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EEG during pedaling: Evidence for cortical control of locomotor tasks

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HIGHLIGHTS

- Pedaling produces slow changes in brain potentials with a frequency of double the pedaling frequency, correlated with transition muscle activity.
- Pedaling results in beta desynchronization in scalp regions associated with motor activities.
- There are differences in brain potentials associated with active and passive pedaling.

ABSTRACT

Objective: This study characterized the brain electrical activity during pedaling, a locomotor-like task, in humans. We postulated that phasic brain activity would be associated with active pedaling, consistent with a cortical role in locomotor tasks.
Methods: Sixty four channels of electroencephalogram (EEG) and 10 channels of electromyogram (EMG) data were recorded from 10 neurologically-intact volunteers while they performed active and passive (no effort) pedaling on a custom-designed stationary bicycle. Ensemble averaged waveforms, 2 dimensional topographic maps and amplitude of the β (13–35 Hz) frequency band were analyzed and compared between active and passive trials.
Results: The peak-to-peak amplitude (peak positive–peak negative) of the EEG waveform recorded at the Cz electrode was higher in the passive than the active trials ($p < 0.01$). β-band oscillations in electrodes overlying the leg representation area of the cortex were significantly desynchronized during active compared to the passive pedaling ($p < 0.01$). A significant negative correlation was observed between the average EEG waveform for active trials and the composite EMG (summated EMG from both limbs for each muscle) of the rectus femoris ($r = -0.77, p < 0.01$) the medial hamstrings ($r = -0.85$, $p < 0.01$) and the tibialis anterior ($r = -0.70$, $p < 0.01$) muscles.
Conclusions: These results demonstrated that substantial sensorimotor processing occurs in the brain during pedaling in humans. Further, cortical activity seemed to be greatest during recruitment of the muscles critical for transitioning the legs from flexion to extension and vice versa.
Significance: This is the first study demonstrating the feasibility of EEG recording during pedaling, and owing to similarities between pedaling and bipedal walking, may provide valuable insight into brain activity during locomotion in humans.

1. Introduction

In humans, the cerebral cortex may play an important role in the control of locomotor function. The role of the cortex may be particularly strong in humans since a unique characteristic of human locomotion, in comparison to other primates, is 'habitual bipedalism with the trunk and head in an erect posture' (reviewed in (Schmitt, 2003)). This type of locomotion has provided humans with a distinct evolutionary advantage over other animals by freeing the upper limbs during locomotion, and significantly decreasing the energy cost of walking (Sockol et al., 2007). However, it has also made the task of walking more complex and possibly more dependent on corticospinal function for humans, compared to low-

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er animals (reviewed in (Nielsen, 2003)). Consequently, in contrast to lower animals (rats, (Little et al., 1988) cats, (Rossignol et al., 2004) rabbits (Lyalka et al., 2005)), and non human primates (Courtine et al., 2005; Babu and Namasivayam, 2008), disruption of supraspinal control, as in stroke (Kelly-Hayes et al., 2003) or spinal cord injury (Dobkin et al., 2007), more severely impairs locomotion in humans (reviewed in (Rossignol, 2000)). Thus, characterization of the cortical contribution to locomotor control in humans is important to understanding the pathophysiology of impaired locomotion after an injury to the central nervous system.

Assessing the cortical contribution to locomotor control in humans is challenging due to difficulties in quantifying brain activity during walking. Walking generates head movement and requires the subject to be erect and moving in space, with minimal constraints. In order to circumvent these problems, brain activity has been recorded during conditions that differ from actual walking. Approaches have included recording brain activity immediately after walking (Fukuyama et al., 1997), during imagined walking (Deutschlander et al., 2009; Bakker et al., 2008; Iseki et al., 2008; Wagner et al., 2008), during movement of a single lower extremity joint (Dobkin et al., 2004; Sahyoun et al., 2004; Ciccarelli et al., 2005) and during pedaling a stationary bicycle (Mehta et al., 2009; Christensen et al., 2000). Pedaling was used in the current study because it involves actual movement of the legs, which generates sensory feedback, and the reciprocal, cyclical nature of the task is similar to walking.

Previous measurements of brain activity during pedaling have been limited to techniques that are dependent on hemodynamic/metabolic responses, which have restricted the temporal resolution of the data. For example, brain activity has been measured during pedaling using positron emission tomography (PET) (Christensen et al., 2000) and functional magnetic resonance imaging (fMRI) (Mehta et al., 2009), both of which indicate that primary cortical structures are active during pedaling. Since both fMRI and PET are based on hemodynamic/metabolic responses, temporal resolution necessary to ascertain the timing of the brain activity relative to the pedaling cycle is still unknown, as the pedaling cycle is shorter than the hemodynamic response function. Consequently, the use of electroencephalography (EEG) to monitor cortical activity during pedaling is appealing, since EEG is noninvasive and has the capability of high time resolution.

In order to characterize cortical activity during a locomotor-like task, high density (64 channels) EEG measurements were made while ten young healthy adults pedaled a stationary bicycle. We hypothesized that EEG would demonstrate brain activation over anatomically appropriate scalp regions, i.e. over the expected leg representation area of the sensorimotor cortex, with different patterns of activation during active vs. passive pedaling. Further, a correlation between the EEG activity over these regions of the brain and activity of the leg muscles was expected.

2. Methods

2.1. Study participants

Ten young, healthy, neurologically intact individuals who were comfortable pedaling for half an hour participated in this study (age 22–32 years, median 26 years). The study protocol was approved by the Institutional Review Board of Marquette University, Milwaukee, Wisconsin. Written informed consent was obtained from all subjects prior to participation in the study.

2.2. Pedaling device

The pedaling device and acquisition of crank position data has been described previously (Schindler-Ivens et al., 2008). Briefly, a custom-designed stationary bicycle with a rigid, reclined backboard was used as the pedaling device (Fig. 1). The backboard supported the subject's head and trunk during pedaling, thus reducing movement and neck EMG artifacts in the EEG recordings. An optical encoder (BEI Technologies Inc., Goleta, CA) coupled to the crankshaft via a chain and sprocket assembly was used for digitizing the angular position of the pedals. The digital signal from the optical encoder was converted to an analog signal using a digital to analog converter before sampling by the main data acquisition computer.

2.3. EEG and EMG recording systems

The QuikCap electrode cap (Compumedics Neuroscan, El Paso, TX) was used for EEG electrode placement. The stretchable electrode cap contained 64 sintered Ag–AgCl electrodes arranged according to the modified combinatorial system of electrode placement (American Clinical Neurophysiology Society, 2006). The reference electrode was positioned near the vertex between the Cz and CPz electrodes and the ground electrode was located over the frontal area of the scalp, between the Fz and FPz electrodes. The Ag–AgCl electrodes were located within small receptacles on the scalp side of the cap, which housed sponge-backed felt discs. The electrodes were connected to the EEG amplifier via a headbox, and the headbox was connected to a high input impedance Synamps^2 amplifier (Compumedics Neuroscan). Before each recording, disposable sponge discs were inserted into the electrode receptacles and the QuikCap was secured to the subject's head with a chin strap. The sponge discs were hydrated with about 0.2 ml of a proprietary electrolyte solution (Compumedics Neuroscan) which then expanded to make contact with the scalp. Electrode impedances were decreased by additional incremental hydration and maintained below 10 kΩ. The electrodes were connected to the Synamps^2 EEG amplifier (Compumedics Neuroscan), which in turn, was connected to a PC for data acquisition.

EMG was recorded bilaterally using bipolar skin electrodes (10 mm length, 1 mm width, 1 cm inter-electrode distance, DelSys, Inc., Boston, MA) from the Soleus (SOL), Vastus Medialis (VM), Tibialis Anterior (TA), Medial Hamstrings (MH) (approximately over the semimembranosus muscle belly) and the Rectus Femoris (RF) muscles. EMG signals were pre-amplified 10× at the electrode site. Remote differential amplification at 1000× was done using an EMG amplifier system (DelSys Bagnoli-8 EMG System, DelSys, Inc.) with a common mode rejection ratio of 92 dB and a frequency bandwidth of 20–450 Hz. This amplifier was connected to a PC via a 16 bit A/D converter (Micro 1401 mk(II), Cambridge Electronic Design, Cambridge, England) for acquiring the EMG signals.

2.4. Experimental protocol

Subjects were seated on the cushioned seat of the stationary bicycle, with their back reclined on the rigid backboard. The subject's trunk was snugly strapped to the rigid backboard and the head was placed on a bead-filled pillow for stabilization. Each subject performed active and passive pedaling in a single experimental session. During pedaling, whenever the crank rotated through the top dead center position of the right leg (TDC; right leg completely flexed and left leg completed extended (Raasch and Zajac, 1999), a 10 V pulse was generated by the optical encoder. This pulse was routed to the EEG and EMG recordings to track the start of every pedaling cycle.

(i) *Active pedaling:* For active trials, subjects were asked to pedal forward at a comfortable speed. The eyes were closed to minimize eye movements and blink artifacts and to prevent any visual feedback of the pedaling speed and leg position. Subjects were instructed to pedal at a slow, comfortable rate. No effort was made