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Neural pattern similarity between contra- and ipsilateral movements in high-frequency band of human electrocorticograms

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A R T I C L E I N F O

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A B S T R A C T

The cortical motor areas are activated not only during contralateral limb movements but also during ipsilateral limb movements. Although these ipsilateral activities have been observed in several brain imaging studies, their functional role is poorly understood. Due to its high temporal resolution and low susceptibility to artifacts from body movements, the electrocorticogram (ECoG) is an advantageous measurement method for assessing the human brain function of motor behaviors. Here, we demonstrate that contra- and ipsilateral movements share a similarity in the high-frequency band of human ECoG signals. The ECoG signals were measured from the unilateral sensorimotor cortex while patients conducted self-paced movements of different body parts, contra- or ipsilateral to the measurement side. The movement categories (wrist, shoulder, or ankle) of ipsilateral movements were decoded as accurately as those of contralateral movements from spatial patterns of the high-frequency band of the precentral motor area (the primary motor and premotor areas). The decoder, trained in the high-frequency band of ipsilateral movements generalized to contralateral movements, and vice versa, confirmed that the activity patterns related to ipsilateral limb movements were similar to contralateral ones in the precentral motor area. Our results suggest that the high-frequency band activity patterns of ipsilateral and contralateral movements might be functionally coupled to control limbs, even during unilateral movements.

1. Introduction

The precentral motor cortex (the primary motor [M1] and premotor [PM] areas) that mainly controls contralateral limbs, also demonstrates activity change related to ipsilateral limb movements in monkeys (Cisek et al., 2003; Donchin et al., 1998; Matsunami and Hamada, 1981; Tanji et al., 1988) and humans (Shibasaki and Kato, 1975; Kim et al., 1993; Salmelin et al., 1995a; Kawashima et al., 1998; Cramer et al., 1999; Toma et al., 2002; Verstynen, 2004). After damage to a unilateral sensorimotor area, the brain activity on the side ipsilateral to the paralyzed limb increases to compensate for the affected contralateral area (Johansen-Berg et al., 2002; Gerloff, 2006; Lotze, 2006). Modulation of ipsilateral arm muscle activation by transcranial magnetic stimulation (TMS) of M1 has also been found in healthy subjects (Tazoe and Perez, 2014). Anatomically, homologous regions of both hemispheres (e.g., left and right M1s) are inter-connected via the corpus callosum (Killackey et al., 1983; Zarei et al., 2006; Wahl et al., 2007), and a portion of corticospinal fibers from the M1 and premotor area terminate on ipsilateral ventral horn in the spinal cord (Dum and Strick, 1991, 1996). The neural activity during ipsilateral movements might depend on this structure.

Recently, decoding analysis has been developed to characterize neural ensembles, in which multivariate signals from brain activity (multiunit

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recording, electroencephalogram [EEG], magnetoencephalogram [MEG], electrocorticogram [ECoG], and functional magnetic resonance imaging [fMRI]) are weighted and combined to decode perceptions and motor behaviors (e.g., movement direction or trajectory) (Taylor et al., 2002; Leuthardt et al., 2004; Kamitani and Tong, 2005; Yanagisawa et al., 2009; Bradberry et al., 2010; Pasley et al., 2012; Haar et al., 2015). A merit of such decoding analysis is that it can assess the differences in neural patterns or multivariate activities with regard to movement categories (e.g., wrist and shoulder), indistinguishable by univariate analysis (e.g., average of activity pattern). If the pattern of neural population varies systematically with movement categories, it is possible to decode them. Using this technique, ipsilateral movements have recently been decoded from EEG (Bundy et al., 2012), ECoG (Scherer et al., 2009; Liu et al., 2010; Hotson et al., 2014), and fMRI (Diedrichsen et al., 2013). However, these studies did not clarify the similarity or disparity between neural representations of contra- and ipsilateral movements.

Here, we hypothesize that ipsilateral movements are coded in the same fashion as contralateral movements in the precentral motor cortex. This hypothesis can be verified by the cross-decoding technique (Stokes et al., 2009), that is, if a decoder trained with one condition (e.g., visual perception) is generalized to the other condition (e.g., visual imagery), one can argue that the neural representations are consistent across the two conditions.

It has long been thought that multiple bands of neural oscillations have a role in movement. The amplitude of the low-frequency band (8–12 Hz, called mu) is typically decreased by actual movements or motor imagery, whereas the amplitude of the middle-frequency band (18–26 Hz, called beta) is increased by such movements or imagery (Salmelin et al., 1995b; Pfurtscheller and Lopes da Silva, 1999; Miller et al., 2010). The scalp EEG (Ball et al., 2008), ECoG (Miller et al., 2007, 2009; Yanagisawa et al., 2011; Pistohl et al., 2012), and MEG (Cheyne et al., 2008) studies have reported that the amplitude of the high-frequency band (50–150 Hz, called high gamma) increases with movement. Several ECoG studies have succeeded in decoding the information on movements from the high-frequency bands (Kubánek et al., 2009; Yanagisawa et al., 2011; Pistohl et al., 2012), and these movement-related modulations were also observed in ipsilateral movements (Ohara, 2000; Jurkiewicz et al., 2006).

In this study, we analyzed ECoG data to assess which frequency band had a similar pattern between contra- and ipsilateral movements. ECoG is advantageous for investigation of motor behaviors because of its high temporal and spatial resolution, high signal-to-noise ratio, and data free from artifacts of limb movements. In particular, it is easier to detect high-frequency (high gamma) bands related to motor behavior with ECoG than with scalp EEG. ECoG data were measured from electrodes covering the unihemispheric sensorimotor area while patients conducted self-paced movements of different body parts (wrist extension, shoulder abduction, and ankle dorsiflexion), contra- or ipsilateral to the measurement side. The decoding analysis conducted separately for contra- and ipsilateral movements demonstrated that the high-frequency band of the precentral motor area (the primary motor and premotor areas) was informative in classifying the movement categories in both conditions. We, then, performed cross-decoding across contra- and ipsilateral movements, in which the decoder trained with the data of contralateral (ipsilateral) condition was generalized to the data of the ipsilateral (contralateral) condition. Using the high-frequency band in the precentral motor cortex, the decoder was generalized across the two conditions. These results confirmed that the high-frequency band in the precentral motor cortex shares similarity across contra- and ipsilateral movements.

2. Methods

2.1. Subjects

Three patients (Patient 1, age 35; Patient 2, age 34; Patient 3, age 61; all male subjects) underwent chronic subdural electrode placement over the frontoparietal area for functional mapping around a lesion (all cases), and presurgical evaluation of intractable epilepsy (Patients 2 and 3). Subdural grid or strip electrodes were placed according to the clinical needs. Electrodes were made of platinum, with a recording diameter of 2.3 mm, and a center-to-center interelectrode distance of 1 cm (Ad-Tech, Racine, WI). All patients had tumorous lesions in the hemisphere where electrodes were implanted (right dorsomedial prefrontal cortex in Patient 1, left dorsomedial prefrontal cortex in Patient 2, and left supramarginal gyrus in Patient 3). Two of three patients (Patients 2 and 3) had intractable partial epilepsy, which was suspected of having arisen from around the lesion. No seizure activity was observed in the ECoG data used in the present study.

To define the location of subdural electrodes on the cortical surface, electrodes were co-registered to a structural MRI that was reconstructed from a magnetization-prepared rapid gradient echo (MPRAGE) sequence. The MPRAGE volumetric scan was performed before and after implantation of subdural electrodes, as a part of the presurgical evaluations. In the volumetric scan taken after implantation, the location of each electrode was identified on the 2D slices using its signal void, which occurred due to a property of the platinum alloy (Matsumoto et al., 2004).

The present study was approved by the Ethics Committee of Kyoto University Graduate School of Medicine (No. 79, C533). Written informed consent was obtained from all patients.

2.2. Task

The patients performed self-paced brisk movements at intervals of around 10 s. The movement involved wrist extension, shoulder abduction, and ankle dorsiflexion. The movements were performed separately in the sides ipsilateral and contralateral to the recording hemisphere. Actual motor tasks were determined based on each patient's condition- Patient 1: wrist and shoulder; Patient 2: shoulder and ankle; Patient 3: wrist, shoulder, and ankle. The patients were instructed to make brisk movements while keeping their muscles relaxed between movements. ECoGs of at least 100 trials were recorded for each movement category.

2.3. Data recording

ECoG and EMG were recorded in Patients 1 and 2 at a sampling rate of 2000 Hz, and in Patient 3 at a sampling rate of 1000 Hz (EEG1100, Nihon Kohden Co., Tokyo, Japan. The sampling rate of this measurement system degrades to 1000 Hz when the number of electrodes exceeds 70 [106 electrodes in Patient 3]). Recordings from subdural electrodes were referenced to a scalp electrode placed on the skin over the mastoid process, contralateral to the side of electrode implantation. Target muscle activation was monitored by electromyogram (EMG) so that movement onset could be easily identified visually. We bilaterally placed a pair of shallow cup electrodes 2-cm apart on the skin over each corresponding muscle: the extensor digitorum communis (EDC) and the deltoideus (DEL) in Patient 1; the extensor carpi ulnaris (ECU), DEL, and the tibialis anterior (TA) in Patient 2; and the extensor carpi radialis (ECR), DEL, and TA in Patient 3.

2.4. Functional cortical mapping by high-frequency electrical cortical stimulation

High-frequency electrical cortical stimulation for functional cortical mapping was performed as a part of the routine presurgical evaluation. Repetitive square wave electrical currents of alternating polarity with a pulse width of 0.3 ms and a frequency of 50 Hz were delivered for 2–5 s via an electrical stimulator (SEN-7203 for Patient 1, and MS-120B/MEE-1232 for Patients 2 and 3, both manufactured by Nihon Kohden). Details of the methodology for cortical stimulation and subsequent cortical mapping have been described elsewhere (Luders, 1987;