Cortical Control of Human Motoneuron Firing During Isometric Contraction

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Salenius, Stephan, Karin Portin, Matti Kajola, Riitta Salmelin, and Riitta Hari. Cortical control of human motoneuron firing during isometric contraction. J. Neurophysiol. 77: 3401 ± 3405, 1997. We recorded whole scalp magnetoencephalographic (MEG) signals simultaneously with the surface electromyogram from upper and lower limb muscles of six healthy right-handed adults during voluntary isometric contraction. The 15- to 33-Hz MEG signals, originating from the anterior bank of the central sulcus, i.e., the primary motor cortex, were coherent with motor unit firing in all subjects and for all muscles. The coherent cortical rhythms originated in the hand motor area for upper limb muscles (1st dorsal interosseus, extensor indicis proprius, and biceps brachii) and close to the foot area for lower limb muscles (flexor hallucis brevis). The sites of origin corresponding to different upper limb muscles did not differ significantly. The cortical signals preceded motor unit firing by 12–53 ms. The lags were shortest for the biceps brachii and increased systematically with increasing cortico-muscular distance. We suggest that the motor cortex drives the spinal motoneuronal pool during sustained contractions, with the observed cortical rhythmic activity influencing the timing of efferent commands. The cortical rhythms could be related to motor binding, but the rhythmic output may also serve to optimize motor cortex output during isometric contractions.

INTRODUCTION

Control of voluntary muscle movements is accomplished by a smooth cooperation of several neural systems, including the spinal cord, brain stem, basal ganglia, cerebellum, primary motor cortex, and premotor cortices. All neural activity related to both reflex and voluntary actions ultimately converges onto the spinal motoneuron pool, which represents the Sherringtonian “final common pathway.” During voluntary muscle contraction motor units tend to discharge rhythmically and synchronously at frequencies of 16–32 Hz, possibly paced by supraspinal input (Datta et al. 1991; Farmer et al. 1993a,b), whereas cortical sensorimotor rhythmic activity is generally attenuated (“desynchronized”) by movements (Chatrian et al. 1959; Pfurtscheller and Aranibar 1979; Salmelin and Hari 1994). However, the view that cortical rhythms are entirely suppressed during cortical activation has been challenged (Munk et al. 1996; Steriade et al. 1996). In fact, it was recently discovered that motor units and cortical neurons fire synchronously during sustained contractions (Conway et al. 1995) and slow movements (Salenius et al. 1996) of hand muscles. In the present study, we investigated, by means of whole scalp magnetoencephalography (MEG), the relation between human cortical rhythms and motor unit activity, to elucidate cortical control of voluntary contractions of upper and lower limb muscles. MEG reflects post-synaptic currents flowing mainly in the fissural cortex. It allows noninvasive monitoring of cortical activity with a reasonable spatial accuracy while maintaining an excellent temporal resolution (Hämäläinen et al. 1993).

METHODS

Six healthy right-handed subjects (3 females, 3 males; 22–34 yr) upheld isometric contraction for 4–5 min in a hand muscle (1st dorsal interosseus), in more proximal upper limb muscles (extensor indicis proprius or biceps brachii), or in a foot muscle (flexor hallucis brevis), in different runs for right and left side. The contraction force was optimized for each muscle and, to a smaller extent, for each individual, to reveal distinct motor unit potentials in the electromyogram (EMG). The strength was very weak (near the contraction threshold) for the interosseus muscle, medium for the foot and index finger extensor muscles, and strong for the biceps muscle. Informed consent was obtained from all subjects before the experiments. Cortical signals were recorded with a whole scalp neuromagnetometer in a magnetically shielded room simultaneously with surface EMG from the contracting muscle. The subject supported the head against the helmet-shaped bottom surface of a Neumag-122 magnetometer (Ahonen et al. 1993). MEG and EMG signals were recorded with passbands of 0.03–330 Hz and 3–300 Hz, respectively, digitized at 1 kHz, and stored on magneto-optic disks for off-line analysis. The exact position of the head with respect to the sensor array was determined by measuring magnetic signals from three indicator coils placed on the scalp. The coil locations, with respect to three predetermined landmarks on the skull, were identified with a three-dimensional digitizer, and this information was used to superimpose sources for the MEG signals on individual magnetic resonance images obtained with a 1-T Siemens Magnetom device.

Coherence spectra between MEG and rectified EMG were calculated with a frequency resolution of 1 Hz and averaged over 4–5 min of sustained contraction. To establish the significance of the observed peaks in the coherence spectra, we estimated the noise by calculating the variation of coherence amplitudes with the EMG signal shifted by 1 s (and any true coherence thereby abolished). The amplitudes of these random coherences remained below the significance level (Fig. 1, dashed lines) at 99% probability. For all muscles the coherence clearly exceeded the estimated significance level in the 15- to 33-Hz range.

Sources of oscillatory signals were modeled in time domain as equivalent current dipoles (Hämäläinen et al. 1993), found by a least-squares search of the distribution of the MEG-triggered averaged signals. The planar gradiometers in our whole scalp magnetometer show the largest signal above the cortical source current; thus the source identification could be restricted to sets of 40 detectors centered over the rolandic area in each hemisphere, well covering the signal extrema. The locations, orientations, and strengths of the equivalent current dipoles were determined at 1-ms intervals (~100–100 ms); only sources that accounted for >85% of the field variance were accepted.
RESULTS

At rest, the rolandic MEG was dominated by rhythmic activity around 10 and 20 Hz. During isometric contraction, the 10-Hz activity diminished and the 20-Hz activity almost disappeared.

Figure 1A shows EMG and the simultaneously recorded MEG above the motor cortex. Both signals are periodic with a frequency of ~20 Hz. The coherence spectra between rectified EMG and MEG (Fig. 1B) show distinct peaks close to 20 Hz for both hand and foot muscle contractions. Small peaks at corresponding frequencies were discerned in the MEG spectrum. The coherence is spatially restricted, revealing cortical activity coherent with EMG close to the contralateral central sulcus: near the interhemispheric fissure for foot muscles and more laterally for hand muscles.

To define the exact temporal relation between the cortical and muscular signals, MEG was averaged with respect to onsets of motor unit potentials in the EMG. The averaged MEG signals (Fig. 1D) show clear periodicity, and the strongest upward MEG deflection occurs 23–25 ms earlier for foot than hand muscles.

The peak frequencies of the coherence ranged from 15 to 33 Hz in different subjects and for different muscles (20.7 ± 0.7 Hz, mean ± SE), with peak widths of 5–12 Hz (Fig. 1). Occasionally, another distinct but smaller coherence peak was discerned at 7–11 Hz or, less frequently, at 35–40 Hz. In all subjects and for all muscles the MEG-EMG coherence was statistically significant, with the coherent frequency independent of the moving muscle.

Source modeling indicated that the coherent cortical activity originates, in all subjects, in the motor cortex (Brodman’s area 4) in the posterior bank of the precentral gyrus (Fig. 2). Source currents corresponding to upper limb mus-
Figure 3 summarizes the mean time lags between the averaged MEG and EMG signals for all muscles. The lag was consistent over subjects and for each muscle, and it changed systematically with increasing distance from cortex to the muscle, ranging from $12 \pm 1$ ms for biceps to $52 \pm 1$ ms for flexor hallucis brevis. Time lags were determined from EMG-triggered averages of cortical signals; during the main MEG deflection the current was directed from deep to superficial layers of the cortex. As an alternative approach, cross-correlograms were obtained in the time domain by applying an inverse Fourier transform to the averaged coherence spectrum. The cross-correlograms showed the same latency trend as the EMG-triggered averages, but they are inherently very sensitive to changes in the signal waveforms, and may thus be influenced, e.g., by the size of the sampled motor units, contraction strength, and muscle temperature. For example, cooling of the skin above the interosseus muscle by 15°C before the isometric contraction increased the latency measured from the cross-correlograms by 7–10 ms. This change in latency, not visible in the EMG-triggered averaged MEG, may be accounted for by the increased duration of the motor unit action potential in the cooled muscle.

Two subjects performed, in a separate session, simultaneous contractions of two muscles: the interosseus muscles bilaterally, one upper limb and one foot muscle (right index finger extensor and hallucis brevis), and two upper limb muscles (right index finger extensor and interosseus). For the two hand muscles, the EMGs were coherent at frequencies corresponding to the coherence with the cortical signals. For the other muscles, no EMG-EMG coherence was observed although the MEG-EMG coherence occurred at overlapping frequencies.

**DISCUSSION**

The gross somatotopic configuration of the coherent rhythms in the 15- to 33-Hz range resembles the source sites of rolandic 20-Hz bursts following voluntary movements of index fingers, toes, and mouth (Salmelin et al. 1995). Despite the clear distinction between source areas related to hand and foot muscles, the mean source locations for the three upper limb muscles did not differ significantly from each other. This result is consistent with the emerging view that hand and finger movements are represented by distributed, multifocal, and extensively overlapping networks that share neural circuitry with proximal upper limb movements (Hyde et al. 1995; Sanes et al. 1995; Schieber and Hibbard 1993). This contrasts with the classical notion of discrete, adjacent motor representations for different parts of the hand and arm (Penfield and Rasmussen 1950).

The MEG-EMG coherence may be produced by small local generators in the motor cortex, which could influence both the timing of the motor cortex output and the extracranially measured magnetic fields. The observed rhythmic MEG activity could reflect unification, binding together, of neurons into temporary ensembles that control the contraction of a specific muscle. Cortical neurons may intermittently associate in functional groups by modifying their coupling to other neurons, which is reflected in more correlated firing but not necessarily in changed mean firing rate (deCharms and Merzenich 1996; Vaadia et al. 1995). The correlation

![Diagram of hand and foot muscles](image-url)
found between firing of the two muscles acting on the index finger (index finger extensor and interosseus) could reflect branched input to the motor units from pyramidal tract neurons, and agrees with the synchronization observed for motor units from different muscles (Bremner et al. 1991). Whether the corresponding cortical rhythms serve to integrate distributed cortical activity controlling complex movements remains an open question.

Because the frequency of the coherent cortical rhythms did not depend on the corticomuscular distance, it seems implausible that the periodic activity is generated by a feedback loop between the periphery and the CNS. On the contrary, the cortical rhythm may serve as a modulatory signal that would periodically facilitate the firing of motor cortical efferents. The cortical output neurons, and the motor units, could fire at a rate different from the modulatory signal (and thus the cortical rhythm) and also change their firing rates independently of this signal. The influence of the modulatory, periodically facilitating signal could still be discernible in the surface EMG, which reflects the activity of a small population of motor units. The rhythmic output of the motor cortex could enable precise coordination of muscle activity needed, e.g., to generate the rhythmic structure of voluntary movements (Vallbo and Wessberg 1993; Wessberg and Vallbo 1996).

On the other hand, repetitive stimulation of motoneurons through corticospinal fibers results in gradually increasing amplitudes of excitatory postsynaptic potentials (Porter and Lemon 1993). This facilitation of corticomotoneuronal excitation is strong for short interspike intervals (<10 ms), partly because of temporal summation of successive responses. However, the facilitation is, unexpectedly, strong also at interspike intervals of 40–60 ms, corresponding to frequencies of 16–25 Hz. Therefore a rhythmic 20-Hz drive may serve to optimize motor cortex output during isometric contractions, producing maximum motoneuronal activation at minimum pyramidal tract discharge.

The cortex-muscle time lags for foot and hand (interosseus) muscles differed by 21 ± 1 ms, in good agreement with the corresponding differences in conduction times. However, the differences between the interosseus and the index finger extensor muscle (10 ± 1 ms), and between the
index finger extensor and biceps muscle (9 ± 1 ms), were about twice the differences predicted from conduction velocities of the fastest-conducting fibers. These latency discrepancies could, at least in part, be due to the stronger conduction force exerted with the index finger extensor and biceps brachii than with the interosseous muscle, associated with activation of larger motor units with fast-conducting nerve fibers.

In a recent MEG study, resting tremor (3–6 Hz) of parkinsonian patients was found to be coherent with oscillatory activity of the premotor and sensorimotor cortices (Volkmann et al. 1996). The coherence was interpreted to result from transmission of abnormal rhythmic activity, possibly from thalamus, to the periphery via the motor cortex. The faster coherent rhythms observed in the present study could obviously also be related to thalamic activity. On the other hand, the cerebellum might entrain firing of motor neurons (Welsh et al. 1995); interestingly, the human cerebellum displays a somatotopic motor representation without evidence for within-limb functional segregation (Nitschke et al. 1996), thus resembling our data on the within-limb coherence clusters.

Our results thus suggest that the motor cortex, known to be involved in the initiation and alteration of movements, also influences the timing of motor units during maintained contraction. Cortical neuronal ensembles appear to form oscillatory somatotopic networks that drive the final output level of the nervous system, the spinal motoneuronal pool, with a characteristic frequency.

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REFERENCES


