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Research report

Rate control and quality assurance during rhythmic force tracking

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ABSTRACT

Movement characteristics can be coded in the single neurons or in the summed activity of neural populations. However, whether neural oscillations are conditional to the frequency demand and task quality of rhythmic force regulation is still unclear. This study was undertaken to investigate EEG dynamics and behavior correlates during force-tracking at different target rates. Fourteen healthy volunteers conducted load-varying isometric abduction of the index finger by coupling the force output to sinusoidal targets at 0.5 Hz, 1.0 Hz, and 2.0 Hz. Our results showed that frequency demand significantly affected EEG delta oscillation (1–4 Hz) in the C3, CP3, CPz, and CP4 electrodes, with the greatest delta power and lowest delta peak around 1.5 Hz for slower tracking at 0.5 Hz. Those who had superior tracking congruency also manifested enhanced alpha oscillation (8–12 Hz). Alpha rhythms of the skilled performers during slow tracking spread through the whole target cycle, except for the phase of direction changes. However, the alpha rhythms centered at the mid phase of a target cycle with increasing target rate. In conclusion, our findings clearly suggest two advanced roles of cortical oscillation in rhythmic force regulation. Rate-dependent delta oscillation involves a paradigm shift in force control under different time scales. Phasic organization of alpha rhythms during rhythmic force tracking is related to behavioral success underlying the selective use of bimodal controls (feedback and feedforward processes) and the timing of attentional focus on the target's peak velocity.

1. Introduction

The act of visuomotor tracking is tuned to achieve a target goal with feedback and feedforward processes. The relative significance of the two processes depends on the frequency demand of tracking, which affects the effectiveness of online use of feedback sources [36,49]. During slower tracking, under 1 Hz, the feedback process is predominant and reference tracking performance improves [36]. When the target rate increases to 2 Hz, the feedforward process of the tracking response predicts the upcoming state of a fast-moving target. Both image and invasive primate studies have shown that speed variables are scaled in the bilateral basal ganglia, sensorimotor cortices, and ipsilateral cerebellum [41,54,55], and those spatially-segregated neural elements are integral to brain oscillatory function [27,51]. Despite a lack of direct neurophysiological evidence, strategic planning for visuomotor tracking is presumably generalized to a shared model along a continuum from feedback to feedforward [44].

Strategic planning and kinematic properties of motor acts can be indexed with low-frequency cortical oscillations. The velocity information of hand movement is coded with delta-band (1–4 Hz) coupling in large-scale sensorimotor networks during a continuous visuomotor task [23,28]. Delta cortical activity of the contralateral sensorimotor cortex is also phase-locked to 3 Hz self-paced hand movements [3,4]. Alpha oscillation (8–12 Hz) is also frequently present in execution of repetitive motor responses. Alpha oscillation is rate-dependent and response-triggered during low-frequency (<2 Hz) auditory paced movement [8]. During force-tracking, superior task performance concurred with greater alpha-band power in the occipital/motor regions [22] and alpha occipitocentral coherence [40]. There are currently two hypothetical explanations for the gating of alpha rhythms in a motor task. The first is that the alpha rhythm can serve both phase transition [52] and timing of inhibitory control [24,37]. The second is that the alpha rhythm is involved in visual detection of motor error [10,53] and selective switching in mental alertness [9]. A higher alpha rhythm indicates fine task execution without intensive error commitments and arousal of awareness.

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Although the local field potential in the motor cortex [1,6,39] and cortical rhythms [23,28] has been shown to code kinematic variables, to our knowledge, no putative relationship between cortical oscillation and force behaviors has been established. It seems that the behavior contexts of force production, such as direction of force exertion, are not directly coded in single cellular activity in the motor cortex [16]. Known evidence of force control involvement with large-scale networks is that corticomuscular rhythms at the beta (13–20 Hz) and gamma rhythms (30–50 Hz) are central oscillatory drives to muscles in control of the level of force exertion during static isometric contraction [5,33,43]. In addition, Classen et al. [8] reported widespread alpha and beta coherent activities between the visual and motor cortices during a low frequency (0.2 Hz) visuomotor force-tracking task. However, it still remains unanswered how muscle force of different rates is represented by the population of cortical neurons. To this aim, the present study was conducted to investigate the cortical oscillatory activities operative for switching force rate. Next, we sought to correlate the behavioral success of force-tracking tasks with the responsible cortical rhythms. It was hypothesized that (1) rate-dependent force regulation was regulated by low-frequency delta rhythm; and (2) the task quality of force-tracking at different target rates was linked to temporo-spatial patterns of the alpha rhythm. Our findings delineate the respective roles of delta and alpha oscillations in rate control and task quality for rhythmic force production.

2. Methods

2.1. Experimental procedures and apparatus

The study was conducted in 14 healthy right-handed volunteers (7 males; 7 females; mean age 23.6 ± 1.8 years), who signed personal consent forms to protect the rights of human subjects in accordance with the Declaration of Helsinki. All subjects in this study were volunteers from a university campus and received no reimbursement.

The subjects sat comfortably on a chair with right forearm pronated and semi-flexed on a table, and the forearm and hand were fixed in a thermoplastic splint. The subjects placed their proximal interphalangeal joints of the right index fingers on the touch plate connected to a digital force gauge (sensitivity: 0.01 N, bandwidth = DC-1 kHz, Model: 9820P, AIKOH, Japan) and an analog amplifier (Model: PS-30A-1, Entran, UK). Maximal force of isometric abduction of the index finger was predetermined by averaging the maximal force of three maximal voluntary contraction (MVC) trials of 5 s separated by 3-min pauses. Subjects were asked to track a target signal by exerting force isometrically against the force gauge with the right index finger. The target signal consisted of a horizontal bar that moved sinusoidally up and down on an oscilloscope screen (screen size: 11.5 cm × 8.5 cm, Model: TDS2002, Tektronix, USA) at 0.5 Hz, 1.0 Hz, or 2.0 Hz, varied within a range of 25 ± 12.5% MVC. The visual target and force signal were displayed in a line-mode manner by setting the refresh rate (time scale) of the oscilloscope to 1 ms (Fig. 1). Subjects needed to control the vertical position of the force line on the screen while keeping their eyes on the middle point of the target and force lines to avoid horizontal eye movement. The three force-tracking protocols of different target rates were randomized for each subject. Each protocol contained ten 30-s tracking trials with a 1-min resting period between the tracking trials. Cortical activities during tracking maneuvers were recorded using a Quick-Cap Electrode Helmet and an EEG amplifier system (NeuroScan Inc., EI Paso, TX, USA). The Ag/AgCl EEG electrodes were positioned at 17 scalp positions (Fp1/2, Fz, F3/4, FCz, FC3/4, Cz, C3/4, CPz, CP3/4, Pz, P3/4) according to the 10–20 International System. The ground electrode was placed along the midline ahead of Fz. Eye movements and blinks were monitored by

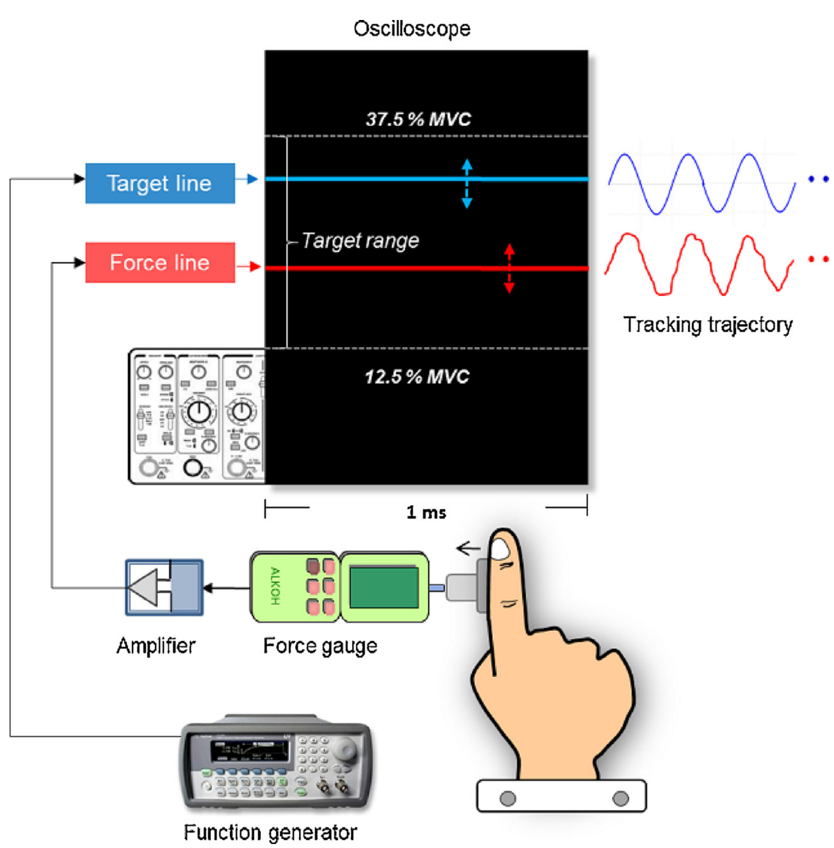

Fig. 1. Diagram of experimental setup and schematic illustration of the target and force exertion lines.