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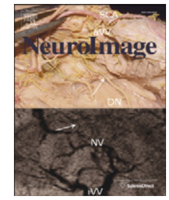

# Local field potentials in primate motor cortex encode grasp kinetic parameters

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ABSTRACT

Reach and grasp kinematics are known to be encoded in the spiking activity of neuronal ensembles and in local field potentials (LFPs) recorded from primate motor cortex during movement planning and execution. However, little is known, especially in LFPs, about the encoding of kinetic parameters, such as forces exerted on the object during the same actions. We implanted two monkeys with microelectrode arrays in the motor cortical areas MI and PMd to investigate encoding of grasp-related parameters in motor cortical LFPs during planning and execution of reach-and-grasp movements. We identified three components of the LFP that modulated during grasps corresponding to low (0.3–7 Hz), intermediate (~10–~40 Hz) and high (~80–250 Hz) frequency bands. We show that all three components can be used to classify not only grip types but also object loads during planning and execution of a grasping movement. In addition, we demonstrate that all three components recorded during planning or execution can be used to continuously decode finger pressure forces and hand position related to the grasping movement. Low and high frequency components provide similar classification and decoding accuracies, which were substantially higher than those obtained from the intermediate frequency component. Our results demonstrate that intended reach and grasp kinetic parameters are encoded in multiple LFP bands during both movement planning and execution. These findings also suggest that the LFP is a reliable signal for the control of parameters related to object load and applied pressure forces in brain–machine interfaces.


## Introduction

Advances in chronically implanted intracortical multielectrode technology pave the way in understanding the function of motor cortex in complex upper limb control. Neural recordings obtained from microelectrode arrays contain action potentials (spikes) of an ensemble of neurons as well as local field potentials (LFPs), which are thought to represent a population measure that mainly reflects the local synaptic activity, with contributions from spike after-potentials and intrinsic trans-membrane current changes in the vicinity of the recording electrodes (Buzsaki et al., 2012; Logothetis et al., 2007; Mitzdorf, 1985; Reimann et al., 2013; Waldert et al., 2013). Large number of electrodes and high sampling rates in microelectrode arrays offer the opportunity to investigate the temporal evolution of stimulus and behavior-related information encoded in the recorded neural signals and, thus, estimate the function of the implanted cortical area.

Recently, it has been shown that hand and finger kinematics are accurately encoded in the spiking activity of motor cortical neurons (Bansal et al., 2012; Saleh et al., 2012; Vargas-Irwin et al., 2010). It has also been shown that spiking activity of motor cortical neurons encodes different grip types (Mollazadeh et al., 2011). Furthermore, it has been reported that movement direction and different grip types can be reliably classified from the modulation of single unit activities preceding movement execution (Carpaneto et al., 2011; Santhanam et al., 2006;

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Townsend et al., 2011). Modulation of motor cortical firing rates related to grip aperture, grip type and grip force preceding and during grasp movements was also demonstrated (Hendrix et al., 2009).

Previous studies reported that the LFP also encodes movement kinematics, such as reaching direction (Flint et al., 2012b; Mehring et al., 2003; Rickert et al., 2005), grip types (Li et al., 2012; Mollazadeh et al., 2011), hand and finger kinematics (Bansal et al., 2012) as well as arm muscle activation during reach-and-grasp movements (Flint et al., 2012a). However, the presence of grasp-related information, in particular kinetic parameters during both movement planning and execution, has not yet been demonstrated in LFP signals recorded from motor cortical areas. In particular, the understanding of the temporal dynamics of grasp encoding in motor cortical LFPs is still lacking.

Several recent studies examined grasp-related information in motor cortical areas by investigating recordings of cortical surface potentials (electrocorticography; ECoG) in monkeys (Chen et al., 2014) and humans (Flint et al., 2014; Pistohl et al., 2012). These studies demonstrated that ECoG accurately encodes different grasp types, finger pressure forces and activity of finger muscles during the grasp execution. ECoG is thought to represent summed postsynaptic potentials originating at the cortical surface (Miller, 2010; Miller et al., 2009). Deeper cortical layers perform computation and their activity, thus, may differ from that at the surface (Leski et al., 2013). The spatial resolution of LFPs recorded with microelectrodes is adequate to analyze signals originating from deeper cortical layers without interference from surface potentials (Leski et al., 2013; Xing et al., 2009), as shown by different amounts of behavior-related information present in the LFPs recorded at different cortical depths (Markowitz et al., 2011). On the other hand, the ECoG spatial resolution is substantially lower than that of LFPs recorded with microelectrodes, which can lead to lower signal-to-noise ratio of signals originating from sparsely distributed sources. Several studies suggested that finger force representations may indeed be distributed sparsely throughout the motor cortical areas (Flint et al., 2014; Kubanek et al., 2009; Schieber and Poliakov, 1998). Furthermore, to our knowledge, a systematic assessment of force information as well as the time course of kinetic information during both preparation and execution of reach/grasp actions has not been done previously. For all these reasons, an investigation of grasp-related information collected from LFPs recorded from deeper cortical layers may provide an important advance with respect to the above mentioned previous studies.

Here, we analyzed LFP signals recorded from the motor cortex of two monkeys performing an instructed delayed reach-to-grasp task. LFP modulations were investigated in relation to two task parameters: (i) the grip type used to grasp the object and (ii) the object load. We also recorded pressure forces of thumb, index finger and middle finger while the monkey was holding the object. We demonstrate that, by using low (0.3–7 Hz bandpass filtered signal) and high (spectral amplitude in ~80–250 Hz band) frequency components of the LFPs, grip type and loading force can be classified with different levels of accuracy long before movement initiation. Additionally, we show that intended finger pressure forces applied on the object during object movement can be reliably decoded from LFP signals recorded both during the delay period of the trial and during the execution of the grasp movement. Finally, using a time-resolved analysis of decoding, we mapped the temporal evolution of the grasp-related information encoded in motor cortical LFPs.

## Methods

### *Behavioral task*

Two female macaque monkeys (L and T, 4.5 and 5.5 kg) performed an instructed and delayed object reach, grasp and pull task previously described in Riehle et al. (2013) and summarized in Fig. 1a and b. Monkey L performed the task with her left hand and monkey T with her right hand. The target object was a stainless steel parallelepiped (40 mm × 16 mm × 10 mm) mounted on a horizontal shuttle and rotated at a 45° angle from the vertical axis. The object was located about 20 cm away from the monkey. Monkeys were instructed to grasp the object using one of two distinct grips: (i) a precision grip (PG) or (ii) a side grip (SG; Fig. 1). In PG, they placed the tips of the index and the thumb in a groove on the upper and lower sides of the object, respectively. In PGs, the monkeys also placed the lateral side of the middle finger in contact with the left (monkey L) or the right (monkey T) side of the object. In SG, they placed the thumb and the lateral side of the middle finger on the opposite sides of the object while placing the index finger in the upper groove (monkey L: thumb — right; middle finger — left; monkey T: thumb — left; middle finger — right; Fig. 1c). The monkeys pulled the object towards their bodies against a high force (HF) or a low force (LF). LF and HF were imposed by a weight connected to the back side of the object (object load) hidden from the monkeys and were roughly 0.6 N and 1.6 N for monkey T and 1 N and 2 N for monkey L. Changes in weights between trials were computer controlled and were occluded from the monkeys' view. The detection of correct grip types was performed online by controlling that the pressure force applied by the thumb exceeded a 0.2 N threshold on a predefined sensor of the object. Thumb pressure force had to exceed the threshold on the bottom sensor in PG trials for both monkeys; and on the right or left sensor in SG trials for monkey L and T, respectively. Visual inspection during training sessions demonstrated that each monkey adopted a stereotyped strategy to grasp the object and that these criteria were highly reliable to classify between precision grip and side grip trials during performance of the task. In addition, monkeys were video monitored during all recording sessions to ensure that they always used the same position of the fingers in respect to the object. Force sensing resistor (FSR) covered each side of the object and were in turn covered by thin metal plates on which the monkey placed his fingers (Supplementary Fig. 1). Thin hemispheric plastic pads, 5 mm in diameter, were glued bellow the plate to transfer any force applied on the plate in a force applied at a single contact point on the FSR. This design provided a continuous measure of the pressure forces on each side of the object. In addition, a hall-effect sensor measured the horizontal displacement of the object over a maximal distance of 15 mm. The light in the room was dimmed and monkeys could see the object during the execution of the task. A square of 4 red light-emitting diodes (LEDs) with one yellow LED in the center was used to display the task instructions. To initiate a trial, monkeys had to press the home switch, positioned at waist-level, with their trained hand. After 400 ms, the yellow LED was turned on to mark the trial onset. Following another 400 ms, an informative cue, in the following called "CUE", was presented, disclosing either the grip type (grip cue task; GRIP) or the object load (force cue task; FORCE). The cue was given by illuminating two out of four LEDs. The meaning of the cue was as follows: (i) the two bottom LEDs for LF, (ii) the two top LEDs for HF, (iii) the two left LEDs for SG, and (iv) the two right LEDs for PG. The cue was presented for 300 ms and was followed by a 1 s preparatory delay period. At the end of the delay period, the go signal, in the following called "GO", provided the remaining information either about the force (in GRIP) or the grip (in FORCE) by illuminating the appropriate combination of LEDs. GRIP and FORCE conditions were tested in separate "sessions", here defined as periods during which monkeys performed the task without a pause. Thus, GRIP sessions consisted of SG/HF, SG/LF, PG/HF and PG/LF trials, while FORCE sessions consisted of HF/SG, LF/SG, HF/PG and LF/PG trials. The different trial types were presented in a randomized order. GO also served as imperative signal instructing the monkeys to release the switch and to reach and grasp the object and pull it towards them. We refer to the start of the object manipulating movement as "object movement onset". Monkeys were rewarded with a drop of mixture composed of 50% apple sauce and 50% water. To receive the reward, the monkeys had to release the switch within 1 s after the GO, grasp the object with their trained hand using the instructed grasp type, pull the object