# Unique Cortical Physiology Associated With Ipsilateral Hand Movements and Neuroprosthetic Implications

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*Background and Purpose*—Brain computer interfaces (BCIs) offer little direct benefit to patients with hemispheric stroke because current platforms rely on signals derived from the contralateral motor cortex (the same region injured by the stroke). For BCIs to assist hemiparetic patients, the implant must use unaffected cortex ipsilateral to the affected limb. This requires the identification of distinct electrophysiological features from the motor cortex associated with ipsilateral hand movements.

*Methods*—In this study we studied 6 patients undergoing temporary placement of intracranial electrode arrays. Electrocorticographic (ECoG) signals were recorded while the subjects engaged in specific ipsilateral or contralateral hand motor tasks. Spectral changes were identified with regards to frequency, location, and timing.

*Results*—Ipsilateral hand movements were associated with electrophysiological changes that occur in lower frequency spectra, at distinct anatomic locations, and earlier than changes associated with contralateral hand movements. In a subset of 3 patients, features specific to ipsilateral and contralateral hand movements were used to control a cursor on a screen in real time. In ipsilateral derived control this was optimal with lower frequency spectra.

*Conclusions*—There are distinctive cortical electrophysiological features associated with ipsilateral movements which can be used for device control. These findings have implications for patients with hemispheric stroke because they offer a potential methodology for which a single hemisphere can be used to enhance the function of a stroke induced hemiparesis. (*Stroke*. 2008;39:3351-3359.)

**Key Words:** electroencephalography ■ motor activity ■ upper extremity ■ advances in stroke

A Brain Computer Interface (BCI) is a device that can decode human intent from brain activity alone to create an alternate control channel for people with severe motor impairments. BCIs have been used to achieve basic control in humans with amyotrophic lateral sclerosis (ALS) and spinal cord injury.[1,2] Current systems, however, offer little hope for patients suffering from hemispheric stroke. The majority of methods that have been developed are based on using functioning cortex capable of controlling the contralateral side of the body.[3–7] This is the exact situation that does not exist in patients with unilateral stroke. To assist a hemiparetic patient in a manner that is more intuitive with regards to motor intentions, the BCI must use unaffected motor cortex ipsilateral to the affected limb (opposite the side of the stroke). Buch et al demonstrated this to be possible using MEG in a limited number of patients. To achieve a functional BCI for the future, an expanded understanding of how motor cortex participates in processing ipsilateral arm and hand movements is essential.

The notion that motor cortex plays a role in ipsilateral body movements has gained support over the past few decades.

Clinical studies have demonstrated that injury to motor cortex not only affects contralateral movements, but also has a functional impact on the ipsilateral "unaffected" limb indicating the involvement of ipsilateral cortex in motor control.[8] Imaging studies with functional MRI (fMRI), positron emission tomography (PET), and single photon emission computed tomography (SPECT) have further confirmed in normal human subjects that various levels of ipsilateral motor and motor-associated cortex are active with ipsilateral hand movements.[9–19] Recent findings have extended this concept by showing these regions to be anatomically distinct, located anterior, ventral, and lateral to the activations induced by contralateral hand movements.[20–22] Additionally, this activation appears to be more closely associated with hand movements that are more complex or lengthy in sequence duration.[11,15–17,21,23,24] The hemispheric distribution has also been found to be asymmetrical, favoring the left hemisphere in right-handed subjects.[12–14,20,21,25,26] These findings of distinct anatomic position, association with increased manual complexity, and hemispheric dominance in normal human subjects have been further corroborated by magnetoencephalog-

**Table 1.    Summary of Patients' Clinical Demographics**

| Subject # | Age | Gender | Cognitive Ability | Handedness | Array Location | Seizure Onset Location |
|-----------|-----|--------|-------------------|------------|----------------|------------------------|
| 1 | 14 | Male | Normal range | Right | Left fronto-parietal (8×8) | Left mesial frontal |
| 2 | 11 | Male | Normal range | Right | Right frontal (8×8) | Inferior lateral frontal |
| 3 | 24 | Male | Normal range | Right | Bi-frontal strips (1×8)'s | Multifocal |
| 4 | 27 | Female | Normal range | Right | Bi-frontal strips (1×8)'s | Right medial temporal |
| 5 | 12 | Female | Normal range | Right | Left temporo-occiptal (8×8) | Left basal temporal |
| 6 | 46 | Female | Normal range | Right | Right fronto-temporal (8×8) | Multifocal |

raphy (MEG) and transcranial magnetic stimulation (TMS).[27–35]

The actual manner that motor cortex is involved with ipsilateral movements in humans, however, is currently not well defined; moreover, the extant literature has conflicting findings.[21,36–40] Thus far, definitive electrophysiological studies in humans to describe the role that motor cortex plays in ipsilateral hand movements and how it is physiologically encoded have been limited. This is attributable either to the limitations of the modality used or to the study design. To date, the majority of electrophysiological studies of human brain function have used EEG. Brain activity has been assessed by either quantifying alterations in evoked potentials or by measuring the spectral changes of oscillating brain activity (aka sensorimotor rhythms). The EEG modality, however, is limited by poor spatial resolution and narrow spectral bandwidth.[41–43] This ultimately limits the precision with which it can describe the anatomy and signal characteristics of the cortical electrophysiology underlying ipsilateral motor processing.

Electrocorticography (ECoG) recorded from the cortical surface offers an opportunity to clarify some of the disparate findings related to ipsilateral motor involvement. The ECoG signal is more robust than the EEG signal: its magnitude is typically 5 times larger, its spatial resolution as it relates to independent signals is much greater (0.125 versus 3.0 cm for EEG), and its frequency bandwidth is significantly broader (0 to 500 Hz versus 0 to 40 Hz for EEG).[41–43] The breadth of frequency information that can be acquired through intracranial recording is important on a functional level, because many studies demonstrate that different frequency bandwidths carry specific and anatomically focal information about cortical processing.[21,22] Thus far, no studies have used these spectral features exclusive to ECoG to analyze cortical processing of ipsilateral movements.

The same advantages in signal resolution that make ECoG analysis a superb method for brain mapping also confer advantages for neuroprosthetic application. In 2004, Leuthardt et al revealed the first use of ECoG in closed-loop computer control with minimal training requirements.[7] In additional experiments, the same group demonstrated that specific ECoG features encode specific information about hand movements.[7,44] Taken together, these studies demonstrate the value of improved anatomic and signal resolution offered by ECoG in its application toward rapid and effective device control.

Based on these previous studies performed using signals from the contralateral cortex, the current study set out to identify the distinct electrophysiological features of ipsilateral hand movements and to use these features for neuroprosthetic application. Our study demonstrates that ipsilateral hand movements are associated with a distinct spectra, timing, and location of brain signal alteration. Additionally, this is the first study to use distinct signals explicitly associated with ipsilateral motor processing for a BCI application. These findings could have implications in the future for patients with hemispheric stroke because they demonstrate a method that would allow a single unaffected hemisphere to potentially enhance function lost attributable to unilateral cerebral insult.

## Methods

### Subjects
Six subjects (ages 11 to 46 years) participated in this study. All subjects were diagnosed with intractable epilepsy and underwent temporary placement of intracranial electrode arrays to localize seizure foci before surgical resection (clinical data summarized in Table 1). All subjects gave informed consent. The study was approved by the Washington University Human Research Protection Office. The amount of data obtained varied between subjects and depended on each subject's physical state and willingness to continue.

### Recordings and Data Collection
Each subject sat in their hospital bed 75 cm from a 17-inch video screen. All cues for movement were presented using the BCI2000 program.[45] Data were collected through implanted platinum electrode arrays (Ad-Tech). All electrodes were referenced to an inactive intracranial electrode on the dura. The signal recorded for the seizure monitoring unit was split using 2 custom 32-channel electrode splitter cables that were routed to our BCI system. The sampling frequency was 1200 Hz, and a band-pass filter (0.5 to 500 Hz) was used. The BCI system consisted of 4 optically isolated 16 channel g.USBamp amplifiers (Guger Technologies) and a Dell Optiplex GX 270 computer (Dell). ECoG signals were acquired using the BCI2000 software, stored, and converted to MATLAB files for analysis.
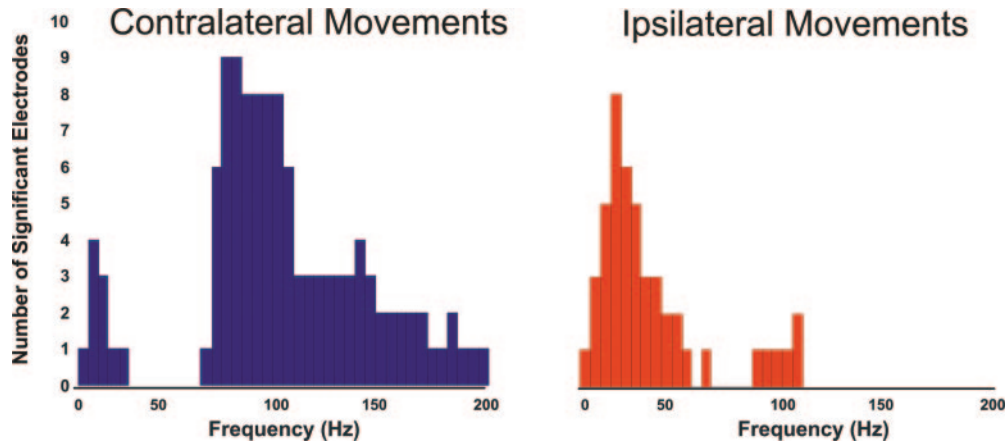
### Behavioral Tasks

#### Hand Screening Task
Hand movement during this task was defined as repeatedly opening and closing the cued hand (either ipsilateral or contralateral) when a visual cue was present (3 second trials). The cues were randomly generated during each run. With no movement cue, the patients were instructed to stop moving and this was considered the resting condition (3 second trials). Twenty trials for each hand were performed per run. Each patient performed an average of 3 runs (total time 6 minutes).

#### Joystick Screening Task
Three subjects (1, 3, and 6) performed a cue-directed hand-controlled joystick center-out task. The task consisted of using either the

**Figure 1.** Ipsilateral hand movements produce changes in lower frequencies than contralateral movements. The bar histograms show the number of electrode sites demonstrating significant cortical activity (spectral power changes with probability value <0.001) at a given frequency for ipsilateral (left plot) and contralateral (right plot) hand movements.

contralateral or ipsilateral hand to control a force feedback joystick (Microsoft Sidewinder Joystick). This task consisted of 80 trials, each of which required the subject to begin with the cursor at the center target, watch for 1 of the 8 radially located targets to highlight, wait for the cue, and move the cursor to the target that had been highlighted.

### Signal Analysis

All ECoG data sets were rereferenced to the common average obtained from the data for each run. For all analyses, the time-series ECoG data were converted into the frequency domain using an autoregressive model, as in Leuthardt.[7] All spectral amplitudes for analysis were calculated between 0 and 500 Hz in 2-Hz bins. A regression analysis was performed between the movement trials and rest condition of each task to identify the spatial locations and signal frequency bands in which the amplitude of the power was significantly different (ie, the highest coefficient of determination values, or $r^2$). These channels with the highest $r^2$ were further analyzed in the temporal domain using time-frequency plots as well as in the spatial domain. Separately, probability values were calculated using a balanced 1-way ANOVA with the same frequency power alterations. Each probability value was Bonferroni-corrected to account for multiple comparisons across electrodes. All statistical comparisons between sets of 2 populations (including contralateral and ipsilateral frequencies and temporal activations) were calculated using 2-sample *t* tests. Results presented were significant with a probability value of less than 0.001. Normalizations for frequency spectral analysis were preformed on each subject's data by dividing the magnitude of the power at each frequency by maximal power for that subject. Data were then averaged across subjects.

### ECoG Controlled Cursor Movement Online

Those features associated with either ipsilateral or contralateral hand movements were then coded into BCI2000 for use during the subsequent online closed-loop session (Subjects 1, 5, and 6). During this task subjects received online feedback that consisted of one-dimensional horizontal cursor movement controlled by ECoG signal features resulting from their overt hand movements (updating every 40 ms by a translation algorithm based on a weighted, linear summation of the amplitudes in the identified frequency bands from the identified electrodes over the previous 280 ms). A cursor would appear in the center of the screen. Concurrently, a target would appear on the right or left side of the screen. The patient would then move the specified hand to induce cortical changes to direct the cursor to the respective target. Each run consisted of 30 target presentations, and all 3 subjects performed 3 runs under both the contralateral and ipsilateral conditions.

Three different control scenarios in these 3 subjects were tested in which ipsilateral spectral power changes were: (1) different from contralateral features in both anatomic location and frequency (Subject 1), (2) the same anatomic location and the same frequency,100Hz (Subject 5), and (3) the same location with different frequency (ipsilateral - 20Hz, contralateral - 100Hz; Subject 6). Performance was measured in accuracy of target acquisition and time required to reach target.
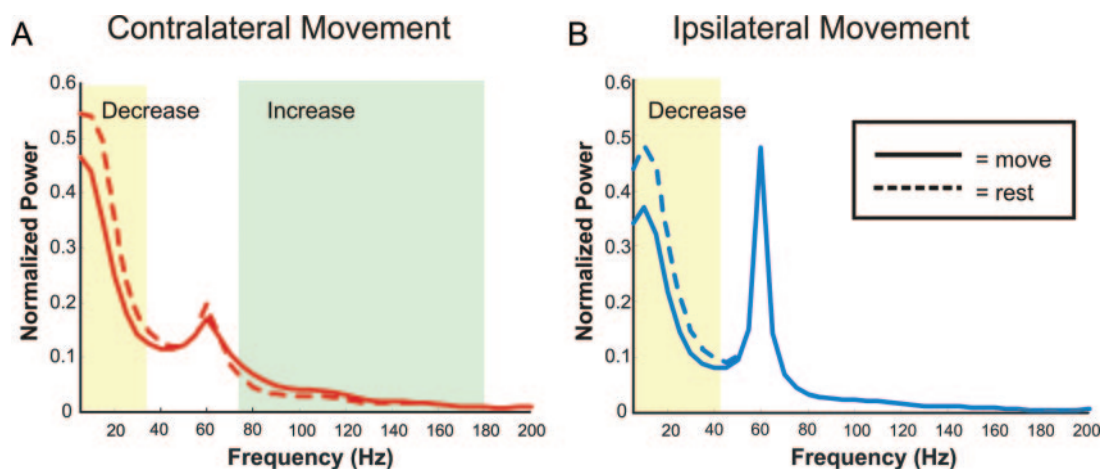
### Anatomic Mapping

Radiographs were used to identify the stereotactic coordinates of each grid electrode,[46] and cortical areas were defined using Talairach's Co-Planar Stereotaxic Atlas of the Human Brain[47] and a Talairach transformation database (http://ric.uthscsa.edu/projects/talairachdaemon.html). Stereotactically defined electrodes were then mapped to the standardized brain model from the AFNI SUMA Web site (http://afni.nimh.nih.gov/afni/suma). The experimental results were collated with anatomic and functional mapping data.

## Results

### Ipsilateral Hand Movements Have Unique Electrophysiological Features and Timing

Spectral features for both ipsilateral and contralateral hand movements were identified and quantified based on the hand motor screening task performed by all 6 subjects. Each hand movement condition was compared to the rest condition to identify electrodes and frequency bins that demonstrated the most significant spectral changes. The features of the signal from the most significant electrodes identified from movement of the ipsilateral and contralateral hands were then compared. For all subjects there were electrode sites and frequency spectra that were distinct between ipsilateral and contralateral hand movements.

The number of electrode sites that showed significant cortical activity (spectral power changes with probability value <0.001) were plotted against the frequency at which this significant activity occurred for ipsilateral and contralateral hand movements (summarized in Figure 1). There is a significant difference between the lower frequencies related to ipsilateral movements (average 37.3 Hz, SD±9.4) and the higher frequencies of the contralateral movements (average 106.9 Hz, SD±14.2).

**Figure 2.** A, Average power magnitude vs frequency for the contralateral movement condition (solid line) and the corresponding rest condition (dashed line). In the movement condition, there is a decrease in power at low frequencies (highlighted in yellow) and an increase in power at high frequencies (highlighted in green) as compared to rest. B, Average power magnitude vs frequency for the ipsilateral movement condition (solid line) and the corresponding rest condition (dashed line). In the movement condition there is a decrease in power at low frequencies (highlighted in yellow).

To assess the full frequency spectra, the changes in spectral power (ie, increase or decrease) for each motor condition were normalized and averaged across all patients (summarized in Figure 2). These plots show that both the ipsilateral and contralateral movement conditions were associated with a significant decrease in power at low frequencies (0 to 40 Hz). In the higher (gamma) frequencies, specifically 75 to 180 Hz, the contralateral spectra shows a significant increase in power as compared to the rest condition that is not present in the ipsilateral condition.

The anatomic locations of electrode sites that demonstrated significant signal change with ipsilateral and contralateral hand movements were compared across all subjects (summarized in Figure 3). Of the electrode sites showing significant power changes, 33% were unique to ipsilateral hand movement (8 sites), 38% were unique to contralateral hand movement (9 sites), and 29% of sites showed activation with both ipsilateral and contralateral hand movements (7 sites). In sites with both ipsilateral and contralateral activation, ipsilateral and contralateral movements were still found to maintain different average frequency spectra (ipsilateral 40.2 Hz, SD±10.3 and contralateral 110.9 Hz, SD±16.7). Most sites associated with "contralateral only" activations were more significantly represented in somatosensory cortex than ipsilateral movements, which were predominantly found in premotor and nonsensorimotor areas.

The average Talairach coordinates of all significant electrodes in both the right and left hemispheres were calculated. This average location differs in the Z plane for both significant contralateral (LEFT: mean=61.3; range=[53 to 66], RIGHT: mean=36.7; range=[17 to 47]) and significant ipsilateral electrodes (LEFT: mean=56.0; range=[50 to 66], RIGHT: mean=36.2; range=[23 to 47]), whereas in the Y plane, the average locations were not significantly different between hemispheres.

To define the timing of ipsilateral motor processing, three subjects (1, 3, and 6) performed cue-directed hand-controlled joystick center-out tasks with both the right and left hand.

This allowed for precise coregistration of movement cues, initiation and tracking of movement, and coinciding signal alteration. Ipsilateral hand movements were associated with earlier changes in the lower frequency than were contralateral hand movements (summarized in Figure 3). Figure 3 presents a bar histogram that shows the peak time of signal correlation with the active condition (time of cue presentation/movement against rest) averaged across the three subjects. Ipsilateral spectral changes preceded similar changes with contralateral movements on average by 160 ms.
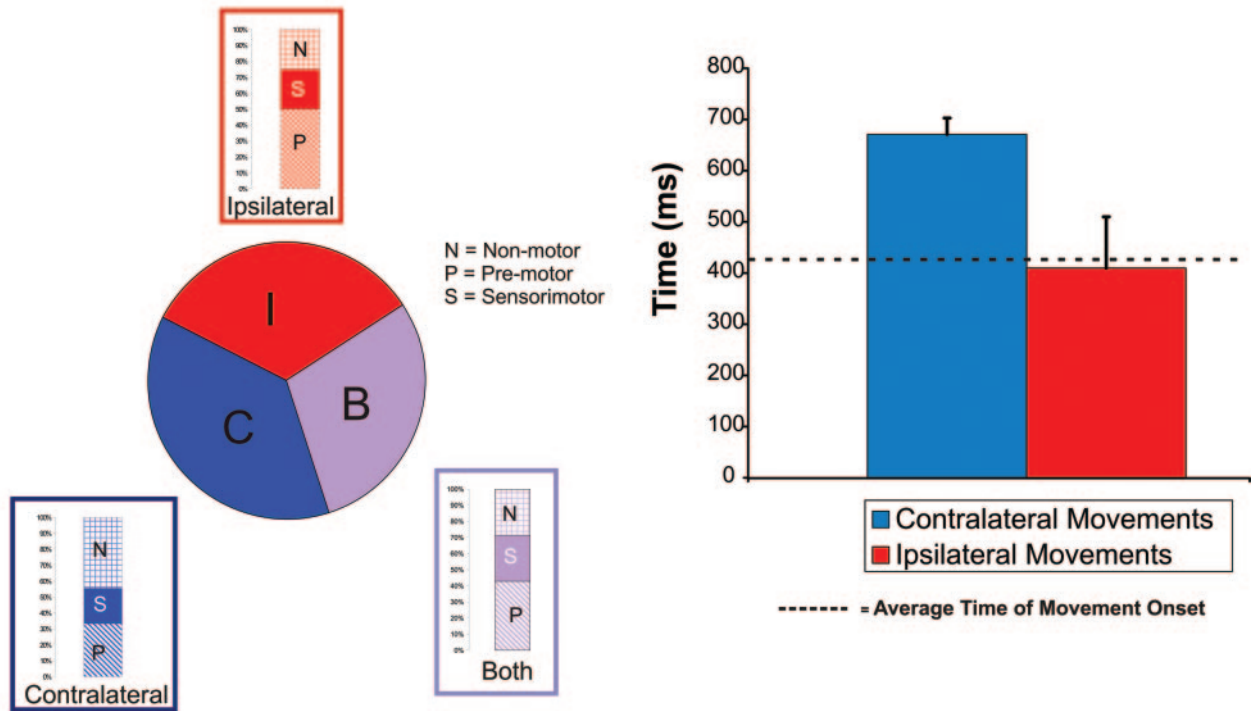
## Achieving Online Control of a Cursor With Ipsilateral and Contralateral Hand-Derived ECoG Signals

To determine whether signals associated with ipsilateral hand movements could be used for BCI control, 3 of the 6 subjects (1, 5, and 6) who performed hand screening tasks were also tested in a real-time online cursor control task. This task used features that were previously identified as being significantly associated with ipsilateral or contralateral overt hand movements to control a cursor on a computer screen. Patients received online feedback that consisted of one-dimensional horizontal cursor movement that was controlled by the identified ECoG features. For the 3 subjects, control was achieved using ipsilateral and contralateral ECoG features that had one of: (1) different anatomic location/ different frequency spectra, (2) same anatomic location/same frequency spectra, and (3) same location/different frequency spectra.

Signals derived from both ipsilateral and contralateral motor movements achieved a high level of control with final target accuracies between 70% to 96% and 95% to 100%, respectively. Ipsilateral control was best achieved (91% to 96% target accuracies) when electrode locations were distinct from contralateral locations or low-frequency spectra associated with ipsilateral movements were used. The results are summarized in Table 2. For all scenarios performance increased with time for both ipsilateral and contralateral control

## A  Anatomic Locations of Activations  B  Timing of Peak Activation



**Figure 3.** Left, The number of locations identified with statistically significant power change (across all frequencies) that correlated with ipsilateral and contralateral hand movements. (I=Ipsilateral movements, red; C=Contralateral movements, blue; B=Both, purple). The anatomic distribution of ipsilateral and contralateral movement activations were also distinct with regard to Brodmann areas. Ipsilateral activations show a larger representation in premotor regions as compared to contralateral activations. (N=Nonmotor, P=Premotor, S=Sensorimotor). Right, The peak of signal correlation with the movement of a hand-operated joystick were averaged for 3 subjects (1, 3, and 6). Ipsilateral hand movement preceded contralateral hand movement by 160 ms. The dashed line represents average time of movement initiation.

(Figure 4A). When identical location and frequency (gamma, 100Hz) were used for control, contralateral control maintained a high level of performance with a steep learning curve whereas ipsilateral derived control had poorer performance with a less robust learning curve.
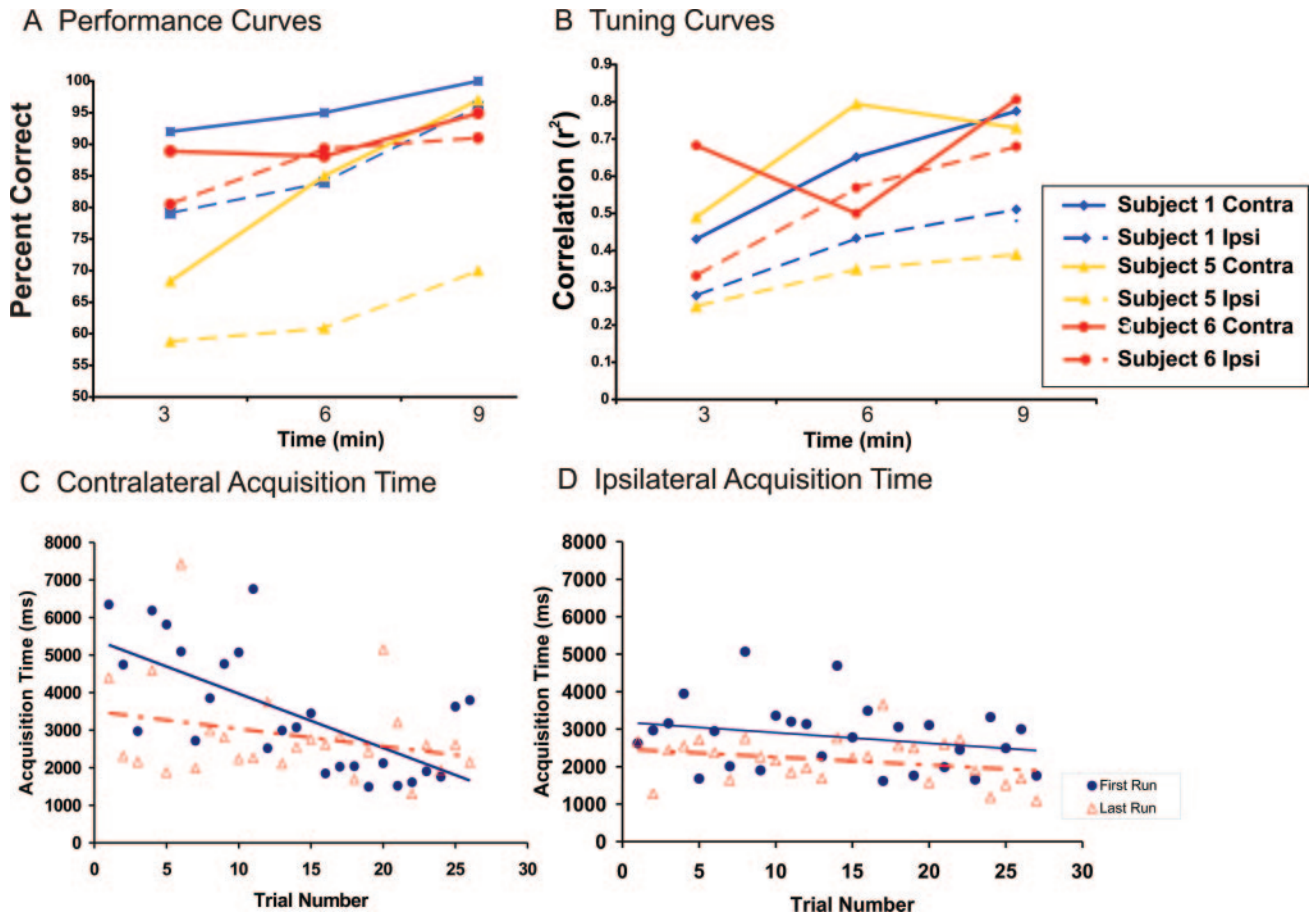
To account for the change in performance, the progression of correlation between movement conditions and rest (as measured by $r^2$) of the ECoG features selected for control (specific frequency from specific electrode) across the 3 runs were examined. Correlation of the control feature with the respective correct target increased over the time course of minutes (Figure 4B). Similar to the performance curve results, the level of correlation was highest with contralateral tasks using high frequencies (100Hz) and for ipsilateral tasks using low frequency spectra (20 to 25Hz).

To further quantify learning, performance across trials and runs with respect to the time of target acquisition was measured. The time it took subjects to hit a target for each trial during the first and the last run were plotted individually for each trial, and trend lines were best fit regressed to assess progression of performance (Figure 4, C and D). Performance was measured as the time from the appearance of the target to target acquisition. As control task proficiency increased, the cursor moved more quickly and directly toward the target, resulting in decreased acquisition times. For contralateral derived control, the time it took for the subject to reach the target decreased significantly across trials during the first run and this speed was maintained through the third run. In contrast, ipsilateral control shows a less dramatic improvement in performance speed that is not significant. However,

**Table 2.  Summary of Online Closed Control Features and Performance**

| Subject | Hand Motor Action | Anatomic Location | Frequency (Hz) | Final Target Accuracy (%) |
|---|---|---|---|---|
| 1: Different location/different frequency spectra | Ipsilateral | Primary sensorimotor cortex | 25 | 96 |
| | Contralateral | Primary sensorimotor cortex | 100 | 100 |
| 5: Same location/same frequency spectra | Ipsilateral | Primary sensorimotor cortex* | 100 | 70 |
| | Contralateral | Primary sensorimotor cortex* | 100 | 97 |
| 6: Same location/different frequency spectra | Ipsilateral | Primary sensorimotor cortex* | 20 | 91 |
| | Contralateral | Primary sensorimotor cortex* | 100 | 95 |

*Ipsilateral and contralateral electrode used for control in same location.

## A Performance Curves



## B Tuning Curves



## C Contralateral Acquisition Time



## D Ipsilateral Acquisition Time



**Figure 4.** A, Performance curves. The data demonstrate the ability of 3 subjects to use ECoG signals associated with either ipsilateral or contralateral hand movements to control a cursor on a computer screen. For the 3 subjects, 3 different control scenarios were tested: (1) different anatomic location/different frequency spectra, (2) same anatomic location/same frequency spectra, and (3) same location/different frequency spectra. These results demonstrate that optimal control can be achieved using either distinct locations or distinct frequency spectra. B, Tuning curves. The level of correlation (as measured by $r^2$) with the respectively chosen frequency band used for control with the respective targets shows increased correlation over time. This demonstrates cortical plasticity with ongoing feedback. C and D, Progression of average target acquisition during closed loop control time for each trial for both contralateral (C) and ipsilateral (D) control task. Time for first run trials represented with blue diamonds and final run with red triangles. Best fit regression lines for first run (blue solid) and final run (red dashed).

subjects perform significantly faster in initial trials of the first ipsilateral run than the initial trials of the first contralateral run (probability value <0.001). The final speeds, on the other hand, were not statistically different (probability value >0.7).

## Discussion

One fifth to half of hemispheric stroke patients are chronically left with permanent loss of function in their affected hand.[48,49] The role that the nonlesional hemisphere plays remains controversial. In the short term, ipsilateral primary motor cortex has been shown to compensate for an acute loss of the opposite sided primary motor cortex.[50] In the long term, in chronically effected subjects contralesional primary motor cortex does not seem to be involved in functional recovery.[51] Functional imaging has shown these severely affected patients to have an increased activity in the premotor regions of their unaffected hemispheres.[52,53] The exact role this plays to date is unclear as to whether this is simply an indicator of more severe outcome[54] or an adaptive mechanism to optimize an already poor situation.[55,56] TMS suggest that interference with this activity, however, will worsen the

already compromised or negligible function.[56] In normal subjects, several modalities suggest that ipsilateral motor processing is more involved in the planning and selection of the movement rather than the execution.[11,15–17,23,24] Thus incomplete recovery and its association with heightened ipsilateral activation may reflect the upregulated attempt at creating motor commands with an inability to execute or actuate the selected motor choice. Here a Brain Computer Interface may provide a unique opportunity to aid in actuating the nascent premotor commands. By detecting the brain signals associated with these motor choices the neuroprosthetic may then convert these signals into machine commands that could control a robotic assist device that would allow for improved hand function (ie, a robotic glove which opens and closes the hand). The BCI would allow the ipsilateral premotor cortex to bypass the physiological bottle neck determined by the small and variable percentage of uncrossed motor fibers. This new methodology would allow for restoration of function in chronically and severely affected subjects for whom methods of rehabilitation have not sufficiently accomplished a functional recovery.

In this study, we have demonstrated for the first time that the cortical physiological changes that occur with ipsilateral hand movements are separable from those changes that occur with contralateral hand movements. We have identified distinct low frequency spectra, anatomically separable cortical sites, and earlier time of onset for ipsilateral activations when compared with the physiological changes associated with contralateral hand movements. All of these findings support the notion that a different and active phenomena associated with cortical planning of ipsilateral hand movements is occurring. This distinct physiology, and the demonstration that it can be used for external device control, creates the possibility for novel neuroprosthetic solutions for stroke induced hemiparesis in the future.

We have identified that contralateral movement, as previously reported, shows frequency power changes that occur in both low- (<40Hz) and high-frequency bands (>40Hz).[57,58] Though low frequency power changes are present, the contralateral movement is more robustly represented in the higher gamma frequencies. Ipsilateral movement, however, is most significantly represented by power changes in the low to intermediate frequencies (average 37.3 Hz, SD±9.4; Figure 1A). These lower frequency bands are associated with a decrease in power similar in nature to changes that occur within the high frequency component during contralateral movement. This supports the concept that an active process is occurring in both scenarios and is in contradistinction to previous assertions that cortical changes associated with ipsilateral movements are the result of inhibition.[37,39] If this were the case, one would expect the opposite phenomenon to occur with ipsilateral movement, namely, an increase in power at the lower frequencies.

Additionally, the timing of signal alteration supports the role of ipsilateral cortex in planning of movements. In all subjects, the signal changes occurred earlier with ipsilateral movement than contralateral hand movement after cue presentation. Three subjects additionally performed a hand controlled joystick task to specifically address how these changes occurred relative to movement onset. This task demonstrated that the lower frequency power suppressions occurred before, or immediately during, the onset of movement, whereas the low frequency power suppressions associated with contralateral movement occurred predominantly during the execution of movement.

The frequency differences between ipsilateral and contralateral hand movements may clarify some of the disparities of results on previously published works. Because the lower frequency bands have significantly higher amplitudes than higher gamma, they are more likely to contribute to evoked potentials and dipole moments detected with EEG and MEG. Hence, the consistent findings of the "premotor positivity" and the earlier dipole moments detected with MEG[28,59,60] are similar to our findings of low frequency band power suppression that occur earlier than changes associated with contralateral movement onset and before initiation of ipsilateral movement. Newton et al demonstrated that there was a negative baseline change in fMRI bold sequence in M1 associated with ipsilateral movements and postulated this to represent increased inhibition.[37] The difference in frequency representation of ipsilateral and contralateral movements may provide an alternative explanation. Because the low frequencies have a high amplitude at rest and are predominantly associated with power suppression with ipsilateral movement, the negative baseline finding seen on fMRI (or reduction in metabolic demand) may represent the coinciding reduction in synaptic metabolism associated with maintaining the motor cortex in an inhibited state. Thus, the reduction in BOLD signal may be paralleling the reduction in amplitude of the lower frequencies. Conversely, gamma rhythms have been found to be closely coupled to increases in fMRI bold signal.[61,62] The associated increase in fMRI bold signal identified during contralateral movement would thus support our findings of high frequency gamma predominance with contralateral hand movements. This would also explain Verstynen et al's findings in which they did not see ipsilateral bold signals during motor planning and asserted the ipsilateral process was most consistent with motor execution.[21]

We have further demonstrated for the first time that the features associated with ipsilateral hand movements can be used by a human subject for effective BCI control. Ipsilateral-derived control was comparable to contralateral-derived control in accuracy and speed. Of note, ipsilateral control had an initially faster speed of control than that of contralaterally derived control. The difference in rates of target acquisition support the notion that different neuronal populations are participating in device control. For both ipsilaterally and contralaterally derived control the improved performance measured by accuracy showed a commensurate tuning of the brain signal to match the feature explicitly used for device control (Figure 4B). This increased correlation (measured by $r^2$) of brain signal to identified feature to optimize performance reveals the significant plasticity of the cortex and its ability to alter its electrophysiology for both contralateral (as previously reported[7,63]) as well as ipsilateral derived signals with biofeedback for both modes of control.

In sum, this work is a further demonstration that a given hemisphere plays a larger role in motor control of both hands than has been classically understood. The unique aspects of the electrophysiology of ipsilateral and contralateral hand movements and their ability to be separated for use in device control offers a potential new strategy in which a single hemisphere could compensate for opposite sided hemispheric damage. Through the use of a BCI a single unaffected hemisphere could achieve "bisomatic" control in which the contralateral limb is controlled through normal physiological operation whereas the affected ipsilateral limb is facilitated through neuroprosthetic assistance.

## Disclosures
None.

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