Mirror Training Augments the Cross-education of Strength and Affects Inhibitory Paths

TJERK ZULT[1], STUART GOODALL[2], KEVIN THOMAS[2], STANISLAW SOLNIK[3,4], TIBOR HORTOBÁGYI[1,2], and GLYN HOWATSON[2,5]

[1]University of Groningen, University Medical Center Groningen, Center for Human Movement Sciences, Groningen, THE NETHERLANDS; [2]Faculty of Health and Life Sciences, Department of Sport, Exercise and Rehabilitation, Northumbria University, Newcastle-upon-Tyne, UNITED KINGDOM; [3]Motor Control Laboratory, Department of Kinesiology, Pennsylvania State University, State College, PA; [4]University School of Physical Education, Wroclaw, POLAND; and [5]Water Research Group, School of Biological Sciences, North West University, Potchefstroom, SOUTH AFRICA

ABSTRACT

ZULT, T., S. GOODALL, K. THOMAS, S. SOLNIK, T. HORTOBÁGYI, and G. HOWATSON. Mirror Training Augments the Cross-education of Strength and Affects Inhibitory Paths. *Med. Sci. Sports Exerc.*, Vol. 48, No. 6, pp. 1001–1013, 2016. **Purpose**: Unilateral strength training strengthens not only the muscles on the trained side but also the homologous muscles on the untrained side; however, the magnitude of this interlimb cross-education is modest. We tested the hypothesis that heightened sensory feedback by mirror viewing the exercising hand would augment cross education by modulating neuronal excitability. **Methods**: Healthy adults were randomized into a mirror training group (MG, $N = 11$) and a no-mirror training group (NMG, $N = 12$) and performed 640 shortening muscle contractions of the right wrist flexors at 80% maximum voluntary contraction (MVC) during 15 sessions for 3 wk. Maximal strength and specific transcranial magnetic stimulation metrics of neuronal excitability, measured in the mirror and no-mirror setup at rest and during unilateral contractions at 60% MVC, were assessed before and after the strength intervention. **Results**: Trained wrist flexor MVC increased 72% across groups, whereas cross-education was higher for the MG (61%) than NMG (34%, $P = 0.047$). The MG showed a reduction (15%–16%) in the contralateral silent period duration measured from the contracting left-untrained flexor carpi radialis, whereas the NMG showed an increase (12%, $P \leq 0.030$). Interhemispheric inhibition, measured from the trained to the untrained primary motor cortex, increased in the MG (11%) but decreased in the NMG (15%) when measured in the mirror setup at rest ($P = 0.048$). Other transcranial magnetic stimulation measures did not change. **Conclusion**: Viewing the exercising hand in a mirror can augment the cross-education effect. The use of a mirror in future studies can potentially accelerate functional recovery from unilateral impairment due to stroke or upper limb fracture. **Key Words:** FLEXOR CARPI RADIALIS, INHIBITION, INTERLIMB TRANSFER, MOTOR CORTEX, STRENGTH TRAINING, TRANSCRANIAL MAGNETIC STIMULATION

BASIC SCIENCES

It has been known for more than 100 yr that unilateral resistance training strengthens the actively contracting muscles and also the homologous muscles on the untrained side (38)—a phenomenon called *cross-education*. This interlimb transfer to produce maximal voluntary force is most likely mediated by neural mechanisms because the force in the untrained muscles increases without changes in muscle size (10). A growing body of evidence suggests that the transfer is predominantly of cortical origin, but the involvement of subcortical and spinal levels cannot be ruled out (4). Unilateral forceful contractions result in an increased excitability of the primary motor cortex (M1) contralateral to the movement side. At the same time, the ipsilateral M1, modulated by neural interactions between GABAergic intracortical circuits that mediate short-interval intracortical inhibition (SICI) and interhemispheric glutamatergic projections from the contralateral to ipsilateral M1 (32), controls the corticospinal output to the resting hand. After multiple sessions of unilateral forceful contractions, the interlimb transfer may occur according to one of two models (36). First, the cross-activation model suggests that bilateral cortical activity observed during unilateral strength training induces task-specific changes in the contralateral and ipsilateral cortical motor networks, respectively, controlling the trained and untrained contralateral homologous muscles. Second, the bilateral access model posits that unilateral strength training creates motor engrams at a locus that is accessible for the motor control of both the trained and the contralateral untrained limb. In both models, experimental data assign a key role to the untrained M1 in mediating cross education. For example, a functional magnetic resonance imaging study (9) showed that the cross-education of strength was accompanied by the enlarged neuronal activation of the untrained sensorimotor cortex (10), and transcranial magnetic stimulation

Address for correspondence: Tjerk Zult, M.Sc., Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, A. Deusinglaan 1, 9700 AD Groningen, The Netherlands; E-mail: t.d.zult@umcg.nl.
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(TMS) studies (13,16,22) have demonstrated that the neuronal excitability from the untrained M1 to the transfer muscles increased after unilateral strength training. Also, the force transfer is associated with reductions in SICI of the untrained M1 (13), contralateral silent period (cSP) duration (26), and interhemispheric inhibition (IHI) from trained to untrained M1 (16). Collectively, these lines of experimental evidence suggest that cortical and corticospinal paths, possibly modulated via transcallosal connections, mediate the cross-education of strength.

The magnitude of cross-education is modest, approximately 8% (29). However, a recent review has proposed the idea that viewing the movements of the exercising hand in a mirror could amplify the magnitude of strength transfer (17). This expectation is based on the idea that the stationary hand on which the mirror image is superimposed is moving, and this visual illusion of the muscles contracting activates the mirror–neuron system (MNS). The MNS connects sensory neurons that respond to the visual properties of an observed action and motor neurons that depolarize during the execution of a similar action, resulting in altered corticospinal excitability that reflects the pattern of muscle activity of the observed action (40). The action observation using a mirror might therefore alter the M1 excitability of the inactive hemisphere, leading to behavioral performance gains of the untrained hand behind the mirror (30). An alternative hypothesis is based on the dominance of vision over proprioception (41), where the mirror-induced increase in attention toward the hand behind the mirror leads to the activation of motor networks within the untrained hemisphere. Although the precise neurophysiological mechanisms of mirror training are still poorly understood, it seems that the performance gains after mirror training are a result of the mutual interaction between perceptual and motor activity at a cortical level. Thus, it is possible that elements of the perceptuomotor system, activated by mirror viewing the exercising arm but not activated during unilateral training without a mirror, provide extra input to the untrained M1 and could therefore augment the strength transfer effect. Indeed, as a first step, we recently demonstrated that mirror viewing a slow and forceful right wrist flexion contraction reduced SICI in the right ipsilateral M1 compared with a no-mirror condition (47). Therefore, we hypothesized that the illusion of the stationary hand moving and its muscles contracting during unilateral strength training modifies the excitability of the untrained M1 and also perceptuomotor circuits with inputs to this M1, thereby magnifying the cross-education effect. We examined this possibility by comparing the effect of unilateral strength training performed with and without a mirror on cross education and on intracortical and interhemispheric TMS metrics. Because the key element of the stimulus is the illusion of the resting hand to be moving and its muscles contracting, we expected to find a more pronounced modulation of neuronal excitability when tested during muscle contraction when subjects viewed the contracting right hand in the mirror compared with a no-mirror contraction condition and at rest.

MATERIALS AND METHODS

Participants and design. A total of 24 right-handed (31) healthy volunteers (19 men and 5 women) participated in the study. A stratified, randomized, matched-pair design was used to control for the confounding effect of baseline strength between groups. Participants with similar maximal dynamic (i.e., shortening) right wrist flexion strength were grouped into pairs, from which one participant was randomly assigned to the no-mirror training group (NMG, $N = 12$, age = 29 ± 9 yr, height = 1.74 ± 0.07 m, mass = 75.8 ± 14.0 kg, BMI = 25.0 ± 3.4 $kg \cdot m^{-2}$) and the other to the mirror training group (MG, $N = 12$, age = 25 ± 4 yr, height = 1.78 ± 0.08 m, mass = 76.3 ± 13.8 kg, BMI = 24.0 ± 2.5 $kg \cdot m^{-2}$). One participant from the MG had to withdraw after the pretest because of illness unrelated to the study. Before the start of the study, participants completed a comprehensive questionnaire to determine experimental and medical contraindications to the protocol. All participants provided written informed consent to the experimental procedures, which were approved by the university's Research Ethics Committee and in accordance with the Declaration of Helsinki.

Figure 1A outlines the design. Participants visited the laboratory 18 times. Training consisted of 15 strength-training sessions of the right wrist flexors, while the left wrist was at rest. The NMG performed the training with views of both hands blocked, whereas the MG viewed the mirror image of the exercising right hand, which created the illusion that the left hand was performing the training. One week before the start of the study, participants visited the laboratory for a 30-min-long familiarization session that involved exposure to peripheral nerve stimulation and to single-pulse TMS. The week before and after the intervention, maximal torque was recorded for the dominant (right) and nondominant (left) wrist flexor muscles followed by a neurophysiological assessment, using peripheral nerve stimulation and TMS.

Experimental setup. Figure 1B illustrates the experimental setup that was used for training and neurophysiological testing. Participants sat comfortably in a chair with both forearms placed in a neutral position on a custom-built table and elbows flexed at 90°. The metacarpophalangeal joint was placed on a plastic-covered manipulandum that projected vertically downward toward the table surface and was attached to the lever arm of an isokinetic dynamometer (Biodex, System 4; Medical Systems, Shirley, NY, USA). The thumb was uppermost and the fingers extended to avoid passive insufficiency during wrist flexion (27). For each participant, the distance between the metacarpophalangeal joint position on the manipulandum and the axis of rotation was held at a constant length but was adjusted between participants to account for anatomical differences. The vision of both forearms was blocked by placing them inside two separate boxes. Because training and testing required a no-mirror and a mirror setup, a cardboard wall or a mirror, respectively, was mounted on the central vertical wall of the left box and was aligned in the sagittal plane in front of the participant. In the no-mirror setup, participants' view of both forearms was blocked, and volunteers were instructed to

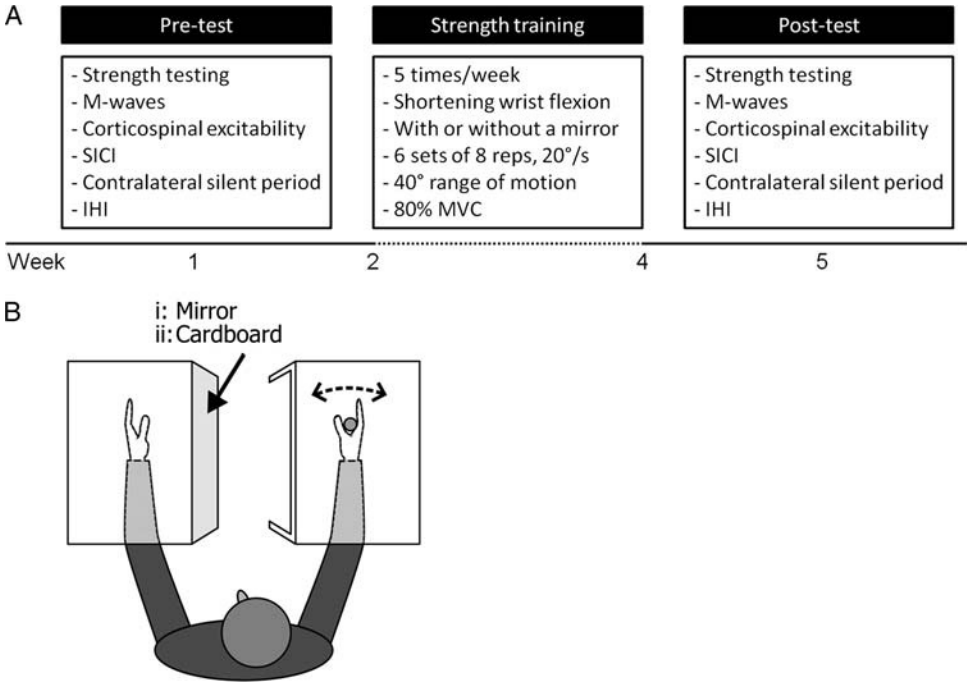

FIGURE 1—Schematic representation of the experimental design (A) and experimental setup (B). A, Measurements were performed before and after 3 wk of dynamic right wrist flexor strength training with or without a mirror. B, Both forearms were resting on a custom-built table and placed inside two different boxes, blocking their view to the participant. The mirror mounted on the central vertical wall of the left box creates the illusion of the left hand by actually mirror viewing the right hand (i, mirror setup), and the cardboard wall mounted on the central vertical wall of the left box blocks the view of either hands (ii, no-mirror setup).

fix their gaze on a mark placed on the cardboard wall to maintain constant head position. In the mirror setup, participants focused on the mirror image of the right forearm, which created the illusion of seeing the left forearm. The left arm was placed in the same anatomical position as the right arm. Participants removed jewelry, watches, and other adornments to avoid visual or kinesthetic distractions or inconsistencies between limbs while training and testing.

All the training, and part of the neurophysiological testing, involved dynamic right wrist flexion contractions, which were performed in the transverse plane over the table surface by pressing at the metacarpophalangeal joint against the manipulandum. The shoulder and the forearm were not strapped, but visual inspection ensured that the shoulder and the forearm did not contribute to the wrist flexion movement. Contractions started with the wrist at 20° extension and ended with the wrist at 20° flexion, resulting in a 40° range of motion. Contractions were performed at $20°\cdot s^{-1}$. Participants received constant verbal feedback from the investigator to ensure the requisite torque was attained; no visual feedback was provided at any point to avoid distraction of gaze from the mirror image or cardboard wall.

MVC. Dynamic and isometric MVC values for the dominant (right) and nondominant (left) wrist were measured, using the aforementioned experimental setup but without the two boxes. Torque for the dynamic wrist flexion MVC was recorded when the wrist past anatomical zero (0°). Isometric wrist flexion MVC values were measured during the 5-s effort at the 0° position. Participants performed three dynamic MVC followed by three isometric wrist flexion MVC with the left and right wrist; this was preceded by a warm-up for each wrist (10 dynamic contractions at an estimated 50% of maximal effort). The highest of the three contractions was recorded as the contraction-specific MVC. After completion of the pre- and posttest, dynamic MVC torque was measured in a subsample of participants (pretest: $n = 5$; posttest: $n = 14$) to examine the presence of fatigue. During MVC, mean surface EMG was calculated for a 200-ms period.

Surface EMG. Surface EMG was recorded from the left and right flexor carpi radialis (FCR) to quantify voluntary muscle activity and evoked responses from peripheral (maximal M-wave amplitude [M_{max}]) and cortical (motor-evoked potential [MEP]) stimulation. The skin surface was shaved and cleaned, before the electrodes (model 1041PTS; Kendall, Tyco Healthcare Group, Mansfield, MA, USA) were placed on the muscle belly (interelectrode distance, 2 cm) with the ground electrode fixed on the distal styloid process of the left radius. Surface EMG was band-pass filtered at 20–2000 Hz, amplified ×1000 (CED 1902, Cambridge Electronic Design, Cambridge, UK; Digitimer, Hertfordshire, UK), sampled at 5 kHz (CED Power 1401; Cambridge Electronic Design), and recorded on a personal computer. Surface EMG was calculated as the mean rectified EMG activity, expressed relative to M_{max}.

Neurophysiological measurements. The neurophysiological assessment was performed according to current methodological (6), safety, and ethical (34) guidelines. Corticospinal and motor cortical excitability levels of both M1 were

evaluated using TMS in the mirror and no-mirror setup at rest and during forceful dynamic and isometric unilateral wrist flexion contractions (47). Table 1 summarizes the TMS measures. To determine the effect of unilateral strength training on the left-trained M1, corticospinal excitability and SICI were examined in the no-mirror setup at rest and recorded from the right FCR. To determine the effect of unilateral strength training on the corticospinal excitability and SICI of the right-untrained M1, single and paired pulse TMS values were presented in random order in the mirror and no-mirror setup at rest and during dynamic right wrist flexor contractions at 60% MVC. The muscle contraction phase did not affect the MEP amplitude recorded from the contralateral homologous resting muscle during unilateral dynamic contractions (42). Therefore, during dynamic contractions, we delivered TMS stimuli to the right-untrained M1 at a standardized position when the right wrist past through 0°. During all conditions where corticospinal excitability and SICI of the untrained-right M1 were measured, MEP amplitudes were recorded from the resting left FCR. The order of the contraction and resting conditions was randomized between participants. The cSP, measured in the no-mirror setup only, was elicited in the left FCR by the stimulation of the right-untrained M1 and right FCR by the stimulation of the left-trained M1 during either isometric left or right wrist flexion contractions. All unilateral contractions were performed at 60% MVC. During the posttest, contractions were performed at 60% pretest MVC and 60% posttest MVC (in other words, relative to the post-training MVC). To determine whether IHI was further diminished after unilateral strength training with than without the mirror, we measured IHI from left-trained to right-untrained M1 at rest in the mirror and no-mirror setup. Data acquisition was initiated 30 ms before the TMS stimulus was delivered. MEP amplitudes were analyzed offline for peak-to-peak amplitude (Signal, v. 5.04; Cambridge Electronic Design). The EMG activity arising before the stimulus was rectified and computed for a 30-ms period before stimulation artifact.

The influence of associated activity (i.e., the EMG activity of the contralateral resting muscles during a right-unilateral muscle contraction) on cortical and corticospinal excitability remains unclear. Therefore, 60% MVC was used as the contraction intensity because participants were less able to prevent associated EMG activity at higher force levels (46). During the experimental conditions, participants were frequently reminded to relax the nonexercising arm when performing wrist flexion contractions. Trials ($n = 43$ of a total of $N = 2760$; ~1.5%) in which associated FCR activity exceeded the background noise level of 25 μV were excluded from the analyses (32).

TMS of the M1. To assess corticospinal excitability, SICI, and cSP, TMS was delivered from a magnetic stimulator (Magstim 200^2; Magstim Company Ltd., Carmarthenshire, UK) through a figure-of-8 coil (loop diameter 90 mm; Magstim, Spring Gardens, Wales, UK) with a monophasic current waveform. With the addition of a second Magstim 200^2 stimulator, equipped with a BiStim^2 timing module, paired pulses were delivered through the same figure-of-8 coil. The coil was moved in 0.5-cm steps for the M1 to identify the optimal scalp position, i.e., hotspot, for the activation of the left FCR overlying the right M1 and the right FCR overlying the left M1. The handle of the coil was pointing backward and was held approximately 45° away from the midline so the direction of the current induced in the M1 was from posterior to anterior. Initially, the "hotspot" was located on each participant. The hotspot was defined as the lowest threshold capable of evoking the biggest potential in the targeted muscle (35). A marker pen was used to mark this optimal position of the coil on the scalp to ensure the constant positioning of the coil throughout the experiment. After the hotspot had been identified, resting motor threshold (rMT) was determined as the lowest stimulator intensity to produce a peak-to-peak MEP amplitude ≥50 μV in 5 of 10 trials (35).

Corticospinal excitability was measured as part of the SICI measurement by a single TMS pulse delivered at an intensity of 120% rMT. For measuring SICI, a conditioning pulse at 80% rMT preceded the test pulse of 120% rMT with an interstimulus interval of 2 ms to create an inhibition that is normally deeper than the inhibition created at neighboring interstimulus intervals (24). A total of 20 MEP amplitudes were evoked in each condition: 10 MEP amplitudes for measuring SICI and 10 MEP amplitudes for measuring corticospinal excitability, with an interval of ~5 s between stimuli. For determining SICI, the conditioned MEP amplitudes were expressed relative to the MEP amplitudes from the unconditioned test pulse.

To evoke a cSP, a single TMS pulse was applied at an intensity of 160% rMT. The cSP was determined by using a previously described method (44). Briefly, the duration of the cSP was calculated in eight single EMG trials from the stimulus onset to the end of the cSP, which was defined as the point where the first burst of EMG activity was seen after the period of EMG silence. In the same trials, active amplitudes

TABLE 1. TMS measurements at the pre- and posttest.

Setup	Stimulated M1	Corticospinal Excitability	SICI	IHI	cSP
No-mirror, at rest	Left	X	X	X (conditioning pulse)	—
	Right	X	X	X (test pulse)	—
Mirror, at rest	Left	—	—	X (conditioning pulse)	—
	Right	X	X	X (test pulse)	—
No-mirror, dynamic right wrist contractions at 60% MVC[a]	Right	X	X	—	—
Mirror, dynamic right wrist contractions at 60% MVC[a]	Right	X	X	—	—
No-mirror, isometric right wrist contractions at 60% MVC[a]	Left	—	—	—	X
No-mirror, isometric left wrist contractions at 60% MVC[a]	Right	—	—	—	X

X denotes that a measurement was administered; — denotes that a measurement was not administered.
IHI measured from the left-trained to the right-untrained M1.
[a]Measured at 60% pretest MVC during the pretest and measured at 60% pre- and posttest MVC during the posttest.

recorded from the contracting FCR were defined as the peak-to-peak MEP amplitude evoked by the single TMS pulse. Participants were constantly reminded to "push through" the silent period. All data processing was completed by the same investigator.

IHI from the left-trained to the right-untrained M1 was determined by using an established method (12). Two custom-built figure-of-8 coils (loop diameter 60 mm, model D60 mm; Magstim, Spring Gardens, Wales, UK) were positioned at the optimal scalp position for eliciting MEP amplitudes in the left and right FCR, respectively. The handles of the two coils were pointed ~45° backward away from the midline with a posterior to anterior current direction (16). The rMT for each hemisphere was determined using the aforementioned method, and the intensity used for the IHI conditioning and test stimulus was 120% rMT. To evoke inhibition, the conditioning stimulus was delivered to the left M1 10 ms before the test stimulus was given to the right M1 (12). Ten test stimuli and 10 conditioned test stimuli were presented in random order with ~5.5 s between each trial; MEP amplitudes were recorded from the left FCR. For determining IHI, the conditioned MEP amplitudes were expressed relative to the MEP amplitudes elicited by the test stimulus alone.

In four participants (two from the NMG and two from the MG), it was not possible to measure IHI because the two coils could not be positioned without causing interference of the optimal coil placement or the magnetic field. In addition, in three participants (two from the NMG and one from the MG), we were not able to elicit MEP amplitudes during the posttest assessment; therefore, IHI was reported for 16 participants (eight from each group).

Peripheral nerve stimulation. The M_{max} of the left and right FCR was determined by delivering a 1-ms, rectangular pulse, percutaneous electrical stimulation (model DS7A; Digitimer, Welwyn Garden City, UK) at the medial aspect of the elbow over the median nerve. The electrode was moved systematically to find the optimal stimulation position to elicit the M-wave, while both forearms were rested on a custom-built table with the hands in a supine position. Stimulation intensity was increased incrementally until there was no further increase in M-wave size. M_{max} was used to standardize corticospinal excitability and mean surface EMG data for different test sessions.

Strength training. Participants attended 20-min-long training sessions 15 times during a 3-wk period (five sessions per week) and performed dynamic wrist flexions with the dominant (right) wrist at 80% maximum voluntary contraction (MVC). The NMG used the no-mirror setup for training, whereas the MG used the mirror setup where mirror viewing the right exercising hand created the illusion that the left hand was exercising. Each week, dynamic right wrist flexor MVC was measured to reestablish the 80% MVC training intensity for that week. During every training session, participants performed one set of 10 repetitions at 50% MVC as a warm-up followed by six sets of eight repetitions, separated by 60 s of rest. The training program was based on a previous study showing cross education and was progressive in nature, beginning with three sets of eight repetitions and increasing the volume by one additional set each training day, up to a maximal training volume of six sets (11). We used 80% instead of 100% MVC exercise intensity to prevent the participants from getting too fatigued; in addition, during the exercise, participants were frequently reminded to completely relax the left arm. All training sessions were supervised and coached, whereby the participants received verbal feedback from the investigator to reach the target torque. All participants completed the 15 training sessions successfully, apart from one participant from the MG who completed 14 training sessions. In two participants from each group, the EMG activity of the left and right FCR was recorded during the 5th, 10th, and 15th training sessions to examine if the left hand was at rest and if the mirror affected EMG activity. The mean surface EMG was calculated for a 200-ms period during the main contraction phase of the right FCR.

Statistical analysis. Data in the text and figures are presented as mean ± SD. Each variable was checked for normality before the analysis. Corticospinal excitability, SICI, and prestimulus EMG were log transformed to correct for nonnormally distributed data. The main analysis, used for analyzing each outcome measure (MVC, M_{max}, rMT, corticospinal excitability, SICI, cSP, IHI, and prestimulus EMG activity), was a group (MG and NMG) × time (pre- and posttest) repeated-measures ANOVA. Where appropriate, interaction effects were subjected to a Tukey HSD *post hoc* pairwise comparison. Partial eta squared (η_P^2) and Cohen's d were calculated as measures of effect size. Cutoffs for η_P^2 are ≥0.01 (small), ≥0.06 (medium), and ≥0.14 (large) (7). Between-group equality at baseline was tested by an independent-sample t-test for all variables. A paired-sample t-test was used (1) to examine differences in maximal torque at the start and end of the pre- and posttest to verify that fatigue did not affect the results and (2) to test if the produced torque during the TMS measurements was equal to the target torque. A Friedman's ANOVA was performed to test if EMG activity in a population subset (n = 4) of the left and right FCR was different between the 5th, 10th, and 15th training sessions. SPSS for Windows (version 22; SPSS Inc., Chicago, IL, USA) was used for the statistical analysis, and significance was accepted as $P < 0.05$.

RESULTS

MVC torque and EMG right-trained wrist. Individual and group data for changes in MVC torque in the right-trained wrist are presented in Figures 2A and 2B. The two groups did not differ in dynamic MVC torque ($t_{21} = 0.2$, $P = 0.878$) and isometric MVC torque ($t_{21} = 0.7$, $P = 0.501$) at baseline. There was no group–time interaction for dynamic MVC torque ($F_{1,21} < 0.1$, $P = 0.961$) or isometric MVC torque ($F_{1,21} < 0.1$, $P = 0.867$), suggesting that strength gains after training were not different between groups. The time main effect was observed for both dynamic MVC torque ($F_{1,21} = 110.5$, $P < 0.001$, $\eta_P^2 = 0.840$) and isometric MVC

torque ($F_{1,21}$ = 73.2, P < 0.001, η_P^2 = 0.777); dynamic training increased dynamic MVC torque by 72% (pretest = 13.3 ± 3.8 N·m, posttest = 22.9 ± 6.1 N·m) and isometric MVC torque by 66% (pretest = 18.8 ± 4.0 N·m, posttest = 27.6 ± 6.7 N·m) across groups. The M_{max}-normalized EMG activity measured during these MVC torque tests revealed no group–time interactions and time main effects under dynamic and static conditions (all P values ≥ 0.174, $\eta_P^2 \leq 0.086$).

MVC torque and EMG left-untrained wrist. Figures 2C and 2D show the individual and group data for changes in MVC torque in the left-untrained wrist, with the two groups being not different in dynamic MVC torque (t_{21} = −0.3, P = 0.740) and isometric MVC torque (t_{21} = 0.1, P = 0.916) at baseline. There was a group–time interaction for dynamic MVC torque ($F_{1,21}$ = 4.5, P = 0.047, η_P^2 = 0.176) but not for static MVC torque ($F_{1,21}$ = 1.3, P = 0.268, η_P^2 = 0.058). Dynamic MVC torque increased 61% for the MG (pretest = 9.0 ± 3.0 N·m, posttest = 14.4 ± 2.5 N·m) and 34% for the NMG (pretest = 9.5 ± 3.7 N·m, posttest 12.7 ± 4.4 N·m). *Post hoc* analysis revealed that dynamic posttest MVC torque was 13% higher in the MG than that in the NMG (P < 0.05, d = 0.50), suggesting that viewing the exercising hand in the mirror increased the training-specific torque in the untrained wrist. Likewise, there was a time main effect for dynamic MVC torque ($F_{1,21}$ = 47.4, P < 0.001, η_P^2 = 0.693) and isometric MVC torque ($F_{1,21}$ = 52.5, P < 0.001, η_P^2 = 0.714), increasing 48% and 42% across groups, respectively. The M_{max}-normalized EMG activity recorded during these MVC torque tests showed no interaction under dynamic and static conditions (all P values ≥ 0.820, $\eta_P^2 \leq 0.003$). There was a time main effect for the EMG activity measured during dynamic MVC torque ($F_{1,21}$ = 10.3, P = 0.004, η_P^2 = 0.330) and isometric MVC torque ($F_{1,21}$ = 10.9, P = 0.003, η_P^2 = 0.342), increasing 36% across groups (pretest = 4.0 ± 2.0% M_{max}, posttest = 5.5 ± 1.8% M_{max}) and 38% across groups (pretest = 3.6 ± 2.1% M_{max}, posttest = 4.9 ± 1.4% M_{max}), respectively. Dynamic wrist flexion MVC was not different before and after assessments before or after the training intervention ($P \geq 0.124$), indicating that the testing protocol did not induce fatigue.

rMT and M_{max}. The rMT and the M_{max} data were not different between groups at baseline and showed no interaction or time effect (all P values ≥ 0.081). The rMT of the left-trained M1 was on average 53 ± 10% of the maximal stimulator output, and the rMT of the right-untrained M1 was on average 59 ± 9% of the maximal stimulator output.

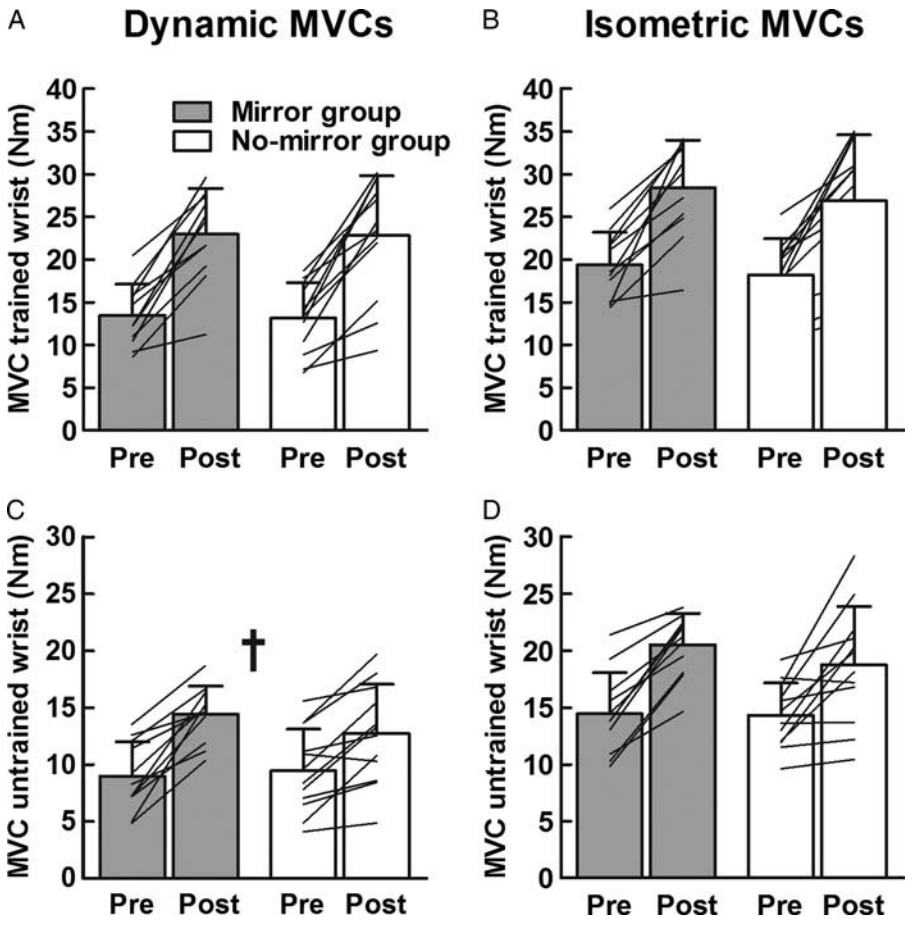

FIGURE 2—Change in maximal voluntary force in the right-trained wrist flexor muscles (A, training-specific dynamic contraction; B, isometric contraction) and left-untrained wrist flexor muscles (C, training-specific dynamic contraction; D, isometric contraction). The black solid lines represent the individual torque changes. †Group–time interaction (P < 0.05).

The M_{max} was on average 5.64 ± 1.96 mV for the right-trained FCR and 5.02 ± 1.46 mV for the left-untrained FCR.

Prestimulus EMG. For corticospinal excitability, SICI, and IHI, prestimulus EMG activity on which the MEP amplitudes were evoked was not different between groups at baseline and showed no interaction (all P values > 0.05). A time main effect in the prestimulus EMG activity of the left FCR was observed for corticospinal excitability and SICI in the mirror and no-mirror setup when right wrist flexion contractions were performed at 60% posttest MVC ($P < 0.001$). Although prestimulus EMG recorded from the left FCR was higher at the posttest than the pretest (~0.15 vs ~0.05% M_{max}), it is unlikely that these small differences in prestimulus EMG have affected corticospinal excitability or SICI. For the cSP, prestimulus EMG recorded from the isometrically contracting FCR showed no between-group differences at baseline and no interaction (all P values ≥ 0.264). A time main effect was caused by the 35% higher prestimulus EMG activity observed during contractions at 60% posttest MVC compared with 60% pretest MVC (2.8% vs 2.1% M_{max}, $P \leq 0.021$), but the difference in EMG activity did not affect cSP duration or MEP amplitude.

Target torque. Not all produced torques during the TMS measurements were equal to the target torque of 60% MVC. The mean maximal torque offset of the contractions that were different from the target torque was 0.64 N·m, which was less than 7% of the target torque. It is therefore unlikely that such a small torque offset would have affected TMS outcomes.

Corticospinal excitability left-trained M1. The corticospinal excitability of the left-trained M1, recorded from the right FCR in the no-mirror setup at rest, was not different between groups at baseline and showed no group–time interaction or time main effect (all P values ≥ 0.262).

Corticospinal excitability right-untrained M1. Table 2 shows the corticospinal excitability of the right-untrained M1, recorded from the resting left FCR in the no-mirror and mirror setup at rest and during dynamic right wrist flexion contractions. The corticospinal excitability of the right-untrained M1 was not different between groups at baseline in all setup (t_{21} = −0.8 to 0.1, $P \geq 0.446$). No interaction was observed in any of the setup ($P \geq 0.167$), and there was only a time main effect when the corticospinal excitability of the right-untrained M1 was measured in the no-mirror ($F_{1,21} = 4.4$, $P = 0.049$, $\eta_P^2 = 0.172$) and mirror setup ($F_{1,21} = 9.5$, $P = 0.006$, $\eta_P^2 = 0.312$) during right wrist flexion contractions performed at 60% posttest MVC; right M1 corticospinal excitability increased after unilateral strength training, 49% across groups when measured in the no-mirror setup and 55% across groups when measured in the mirror setup.

SICI left-trained M1. The SICI of the left-trained M1, recorded from the right-trained FCR in the no-mirror setup at rest, was not different between groups at baseline and showed no interaction or time main effect (all P values ≥ 0.262).

SICI right-untrained M1. Table 2 shows the SICI of the right-untrained M1 recorded from the left FCR in the no-mirror and mirror setup at rest and during dynamic right wrist flexion contractions. The SICI of the right M1 was not different between groups at baseline in all setup (t_{21} = −0.1 to 0.7, $P \geq 0.483$). No group–time interaction was observed in any of the setup ($P \geq 0.078$), and only a time main effect was observed when the SICI of the right-untrained M1 was measured in the no-mirror ($F_{1,21} = 10.6$, $P < 0.004$, $\eta_P^2 = 0.335$) and mirror setup ($F_{1,21} = 10.0$, $P = 0.005$, $\eta_P^2 = 0.322$) during right wrist flexion contractions performed at 60% posttest MVC. The time main effect showed that the SICI of the right M1 was diminished after unilateral strength training, 45% across groups when measured in the no-mirror setup and 28% across groups when measured in the mirror setup.

cSP right-trained FCR. Figures 3A and 3B show the cSP duration recorded from the isometrically contracting right-trained FCR after the stimulation of the left-trained M1. The cSP duration was not different between groups at baseline (t_{21} = −0.5, $P = 0.650$), and no group–time interaction or time main effect was observed for contractions performed at 60% pretest MVC and 60% posttest MVC (all P values ≥ 0.508).

cSP left-untrained FCR. Figure 3C illustrates a representative cSP trace for a single participant illustrating the cSP duration recorded from the isometrically contracting left FCR after the stimulation of the right-untrained M1. Figures 3D and 2E show the cSP duration group data recorded from the left-untrained FCR. The cSP did not differ between groups at baseline ($t_{21} = 0.9$, $P = 0.355$), and a group–time interaction was observed for contractions performed at 60% pretest MVC ($F_{1,21} = 8.5$, $P = 0.008$, $\eta_P^2 = 0.289$) and 60% posttest

TABLE 2. Descriptive data for the corticospinal excitability and SICI of the right-untrained M1 (mean ± SD).

		Corticospinal Excitability (% M_{max})		SICI (% Test Alone)	
Condition	**Group**	**Pretest**	**Posttest**	**Pretest**	**Posttest**
No-mirror setup, rest	Mirror	3.7 ± 3.7	3.7 ± 2.4	42.8 ± 30.2	46.4 ± 34.2
	No-mirror	4.1 ± 2.6	5.3 ± 4.6	38.0 ± 16.4	36.7 ± 27.3
Mirror setup, rest	Mirror	3.9 ± 2.7	3.7 ± 2.6	41.3 ± 27.4	49.9 ± 24.7
	No-mirror	4.5 ± 2.7	5.3 ± 4.6	39.8 ± 26.9	41.0 ± 26.5
No-mirror setup, 60% pretest MVC right-trained wrist	Mirror	8.1 ± 3.2	8.5 ± 6.1	37.9 ± 19.3	50.9 ± 19.4
	No-mirror	8.6 ± 5.8	12.1 ± 7.3	37.4 ± 16.3	38.9 ± 25.4
Mirror setup, 60% pretest MVC right-trained wrist	Mirror	7.7 ± 5.0	8.4 ± 5.8	47.7 ± 18.6	57.5 ± 22.3
	No-mirror	8.0 ± 4.6	10.4 ± 6.2	42.1 ± 18.8	41.3 ± 22.9
No-mirror setup, 60% posttest MVC right-trained wrist[a]	Mirror	8.1 ± 3.2	11.9 ± 7.9*	37.9 ± 19.3	56.9 ± 25.4*
	No-mirror	8.6 ± 5.8	12.9 ± 6.5*	37.4 ± 16.3	52.7 ± 21.2*
Mirror setup, 60% posttest MVC right-trained wrist[a]	Mirror	7.7 ± 5.0	9.7 ± 5.8*	47.7 ± 18.6	66.1 ± 21.2*
	No-mirror	8.0 ± 4.6	14.5 ± 6.9*	42.1 ± 18.8	49.7 ± 19.4*

*Significant time main effect ($P < 0.05$).
[a]At the pretest, contractions are performed at 60% pretest MVC, and at the posttest, contractions are performed at 60% posttest MVC.

MVC ($F_{1,21}$ = 5.4, P = 0.030, η_P^2 = 0.206). Follow-up analysis revealed that the posttest cSP duration differed for the MG compared with the NMG when measured on left wrist flexion contractions at 60% pretest MVC ($P < 0.05$, $d = -0.83$) and 60% posttest MVC ($P < 0.05$, $d = -0.56$). Thereby, the cSP duration measured on contractions at 60% pretest MVC became 16% shorter for the MG and 12% longer for the NMG after unilateral strength training ($P < 0.05$). When the cSP was measured on left wrist flexion contractions at 60% posttest MVC, the cSP duration decreased 15% for the MG ($P < 0.05$) but remained unchanged for the NMG ($P > 0.10$). There was no time main effect ($P \geq 0.423$).

MEP recorded from the contracting FCR. MEP values recorded from the isometrically contracting right-trained and left-untrained FCR were not different for both groups at baseline, and no group–time interaction or time main effect was observed for contractions performed at 60% pretest MVC and 60% posttest MVC (all P values ≥ 0.161). MEP evoked upon the contracting right FCR had an average amplitude of 40.6 ± 17.0% M_{max}, and MEP evoked on the contracting left FCR had an average amplitude of 40.5 ± 14.3% M_{max}.

IHI. Figure 4 shows IHI from left-trained to right-untrained M1, recorded from the left-untrained FCR, measured in the no-mirror and mirror setup at rest. IHI was not different between groups at baseline. IHI measured in the no-mirror setup showed no group–time interaction ($F_{1,14}$ = 1.5, P = 0.235), but there was a time main effect ($F_{1,14}$ = 11.1, P = 0.007, η_P^2 = 0.418); training increased IHI by 26% across groups. An

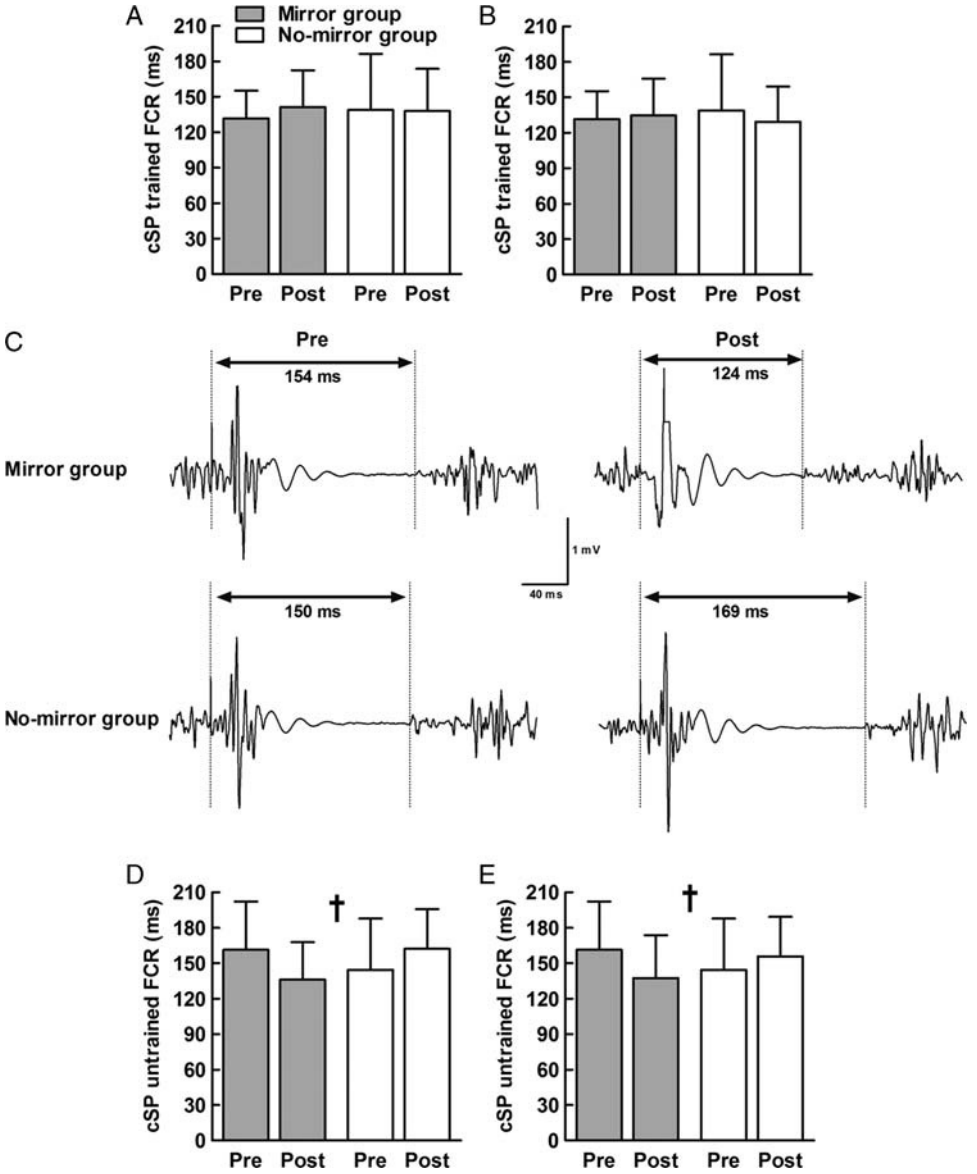

FIGURE 3—Group data of the cSP duration measured during isometric contractions of the right-trained wrist at 60% pretest MVC (A) and at 60% posttest MVC (B). Panel C shows representative traces of the cSP of a single participant recorded from the isometrically contracting left-untrained FCR. Each trace comprises one trial. Note that the participant in the mirror group exhibits a shortening, whereas the participant in the no-mirror group reveals a lengthening of the cSP, results also born out by the group data in panel D (contractions performed at 60% pretest MVC) and panel E (contractions performed at 60% posttest MVC). †Group–time interaction ($P < 0.05$).

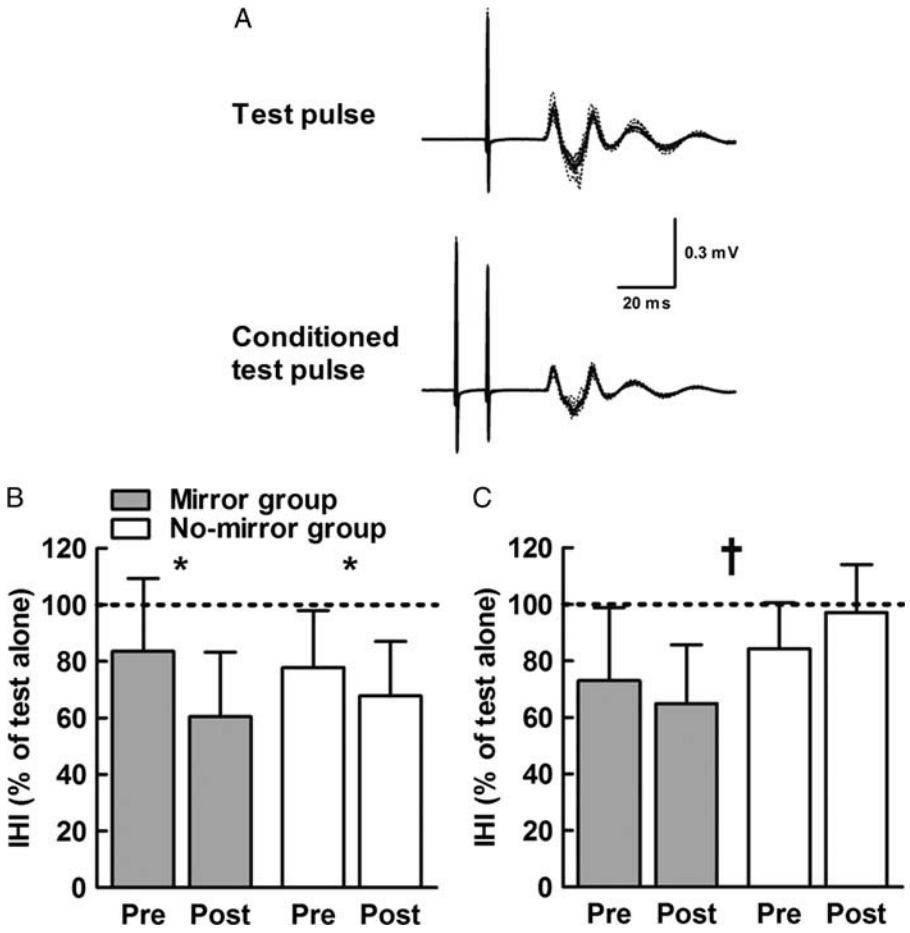

FIGURE 4—IHI from left-trained to right-untrained M1 measured at rest and recorded from the left-untrained FCR. A, Representative MEP waveforms of a single participant. *Dotted lines* are single trials, and the *thick solid line* represents the average of the ten single trials. The conditioned MEP size is ~75% of test alone. B, Group data of IHI measured in the no-mirror setup at rest. C, Group data of IHI measured in the mirror setup at rest. A higher value means less IHI. The *horizontal dashed line* at 100% represents the control value, i.e., absence of inhibition and facilitation. *Time main effect ($P < 0.05$). †Group–time interaction ($P < 0.05$).

interaction ($F_{1,14} = 4.7$, $P = 0.048$, $\eta_P^2 = 0.251$) but no time main effect ($F_{1,14} = 0.2$, $P = 0.634$) was observed for IHI measured in the mirror setup; IHI of the MG increased by 11%, whereas IHI of the NMG decreased by 15% after the strength intervention.

The size of the test pulse, which was used as a control value for determining IHI, was not different for both groups at baseline, and no interaction or time main effect was observed (all P values ≥ 0.227). The size of the test pulse was ~0.3 mV in the MG and NMG and was stable across test sessions. Also, the one-sample t-tests showed that IHI was significantly different from 100% during all IHI measurements (all P values < 0.01).

EMG activity during training. The EMG activity of the contracting right FCR and resting left FCR was measured during the 5th, 10th, and 15th training sessions in two participants from each training group. Overall, mean EMG activity did not increase over time for the right FCR (session 5: 4.5 ± 1.5% M_{max}; session 10: 5.3 ± 2.2% M_{max}; session 15: 6.9 ± 6.5% M_{max}; $\chi^2(2) = 0.5$, $P = 0.779$) and left FCR (session 5: 0.3 ± 0.1% M_{max}; session 10: 0.5 ± 0.3% M_{max}; session 15: 0.6 ± 0.3% M_{max}; $\chi^2(2) = 4.5$, $P = 0.105$). Because of the small sample size, we were not able to calculate between-group comparisons.

DISCUSSION

In line with our expectations, 3 wk of unilateral strength training using a mirror produced greater cross-education from the trained to untrained wrist flexor muscles (61%) compared with training without a mirror (34%) where no visual feedback was provided. This increased cross-education was accompanied by an increase in IHI from the trained to untrained M1 measured at rest and by a decrease in cSP duration of the left-untrained FCR measured during contraction. Mirror-viewing did not further increase the strength gains in the trained hand. These results provide the first evidence that unilateral strength training with a mirror can augment the magnitude of cross-education.

Behavioral changes. Viewing the mirror did not affect the magnitude of strength gains in the trained wrist but caused greater cross-education. The 72% strength gain observed in

the trained wrist after 640 wrist flexion contractions for 15 training sessions is higher than the 45% increase previously reported using a wrist task (10). However, the aforementioned study used isometric wrist contractions, whereas subjects in the present study performed dynamic contractions, suggesting that motor practice with dynamic contractions could provide a stimulus for greater strength gains. A lack of mirror effect in the trained hand is compatible with the idea that looking at the illusionary motion of the untrained hand does not provide an additional training stimulus relative to the main training stimulus provided by muscle contraction.

According to our prediction, unilateral training with the mirror produced greater cross-education than training without the mirror, which equated to 27% or 2.2 N·m more transfer. This preferential increase in strength occurred only when the effect was tested by dynamic but not isometric contractions. Thus, in line with our expectations, the illusionary movement of the stationary hand was likely a critical element in the mirror-magnifying effect of cross-education. The magnitude of cross-education in the present study was 61% with the mirror and 34% without the mirror, which exceeds the values of −3% to 22% reported previously (29); importantly, >50% of the studies included in these meta-analyses used isometric instead of dynamic training. The greater cross-education observed in the current compared with previous studies was not inconceivably caused by the dynamic muscle contraction, as there also was 47% increase in strength after 12 dynamic wrist flexion-training sessions without the use of a mirror (20). Most likely, the novelty and unusual nature of the wrist flexion task could therefore provide a greater scope for performance improvement, an observation that was also suggested in a previous cross-education study that used an ulnar deviation training task (10). The strength improvement in the untrained wrist flexors was accompanied by a 36% increase in surface EMG activity (during the MVC), suggesting that an increase in neural drive contributed to the cross-education effect. However, the increase in surface EMG was similar in the MG and NMG, despite the MG showing greater cross-education. Therefore, other neural adaptations not captured by surface EMG might also contribute to the greater cross-education effect produced by the mirror.

Corticospinal and motor cortical excitability: trained M1. Changes in corticospinal excitability are thought to reflect neuronal adaptations in long-term potentiation-like mechanisms (3). A human study suggested that skill training comprising low-force but highly variable movements (as opposed to strength training, using high-force monotonic movements) would preferentially cause plasticity as measured by increases in corticospinal excitability (19). Although corticospinal excitability remained unchanged after strength training of the finger (21), wrist (present study), and leg (26), strength training of a leg muscle, in the context of cross-education, increased the peak height of the recruitment curve by 53% (13). Notwithstanding, the lack of changes in corticospinal excitability in the trained M1 seems to imply the involvement of the untrained hemisphere in cross-education. Our results add to the evidence that motor practice with high-force monotonic movements does not change corticospinal excitability and causes little or no plastic changes in the corticospinal path. However, these findings require further verification (2).

To quantify the potential role of intracortical circuits, we measured SICI in the trained M1. $GABA_A$ receptors are thought to mediate SICI (24). Increases in $GABA_A$ receptor function tend to diminish motor learning by blocking the induction of long-term potentiation (3). Previous strength studies reported no change (1) or a decrease (43) in SICI. Our data add to the prevailing view that $GABA_A$-mediated long-term potentiation-like mechanisms probably play little or no role in strength gains produced by strength training. The absence of changes in SICI points to the involvement of the untrained hemisphere in evoking cross-education.

The cSP is the interruption of ongoing EMG activity by TMS discharged for the contralateral M1. Although ~50 ms of the initial part of the cSP is due to spinal inhibition (45), the latter part of the cSP, as suggested by direct cortical (23), transcranial electrical, and magnetic stimulation (18), is of motor cortical origin mediated by $GABA_B$ receptors (39). Our cSP of 135 ms at baseline is well within the 90- to 190-ms range reported in healthy humans arm muscles (33). Previously, finger and leg strength-training studies reported 3% to 26% reductions in cSP duration at stimulation intensities of 5% to 20% above the active motor threshold in the presence of 21% to 34% strength gains (21,26), but we observed no changes in cSP. To increase the specificity of the recording conditions and to capture changes in inhibition by referencing it to the training stimulus, we measured the cSP at a background contraction of 60% MVC, an intensity much higher than that previously recorded. However, this difference in contraction intensity is unlikely to account for a lack of change in our cSP because contractions higher than 20% MVC tend not to further increase cSP duration (33).

Corticospinal and motor cortical excitability: untrained M1. In line with the cross-activation model (36), studies reported increases in corticospinal excitability measured in the untrained M1 at rest (16) and during weak muscle contractions (10% MVC) of the untrained upper (22) and untrained lower (13) extremities. There is a tendency for smaller changes (6%) when measured at rest compared with contractions of the trained hand (10% and 64% at 20% and 80% MVC, respectively) (16), assigning specificity and functionality of these neuronal changes to cross-education. Our data concur with previous data as we observed no changes in corticospinal excitability at rest, but we found 49% and 55% increases in the mirror and no-mirror condition during dynamic contractions of the trained wrist at 60% posttest MVC. Our data also support the notion that strength training of one hand increases the neural drive from the untrained M1 to the untrained wrist muscles, and this increase in excitability contributes to cross-education. These results, however, must be interpreted with caution because corticospinal excitability did not increase when subjects performed the contractions of the trained wrist at 60% pretest MVC. Thus, the mechanism

for the increased neural drive to the untrained wrist is due to the test being conducted at a higher relative contraction intensity at the posttest (60% posttest MVC vs 60% pretest MVC) (32). Importantly, our data show that the increase in excitability occurred independent of mirror use. That is, the mirror-augmented cross-education of strength is caused by mechanisms other than corticospinal excitability.

The size of SICI becomes smaller in the ipsilateral M1 when healthy subjects perform a forceful voluntary contraction with versus without a mirror (47). However, training did not further decrease SICI. In the context of the cross-education of strength, SICI in the untrained M1 measured at rest remained unchanged after 8 wk of index finger strength training (16). Past and present data collectively suggest that SICI in relation to unilateral strength training is not sensitive to changes when measured at rest. However, when measured during 10% MVC of the untrained rectus femoris, SICI decreased by 21% in the untrained M1 after 3 wk of unilateral leg strength training (13), and it further decreased (32%) when measured at a 40% MVC contraction of the untrained wrist flexors (20). We also observed a reduction in SICI (45% in the no-mirror setup and 28% in the mirror setup) in the right-untrained ipsilateral M1 when measured during a 60% dynamic MVC of the trained-right hand. Together, $GABA_A$-mediated intracortical inhibitory circuits become especially sensitive to the effects of unilateral strength training when tested during a muscle contraction, but this effect, similar to corticospinal excitability, is independent of training with or without a mirror.

The modulation of cSP arguably provides the strongest evidence to support the mirror training effects in the present study. The cSP duration in the left-untrained FCR, measured at 60% pretest MVC, decreased by 16% for the MG and increased by 12% for the NMG after the intervention, a pattern replicated for the MG when measured at 60% posttest MVC (15% decrease for the MG vs no change for the NMG; Figures 3D and 3E). A reduction in cSP duration has been previously linked to cross-education without a mirror (26), and a recent study showed that the 19% extra cross-education produced by eccentric versus concentric strength training was accompanied by a 27% reduction in cSP duration (20). These results and our data strengthen the potential importance of this inhibitory path in cross-education. We used cSP as a surrogate measure of $GABA_B$-mediated inhibition, but we acknowledge that the observed reduction in cSP duration could be of cortical origin, spinal origin, or both. It is less likely that spinal mechanisms play a role in evoking cross-education (25). Therefore, we speculate that the reduction in cSP duration is likely due to a mirror training–induced reduction in $GABA_B$-mediated intracortical inhibition.

IHI from trained to untrained M1. The IHI measured from the trained to the untrained M1 provides information on the interhemispheric glutaminergic connectivity that arises from the trained M1 and projects to local GABAergic inhibitory interneurons located in the untrained M1 (12). Eight weeks of isometric index finger strength training without a mirror resulted in 28% cross-education accompanied by a reduction in IHI from the trained to untrained M1 (16). In contrast, IHI increased in both the MG and the NMG in the present study when measured in the no-mirror setup at rest and increased for the MG. However, IHI decreased in the NMG when recorded in the mirror setup at rest. These IHI data tentatively suggest (n = 8 per group) that interhemispheric plasticity contributes to cross-education and that the nature of the interhemispheric communication is altered in a training-specific manner. The functional interpretation of these data is complex. First, the IHI data were obtained at rest, and the small sample size restricted us from calculating correlations between the changes in IHI at rest and the magnitude of cross-education. Second, cross-sectional studies showed that IHI, SICI, and their interaction contribute to the control of corticospinal output to the resting hand during the execution of forceful unilateral wrist flexion contractions (32). However, we found no such effect as both corticospinal excitability and SICI, but not IHI measured at rest, were unchanged after unilateral strength training. Although we did not measure directly the effects of IHI on CSE and SICI before and after the intervention, changes in IHI without changes in CSE and SICI might suggest that IHI effects were isolated. Thus, any of its effects did not become manifested in cross-education through CSE and SICI but instead through the modifications of interhemispheric connections. Such changes may have some functional effects especially for the MG as there is evidence that anterior callosal regions associated with IHI contribute to the integration of perception and action within a subcorticocortical network, promoting a unified experience of how we perceive the visual world and prepare our actions (37). It is suggested that the stimulus-driven activity in one hemisphere suppresses the activity in the opposite hemisphere by increasing the amount of IHI, which is compatible with the increased IHI in our MG (5). Therefore, 3 wk of unilateral strength training while mirror-viewing the moving right hand induces a shift in attention to the untrained M1 associated with the mirror image by increasing inhibition from the trained to the untrained M1. Future research should elucidate the role of IHI in unilateral strength training using a mirror, specifically in stroke patients where the modulation of IHI seems to be an important factor for improving the motor function of the paretic side.

Associated EMG activity. Many participants showed associated EMG activity in the homologous resting muscles during unilateral contractions, confirming previous work (15,46). This activity is thought to represent the increased activity of task-specific brain areas during and after motor practice and hence contributes to the improved motor control and strength of the untrained homologous muscles (17). It is possible that the use of the mirror increased associated activity, which in turn augmented cross-education. We expected that the associated activity during training would be higher for the MG than the NMG, but data from a few subjects suggested no such effect. Because of the magnitude of associated activity in strong muscle contractions, future studies will clarify this activity in cross-education. Such work is needed because weak muscle

contractions, corresponding to forces predicted by associated activity, can increase maximal voluntary muscle strength (9).

Limitations. During unilateral motor practice, subjects tend to direct their attention to the moving limb. A limitation of the present study is that without an active-vision group, we cannot exclude the possibility that viewing the moving limb *per se* could have also augmented cross-education. However, mirror training augmented the cross-education of fine motor skills more than the direct viewing of the practicing limb (14). Thus, it is the mirror illusion instead of the view of the hand moving that was the likely factor augmenting cross-education in the present study.

The observed changes in IHI and cSP duration after mirror training suggest that $GABA_B$-mediated circuits are probably involved in the augmented cross-education of strength. Two other circuits that are believed to be dependent on $GABA_B$-mediated neurotransmission are long-interval intracortical inhibition (LICI) and long-latency IHI (LIHI), both infrequently if at all measured in relation to cross-education. Thus, future studies should also focus on $GABA_B$-mediated LICI and LIHI to disentangle the cortical mechanisms that are involved in cross-education.

In addition to cortical mechanisms, the involvement of subcortical and spinal circuits should not be excluded (4). Increased spinal reflex excitability, expressed as an increase in H-reflex amplitude, contributed to the strength improvement of the trained limb but not the strength improvement of the contralateral untrained limb (25). Although an increased H-reflex excitability might contribute to the cross-education of strength, either by increasing motoneuronal excitability or by reducing presynaptic inhibition, unequivocal evidence for the involvement of spinal mechanisms is still needed.

CONCLUSIONS

The present study provides initial evidence that the use of a mirror can augment strength in a cross-education paradigm. The neurophysiological basis for the augmented cross-education seems to be related to altered inhibition as measured by cSP and IHI. Additional candidate areas other than M1 include somatosensory areas and elements of the MNS, which we, by TMS, could not measure. The present data warrant further studies that involve connectivity analyses using TMS, EEG, and imaging to help determine the brain areas and mechanism that underpin how viewing one's own hand in a mirror can facilitate the cross-education of strength. In summary, this study provides important information that viewing the exercising hand in a mirror can augment the cross-education effect and potentially accelerate functional recovery from unilateral impairment. Regardless of the underlying mechanisms, there is now accumulating evidence that patients with unilateral orthopedic (28) and neurological (8) impairments can benefit from the cross-education of strength, a phenomenon that mirror-viewing could further augment.

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