Corticomuscular coherence with and without additional task in the elderly

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Aging and dual-task paradigms often degrade fine motor performance, but the effects of aging on correlated neural activity between motor cortex and contracting muscle are unknown during dual tasks requiring fine motor performance. The purpose of this study was to compare corticomuscular coherence between young and elderly adults during the performance of a unilateral fine motor task and concurrent motor and cognitive tasks. Twenty-nine healthy young (18–38 yr) and elderly (61–75 yr) adults performed unilateral motor, bilateral motor, concurrent motor-cognitive, and cognitive tasks. Peak corticomuscular coherence between the primary motor cortex and surface electromyogram from the first dorsal interosseous muscle was compared during steady abduction of the index finger with visual feedback. In the alpha-band (8–14 Hz), corticomuscular coherence was greater in elderly than young adults especially during the motor-cognitive task. The beta-band (15–32 Hz) corticomuscular coherence was higher in elderly than young adults across unilateral motor and dual tasks. In addition, beta-band corticomuscular coherence in the motor-cognitive task was negatively correlated with motor output error across young but not elderly adults. The results suggest that 1) corticomuscular coherence was increased in senior age with a greater influence of an additional cognitive task in the alpha-band and 2) individuals with greater beta-band corticomuscular coherence may exhibit more accurate motor output in young, but not elderly adults, during steady contraction with visual feedback.

aging; dexterity; divided attention; dual task; motor control

Advanced Aging Often Degrades Fine Motor Performance, which can be attributed to several factors including age-associated alterations in information processing, motor neuron organization, and neuromotor activity (11, 49, 51–55). As one feature of neuromotor activity involved in fine motor performance, corticomuscular coherence between electromyogram (EMG) in a contracting muscle and electroencephalogram (EEG) or magnetoencephalogram (MEG) in the corresponding primary motor cortex of the contralateral hemisphere has been investigated and shown to represent the synchronized oscillatory discharges of corticospinal cells that are transmitted to motor neurons in the spinal cord (2, 7, 32). This synchronized oscillatory activity is dominant within the beta-band (~15–30 Hz) for motor tasks (7, 21, 27, 31, 40). Alpha-band (8–14 Hz) corticomuscular coherence is not dominant during motor tasks; however, significant peaks of corticomuscular coherence have been observed within the alpha-band in some motor tasks requiring a distribution of attention to the task (14, 34) and rapid movements (8). Alterations in the magnitude of corticomuscular coherence are regarded as the net result of multiple factors. Corticomuscular coherence appears to be influenced by task characteristics (14, 27, 31, 34, 41), muscle (19, 57), and visuo-motor learning (45). However, the influence of advanced aging on and the functional significance of corticomuscular coherence is unclear.

While neural activity during motor tasks is often altered in elderly adults compared with young adults in various aspects including EMG power (18, 55, 58), EEG power (49, 59), and motor unit discharge strategies such as coherent discharges (50–52), the effects of aging on corticomuscular coherence have been observed from childhood to middle age only (18, 26). During unilateral task, corticomuscular coherence within the beta-band increased with development and aging from childhood (0 yr old) to middle age (35 and 59 yr old; Refs. 18, 26) but not to senior age (55–80 yr old; Ref. 18). Alpha-band corticomuscular coherence during unilateral task was observed in elderly adults (55–80 yr old) in more cases than in young adults (21–35 yr old), but no significant difference was reported on the magnitude of coherence between the age groups (18). Hence, the current knowledge from only a few studies for elderly adults is that there is no significant change in the magnitude of beta-band corticomuscular coherence postadulthood (>60 yr old), while alpha-band corticomuscular coherence might increase at senior age.

One important insight into the influence of aging on neural activity and motor performance is the consideration of task dependency. The current study intends to examine the corticomuscular coherence in elderly adults in light of attention to the task because previous studies (18, 26) on aging used simple unilateral tasks that required little awareness of attention to the task. Divided or reduced attention to a motor task influences neural activity, such as increased cortical activation of the supplementary motor area (17) and areas controlling higher order processing (23). Beta-band corticomuscular coherence was suggested to be attenuated with reduced attention to a motor task (27, 34). For the alpha-band, awareness on attention to the task may increase corticomuscular coherence because significant corticomuscular coherence was observed only during tasks requiring attention to task or cognitive processing (34). The execution of a task requiring divided attention degrades performance and often more so in elderly adults (5, 24, 63, 67). In particular, divided attention with dual task induces greater changes in neuromuscular activity (39, 46) and task performance in elderly than young adults (38, 63, 64) likely because elderly adults have less attentional resources or require more attention for performing a task (60). Considering these more responsive neuromotor characteristics with regard to attention in elderly than young adults, corticomuscular coherence in elderly adults would be less in beta-band and
more in alpha-band compared with young adults if they perform tasks requiring substantial divided attention.

For functional significance of corticomuscular coherence, some studies have suggested an association between corticomuscular coherence and fine motor performance within young adults. For motor output error from a target, trial segments with higher beta-band corticomuscular coherence had less error in force production for a unilateral motor task (35). For motor output variability, a reduction in beta-band corticomuscular coherence after immobilization was accompanied by an increase in variability in EMG amplitude in young adults (36), suggesting a negative association between beta-band corticomuscular coherence and EMG variability within young adults. In a study that examined statistical correlation (18), a significant negative correlation between beta-band corticomuscular coherence and EMG variability across multiple trials was observed within some young adults but not within elderly adults. Despite these implications for negative association between beta-band corticomuscular coherence with motor error or variability within young adults, no association has been found across young or elderly adults (27, 45). However, these studies employed unilateral tasks or a relatively simple dual task (18, 27, 35, 36, 45). Since reduced attention to a task may decrease beta-band corticomuscular coherence (27, 34) and fine motor performance (64), the individuals’ variability in their responsiveness to divided attention during tasks requiring divided attention may give rise to a negative association between beta-band corticomuscular coherence with motor output error or variability across young adults. An appearance of an association across elderly adults was not expected because there is no report that has demonstrated an association across trials within elderly adults.

The purpose of this study was therefore to compare task-dependent corticomuscular coherence and fine motor performance between young and elderly adults during the execution of a unilateral fine motor task and concurrent tasks that required substantial divided attention. It was hypothesized for aging that corticomuscular coherence in elderly adults would be less in beta-band and more in alpha-band compared with young adults during dual tasks. For functional significance, a negative association between beta-band corticomuscular coherence and motor output error or variability was expected across young, but not elderly, adults during dual tasks.

METHODS

Subjects

Twenty-nine healthy right-handed young (n = 16; 23.9 ± 5.8 yr; ranging 18–38 yr; 10 women and 6 men) and elderly (n = 13; 69.2 ± 4.7 yr; ranging 61–75 yr; 7 women and 6 men) adults participated in the study. The exclusion criteria for subjects included a history of hypertension, diabetes, neurological disorders, and arthritis in the hands. Subjects refrained from caffeine and nicotine 3 h before their experiment session. Before the subjects began the experiment, hand dominance and cognitive state were measured according to the Edinburgh Handedness Inventory (44) and a modified Mini-Mental State Exam (MMSE; Ref. 15), respectively. Subject’s written consent was obtained before the experiment in accordance with the Institutional Review Board of the Georgia Institute of Technology and has therefore been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. The Institutional Review Board of the Georgia Institute of Technology approved the study.

Experimental Design

Setup. Subjects were seated in an electrically shielded, dimly lit room with their hands and forearms pronated and supported in rigid vacuum foam pads. The left and right shoulders were abducted at ~35°. The index finger was placed in a finger splint with all interphalangeal joints extended. The metacarpophalangeal joint was in the neutral position so the index finger was level with a force transducer during the measurement. All other fingers were fixed to a platform with Velcro straps.

Maximal voluntary contraction. Before the experimental tasks, maximal voluntary contraction (MVC) of the first dorsal interosseous muscle was performed to obtain the maximum isometric abdution force exerted by the right and left index fingers independently. The MVC task consisted of a gradual increase in force from zero to maximum over 3 s with the maximal force held for 2 to 3 s. The task was conducted by abducting the index finger and pulling on a rigid piece connected to a force transducer (21.3 N/V; model 34, Honeywell). Subjects were verbally encouraged to achieve maximal force while the force was visually displayed on a monitor in front of the subject. Three to four trials were performed, excluding trials not within 5% of maximal force of each other. The highest peak force across trials was determined as MVC force.

Tasks. Five tasks were performed: unilateral abdution of the right index finger (unilateral motor task); unilateral abduction of the left index finger; cognitive task involving arithmetic and memory (cognitive task); concurrent motor-cognitive task with the right finger (motor-cognitive task); and bilateral motor task with the left and right index fingers (bilateral motor task). A unilateral motor task with the left hand and an independent cognitive task were included to yield control values for comparison to additional motor and cognitive tasks. Unless stated specifically with the left hand, the unilateral motor task refers to the task with the right hand. Each subject performed eight trials for each task.

Subjects were instructed to keep their head straight and minimize the number of extraneous movements, including eye blinks, during the actual trial for all tasks. Instructions were provided to wait for a signal on the screen to begin the trial after the experimenter counted down from three to one. The subject was prepared. After a 2-s delay, a red box on the monitor turned green indicating to the subject to begin the trial.

Motor tasks. The motor tasks involved abduction of the index finger. A light-weight compliant spring (stiffness: 0.8 N/mm; mass: 0.24 g) was attached to a finger splint between the ulnar side of the index finger at the distal interphalangeal joint and a force transducer (9.2 N/V; model 31; Honeywell). When the index finger was abducted, the spring would pull on the force transducer. The spring was used because corticomuscular coherence is more evident with an addition of compliance in the transmission of force (31).

Subjects were instructed to produce finger abduction force as accurate and steady as possible with visual feedback while keeping their interphalangeal joints of the index finger fully extended in the finger splint. For the unilateral motor task with the right hand, subjects were instructed to abduct the right index finger to exert a force matching 5% of their MVC force for 10 s with 2 s for ramping to the level. For the unilateral motor task with the left hand, subjects were instructed to abduct the left index finger to exert forces matching the target varying between 2.5, 5, and 7.5% of their MVC force within a trial. They matched each level for 2 s with 2 s for ramping to the next level continuously, and the order of target level to match was randomized across subjects. Visual feedback of target and actual force level was displayed on the monitor. The scale for each hand was relative to 10% of MVC for that hand (57.8 pixels/% MVC or 263.5 pixels/N on average). For the bilateral motor task, the motor tasks for the right and left hands were performed concurrently (Fig. 1), and there was no instruction with regard to the prioritization to either of the task. Each trial was 12 s in duration. The task duration was implemented for several reasons. First, prolonged task durations decrease the magnitude of significant coherence observed (31). Sec-
ond, 12-s task durations will not fatigue healthy subjects. Third, subjects may become irritable with longer task durations as observed especially in elderly adults in the pilot experiments.

**Cognitive tasks.** During the cognitive task, subjects were asked to solve three mathematical problems (2-digit addition and subtraction) and remember the answers until the end of each trial (12-s duration). The mathematical problems were displayed on the monitor in front of the subjects, and they were asked to verbally recall the three answers at the end of the trial. The cognitive task was performed concurrently with the unilateral motor task in the right hand for the motor-cognitive task.

**Recordings**

**EMG.** Surface EMG was recorded from the first dorsal interosseous muscle on the left and right hands during the motor tasks. The ActiveTwo Biosemi electrode system (Biosemi, Amsterdam, The Netherlands) was used to obtain EMG. This system is equipped with a miniature preamp adjacent to each electrode to reduce the contamination of electrical noise. To further reduce the noise, this system is made of a battery powered A/D box that digitizes the signals and transfers them to a computer through a fiber optic connection. One active Ag-AgCl EMG electrode (diameter: 4 mm) was placed over the belly of the muscle and the other was attached to the skin over the base of the proximal phalanx of the index finger. A reference electrode was placed on the radial styloid process of the hand.

**EEG.** Cortical EEG signals were recorded using the international 10–20 electrode placement method from C3 (left motor cortex) and C4 (right motor cortex) referenced to Cz. The electro-oculogram (EOG) generated from blinks, and eye movement was recorded from three facial electrodes: one ~1 cm to the left of the left eye, one ~1 cm to the right of the right eye, and one in between the left and right eyebrows. EEG and EOG were also obtained with the ActiveTwo Biosemi electrode system. The ground signal was recorded from a scalp electrode in the center of the EEG electrode array. The ActiveTwo system uses a gain of least significant bit equal to 31.25 nV, with a 1% gain accuracy. All bioelectric signals were digitized on a computer using ActiView software (Biosemi) and sampled at 2048 samples/s.

**Force.** Force due to index finger abduction was sensed by the transducer connected to an amplifier (Transbridge 4M; World Precision Instruments, Sarasota, Florida, USA). Target and actual forces were digitized at 2,048 samples/s, in parallel with electrophysiological data, using an analog-to-digital converter (Power 1401; Cambridge Electronic Design, Cambridge, UK). The force and electrophysiological data were synchronized with the concurrent recording of the synchronization pulse.

**Data Analysis**

The focus of this work was corticomuscular coherence between the EEG in the left motor cortex (C3) and EMG in the right hand. All data were analyzed offline using custom written script in MATLAB (Mathworks, Natick, MA). Data during the steady phases of force (10-s period) in the right hand were used for analysis (Fig. 1). EOG data were monitored in real-time for excessive eye blinks. Trials with excessive eye blinks (>5 blinks per 12 s) were excluded, and subjects were asked to repeat the trial.

**EEG and EMG power.** The EEG signal was band-pass filtered (5–200 Hz) and detrended. The EMG signal was obtained from the bipolar EMG that was band-pass filtered (10–500 Hz) and detrended.
(Fig. 1). The process of rectifying the EMG signal introduces a nonlinearity into the frequency characteristics of the EMG (12, 42, 43, 56) altering the identification of neural oscillations, thus suggesting that unrectified EMG is more appropriate for assessing the frequency content of the EMG signal. Accordingly, the current analysis used variables with unrectified EMG as the primary dependent variables for testing the hypothesis. Nonetheless, analysis with rectified EMG was also incorporated for the purpose of comparing the findings with those in the literature that used rectified EMG (18, 26). The EMG data during all trials were concatenated (28) for each task individually, as were the EEG data, and the power spectrum of EEG, power spectrum of EMG, and coherence between EEG and EMG were computed. Power spectra and coherence were calculated over 2,048-point fast Fourier transform segments. 

\[ P_x(f) = \frac{1}{n} \sum_{i=1}^{n} C_i(f)C_i^*(f) \]  

(1)

\[ P_x(f) \] is the power spectra for a channel \( x \) at the frequency \( f \). \( C_i \) represents the Fourier transform of data segments \( i \) corresponding to channel \( x \). \( C_i^* \) with an asterisk (*) represents the complex conjugate of \( C_i \). The power of the EEG and EMG signals was calculated within the alpha (8–14 Hz)- and beta (15–32 Hz)-bands and normalized to the total power.

**Coherence.** Coherence between EEG in the left motor cortex (C3) and EMG in the right hand was calculated for each frequency bin of interest, \( f \), as described in the following equation according to Hattaday et al. (22):

\[ \text{Coh}_x(y) = \left| R_{xy}(f) \right|^2 = \left| \frac{P_{xy}(f)}{P_{xx}(f)P_{yy}(f)} \right| \]  

(2)

where \( \text{Coh}_x(y) \) is the coherence between signal \( (x) \) and \( (y) \), \( P_{xy} \) is the cross-power spectrum for the EEG signal \( (x) \) and the EMG signal \( (y) \) at a given frequency bin \( (f) \), and \( P_{xx} \) and \( P_{yy} \) are the respective power spectrums for the EEG signal and EMG signal at the same frequency (Fig. 2). Coherence is a real number between 0 and 1 that provides a summary measure of the amount of surface EMG and EEG that can be explained in each other (or that are correlated). An arc hyperbolic tangent transform was used to stabilize the variance in the distribution of coherence (22). The confidence interval (CI) of the coherence function was calculated at the \( \alpha \)-quantile for \( L \) number of segments. This formula is given for coherence calculations that are based on the Fourier transform (47).

\[ CI(\alpha = 0.95) = 1 - \frac{1}{(L-1)} \]  

(3)

where \( L \) is the signal duration, divided by the window length. Noncorrelated activity at each frequency is considered to be below the confidence interval. Pooled corticomuscular coherence (20) was computed to summarize the effects of aging on corticomuscular coherence. Coherence was considered to be significant if the value was above the 95% confidence interval for significant difference from zero. The peak value of the coherence in the alpha- and beta-bands was independently determined in each task. This approach considered potential shifts in the location of peak coherence between tasks so essential information on the correlated activity of the EEG and EMG within each task would not be overlooked. Interhemispheric cortico-cortical coherence (C3–C4) was also calculated in a similar manner.

**Fine motor skills.** Variability and accuracy of motor output were used for assessing fine motor skills. Force exerted by the right hand was analyzed to determine the motor output variability and accuracy of subjects during each motor task. Force signals were low-pass filtered at 100 Hz and detrended. The coefficient of variation (CV; SD divided by mean) was determined for variability. To assess the accuracy of motor output, absolute error was calculated as the error ratio using the following equation.

\[ \text{error ratio} = \left| \frac{\text{EF} - \text{TF}}{\text{TF}} \right| \times 100\% \]  

(4)

where EF is exerted force and TF is target force. In addition, variability of muscle activity in the right hand was assessed with the CV of EMG that was full-wave rectified, low-pass filtered at 5 Hz, and detrended. Motor performance in the left hand was assessed by analyzing the root mean square error (RMSE) of force in the left hand.

**Cognitive accuracy.** Cognitive accuracy was measured at the termination of each trial for the individual cognitive task and the motor-cognitive task. Cognitive accuracy was calculated as the ratio between the number of correct responses and the number of the math problems in percentage. If a subject answered with the exact value for the problem set it was considered correct, any other response was considered incorrect.

**Statistical Analysis**

To test the effect of age and hand on MVC, a two-factor, 2 \( \times \) 2 ANOVA with repeated measures was performed. Statistical significance of handedness and MMSE score between ages were assessed.
using a Student’s paired t-test. The dependent variables during the unilateral, bilateral, and motor-cognitive tasks were peak corticomuscular coherence and cortico-cortical coherence in each band, frequency at which peak value in coherence was observed in each band, normalized EEG (C3 and C4) and EMG spectral power in each band, CV of force and EMG, and error ratio of force in the right hand. The statistical significance of these dependent variables was tested between ages (young and elderly) and tasks (unilateral motor, bilateral motor, and motor-cognitive tasks) for appropriate combinations. To test the effects of age and task on variables associated with the right-hand task [peak coherence (using unrectified and rectified EMG) between EEG in the left motor cortex and EMG in the right hand, normalized spectral power of those EEG and EMG], a two-factor, 2 × 2 ANOVA with repeated measures was performed. The effects of age and task on cognitive accuracy were assessed with a 2 × 2 ANOVA with repeated measures. The effects of age and task on cognitive accuracy were assessed with a 2 × 2 ANOVA with repeated measures. An alpha-level of 0.05 was chosen for all statistical analyses. An alpha-level of 0.05 was chosen for all statistical comparisons. P < 0.05 or P < 0.01 was additionally noted where appropriate. All statistical analyses were performed using Statistica 9.0 software (StatSoft, Tulsa, OK). Unless stated otherwise, the data are presented as means ± SD in the text and tables and means ± SE in the figures.

RESULTS

The MVC force was comparable between young and elderly adults for both the right (young: 21.7 ± 6.2 N; elderly: 19.6 ± 8.1 N) and left (young: 18.3 ± 4.3 N; elderly: 19.4 ± 8.4 N) hands. The handedness test confirmed that all subjects were right hand dominant, with a slightly higher index in elderly adults (0.92 ± 0.10) compared with young adults (0.80 ± 0.17; P < 0.05). According to the MMSE, there were no signs of cognitive impairment in the subjects, with all scores ≥27 although there was a small difference between young (29.8 ± 0.4) and elderly adults (28.6 ± 1.0; P < 0.01).

Coherence

In using unrectified EMG, all subjects had significant corticomuscular coherence between the left motor cortex (C3) and the right hand in the beta-band with peak value at similar frequencies of 24.7 ± 4.8 Hz in young subjects and 22.6 ± 5.7 Hz in elderly subjects during the unilateral motor task. This beta-band frequency for peak coherence was not influenced by age or task. The magnitude of beta-band peak corticomuscular coherence was higher in elderly adults compared with young adults across tasks [main effect of age, F(1, 27) = 10.59; P < 0.01; Fig. 3D]. A main effect of task was observed within the beta-band [F(2, 54) = 4.26; P < 0.05]. Apparent changes in beta-band corticomuscular coherence with additional concurrent tasks were not statistically different compared with the unilateral motor task (Fig. 3C). However, when compared with the bilateral motor task (0.074 ± 0.039), beta-band corticomuscular coherence during the motor-cognitive task (0.102 ± 0.078) was greater (P < 0.05). There was no significant interaction between age and task. There was a positive association between subject age and beta-band corticomuscular coherence with unrectified EMG [correlation coefficient (r): 0.381; P < 0.01].

Within the alpha-band using unrectified EMG, all but one young subject had significant corticomuscular coherence with the peak value at similar frequencies of 11.6 ± 2.3 Hz in young adults and 12.3 ± 2.4 Hz in elderly adults during the unilateral motor task. This alpha-band frequency for peak coherence was not influenced by age or task. Elderly adults also exhibited higher magnitude of corticomuscular coherence within the alpha-band compared with young adults [main effect of age, F(1, 27) = 6.62; P < 0.05; Fig. 3B]. This difference appears to result mostly from the large increase during the motor-cognitive task in elderly adults. As a main effect of task, alpha-band corticomuscular coherence was higher in the motor-cognitive task (0.087 ± 0.097) compared with the unilateral motor task [0.046 ± 0.030; F(2, 54) = 4.83; P < 0.05; Fig. 3A]. As an interaction of age and task [F(2, 54) = 3.21; P < 0.05], alpha-band corticomuscular coherence during the motor-cognitive task was higher (P < 0.05) in elderly than young adults, whereas no significant age-associated difference was observed in other tasks.

For corticomuscular coherence with rectified EMG, elderly adults exhibited higher corticomuscular coherence within the beta-band [F(1, 27) = 10.15; P < 0.01; Fig. 4D]. A significant
effect of task was not observed when rectified EMG was used. There was a positive association between subject age and beta-band corticomuscular coherence with rectified EMG ($r = 0.374; P < 0.01$). Elderly adults also exhibited higher corticomuscular coherence with rectified EMG in the alpha-band ($F(1,27) = 8.25; P < 0.01$; Fig. 4B). This age-associated difference appears to result mostly from the large increase during the motor-cognitive task in elderly adults. As an interaction of age and task ($F(2,54) = 5.21; P < 0.01$), alpha-band corticomuscular coherence with rectified EMG during the motor-cognitive task was higher ($P < 0.01$) in elderly than young adults (Fig. 4A).

To summarize the age-associated difference in corticomuscular coherence, pooled coherence was further calculated. For corticomuscular coherence with unrectified EMG, significant pooled coherence was observed between 9 and 32 Hz for young adults and between 10 and 26 Hz for elderly adults (Fig. 5A). With the use of rectified EMG, significant pooled coherence was observed between 9 and 32 Hz for young adults and between 9 and 26 Hz for elderly adults (Fig. 5B). In both cases (using unrectified and rectified EMG), the pooled coherence visually displayed greater corticomuscular coherence in elderly adults compared with young adults.

Interhemispheric cortico-cortico coherence between C3 and C4 EEGs tended to be higher in alpha-band in elderly adults, on average, but did not have any significant effect of age or task (Table 1).

Table 1. Interhemispheric cortico-cortico coherence between C3 and C4 EEGs in alpha- and beta-bands during the unilateral motor, bilateral motor, and motor-cognitive tasks in young and elderly adults

<table>
<thead>
<tr>
<th></th>
<th>Young ($n = 16$)</th>
<th>Elderly ($n = 13$)</th>
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<tbody>
<tr>
<td>Alpha-band (8–14 Hz)</td>
<td></td>
<td></td>
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<tr>
<td>Unilateral motor</td>
<td>0.15 ± 0.07</td>
<td>0.14 ± 0.04</td>
</tr>
<tr>
<td>Bilateral motor</td>
<td>0.12 ± 0.10</td>
<td>0.15 ± 0.07</td>
</tr>
<tr>
<td>Motor-cognitive</td>
<td>0.16 ± 0.09</td>
<td>0.13 ± 0.07</td>
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<tr>
<td>Beta-band (15–32 Hz)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unilateral motor</td>
<td>0.16 ± 0.12</td>
<td>0.20 ± 0.09</td>
</tr>
<tr>
<td>Bilateral motor</td>
<td>0.14 ± 0.08</td>
<td>0.22 ± 0.10</td>
</tr>
<tr>
<td>Motor-cognitive</td>
<td>0.15 ± 0.11</td>
<td>0.19 ± 0.10</td>
</tr>
</tbody>
</table>

Data are means ± SD. There was no significant effect of age or task. C3, left motor cortex; C4, right motor cortex.
Table 2. Frequency power of EEG in the left motor cortex (C3) and EMG (unrectified and rectified) in the right hand in alpha- and beta-bands during the unilateral motor, bilateral motor, and motor-cognitive tasks in young and elderly adults

<table>
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<tr>
<th></th>
<th>Young (n = 16)</th>
<th>Elderly (n = 13)</th>
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<tbody>
<tr>
<td>EEG power in the left</td>
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<tr>
<td>motor cortex (C3)</td>
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<tr>
<td>Alpha-band</td>
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<tr>
<td>Unilateral motor</td>
<td>0.338 ± 0.131</td>
<td>0.298 ± 0.139</td>
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<tr>
<td>Bilateral motor</td>
<td>0.332 ± 0.126</td>
<td>0.275 ± 0.080</td>
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<tr>
<td>Motor-cognitive</td>
<td>0.342 ± 0.132</td>
<td>0.319 ± 0.108</td>
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<tr>
<td>Beta-band</td>
<td></td>
<td></td>
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<tr>
<td>Unilateral motor</td>
<td>0.337 ± 0.084</td>
<td>0.436 ± 0.133†</td>
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<tr>
<td>Bilateral motor</td>
<td>0.318 ± 0.079†</td>
<td>0.449 ± 0.123‡</td>
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<tr>
<td>Motor-cognitive</td>
<td>0.340 ± 0.083†</td>
<td>0.478 ± 0.096‡‡</td>
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<td>Unrectified EMG power</td>
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<tr>
<td>in the right hand</td>
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<tr>
<td>Alpha-band</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unilateral motor</td>
<td>0.022 ± 0.006‡</td>
<td>0.029 ± 0.009*‡</td>
</tr>
<tr>
<td>Bilateral motor</td>
<td>0.024 ± 0.008‡</td>
<td>0.029 ± 0.009*‡</td>
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<tr>
<td>Motor-cognitive</td>
<td>0.024 ± 0.009‡</td>
<td>0.033 ± 0.012‡‡</td>
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<tr>
<td>Beta-band</td>
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<tr>
<td>Unilateral motor</td>
<td>0.288 ± 0.048‡</td>
<td>0.316 ± 0.056‡</td>
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<td>0.293 ± 0.043‡</td>
<td>0.320 ± 0.055‡</td>
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<td>0.304 ± 0.036‡</td>
<td>0.325 ± 0.047‡</td>
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<td>Rectified EMG power</td>
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<td>in the right hand</td>
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<tr>
<td>Alpha-band</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unilateral motor</td>
<td>0.138 ± 0.071</td>
<td>0.189 ± 0.026*</td>
</tr>
<tr>
<td>Bilateral motor</td>
<td>0.135 ± 0.067</td>
<td>0.178 ± 0.024*</td>
</tr>
<tr>
<td>Motor-cognitive</td>
<td>0.139 ± 0.079</td>
<td>0.184 ± 0.035*</td>
</tr>
<tr>
<td>Beta-band</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unilateral motor</td>
<td>0.366 ± 0.064</td>
<td>0.370 ± 0.044</td>
</tr>
<tr>
<td>Bilateral motor</td>
<td>0.371 ± 0.052</td>
<td>0.376 ± 0.043</td>
</tr>
<tr>
<td>Motor-cognitive</td>
<td>0.376 ± 0.052</td>
<td>0.383 ± 0.052</td>
</tr>
</tbody>
</table>

Data are means ± SD. Power in each band is normalized to total power. EMG, electromyogram. *P < 0.05 vs. young; †P < 0.01 vs. young; ‡P < 0.05 due to task effect.

Significant effects of age or task were observed on EMG power in the right hand across frequency bands (Table 2). Compared with the unilateral motor task (alpha: 0.025 ± 0.008, beta: 0.301 ± 0.053), unrectified EMG power during the motor-cognitive task was slightly increased in both alpha (0.028 ± 0.011; P < 0.05) and beta (0.314 ± 0.042; P < 0.05) bands as a main effect of task [alpha: F(2,54) = 3.54; P < 0.05; beta: F(2,54) = 4.34; P < 0.05]. Beta-band unrectified EMG power was positively correlated with beta-band cortico-muscular coherence (r = 0.360; P < 0.01) when the data from all subjects and tasks were included. Elderly adults exhibited greater alpha-band unrectified EMG power compared with young adults [main effect of age, F(1,27) = 5.07, P < 0.05; elderly: 0.030 ± 0.010, young: 0.023 ± 0.008]. Elderly adults also exhibited greater alpha-band rectified EMG power compared with young adults [main effect of age, F(1,27) = 5.00, P < 0.05; elderly: 0.183 ± 0.028, young: 0.137 ± 0.071].

Coherence and Fine Motor Performance

Motor output variability during steady contraction in the right hand was assessed for the fluctuations in force and EMG. The CV of force was greater in elderly adults compared with young adults [main effect of age, F(1,27) = 10.60; P < 0.01; Fig. 6B]. As a main effect of task [F(2,54) = 20.83; P < 0.01], the CV of force during bilateral motor (0.058 ± 0.062; P < 0.05) and motor-cognitive (0.061 ± 0.052; P < 0.05) tasks were greater compared with the unilateral motor task (0.027 ± 0.021). This task effect appears to be greater in elderly adults based on the age and task interaction showing that the CV of force increased by more than two times with an additional motor (P < 0.01) and cognitive task (P < 0.01) in elderly adults [F(2,54) = 6.45; P < 0.01], but not in young adults (Fig. 6A). For another measure of motor output variability, the CV of EMG was greater in elderly than young adults [main effect of age, F(1,27) = 8.01; P < 0.01; Fig. 6D]. Motor output error was assessed by the error ratio of the mean exerted force. Error ratio was greater in elderly than young adults [F(1,27) = 11.92; P < 0.01; Fig. 4F]. As a main effect of task, error ratio during the motor-cognitive task (9.1 ± 4.34; P < 0.01) when the data from all subjects and tasks were included. Elderly adults exhibited greater alpha-band unrectified EMG power compared with young adults [main effect of age, F(1,27) = 5.07, P < 0.05; elderly: 0.030 ± 0.010, young: 0.023 ± 0.008]. Elderly adults also exhibited greater alpha-band rectified EMG power compared with young adults [main effect of age, F(1,27) = 5.00, P < 0.05; elderly: 0.183 ± 0.028, young: 0.137 ± 0.071].

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7.7%) was greater compared with the unilateral motor task [5.1 ± 3.3%; *P < 0.05; *F(2,54) = 12.37; *P < 0.01; Fig. 6E]. The increase in error ratio in elderly adults appears to result mainly from larger values in elderly adults during the bilateral motor task and motor-cognitive tasks, with a greater influence from the latter. As an interaction of age and task [*F(2,54) = 5.03; *P < 0.05], error ratio during the bilateral motor (*P < 0.01) and motor-cognitive (*P < 0.01) tasks were greater in elderly than young adults, with a greater value in the latter compared with the former (*P < 0.05). In addition, error ratio during the motor-cognitive task was greater compared with the unilateral motor task in both young (*P < 0.01) and elderly (*P < 0.05) adults but greater compared with the bilateral motor task only in elderly adults (*P < 0.05).

With the use of unrectified EMG, significant correlations between beta-band corticomuscular coherence and fine motor performance were observed only for the motor-cognitive task. There was a negative correlation between error ratio and beta-band corticomuscular coherence using unrectified EMG (*r = −0.629; *P < 0.01) but not rectified EMG (*r = −0.417; *P = 0.11), across young adults during the motor-cognitive task. Thus young adults that showed a higher coherence showed a lower error rate during the motor-cognitive task. With the use of rectified EMG, a significant negative correlation between the CV of force and beta-band corticomuscular coherence appeared across young adults during the unilateral motor task (*r = −0.541; *P < 0.05), which was not significant when unrectified EMG was used (*r = −0.328; *P = 0.22). Significant associations were not observed for other measures of fine motor performance or in elderly adults whether rectified or unrectified EMG was used for coherence calculation.

Motor Performance in the Left Hand

The RMSE of force was greater in elderly adults compared with young adults across tasks [main effect of age, *F(1,27) = 19.58; *P < 0.01]. As a main effect of task, the RMSE of force in the left hand during bilateral motor (0.361 ± 0.234 N) tasks was greater compared with the unilateral motor task with the left hand [0.276 ± 0.234 N; *F(1,27) = 6.77; *P < 0.05]. There was no significant interaction of age and task.

Cognitive Accuracy

Cognitive accuracy was measured as the percentage of correct responses to cognitive problems. Cognitive accuracy was greater in young than elderly subjects [main effect of age, *F(1,27) = 10.52; *P < 0.01; Table 3]. As a main effect of task, cognitive accuracy decreased by ~9% during the motor-cognitive task compared with the cognitive task [*F(1,27) = 15.07; *P < 0.01]. This difference appears to be mainly due to a large decline in elderly adults during the motor-cognitive task. Cognitive accuracy in elderly adults during the motor-cognitive task was significantly less compared with the cognitive task (*P < 0.01) as an interaction of age and task [*F(1,27) = 4.46; *P < 0.01].

Table 3. Cognitive accuracy during the cognitive task, motor-cognitive task, and average across tasks in young and elderly adults

<table>
<thead>
<tr>
<th></th>
<th>Young (n = 16)</th>
<th>Elderly (n = 13)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cognitive</td>
<td>88.3 ± 9.8%</td>
<td>72.1 ± 22.5%*</td>
<td>81.0% ± 18.3%</td>
</tr>
<tr>
<td>Motor-cognitive</td>
<td>84.1 ± 12.6%</td>
<td>58.0 ± 27.0%*†</td>
<td>72.4% ± 23.9%†</td>
</tr>
<tr>
<td>Average</td>
<td>86.2 ± 11.3%</td>
<td>65.1 ± 25.4%*</td>
<td></td>
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Data are means ± SD. *P < 0.01 vs. young; †P < 0.01 vs. cognitive.
intervals between pairs of motor units in the first dorsal interosseus muscle tended to be greater within the beta-band in elderly adults (70.4 ± 5.9 yr) during steady isometric contraction ≥10% MVC with visual feedback of force (50). In the study that did not observe a difference on beta-band corticomuscular coherence between young and elderly adults on the opponens pollicis muscle (18), subjects tried to squeeze an object gently and steadily with the thumb and index finger without visual feedback of force, and the steadiness of exerted force was not quantified. Presence or absence of visual feedback may influence muscle activity and force steadiness (3, 65), and potential associations between motor output steadiness and beta-band corticomuscular coherence were suggested (18, 35). Thus the absence of visual feedback and/or the variability in the steadiness of motor output may have influenced the comparable beta-band corticomuscular coherence between young and elderly adults in the previous study (18). Until these possibilities are clarified in future studies, it would be safer to state that beta-band corticomuscular coherence is greater in elderly than young adults during steady contraction with visual feedback.

Corticomuscular coherence originates from oscillatory activity in the cortex, but the influence of aging on cortical spectral power has been unclear at senior age. We would propose that the inconsistency in beta-band EEG power reported with senior age was probably because of the inclusion of clinical populations. In some reports that showed decreases or no change in beta-band EEG power in elderly adults (25, 48), subjects were not considered to be healthy because of psychogenic disease, mild psychological disorders, or physical disability. In other studies that did not mention the inclusion or exclusion of clinical populations, an increase in beta-band EEG power with age was reported (9, 10, 29, 33, 61). Care was taken in the present study to control for extraneous factors that might influence neural activity (i.e., inclusion and exclusion criteria). The comparable MVC values between young and elderly subjects support the healthy status of one aspect of their neuromuscular system. Although the present study did not examine clinical populations, the current results are in favor of the contention that beta-band EEG power during motor tasks is increased in healthy elderly adults.

The increase in both EEG power and corticomuscular coherence in the beta-band suggests a potential association between the two. A study (35) reported a positive correlation between beta-band cortical power and corticomuscular coherence in the flexor digitorum superficialis muscle during isometric flexion of the index finger. This observation was supported by the current finding of a positive correlation between beta-band cortical power and corticomuscular coherence (r = 0.392). Mathematically speaking, a decrease in corticomuscular coherence would result due to an independent increase in EEG power with no change in correlation between EEG and EMG in the beta-band (see Eq. 2). Therefore, the positive correlation in the previous (35) and current studies implied that greater beta-band EEG power significantly contributed to producing greater correlated corticomuscular coherence in the beta-band in elderly adults. Hence, the current results are interpreted that beta-band corticomuscular coherence in healthy elderly adults is increased due to increased oscillatory synchronous discharges of corticospinal cells.

The greater beta-band corticomuscular coherence in elderly compared with young adults across unilateral and dual tasks (Figs. 3D and 4D) was opposite to our hypothesis. Measurement of corticomuscular coherence is regarded as the net result of multiple factors that may independently increase or decrease coherence. Potential factors that were likely involved in the current protocol include attention, stress, and activation of the supplementary motor area. First, the distribution of attention to an additional task would reduce beta-band corticomuscular coherence in the primary motor task (14, 27, 34). Second, the increased stress due to increased task difficulty with an additional task may increase coherence because various forms of stress appear to increase cortical spectral power. Stress from mental arithmetic increased beta-band cortical activity in humans (66) and posttraumatic stress disorder increased beta-band power in the central (13.5–18 Hz) and frontal (18.5–30 Hz) regions in posttraumatic stress disorder subjects compared with control subjects (6). Third, an additional cognitive task may increase cortical activity of the supplementary motor area (30) when a sensorimotor loop may have become engaged contributing to the increase in corticomuscular coherence (1). Although the apparent net results in beta-band corticomuscular coherence were similar between age groups (Figs. 3C and 4C), it is unknown if neural activity was similarly or differentially influenced by each factor. The current study originally focused on the potential influence of the first factor (attention) in building the hypothesis, but the effects of second and third factors above appear to have overridden it.

Considering the reported differences in the responsiveness to the listed factors (38, 61, 62) and in the employed neural strategy for coping with dual tasks between young and elderly adults (16, 17, 23), it would be worthwhile to speculate the possibility that neural activity was differentially influenced by different factors between age groups. Different neural strategies between ages have been observed as increased activation of sensorimotor and frontal cortex regions in elderly adults during interlimb dual tasks (23) and bimanual in-phase and anti-phase movements of the wrist (17). Dual-task paradigms are known to attenuate performance in elderly adults to a greater magnitude compared with young adults (17, 63) (Fig. 6 and Table 3). The greater increasing trend in beta-band corticomuscular coherence with additional tasks in elderly adults may imply that they have been influenced more by one or both of the latter two upregulating factors (stress and activation of supplementary motor area) compared with young adults. In line with this speculation, elderly adults in the current study demonstrated greater impairment in fine motor (Fig. 6) and cognitive performances (Table 3) and verbally expressed frustration and anxiety, especially during the motor-cognitive task. Future studies are warranted on clarifying the specific influence of each factor on beta-band corticomuscular coherence and on directly quantifying the involvement of each factor in young and elderly adults.

An increase of beta-band corticomuscular coherence in elderly compared with young adults across unilateral and dual tasks was also observed for the inclusion of rectified EMG. However, a significant difference in corticomuscular coherence across task was not observed when rectified EMG was used (Fig. 4, C and D). The frequency range of significant coherence as observed from the pooled coherence was similar between young and elderly compared with senior age was probably because of the inclusion of clinical populations. In some reports that showed decreases or no change in beta-band EEG power in elderly adults (25, 48), it is unknown if neural activity was similarly or differentially influenced by each factor. The current study originally focused on the potential influence of the first factor (attention) in building the hypothesis, but the effects of second and third factors above appear to have overridden it.

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fied EMG (Fig. 5). The similar result of increase in corticomuscular coherence with age using unrectified and rectified EMG supports the continued increase in beta-band corticomuscular coherence postadulthood into senior age. According to the most recent examination (4) on coherence calculation with rectified EMG, when a single EEG channel is used, signal interference from other sources in the brain appears to be more reflected in corticomuscular coherence with rectified EMG than unrectified EMG. Differences in the influence of task highlighted the potential sensitivity of rectification for detecting changes in specific neural activity across tasks.

Alpha-Band

Until the present study was conducted, the only implication about the influence of healthy aging on alpha-band corticomuscular coherence had been a possible increase with healthy aging because alpha-band corticomuscular coherence was observed in elderly adults in more cases than in young adults for the right opponens pollicis muscle during an isometric pinch-grip task (18). The current study considered the potential influence of attention on this implication because significant alpha-band corticomuscular coherence was observed during tasks requiring divided attention between motor and arithmetic tasks (34) or focused attention to complete a rapid movement of the index finger to the same positions (14). As a result, the greater alpha-band corticomuscular coherence during the motor-cognitive task in elderly adults (Figs. 3A and 4A) was consistent with our hypothesis. The level of attention required to perform the task was different between the present and previous studies (18). In this previous study (18), subjects performed a unilateral task and did not have a specific target to focus because feedback of force was not provided. The increase in alpha-band corticomuscular coherence with an addition of a cognitive task in young and elderly adults (Fig. 3) was consistent with the presence of significant alpha-band corticomuscular activity during motor tasks involving additional cognitive task (34). For the bilateral motor task, the amount of divided attention in the current protocol was likely less than the motor-cognitive task according to a smaller increase in motor output error (Fig. 6E). Hence, divided attention with an addition of a contralateral motor task in the current protocol may not have been large enough to increase alpha-band corticomuscular coherence by an effective amount. The findings indicated that the influence of aging on alpha-band corticomuscular coherence is task dependent, and collectively with the knowledge in the literature, attention-related cognitive components appear to play a role.

As with the beta-band, the influence of aging on alpha-band cortical spectral power had been unclear in senior age. From adulthood to senior age, some reports indicated no change in the occipital region (9) and the sensorimotor cortex (18), and others (33) indicated a decrease on average across the prefrontal, temporal, central, and occipital regions in alpha-band EEG power. In agreement with the former two studies, no change was observed in alpha-band EEG power in the sensorimotor cortex between young and elderly adults in the current study. The similarity between young and elderly adults may be related to the healthy status of the young adults included and cortical regions observed. The absence of an association between EEG power and corticomuscular coherence suggested that aging and additional cognitive task can increase alpha-band corticomuscular coherence independent of the relative amount of oscillatory discharges of corticospinal cells in the alpha-band.

Similar results for corticomuscular coherence with rectified and unrectified EMG were observed. In both cases, alpha-band corticomuscular coherence increased in elderly compared with young adults (Figs. 3B and 4B). This increase was primarily due to the significant increase during the motor-cognitive task in elderly adults. The findings with unrectified and rectified EMG further support the influence of healthy aging on alpha-band corticomuscular coherence.

Corticomuscular Coherence and Fine Motor Performance

As a potential functional significance of corticomuscular coherence, the association between beta-band corticomuscular coherence and fine motor performance (motor output error and variability) had been demonstrated across trials or segments within subjects (18, 35, 36) but not across subjects. For motor output error, no correlation across subjects was found between beta-band corticomuscular coherence and position error during unilateral ankle dorsiflexion (45) or force error during index finger abduction in either single- or simple dual-task paradigms (27). The absence of correlation across subjects during the unilateral motor task was consistent with these studies (27, 45). With a difficult motor-cognitive task, a negative correlation appeared between beta-band corticomuscular coherence and motor output error across young, but not elderly adults. Although the correlation did not reach statistical significance when rectified EMG was used, these new results were in line with our expectation. The difficulty of the current motor-cognitive task was evident from the greater motor error for this task than other tasks (Fig. 6E). The results thus indicated that in a difficult dual task that divides attention and requires substantial cognitive processing, young adults with greater beta-band corticomuscular coherence tend to produce less error (i.e., higher motor accuracy). The absence of correlation across elderly adults between beta-band corticomuscular coherence and motor output error was as expected. The age-related discrepancy in this correlation underscored the distinction in neural strategy for accomplishing dual task between young and elderly adults, such as increased activation of additional cortical regions besides the primary motor cortex in elderly adults (37).

For motor output variability, in our previous study on the first dorsal interosseus muscle (27), no correlation was found across young adults between beta-band corticomuscular coherence and force variability or EMG variability. The absence of correlation between beta-band corticomuscular coherence, using unrectified EMG, and motor output variability across young or elderly adults followed the previous findings (27) and was against our expectation for young adults but not for elderly adults. In young adults, neither additional task induced any significant change in motor output variability (Fig. 6E), indicating that the employed additional task was not influential to motor output variability in young adults. In elderly adults, large changes in the force variability with little change in EMG variability implied an involvement of antagonist muscle that would counter an association between motor output variability and beta-band corticomuscular coherence in the agonist muscle. When rectified EMG was used, there was an unexpected appearance of a significant negative correlation between beta-
band corticomuscular coherence and the CV of force during the unilateral motor task across young subjects. Considering that this correlation has not been observed in the literature (27, 45) and that corticomuscular coherence using a single EEG channel with rectified EMG may involve greater interference from other sources than with unrectified EMG (4), this inconsistent finding may possibly be influenced by neural activity in areas other than C3. Clarification of this matter would require a study with multichannel EEG.

Collectively with the findings in the literature, the following possibilities appear to exist for the potential association between beta-band corticomuscular coherence and fine motor performance. Trials or segments with higher beta-band corticomuscular coherence may produce less motor output errors and variability in some tasks or individuals in young (18, 36) but not elderly adults. Individuals with greater beta-band corticomuscular coherence do not show smaller motor output variability (Ref. 27 and current study) but may exhibit more accurate motor output (Ref. 35 and current study) in young but not elderly adults.

Conclusions

In conclusion, the present study showed that corticomuscular coherence during steady contraction with visual feedback was higher in elderly adults compared with young adults in the alpha- and beta-bands across unilateral and dual tasks. In the alpha-band, the increase in corticomuscular coherence was largest with an additional cognitive task in elderly adults. In the beta-band, corticomuscular coherence was increased with an additional task in the same manner between young and elderly subjects. In addition, beta-band corticomuscular coherence in the motor-cognitive task was negatively correlated with motor output error across young but not elderly adults. The results suggested that 1) corticomuscular coherence was increased in senior age with a greater influence of an additional cognitive task in the alpha-band, and 2) individuals with greater beta-band corticomuscular coherence may exhibit more accurate motor output in young, but not elderly, adults during steady contraction with visual feedback.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: A.N.J. and M.S. conception and design of research; A.N.J. performed experiments; A.N.J. analyzed data; A.N.J. and M.S. interpreted results of experiments; A.N.J. prepared figures; A.N.J. drafted manuscript; A.N.J. and M.S. edited and revised manuscript; A.N.J. and M.S. approved final version of manuscript.

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