Prediction of Human Movement Intention for Brain-Computer Interface: Highlights the Future

Ou Bai, Ph.D.
obai@vcu.edu

EEG and BCI Laboratory
Department of Biomedical Engineering
Virginia Commonwealth University

Human Motor Control Section
National Institute of Neurological Disorders and Stroke
National Institutes of Health
Brain Communication with Environment: Science Fiction?
What is Brain-Computer Interface (BCI)

To provide an alternative pathway bypassing damage to restore human motor functions for people with neurological diseases, in particular, for those who are totally paralyzed or “locked-in”

Amyotrophic lateral Sclerosis (ALS)
Primary Lateral Sclerosis (PLS)
Stroke
Cerebral palsy
Amputees
Spinal Cord Injury
BCI Requires System Approaches

Integrating Technologies:

- System Design and Integration;
- Data Acquisition from Human Subjects;
- Signal Processing, Machine Learning, and Control Technology.
Interfacing Categories (1)

- **Invasive technology**
  - Electrode matrix Implanted in cortex
  - Neuronal action potentials or local field potentials
  - Supposed to collect multidimensional information
  - Substantial technical difficulties and clinical risks
Interfacing Categories (2)

- Noninvasive technology
  - Scalp EEG or MEG signals
  - Supposed to collect very limited information
  - Minimal risk in clinical practice
Cortical recording (ECoG)

- Signal from cortical surface
- Potential to collect more information than scalp recording
- Using routine surgical operation

Image adopted from Dr. Zoltan
Outcomes of Invasive Approaches (1)

Dr. Donoghue’s group of Brown University
Primates and human subjects
Decoding of neuronal firing rates/local field potentials from motor cortex
http://donoghue.neuro.brown.edu/research.php
Outcomes of Invasive Approaches (2)

Dr. Schwartz’s group of Pittsburgh University
Primates subjects
Decoding of neuronal firing rates from motor cortex
http://motorlab.neurobio.pitt.edu/
Outcomes of Invasive Approaches (3)

Dr. Nicolelis’s group of Duke University

Primates subjects

Decoding of local field potentials from motor cortex

http://www.nicolelislab.net/NLNet/Loa d/index.htm
Dr. Andersen’s group of California Institute of Technology
Primates subjects
Decoding of neuronal firing rates from parietal reach region (PRR)
Cognitive control signals for neural prosthetics. Science 305: 258-262
Outcomes of Noninvasive Approaches (1)
Slow cortical Potentials

Dr. Birbaumer’s group of University of Tubingen
Human subjects (PLS patients)
Decoding of EEG slow cortical potentials over motor cortex
Outcomes of Noninvasive Approaches (1)

--- Continue

Outcomes of Noninvasive Approaches (2)
Event-related Potentials

Dr. Donchin’s group of University of Illinois
Human subjects
Decoding of EEG Event-related Potentials (P300) over central-parietal areas
Outcomes of Noninvasive Approaches (3)

--- Continue

Outcomes of Noninvasive Approaches (4)
Learning to control EEG Rhythms

Dr. Wolpaw’s group of Wadsworth Center, NY

Human subjects

Decoding of EEG mu and beta rhythms over sensorimotor areas

Outcomes of Noninvasive Approaches

(4)

--- Continue

Brain Signals for BCI

- **Invasive methods:** single neuron activity or local field potentials
  - Collects multi-dimensional information
  - Substantial technical difficulties and clinical risks

- **Noninvasive methods:** EEG/MEG/fMRI and semi-invasive method: ECoG
  - Collect very limited information
  - Minimal risk in clinical practice
  - Usually long-term training required
Development (Testing) BCI using Real Brain Signals

- The simplest and direct way is to test on targeted patients, say “locked-in” patients
- However, it is difficult to find targeted patients to participate in pre-clinical BCI development, partly because those patients are usually very weak, and particularly since:

Current BCIs are not user-friendly

- Usually requires long-term training, e.g. cursor control by regulating Mu rhythm took 180 hour training (lasting over half year), Wolpaw and McFarland, 2004
- Extreme mental load to drive the BCI, i.e. easy fatigue
- Limited information transfer rate
BCI Development in Human Motor Control Section

- Development of BCI using human real brain signals
  - Performing patient studies
  - Extensive neurophysiological analysis to exclude possible contamination of various artifacts

- Development of user-friendly BCI
  - No or minimal training required BCI
  - BCI created by human natural behaviors instead of using artificial brain signal which requires extensive mental work
Technical Development of BCI System

- Hardware system design:
  - Real-time EEG data acquisition
  - High-speed online data processing
  - Provide biofeedback control

- Software system design:
  - Signal processing and pattern recognition/machine learning algorithms
  - Data visualization
  - Computer vision and graphic user interface
Hardware System Design

Signal Processing

Spatial Filtering
1. None
2. Principal Component Analysis
3. Independent Component Analysis
4. Common Spatial Pattern Analysis
5. Simple surface Laplacian Derivation

Temporal Filtering
1. Wide Band Power
2. Narrow Band Power with Welch Method Estimation
3. Narrow Band Power with Discrete Wavelet Transformation

Modeling & Classification
1. Linear Discrimination
2. Quadratic Discrimination
3. Bayesian Classification
4. Multilayer Perceptron Neural Network
5. Probabilistic Neural Networks
6. Support Vector Machine

Data Acquisition System

Work Station

AD Converter

Target Stimulation System

Virtual Control/Computer Game

Feedback Control

Virtual Reality System

Visual Paradigm

Auditory Paradigm

Amplifier

Synchronization Signal
Software System Design

Brain-Computer Interface to Virtual Reality (BCI2VR)

Welcome to BCI Virtual Reality

Data Acquisition  Target Stimuli

Model Optimization  Virtual Reality

Developed by Dr. Bai. All Rights Reserved.
Exploration of Computational Methods for Single-Trial EEG Classification
A mathematical approach

Multiple comparison with Bonferroni correction

Spatial Filter

Temporal Filter

Classification

A User-friendly BCI: Neurophysiological Rationale

- Human motor control physiology
  - Human possess the intention to move
  - Humans can perceive intention prior to the voluntary movement
  - Human movement intention can be observed in EEG signals

Therefore, we may detect human movement intention from EEG
  - even in the absence of movement
  - Or, just thinking about the movement
Movement-Related Cortical Potentials (MRCP)

ERD/ ERS in Central Beta Band

Binary-Cursor Control: Paradigm Design
Neurophysiological Validation from MEG study (SAM)
Online Validation: Testing with Binary-Cursor Control Game
2D-Cursor Control: Improving Information Transfer rate
Neurophysiological Validation from MEG study (SAM)
Online Validation: Testing with Binary-Cursor Control Game
## Acknowledgments

**Senior Investigators:**
- Dr. Mark Hallett
- Dr. Mary Kay Floeter
- Dr. Hiroshi Shibasaki

**Fellow Colleagues:**
- Dr. Noriaki Hattori
- Dr. Jiang Li
- Dr. Masao Matsuhashi
- Dr. Yohei Tamura
- Dr. Nolte Guido
- Dr. Mari Zoltan
- Dr. Lewis Wheaton

**Student/Interns:**
- Rebecca Williams
- Turan Kayagil
- Valerie Morash
- Claudia Bonin
- Steve Furlani
- Casey Holliday
- Mukilan Nataraj
- Michael Apanius
EEG-Based Non-invasive BCI

- EEG: detects brain electrical activity from scalp of brain
  - EEG device is portable
  - Less expensive
  - Safe for clinical applications
- However, it is extremely difficult to extract meaningful information from EEG, because
  - Human skull and scalp may blur the neuronal activity in the cortex of brain
  - Various artifacts contaminated: EMG, EOG etc.
Are these “Brain-Computer Interface”?  

**NeuroSky**: gel-free sensor reading ‘brain wave’ from forehead  

**Emotiv**: detects a user’s expressions, feelings and thoughts.
BCI: Yes or No

- No physiological data provided from either company

However, we can interpret

- Sensors from forehead mainly sampled EOG activity
- No physiological evidence shows EEG can pick up neuronal activity in frontal lobe
- Sensors from temporal lobe mainly sampled EMG activity
- Physiologically, EEG is used to detect epileptic seizures from temporal areas
BCI provides a **non-muscular channel**

- Both EOG and EMG are associated with movement
- Any interface using those electrical activity (or artifacts named in EEG community) can be called ‘BCI’?

**Our answer is definitely ‘NO’, at least in the strict sense**

**Although**

- These artifacts may be more easily detected
- The detection, therefore, may be more robust
Are we developing ‘real’ BCI

- It is almost impossible to find totally ‘locked-in’ patients; most of them reserve the ability to move their eyes
- Therefore, do we know any muscular activity contaminated our BCI experiment?

The answer is negative

- Two recent papers argued that most BCI researchers didn’t pay attention to possible contamination of EOG and EMG artifacts, in particular, during early training
BCI 2VR: Data Acquisition
Online data acquisition and monitoring
BCI 2VR: Target Stimuli
Visual/auditory stimulation with synchronization with data acquisition
BCI 2VR: Model Optimization

Data analysis and model optimization with cutting-edge signal processing and classification technologies
BCI 2VR: Virtual Reality
Brain interface to virtual environment
Exploration of Computational Methods for Single-Trial EEG Classification
A mathematical approach

- **Experimental Paradigm:** Self-paced key-stroke on either hand determined by subject himself
- **Subjects:** 12 right-handed healthy volunteers
- **Data for classification:** -1.5 s to movement onset, about 150 samples of each movement for each subject
- **Strategy:** Comparison study on **90 combinations** of computation methods
Future Directions

- Cognitive spelling machine
- Interface for device/robotic control
- BCI-based sensorimotor rehabilitation
Cognitive Spelling Machine

- Purpose: Unlock the patients with ‘locked-in’ syndrome
Cognitive Spelling Machine

- Neurophysiological study on patients with ‘Locked-in’ syndrome
  - ALS patients
  - Neurophysiological features (ERD/ERS) associated with movement intention

- Mental strategies for enhancing the efficiency
  - Static detection of movement intention from ERD
  - Dynamic detection of movement intention from ERS and ERD
Interface for Device Control

- Purposes:
  - Alleviating human suffering and improving quality of life
  - Reducing the health care costs
Interface Device Control

- Investigation on detection of multiple movement intention: From offline to online prediction/detection
BCI-based Sensorimotor Rehabilitation

- Integrate movement intention-based BCI and rehabilitation robots
BCI-based Sensorimotor Rehabilitation

- Evidence from motor imagery-based stroke rehabilitation
  - Motor imagery has been proven as an effective method for functional rehabilitation for chronic stroke patients, which may also reduce pain in paretic limbs
  - However, as there is no feedback in the motor imagery-based stroke rehabilitation, patients may easily lose interest in the training and therapists would have difficulty in providing correction during the training
  - BCIs that can monitor motor imagery might provide a possible biofeedback for both patients and therapists so the efficiency of motor imagery-based stroke rehabilitation may be improved.