Table 1 - Excluded studies (n = 33)

Authors (# Ref)	Year	Title	Reason for exclusion
Abazovíc et al. (2)	2015	The effect of training of the non-dominant knee muscles on ipsi- and contralateral strength gains	No neurophysiological data reported
Beyer et al. (4)	2016	Short-term unilateral resistance training results in cross education of strength without changes in muscle size, activation, or endocrine response	Full body training
Coratella et al. (13)	2015	Cross-education effect after unilateral eccentric-only isokinetic vs dynamic constant external resistance training	No neurophysiological data reported
Dragert and Zehr (14)	2011	Bilateral neuromuscular plasticity from unilateral training of the ankle dorsiflexors	Absence of a no-training control group
Farthing et al. (18)	2007	Neuro-physiological adaptations associated with cross-education of strength	Absence of a no-training control group
Farthing and Chilibeck (19)	2003	The effect of eccentric training at different velocities on cross-education	Neurophysiological measure employed only acutely (EMG)
Frazer et al. (24)	2017	Cross-education of muscular strength is facilitated by homeostatic plasticity.	Absence of a no-training control group
Goodwill and Kidgell (26)	2012	The effects of whole-body vibration on the cross-transfer of strength	Same dataset of another included study
Hendy et al. (30)	2015	Anodal transcranial direct current stimulation prolongs the cross-education of strength and corticomotor plasticity	Absence of a no-training control group
Hortobagyi et al. (32)	1996	Greater initial adaptations to submaximal muscle lengthening than maximal shortening	Not a cross-education study

Housh et al. (38)	1996	Effects of eccentric-only resistance training and detraining	No neurophysiological data reported
Housh et al. (39)	1996	Effects of unilateral concentric-only dynamic constant external resistance training	No neurophysiological data reported
Jensen et al. (41)	2005	Motor skill training and strength training are associated with different plastic hanges in the central nervous system	Not a cross-education study
Kannus et al. (42)	1992	Effect of one-legged exercise on the strength, power and endurance of the contralateral leg	No neurophysiological data reported
Khouw and Herbert (45)	1998	Optimisation of isometric strength training intensity	Absence of a no-training control group
Komi et al. (51)	1978	Effect of isometric strength training of mechanical, electrical, and metabolic aspects of muscle function	Enrollment of subjects in developmental age
Leung et al. (59)	2015	Motor cortex excitability is not differentially modulated following skill and strength training	Acute training
Magnus et al. (60)	2010	Effects of cross-education on the muscle after a period of unilateral limb immobilization using a shoulder sling and swathe	Unilateral limb immobilization
Manca et al. (63)	2015*a*	A comprehensive assessment of the cross-training effect in ankle dorsiflexors of healthy subjects: A randomized controlled study	No neurophysiological data reported
Manca et al. (64)	2015*b*	Characterization of ankle dorsiflexors performance in healthy subjects following maximal-intensity isokinetic resistance training	No neurophysiological data reported
Meyers (67)	1967	Effects of two isometric routines on strength, size, and endurance in exercised and nonexercised arms	No neurophysiological data reported
Munn et al. (72)	2005	Training with unilateral resistance exercise increases contralateral strength	No neurophysiological data reported
Palmer et al. (73)	2013	Structural brain changes after 4 wk of unilateral strength training of the lower limb	No neurophysiological data reported
Pearce et al. (74)	2013	Corticospinal adaptations and strength maintenance in the immobilized arm following 3 weeks unilateral strength training	Unilateral limb immobilization

Sariyildiz et al. (83)	2011	Cross-education of muscle strength: cross-training effects are not confined to untrained contralateral homologous muscle	No resistance training administered (the intervention consisted of electrical muscle stimulation)
Shaver et al. (84)	1970	Effects of training on relative muscular endurance in ipsilateral and contralateral arms	No neurophysiological data reported
Shaver et al. (85)	1975	Cross transfer effects of conditioning and deconditioning on muscular strength	No neurophysiological data reported
Uh et al. (91)	2000	The benefit of a single-leg strength training program for the muscles around the untrained ankle: A prospective, randomized, controlled study	No neurophysiological data reported
Vercauteren et al. (93)	2008	Unimanual muscle activation increases interhemispheric inhibition from the active to the resting hemisphere	Acute training
Weier et al. (94)	2012	Strength training reduces intracortical inhibition	Not a cross-education study
Weir et al. (95)	1995	The effect of unilateral eccentric weight training and detraining on joint angle specificity, cross-training, and the bilateral deficit	No neurophysiological data reported
Weir et al. (96)	1997	The effect of unilateral concentric weight training and detraining on joint angle specificity, cross-training, and the bilateral deficit	No neurophysiological data reported
Zult et al. (101)	2016	Mirror training augments the cross-education of strength and affects inhibitory paths	Mirror training paradigm

Table 2. Characteristics of the studies included in the qualitative analysis (*n* = 22).

Reference	*Subjects*	*Muscle Group*	*Intervention*		*Neurophysiological measures*	*Changes in neurophysiological measures*		*Testing mode*	*Change in contralateral strength (95% CI)*	
						Untrained side	*Trained side*		*#Within Subjects*	*§Between Groups*
Cannon and Cafarelli (1987) (5)	16 participants (7 control subjects, 9 experimental subjects); Age: n.s. Gender: n.s.	Thumb adductors	Isometric: 15 reps X 3- 4-s MVC; 3/wk X 5 wks		EMG	=	=	Isom	9.5%* (0.1 to 19.1)	9.1 (-5.8 to 24.0)
Carolan and Cafarelli (1992) (6)	20 sedentary males (10 control subjects, 10 experimental subjects) Age: 21.8±0.8 yrs	Knee extensors	Isometric: 30 reps X 3- 4-s MVC; 3/wk X 8 wks		EMG	=	=	Isom	16.2%* (-6.3 to 38.7)	18.2 (-2.9 to 39.3)
Coombs et al. (2016) (12)	23 participants [7 control subjects, 16 experimental subjects (8 to right hand training, 8 to left hand training)] Age range: 18-36 yrs Gender: 11 males, 12 females	Wrist extensors	Isotonic: 6-8 reps X 4 sets at 70% 1RM with a weighted dumbbell, with increments by 5%; 3/wk X 3 wks	Arm 1: Left hand	M-wave MEP cSP (120% AMT) cSP (130% AMT) cSP (140% AMT) SICI	= ↓ = ↓ = =	= = ↓* ↓ ↓ =	1-RM	15.9%* (9.0 to 22.8)	14.9* (9.2 to 20.6)
				Arm 2: Right hand	M-wave MEP cSP (120% AMT) cSP (130% AMT) cSP (140% AMT) SICI	= ↓* = ↓* ↓* =	= = ↓ ↓ ↓ =	1-RM	10%* (5.7 to 14.3)	9.0* (5.4 to 12.6)

Evetovich et al. (2001) (16)	20 males (9 control subjects, 11experimental subjects) Age: 22.2±2.8 yrs	Knee extensors	Isokinetic concentric at 90°/s: 6–8 reps MVC X 3–6 sets (periodization principle); 3/wk X 12 wks		EMG	=	=	Isok	5.5%* (1.7 to 9.3)	4.5 (-0.8 to 9.8)
Farthing et al. (2005) (20)	39 right-handed females [14 control subjects, 25 experimental subjects (13 to left-hand training, 12 to right-hand training)] Age: 20.8±0.4 yrs	Left ulnar deviators	Isometric training (arm 1: left wrist; arm 2: right wrist): 8 2-s reps MVC X 2-6 sets (periodization principle); 4/wk X 6 wks		EMG	↓*	↑*	Isom	-7.4% (-10.4 to 25.2)	-3.0 (-38.6 to 32.6)
		Right ulnar deviators			EMG	↓*	↑*	Isom	39.0%* (11.3 to 66.7)	28.6 (-11.7 to 68.9)
Fimland et al. (2009) (23)	26 recreationally active subjects (11 control subjects, 15 experimental subjects) Age: 24±2 yrs Gender: 9 males, 17 females	Ankle plantarflexors	Isometric: 6 sets X 6 (4-s) reps MVC; 4/wk X 4 wks		EMG M-wave H-reflex V-wave	↑* = = ↑*	↑* = = ↑*	Isom	27.3%* (6.4 to 48.2)	34.0* (5.4 to 62.6)
Garfinkel and Cafarelli (1992) (25)	15 sedentary females (7 control subjects, 8 experimental subjects) Age: 21.9±2.7 yrs	Knee extensors	Isometric: 3 sets X 10 X 3- to 5-s MVC; 3/wk X 8 wks		EMG	=	=	Isom	3.0% (-7.9 to 13.9)	3.1 (-10.2 to 16.4)
Goodwill et al. (2012) (27)	14 healthy subjects (7 control subjects, 7 experimental subjects) Age range: 18-35 yrs Gender: 7 males, 7 females	Lower limb (single leg squat)	Isotonic: 6-8 reps X 4 sets progressed from 80% to 82.5% to 85% of 1 RM; 3/wk X 3 wks		MEP RC (peak height) SICI	↑* ↑* ↓*	↑* ↑* ↓*	1-RM	35.4%* (21.2 to 49.6)	34.4* (20.8 to 48.0)
Hortobagyi et al. (1997) (33)	21 sedentary males (6 control subjects, 15 experimental subjects: 8 assigned to concentric group; 7 assigned to eccentric group) Age: 21.3±1.9 yrs	Knee extensors	Isokinetic training (8–12 reps MVC X 4–6 sets (periodization principle); 4/wk X 12 wks	Arm 1: Concentric	EMG	↑*	↑*	Isok	30.0%* (21.2 to 38.8)	10.7* (4.4 to 17.1)
				Arm 2: Eccentric	EMG	↑*	↑*	Isok	77%* (0.5 to 153.5)	20.9* (11.5 to 30.3)

Hortobagyi et al. (1999) (36)	16 sedentary females (8 control subjects, 8 experimental subjects) Age: 24.8±4.5 yrs	Knee extensors	Isokinetic eccentric: 4–6 sets X 6–8 reps (periodization principle); 4/wk X 6 wks		EMG	↑*	↑*	Isok	23.0%* (-3.8 to 49.8)	19.0 (-6.0 to 43.9)
Hortobagyi et al. (2011) (35)	20 healthy adults (8 control subjects, 12 experimental subjects) Age: 21.3±1.9 yrs Gender: 12 males, 8 females	First dorsal interosseus	Isometric: 10 (4-s) reps (at 80% MVC) X 5 sets; 3/wk X 4 wks		EMG MEP RC SICI ICF IHI	↑* ↑* ↑* ↓ = ↓*	n.r. n.r. n.r. n.r. n.r. n.r.	Isom	21.8%* (20.3 to 23.3)	23.7* (20.9 to 26.5)
Kidgell et al. (2011) (50)	26 healthy participants (13 control subjects, 13 experimental subjects) Age: 26.8±7 yrs Gender: 12 males, 14 females	Elbow Flexors	Isotonic: 6-8 reps X 4 sets at 80% 1RM with a weighted dumbbell, with increments by 5%; 3/wk X 4 wks		EMG MEP RC cSP	= ↑* = =	= ↑* = ↓	1-RM	19.2%* (9.5 to 28.9)	17.5* (8.6 to 26.4)
Kidgell et al. (2015) (46)	27 right-handed subjects [9 control subjects, 18 experimental subjects (9 to concentric training, 9 to eccentric training)] Age range: 25-27 yrs Gender: 15 males, 12 females	Wrist Flexors	Isokinetic training at 20°/s: 8 reps MVC X 4 sets; 3/wk X 4 wks	Arm 1: Concentric	M-wave MEP RC cSP SICI	= = = = =	n.r. n.r. n.r. n.r. n.r.	Isom	40.0%* (12.4 to 67.6)	22.2 (-49.8 to 94.2)
				Arm 2: Eccentric	M-wave MEP RC cSP SICI	= ↑* ↑* ↓* ↓*	n.r. n.r. n.r. n.r. n.r.	Isom	47.8%* (44.4 to 51.2)	40.1 (-9.2 to 89.4)
Lagerquist et al. (2006) (53)	16 healthy subjects (6 control subjects, 10 experimental subjects) Age range: 22–42 yrs Gender: 6 males , 10 females	Ankle plantarflexors	Isometric: 8 6-s reps MVC X 5 sets; 3/wk X 5 wks		M-wave H-reflex	= =	= ↑*	Isom	17.8%* (-0.5 to 36.0)	14.9 (-10.1 to 39.9)
Latella et al. (2012) (54)	18 healthy subjects (9 control subjects, 9 experimental subjects) Age range: 18-35 yrs Gender: 14 males, 4 females	Lower limb (single leg press)	Isotonic: 6-8 reps X 4 sets progressed from 78% to 88.5% of 1 RM; 3/wk X 8 wks		EMG MEP cSP	= = ↓*	= = ↓*	1-RM	20.4%* (8.6 to 32.2)	24.4* (13.6 to 35.2)

Lee et al. (2009*a*) (56)	20 right-handed healthy subjects (10 control subjects, 10 experimental subjects) Age range: 18-24 yrs Gender: 13 males, 7 females	Wrist extensors	Isometric: 10 (1-2s) reps MVC X 4 sets; 3/wk X 4 wks	SIT	↓*	n.r.	Isom	8.2%* (2.3 to 16.3)	9.7* (2.1 to 17.4)
Lee et al. (2009*b*) (57)	23 healthy subjects (4 left-handed and 19 right-handed; 11 controls and 12 experimental subjects) Age range: 18-51 yrs Gender: 16 males, 7 females	Wrist abductors	Isotonic: 8 reps X 4 sets progressed from 70% to 85% of 1 RM; 3/wk X 4 wks	SIT	↑*	n.r.	Isom	4.1% (-23.5 to 31.7)	1.7% (-25.0 to 8.7)
Lepley et al. (2014) (58)	18 healthy subjects(9 control subjects, 9 experimental subjects) Age: 22.9±3 yrs Gender: 8 males, 10 females	Knee extensors	Isokinetic eccentric at 60°/s: 10 reps MVC X 4 sets; 3/wk X 5 wks	SIB	↑	=	Isok	46.5%* (0.4 to 92.6)	36.4 (-12.5 to 85.3)
Manca et al. (2016) (62)	34 right-handed subjects (17 control subjects, 17 experimental subjects) Age: 25.5±6 yrs Gender: 23 males, 11 females	First dorsal interosseus	Isometric: 10 (5-s) reps MVC X 5 sets; 3/wk X 4 wks	MEP RC SICF SICI ICF IHI SAI LAI	= = = ↓ = = = =	= = = = = = = =	Isom	6.4% (-10.3 to 23.2)	6.4 (-13.2 to 26.0)
Mason et al. (2017) (66)	20 right-handed subjects (10 control subjects, 10 experimental subjects) Age range: 18-35 yrs Gender: 10 males, 10 females	Elbow Flexors	Isotonic: 8 reps X 4 sets at 80% 1RM with increments by 5%; 3/wk X 3 wks	EMG M-wave MEP RC cSP	= = ↑* ↑* ↓*	n.r. n.r. n.r. n.r. n.r.	Isom	23%* (13.3 to 32.7)	18%* (11.9 to 24.1)
Shima et al. (2002) (86)	15 healthy active males (6 control subjects, 9 experimental subjects) Age: 26.2±4.6 yrs	Ankle plantarflexors	Isotonic: plantarflexion against foot plate; 10–12 reps X 3 sets at (70–75% of 1 RM) for each exercise; 4/wk X 6 wks	EMG	↑*	↑*	Isom	7.8%* (-9.4 to 25.0)	4.0 (-13.7 to 21.7)

Yue and Cole (1992) (97)	20 healthy subjects (10 control subjects, 10 experimental subjects) Age range: 21–29 yrs Gender: n.s.	Fifth finger abductors	Isometric: 15 reps X 10-s MVC; 5/wk X 4 wks	EMG	↑*	↑*	Isom	14.5%* (-3.8 to 32.8)	12.1 (-11.7 to 35.9)

CE, Cross education; CI, 95% confidence interval; yrs, years; reps, repetitions; RM, repetition maximum; wk, week; MVC, maximal voluntary contraction; s, second; °/s, degree/seconds of angular velocity. Magnitude of the cross-education effect as reported by the authors of the individual studies for the intervention group ([#]within-subjects results; [§]between-groups results). Isom, isometric; Isok, isokinetic; 1-RM, one repetition maximum. EMG, electromyography; cSP, cortical silent period; M-wave, maximum direct motor response; H-reflex, Hoffmann reflex; V-wave, volitional wave; MEP, motor evoked potential; SICF, short-interval intracortical inhibition; SICI, short-interval intracortical inhibition; ICF, intracortical facilitation; IHI, interhemispheric inhibition; SAI, Short afferent intracortical inhibition; LAI, Long latency intracortical inhibition; SIT, super-imposed twitch amplitude; SIB, super-imposed burst technique obtained by delivering a supramaximal electrical stimulus at MVC. Changes in neurophysiological measures as reported in the full-text manuscript: ↑, increase; ↓, decrease; *significant for p <0.05; =, no change; n.r., not reported.

Figure 1

Figure 1 Study flow chart
CE, cross education; ST, strength training.

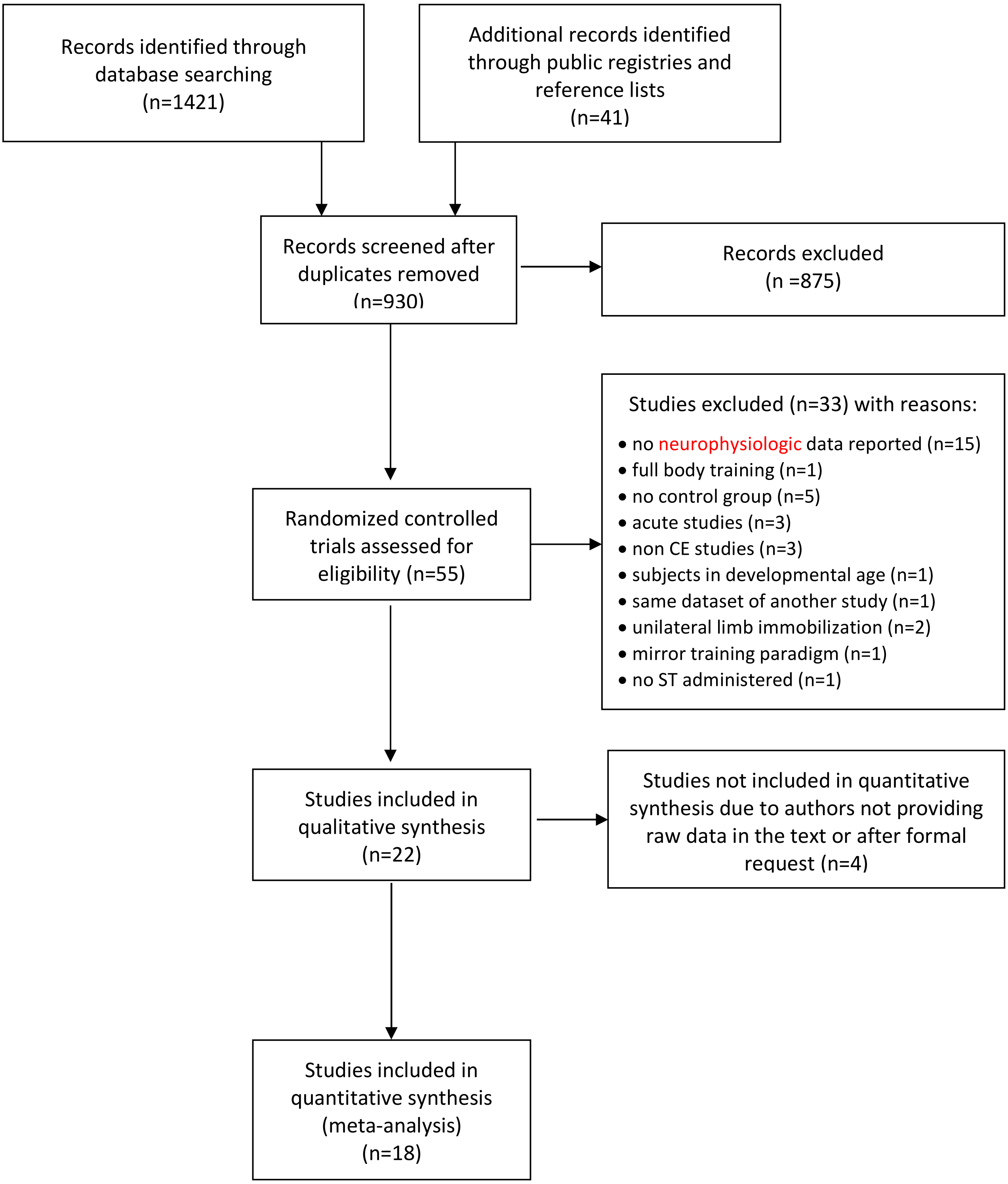


Figure 3

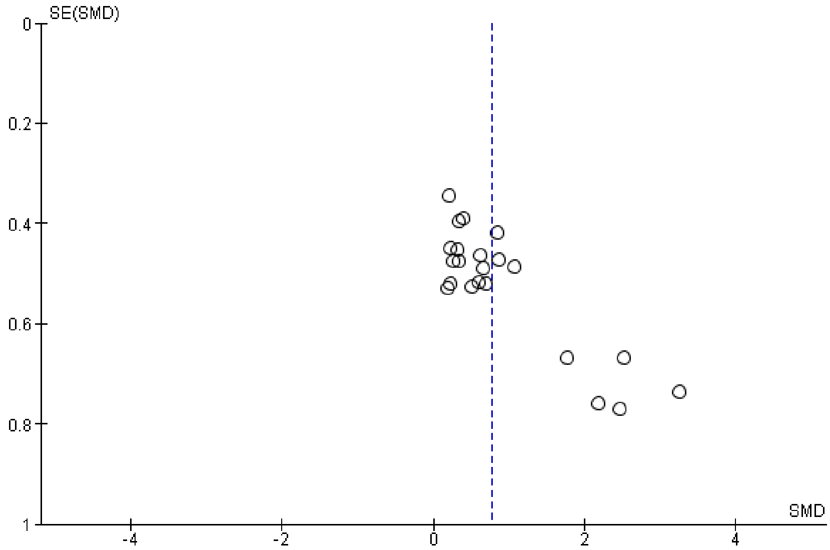
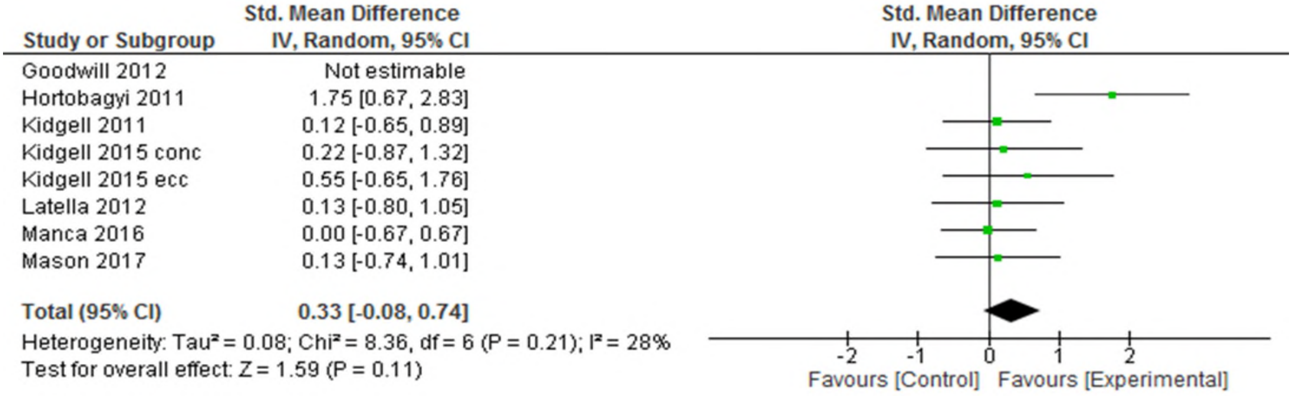
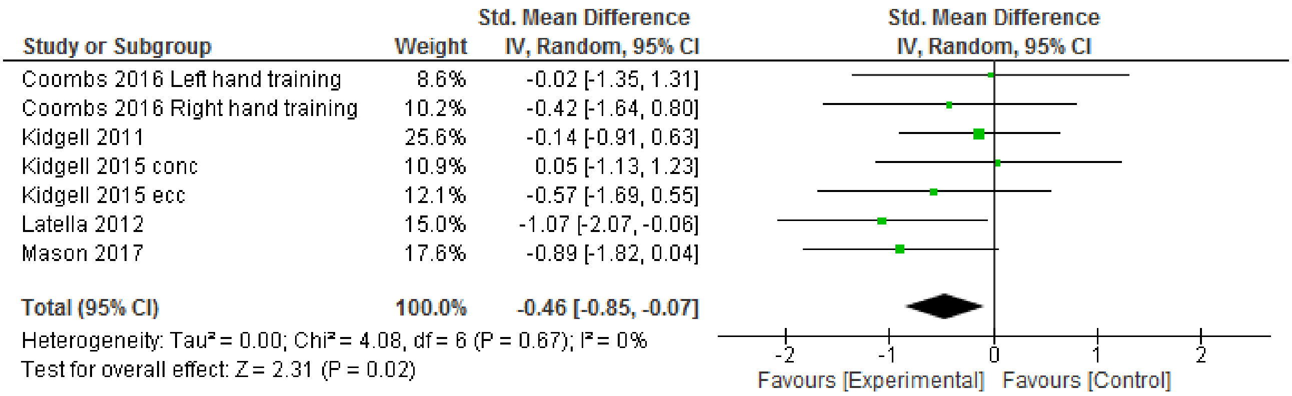


Figure 5

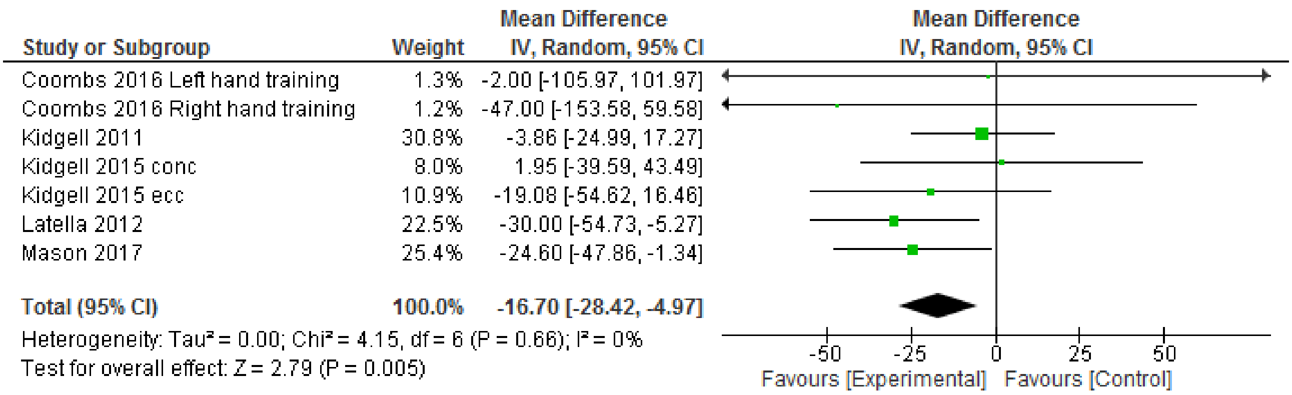
A. Motor Evoked Potentials



B. Cortical Silent Period (SMD analysis)



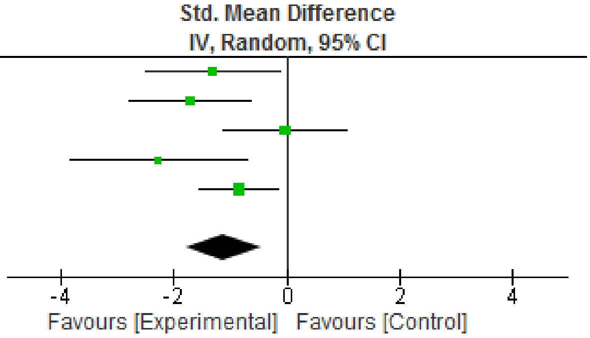
C. Cortical Silent Period (MD analysis in milliseconds)



D. Short-interval intracortical inhibition

Study or Subgroup	Weight	Std. Mean Difference IV, Random, 95% CI
Goodwill 2012	18.1%	-1.31 [-2.50, -0.11]
Hortobagyi 2011	20.3%	-1.71 [-2.78, -0.64]
Kidgell 2015 conc	19.9%	-0.03 [-1.12, 1.07]
Kidgell 2015 ecc	12.6%	-2.28 [-3.85, -0.70]
Manca 2016	29.0%	-0.84 [-1.55, -0.14]
Total (95% CI)	**100.0%**	**-1.12 [-1.79, -0.46]**

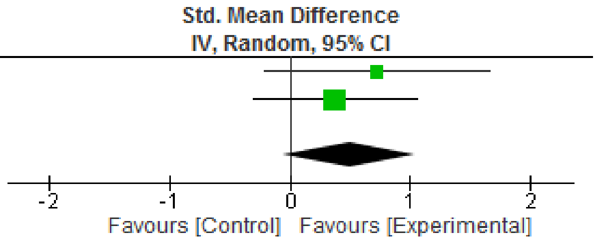
Heterogeneity: Tau^2 = 0.27; Chi^2 = 7.65, df = 4 (P = 0.11); I^2 = 48%
Test for overall effect: Z = 3.30 (P = 0.0010)



E. Intracortical facilitation

Study or Subgroup	Std. Mean Difference IV, Random, 95% CI
Hortobagyi 2011	0.72 [-0.21, 1.65]
Manca 2016	0.38 [-0.30, 1.06]
Total (95% CI)	**0.50 [-0.05, 1.04]**

Heterogeneity: Tau^2 = 0.00; Chi^2 = 0.34, df = 1 (P = 0.56); I^2 = 0%
Test for overall effect: Z = 1.77 (P = 0.08)



F. Interhemispheric inhibition

Study or Subgroup	Weight	Std. Mean Difference IV, Random, 95% CI
Hortobagyi 2011	48.7%	-9.21 [-12.51, -5.90]
Manca 2016	51.3%	0.92 [0.21, 1.64]
Total (95% CI)	**100.0%**	**-4.01 [-13.93, 5.92]**

Heterogeneity: Tau^2 = 49.83; Chi^2 = 34.46, df = 1 (P < 0.00001); I^2 = 97%
Test for overall effect: Z = 0.79 (P = 0.43)