Self-paced movements induce high-frequency gamma oscillations in primary motor cortex

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There has been increasing interest in the role of high-frequency (>30 Hz) cortical oscillations accompanying various sensorimotor and cognitive tasks in humans. Similar “high gamma” activity has been observed in the primary motor cortex, although the role of this activity in motor control is unknown. Using whole-head MEG recordings combined with advanced source localization methods, we identified high-frequency (65 to 80 Hz) gamma oscillations in the primary motor cortex during self-paced movements of the upper and lower limbs. Brief bursts of gamma activity were localized to the contralateral precentral gyrus (MI) during self-paced index finger abductions, elbow flexions and foot dorsiflexions. In comparison to lower frequency (10–30 Hz) sensorimotor rhythms that are bilaterally suppressed prior to and during movement (Jurkiewicz et al., 2006), high gamma activity increased only during movement, reaching maximal increase 100 to 250 ms following EMG onset, and was lateralized to contralateral MI, similar to findings from intracranial EEG studies. Peak frequency of gamma activity was significantly lower during foot dorsiflexion (67.4 ± 5.2 Hz) than during finger abduction (75.3 ± 4.4 Hz) and elbow flexion (73.9 ± 3.7 Hz) although markedly similar for left and right movements of the same body part within subjects, suggesting activation of a common underlying network for gamma oscillations in the left and right motor cortex. These findings demonstrate that voluntary movements elicit high-frequency gamma oscillations in the primary motor cortex that are effector specific, and possibly reflect the activation of cortico-subcortical networks involved in the feedback control of discrete movements.

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with implanted subdural electrode grids using movements of various body parts (based on grid location), showing somatotopically specific increases in the 76–100 Hz frequency band during continuous movements in comparison to resting state (Miller et al., 2007). ECoG studies have also shown evidence of corticomuscular coherence within the gamma band including frequencies above 60 Hz (Marsden et al., 2000). Thus, invasive recordings in humans have shown frequent evidence of gamma oscillations in cortical motor areas, although the precise localization of the generators of this activity has been limited to information derived from depth electrodes or subdural recordings in or near motor areas in surgical patients. Movement-related gamma activity has been reported in scalp EEG recordings (Shibata et al., 1999) although EEG studies of gamma activity are hampered by the limited ability to localize the underlying generators, and the potential contamination of high-frequency EEG signals by muscle activity. A number of recent MEG studies have also reported gamma band activity in the 30 to 120 Hz range during various cognitive and sensorimotor tasks. Increases in corticomuscular coherence in the 40 to 60 Hz band were observed in MEG signals overlying the motor cortex during preparation to respond to a visual stimulus (Schoffelen et al., 2005). Increased high (61 to 90 Hz) gamma activity during a maintained isometric contraction task was localized to the hand motor cortex using a novel MEG source modeling approach (Tecchio et al., 2008) and a recent study reported increased power in the 62 to 87 Hz frequency band in MEG sensors overlying the contralateral sensorimotor cortex when subjects moved a joystick in self-selected directions to a visual cue (Waldert et al., 2008).

Although a number of studies using non-invasive EEG and MEG methods have reported both changes in power and coherence in the higher gamma frequency range within or overlying cortical motor areas during tasks that involve visuomotor control or sensorimotor coordination, there have been relatively few studies examining changes in the high gamma band during simple self-paced movements. Previous studies have reported changes in either spectral power, or in corticomuscular coherence (with or without concomitant increases in spectral power) over variable duration time windows encompassing either periods of continuous muscular contraction, motor preparation, or both. In addition, the terms ‘gamma’ and ‘high gamma’ are used somewhat inconsistently with regard to the specific frequency range of analysis, or choice of on-line filter settings, making it difficult to compare results across studies. In contrast, intracranial EEG studies have shown increases in spectral power the 70 to 80 Hz range, and specifically during movement execution rather than movement preparation (Brovelli et al., 2005; Pfurtscheller et al., 2003). This raises questions regarding the role of somatosensory or proprioceptive feedback in eliciting high gamma band oscillations in sensorimotor regions during tasks that involve motor responses, and their relationship to frequency changes in other brain areas as the result of sensory input. For example, Bauer and colleagues reported increased gamma activity in the primary somatosensory cortex during simple tactile stimulation (Bauer et al., 2006). Taken together, these findings would predict the presence of high-frequency gamma oscillations in either motor or somatosensory areas during any task involving simple transient movements, although the question remains whether such high-frequency gamma activity reflects cognitive aspects of motor preparation or control, or may be simply related to the preparation or execution of discrete movements.

Neuromagnetic recordings combined with recently developed spatial filtering methods based on beamforming algorithms provide a new non-invasive tool for the precise localization of oscillatory brain activity (Hillebrand and Barnes, 2005). We recently demonstrated the localization of movement-related beta and mu band activity to specific regions of the precentral and postcentral cortex in humans using these methods (Jurkiewicz et al., 2006). In the present study, we demonstrate that simple, self-paced movements of the upper and lower limbs in humans are accompanied by a characteristic narrow band burst of high-frequency (65 to 80 Hz) gamma activity and that this activity can be localized to somatotopically specific regions of the primary motor cortex using whole-head MEG recordings and beamformer source analysis.

Materials and methods

Subjects

Nine healthy, right-handed adult subjects (four male, mean age 32, range: 21–47) without prior history of neurological illness participated in the experiment. Informed consent was obtained from all subjects using protocols approved by the Toronto Hospital for Sick Children Research Ethics Board.

Motor tasks and procedure

Neuromagnetic activity was recorded from subjects while they performed self-paced abductions of the left or right index finger; flexions of the left or right elbow (bicep contractions) and dorsiflexions of the left and right foot. Subjects performed all movements while laying supine on a bed with eyes open and fixated. During index finger movements the subject’s arms were held at their side fully pronated. For elbow flexions the subject’s arms were held supine and extended slightly outwards supported by an armrest and during foot dorsiflexions padding was placed under the subject’s knee to minimize body and head movements. Prior to recordings, subjects practiced making brisk self-paced movements of each body part from rest. For arm and foot movements, subjects were instructed to make small amplitude movements to minimize head movement. Movements were performed once every 3–4 s in separate blocks of 400 s duration (100 to 130 movements per block). Three fiducial localization coils placed at the nasion and preauricular points localized the position of the subject’s head relative to the MEG sensors. Digital photographs of coil placement aided the co-registration of MEG data to each subject’s structural MRI. Head position was recorded by the MEG system before and after each movement condition to ensure that head movements did not exceed 5 mm over the duration of the recording. Movement onset was determined from bipolar surface electromyographic (EMG) record-ings from the left and right first dorsal interosseus, left and right biceps brachii, and left and right tibialis anterior muscles.

Data acquisition

Neuromagnetic activity was recorded during the motor tasks using a whole head 151-channel CTF MEG system (VSM MedTech Ltd) located inside a magnetically shielded room. Both MEG and EMG signals were recorded simultaneously using continuous data acquisition at a sample rate of 625 samples/s with an on-line bandpass of 0 to 200 Hz. EMG signals were band-pass filtered off-line from 15 to 200 Hz and full-wave rectified. EMG onsets were marked using an automated algorithm that detected increases in the rectified EMG signal above baseline by 3 standard deviations, reaching peak amplitude (2.5 threshold) within a 400 ms time window, and then visually

inspected for false positives. Two-second epochs (1.5 s preceding and 0.5 s following EMG onset) time-locked to EMG onset were then extracted from the continuous data for further analysis ensuring that there were at least 2 s between individual EMG bursts. For signal modeling and anatomical co-registration, T1-weighted structural MR images (3D SPGR) were obtained for each subject using a 1.5 T Signa Advantage system (GE Medical Systems, Milwaukee, WI, USA).

**Beamformer source analysis**

A spatial filtering algorithm based on minimum-variance beamforming (Robinson and Vrba, 1999; Van Veen et al., 1997) was used to localize neural activity in specific frequency bands over the entire brain. We used a scalar minimum-variance beamformer algorithm that estimates a single optimal current orientation at each voxel. This orientation is obtained by first computing a vector beamformer with two orthogonal dipole sources at each location; the dominant orientation is then given by the eigenvector associated with the maximum eigenvalue of the vector beamformer output integrated over all data segments (Cheyne et al., 2007; Sekihara et al., 2004). Changes in source power between and active and baseline time windows were computed using the pseudo-\(t\) statistic, similar to the Synthetic Aperture Magnetometry (SAM) algorithm (Robinson and Vrba, 1999). Beamformer weights were based on covariance estimates derived from all single trial epochs after bandpass filtering to the frequency range of interest. For the forward model, a multiple sphere conductor model (Huang et al., 1999) was used based on an inner skull surface mesh derived from each subject's MRI using the FSL BET2 and BETSURF tools (Jenkinsen et al., 2004; Smith, 2002), with corrections for 3rd order gradient noise reduction and volume currents. We have described the application of this method to the localization of sensorimotor rhythms in the mu and beta frequency bands in a previous report (Jurkiewicz et al., 2006). The scalar beamformer algorithm also provides single-trial source activity waveforms for each voxel in the reconstructed source images, allowing for the time–frequency analysis of changes in spectral power at specific 225 locations of interest in the brain over the entire pre- and post- movement interval.

Localization of gamma band activity in the current study was performed as follows. In an initial exploratory analysis of the data, voxel locations of functional areas of the primary motor cortex were identified. The scalp beamformer algorithm also provides single-trial source activity waveforms for each voxel in the reconstructed source images, allowing for the time–frequency analysis of changes in spectral power at specific locations of interest in the brain over the entire pre- and post- movement interval.

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**Fig. 1. Movement-related brain activity and analysis of gamma band activity in a single subject performing left index finger abductions.** (a) MEG trace from a sensor overlying the right motor cortex (channel MRC13, bandpass: 1 to 30 Hz) and rectified EMG activity (bandpass: 15–200 Hz) recorded from the left 1st dorsal interosseous muscle (0 s = EMG onset) showing typical motor field and movement-evoked fields in the averaged data relative to movement onset. Shaded rectangles show the time windows used in the estimation of changes in source activity during the post-movement interval (0 to 300 ms) relative to the pre-movement baseline (−1.3 to −1 s). Below is the topographic plot of increased RMS amplitude (red colours) over the head (nose upwards) summed over all single trials and samples for the 0 to 300 ms (active) time window relative to the baseline window. (b) Time–frequency plot showing increases (red) and decreases (blue) in source activity over all trials derived from a beamformer spatial filter in the right precentral gyrus in units of percent change above the pre-movement baseline. A brief burst of post-movement gamma band activity centered around 70 Hz is indicated by the red arrow. The beamformer reconstruction of increased source power in the 60 to 90 Hz range during the 0 to 300 ms post-movement time period is shown projected onto the 3-dimensional rendered image of the MNI (CH) template brain (Collins et al., 1994) using the mri3dx program (http://imaging.aston.ac.uk/mri3dX/index.shtml) revealing localization to the contralateral precentral gyrus.

Fig. 2. Time–frequency plots for source activity from peak locations in the contralateral primary motor cortex for individual subjects for left and right index finger abductions. Red and blue colours indicate increases and decreases, respectively, in units of normalized source power (pseudo-β). The vertical line (0 ms) indicates EMG onset.

Source power - contralateral MI

Left index

Right index

Average

Left index

Right index
were identified for the peak of the motor field accompanying movement onset for different movements using an event-related beamformer algorithm (Cheyne et al., 2006). Single trial source activity waveforms were derived for these locations, and time–frequency plots of source power activity over the entire pre- and post-movement interval, integrated over all trials, computed using a Morlet wavelet transform (Tallon-Baudry et al., 1996) over the entire frequency range of 2 to 110 Hz. Source power was plotted as percentage increase above baseline to account for non-linear decreases in power with increasing frequency. This revealed both the expected suppression of mu and beta band activity prior to and during each movement, as well as a marked increase in signal power in the high gamma band with a peak frequency ranging from about 60 to 90 Hz and approximately 200 to 300 ms in duration, typically beginning within the first 100 ms following EMG onset. Based on these observations we computed differential (pseudo-t) source power images over the entire brain at a spatial resolution of 2.5 mm, using a frequency window of 60 to 90 Hz and a time window of 0 to 300 ms following EMG onset to optimally image these brief periods of increased gamma power, relative to a pre-movement baseline of −1.3 to −1 s prior to EMG onset. This baseline was chosen to precede onset of pre-movement activity that typically began between 1 to 0.5 s prior to EMG onset and avoid any remaining effects of preceding movements, although it was noted that no significant power changes were observed in the high gamma range during the entire pre-movement period. Single trial source activity waveforms were then computed for the locations corresponding to peak gamma activity detected in the volumetric source images in individual subjects, and the time–frequency analysis recomputed. This revealed no significant changes in the timing of the gamma band activity and no further adjustments of the analysis time or frequency windows were made. Beamformer source analysis was thus performed using a fixed time window (0–300 ms) and frequency range (60–90 Hz) for all movement conditions. We then identified locations of peak high gamma in individual subjects and used these locations to recompute time–frequency plots in each subject. Time–frequency plots for peak voxels were also averaged across subjects.

### Group analysis

In order to combine source localization results across subjects, pseudo-t source images co-registered to each individual subject’s MRI were spatially normalized to the MNI (T1) template brain using SPM2 (Welcome Institute of Cognitive Neurology, London, UK). Linear and non-linear warping parameters were obtained from each individual's T1-weighted structural image and used to warp source images to a standardized stereotactic (MNI) space prior to averaging across subjects. Significant peaks of activity in the group images were identified after thresholding images using a non-parametric permutation test (Nichols and Holmes, 2002) adapted for differential beamformer source imaging (Singh et al., 2003). Talairach coordinates of peak activations were determined from the normalized images using the MNI to Talairach conversion daemon (Lancaster et al., 2000).

### Results

#### Time–frequency analysis of movement-related gamma activity

Fig. 1 shows an example of the data analysis results for the localization of gamma oscillatory activity in one subject performing left index finger abductions. This shows the expected motor field and field-evoked field components (Kristeva et al., 1991) at 288 latencies of −25 ms and 62 ms with respect to EMG onset, respectively in the averaged data. However, a topographic plot of the RMS amplitude of the MEG signals in a 60 to 90 Hz bandwidth shows a dipolar like reversal over the right motor cortex. The RMS amplitudes of these field maxima are relatively small (corresponding to peak-to-peak amplitudes of less than 30 μT) and it should be noted that these were not clearly discernable in the topographic plots for all subjects. Fig. 1(b) shows the beamformer source localization for the high gamma activity in the same subject. The upper plot shows the time–frequency plot of changes in source activity in units of percent change computed at the peak voxel location in the differential beamformer image corresponding to the contralateral (right) primary motor cortex. At the lower frequency range (around 20 Hz) prolonged decreases in spectral power can be seen throughout the pre- and post-movement period.

#### Table 1

<table>
<thead>
<tr>
<th>Subject</th>
<th>Peak frequency (Hz)</th>
<th>Bicep contraction</th>
<th>Foot dorsiflexion</th>
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<td>1</td>
</tr>
<tr>
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<td>73</td>
<td>1</td>
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<td>74.8</td>
<td>75.9</td>
<td>−1.1 *</td>
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<td>(4.2)</td>
<td>(4.8)</td>
<td>(2.8)</td>
</tr>
<tr>
<td>t1.17</td>
<td>Left+Right</td>
<td>Left+Right</td>
<td>Left+Right</td>
</tr>
<tr>
<td>t1.18</td>
<td>75.3</td>
<td>73.9</td>
<td>0.81 **</td>
</tr>
<tr>
<td>t1.19</td>
<td>(4.4)</td>
<td>(3.7)</td>
<td></td>
</tr>
</tbody>
</table>

*no significant differences were found between left and right movements (paired t-test).

**significant difference between foot and index, and between foot and bicep (p<0.001).

Fig. 3. (a) Group averaged beamformer source images (pseudo-t images) for high-frequency (60–90 Hz) gamma band activity superimposed on the Talairach grid for all movement conditions. All plots are thresholded at the $p < 0.05$ level. (b) Group averaged time–frequency plots of source activity at the location of high gamma activity in the contralateral motor cortex in each subject. Red and blue colours indicate increases and decreases, respectively, in units of percent change in source power above baseline. Talairach coordinates are shown in parenthesis above each plot. The group averaged rectified surface EMG traces from the active muscles, left and right 1st dorsal interosseus (1DI), left and right biceps brachii (bic. brachii) and left and right tibialis anterior (tibialis ant.) muscles are shown superimposed on the corresponding time–frequency plot for each movement condition (blue traces).
Fig. 2 shows the time–frequency plots for the location of peak gamma power increase in the contralateral motor cortex for left and right index finger movement conditions in individual subjects. Bursts of high gamma band activity following onset of movement can be seen in all subjects, ranging in peak frequency from 66 Hz to 85 Hz and beginning around EMG onset. It should be noted that we report here the “peak” frequency and latency of detected increases in source power derived from the wavelet based time–frequency analysis. However, due to temporal smearing by the wavelet transform (using a wavenumber of 7 with a corresponding temporal and frequency resolution of approximately of 29 ms and 21 Hz at 75 Hz) it difficult to identify the precise onset and duration of increases in gamma power in individual subjects. In addition, for consistency with the beamformer source localization procedure that is based on the spatial distribution of noise-normalized source power, increased energy in the time–frequency plots are shown here in units of normalized source power (pseudo-$z^2$). It can be seen that in some subjects gamma bursts were somewhat weak and temporally smeared, while other subjects showed extremely robust and distinct bursts. Peak pseudo-$z^2$ values ranged from approximately 2.0 to 20.0 corresponding to approximately 45% to 600% increases above pre-movement baseline. The group averaged time–frequency plot is also shown, demonstrating a mean increase in gamma power above baseline of approximately 184% (pseudo-$z^2$ = 6.4) and 149% (pseudo-$z^2$ = 5.8) for left and right index finger movements, respectively. Gamma activity typically reached peak amplitude within the first 300 ms following EMG onset reaching maximal intensity at latencies of 96±48 ms and 117±33 ms for left and right index movements, respectively. As can also be seen in the individual time–frequency plots in Fig. 2, although there was a significant degree of inter-subject variability in gamma activity, there was a remarkable similarity in the relative intensity, peak frequency and overall timing of the gamma bursts within subjects for left and right-sided index finger movements. This was most pronounced for peak frequency as shown in Table 1, which compares peak gamma frequency between left and right-sided movements in individual subjects for all movement conditions. It can be seen that mean pairwise differences in peak frequency between left and right-sided movements for the same body part were small ($\pm$1 Hz for index and bicep movements) and were not significantly different for left and right movements of the same body part for all movement conditions (paired r-test). However, mean peak frequency for foot dorsiflexions was significantly lower than for both finger and bicep movement conditions, when combined across left and right-sided movements ($p<0.001$, paired r-test, corrected). For bicep contractions and foot dorsiflexions, peaks of increased gamma activity were not clearly discernable in 3 of the 9 subjects for either one or both movement sides and these subjects were excluded from group analysis for these movement conditions. This was typically due to poor timing of EMG movement onset and/or excessive head movement due to greater difficulty in making isolated movements of these body parts.

**Localization of movement-related gamma activity**

Fig. 3(a) shows the group averaged gamma band source images for each movement condition. Group images were thresholded ($p<0.05$) using the maximal voxel (omnibus) permutation test (Nichols and Holmes, 2002; Singh et al., 2003) revealing a single 363 significant peak of focal activity in the contralateral precentral gyrus 364 for both left and right index finger abductions and left and right bicep 365 contractions, and in the paracentral lobule of the contralateral mesial 366 cortex within the inter-hemispheric fissure for foot dorsiflexions, 367 corresponding to the known homuncular organization of ML 368. Comparison of coordinates of source locations (Table 2) for index 369 and bicep movement conditions across subjects revealed that gamma 370 band source locations for index finger abductions were significantly 371 more lateral by 2.3 mm (left movements) and 5.8 mm (right movements) 372 than source locations for bicep contractions ($p<0.05$, 373 paired r-tests). Locations for index finger movements were also more 374 anterior and inferior, although this was only statistically significant 375 for left side movements ($p<0.05$, paired r-test, corrected). Fig. 3(b) 376 shows the group averaged time–frequency analysis for source 377 activity at the peak source location identified in individual subjects 378 for each movement. We based our analysis on these locations, as 379 the peaks detected in the group averaged source images, shown in 380 Fig. 3(a), may be slightly biased by the large range of maximum 381 power increases across subjects. The mean latency and peak 382 frequency of gamma power corresponding to this source activity is 383 shown in Table 2. Similar to mean peak frequency, the mean latency 384 of the peak increase in gamma was similar for movements of similar 385 body parts, with slightly longer latencies index finger movements 386 and longest and most variable for bicep contractions that also appear 387 slightly longer in duration. Superimposed on the normalized MRI template brain.

Discussion

In a previous study, we described the localization of mu band (8–15 Hz) and beta band (15–30 Hz) oscillatory changes during
finger movements to distributed and bilateral regions of the postcentral and precentral cortex, respectively, using a similar paradigm and source localization method (Jurkiewicz et al., 2006).

In contrast to these lower frequency sensorimotor rhythms that are typically observed bilaterally for unilateral movements, and show decreased power throughout the movement period, movement-evoked gamma increases observed in the current study were highly time-locked to, and followed movement onset, and observed only in the contralateral motor cortex for unilateral movements. Time–frequency analysis revealed that these gamma bursts were very brief in duration (only 100 to 200 ms in duration in some individuals) with energy concentrated over a relatively narrow frequency band, with a mean peak frequency of around 75 Hz for upper limb movements, with slightly lower mean frequency around 68 Hz for foot movements. Although we observed a high degree of inter-subject variability in these post-movement gamma bursts, their relative intensity, timing and mean peak frequency were markedly similar for left and right movements of the same body part within individual subjects. Our source localization results indicated that these gamma oscillations arise from somatotopically organized neural populations within the primary motor cortex (MI). It was noted that the separation between source locations for index finger abductions and bicep contractions, although statistically significant, was rather small (<1 cm). In addition, gamma activity for finger and arm movements was similar in peak frequency, suggesting the activation of overlapping neural populations in the hand–arm area of MI for movements of the upper limbs, although we cannot exclude the possibility the subjects may have made small co-contractions of their wrist flexors or other arm muscles during the elbow flexion task. It is not possible to determine from the current approach the precise neural populations within MI that are involved in generating gamma oscillations.

Comparisons to the Talairach atlas provided by Lancaster et al. (Lancaster et al., 2000) indicated locations in Brodmann area 4 in three of the four upper limb movement conditions in the group data, suggesting the involvement of neural populations in the primary motor cortex (MI). Similarly, comparisons to cytoarchitectonic probabilistic maps for Brodmann areas 4a and 4p (http://www.bic.mni.mcgill.ca/cytoarchitectonics) also indicated that source locations were in or near the region of the primary motor cortex (Geyer et al., 1996). The location of sources for foot dorsiflexions were also localized to expected anatomical location for lower limb movements in the paracentral lobule of the inter-hemispheric fissure, indicating that sources of high-frequency gamma activity correspond to the known homuncular organization of the primary motor cortex. Coordinates of gamma sources were similar to those reported in recent fMRI studies of upper and lower limb movements (Alkadhi et al., 2002; Ciccarelli et al., 2005), although slightly deeper in the inferior–superior direction. This may reflect differences in the two methods, or a slight bias in the beamformer images towards deeper localization (Cheyne et al., 2007). We also noted that locations for gamma sources for index finger movements in the current study were similar to those we previously reported for beta band “rebound” using a similar motor task and localization approach (Jurkiewicz et al., 2006).

The observed somatotopy of high gamma band activity during movement corresponds to that originally reported in ECoG recordings by Cronel et al. (Cronel et al., 1998) and shown in more recent intracranial EEG studies, although many of these studies involved the use of variable frequency bands and differing methods of spectral analysis. For example, a study by Miller et al. (Miller et al., 2007) showed somatotopic gamma increases over the entire period of movement for different body parts, although for power extending over the 76–100 Hz range resulting in a lower cutoff frequency exactly at the peak frequency of our observed gamma band increases. More time–resolved analyses of movement-related cortical oscillations have been reported by Pfurtscheller et al. (Pfurtscheller et al., 2003), who found brief narrow band increases in the ECoG overlying the contralateral motor cortex following movement onset in four patients, and by Szurhaj et al. (Szurhaj et al., 2006), who also showed increased gamma power following movement onset in eight patients from selected grid locations overlying the motor cortex, although in the latter study analysis was limited to a 40 to 60 Hz frequency band. In spite of these differences, we conclude that the reported movement-related increases in high-frequency (60 to 100 Hz) brain activity in intracranial EEG studies are closely related to the gamma band bursts we observed non-invasively in our MEG recordings in healthy volunteers. However, whereas ECoG studies are limited to studying movements based on the locations of the recording grids for surgical planning, we were able to study movement-related gamma activity for left and right movements of both upper and lower limbs, revealing frequency specificity for movements of different body parts as well as similarities between homologous regions of the left and right motor cortex within the same subjects.

The underlying physiological mechanism of high-frequency gamma bursts in motor cortex remains to be determined. The timing and somatotopic organization of high gamma bursts observed in the current study suggest that they could be the result of reafferent feedback to the primary motor cortex during movement. It is known that muscle afferent input reaches MI within 100 ms following onset of EMG as a result from either direct input via the thalamus (Lemon and van der Burg, 1979) or indirectly through primary somatosensory areas receiving proprioceptive and tactile inputs during movement (Naito, 2004). Thus, gamma oscillations following EMG onset may reflect the activation of local oscillatory networks in MI by peripheral input. However, MI gamma activity may also reflect activation of more distributed networks involved in ongoing control of muscular activity. We noted that the oscillations in MI observed in the current study were markedly similar in frequency and latency to those recently reported 70 to 80 Hz oscillations in the subthalamic nucleus (STN) during wrist extensions in Parkinson patients with implanted stimulating electrodes (Alegre et al., 2005). It has been speculated that the ameliorative effects of STN stimulation in these patients may be related to the normally cortically mediated dampening of oscillatory activity within basal ganglia motor structures which in turn facilitates movement (Aminovin et al., 2004). There is evidence that direct projections from MI to the STN mediate both beta and low gamma oscillatory activity within cortical–basal ganglia loops (Brown, 2003) and a recent study showed evidence of bidirectional connectivity between MI and the STN in Parkinson patients involving increased coherence between scalp EEG and STN electrodes in the high (65 to 90 Hz) gamma band during movement (Lalo et al., 2008). Thus, the gamma oscillations observed in our current study may reflect the activity of these cortical–basal ganglia pathways in healthy subjects. Although this interpretation is highly speculative, it is somewhat supported by our observation of marked similarity in gamma oscillations observed in the left and right motor cortices for movements of the same body part within each subject. For example, subjects that had very large amplitude and time-locked gamma bursts for left-sided index finger movements had similarly...
robust gamma activity for right-sided finger movements and often with identical peak frequency (see Fig. 2 and Table 1). This might be taken as evidence of a common underlying generator or network for MI gamma oscillations in different hemispheres for left and right-sided movements, rather than local, independent oscillatory networks in MI. Similarly, gamma oscillations in the foot representation area showed a lower mean gamma frequency than that for upper limb movements, possibly reflecting different oscillatory networks for upper and lower limb movements that are independent of side of movement. Since we did not detect changes in the high gamma band in any other cortical areas, we conclude that such a network must involve either subcortical motor structures or interactions with peripheral inputs. The duration of gamma cycles in the 70 to 80 Hz range would be too short to involve peripheral feedback mechanisms, and would also predict temporal differences for contractions of intrinsic muscles of the hand in comparison to the biceps brachii muscles due to differences in conduction times from the motor cortex to muscle (Eyre et al., 1991). In addition, we observed highly similar gamma frequencies for contractions of the index finger abductor and biceps muscles, suggesting that differences in muscle size and peripheral conduction times did not play a role in determining the frequency of gamma oscillations in MI. Taken together with reported observations of 70 to 80 Hz gamma activity in structures such as the STN during movement, we propose that motor cortex gamma oscillations observed in our study may reflect the activation of cortical–subcortical networks during the onset of discrete movements, perhaps signaling the direct modulation of output of the STN to the basal ganglia, thereby facilitating movement execution. There has been increasing interest in the role of such networks in the voluntary control of motor responses and response inhibition (Aron, 2007; van den Wildenberg et al., 2006) and non-invasive studies of motor cortex gamma activity using MEG may provide further insight into such mechanisms.

The functional role of rhythmic activity in the sensorimotor cortex is not well understood. There is evidence from transcranial stimulation studies that modulation of mu and beta band activity may correspond to periods of enhanced excitability or increased inhibition in the motor cortex following movement (Chen et al., 1998). It is known that motor cortex oscillations in the beta band are coherent with EMG activity and may reflect an efficient mechanism for cortical drive to the muscles during sustained contractions (Baker et al., 1999; Conway et al., 1995). Changes in coherence between MEG and EMG in the beta frequency band have also been shown to be related to dynamic adjustments of force (Kilner et al., 2000) and increases in coherence between EEG recordings over motor cortex and the EMG have been shown for transient movements in the beta (Feige et al., 2000) and gamma (Shibata et al., 1999) frequency bands. A recent MEG study showed changes in corticospinal coherence in the gamma band in recordings overlying contralateral motor areas (Schoffelen et al., 2005) although these were over a wider and somewhat lower range of frequencies (40 to 70 Hz) and persisted throughout the period of movement preparation. In a recent EEG study, Omlar et al. (Omlor et al., 2007) found that when comparing conditions of static versus dynamic control of muscular force, the frequency of corticospinal coherence shifted from the beta (15 to 30 Hz) to low gamma (30 to 45 Hz) frequency band in individual subjects, indicating that high-frequency oscillations may play a greater role in sensorimotor integration during more dynamic and transient movements. We did not describe coherence between gamma band activity and EMG in the current study, as initial attempts to compute corticomuscular coherence for the post-movement interval did not yield significant levels of coherence at any frequency. However, this is likely due to the fact that increases in gamma activity occurred only over very brief periods of time (100 to 300 ms) making accurate estimates of coherence difficult in comparison to that estimated from extended periods of isometric contractions. Moreover, as shown in Fig. 3, there was no clear temporal relationship between peak EMG activity and increased gamma activity that reached maximal levels 50 to 200 ms later. Finally, it should be noted that gamma band increases within a similar 70 to 80 Hz frequency range have been observed in other cortical areas, such as the occipital cortex during visual stimulation (Hoogenboom et al., 2006). This suggests that gamma band oscillations demonstrate differences in both anatomical location and frequency depending on the motoric and sensory processing demands of the task, and that it is important to distinguish gamma band activity within motor areas associated with motor output from that evoked by stimulus processing during complex visuomotor or cognitive tasks.

In conclusion, we show evidence of highly stereotyped bursts of high-frequency gamma activity in the primary motor cortex of humans using non-invasive MEG recordings. These gamma band oscillations were specific to movement execution and most likely correspond to post-movement gamma increases observed in intracranial EEG recordings overlying motor areas. The functional role of these motor cortex oscillations remains unclear, although our current results suggest that they may reflect the processing of proprioceptive information by cortico-subcortical networks during the sensory feedback control of discrete movements. These new findings demonstrate that MEG measures combined with spatial filtering techniques can provide a new avenue for the non-invasive study of the functional significance of these networks in human motor control.

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References


