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CORTICOKINEMATIC COHERENCE DURING ACTIVE AND PASSIVE FINGER MOVEMENTS

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Abstract—Corticokinematic coherence (CKC) refers to coupling between magnetoencephalographic (MEG) brain activity and hand kinematics. For voluntary hand movements, CKC originates mainly from the primary sensorimotor (SM1) cortex. To learn about the relative motor and sensory contributions to CKC, we recorded CKC from 15 healthy subjects during *active* and *passive* right index-finger movements. The fingertip was either touching or not touching table, resulting in *active-touch*, *active-no-touch*, *passive-touch*, and *passive-no-touch* conditions. The kinematics of the index-finger was measured with a 3-axis accelerometer. Beamformer analysis was used to locate brain activations for the movements; somatosensory-evoked fields (SEFs) elicited by pneumatic tactile stimulation of the index finger served as a functional landmark for cutaneous input. All *active* and *passive* movements resulted in statistically significant CKC at the movement frequency (F0) and its first harmonic (F1). The main CKC sources at F0 and F1 were in the contralateral SM1 cortex with no spatial differences between conditions, and distinct from the SEF sources. At F1, the coherence was by two thirds stronger for *passive* than *active* movements, with no difference between *touch vs. no-touch* conditions. Our results suggest that the CKC occurring during repetitive finger movements is mainly driven by somatosensory, primarily proprioceptive, afferent input to the SM1 cortex, with negligible effect of cutaneous input.

Key words: acceleration, human brain, magnetoencephalography, proprioception, sensorimotor cortex.

INTRODUCTION

Kinematics of repetitive executed and observed hand movements is coherent with magnetoencephalographic (MEG) brain activity both at the movement frequency (F0) and its first harmonic (F1) (Jerbi et al., 2007; Bourguignon et al., 2011, 2012, 2013b; Piitulainen et al., 2013). The cortical sources of this corticokinematic coherence (CKC) are located in the contralateral primary sensorimotor (SM1) cortex. However, the relative motor and sensory contributions to CKC in the context of self-executed hand movements are still unknown. One approach to unravel these contributions is to compare CKC under *active vs. passive* movements and to vary the level of cutaneous tactile input. During passive movements, the effect of corticospinal efferents is negligible while movement-related afferent somatosensory information is preserved.

According to single-neuron recordings, both the primary motor (M1) and primary somatosensory (S1) cortices receive proprioceptive feedback, and certain human M1 neurons discharge during both active and passive hand movements while remaining silent during tactile stimulation (Goldring and Ratcheson, 1972). In neuroimaging studies, both active and passive upper limb (hand and elbow) movements may result in strikingly similar activation patterns in the contralateral SM1 cortex, covering both the M1 and S1 cortices (positron emission tomography, PET, (Weiller et al., 1996); functional magnetic resonance imaging fMRI, (Reddy et al., 2001; Kocak et al., 2009)). According to MEG recordings, passive finger and toe movements activate S1 and secondary somatosensory cortices, but the results have been more diverse on M1 involvement (Xiang et al., 1997a,b; Mima et al., 1999; Alary et al., 2002; Woldag et al., 2003).

We aimed to disentangle motor and sensory contributions to CKC by (1) comparing coherence strength during continuous *active* and *passive* right index-finger movements, (2) comparing the cortical source locations between *active* and *passive* movements and with respect to the sources of somatosensory-evoked fields (SEFs), and (3) evaluating the effect of tactile input on coherence. We hypothesized that cortical CKC sources would be more

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Abbreviations: CKC, corticokinematic coherence; DICS, dynamic imaging of coherent sources; EMG, electromyography; F0, movement frequency of finger movements; fMRI, functional magnetic resonance imaging; F1, first harmonic of finger movement frequency; M1 cortex, primary motor cortex; MRIs, magnetic resonance images; MEG, magnetoencephalography; MNI brain, standard Montreal Neurological Institute brain; PET, positron emission tomography; S1 cortex, primary somatosensory cortex; SM1, primary sensorimotor cortex; SEF, somatosensory-evoked field; SEP, somatosensory-evoked potential.

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posterior for *passive* than *active* movements due to a posterior shift of the center of gravity of SM1 activation because of decreased motor–cortex involvement (Reddy et al., 2001). Furthermore, by varying the amount of tactile input (the moved finger either touching or not touching the table supporting the hand), we attempted to locate CKC sources with respect to S1 index-finger area, indentified by tactile SEFs. Finally, we expected the strength of CKC in different conditions to inform about the relative motor and sensory contributions.

EXPERIMENTAL PROCEDURES

Subjects

Fifteen healthy subjects (mean age 29.4 yrs, range 21–38; 8 males, 7 females) without any history of neuropsychiatric disease or movement disorders were studied. According to Edinburgh handedness scale (Oldfield 1971), 14 subjects were right-handed (mean 92, range 67–100; left–right scale from −100 to +100) and one subject was ambidextrous (−20).

The study had a prior approval by the ethics committee of the Helsinki and Uusimaa district, and the subjects gave written informed consent before participation. Subjects were compensated monetarily for the lost working hours and travel expenses.

Experimental protocol

During MEG recordings, subjects sat with the left hand on the thigh and the right hand on a table positioned in front of them. Earplugs were used to reduce concomitant auditory noise. Subjects were instructed to fixate a self-chosen detail in a picture ($21 \times 30\ \text{cm}^2$) on the wall of the magnetically shielded room, positioned 2.8 m in front of them, 11 deg to the left from the midline. A white paper sheet taped vertically on the MEG gantry prevented the subjects from seeing their right hand moving.

Subjects underwent six experimental conditions (four movement conditions, SEFs to tactile stimulation, and a *rest* condition). The order of the six conditions was randomized for each subject. The four movement conditions (*active-touch*, *active-no-touch*, *passive-touch*, and *passive-no-touch*) involved continuous flexion–extension of the right index-finger at a frequency around 4 Hz for 3.5 min, and they comprised two movement tasks, *active* and *passive*, and two movement types, *touch* and *no-touch*. The finger movements occurred mainly at the metacarpophalangeal joint. In *touch* conditions, the tip of the index finger touched the table whereas in *no-touch* conditions it did not. Subject performed the *active* movements with a self-paced rate. In the *passive* task, the investigator moved a light aluminum stick, attached with Velcro strap to the middle segment of the subjects right index-finger, with a self-paced rate around 4 Hz (Fig. 1, right). To reduce cutaneous stimulation during passive movements, the middle phalanx of the index finger was covered with surgical paper tape prior to the placement of the Velcro strap. Subjects did not see the investigator who sat on the right side behind the paper screen.

The kinematics of the right index-finger was monitored with a 3-axis accelerometer (ADXL335 iMEMS Accelerometer, Analog Devices, Inc., Norwood, MA, USA) attached to the index-finger nail (Fig. 1). The accelerometer did not produce artifacts to the MEG signals.

For SEF recordings, tactile pneumatic stimuli (duration 183 ms, peak at 36 ms) were delivered to subject's right fingertip once every 500 ms, for 4 min, which resulted in about 480 stimuli.

In the *rest* condition, carried out for noise estimation, subjects rested eyes open during 3.5 min.

Measurements

MEG. The measurements were carried out at the MEG Core of the Brain Research Unit, Aalto University. Cerebral activity was recorded in a magnetically shielded room (Imedco AG, Hägendorf, Switzerland) with a 306-channel whole-scalp neuromagnetometer (Elekta Neuromag™, Elekta Oy, Helsinki, Finland). The recording passband was 0.1–330 Hz and the signals were sampled at 1 kHz. The subject's head position inside the MEG helmet was continuously monitored by feeding current to four head-tracking coils located on the scalp. The locations of the coils with respect to anatomical fiducials were determined with an electromagnetic tracker (Fastrak, Polhemus, Colchester, VT, USA). Co-registration with the MRI images was based on three anatomical fiducials and additional digitization points.

Acceleration and EMG. Accelerometer and surface electromyographic (EMG) signals were recorded time-locked to MEG signals, low-pass filtered at 330 Hz and sampled at 1 kHz (Fig. 1). EMG electrodes were placed in bipolar configuration (impedance $< 10\ \text{k}\Omega$) with 20-mm inter-electrode distance over *extensor digitorum* and *flexor carpi radialis* muscles. A ground electrode was placed on left side of the subject's neck.

MRI. 3D-T1 magnetic resonance images (MRIs) were acquired with whole-body General Electric Signa® VR 3.0T MRI scanner (Signa VH/i, General Electric, Milwaukee, WI) at the AMI Centre of the Aalto University.

Data processing

MEG and MRI pre-processing. Continuous MEG data were pre-processed off-line using the signal-space-separation (SSS) method to suppress external interferences, correct for head movements, and align head positions across the sessions (Taulu et al., 2004). The signals were band-pass filtered through 1–195 Hz off-line and epochs exceeding 3 pT (magnetometers) or 0.7 pT/cm (gradiometers) were excluded to avoid contamination by eye movements, muscle activity, and artifacts in MEG sensors. Individual MRIs were segmented using Freesurfer software (Martinos Center for Biomedical Imaging, Massachusetts, USA). Then, the MEG forward model for two orthogonal tangential current dipoles was computed for each node of a 5-mm mesh of the white–gray matter interface using MNE suite (Martinos Center for Biomedical Imaging, Massachusetts, USA).

Coherence analysis. To perform frequency and coherence analyses between the index-finger acceleration and MEG signals of the four movement conditions, continuous data were split into 2048-ms epochs with 1638-ms epoch overlap, leading to frequency resolution of ∼0.5 Hz (Bortel and Sovka, 2007). Acceleration corresponding to each epoch was computed at every sample as the Euclidian norm of the three band-passed (1–195 Hz) acceleration signals (Bourguignon et al., 2011). The use of the Euclidian norm of the accelerometer channels allowed us to quantify finger kinematics regardless of hand position. Before the coherence analysis, each epoch of acceleration was normalized by its Euclidian norm. Frequencies of interest, showing consistent coherence across subjects, were applied for source analyses, where cross-spectral density