Cortico-muscular synchronization by proprioceptive afferents from the tongue muscles during isometric tongue protrusion

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ABSTRACT

Tongue movements contribute to oral functions including swallowing, vocalizing, and breathing. Fine tongue movements are regulated through efferent and afferent connections between the cortex and tongue. It has been demonstrated that cortico-muscular coherence (CMC) is reflected at two frequency bands during isometric tongue protrusions: the beta (β) band at 15–35 Hz and the low-frequency band at 2–10 Hz. The CMC at the β band (β-CMC) reflects motor commands from the primary motor cortex (M1) to the tongue muscles through hypoglossal motoneuron pools. However, the generator mechanism of the CMC at the low-frequency band (low-CMC) remains unknown. Here, we evaluated the mechanism of low-CMC during isometric tongue protrusion using magnetoencephalography (MEG). Somatosensory evoked fields (SEFs) were also recorded following electrical tongue stimulation. Significant low-CMC and β-CMC were observed over both hemispheres for each side of the tongue. Time-domain analysis showed that the MEG signal followed the electromyography signal for low-CMC, which was contrary to the finding that the MEG signal preceded the electromyography signal for β-CMC. The mean conduction time from the tongue to the cortex was not significantly different between the low-CMC (mean, 80.9 ms) and SEFs (mean, 71.1 ms). The cortical sources of low-CMC were located significantly posterior (mean, 10.1 mm) to the sources of β-CMC in M1, but were in the same area as tongue SEFs in the primary somatosensory cortex (S1). These results reveal that the low-CMC may be driven by proprioceptive afferents from the tongue muscles to S1, and that the oscillatory interaction was derived from each side of the tongue to both hemispheres. Oscillatory proprioceptive feedback from the tongue muscles may aid in the coordination of sophisticated tongue movements in humans.

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Introduction

Sophisticated tongue movements play essential roles in vital oral functions such as speech articulation, mastication, swallowing, and airway patency. These fine tongue movements are accurately regulated by descending motor commands from the cortex to the tongue muscles and by afferent sensory feedback from the tongue muscles to the cortex. Such bi-directional functional connections between the cortex and muscles are mainly reflected in the cortico-muscular coherence (CMC) (Mima and Hallett, 1999; van Wijk et al., 2012).

The physiological interpretation of CMC varies according to the frequency band. The CMC in the beta (β) frequency band at 15–35 Hz (β-CMC) is generally thought to reflect the cortical interaction of motoneuron pools (Farmer et al., 1993; Mills and Schubert, 1995). Magnetoencephalography (MEG) and electroencephalography (EEG) studies have shown that the β-CMC is derived from the primary motor cortex (M1) and drives the muscle activities of the limbs and fingers through spinal motoneurons (MEG: Conway et al., 1995; Salenius et al., 1996, 1997; Brown et al., 1998; Gross et al., 2000) (EEG: Halliday et al., 1998; Mima et al., 2000). In our previous MEG study (Maezawa et al., 2014c), in addition to finding that the β-CMC for the thumb occurred over the contralateral hemisphere, we also found that the CMC for the tongue was detected at two different frequency bands (the β band and a low-frequency band at 2–10 Hz) over both hemispheres during isometric tongue protrusion for each side of the tongue. We concluded that the β-CMC for the tongue reflects the descending motor commands from M1 bilaterally to each side of the tongue through hypoglossal motoneuron pools. However, the mechanism of the CMC at the low-frequency band (low-CMC) is still unclear.

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Recent studies on cortico-kinematic coherence (CKC) using an accelerometer demonstrated that the primary sensorimotor cortex (SM1) is strongly coherent at the low frequency band during repetitive finger movements (Piitulainen et al., 2013a,b; Bourguignon et al., 2015). These studies suggest that the CKC at the low frequency band mainly reflects proprioceptive afferent input from muscle spindles to the contralateral SM1. Thus, as the human tongue muscles are rich in muscle spindles, the low-CMC for the tongue may be related to proprioceptive afferents from the tongue muscles.

The object of the present study was to investigate the generator mechanism of the low-CMC during human tongue protrusion using MEG. To do this, we first identified the conduction time of the low-CMC between the cortex and tongue, and compared it with the conduction times of the β-CMC and the somatosensory evoked fields (SEFs) following tongue stimulation. Second, we examined the location of the cortical sources for the low-CMC compared with the source locations of the β-CMC and tongue SEFs.

Materials and methods

Subjects

Twenty-one right-handed healthy volunteers (14 men, 7 women; aged 20–37 years; mean age, 28.0 years) were studied. None of the subjects had a history of neurological or psychiatric disorders. Written informed consent was obtained from all subjects before they were included in the study. The protocol for this study was approved by the Ethical Committee of Dental Medicine of Hokkaido University. A portion of this study (β-CMC) has been reported previously using different analysis methods in 15 subjects (Maezawa et al., 2014c).

MEG recordings

Neuromagnetic signals were measured with a helmet-shaped 306-channel apparatus (VectorView, Elekta Neuromag, Helsinki, Finland) in a magnetically shielded room. This device had 102 trios that were composed of a magnetometer and a pair of planar gradiometers oriented orthogonally. Only 204 planar gradiometers were used for the analysis, detecting the largest signal above the corresponding generator source (Hämäläinen et al., 1993).

The exact position of the head with respect to the sensor array was determined by measuring the magnetic signals from four indicator coils placed on the scalp. The coil locations, as well as three predetermined landmarks on the skull, were identified with a three-dimensional digitizer (Isotrak 3S1002; Polhemus Navigation Sciences, Colchester, VT). This information was used to co-register the MEG signal and the individual magnetic resonance images (MRIs) obtained with a Signa Echo-Speed 1.5-Tesla system (General Electric, Milwaukee, WI).

Coherence recordings

Subjects performed a task requiring weak and sustained forward tongue protrusions (20–30% of the maximal strength on a subjective scale). The tongue movements required subjects to have their mouths open slightly, however they were asked not to touch their tongue to their lips to prevent any sensory feedback from the mouth and lips. The tongue protrusion task was performed for approximately 10–15 min, with each 2-min recording period being separated by a 30-s rest period. Surface electromyography (EMG) activity was recorded from the dorsum of the tongue bilaterally using disposable EMG electrode pairs (Vitrode V, Nihon Kohden, Tokyo, Japan). Simultaneous recording of MEG and EMG signals was performed with a bandpass filter of 0.1–300 Hz and digitized at 997 Hz.

SEF recordings

SEFs were recorded following electrical tongue stimulation in 16 subjects (10 men, 6 women; aged 20–37 years; mean age, 29.5 years).

Stimulation was applied on the right side of the tongue using an electrical stimulator (SEN-3401, Nihon Kohden, Tokyo, Japan). We used a pair of pin electrodes (400-μm diameter) with an inter-electrode distance of 3 mm for stimulation because they can safely deliver a low-intensity stimulus to a small oral region (Maezawa et al., 2008, 2011, 2014b). Tongue stimulation was applied 1 cm from the edge of the tongue, 3–4 cm from the tongue tip (Maezawa et al., 2014a). We confirmed through self-reports that electrical stimulation occurred only at the stimulation site. The stimulus consisted of square, biphasic, constant-current electric pulses (0.5 ms for 1 phase) applied once every 1 s. The intensity at each stimulation site was set to 2.5 to 3 times the sensory threshold for that stimulation site in each subject. Stimulation was applied at least 240 times. The recording passband was 0.1–330 Hz and the sampling rate was 997 Hz. The analysis window for averaging was from 100 ms before to 500 ms after each trigger signal. The baseline was calculated from −50 to −5 ms before stimulation onset.

Data analysis

Coherence analysis

For each side of the tongue, the EMG signals were high-pass filtered at 1 Hz and rectified to extract the motor unit potential timing information (Rosenberg et al., 1989). To calculate the spectral coherence between the MEG and rectified EMG signals at the low frequency band within 2–10 Hz, we used Welch's method (Welch, 1967) of spectral density estimation with a Hanning window, frequency resolution of 0.5 Hz, and half-overlapping samples, with the maximum frequency set to 15 Hz. To calculate the CMC spectrum at the β band, we again used Welch's method (Welch, 1967) with a Hanning window, frequency resolution of 0.5 Hz, and half-overlapping samples.

CMC values (Cohxy) were calculated according to the following equation:

$$\mathrm{Coh}xy(\lambda) = |\mathrm{R}xy(\lambda)|^2 = \frac{|fxy(\lambda)|^2}{fxx(\lambda) \cdot fyy(\lambda)}.$$

In this equation, $fxx(\lambda)$ and $fyy(\lambda)$ are values of the auto-spectra of the MEG and rectified EMG signals for a given frequency λ, and $fxy(\lambda)$ is the cross-spectrum between them. The muscular-muscular coherence (MMC) spectrum between sides of the tongue was also calculated in the same manner as the β-CMC spectrum.

We excluded the initial 5 s of each EMG signal recorded during the task from the analysis. We also rejected epochs with artifacts identified by visual inspection for either side from the analysis, thus yielding 620 ± 122 (mean ± standard deviation) total samples. Based on the method by Rosenberg et al. (1989), coherence above Z was considered to be significant at p < 0.01, where $Z = 1 - 0.01^{(1/L - 1)}$. L was the total number of samples used in the estimation of the auto- and cross-spectra.

A cross-correlogram in the time domain was investigated by applying an inverse Fourier transformation to the averaged cross-spectrum of the right side of the tongue for each frequency band (low-frequency band and β band). Next, we constructed isocontour maps at the time points that showed cross-correlogram peaks for each frequency band. Equivalent current dipoles (ECDs) were used to model the sources of the oscillatory MEG signals. A spherical head model was used to estimate the location of the ECDs over the contralateral (left) hemisphere for each frequency band. The center of this head model fit the local curvature of the surface of an individual's brain, as determined by their MRIs (Sarvas, 1987). Only ECDs attaining an 85% goodness-of-fit and a confidence volume smaller than 3000 mm³ were accepted.

SEF analysis

The peak latency of SEFs was measured from the channel showing the maximal signal over the contralateral (left) hemisphere. Isocontour maps were constructed at the peak latency. The digitized shape of each