + pBFR Group: This group underwent sham tDCS, where current was ramped up briefly and then discontinued after 30 seconds to ensure blinding. Immediately afterward, participants performed the same pBFR exercise protocol as the tDCS + pBFR group.

tDCS-Only Group: Participants in the tDCS-only group received anodal tDCS (1.5 mA, 15 minutes) without performing any exercise. Sessions were scheduled three times per week over four weeks (4–7 pm). No physical training was performed during the pre- and post-test period.

Control Group: Participants in the control group did not receive any stimulation or exercise intervention. They only participated in the pre- and post-test assessments. (Fig. 3)

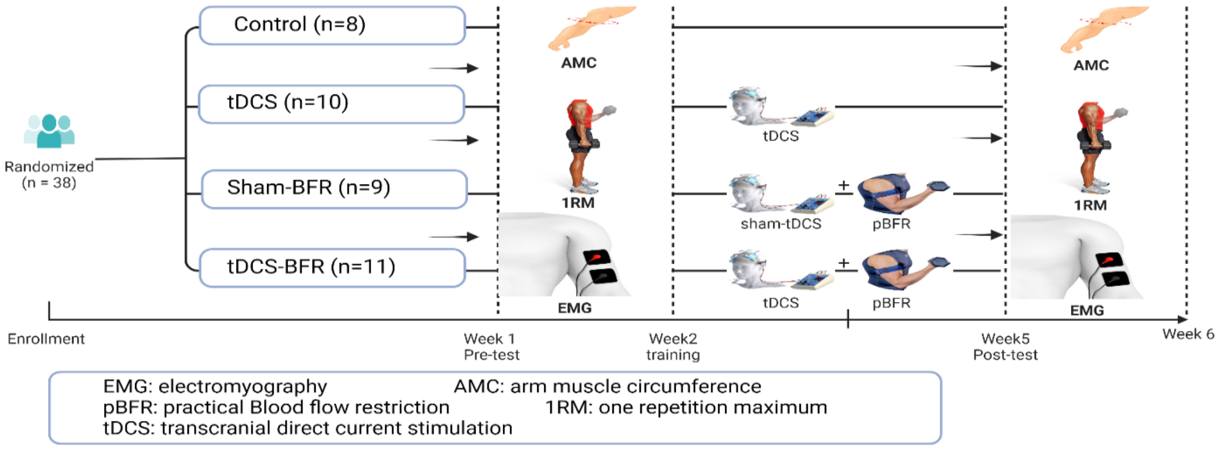

Figure 3. Study timeline.

Pre-Test and Post-Test

During the pre-test session, participants first underwent measurements of height, body weight, and arm circumference. Following a general and specific warm-up, the one-repetition maximum (1RM) of the untrained, contralateral arm was estimated using the Brzycki method (20). After a 3-minute rest, EMG signals were recorded from the biceps brachii of the untrained arm during maximal voluntary isometric contraction (MVIC). Subsequently, after another 3-minute rest, electrical activity of the biceps was recorded during three repetitions of unilateral dumbbell curl at 80% of the 1RM, performed at a controlled rhythm of 20 beats per minute (BPM).

Following twelve training sessions over four weeks, the post-test assessments mirrored the pre-test procedures to evaluate changes in strength, EMG activity, and arm muscle circumference of the untrained contralateral arm, capturing potential cross-education effects.

Statistical Analyses

Data were first checked for normality using the Shapiro-Wilk test and for homogeneity of variance using Levene’s test. After confirming these assumptions, analysis of covariance (ANCOVA) was conducted, with pre-test values included as a covariate. Pairwise comparisons were performed using Bonferroni post-hoc analysis. Effect sizes were reported as partial eta squared (η^2). Descriptive statistics are presented as mean ± standard deviation in text and tables, and mean ± standard error in figures. Statistical analyses were performed using SPSS 27, and G-Power 3.1 was used to calculate the actual power of the tests. The significance level was set at $p < 0.05$.

Findings and Results

A total of 44 participants were initially enrolled and randomized into four groups. However, six individuals did not complete the intervention protocol, resulting in the following final group distribution: tDCS-pBFR (n = 11), Sham-pBFR (n = 9), tDCS (n = 10), and Control (n = 8). The inclusion criteria were: (1) male participants; (2) no prior exposure to tDCS, BFR, or structured resistance training; (3) absence of upper limb injuries; (4) recreationally active university students (engaged in 2–3 hours of physical activity per week); and (5) good overall health as confirmed by the PAR-Q questionnaire. The PAR-Q comprised ten items addressing potential risks related to cardiovascular, neurological (e.g., epilepsy, stroke), respiratory, metabolic, and psychological conditions (23).

Thirty-eight participants successfully completed the 4-week experimental period. Table 1 presents the descriptive characteristics of the participants. No significant baseline differences were observed among the groups in terms of age (P = 0.352), height (P = 0.128), body weight (P = 0.214), or body mass index (BMI) (P = 0.579).

Table 1. Anthropometric characteristics of the participants

Items	(tDCS-pBFR)	(Sham-pBFR)	(tDCS)	Control	p-value
	(n=11)	(n=9)	(n=10)	(n=8)	
Height (cm)	178±5.5	173.6±7	179.4±8	173.2±4.7	0.121
Age (years)	20±1	20.3±1.2	20.4±1.1	21±1.3	0.364
Body Weight (kg)	75±7.6	67±12.9	75.5±11.4	69.1±10.4	0.197
(BMI) (kg/m^2)	23.7±2.2	22.1±3.2	23.3±2.2	23±2.5	0.562

The data is presented as Mean ± Sd. (tDCS) transcranial direct current stimulation. (pBFR) practical blood flow restriction. (BMI) body mass index.

Table 2. Analysis of the research parameters using ANCOVA

Groups		(tDCS-pBFR)	(Sham-pBFR)	(tDCS)	Control	p-value	Effect size	Test Power
(AMC) (cm)	pre	28.7±2.1	26.6±3.2	28.6±1.6	27.8±2.5	0.01*	0.280	0.819
	post	29.2±1.9	27.7±3.3	28.8± 1.5	27.9± 2.9			
(Δ 1RM) (Kg)	pre	13.18±1.7	12.11±2.3	13.2±2	11.2±1.6	0.001*	0.420	0.982
	post	14.36± 1.6	13.22± 2.3	14.6 ± 2.1	11.1± 1.6			
Normalized (RMS) (Δ %MVIC)	pre	69.09±23.09	76.21±23.5	55.3±22.4	64.4±17.4	0.355	0.092	0.272
	post	54.3±17.11	51.12±7.03	59.1±25.8	65.9±24.9			

The parameters tested demonstrated significant effects or interactions. The data is presented as Mean ± Sd; * indicates a significant group difference at P<0.05 ANCOVA. (tDCS) transcranial direct current stimulation. (tDCS-pBFR) tDCS-practical blood flow restriction, (Sham-pBFR) sham- practical blood flow restriction, (AMC) arm muscle circumference. (1RM) one repetition maximum. (RMS) root mean square.

Muscle volume

After the 4-week intervention period, alterations in the arm muscle circumference (AMC) of the untrained arm are illustrated in Fig. 4A. Analysis revealed that the Sham-pBFR group demonstrated a significantly greater increase in AMC compared with both the control and tDCS groups ($p < 0.05$). No significant difference was observed between the tDCS-pBFR and Sham-pBFR groups ($p = 0.268$), while the control and tDCS groups showed comparable results ($p = 0.987$).

Muscle Electrical Activity

In the untrained arm, RMS values showed a slight reduction in both the tDCS-pBFR and Sham-pBFR groups following the 4-week intervention. However, statistical analysis revealed no significant differences in muscle electrical activity between the experimental and control groups ($p = 0.355$).

Muscle Strength

Figure 4C presents the one-repetition maximum (1RM) strength values for the untrained arm. Post-test analysis indicated that the tDCS-pBFR group achieved significantly greater improvements in 1RM compared with the control group ($p < 0.05$). However, no significant differences were found between the tDCS-pBFR group and either the tDCS group ($p = 0.842$) or the Sham-pBFR group ($p = 0.947$). Similarly, the Sham-pBFR group demonstrated significantly higher 1RM compared with the control group ($p < 0.05$), but did not differ significantly from the tDCS group ($p = 0.653$). In addition, the tDCS group also exhibited a significant improvement in strength relative to the control group ($p < 0.05$).

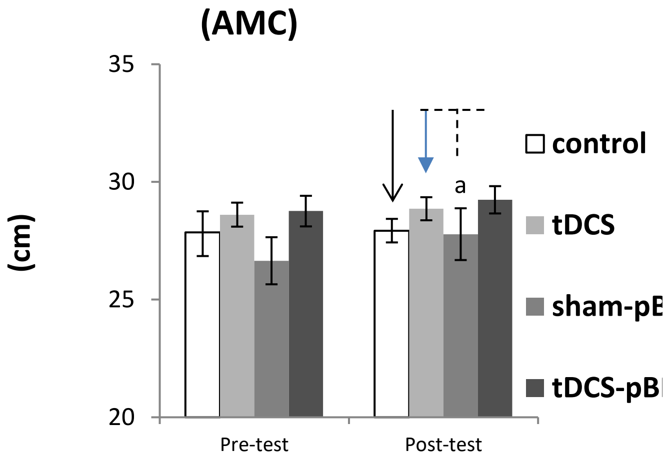

Figure 4A. Pre- and post-trial group scores for biceps volume at 50% of the distance from the acromion process to the olecranon process. The letter "a" indicates a significant difference from control and tDCS groups ($p<0.05$). The comparison of the four groups in the pre-test was not statistically significant ($p= 0.185$).

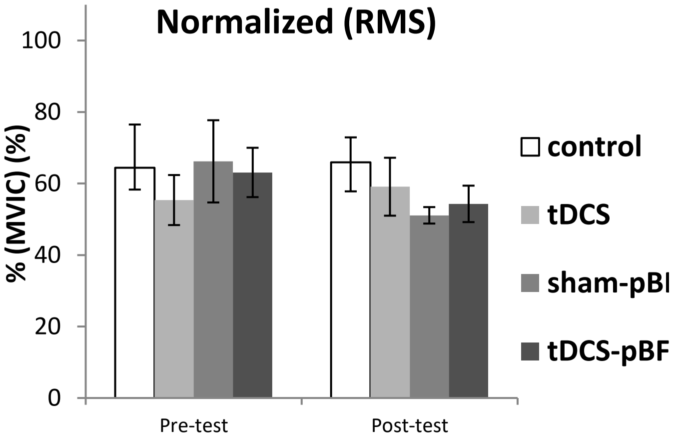

Figure 4B. pre- and post-trial group scores for biceps normalized RMS. The comparison of the four groups in the pre- and post-test was not statistically significant ($p= 0.355$).

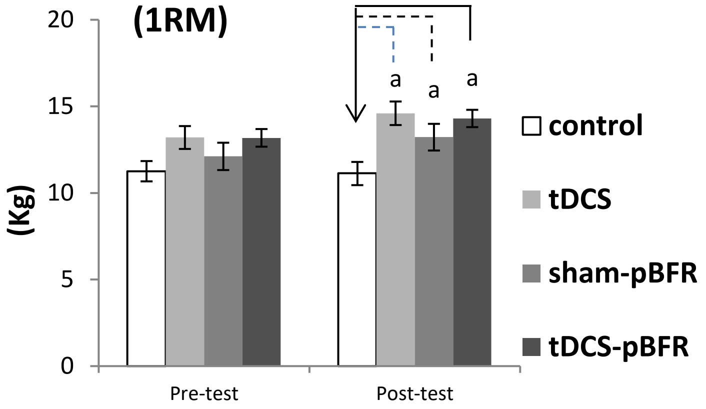

Figure 4C. Pre- and post-trial group scores for biceps 1RM. The letter "a" indicates a significant difference from control ($p<0.05$). The comparison of the four groups in the pre-test was not statistically significant ($p= 0.286$).

Fig. 4 Data expressed as Mean ± SE. according to Bonferronie. (tDCS) transcranial direct current stimulation. (tDCS-pBFR) tDCS-practical blood flow restriction, (sham-pBFR) sham-practical blood flow restriction, (AMC) arm muscle circumferenc. (RMS) root mean square, (MVIC) maximum voluntary isometric contraction. (1RM) one repetition maximum.

Discussion and Conclusion

The present study investigated the effects of unilateral practical blood flow restriction (pBFR) training combined with anodal transcranial direct current stimulation (tDCS) on cross-education in healthy young men. Our findings demonstrated that unilateral pBFR training, with or without tDCS, led to significant strength improvements in the untrained contralateral arm. However, no additional benefits of combining tDCS with BFR were observed in terms of muscle volume or electromyographic activity.

Previous studies have consistently shown that BFR training, despite the use of low loads, can induce hypertrophy and strength gains comparable to high-load training (4, 5). These adaptations have been primarily attributed to peripheral mechanisms such as metabolic stress, cell swelling, and muscle protein synthesis (6). At the same time, evidence for robust neural adaptations with BFR training has been limited. This is consistent with our findings, where contralateral improvements in strength were not accompanied by significant changes in EMG activity or muscle size in the untrained arm.

On the other hand, tDCS has been widely investigated as a non-invasive neuromodulatory technique to enhance motor performance. Several studies reported that anodal stimulation of the primary motor cortex can increase corticospinal excitability and improve force generation (9, 24). For example, Hikosaka et al. (2021) showed that a single session of tDCS increased handgrip strength, supporting the idea of acute neuromodulatory effects (13). Similarly, other trials combining tDCS with resistance training have suggested a potentiation of strength outcomes (10). In contrast to these reports, the present study found no clear additive effect of tDCS when combined with pBFR training on cross-education.

The phenomenon of cross-education itself has been extensively studied, with neural factors such as interhemispheric communication and cortical plasticity proposed as the main mediators (11, 12). Traditional high-load unilateral training reliably produces strength transfer to the untrained limb, often accompanied by neural adaptations measurable by EMG or cortical excitability. What distinguishes our study is the use of low-intensity pBFR training, which imposes minimal mechanical stress yet still produced significant contralateral strength gains. This suggests that even in the absence of high external loads, unilateral training is sufficient to induce cross-education, making it a promising strategy for clinical and rehabilitative populations who cannot tolerate heavy resistance.

A unique contribution of our work is the combined application of pBFR and tDCS to test whether targeting both peripheral and neural mechanisms could synergistically enhance cross-education. Although our data did not show additional benefits of tDCS beyond those achieved by pBFR alone, the overall pattern reinforces the role of neural mechanisms in strength transfer. The absence of additive effects may be due to several factors, including the relatively short intervention duration (four weeks), the intensity of stimulation, or ceiling effects where pBFR alone already maximized possible neural contributions.

Taken together, these results highlight that unilateral pBFR training is a viable method to induce cross-education effects, with potential implications for rehabilitation settings such as recovery from unilateral injury, immobilization, or post-surgical conditions. Future studies should consider longer intervention periods, different stimulation parameters, or the inclusion of neurophysiological measures (e.g., transcranial magnetic stimulation, cortical excitability mapping) to clarify the specific contributions of tDCS to cross-education.

This study examined the combined effects of transcranial direct current stimulation (tDCS) and practical blood flow restriction (pBFR) training on muscular strength and cross-education outcomes following unilateral dumbbell curl exercise. While improvements in strength were observed across all groups, the combination of tDCS and pBFR did not yield statistically significant advantages compared with either intervention alone. Nevertheless, the pattern of adaptations suggests that integrating neuromodulation with peripheral training strategies holds potential for optimizing both local and contralateral strength gains.

Importantly, our findings contribute to the growing body of evidence exploring alternative methods for populations unable to tolerate high-load resistance exercise. Although no synergistic effects were conclusively demonstrated, the present work highlights the feasibility of pairing neural and peripheral interventions to target both central and muscular pathways. Future studies with larger sample sizes, longer intervention durations, and more sensitive neurophysiological measures are warranted to clarify the extent to which such combined strategies may enhance cross-education and rehabilitation outcomes.

Several limitations should be acknowledged. First, the study included only healthy young men, which limits the generalizability of the findings to women, older adults, or clinical populations. Second, the intervention period was relatively short (four weeks), and longer-term effects of tDCS and pBFR on cross-education remain unknown. Third, only the biceps brachii was assessed, and it is unclear whether similar effects occur in other muscle groups. Finally, while EMG was used to evaluate muscle activity, more advanced neurophysiological measurements, such as transcranial magnetic stimulation (TMS), could provide deeper insights into the neural mechanisms underlying cross-education.

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Authors' Contributions

This study was conducted collaboratively by all authors. Z. Fallahmohamadi and B. Taheri were responsible for the study design and the execution of the experimental procedures. KH. Irandoost and S. Namdar coordinated the study, performed statistical analyses, and assisted in manuscript preparation. All authors reviewed and approved the final manuscript

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

All ethical principles were adhered in conducting and writing this article.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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