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From mental power to muscle power—gaining strength by using the mind

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Abstract

The purposes of this project were to determine mental training-induced strength gains (without performing physical exercises) in the little finger abductor as well as in the elbow flexor muscles, which are frequently used during daily living, and to quantify cortical signals that mediate maximal voluntary contractions (MVCs) of the two muscle groups. Thirty young, healthy volunteers participated in the study. The first group ($N = 8$) was trained to perform "mental contractions" of little finger abduction (ABD); the second group ($N = 8$) performed mental contractions of elbow (ELB) flexion; and the third group ($N = 8$) was not trained but participated in all measurements and served as a control group. Finally, six volunteers performed training of physical maximal finger abductions. Training lasted for 12 weeks (15 min per day, 5 days per week). At the end of training, we found that the ABD group had increased their finger abduction strength by 35% ($P < 0.005$) and the ELB group augmented their elbow flexion strength by 13.5% ($P < 0.001$). The physical training group increased the finger abduction strength by 53% ($P < 0.01$). The control group showed no significant changes in strength for either finger abduction or elbow flexion tasks. The improvement in muscle strength for trained groups was accompanied by significant increases in electroencephalogram-derived cortical potential, a measure previously shown to be directly related to control of voluntary muscle contractions. We conclude that the mental training employed by this study enhances the cortical output signal, which drives the muscles to a higher activation level and increases strength.

Keywords: Mental training; Imagery; Muscle strength; Maximal voluntary contraction (MVC); MVC-related cortical potential (MRCP)

1. Introduction

Despite extensive reports regarding neural contributions to voluntary strength gains following conventional strength training programs, the exact neural mechanisms underlying human voluntary muscle strengthening are poorly understood. A common opinion is that gains in voluntary muscle force result from two main factors: neural adaptation and muscle hypertrophy. Strength gains in the early stage of a training program result mainly from changes in the nervous system (Enoka, 1988; Sale, 1988). Additionally, training of one limb is associated with an increase in the voluntary strength of the contralateral untrained muscles, even though the contralateral muscles remained quiescent during training (Houston, Froese, Valeriote, Green, & Ranney, 1983; Yasuda & Miyamura, 1983). The phenomenon of increased strength in the untrained contralateral muscle raises the intriguing possibility that muscle strength may be improved without repetitive muscle activation or without repetitive activation of motor neurons and descending motor pathways. This possibility has not been extensively explored despite its scientific significance and clinical relevance.

Research on motor skill acquisition has demonstrated clearly that mental practice leads to improved performance (Corbin, 1972; Feltz & Landers, 1983). Thus, the neural events controlling the muscle parameters for performance (e.g., amplitude, timing) can be improved through mental practice. This interpretation is supported by evidence that during motor learning, neural activity in various regions of the brain changes according to the level of the motor skill achieved (Karni et al., 1995; Pascual-Leone, Grafman, & Hallett, 1994). One recent study showed that physical training and mental practice of a motor skill resulted in a

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similar amount of improvement in performance and a similar pattern of adaptation in the primary motor cortex in human participants (Pascual-Leone et al., 1995).

The above-mentioned findings led us to a question: If mental practice of a motor skill can modify neural substrates for physical performance, can mental practice of maximal voluntary contractions (MVCs) alter neural signals for muscle strength? Yue and Cole (1992) trained a group of volunteers with "imagined maximal contractions" of the fifth finger abductor muscle for 4 weeks and found a 22% increase in strength of the muscle. The authors attributed the strength gain to training-induced changes in central programming, although no related central nervous system (CNS) data could be acquired then. It is unknown whether mental training, such as the one employed in this 1992 study, changes the CNS command to muscle. Moreover, because this observation was made on a hand muscle, one might ask whether the strength gain following mental training could be realized in a larger, more proximal muscle group, such as the elbow flexor muscles (Herbert, Dean, & Gandevia, 1998). Distal and proximal muscles differ in the size of cortical representation (Penfield & Rasmussen, 1950), the extent of monosynaptic corticospinal projection (Ghez, 1991; Kuypers, 1981), and the relative contribution of motor unit recruitment and modulation of discharge rate to the gradation of muscle force (DeLuca, LeFever, McCue, & Xenakis, 1982; Kukulka & Clamann, 1981; Milner-Brown, Stein, & Yemm, 1973; Monster & Chan, 1977).

A recent mental imagery study (Herbert et al., 1998) aimed to improve elbow flexor muscle strength found no significant difference in strength changes between mental training and control groups after the training program. This could be due to the relatively small cortical representation of the muscles and monosynaptic corticospinal projection to their motoneuron pools mentioned above. In addition, the elbow flexor muscles are frequently used for daily activities and may be considered as "highly trained" with little room for neural adaptation-induced strength improvements. Finally, there was a possibility that the instruction given to the training subjects for mental imagery was external imagery type that produces little physiological responses (Lang, 1979; Lang, Kozak, Miller, Levin, & McLean, 1980; Wang & Morgan, 1992) and is not as effective in enhancing muscle force as internal imagery training (Ranganathan, Kuykendall, Siemionow, & Yue, 2002). If the subjects indeed performed the imagery training with mental processes similar to those described by external imagery in the study of Herbert et al. (1998), then the question of whether voluntary strength of large, proximal muscle groups such as elbow flexors could be improved by mental training was still an unsettled issue.

The purpose of this study was to determine the effects of mental training that uses internal or kinesthetic imagery on voluntary strength of the fifth finger abductor (a distal muscle) and the elbow flexors (a proximal muscle group) of the dominant arm and quantify the mental training-induced cortical signal alterations. We chose the little finger abductor based on an assumption that this muscle is used relatively less frequently during daily living and thus has a greater capacity for training-induced strength improvements compared with the elbow flexor muscles. Preliminary results of the study have appeared in abstract form (Ranganathan, Siemionow, Sahgal, & Yue, 2001).

2. Materials and methods

2.1. Subjects

Thirty young, healthy, right-handed, previously untrained subjects participated in this study. Of the 30, 16 (age, 29.7±4.8 years; weight, 68.9±15 kg; height, 168.6±10 cm; eight women) were initially recruited and were randomly assigned to either mental training of finger abduction (ABD) or elbow flexion (ELB) group. To compare the effects of no practice, a control (CTRL) group of eight subjects (age, 30.1±4.1 years; weight, 74.8±19 kg; height, 166.6±11 cm; four women) was recruited later, and their strength changes were compared against those of the ABD and ELB groups. Finally, six volunteers were recruited and trained with conventional physical maximal muscle contractions (see descriptions below). The Institutional Review Board at The Cleveland Clinic Foundation approved the study and all participants gave their informed consent prior to participation.

2.2. Mental training

The mental training lasted for 12 weeks with five 15 min training sessions per week. During each training session, participants were instructed to perform mental contractions of the fifth finger abduction (ABD group) or elbow flexion (ELB group) for 5 s followed by a 5 s rest for 50 trials. The subjects were given a 2 min rest after the first 25 trials. During each trial, they were instructed to imagine their finger or forearm pushing maximally against the force transducer that was used for the strength measurements during the pre-training tests or against a heavy object. It should be noted that this mental exercise was not simply a visualization of oneself performing the task; rather, the performers were instructed to adopt a kinesthetic imagery approach, in which they urged the muscles to contract maximally, and this was accompanied by significantly elevated physiological responses (see Section 3). We call this mental process *visualization-guided brain activation* (VGBA) training. In this process, an ABD participant first visualized that his/her dominant hand was positioned on the support surface with the lateral side of the little finger against the force transducer. The subject then imagined, with maximal effort, pushing the transducer away by abducting the finger. For the ELB group, subjects visualized that their wrist was located under the transducer and mentally tried very hard to push the transducer up by flexing the elbow joint. Many ELB participants visualized putting the forearm under a heavy table and then tried very hard mentally to lift the table. For both ABD and ELB groups, the training and testing setup were the same. For the finger ABD task, the hand was positioned in front of the subject; for the ELB task, the arm was held on the side of the body. For both the tasks, subjects could see the stationary hand or arm when imagining the contraction. However, a majority of the subjects performed the mental exercises with their eyes closed.

Surface EMG of the finger abductor (ABD group) and biceps brachii (ELB group) muscles was monitored during all training sessions. The EMG signals during the mental contractions were quantified by rectifying and averaging the middle 3 s of each 5 s trial, obtaining a mean value for the total trials of each training day and week, and finally obtaining a mean value for the entire 12-week training program. The CTRL group did not perform any training task but participated in all the tests.

2.3. Strength measurement

The finger abduction force was measured using a load cell (range, 0–50 Pbs; Sensotec Inc., Columbus, OH) housed between two plastic plates. The lateral side of the right fifth finger was positioned against the load cell while the other four fingers, the hand, and the forearm were restrained (Fig. 1A). In each trial, the participants pushed as hard as possible against the load cell by abducting the right little finger. The load cell was positioned against the distal interphalangeal joint. The load cell's voltage output was amplified (1000×), digitized (100 samples/s), and recorded on the hard disk of a personal computer using the Spike2 data-acquisition system (1401 Plus, Cambridge Electronic Design Ltd., Cambridge, UK).

Elbow flexion force was measured (Fig. 1B; JR3 Universal Force-Moment Sensor System, Woodland, CA) with subjects seated, their forearm in a neutral position and an elbow joint angle of ∼100° (Siemionow, Yue, Ranganathan, Liu & Sahgal, 2000). For each task, three trials were performed in each measurement session and the highest force among the trials was analyzed. For each trial, participants were verbally encouraged to exert maximal strength. Three baseline strength measurements were made before training (once per week), and strength was assessed every other week during training (12 weeks) and detraining (12 weeks for the ELB and CTRL groups and 18 weeks for the ABD group) periods. Because the strength of the ABD group was still significantly greater than the pre-training level 12 weeks after the training had ended, the detraining for this group was extended to 18 weeks. The strength measurement conditions

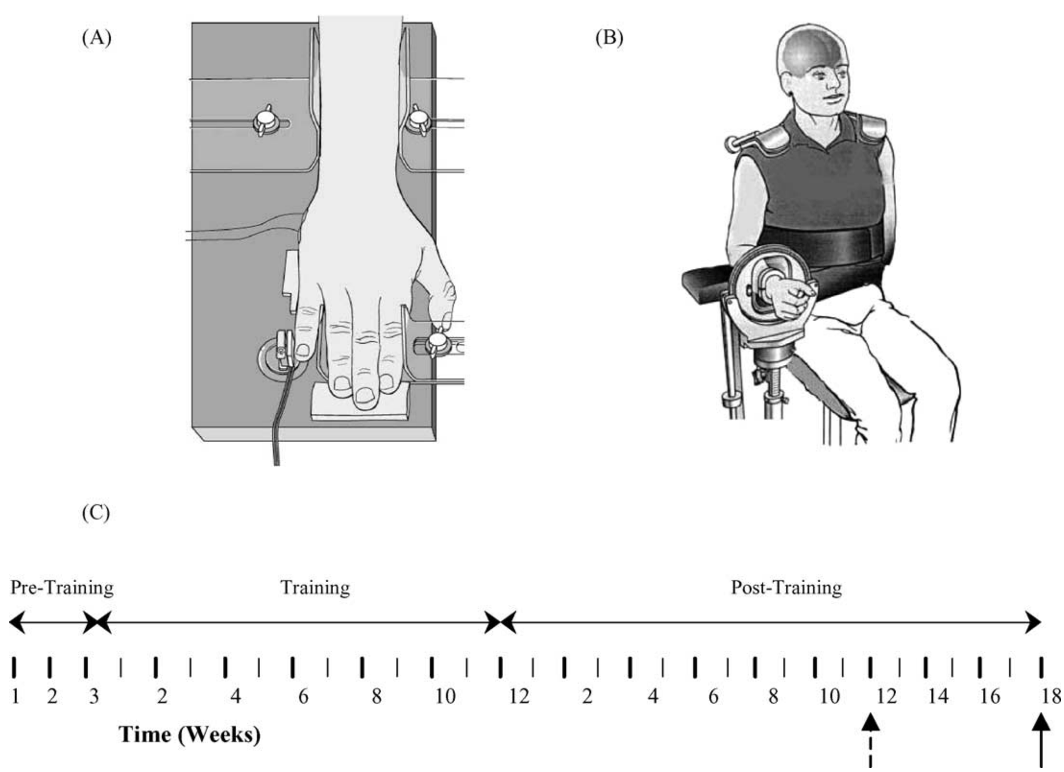

Fig. 1. Experimental setup for finger abduction (A) and elbow flexion (B) tasks. The setups were used for both training and testing. (C) A schematic diagram showing the pre-training, training, and detraining schedule (in weeks) for strength measurements. Vertical lines indicate time in weeks, with the thin lines representing odd numbers and thick lines even numbers for the training and detraining periods. Each thick vertical line also indicates a strength measurement session. The dashed-line arrow indicates the conclusion of the detraining for the ELB group, and the solid-line arrow shows the time when the detraining for the ABD group was terminated.

(such as finger, arm and body positions), and joint angles were carefully measured each time and maintained as consistently as possible over the sessions. In addition, the verbal instruction and encouragement for maximal force production were the same for all measurement sessions. Fig. 1C illustrates the strength measurement schedule for the three groups.

2.4. MRCP measurement

EEG electrodes were placed on the scalp roughly overlying the supplementary motor area (Cz), contralateral (C3) and ipsilateral (C4) sensorimotor regions, and central location of the prefrontal cortex (Fz). Electrode locations were determined based on the International 10–20 System (Jasper, 1958). Conducting gel (Electro-gel™, Electro-Cap International Inc., Eaton, OH) was injected into each electrode to connect the recording surface of the electrode with the scalp. Impedance between each electrode and the skin was maintained below 5000 ohms (at 30 Hz). The EEG signal was amplified (20,000×; Model 15A54, Grass Instrument Co., Quincy, MA), band-pass filtered (0.1–100 Hz), digitized (200 samples/s) using the Spike2 system and stored on the hard disk of a personal computer.

The EEG data were acquired during four of the strength measurement sessions: before training, 6 weeks into the training, at the end of training, and 12 weeks after completion of training. In each EEG session, participants performed 30-finger abduction or elbow flexion MVCs (once every 10 s). It is necessary to perform multiple MVC trials to obtain triggered averaging of the MVC-related cortical potential (MRCP). Raw EEG data were visually examined, and trials with artifacts (such as eye blinks) were excluded. For each MVC trial, a 4 s window of the EEG was triggered by the force output (threshold = 5% initial MVC force), 2 s before and 2 s after the trigger (Fang, Siemionow, Sahgal, Xiong, & Yue, 2001; Siemionow et al., 2000). The Spike2 data analysis software performed signal averaging over the 30 trials. The amplitude of each averaged MRCP was measured from the baseline to the peak of the negative potential (Fang et al., 2001; Siemionow et al., 2000; Yue et al., 2000). Because the MRCP was time-locked to each MVC, it was considered directly related to the planning and execution of the MVC. Thus, increases in MRCP amplitude after mental training can be considered a direct indication of an enhancement in the descending command to the target muscle.

In the case of measuring MRCP for mental MVCs, scalp EEG was trigger-averaged over 40 mental MVC trials (once every 10 s). Participants were given two soft auditory signals (beeps generated by a digital stimulator): the first alerted them and the second signaled them to perform the mental contraction. The interval between the first and second beeps was 2 s. The stimulator output (second beep) also served as the trigger signal for averaging the mental MRCP. Simultaneous EMG recordings from the finger abductor or elbow flexor muscles showed no apparent muscle activities during the mental MVCs. The same triggered-EEG averaging was performed over the data obtained when participants only listened to the beeps over 40 trials as a control task. Data analysis showed that no apparent brain potential changes occurred at the four recording locations when participants only listened to the auditory signals that were used for triggering EEG signals for mental MVC.

2.5. EMG measurement

MVC surface EMG was collected with bipolar recordings and quantified by rectifying and averaging the signals in a 0.5 s period that covered the peak force. For the finger abductor muscle, electrodes (4 mm diameter) were applied to the skin over the abductor digiti minimi (ADM) muscle belly, oriented in a line roughly parallel to the muscle fibers with ∼15 mm between the centers of the electrodes. It was not possible to selectively record from an antagonist muscle to the little finger abductor by surface electrodes. Compound muscle action potential (M wave) was recorded from the ADM muscle by stimulating the ulnar nerve using bar electrodes spaced 30 mm apart placed on anterior-medial aspect of the skin near the wrist joint. The stimulation intensity was increased until a maximal M-wave was observed. The average ADM EMG recorded during maximal force contractions was normalized to the maximal M-wave recorded during the same measurement session. For the ELB group, MVC EMG was recorded using surface electrodes (8 mm diameter) from the belly of the biceps brachii (BB), brachioradialis (BR), and triceps brachii (TB) muscles. The maximal M-wave was recorded from the BR muscle by stimulating the radial nerve at the lateral side of the upper arm, near the middle point between the elbow and shoulder joints. The BR EMG recorded during maximal elbow flexion contractions was normalized to the maximal BR M-wave. The average BB EMG was used for analysis without normalization because it was difficult to elicit an M wave from the BB muscle. The TB EMG during the maximal elbow flexion contractions was normalized to the TB EMG recorded during the maximal elbow extension contractions and was a measure of the antagonist (TB) muscle activity during strength performance of the agonist (elbow flexor) muscle group. The EMG signal was amplified (1000×), band-pass filtered (3–1 kHz), digitized (1000 samples/s), and recorded using the Spike2 system.

2.6. Heart rate and blood pressure measurements

Previous research has indicated that effective mental training accompanies elevated physiological responses, such as heart rate, blood pressure, and skin temperature (Decety, Jeannerod, Germain, & Pastene, 1991; Deschaumes-Molinaro, Dittmar, & Vernet-Maury, 1991; Wang & Morgan, 1992; Wuyam et al., 1995). In this study, heart rate (HR) and blood pressure (BP) were recorded randomly (approximately once per week and three to five times during each session) throughout the training course in the ABD group to monitor autonomic changes reported by previous studies. These measurements were done by the same investigator (VKR), using a commercially available BP monitor (model HEM-712C, Omron Healthcare, IL).

2.7. Finger abduction MVC training

Because mental training of the ABD group resulted in a substantial (40%) increase in finger abduction strength, we wondered whether a greater strength improvement could be realized by MVC (physical exercise) training. Six subjects (age, 24.8 ± 8.5 year; two women) performed 50 MVC trials of right little finger abduction (ABD MVC group) Monday through Friday for 12 weeks. (One subject dropped out the training program later on for reasons not related to the study, and thus, the analysis was based on data of the five subjects in this group.) The subjects pushed the load cell device maximally by abducting the little finger as they did during the strength tests. Each trial lasted 5 s, and the inter-trial interval was 20 s. In each training session, there was a 2 min rest break between the first and second 25-trial blocks. Thus, the number of training sessions and trials performed were the same between the physical and mental training groups. Finger abduction strength was measured at time-points similar to those of mental training (ABD) group (i.e., three pre-training measurements and a measurement session every other week during training).

2.8. Muscle volume using MRI

Because muscle hypertrophy was expected following the MVC training, images of the ADM muscle in the right hand of subjects in the ABD MVC group were acquired before and immediately after the 12-week training program using a 1.5 T Siemens Vision scanner and a circularly polarized head coil. The subject lay prone in the MRI scanner with the right arm extended forward and the right hand positioned close to the center of the head coil and aligned along the main magnet. The position of the hand was carefully marked for the consistency across sessions. Twenty contiguous slices (5 mm thickness), which covered the whole muscle, were acquired in the transverse planes (perpendicular to the longitudinal axis of the hand). A slice was always placed between the proximal phalanx and metacarpal bones to ensure consistent positioning of the slices for repeated measurements. The field of view was 200 mm × 200 mm, and the image matrix was 256 × 256, yielding an in-plane spatial resolution of 0.78 mm × 0.78 mm. The imaging parameters were: TR = 440 ms, TE = 10 ms, and flip angle = 60°. The area belonging to the ADM muscle in each image slice was manually circled using the graphical tools in MEDx 3.2 software (Sensor Systems Inc., Sterling, VA). The number of pixels in the regions of interest was summed up over the 20 slices, and the muscle volume for each subject was calculated as the number of pixels multiplied by a unit volume ($0.78\,mm \times 0.78\,mm \times 5\,mm = 3.05\,mm^3$).

2.9. Statistical analysis

Strength, MRCP, and EMG measurements were compared before and after the initiation of training within the groups and between the training and control groups. Due to the repeated nature of the measurements, a repeated-measures analysis of variance (ANOVA) model was used. The pre-training data were compared between the training and control groups by fitting a repeated-measures model using Proc Mixed in SAS. If the differences in average pre-training values between the training and control groups were statistically significant, we normalized the subsequent values by subtracting the mean of the pre-test values for each subject and then dividing it by the mean of the pre-test values. The adjusted data were then fit using a repeated-measures model with a compound symmetry (CS) covariance structure between repeated force measurements on any subject. The CS structure models an equal variance value for each measurement and also assumes an equal covariance value (which could be different from the variance value) for any pair of repeated measurements. Comparisons between the groups and across time-points (during training versus post-training) were made using the adjusted data and treated with Bonferroni correction. Heart rate and blood pressure data were compared using the paired *t*-test, since only one group (ABD) was examined. Because the group trained by physical MVCs was recruited later and with a smaller number of subjects, the dependent variables of this group were also compared with paired *t*-tests. The significance level was determined at $P \leq 0.05$.

3. Results

3.1. Strength gains following mental training

Both mental training groups increased their muscle strength significantly. The abduction strength of the little finger (ABD group) increased almost linearly throughout the training. At the end of the training (12 weeks), the improvement was 35% ($F = 10.3$, $P < 0.001$) compared to pre-training values. However, the greatest gain (40%) was not achieved until 4 weeks after the training had ended (Fig. 2A). The strength gain in the ABD group was significantly different ($P < 0.05$) from the changes seen in the control group. The elbow flexion strength of the arm (ELB group) had a maximal improvement of 13.5% ($F = 6.8$, $P < 0.005$) at the end of training (Fig. 2B), but that was not significantly different ($P > 0.05$) from the change observed in the control group. The control (CTRL) group did not show any significant changes in either finger abduction (range, −3.7 to 4.8%; $F = 0.10$, $P > 0.5$) or elbow flexion (range, −3.6 to 6%; $F = 0.34$, $P > 0.1$) strength during the entire study period. For both the ABD and ELB groups, because the three pre-training strength values showed no significant difference (ABD group, mean ± S.D.: test 1, 12.1 ± 3.3 N;

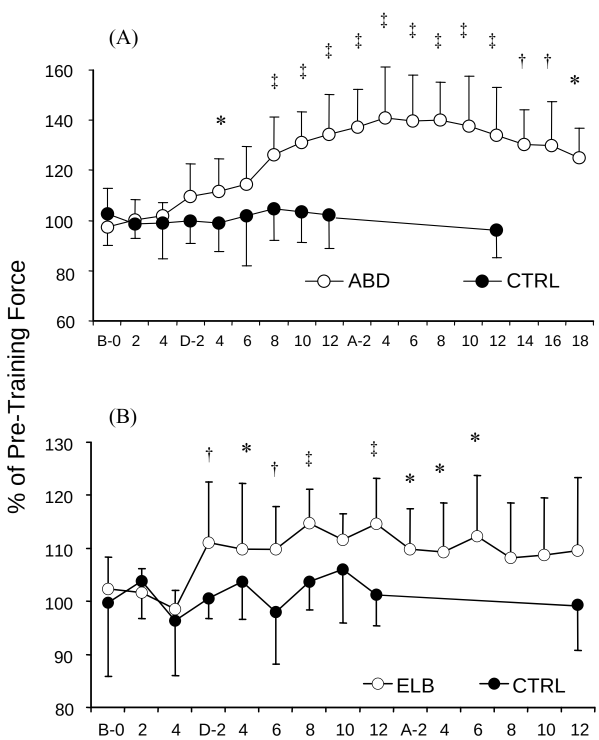

Fig. 2. (A) The ABD group increased finger abduction strength by 35% at the end of training and attained the maximal gain (40%) 4 weeks after the training had ended. (B) The ELB group increased elbow flexion strength by 13.5% at the end of training. The CTRL groups did not have any significant changes in strength. In the *X*-axis, B-0 to B-4 are before training, D-2 to D-12 during training, and A-2 to A-18 (A-2 to A-12 for ELB) after-training measurements. (*Note*: The after-training duration for the ABD group was extended by 6 weeks for a total of 18 weeks since, unlike the ELB group, the changes in strength were still significant at the end of 12 weeks after cessation of training.) The average of the three pre-training (B-0 to B-4) measurements is considered as baseline force (100%). Results shown as mean ± S.D. The significance levels were with respect to the baseline force (* $P < 0.05$, † $P < 0.01$, and ‡ $P < 0.005$).

test 2, 12.8 ± 4.5 N; test 3, 12.7 ± 3.7 N; $P > 0.2$. ELB group, test 1, 234.3 ± 71.3 N; test 2, 238.4 ± 73.2 N; test 3, 236.9 ± 71.7 N; $P > 0.45$), we took the mean of the three tests to represent the baseline measurement (100%). It should be noted that whereas the pre-training elbow flexion MVC force was similar between the CTRL group and the ELB group (240 N versus 236 N), there was a significant difference in the pre-training finger abduction MVC force between the CTRL and ABD groups (19 N versus 12.4 N).

The discrepancy in pre-training finger abduction strength between the ABD and CTRL groups was primarily due to the difficulty of recruiting all the subjects before the training began, and the subsequent inability to randomly divide them into the three groups. Because the study required a long time commitment (27 weeks, including pre-training tests, training, and detraining evaluations), which discouraged many potential subjects from participating in the study, we could not recruit a sufficient number of subjects for the three-group random assignment as originally planned. Instead, we were only able to recruit a sufficient number of subjects for a two-group (ABD and ELB) random assignment. Because subjects in the ABD and CTRL groups were not randomly assigned, the ABD group's pre-training strength differed significantly from that of the CTRL group and this might have increased the possibility of subject allocation bias. Nevertheless, all subjects were carefully screened to ensure that they were not participating in any type of training (physical or mental) and they had not participated in any type of training for at least 2 years before they were recruited.

3.2. Alterations in MVC-related cortical potential (MRCP)

The amplitude of MRCP recorded from scalp electrodes Cz, C3, C4 and Fz for the ABD group increased by 42, 33, 24 and 27% ($F = 9.1$–15.3, $P < 0.005$), respectively, for the MVC task and by 27, 51, 34 and 40% ($F = 6.5$–17.7, $P < 0.005$), respectively, for the mental MVC task. There was no significant difference in the pre-training MRCP values for MVC ($P = 0.225$) or mental MVC ($P = 0.687$) task between ABD and CTRL groups, but the MRCP values for both tasks after training in ABD group were significantly different ($P < 0.001$) from those measured in CTRL group. The MRCP amplitude of the MVC task was significantly higher ($P < 0.005$) compared to that of the mental task for all electrode locations. Potential muscle fatigue due to performing the 30 MVC trials was assessed by measuring the average force value of the first 5 trials and that of the last 5 trials. Because the MVC was relatively brief (∼1–2 s) in duration, the decrease in MVC force was not significant ($P = 0.09$) at the end of the 30 MVC trials. The average force from the 30 MVC trials associated with the MRCP measurement increased by 22% for the ABD group after training. Similar to the strength data, the MRCP amplitude did not return to the baseline level even 12 weeks after the training was terminated (Fig. 3A–D).

The MRCP data of the ELB group recorded from Cz, C3, C4 and Fz electrode locations increased by 19, 21, 16 and 13% ($F = 2.3$–8.1, $P < 0.01$), respectively, for the MVC task and by 13, 34, 21 and 11% ($F = 2.6$–3.9, $P < 0.05$), respectively, for the mental MVC task (Fig. 4A–D). The pre-training MRCP values were similar between the ELB and CTRL groups for both the MVC ($P > 0.4$) and mental MVC ($P > 0.2$) tasks, but was significantly different ($P < 0.05$) for the MVC task after training. The MRCP amplitude was always higher ($P < 0.1$) for the MVC task than for the mental MVC task for all electrode locations. The average force from the 30 MVC trials associated with the MRCP measurement increased by 23% for the ELB group after training. These MRCP data are the first direct evidence to show that training in general and mental training in particular increase brain signals, most probably the descending command to muscle, which leads to strength improvements. The CTRL group did not show significant MRCP changes (2% to 5% for finger abduction MVC task and −6 to −1%

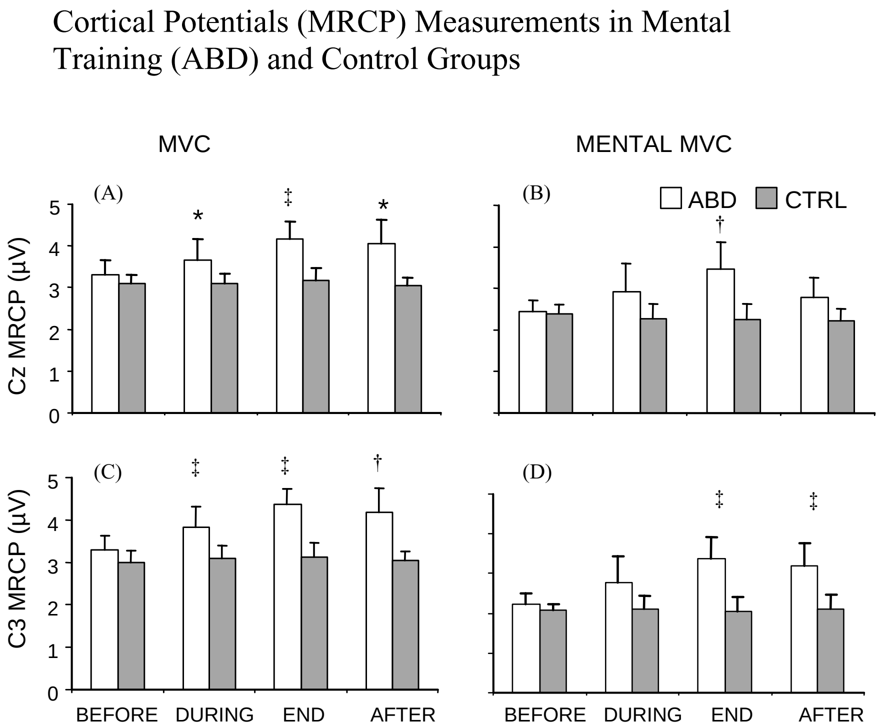

Fig. 3. The MRCP signal from the Cz electrode location during MVC (A) and mental MVC (B) finger abduction tasks increased significantly in the ABD group; at the C3 location, the MRCP had similar significant increases in the ABD group for the MVC and mental MVC tasks (C and D). The increase in MRCP paralleled the increases in the finger abduction force. Significant MRCP increases were also observed at the C4 and Fz locations for the ABD group (see text). The CTRL group did not show any significant changes in MRCP. The significance values are for within group comparisons. Results shown as mean ± S.D.

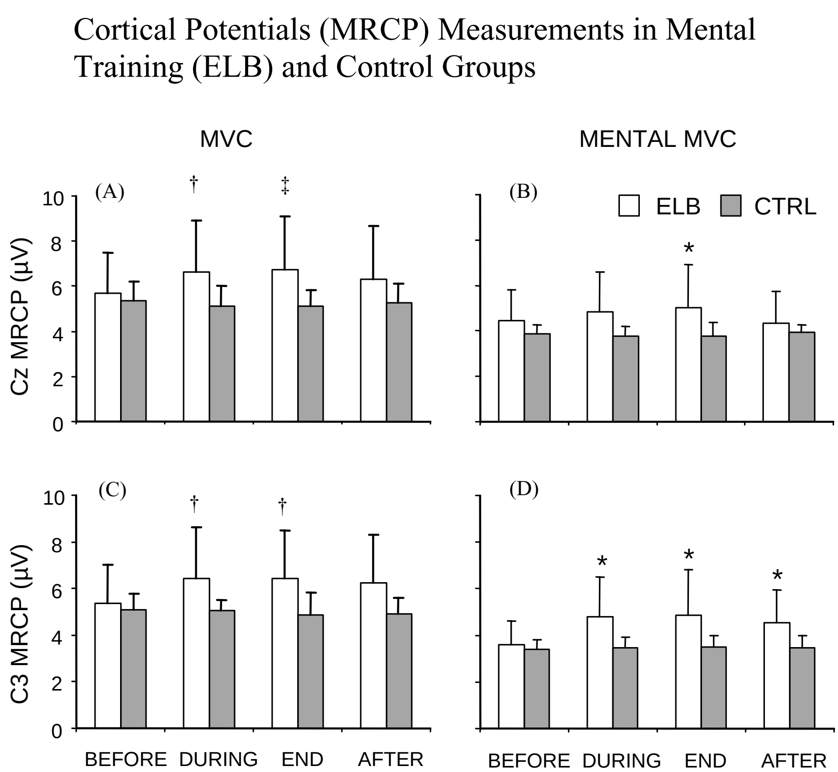

Fig. 4. The MRCP signals for elbow flexion MVC (A and C) and mental elbow flexion MVC (B and D) tasks from the Cz and C3 locations increased significantly in the ELB group. Similar MRCP signal changes were also seen at C4 and Fz locations (see text). The CTRL group did not show any significant MRCP changes. Results shown as mean ± S.D.

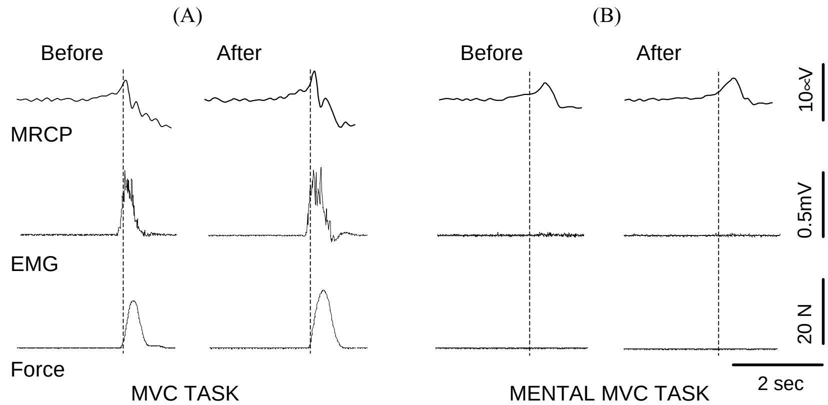

Fig. 5. Average Cz MRCP (upper row), little finger abductor EMG (middle row), and force (bottom row) for MVC (A) and mental MVC (B) finger abduction tasks of a participant. All three measurements for the MVC task increased after training for this individual. For the mental MVC task, although the EMG data indicate that the participant did not apparently contract the muscle, the brain signal (MRCP) associated with the mental contractions was prominent and increased after training. The vertical lines indicate the timing of the trigger.

for mental finger abduction MVC task, $P > 0.5$; and −4.7 to 5% for elbow flexion MVC task and −2.3 to 3.7% for mental elbow flexion MVC task, $P > 0.3$).

It is interesting to note the prominent cortical potential associated with the mental MVCs and its enhancement by mental training (Fig. 5). These data (Fig. 5) provide evidence of cortical activation during mental MVC and indicate that the brain was trained for stronger signal output. There was a possibility that the trained subjects could time the mental contractions better or aligned them more closely with the auditory cue (trigger) than the control subjects could, resulting in a greater cortical potential after training. However,

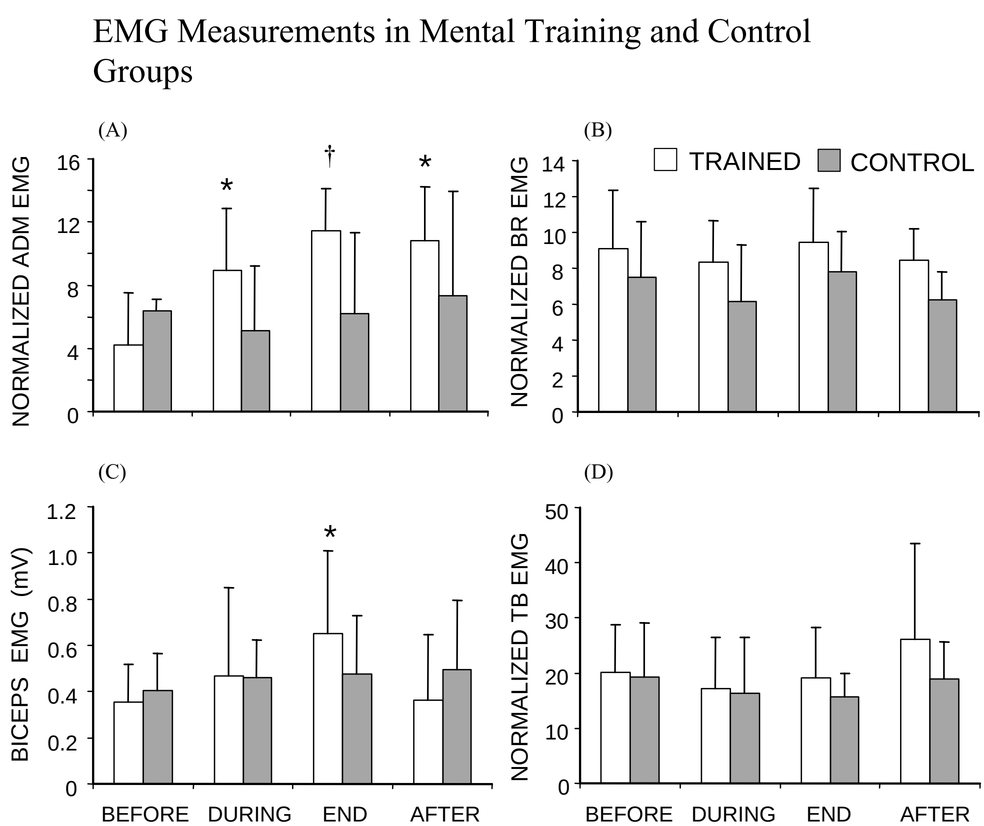

Fig. 6. Little finger abductor EMG increased significantly for the ABD group (A). This increase in EMG paralleled the increases in the MRCP and abduction force for the group. For the ELB group, there was a significant increase in the biceps brachii EMG (C); and the brachioradialis EMG did not show any significant change (B). Antagonist (triceps brachii) EMG during elbow flexion MVC did not change significantly for the ELB group (D). Results shown as mean ± S.D. EMG signals of the control group did not change significantly throughout the study.

this possibility was small because the control subjects who had a same number of EEG measurement sessions as the trained group did not show the mental contraction-induced brain potential increase. In addition, when a mental MVC is performed, an inhibitory process must take place to prevent the actual muscle contraction. How this cortical inhibitory activity would influence the magnitude of the MRCP is not clear.

The slope or rate of force production during the MVC EEG recordings was similar ($P > 0.1$) for both the ADB and the ELB groups before and after training. Hence, the MRCP amplitude changes observed cannot be attributed to changes in the rate of force production (Siemionow et al., 2000).

3.3. EMG, HR and BP

Along with increases in strength and MRCP, the EMG signals augmented significantly in both the ABD ($F = 3.4$, $P < 0.01$) and ELB ($F = 3.53$, $P < 0.01$) groups (Fig. 6). For the ABD group, the EMG of the finger abductor muscle, similar to the MRCP, was still substantially greater ($P < 0.05$) than the pre-training level, even 12 weeks after the training had ended. The triceps EMG level during elbow flexion strength measurements did not change significantly during and at the end of the training period (Fig. 6D), suggesting that the strength increases observed in the ELB group were not contributed significantly by reductions in the antagonist muscle activities. The heart rate and systolic blood pressure during mental ABD training increased significantly in the ABD group (resting HR 72 ± 5.4, mental exercise HR 78 ± 5.8, $P < 0.05$; resting BP 103 ± 3.9, mental exercise BP 111 ± 4.8, $P < 0.05$). Muscle activation level (normalized to pre-training MVC EMG) during mental training of imagined muscle contractions was near zero (1.5 ± 0.7% of pre-training MVC level for ABD group and 1.3 ± 0.8% of pre-training MVC level for ELB group).

3.4. ABD MVC training

In the ABD MVC group, the physical MVC training resulted in a (mean ± S.E.) 53.2 ± 6.85% increase in the finger abduction strength ($P < 0.01$, Fig. 7) and an 8.3 ± 3.7% increase in volume of the abductor digiti minimi muscle ($P = 0.069$). The MRCP amplitude (Fig. 7) measured for MVC task from the C3 and Cz location increased by (mean ± S.E.) 14.9 ± 8.07% ($P < 0.05$) and 10.5 ± 8.22% ($P = 0.12$), respectively. The finger abductor muscle EMG increased but was not significant (45.7 ± 32.9%, $P = 0.2$). The insignificant changes in the muscle volume and EMG measurements were mainly due to the relatively small sample size (five subjects) and large inter-subject variation, particularly for the EMG data.

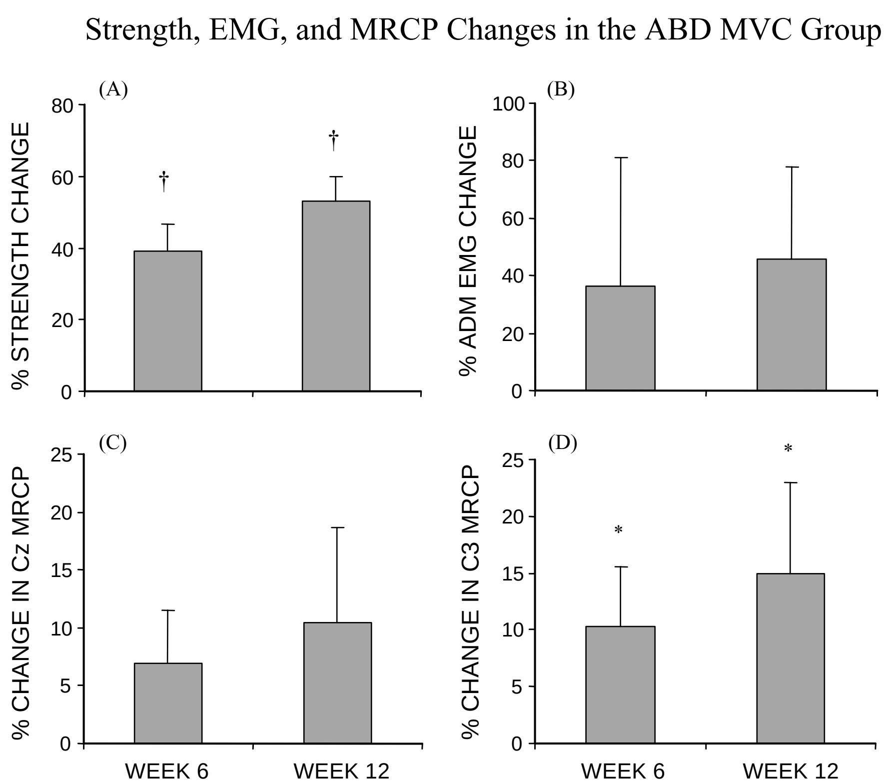

Fig. 7. Finger abduction strength (A) increased by 39% ($P < 0.01$) at the end of 6 weeks and by 53% ($P < 0.01$) at the end of 12 weeks of training for the conventional strength training (ABD MVC) group. This strength increase was accompanied by increases in the abductor digiti minimi EMG (B), EEG-derived MRCP for electrode locations Cz (C) and C3 (D). Data in the figure are presented as mean ± S.E.

4. Discussion

4.1. Mechanisms contributing to the mental training-induced strength gains

The key findings of this study were that mental training increases voluntary strength of both distal and proximal muscles of human upper extremities and the strength improvements accompanied elevations of time-locked (to MVC trials) cortical potential (MRCP). Based on the MRCP data (Figs. 3–5), we are confident that the primary mechanism underlying the strength increase is a mental training-induced enhancement in the central command to muscle. The data suggest that repetitive mental attempts of maximal muscle activation trained and enabled the brain to generate stronger signals to muscle. The relatively consistent MRCP values in the CTRL group (Figs. 3 and 4) throughout the study suggest that the MRCP measurement is reliable even across many sessions and a long period of time. Previous research (Dai, Liu, Sahgal, Brown, & Yue, 2001; Dettmers et al., 1995; Siemionow et al., 2000; Siemionow, Fang, Sahgal, Boros, & Yue, 2002) has shown a proportional relationship between magnitude of brain-to-muscle signal and voluntary muscle force by young human subjects, indicating that greater strength is a consequence of stronger brain activity. A stronger central command could recruit the motor units that were otherwise inactive in an untrained state and/or drive the active motor units to higher intensity (higher discharge rate), leading to greater muscle force. Alternatively, the trained CNS may be able to more effectively remove or reduce inhibitory input to the motoneuron pool of the muscles, resulting in an increase in motoneuron output. Training-induced neural adaptations may also include improvements in muscle coordination, such as reductions in the activity of the antagonist muscles when performing the agonist muscle MVC (Carolan & Cafarelli, 1992). However, our EMG data from the TB muscle, antagonist of the elbow flexor muscles, did not change after training, suggesting that the antagonist muscle did not play a significant role in the strength increase of the elbow flexors.

It is not clear what forms of neural adaptations occurred, and at what levels in the CNS, as a result of the mental training. It is unlikely that major neural adaptations occurred in sub-cortical centers, because the training primarily targeted the cerebral cortex (mental contraction) and the signal did not go down to the muscle level, indicated by the EMG recordings in every training session. We propose that the mental exercise primarily trained higher-order motor cortical regions by the repetitive attempts to maximally activate the muscle. Consequently, these cortical centers could generate stronger signals to the primary motor cortex and the motor neuron pool. This should have resulted in stronger signals from the motor neurons to the target muscles, leading to greater strength. Repetitive attempts of maximal activation during training may also improve excitability of output neurons of the brain regions so that when MVCs were performed during the later test sessions, a greater number of output neurons may be recruited and/or their activation pattern may be changed (e.g., increases in firing rate and level of synchronization) to increase the output signal. The most probable cortical locations that were trained by the mental contractions are secondary and association cortices such as supplementary motor (Roland, Larsen, Lassen, & Skinhøj, 1980) and prefrontal (Frith, Friston, Liddle, & Frackowiak, 1991) areas.

Because the strength gains were based on the pre-training or baseline strength, it was critical that the participants be highly motivated to exert their best efforts during the baseline measurements. Every participant was repeatedly encouraged to exert his/her maximal force during each pre-training measurement session. The fact that the strength measurements among the three pre-training sessions were not significantly different within each group suggests that the measurement was stable and indicated the pre-training maximal level. In addition, individuals in the CTRL group who were tested in the same manner maintained their strength throughout the course of the study, indicating that motivation was at a relatively consistent level for the repeated measures. Pre-training strength could not be improved even if participants were provided with sham information that a majority of people with their age, size, and physical conditions had performed better than their last trials (Yue & Cole, 1992). It is also difficult to argue that the strength improvements in the training groups could be attributed to learning the motor skills because the tasks (isometric little finger abduction and elbow flexion) were so simple and easy to perform that it only took a few trials of practice for participants to correctly perform the tasks. The similarity in strength values for the pre-training tests of the training groups and those of the CTRL group suggests that learning was not likely a significant factor in determining the strength gains.

Although EMG signals of the finger abductor and elbow flexor muscles were monitored in all training sessions to ensure that the muscles were not apparently active, it was difficult to determine whether the participants increased the activity level of the muscles outside the laboratory. Participants were repeatedly told not to attend exercise programs (e.g., weight lifting, aerobic workout, swimming), not to perform physical work (e.g., working on a home improvement project) beyond a normal or average level, and to report any sudden changes in life style, activity pattern, or job demand. All the participants reported that their average daily activity level did not change and they did not participate in any exercise programs except the training. In particular, they stated that they never intentionally exercised their muscles (finger abductor or elbow flexors) outside the laboratory. Earlier studies have reported that in a conventional training program, training intensity up to 60% of the maximal level does not result in significant strength improvements (Atha, 1981; Berger, 1965; Rarick & Larsen, 1959). We are confident that even if the participants had experienced fluctuations in their daily activities during the course of the training, it was very unlikely that such fluctuation in the target muscles could approach 60% maximal intensity and workload of conventional strength training. Because muscles were not trained, the possibility of gaining strength from increased muscle size can also be ruled out.

A recent study reported no significant differences in strength improvement between mental training and control groups following an 8-week mental training program (Herbert et al., 1998). In that study, subjects were trained with either isometric strength training, imagined isometric training or a control task. The imagined isometric training group listened to an audiotape, which instructed them to imagine producing maximal contractions. At the end of the 8-week training period, there was no significant difference in strength changes or the voluntary activation level between the imagined isometric training group and the control task group. Based on these observations, the authors concluded that the mental training does not increase voluntary activation of the muscles and their strength compared to the control group. In our study, a significant gain was observed within 2 weeks after the training began (ELB group). It is critical that a mental training program for strength gains trains the CNS so that stronger signals from the cortex can be sent to muscle. Our mental training program emphasized “activating the brain” for the intended muscle contraction—a strong willing of action was involved. The similarity in MRCP between the MVC and mental MVC indicates that the brain activation patterns for the two tasks were similar (Figs. 3–5). Our mental training is analogous to the so-called “internal imagery” in experimental psychology, in which mental imagery can be termed internal or external. Internal imagery generates significantly greater physiological responses such as blood pressure, heart rate, and respiration rate than external imagery, in which only an image of the motor task is generated in one’s mind, as if the person is viewing him/herself exercising on a television screen (Lang, 1979; Lang et al., 1980; Wang & Morgan, 1992). We found significant increases in heart rate and blood pressure during the mental training of little finger abduction contractions. It is not clear if the mental exercise employed by Herbert et al. (1998), was more like internal or external imagery exercise. We recently found that individuals trained by external imagery did not gain (∼2% increase) strength (Ranganathan et al., 2002). It appears that mental training aimed at strength gains must accompany strong brain activation relevant to the intended muscle action. This brain activation can be directly detected by electrophysiological (e.g., MRCP) or neuroimaging procedures or may be reflected indirectly by physiological measurements such as heart and respiratory rates, representing perhaps a greater metabolic rate of the brain as well as the body’s reproduction of physiological changes as a result of the brain activation.

For both mental training groups, the strength did not return to the baseline level more than 10 weeks after the training had completed. For the ABD group, muscle strength was still significantly greater than the baseline level 18 weeks after the termination of the training program. This finding suggests that the mental training-induced neural adaptations have a long-lasting effect that is reflected by continuously enhanced strength output. Mental training perhaps leaves neural traces, similar to those following motor learning, that are long-lasting and almost unforgettable, such as those from riding a bicycle, ice-skating, and swimming. Strength gains are also maintained long term following conventional training (Hakkinen, Alen, & Komi, 1985; Lemmer et al., 2000), perhaps by long-lasting neural and muscular adaptations.

4.2. Explanation for the discrepancy in strength gain between the ABD and ELB groups

Maximal strength gain for the ABD group (40%) was significantly greater ($P < 0.01$) than that for the ELB group (13.5%). The major reason for the discrepancy is that an individual probably seldom abducts the little finger or contracts the abductor muscle. On the other hand, elbow flexor muscles are used more frequently during daily living; almost all the upper limb activities involving moving the forearm use the elbow flexor muscles. Thus this muscle group may be considered “highly trained,” which allows less improvement capacity compared with the finger abductor muscle. The greater increases in the MRCP, EMG, and strength in the ABD group suggest that this is the case. The fact that most of the increase in the ELB group occurred 2 weeks into the training, after which the strength gain was flat could mean a ceiling effect for mental training or neural adaptation-induced strength gains in a large, frequently used proximal muscle group such as elbow flexors. Other differences between the two muscle groups may also have contributed to the discrepancy in the strength improvements. The finger abductor is a distal muscle that controls a digit, and the elbow flexors are more proximal muscles that control movements of the elbow joint. It is well known that in cortical representation, monosynaptic corticospinal projection, and force grading strategies, a finger muscle differs from proximal muscles, which are not involved in precision control of individual digits. However, no systematic report can be found to suggest that distal muscles share different strengthening mechanisms than more proximal muscles.

It was surprising that the finger abduction strength could increase by 40% from mental training alone. One might ask how much improvement could be realized for this muscle if individuals were trained by conventional resistance exercises. The results from the ABD MVC group showed a 53% strength improvement after 12 weeks of MVC resistance training. The 13% difference between the ABD and ABD MVC groups in strength gain must be due to the muscle hypertrophy (8.3%) achieved by the ABD MVC group. The data suggest that the little-finger abduction strength improvement resulting from the 12-week mental training program were contributed primarily by neural adaptations, most likely an increase in the descending command to the target muscle, whereas, the strength gain achieved by the ABD MVC group was contributed by both the neural adaptation and muscle hypertrophy as both the variables increased in this group.

4.3. Potential clinical relevance

The findings from this study have clinical implications. Many patients with neurological disorders suffer muscle weakness and are unable to perform or have difficulty performing conventional muscle-strengthening exercises such as weightlifting, especially those who have undergone long-term bed rest. Weak patients or frail elderly persons become even weaker as no strengthening programs can take place. This study suggests, however, that patients can use their minds to maintain or enhance the neural signal to maintain or even increase muscle strength. Preliminary research has suggested that mental practices of upper extremity motor activities are beneficial in functional recovery in stroke patients (Page, Levine, Sisto, & Johnston, 2001). The active engagement of the CNS to the intended muscle action (e.g., elbow flexion) during a period when patients are unable to move and usually passively wait for functional recovery may also accelerate the recovery process because the repetitive attempts to activate the muscle may stimulate neuromuscular system for more prompt recovery-related reorganization/adaptation. Indeed, accelerated functional recovery and neural adaptation by the so-called constraint-induced (CI) therapy that forces a stroke patient to use the affected limb while the healthier limb is restrained supports the notion that active participation of the CNS in using a limb, even though the muscles controlling the limb have little functional capabilities, facilitates neural adaptations that lead to functional recovery (Taub & Morris, 2001; Taub, Uswatte, & Pidikiti, 1999). The neural process between our mental training and CI therapy may be similar. During CI therapy, a patient cannot perform much physical work of the affected limb but their mental work in trying to move that limb is strong. This mental work seems to resemble our subjects' mental process of using mental power to move a finger or arm against a strong resistance.

4.4. Concluding remarks

Gaining voluntary muscle strength by mental training alone and showing that the training-induced CNS signal enhancement is responsible for the strength gains are significant steps forward in understanding the neural mechanisms underlying human voluntary muscle strengthening. Our findings demonstrate that the mind has remarkable power over the body and its muscles. The discovery appears to have clinical implications for improving motor function in patients who are too weak to participate in conventional strengthening programs, but are mentally healthy and motivated to engage themselves in mental practice.

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