REVIEW

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The Effect of Contraction Type and Training Volume in Unilateral Exercises on Cross-Education: A Narrative Review Study

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SUMMARY

Objective. The effect of unilateral exercises on the untrained limb, usually called "cross-education," can help treat immobility. Review studies in 2017 have shown that type of contraction, volume, and intensity of training are effective on the rate of cross-education. Therefore, this review study aimed at the kind of contraction and the volume of training on crossed education.

Methods. In this review, we searched PubMed, Science Direct, Google Scholar, Scopus, and Web of Science databases from 2017 to December 2022. We used the keywords ("cross-education" OR "cross-transfer" OR "cross-training" OR "interlimb transfer" OR "strength transfer") AND ("unilateral strength training" OR "contralateral strength training" OR "resistance training" OR "strength training").

Results. Of the 391 studies, 22 articles were selected for final evaluation. Out of 22 studies, five studies compared the effect of eccentric and concentric contractions. Six studies examined the effect of mixed exercise. Four studies examined the effect of coupled eccentric/concentric contractions, one study examined the effect of only eccentric exercises, two studies investigated the effect of concentric contraction on cross-education, three studies examined the effect of only isometric contraction, and two studies evaluated the effects of isokinetic contraction on cross-education. The results of these studies showed that coupled contractions have a more significant effect on cross-education (8.6%-69%). Isokinetic contraction had the most negligible effect on the cross-education. The evaluation of BURST has shown more significant cross-education than the evaluation of the contralateral side.

Conclusions. Combined effect of concentric and eccentric contractions could cause the most cross-education effect, as much as 8.6%-69%. BURST evaluation showed more significant effects on cross-education than contralateral limb evaluation.

KEY WORDS

Contraction; training; resistance; exercise; cross-education.

INTRODUCTION

Unilateral training, commonly referred to as "cross-education," has piqued the curiosity of researchers in recent years (1). Several terms have been used to refer to this phenomenon: cross-transfer, cross-effect, cross-training, contralateral-learning, or inter-limb transfer (2, 3). However, according to Davis (4), the most common term in this field is cross-education. The term of "cross-education" is used to express the theory that the effects of practice on one side of body are transferred to the unpracticed side (4).

During unilateral immobility (non-use/orthopedic injury), cross-education (increasing the strength of contralateral and ipsilateral limb, homologous, and heterologous muscles) (5) can be used as a helpful method (6-8). The effects of cross-education are often evaluated either as a change in the strength or skill of the untrained limb (contralateral and ipsilateral limb) compared to the trained limb (as a percentage of the beneficial effects of the trained limb) or evaluated as a percentage of strength increase in the untrained limb relative to early condition (8, 9). Cross-education is limited to the homologous and heterologous muscles (5) of the untrained limb because the effect of cross-education requires the neural contributions of the trained muscles responsible for maintaining cross-education (10).

While there is much evidence about cross-education, in recent years, most studies have shown that different training protocols created varied cross-education results (1, 11-25). It has shown that the rate of increase in strength of the untrained limb varied from 45.2% (26), 30% (15), and 11% (16) to 5% (12) in the untrained limb. It has been indicated that to optimize the improvement of strength of the untrained limb, training plans should include concentric and eccentric exercises with moderate to high volume and enough rest intervals (27). In this regard, also, Manca *et al.* showed that the size of cross-education in the untrained limb had a proportional relationship with the type of contraction (28). They reported that the rate of cross-education of the isometric exercise isometric was (8.2%), concentric (11.3%), eccentric (17.7%), and isotonic dynamic (15.9%) in the untrained limb (28). Cirer-Sastre *et al.* reported that strength training programs with isometric, concentric, eccentric, or mixed contractions significantly affected cross-education; however, eccentric exercises had the highest effect on cross-education (27).

According to the results of mentioned studies in 2017, the occurrence and amount of cross-education in the untrained limb depends on the type of contraction (27, 28). In addition, the specific effects of cross-education are essential for clinicians who wish to use cross-education as a rehabilitation method. So, the specificity of contraction type in unilateral exercise raises concerns about the incidence and rate of cross-education because it hints at the control and adaptation of the brain on movement (29).

Regarding the different protocols of unilateral exercise, including the type of contraction and volume of exercises (number of sets, sessions, frequency, and repetitions of training), two meta-analyses conducted in 2017 showed that the type of contractions and the volume of exercises can affect the occurrence and rate of cross-education (27, 28). On the other hand, studies published from 2017 until now have used different training volumes with contradictory results about the rate and occurrence of cross-education (1, 11-25). Some studies used ten weeks of training in 20 repetitions (26), and some used 4 to 6 weeks of training in 5 to 8 repetitions (12, 15, 30) or several days of training (11) in their training protocol. It appeared that studies about the rate and occurrence of cross-education used different protocols in their training programs yielded contradictory results (1, 11-25). Combining and investigating the results of these studies can help us deduce the best conclusion about the effect of type of contraction and volume of training in cross-education. This review aimed to conclude which unilateral strength training volume (duration, frequency, intensity, and type of contraction) would optimize the strength increase in the untrained limb.

MATERIALS AND METHODS

In this review, based on the PICO method, we searched the database from January 2017 to December 2022 according to the last review studies carried out in 2017(27, 28). We used the keywords: ("cross-education" OR "cross-transfer" OR "cross-training" OR "interlimb transfer" OR "strength transfer") AND ("unilateral strength training" OR "contralateral strength training" OR "resistance training" OR "strength training") in PubMed, Science Direct, Google Scholar, Scopus, Web of Science databases. We included randomized trials in the English language that had a full text. The search strategy for each database is indicated in **appendix 1**.

Studies were selected for review that did not apply any restrictions on the gender of the sample. They used healthy individuals who had not suffered an injury the year before the intervention. The intervention used in these studies was one-sided exercise programs including concentric, eccentric, isometric resistance, and mixed exercises. The studies which used children and people with stroke, orthopedic disease, and surgical injuries were excluded. The studies that used the dominant and non-dominant limbs, homologous and heterologous muscles, as the target of the investigation were excluded. Moreover, articles that used electrical stimulation, transcranial magnetic or direct electrical stimulation, acupuncture, drugs or nutritional supplements, aquatic exercise, mirror therapy, whole-body vibration, immobilization, and stretching exercise were excluded.

The dependent variable in the selected studies was the strength recorded for the untrained limb (contralateral and ipsilateral limb) *versus* the trained limb. Studies were included that mentioned the average power based on MVIC (maximum voluntary isometric contraction), MVC (maximum voluntary contraction), the amount of power, torque, one-repetition maximum (1 RM), and its standard deviation before and after the intervention for both experimental and control groups. Studies that mentioned EMG as an outcome measure were excluded.

RESULTS

Characteristics of the studies

A total of 440 studies were identified (Web of Science: 95, PubMed: 72, Scopus: 99, Google Scholar: 36, and Science Direct: 136). These studies were screened for duplications based on the title and abstract. Of the 255 selected studies, 221 were excluded based on title and inclusion exclusion criteria. Twelve articles excluded based on methodological

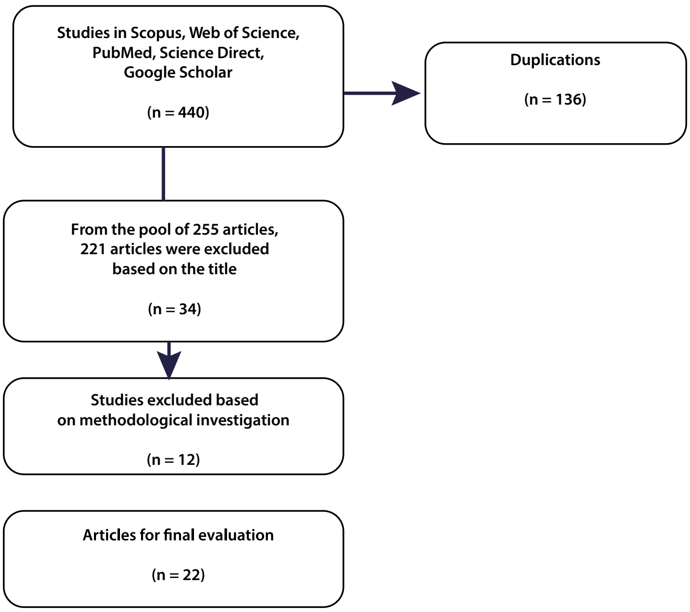

Figure 1. Flowchart of literature search showing the final 22 studies entered into this narrative review.

investigation. So, the final sample of 22 studies was used to conduct a narrative review (**figure 1**).

The results of this review are outlined in **table I**. In this review, the results divided into six parts based on contraction type into: studies with mixed exercise (studies that used aerobic, endurance, and global training as training protocol; the type of contraction is not clarified), compared contractions (studies that compared two contractions such as eccentric *vs* concentric), combined or coupled contraction (studies that added two contractions in one protocol such as eccentric with concentric), isolated eccentric contraction, isolated isometric contraction, isolated concentric contraction, and isolated isokinetic contraction.

Table I. Summary of 22 studies that investigated cross education.

Authors	Participants	Intervention group	Control group	Task/Contraction	load	Week/set/session/repetition	Outcome measure	% cross-education on the untrained side
Sumona Mandal 2022 (21)	-34 - Healthy inactive adult participants -Intervention group: (11 women, 9 men; age: 20.7 ± 1.3, height: 166.2 ± 7.3 cm; weight: 62.8 ± 16.3 kg) -Control group: (8 women, 7 men; age: 21.4 ± 1.8 y; height: 164.4 ± 8.3 cm; weight: 61.5 ± 14.0 kg)	-n = 20 -Calf raises group	-n=14 -Without intervention	-Calf raises -Mixed exercise	70-80% MVC	8/24/3/12	-Concentric and eccentric peak torque and strength via isokinetic in 30°/s and 120°/s	-Strength = 23/4% - Power = 14/6%

Authors	Participants	Intervention group	Control group	Task/Contraction	load	Week/set/session/ repetition	Outcome measure	% cross-education on the untrained side
Coratella 2022 (18)	-60 (Age: 22 ± 4 years, body mass: 60.2 ± 4.3 kg, and stature: 1.64 ± 0.06m) - The participants were not engaged in systematic resistance training for the previous six months	-Unilateral concentric-only (CONC) (n = 15) -Unilateral eccentric-only (ECC) (n = 15) - Concentric– eccentric (TRAD) (n = 15)	-n = 15 -No training	Unilateral strength grip -Concentric -Eccentric -Concentric/Eccentric	- 85%1 RM - 120%1- RM - 90%1 RM	8/6/16/7 -8/5/16/6 -8/4/16/5	Knee extensors isokinetic concentric, eccentric, and isometric peak torque	-CONC: concentric peak torque (9.2%) -ECC: concentric peak torque (11%), Eccentric peak torque (15%), Isometric peak torque (11.3%) -TRAD: concentric peak torque (8.5%), Eccentric peak torque (5.5%), Isometric peak torque(8.6%) -
Bartolomei 2022 (31)	-30 - Participants had a minimum of 2 years of resistance training experience (mean 6 SD, age: 26.4 6 3.3 years, body mass: 76.9 6 6.3 kg, and height: 177.6 ± 5.2 cm) -counterbalanced crossover study	n = 19 -High-intensity group = Bench press -Power group = bench press throw	-n = 11 -Stand quietly for 15 minutes, equal to the time required to perform the experimental protocol	-Bench press - Mixed exercise	-90% 1 RM in 15 minutes, rest 3 min -30%1 RM in 15 minutes with maximum explosive intent, rest 2 minutes	-5set/1 rep -5 set/one rep	-Bench press 1 RM in the post-activation performance enhancement -leg extension force	There was no significant difference between the two types of intervention in leg press extension in the untrained limb.
Aman 2022 (17)	-34 -Thirty-four middle-aged female volunteers (56.05 ± 5.21 years old; 66.88 ± 7.62 kg; 27.70 ± 2.77 kg/m²)	-n = 22 - MRT - DRT	-n = 12 -n = 0 Training	-Lower limb proprioceptive, balance, agility, and resistance exercise -Mixed exercise	10–15 RM	-12/36/60 minutes -12/60/60 minutes	-MVC quadriceps, hamstring, biceps, and trunk muscle	-BURST in hand (biceps) DRT= 45.1% MRT=33.4%
Martinez 2021 (15)	-36 - Men, -Moderately physically active -(Age 21.2 ± 2.76, lean mass 51.49 ± 2.48, height,20.53 ± 2.01)	-1-EG6s n = 12 -2-EG3s n = 11	-n = 13 -No training	-Single-leg decline squat -Eccentric	80%1 RM	6/3/8	-Knee extensor Peak torques (isometric, concentric, eccentric) -1 RM eccentric single-leg decline squat	-Concentric and eccentric peak torques - EG6s :30% - EG3s :21% -Isometric peak torque -EG6s=18% -EG3s=14%
Mendonca 2021 (32)	-30 -Normal body mass index (18.5–24.5 kg/ m²) -Normal blood pressure -Normal fasting glucose levels -normal blood lipids	-HIBFR=dynamic plantar-flexion training interventions (n = 15) - LIBFR with (calf-rotary machine) (n = 15)	-n = 0	-Plantar flexion -2 s concentric/2 s eccentric -1 s concentric/1s eccentric (combined)	-75% of 1 RM -20% of 1 RM	-4/20/4/10 -4/20/4/30+15+15+15	-MVC -Rate of torque development	-MVC=both groups not significant -Rate of torque development = both group (12-26%)

Authors	Participants	Intervention group	Control group	Task/Contraction	load	Week/set/session/ repetition	Outcome measure	% cross-education on the untrained side
Magdi 2021 (26)	-69 -(40 men: 20.1 ± 2.2 ys, 76.1 ± 7.8kg, 178.9 ± 5.7c 29 women: 20.4 ± 2.0yys, 60.2 ± 7.1 kg 165.1 ± 5.6cm. -Physically active individuals engaged in 6–8 h of physical activity per week.	-Accentually unilateral leg press group (n = 46)	-n = 23 -No training	-Accentually unilateral leg press -Coupled concentric combined eccentric contraction (combined)	-Concentric:30%1 RM -Eccentric:105%1 RM	10/4/20/8	-Unilateral leg press and unilateral elbow flexion (1 RM) -MAVIC -Unilateral muscle power at 40, 60, and 80% 1 RM	-Unilateral muscle power at 40, 60, and 80% 1 RM (45.2% in women, (69%) in men) -MVIC (18/2% in women, 32.8% in men) (BURST)
Sato 2021 (19)	32 -Healthy university students -EXT group (age: 20.7 _ 0.9 year; height: 167.1 _ 9.0 cm; body mass: 60.9 _ 11.4 kg) - FLE group (age: 21.4 _ 1.4 year; height: 165.7 _ 7.5 cm; body mass: 58.8_9.9 kg) -Control group (age: 21.1_0.6 year; height: 164.3_6.6 cm; body mass: 57.2_7.9 kg).	-Extended joint training (0°–50°; EXT) with Dumbbell lifting (n = 12) -Flexed joint training (80°–130°; FLE) with Dumbbell lifting (n = 12)	-n = 8 -No training	-Elbow flex/ext - concentric	From 30% (1st session) to 50% (2nd and 3rd sessions), 70% (4th and 5th sessions), 80% (6th and 7th sessions), 90% (8th and 9th sessions), and 100% (10th session) of the MVC-ISO torque at 50° for the EXT, and at 90° for the FLE group	5/10/30	-MVC-ISO -MVC-CON -MVC-ECC	Extension group: -MVC-ISO (15.9 ± 14.8%) -MVC-CON (16.7 ± 20.0%)
Sato 2021 (20)	-31 -Healthy university students - Eccentric training group (5 males, 4 females, age: 21.1 ± 0.9 y, height: 165.9 ± 7.7 cm, body mass: 58.4 ± 8.2 kg) - concentric training group (5 males, 4 females, 20.9 ± 0.6 y, 167.2 ± 7.7 cm, 63.3 ± 10.8 kg) and control group (7 males, 6 females, 20.9 ± 1.9 y, 166.4 ± 8.9 cm, 57.8 ± 7.9 kg).	-Unilateral progressive eccentric training (n = 8) -Unilateral progressive concentric training (n = 8)	-n = 8 -No training	-Elbow flexors With Dum bell -Resistance concentric -Resistance eccentric	-Training load was increased each week from 10 % (week 1), 30 % (week 2), 50 % (week 3), 80 % (week 4), and 100 % (week 5) of MVIC torque for the trained arm.	5/6/10/5	-1 RM of concentric Dum bell curl -MVIC of elbow flexors	-MVIC eccentric training *vs* concentric training (22.7 ± 17.9 % *vs* 12.2 ± 10.2 %) and 1 RM (19.9 ± 14.6 % *vs* 24.0 ± 10.6 %) -MVIC cross-body effect eccentric training *vs* concentric training (90.9 ± 46.7 %) *vs* (49.0 ± 30.0 %).
Pellet 2021 (23)	-50 -Healthy and right-handed participants -26 women, 24 men, aged 19–41 years	-G80=Group 80%+40% 1 RM (n = 16) -G40=Group 40% 1 RM (n = 16)	-n = 16 -No training	-Dumbbell Scott curl -3 seconds Concentric and 3 seconds eccentric (combined)	-80% 1 RM,40% 1 RM -40% 1 RM	4/12/	-Elbow flexion 1 RM in week1 and week4 -MVIC in week1 and week4	-1 RM week 1 = G80(18%) G40 (8.6%) in week1 -1 RM wee4=- Both G80& G40 showed CE -MVIC = there was no significant data (6.67% *vs* 4.12%)

Authors	Participants	Intervention group	Control group	Task/Contraction	load	Week/set/session/ repetition	Outcome measure	% cross-education on the untrained side
Maroto-isquirdo 2021 (33)	-40 -Physically active university students -(EM100:21.3 ± 1.1 y; 76.8 ± 8.2 kg; 180.0 ± 4.6 cm) -(EM150: 21.1 ± 0.6 y; 74.8 ± 6.6 kg; 179.1 ± 6.0 cm) -(FW: 21.4 ± 2.2 y; 75.1 ± 8.9 kg; 175.8 ± 5.9 cm) -Control: 22.7 ± 3.4 y,76.7 ± 11.1 kg, 175.3 ± 5.1 cm)	- Unilateral squat using electric-motor a device with 100% eccentric phase velocity (EM100) (n = 10) - Unilateral squat using electric-motor a device with 150% (EM150) of eccentric phase velocity(n = 10) -Unilateral squat using a conventional flywheel device (FW) (n = 10)	-n = 10 -No training	-Isoinertial squat training -Eccentric/concentric	Isoinertial load (0.05 kg/m²) with 100% velocity and 150 % velocity in the eccentric and concentric phase	6/4/12/7	- Unilateral leg-press 1 RM - Muscle power at 40-80% 1 RM	-Leg press 1 RM strength increased in all training groups (22%-27.8%) -Muscle power in 40% 1 RM in EM150 (6.8%)
Colomer-Poveda 2020 (12)	-42 -Active men 21.8 ± 2.4 yr -Recreational activities included 2-3 h/wk of sports (mostly team sports) or aerobic training -LLF: (20.8 ± 1.3y) -HLLF: (21.4 ± 1.4y) -HLNF:(21.8 ± 1.5y)	-LLF (n = 11) -HLLF (n = 11) -HLNF (n = 11)	-n = 9 -Daily habits activity	-Unilateral knee extension -concentric	-25%1 RM -75%1 RM -75%1 RM	-4/3/5 -4/3/5 -4/6/5	-1 RM -MVIC in knee extensor	-1 RM -HLLF: 5% - HLNF: 6 % in
Hill 2020 (34)	-36 - College-aged women (mean age ± SD = 22 ± 2 yrs; height = 166.0 ± 5.7 cm; body mass = 64.2 ± 6.3 kg)	-Ecc-BFR (n = 12) - Con-BFR (n = 12)	-n = 12 -No intervention	-Forearm flexion -Resistance eccentric isokinetic -Resistance concentric isokinetic	75 eccentric and concentric isokinetic at 120. s -1	4/12/4 /75	-Eccentric peak torque -concentric peak torque -Maximal voluntary isometric contraction torque -Muscle activation in the second and forth weeks	Ecc-BFR: 13% increase in muscle strength in the forth week & 4.9% in the second week
Carr 2019 (35)	-20 -Participants had not engaged in programmed resistance training for at least three months before enrollment -Intervention group:(Three female, two left-hand dominants; age = 23.0 ± 2.0 years, stature = 175.9 ± 10.2 cm, mass = 74.3 ± 10.1 kg) -Control group:(three females, Two left-hand dominants; age = 25 ± 3 years, stature =177.2 ± 0.4 cm, mass= 3.2 ± 15.3 kg)	-Unilateral elbow flexors Strength training (n = 10)	-n = 10 -Without training	-Unilateral elbow flexion -Isometric	80% MVC	4/5/11/5	-MVC strength	-MVC –Strength in week 4 = 49.2% - MVC –Strength in week 2 = 22.3%

Authors	Participants	Intervention group	Control group	Task/Contraction	load	Week/set/session/ repetition	Outcome measure	% cross-education on the untrained side
Tseng 2019 (16)	-48 -healthy men who had not performed any structured regular resistance, aerobic, or flexibility training in the past 1 yr, and who did not carry heavy objects frequently in their daily activities and had no musculoskeletal injuries of the upper extremities -23.2 ± 2.5 yr, 172.6 ± 4.6 cm, 69.4 ± 8.2 kg	-Ipsilateral elbow flexor training at 10%, 30%, 50%, 80%, and 100% of MVC 1-Eccentric training (n = 12) 2-progressive concentric training (n = 12) 3- Il-RB (n = 12) 4-Cl-RB (n = 12)	-The average of the two groups (IL-RB) and (CL-RB)	-Elbow flexion -Eccentric -Concentric	10% to 100% of MVC, followed by 30 maximal eccentric contractions (30maxec) of the untrained elbow flexor one week later	5/5/ 5/6	MVC	MVC -Eccentric (11%) -Concentric (5%)
Farinas 2019 (13)	-35 21-38 years -Traditional group = (24 ± 5 yr, 173 ± 8 cm,3women; 8 men) -Cluster group: (24 ± 2yr,175 ± 9 cm, 4 women; 8 men) -Control group: (23 ± yr,173 ± 10 cm, 5 women; 7 men)	-Traditional training (n = 12) -Cluster training (n = 11)	-n =12 - No training	-Biceps curl -Mixed exercise	-10RM pre-test load	5/5 /10/6/135s rest 5/5/10/30/18.5s rest	-1 RM - (n10RM), -MVC	1 RM -Traditional training:(7.3%) -Cluster training: (6.5%)
Pietrangelon 2019 (36)	-31 - Healthy male (71.77 ± 4.06 years, 80.47 ± 12.09 kg, 1.67 ± 0.08 m) -Reporting current physical inactivity	-Endurance training, vigorous-intensity aerobic activity (n = 10) -Resistance training, leg-press, and leg-extension machines (n = 11)	-n = 10 -No training	-Leg press and leg extension -Mixed exercise	-Endurance training: 0.6– 0.7 of HRtr (1st–4th week, 30' pedaling; 5th–8th week: 40' pedaling) or 0.8 of HRtr (9th–12th week: 40' pedaling) -Resistance training: 1 RM: 1st–4th week, 12 repetitions at 60% 1 RM; 5th–8th week, 10 repetitions at 70–75% RM; 9th–12th week, 6–8 repetitions at 80% RM	-20 min on three days each week -12 / / 6-12	-MVC in leg extension -Hand grip strength	-HS in endurance training (20%) -MVC in resistance training (10%) (BURST)
Neltner 2019 (37)	-27 -Right hand dominant and had no shoulder pathology within the last year - Age: 21.37 ± 2.02 years; height: 167.85 ± 7.63 cm; mass: 74.42 ± 16.73 kg	- Right arm unilateral training (n = 13)	-n = 14 -No training	-Shoulder internal and external rotation -Isokinetic 60, 180, and 300° /s, w	- 10 maximal concentric repetitions of internal/external shoulder rotation	2/4/3/30	Average power in the left arm	There is no significant increase in the untrained limb

Authors	Participants	Intervention group	Control group	Task/Contraction	load	Week/set/session/ repetition	Outcome measure	% cross-education on the untrained side
May 2018 (38)	-24 -Recreationally active young men -BFR (22.6 ± 3.3, 177.6 ± 9.5, 73.0 ± 13.6) -Non-BFR -(22.1 ± 2.5,174.1 ± 6.7,72.4 ± 11.2)	-BFR resistance training group (n = 12)	-n = 12 -Non-BFR training	-Unilateral bicep curls followed by bilateral knee extension and bilateral knee flexion exercise – Mixed exercise	50% 1 RM, then in bilateral knee extension and flexion exercises 30% 1 RM.	7/20/3/10 rep in 50% 1 RM and 30 rep in 30% 1 RM, followed by three sets of 15 rep	1 RM strength using bilateral leg exercises and unilateral bicep curls	There is no significant increase in the untrained limb
Brass 2017 (11)	-20 -Participants had previous experience with resistance training but was instructed not to begin or change their physical activity for the duration of the study -Traditional group:(6 female; 5 male, 24.0 ± 3.0 years, 169.5 ± 10.5 cm, 70.6 ± 14.5 kg) -Daily training:(2 female; 6 male, 22.5 ± 3.5 years, 175.6 ± 9.4 cm, 76.8 ± 14.3 kg)	1-Traditional handgrip training group (n = 11) 2-Daily unilateral handgrip training (n = 8)	-n = 0	-Handgrip -Isometric	Maximum 100% 1 RM	-6/5/3/5 -18 day/5/18/5	-MVC in wrist extensors and flexors -Muscular activation (EMG) in wrist extensors and flexors	-TT: Peak handgrip force (12.5%) -DT: Peak handgrip force 7.8%) -TT: Peak wrist extension and flexion: 32/6/%/ 19/2% TT: Average muscle activity: for FCR (5/2%) and ECR (9/2%)
Boyes 2017 (25)	-19 -Young, healthy adults -Right-handed participant -HF:(age ,24.9 ± 3.9, weight,75.6 ± 13.7, height,174.7 ± 9.2) -LF: (age ,24.6 ± 6.3, weight,74.4 ± 10.2, height,171.5 ± 9.1)	-High Frequency (n = 10) - Low Frequency (n = 9)	-n = 0	-Right-hand Handgrip -Isometric	-90%–100% handgrip MVIC	-4/2 set *6 repetitions 10 times per week =120 -4/5 set *8 repetitions three times per week = 120	- Left-hand grip MVIC -MVC wrist flexion	-HF hand grip: 8.4% in the left limb -LF: hand grip 9.0% in the left limb
Hedayatpour 2017 (39)	-30 -Healthy male subjects (age, mean ± SD, 24.2 ± 1.9 yr., body mass 71.3 ± 10.5 kg, height 1.75 ± 0.05 m) with no history of knee injury or trauma	-High load-low repetition eccentric group (n = 15) -Low load-high repetition concentric group (n = 15)	-n = 0	-Leg press -Eccentric -Concentric	-120% 1 RM -60% 1 RM	-12/3/5 -12/3/10	MVIC in quadriceps	-27% -17%

BFR: blood flow restriction; BURST: Bottom–Up Rise Strength Transfer; CON: concentric; CONC: concentric; (CL-RB): contralateral repeated boot DRT: distributed resistance training; DT: daily training; EMG: electromyography; EG3 s: eccentric group hold of contraction 3 seconds; EG6 s: eccentric group hold of contraction 6 seconds; ECC: eccentric; EM: electric motor; FW: flywheel device; HR tr: Heart rate training; HLF: high load resistance training to failure; HLNF: high load resistance training not to failure; (IL-RB): ipsilateral repeated bout; ISO: isometric; LBFR: low-intensity blood-flow restricted; LLF: low load resistance training to failure; n: number MVIC: maximum voluntary isometric contraction; MRT: massed resistance training; 1 RM: 1 repetition maximum; TRAD: traditional.

Mixed exercise

Out of 22 studies, six studies evaluated the effects of mixed exercise (not clarified the type of contraction) in the form of resistance or non-resistance contraction (13, 17, 21, 31, 36, 38). Exercises in this group could induce significant cross-education in volume: (5-12 weeks, 5 sets, 10-60 sessions, 5-30 repetitions, 70% 1 RM-100% 1 RM or 70-100% MVC or 10-15 10 RM). In other words, training load with high intensity if applied in low volume (*i.e.*, 90% 1 RM in 5 set/1 repetitions) could not create a significant cross-education (12, 31). Aman *et al.* showed that the training protocol distributed in weekly sessions could produce more cross-education than mass training (17). In line with this result, Farinas *et al*. reported that if the rest time between repetitions increases, the cross-education will be increased (13). Pietrangelo demonstrated that resistance training with a volume above 60% 1 RM could produce cross-education in MVC of the untrained side (36). In contrast, May *et al*. showed that training volume with 50% 1 RM in seven weeks and 20 sessions could not produce a contralateral effect on the untrained side (38). The range of induced cross-education was between 6.5-45%. Of course, two studies in this section (17, 36) investigated Bottom-Up Rise Strength Transfer (BURST) that has increased the rate of cross-education (28). We discussed more about BURST in following sections.

Compared contractions

Five studies compared eccentric and concentric exercises (16, 18, 20, 33, 39). The training volume was between 5-12 weeks,5-16 sessions, 5-10 repetitions, and 10-100% 1 RM for concentric and10-120% 1 RM for eccentric contraction. The range of created CE via eccentric exercise was between 11%-27%. The range of created cross-education via concentric exercise was between 5-27%. Corotella *et al*. compared eccentric and concentric contractions with an intensity of 85% 1 RM for concentric contraction and 120% 1 RM for eccentric contraction, and 90% 1 RM for traditional eccentric/concentric contractions (18). They reported that eccentric contraction was the most effective in improving peak torque in the form of concentric, eccentric, and isometric torques (18). In line with these results, other studies (16, 20, 39) also reported that eccentric contraction is more effective than concentric contraction in cross-education. Tseng *et al.* showed ipsilateral elbow flexor training at 10%, 30%, 50%, 80%, and 100% of MVC in four group eccentric training, progressive concentric, ipsilateral-repeated bout, and contralateral repeated bout at volume of training in 5 weeks, 5 sets, 5 session, and 6 repetitions, could produce cross-education as much as 11% in only eccentric contraction group (16). Sato *et al.* showed unilateral progressive eccentric training in form of elbow flexion at weekly increased load from 10% (week 1), 30% (week 2), 50% (week 3), 80% (week 4), and 100% (week 5) of MVIC for the trained arm at a volume of training in 5 weeks, 6 sets, 10 sessions and 5 repetitions could produce cross-education in MVIC as much as 22% *vs* 12% than concentric training group (20). Of course, this rate is lower in eccentric contraction group than concentric contraction group in 1 RM concentric elbow curl measures (19% *vs* 24%) (20). Hedayatpour *et al.* showed high load-low repetition eccentric contraction in 12 weeks, 3 sets, and 5 repetitions in 120% 1 RM could produce more cross-education than concentric training group at 60% 1 RM intensity, 12 weeks, 5 sets, and 10 repetitions (39). Maroto-isquirdo *et al.* reported that eccentric contractions that carried out with squat using electric-motor at 100% and 150% eccentric phase velocity, in each phase of concentric and eccentric contraction, in form of unilateral squat training, are effective in induced cross-education to the same extent (33).

Coupled contraction

Four studies investigated coupled eccentric and concentric contraction (23, 26, 32, 33). Mendonca *et al.* reported that combined eccentric and concentric contraction at either high or low intensity (80 *vs* 20% 1 RM) during four weeks could not produce cross-education in MVIC, but could produce cross-education in the rate of torque development as much as 12-26% (32). Magdi *et al*. reported that combined eccentric/concentric contraction with an intensity of 30% 1 RM and 105% 1 RM in the lower limb could produce cross-education as much as 45.2% and 69% in the power of women and men regularly. Also, they reported that this increment in MVIC was as much as 18.2% in women, and 32.8% in men, regularly (26). Maroto-isquirdo also reported that a combination of eccentric/concentric contraction could produce cross-education as extent as eccentric-only training (33). The training volume was between 5-12 weeks,10-36 sessions, 5-8 repetitions, 10-105%1 RM intensity (33). Pelet *et al.* reported dumbbell Scott Curl in 3 seconds concentric and 3 seconds eccentric contraction at 40+80% 1 RM intensity could produce more cross-education in 1 RM measures than 40% 1 RM training group in week 1 of training (18% *vs* 8.6%) (23). This rate was similar in both group in week 4 of training in 1 RM measure (23). On the other hand, Pelet *et al.* showed MVIC measures did not differ between two groups in term of cross-education (23) The range of created cross-education via combined exercise was between 8.6%-69%.

It is important to notice the new phenomena in this section. Four studies investigated the lower to upper effects of unilateral training (17, 20, 26, 36). These studies investigated the cross-education in the form of Bottom-Up Rise Strength Transfer (BURST). It was reported that the rate of BURST is more than contralateral effects. Sato *et al.* reported training load that was increased each week from 10% (week 1), 30% (week 2), 50% (week 3), 80% (week 4), and 100% (week 5) of MVIC for the trained arm in volume of 5 weeks, 6 sets,10 sessions, and 5 repetitions could produce BURST as much as 90.9% in eccentric training *vs* 49.0% in concentric training group (20). Magdi *et al.* reported accentually unilateral leg press in form of coupled concentric (30% RM) combined eccentric (105% 1 RM) contraction in 10 weeks, 4 sets, 20 sessions and 8 repetitions could produce the induced BURST in 1 RM as much as 45.2% in women, 69% in men and induced BURST in MVIC as much as 18.2% in women, 32.8% in men (26). Pietrangelo *et al.* reported the endurance training with intensity 0.6-0.7 of target heart rate (1^{st}-4^{th} week: 30' pedaling; 5^{th}-8^{th} week: 40' pedaling) or 0.8 of target heart rate (9^{th}-12^{th} week: 40' pedaling) could produce BURST in hand strength as much as 20% and resistance training with intensity, 1^{st}-4^{th} week, 12 repetitions at 60% 1 RM; 5^{th}-8^{th} week, 10 repetitions at 70-75% RM; 9^{th}-12^{th} week, 6-8 repetitions at 80% RM could induced BURST as much as 10% in MVIC measures (36). Aman *et al.* reported the lower limb proprioceptive, balance, agility, and resistance exercise with intensity 10-15 1 RM, in 12 weeks, 60 sessions in 60 minute (distributed resistance training) could produce more cross-education (45.1%) than massed resistance training that carried out in 36 sessions (33.4%) (17).

Eccentric contraction

Studies in this section overlap with the above section because many studies compared eccentric exercise with eccentric or combined eccentric with concentric exercises. Only one study investigated eccentric contraction (15). Martinez *et al.* showed single leg decline squat at 80% 1 RM in eccentric contraction, 6 weeks,3 sets, and 8 repetitions could produce more cross-education in 6 seconds holding contraction time than 3 seconds holding contraction time (15). The range of induced cross-education was between 18-30%.

Concentric contraction

Such as above (only eccentric contraction group) the studies in this section have overlap with compared contraction section studies. Only two studies investigated concentric contraction on cross-education (12, 19). Colomer-Poveda *et al.* showed unilateral knee extension with 75% 1 RM intensity group in 4 weeks, 3 or 6 sets, and 5 repetitions could produce cross-education more than 25% 1 RM intensity load group (12). This rate is significant in 1 RM measures of cross-education, not in MVIC measures (12). According to Sato *et al.*, cross-education was only produced by the elbow extension group, reaching as high as 15.9% in MVIC-isometric and 16.7% in MVIC-concentric (19) when the load was incrementally increased from 30% to 100% MVIC-isometric over the course of five weeks, ten sessions, and thirty repetitions.

Isometric contraction

Three studies evaluated the effect of isometric contraction on cross-education (11, 25, 35). Carr *et al.* reported that unilateral elbow flexion with 80% 1 RM could produce cross-education as much as 22.3% in the second week of 4 weeks of training and 49% in the fourth week of training protocol (35). Barss *et al.* showed, however handgrip training in 100% 1 RM in 6 weeks could induce cross-education as much as 12.5%, but could induce a lesser amount of cross-education in 18 days of training with 100% 1 RM (7.8%) (11). Boys *et al.* reported handgrip isometric training in 80-100% 1 RM in high and low training frequency (10 times a week *vs* three times a week) could make cross-education in MVIC hand grip alike (8.2% *vs* 9%) (25). The amount of isometric training volume in these studies was 18 days, 6 weeks, five sets, 15-120 sessions, and 5-8 repetitions. The range of cross-education in this group was between 5.9%-49%.

Isokinetic contraction

Out of 22 studies, two investigated isokinetic contraction in the form of isokinetic concentric or isokinetic eccentric contraction (34, 37). Neltner *et al.* reported that concentric exercise in the form of isokinetic could not induce cross-education (37). On the other hand, Hill *et al.* stated that eccentric contraction in the form of isokinetic could induce cross-education; in contrast, concentric contraction in the form of isokinetic could not induce cross-education (34). Isokinetic eccentric contractions in 4 weeks, 12 sessions, four sets, and 75 repetitions could induce cross-education as much as 4.9%-13%.

DISCUSSION

This review aimed to infer which volume of unilateral strength training (duration, frequency, intensity, sets, and sessions) and type of contraction optimizes the increase in strength on the untrained limb. Our results indicated that the organization of training content interacts with the increase in strength observed on the untrained side. The result showed that the combination of the eccentric and concentric exercise was the most effective type of contraction, and eccentric, isometric, mixed, concentric, and isokinetic contractions were effective regularly. Besides, the eval-

uation of BURST showed more significant cross-education than the evaluation on the contralateral side.
In addition, the results indicated that training volumes with more than four weeks, distributed sessions, and more rest between repetitions could assist in producing more cross-education. This review suggests that type of contraction has priority over the volume of training on cross-education because the studies that investigated isokinetic contraction have used approximately similar volume to studies that investigated isometric contraction but showed a lower rate of cross-education than isometric group (4.9%-13% *vs* 5.9%-49%).

Mixed exercise

This review showed mixed exercise in the form of traditional, cluster, or other types of exercises in an intensity range (705% 1 RM-100% 1 RM) could produce cross-education as much as 6.5-45% (13, 17, 21, 31, 36, 38). This review has also shown that if exercises are applied with a high intensity, such as 90% 1 RM, but in low volume (5 set/1 rep), could not significantly produce cross-education (31). Then, it seems the multiplying training intensity by the training volume in cross-education could not assist cross-education. Nevertheless, it has been shown that exercises with higher intensity and higher volume could produce a significant cross-education (27) because the higher intensity and volume of training can activate the same hemisphere (40, 41) and reduce the inhibition between the two hemispheres (40). On the other hand, low-intensity exercises usually cannot create a stimulus for the ipsilateral hemisphere, so it affects cross-education rarely (40, 41).

Eccentric *vs* concentric contraction

This review demonstrated that eccentric contraction was more effective than concentric contraction in cross-education size. The range of cross-education effects created via this training protocol was eccentric (11-27%) compared to concentric exercise (5-27%) exercise (16, 18, 20, 33, 39). In addition, in section of only eccentric contractions and only concentric contraction, the rate of induced cross-education in eccentric contraction (18%-30%) (15) is more than only concentric contraction section (5%-16.7%) (12, 19). In agreement with these results, two review studies demonstrated that eccentric contraction was more effective than concentric contraction in cross-education (27, 28). The reason for this may be related to neuromuscular adaptations (42), mutual effects of more intra-cortical facilitation, and reduction of intra-cortical inhibition that eccentric exercise produces (43, 44). It was reported that following eccentric-only *vs* concentric-only training, corticospinal excitability increased more during the eccentric peak torque, with no change observed during the concentric peak torque (44). Additionally, corticospinal and intra-cortical inhibition was overall reduced following eccentric-only, but not concentric-only training (44). Interestingly, performing maximal eccentric actions was also shown to increase the activity of the central nervous system (45), so it is plausible that more significant inter-hemispheric stimuli occurred (10).

Coupled contraction

One of the remarkable points in this review is the combined effect of concentric and eccentric contractions on cross-education, which caused cross-education to 12%-69% (23, 26, 32, 33). Of course, a high increment in the rate of cross-education was only observed in the Magdi's *et al*. study because they evaluated the effects of accentuated unilateral leg training (concentric and eccentric) with an intensity of 30+105% 1 RM on the ipsilateral non-trained arm, not on the untrained leg (26). Otherwise, Mendonca *et al*. and Maroto-isquirdo *et al*. investigated the contralateral side of the trained limb (32, 33). It has been reported that the magnitude of the cross-education gains largely depends on those obtained ipsilaterally rather than contralaterally (28). It has been also showed that BURST induced neural changes in the strength of the untrained side and other untrained areas of the body (26). Moreover, accentuated eccentric loading exercises increase the secretion of insulin-like growth factors, testosterone, and anabolic regulatory factors, which can cause a general effect on the whole body, especially the untrained side, and improve cross-education (46).
According to these findings, Sato *et al.* (20), Pietrangelo *et al.* (36), and Aman *et al.* (17) also examined BURST in their studies in addition to Magdi *et al.* (26). They also reported a high amount of cross-education in BURST (90% in Sato *et al*., 45% in Aman *et al*., and 18-69% in Magdi *et al.*). Pietrangelo *et al*. reported an amount of BURST as much as 20%, which was lower than other studies (36). Because they used endurance training to induce cross-education and resistance training in different intensities (from 60% 1 RM, to 80% 1 RM in 8th-12th weeks), as we expressed earlier, training with lower than 70% 1 RM cannot induce cross-education effectively.

Isometric contraction

This review showed that the range of cross-education via isometric contraction protocols was between 5.9%-49% (11, 25, 35). There is a large amount of cross-education (49%) in Carr *et al.* study (35). One of the reasons for the higher amount of cross-education in the Carr's *et al*. study is that the non-dominant side was trained, and the dominant side was investigated (35). Studies have shown that exercises on the dominant side can be more effective than on the non-dominant side in cross-education (47, 48). In Carr's *et al*. study, also, cross-education was reported in the second week of 4 weeks of training and measured weekly, which creates an additional motor learning stimulus (35). It was reported that the measure of cross-education at an earlier time of intervention could be a factor in increasing the amount of crossed education (47, 48). Furthermore, Barss *et al.* showed that isometric contractions at 100% 1 RM intensity at six weeks of training protocols in 18 sessions had a few more effects on the cross-education than 18 days of training in 18 sessions (7.8 *vs* 12.5%) (11). In this regard, Boys *et al.* reported that both high and low-frequency isometric training with 90-100% 1 RM could produce approximately similar cross-education (8.4% *vs* 9%) (25). Boys *et al.* and Barss *et al.* results contradict the mentioned results in the mixed contraction group that higher intensity and volume of exercise create more cross-education than low-intensity and low-volume exercise. These contradictory results may originate from physiological and biomechanical differences between isometric and dynamic movements. In dynamic movements, cross-bridges have a greater connection (49, 50) and a higher discharge rate for motor units (51, 52) compared with isometric movements. In dynamic movement, also, antagonists are activated (53), while in isometric movement, the agonist is predominantly recruited, and the antagonist plays a minimal role (54). This suggests that the mechanisms which contribute to enhanced cross-education of dynamic strength seem unrelated to the mechanisms which contribute to enhanced cross-education of isometric strength.

Suggestion for future research

It suggested that future studies compare two sex (male or female), since, according to Magdi *et al.*, effect of cross-education varied between men and women (26). Moreover, future studies can be conducted at varied ages (youth or children *vs* adults) since according to Chaouachi *et al.* (55), children or youth people differently reacted to cross-education. Future research should also be conducted to separate the type of contraction in outcome measures of testing protocols.

CONCLUSIONS

This review showed that organized exercises in a more significant number of sessions and higher intensity of 1 RM (above 70% 1 RM) training could increase the strength of the untrained limb. The effects of contraction type in a combination of contractions (concentric+eccentric) on cross-education (8.6%-69%) had more effect on cross-education than isometric (5.9%-49%), mixed (6.5%-45%), eccentric (18%-30%), and concentric contractions (5-16.7%). Evaluation of BURST has indicated more significant amounts of ipsilateral untrained limb effects than only contralateral effects. Effects of training on the strength of ipsilateral untrained limb showed more significant increase than contralateral limb. In the other word, If we want to improve the strength of the untrained limb, it is better to train the limb on the immobile side by combining eccentric and concentric contractions.

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DATA AVAILABILITY

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CONTRIBUTIONS

MMR: conceptualization. MM, MMR, PS: methodology. MM, AD: investigation. MM, PS: data analysis. MM, AD, MMR: writing - original draft. MM, AD: writing - review and editing.

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CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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SUPPLEMENTS

Appendix 1. Search strategy for each database.

PubMed: 72

Search: (((((“cross-education”[Title/Abstract]) OR (“cross-transfer”[Title/Abstract])) OR (“cross-training”[Title/Abstract])) OR (“interlimb transfer”[Title/Abstract])) OR (“strength transfer”[Title/Abstract])) AND ((((“unilateral strength training”[Title/Abstract]) OR (“contralateral strength training”[Title/Abstract])) OR (“resistance training”[Title/Abstract])) OR (“strength training”[Title/Abstract])) Filters: from 2017/1/1 - 2022/12/1 =72

Scopus: 99

(TITLE-ABS-KEY(“unilateral strength training”) OR TITLE-ABS-KEY(“contralateral strength training”) OR TITLE-ABS-KEY(“strength training”) OR TITLE-ABS-KEY(“resistance training”)) AND (TITLE-ABS-KEY(“strength transfer”) OR TITLE-ABS-KEY(“interlimb transfer”) OR TITLE-ABS-KEY(“cross-education”) OR TITLE-ABS-KEY(“cross-training”) OR TITLE-ABS-KEY(“cross-transfer”)) AND (LIMIT-TO (PUBYEAR,2022) OR LIMIT-TO (PUBYEAR,2021) OR LIMIT-TO (PUBYEAR,2020) OR LIMIT-TO (PUBYEAR,2019) OR LIMIT-TO (PUBYEAR,2018) OR LIMIT-TO (PUBYEAR,2017))=99

Web of Science: 94

(((TS=(“cross-transfer”)) OR TS=(“interlimb transfer”)) OR TS=(“cross-education”)) OR TS=(“cross-training”) AND (((TS=(“contralateral strength training”)) OR TS=(“unilateral strength training”)) OR TS=(“strength training”)) OR TS=(“resistance training”) AND 2022 or 2021 or 2020 or 2019 or 2018 or 2017

Science Direct: 136

(“cross-transfer” OR “interlimb transfer” OR “cross-education” OR “cross-training”) AND (“contralateral strength training OR “unilateral strength training” OR “strength training” OR “resistance training”), year: 2017-2022

Google Scholar: 39

(“cross-transfer” OR “interlimb transfer” OR “cross-education” OR “cross-training”) AND (“contralateral strength training OR “unilateral strength training” OR “strength training” OR “resistance training”), year: 2017-2022