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Ascending beta oscillation from finger muscle to sensorimotor cortex contributes to enhanced steady-state isometric contraction in humans

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HIGHLIGHTS

- Bidirectional information flow was estimated between sensorimotor cortex and finger muscle by directed transfer function (DTF) during steady-state contraction.
- Ascending β-band DTF was greater in the thumb muscle than in the little finger muscle.
- Greater ascending β-band DTF was associated with higher EMG stability.

ABSTRACT

Objective: β-Band corticomuscular coherence is suggested as an electrophysiological mechanism that contributes to sensorimotor functioning in the maintenance of steady-state contractions. Converging evidence suggests that not only the descending corticospinal pathway but the ascending sensory feedback pathway is involved in the generation of β-band corticomuscular coherence. The present study aimed to investigate which pathway, descending vs. ascending, contributes more to the stability of muscle contraction, especially for human intrinsic hand muscles.
Methods: In this study, we assessed directed transfer function (DTF) between magnetoencephalography signals over the sensorimotor cortex (SMC) and rectified electromyographic (EMG) signals recorded during steady-state isometric contraction of the right thumb muscle (flexor pollicis brevis, FPB) or right little finger muscle (flexor digiti minimi brevis, FDMB) in 15 right-handed healthy subjects.
Results: β-Band DTF was statistically significant in both descending (SMC → EMG) and ascending (EMG → SMC) directions, and mean phase delays for each direction were in agreement with the conduction time for the descending corticospinal and ascending sensory feedback pathways. The strengths of the β-band DTF (EMG → SMC direction) were greater in the FPB muscle than in the FDMB muscle, while the strengths of the β-band DTF (SMC → EMG direction) were not different between the two muscles. Moreover, the β-band DTF (EMG → SMC direction) was greater in the "Stable" period than in the "Less Stable" period within the FDMB muscle. Greater DTF (EMG → SMC direction) was positively associated with the stability of muscle contraction.
Conclusions: Our findings suggest that ascending β-band oscillatory activity may promote a steady-state isometric contraction by efficiently transmitting sensory feedback from finger muscles to the sensorimotor cortex.
Significance: The results show the differential contribution of the ascending part of the corticomuscular network depending on the functional organization.

1. Introduction

Previous studies with magnetoencephalography (MEG) and electroencephalography (EEG) have shown that neural oscillatory

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activity in the sensorimotor cortex (SMC) is coherent with electromyographic (EMG) activity of the contralateral muscle in the β-band (15–30 Hz) during isometric contraction (Conway et al., 1995; Salenius et al., 1997; Gross et al., 2000; Pohja et al., 2005; Kristeva-Feige et al., 2002; Ushiyama et al., 2010, 2011a,b; Omlor et al., 2007, 2011; Johnson et al., 2011; Perez et al., 2012; Divekar and John, 2013; Mendez-Balbuena et al., 2012; Patino et al., 2008; Pollok et al., 2012). These oscillatory interactions between the cortex and muscle can be assessed by calculation of coherence, which is a measure of linear correlation in the frequency domain. Several studies have observed that β-band corticomuscular coherence is typically strongest during steady-state contraction, while it is reduced or abolished during movement (Murthy and Fetz, 1996; Baker et al., 1997; Kilner et al., 1999, 2000; Riddle and Baker, 2006; Baker, 2007; Engel and Fries, 2010; Petersen et al., 2012). Furthermore, β-band corticomuscular coherence was associated with the performance of static force (Kristeva et al., 2007; Witte et al., 2007) and stability of EMG amplitude (Lim et al., 2011). This accumulating evidence has suggested that β-band corticomuscular coherence is a mechanism for effective corticospinal interaction related to the maintenance of steady-state contractions.

Converging evidence from both human and monkey studies has suggested that not only the descending corticospinal pathway but also the ascending sensory feedback pathway is involved in the generation of β-band corticomuscular coherence (Riddle and Baker, 2005; Baker et al., 2006; Baker, 2007; Fisher et al., 2002; Kilner et al., 2004; Meng et al., 2008; Pohja and Salenius, 2003; Tsujimoto et al., 2009; Witham et al., 2010, 2011). However, previous studies have not examined the descending and ascending pathways separately with regard to maintaining steady-state contraction, thus not being able to discriminate each functional role in motor control.

In our previous study, we showed that the magnitudes of β-band corticomuscular coherence for the flexor pollicis brevis (FPB) muscle were significantly greater than those for the flexor digiti minimi brevis (FDMB) muscle, and greater levels of β-band corticomuscular coherence were associated with higher levels of EMG stability (Lim et al., 2011). The present study aimed to further investigate which descending motor command or ascending sensory feedback contributes to the stability level of muscle contraction, especially for human intrinsic hand muscles. Directional information flow between SMC and EMG was estimated by calculating directed transfer function (DTF) (Kamiński and Blinowska, 1991; Kamiński et al., 2001) based on the multivariate autoregressive (MVAR) model.

It was well described that patients with deafferentiation have trouble maintaining a steady thumb position and a steady isometric torque (Rothwell et al., 1982). This report clearly indicated that afferent sensory feedback from muscle receptors has a crucial role in maintaining a constant level of contraction in hand muscles. Muscle spindle primary afferent seems to be the candidate pathway for carrying oscillatory activity from muscles to the cortex (Baker et al., 2006; Witham et al., 2010). Recent human studies have shown that the relative spindle abundance of the FPB muscle is numerically greater than that of the FDMB muscle (Xie et al., 2012). Therefore, we hypothesized that β-band DTF from EMG to SMC (reflecting sensory feedback) for FPB muscles would be greater than that for FDMB muscles, and that the difference in β-band DTF from EMG to SMC would be associated with the stability levels of muscle contraction. The delays between SMC to EMG signals and vice versa were also calculated from the DTF phase to evaluate the conduction time for both the descending and ascending pathways. Analysis of EMG stability and corticomuscular coherence in 12 subjects has been previously reported (Lim et al., 2011).

2. Methods

2.1. Subjects

Fifteen healthy volunteers (eight men; mean age ± SD; 25.1 ± 2.8 years; range 20–28 years) without a history of any neurological diseases participated in the study. All subjects were right-handed as assessed by the Edinburgh Handedness Inventory (mean ± SD; 88.9 ± 12.6) (Oldfield, 1971). Written informed consent was obtained from every subject. The study was approved by the institutional review board of the Seoul National University Hospital, Seoul, South Korea.

2.2. Task

We briefly describe the experimental paradigm, although it was the same as a previous study by Lim et al. (2011). The subjects were asked to perform steady-state isometric contraction of two different finger muscles for 5 min in a separate block: the flexor pollicis brevis (FPB) of the right thumb, and the flexor digiti minimi brevis (FDMB) of the right little finger. Before the recording, subjects practiced flexion of the finger at the level of the metacarpophalangeal joint. In order to avoid co-movements of other joints and fingers, the medial and distal interphalangeal joints and non-using fingers were fixated by taping. The starting order of the blocks was randomized across the subjects. The mean rectified EMG amplitude during maximal voluntary contraction (MVC) of 3 s was measured at each FPB and FDMB muscle prior to the recording session. Study subjects were asked to produce 20% of the amplitude of the EMG at MVC. The experimenter (M.L.) monitored the recording of EMG signals from the computer screen and confirmed that the amplitude of the EMG signal maintained 20% of the amplitude of the EMG at MVC. Intermittent verbal feedback was given to ask some subjects to produce steady muscle contraction through the microphone outside the shield room when we detected an excessively higher or lower range of EMG amplitude during measurement. However, most subjects maintained 20% of the maximum strength throughout the experiment. None of the subjects reported muscle fatigue and difficulty with the tasks.

2.3. Recordings

Cortical signals were recorded with a 306 channel whole-head neuromagnetometer (VectorView™ Elekta Neuromag Oy, Helsinki, Finland) comprised of 102 identical triple sensors in a magnetically shielded room. Each sensor consisted of two orthogonal planar gradiometers and one magnetometer. Subjects were seated under the helmet-shaped sensor array and asked to keep their head as still as possible during the experiment. The exact location of the head with respect to the sensors was found by measuring magnetic signals produced by electrical currents delivered to four head position indicator coils placed on the scalp. The location of head position indicator coils with respect to three anatomical landmarks, the nasion and two preauricular points, were measured using a three-dimensional digitizer (FASTRAK™, Polhemus, Colchester, Vermont, USA). Surface EMG signals were recorded from the FPB and FDMB of the right hand. The first and the last 10 s of the 5-min measurement were discarded from offline analysis to ensure contraction stability. MEG and EMG signals were recorded with a passband of 0.1–200 Hz and digitized at 1 kHz. To reduce environmental and biological noises, we applied the spatiotemporal signal space separation method, which allows separation of components into brain-related and external interference signals using MaxFilter