ECoG-Based Brain Computer Interfaces and Applications in Chronic Stroke

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Neuroprosthetics:
A Brain Computer Interface, or BCI, is a device that can monitor and decode the electrical signals of the user's thoughts and convert that information into some type of overt machine control.

Leuthardt et al, Neurosurgery, 2006
Lecture Overview

- BCI Overview
  - Signal modalities
  - ECoG Physiology
  - Exemplar ECoG BCI studies
- BCIs for Stroke
- Biomimetic BCI
  - Single-unit physiology
  - Evaluation of ECoG Correlates of 3-dimensional reaching
**Signal Modalities**

**Microelectrodes**
- 100 μm spacing
- Spikes/LFPs
- ~100 mV
- Highly Invasive

**ECoG**
- 0.1-1.0 cm spacing
- LFPs 0-400+ Hz
- ~100 μV
- Moderately invasive

**EEG**
- 3.0-5.0 cm spacing
- LFPs <40 Hz
- ~10 μV
- Non-invasive
ECoG Recordings
Long-Term Goal

Components
- Telemetry
- Power
- Processing
- Amplifier
- Electrodes

Modulate Environment
- Temperature
- Lighting

Communicate
- Internet
- Word processing

Augment
- Monitoring of Attention Level
- BRAKE!

Control
- Prosthetic limbs
- Reanimation of paralyzed limbs

Schalk and Leuthardt, IEEE, *in press*
Current Research Model

- Utilizes patient with intractable epilepsy
- Superimposes research on clinical model
- Unique access to human cortex and cognitive processes
Electrodes

- Clinical Arrays typically 2.3 mm and 1 cm inter-electrode distances
- Research arrays varied in size and dimension

Leuthardt, J Neural Engineering, 2011

Blakely, IEEE, 2009
Clinical Considerations

- Patients participating have had a major neurosurgical procedure.
  - Ability to participate fluctuates
  - pain, seizures, personal/social needs
- Participation limited to duration of monitoring
  - Ongoing studies - which are required for BCI paradigms - can be challenging

Albert G. et al., J Neurosurg, 2010
Limitations - Research Paradigm

Clinical Constraints of the research paradigm
- Clinical needs always take priority over research goals
- Limited amount of time to work with patients (1-2 hours per day for several days)
- Cognitive capability variable -- due to acute medical factors (pain, seizures, medication) and chronic issues (impaired cognition due to epilepsy)

Noisy environment
- electric beds, pressurized stockings, IV Systems

Bottom line:
- Human ECoG recordings represent a unique and important source for neuroscience experiments
- Personnel needs ready to run experiments whenever the opportunity arises
- Researchers must understand that these patients are donating their time during a very stressful clinical experience. A sensitivity to their needs and a respect for their willingness to participate is paramount
Activity detected by electrodes near apical dendrites during EPSPs is dependent on electrode location.

Extracellular electrodes at the sink and source have opposite polarities.

Intracellular potentials have the same polarity regardless of location.
Physiology of Surface Potentials Can be Ambiguous
Finite-element analysis of electrodes of various sizes demonstrate that ECoG recordings represent broad populations of cortex.

Bundy, JNE (in press)
Superimposed Physiologies
Alpha Waves

- EEG was first demonstrated in humans by Hans Berger in 1924.
- He was the first to describe different waves or rhythms.
- I.e. Alpha (7-13 Hz) rhythm that is suppressed when a subject opens their eyes.

Kandel, Schwartz
Event-Related Desynchronization

Pfurtscheller demonstrated a decrease in Alpha/Mu (10-12Hz) and Beta (13-30Hz) immediately before and during execution of motor movements.

Event-related desynchronization (ERD)

After movement there is a period of increased power.

Event-related synchronization (ERS)

Pfurtscheller & Lopes de-Silva, 1993
Anatomic Distribution of Frequencies

Leuthardt et al, Neurosurgery, 2006
Lower Frequency Bands (< 30 Hz)

$\Theta, \alpha, \mu, \beta$

Higher Frequency Bands (> 30 Hz)

Online BCI Examples
Typical Protocol Design

Two Stages:
- Offline Screening
- Online BCI Control
Online BCI Control

Signal Acquisition

Raw ECOG

Signal Processing

Power

Frequency

Control Band

User Application

User Screen

Condition 1. Imagine movement, directs cursor upwards
Condition 2. Rest, directs cursor downward
Early Studies - Motor Signal Derived BCIs

- Leuthardt et al., 2004
  - First demonstration of ECoG for BCI
  - Demonstrated rapid ability to achieve control
Two Dimensional BCI Control

Higher Frequencies Have Higher Anatomic Resolution
ECoG Used for 2D BCI Control

2 D Control Task

Non-motor modalities: Event Related Potentials

Brunner, et al., Frontiers in Neuroscience, 2011

Used event related potentials (primarily from visual cortex) to control a matrix speller

Subject sustained a rate of 17 characters/min (i.e., **69 bits/min**), and achieved a peak rate of 22 characters/min (i.e., **113 bits/min**)

Fastest ECoG BCI to date

Confirmed by similar studies
Non-motor modalities: Event Related Potentials

BCI in Chronic Stroke
C. Neuroprosthetic Restoration

**Brain Computer Interface**
Detects Ipsilateral Premotor Signals And Actuates Motor Commands Through External Effectors

**External Effector** to Paretic Hand (e.g. robotic glove or functional electric stimulation of nerves and muscles of the hand)

Leuthardt, et al, Neurosurgical Focus, 2009
Distinct Timing

Distinct Anatomy

Distinct Frequency Spectra

Wisneski et al., Stroke, 2008
Using Ipsilateral Motor Signals for BCI

Wisneski et al., Stroke, 2008
Can stroke survivors use their unaffected hemisphere to control a BCI?
Ipsilateral, Contralesional Motor Activity after Chronic Stroke

Bundy et al., JNE 2012
Ipsilateral BCI after Stroke

Bundy et al., JNE 2012
Pathways to Translation

**BCI Rehabilitation**
- Fast training
- Stable control signal
- Non-invasive

**Long-Term Device Operation**
- Chronically stable signal
- High degree of information
- Functionally relevant output
Biomimetic BCI
Cosine Tuning in Single Units

The relationship between motor-neuron firing and movement direction was described by Georgopoulous.

Moran and Schwartz extended the description to both speed and direction

\[ D(t - \tau) - b_0 = ||\dot{V}(t)|| (b_n + b_y \sin[\theta(t)] + b_x \cos[\theta(t)]) \]

- \( D \) = firing rate
- \( V \) = velocity
- \( \theta \) = direction of movement
- \( b_x \) and \( b_y \) = regression coefficients

Georgopoulous et al, 1982
Population Vectors

By combing the activity of a population of neurons a population vector can be calculated to accurately predict kinematics:

$$PV_{y,j}(t) = \sum_{i=1}^{\text{num cells}} \frac{D_{i,j}(t-\tau) - A}{M} \cdot \frac{B_{y,i}}{M}$$

Georgopoulos et al, 1986
Robotic Limb Control
Biomimetic studies in ECoG
Two Dimensional Prediction with ECoG

Electrodes demonstrating modulation of spectral activity with kinematics can be located.

Using the modulation of ECoG activity with movement direction, the following model can be regressed:

\[
\bar{P} = B_{p,0} + B_{p,x} \bar{x} + B_{p,y} \bar{y} + B_{p,z} \bar{z}
\]

\[
\bar{P} = B_{v,0} + B_{v,x} \bar{x} + B_{v,y} \bar{y} + B_{v,z} \bar{z}
\]

\(P\) is the average spectral amplitude, \(B_{p:x,y,z}\) and \(B_{v:x,y,z}\) are the regression coefficients with \((B_{px}, B_{py}, B_{pz})\) and \((B_{vx}, B_{vy}, B_{vz})\) the position gradient and preferred direction respectively.
ECoG Signals Encode Directional Motor Kinematics

Joystick Movement Prediction from ECoG in Humans
01/2006  Gerwin Schalk¹,², Jan Kubanek¹
1) Wadsworth Center/NYSDOH; 2) Rensselaer Polytechnic Institute

Subject C  Horizontal Cursor Position Weights
Subject C  Vertical Cursor Position Weights

Local Motor Potential (LMP) Encode Finger Movements


Task Design

A center-out reaching task was designed to evaluate the extent of information that can be decoded from ECoG signals.

ECoG recordings and 3D hand position are simultaneously recorded during task performance.

Separate planning and movement periods allow for separation of planning and execution of motor movements.
Exemplar Cortical Activations: Electrode Location and Limb
Exemplar Cortical Activations: Electrode Location and Timing
Machine Learning Methods

L1-Regularized Least-Squares Linear Regression:

Fit a regression equation:

$$y_i = w_o + \sum_{j=1}^{\text{NumChan}} w_j x_{ij} + \epsilon_j$$

Subject to the constraint:

$$\text{RSS} = \sum_{i=1}^{n} \left( y_i - w_o - \sum_{j=1}^{\text{NumChan}} w_j x_{ij} \right) + \lambda \|w\|_1$$

This forces a sparse solution and minimizes overfitting

Cross-Validation Testing:
Velocity Prediction

<table>
<thead>
<tr>
<th>Patient</th>
<th>Hand</th>
<th>Trials (n)</th>
<th>Average Cross-Validation R-Value</th>
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<td>1</td>
<td>Contra</td>
<td>245</td>
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<td>Ipsi</td>
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Directional Specificity: Single Channels

- As in previous work single channels can be found with spectral power modulated by direction.
- As electrode locations are dependent upon clinical needs, the presence of electrodes with this directional modulation varies.
- Utilizing spatial combinations of electrodes, we can obtain more information about movement kinematics.
Given signals \( X \) with covariance \( C \):

\[
C = \frac{XX'}{n(XX')}
\]

Mean covariances from two classes of data can be combined to form:

\[
C_C = C_1 + C_2
\]

With Eigen-decomposition

\[
C_C = U_C \Lambda_C U_C'
\]

A whitening transform using this combined covariance can be calculated

\[
P = \sqrt{\Lambda_C^{-1}} U_C'
\]

Applying this transform to each class of data, we have

\[
S_1 = P C_1 P', \quad S_2 = P C_2 P'
\]

with property:

\[
S_1 = B \lambda_1 B' \quad \text{and} \quad S_2 = B \lambda_2 B, \quad \text{where} \quad \lambda_1 + \lambda_2 = I
\]

Therefore, we can apply the eigenvectors of \( S_1/S_2 \) as **spatial filters** designed to **maximize/minimize the variance** in our two classes

\[
Z = WX = (B'P)'X
\]
Encoding of Directional Information: Contralateral

Contralateral

CSP 1

Frequency (Hz)

Time (s)

CSP 2

Frequency (Hz)

Time (s)

CSP 64

Frequency (Hz)

Time (s)

CSP 65

Frequency (Hz)

Time (s)
Encoding of Directional Information: Ipsilateral
Future Directions

- ECoG Recordings contain information related to planning and execution of motor movements.
- Speed can be predicted with a high-degree of accuracy.
- ECoG signals also appear to encode directional kinematics.
- Future work will further investigate the utilization of ECoG for off-line prediction of directional kinematics and on-line BCI control based upon this prediction.
Questions?