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Motor Imagery Training Improves Muscle Strength and Cortico-Muscular Connectivity in Old Adults

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Abstract

Background: Aging is associated with declines in muscle strength, a phenomenon demonstrated to be associated with a notable weakening Corticomuscular Connection (CMC), as estimated by the Electroencephalography (EEG) and Electromyography (EMG) signal coherence. However, the extent to which a training method, such as Motor Imagery Training (MIT), designated to enhance muscle strength through neural adaptations, can also elevate CMC in older adults remains unknown. Therefore, the objective of this pilot study was to examine the impact of MIT on both voluntary muscle strength in healthy older adults and the strength of the corticomusclular connection.

Methods: This pilot study utilized a within-subject design, consisting of a single (MIT) group. Fifteen right-handed elderly individuals (73.9±8.0 years, 10 females) were originally recruited for the MIT program, of which ten participants completed the 8-week training (5 sessions/week and 30 minutes/session). The Maximal Voluntary Contraction (MVC) force of the left elbow flexion (trained arm), MVC EMG, and high-density EEG data were recorded both before and after the training period. The CMC was estimated by calculating the EEG (brain) and EMG (muscle) signal coherence along with determining the EEG frequency power.

Results: The findings revealed significant improvements in muscle strength following the 8- week MIT, with a notable increase of 24.3% (P<0.05). Moreover, there were significant increases in EMG amplitude (27.5%, P<0.05) and beta-band EEG power (56.5%, P<0.01). Importantly, this is the first MIT study to demonstrate a significant increase in CMC (22.7%, P<0.05) following the training.

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Conclusions: The findings of this pilot study suggest that MIT is effective in enhancing both muscle strength and CMC in older adults. These results provide further evidence supporting the effectiveness of MIT in enhancing voluntary muscle strength through inducing neural adaptations. This is particularly significant for older individuals who may experience physical weaknesses and encounter challenges with conventional strength training (e.g., weightlifting).

Introduction

Muscle weakness is a widely recognized phenomenon associated with aging, and sarcopenia, the age-related loss of muscle mass, is a primary contributor to this weakness. However, research has indicated that neural impairments, such as lack of ability of the Central Nervous System (CNS) to maximally drive the muscle also contribute to age-related muscle weakness. Several studies [1-4] have demonstrated that neural deficits, including perhaps the reduced recruitment of motor units to participate in maximal voluntary contractions, are associated with aging. Furthermore, a study by [5] revealed that older individuals not only exhibited significantly lower muscle strength but also experienced significantly weakened Corticomuscular Connectivity (CMC), as determined by the Electroencephalography (EEG) and Electromyography (EMG) signal coherence, compared to their younger counterparts. This led [5] to postulate that weakened CMC played a significant role in age-related muscle weakness. Nevertheless, it remains unclear whether a training program aimed at augmenting maximal muscle force can boost the CMC, or whether such training can concurrently enhance both muscle strength and the CMC.

To address the question, it would be helpful to investigate whether a training protocol that only targets modulating the nervous system, such as Motor Imagery Training (MIT), could induce CMC (and/or other neural factors) augmentation and Maximum Voluntary Contraction (MVC) force improvement. If the MVC force or muscle strength increases following the MIT, we know then it is caused by neural adaptations alone because the muscle itself is not trained (and therefore, no muscle hypertrophy). MIT refers to the cognitive process in which individuals imagine themselves performing a motor action without overt physical movements or activities. Studies on MIT have consistently shown that it can effectively improve MVC force [6], and older adults may benefit more from MIT than young adults in gaining muscle strength [7]. MIT has significant applications in rehabilitation medicine as weak patients or frail older adults, who feel difficult or unsafe to participate in conventional high-intensity strength training programs, may enhance their muscle strength through MIT [8]. The effect of MIT on increasing muscle strength can be attributed mainly to the neural adaptations in the CNS (i.e. an increase in the CNS command following MIT). This assumption is supported by the studies conducted by [9-11], all of which have demonstrated a significant change in the CNS signal, evident in the elevation of movement-related cortical potential derived from the EEG recordings during the strength measurement and other types of related neural signal amplitude following MIT. Given that any CNS signal that promotes muscle output must translate to muscle activities, we postulated that MIT would boost the CMC, thereby bolster muscle contraction.

Based on previous studies demonstrating the effectiveness of MIT on improving muscle force through neural adaptations in both young individuals [9-11] and older adults [12], it was hypothesized that MIT would magnify CMC, a link between cortical and muscle activities. Consequently, this enhancement of CMC was expected to lead to an increase in MVC force among older adults.

Research methods

Subjects: The study recruited fifteen healthy, right-handed elderly individuals (73.9±8.0 years, 10 females). Hand dominance was determined by the Edinburgh Handedness Inventor [13].

Training protocol: In this within-subject design, all participants underwent Motor Imagery Training (MIT) for 30 minutes per day, five days a week for eight weeks. The training emphasized left Elbow Flexion (EF) through first-person perspective mental imagery of maximal EF contractions using internal or kinesthetic imagery techniques, as described by [9,10]. During each of the 40 training sessions, the participants completed 30 trials (10s/trial) consisting of three sets of 10 trials each, with a 20-s rest between trials and a 3-minute rest between sets. The participants were instructed to imagine their left arm pulling up maximally against the force transducer used for the EF strength measurements during the pre-training tests. An auditory signal stored on a tape recorder signaled the start and end of each trial. Periodic EMG recordings from the left biceps brachii muscle showed no visible muscle activities during the MIT in all the subjects.

Strength measurements: To assess the effect of the MIT on the enhancement of the EF strength, the isometric EF MVC force was measured before and after the 8-week MIT. Subjects were seated with their forearm in a neutral position and an elbow joint angle of ~100◦. Five trials were performed in each measurement session and the average force among the trials was analyzed. For each trial, participants were verbally encouraged to exert the maximal effort. Submaximal EF contractions were practiced as the warm-up exercise before the strength measurement. For more detailed information on the procedures used to measure and calculate the MVC force data, please refer to [9,10].

EMG and EEG data acquisition: Surface EMG activities were recorded from the Biceps Brachii (BB) and brachioradialis muscles. Bipolar electrodes with a diameter of 8 mm were placed on the skin overlying the muscle belly after cleaning of the skin using alcohol pads for the EMG recording. A 128-channel neuroscan EEG system (neuroscan Labs, El Paso, TX) was used to record the EEG signals during 80% of MVC force trials before and after the training period. The impedance between each electrode and the skin was maintained below 10,000 ohms. The EEG signal was amplified (x20,000), band-pass filtered (0.1-100 Hz), and sampled at 250 Hz before saved on the hard disk of a PC. For more detailed information on the procedures used to acquire, process and measure the EMG and EEG data, please refer to [9,10].

EMG-EEG coherence: The EMG signals of the BB muscle were resampled at 250 Hz to match the sampling frequency of the EEG. We analyzed clusters of EEG electrodes in the right sensorimotor area (surrounding C4 location over the motor cortex on the right hemisphere) along with the EMG activities from the left BB. This approach was chosen since the force was exerted by the left arm and the CMC calculated from this cluster was found to be significantly different between young and older adults [5]. The CMC was only examined in the beta range (13-35 Hz) since the previous studies [14,15] suggest that significant CMC associated with motor output is only found in the beta range, which was confirmed by [5]. Hanning windows were applied during the coherence calculation, with each window length of 512 sample points and a 128-sample overlap when moving the window rightward till the entire trial (~8 s with removal of the first and last second data to ensure steadiness of the data) was analyzed. An average coherence value over the three trials was obtained in each subject. Please see [5] for detailed information on the EEG electrodes cluster locations and CMC calculation. The EEG spectral power of the electrode data used for CMC evaluation was also calculated with 50% overlapping Hanning window using Welch's method, which is a non-parametric Power Spectral Density (PSD) estimation method based on averaging to estimate the signal power at different frequencies. See [16] for details of PSD calculation method.

Statistical analysis Fi: Ve of the fifteen participants did not complete the eight-week's training. Thus, the analysis of MVC force was conducted using the data from the ten participants (8 females) who successfully completed the training. Additionally, four participants' EEG data were contaminated. As a result, the EMG amplitude, EEG frequency power, and EEG-EMG coherence analyses were performed based on the EMG and EEG data from six female participants (75.6±8.5 years). The data of the MVC force, EMG amplitude, EEG power, and EEG-EMG coherence before and after the MIT were analyzed with paired-samples one-tail t tests and the significant level was set at $P \leq 0.05$.

Results

MVC Force and EMG (mv): Following the training, there was a substantial increase (24.3%) in the Elbow Flexion (EF) MVC force. Specifically, the MVC force was 77.1±41.9N before the training, and it rose to 95.9±31.1N after the training. This difference was statistically significant, as indicated by $t(9) = 2.31$, $p < 0.05$. Along with the augmented MVC force, there was a significant increase in the MVC EMG amplitude following MIT. The MVC EMG values were 0.51±0.28mv before the training and 0.65±0.26mv after the training, with $t(5) = 2.57$, $p < 0.05$. The MVC force and EMG results are summarized in Figure 1.

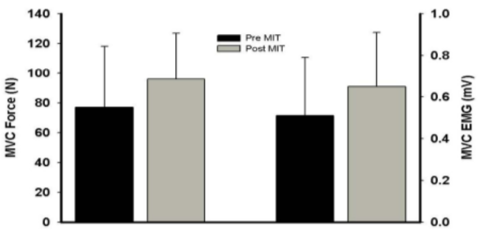

Figure 1

CMC and EEG (nam^2)

Left panel: Means and standard deviations of the left EF MVC force in Newtons (N). The results reveal a significant increase of 24.3% ($p<0.05$) in MVC force following the MIT.

Right panel: Means and standard deviations of the left BB EMG in Millivolts (mv). The findings show a notable 27.5% ($p<0.05$) increase in EMG amplitude after the MIT.

The level CMC between the right side sensorimotor cortical EEG and BB muscle EMG was higher after the training (0.27±0.09) than that before the training (0.22±0.1). Relative EEG Betta- band power was 0.23±0.11nam^2 before the training and 0.36±0.09nam^2 after the training. Both the CMC and relative EEG Betta band power increased significantly after the training, $t(5) = 2.52$, $p < 0.005$, and $t(5) = 5.15$, $p < 0.001$, respectively (Figure 2).

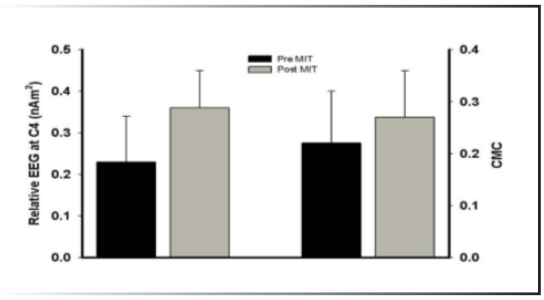

Figure 2

Left panel: Relative Beta power at the C4 cortical region. The results indicate a significant 56.5% ($p<0.01$) increase in Beta power at C4 following the MIT.

Right panel: Means and standard deviations of Corticomuscular Connectivity (CMC), measured as the coherence between EEG beta frequency range (15-25 HZ) at the C4 cortical region and BB muscle EMG. The findings reveal a significant 22.7% ($p<0.05$) increase in CMC.

Discussion

The major objective of this pilot study was to examine whether MIT could enhance corticomuscular Coherence/Connectivity (CMC), leading to an improvement in muscle strength. The findings demonstrated a significant rise in both isometric MVC force and CMC in beta frequency band at 80% MVC force following the 8-weeks MIT. Furthermore, as anticipated, there were significant increases in MVC EMG and relative EEG Beta band power. These findings suggest that the MIT-induced gains in muscle strength are attributed to changes in the CNS (most likely in the brain as the motor imagery primarily occurs at the cortical level). These changes lead to strengthened brain-to-muscle pathway or Corticomusclar Connectivity (CMC), Elevated Muscle activity (EMG), and ultimately result in increased muscle MVC force (strength). A study conducted by [5] revealed that older adults exhibited significantly weaker muscle strength and considerably lower beta-band CMC when compared to their younger counterparts. As a result, the authors attributed at least a portion of the observed weakness or reduced muscle strength in older adults to this decline in CMC. In an earlier study by [4], it was shown that there was a reduced ability to voluntarily activate the muscle with maximal effort in healthy aging. The study [4] found that older subjects had significantly greater evoked force (measured through twitch interpolation) during an MVC compared to young subjects, suggesting a greater deficit in the descending command to recruit motor units or muscle fibers to participate in the MVC in older individuals. This deficit in descending command may have a negative impact on the CMC. Previous research has indicated the crucial role of beta-band CMC in facilitating effective interaction between the corticospinal pathways during tasks involving static muscle force [17]. Additionally, the magnitude of beta-band CMC has consistently been found to be associated with the level of force exerted [5,18]. While previous studies have reported the association between muscle strength and CMC, the current study is the first to demonstrate that both MVC force and CMC were enhanced following MIT. This finding suggests a potential causal relationship between the two, that is an increase in CMC causes an augmentation in muscle force. The observation of elevated EEG beta-band power from the electrodes overlying the contralateral arm area of the motor cortex may partially explain the cause of the CMC increase. Previous research has consistently shown the efficacy of MIT in enhancing muscle strength with EMG and beta-band EEG power increases, both in young adults [9,10] and older adults [12]. However, as aforementioned, this study is the first to demonstrate the effectiveness of MIT in enhancing the interactive activity between the descending and muscle activities, as reflected by CMC. This enhancement in CMC most likely served as a primary neuromuscular mechanism promoting muscle strength for the older adults.

Overall, this study significantly enhances our understanding of the neurophysiological mechanisms involved in muscle strength training among older adults, highlighting the potential of MIT as a promising intervention for improving muscle force production in this population. This finding holds particular importance considering that older adults commonly experience declines in muscle strength and mass, which can adversely impact their overall health and functional capabilities. Additionally, older adults may be susceptible to potential injuries during conventional muscle strength training due to the weakened muscular and skeletal systems associated with this aging. One limitation of this study is the small sample size, which could potentially restrict the generalizability of the findings. Additionally, the absence of a control group makes it challenging to ascertain whether the improvements in motor performance were solely attributed to the MIT program or influenced by other factors. Nonetheless, despite these limitations, the study presents compelling evidence that MIT is an effective approach for enhancing muscle strength in older adults through the facilitation of neural adaptations. To strengthen the evidence base, future research should aim to replicate these findings using larger sample sizes and include control groups. Furthermore, investigating the long-term effects of MIT on motor performance and CMC and/or other neural factors in older adults would be valuable for a comprehensive understanding of its potential physiological and functional benefits.

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