Brain Computer Interface for Neuro-Rehabilitation

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Problem

- There are many neurological conditions that cause paralysis, yet there are no means to reverse the effects of these neurological injuries.
- These conditions tend to lead to prolonged disability, high cost to society and loss of quality of life.
  - Stroke: \(\sim800,000\) new cases per year, \(>7\) million living with chronic stroke
    - Health care cost is \(\sim$50\) billion/year
  - Spinal Cord Injury:
    - \(\sim15,000\) new cases per year, \(\sim250,000\) living with chronic spinal cord injury
      - Health care cost \(\sim$10\) billion/year, another \(\sim$5\) billion in lost productivity/year
• New biomechanical means have been sought to substitute for lost neurological functions
• Brain computer interfaces (BCIs) can potentially act as a neuro-prosthesis to restore or help improve lost functions
• Brain-computer interface (BCI) are systems which translate neurophysiological signals into machine commands, enabling “brain-control” of external devices

• BCIs can potentially enable “brain-control” of prostheses to restore motor function after neurological injuries
BCI: How it works

- A user voluntarily performs a mental task to generate predictable electrophysiological changes
- Signals are acquired
- BCI system decodes these signals to recognize the user’s intentions
- Decoded intentions are mapped to various commands to an external device
Outline

• Physiological basis of BCIs
• BCIs as Neuroprostheses
• BCIs as Neuro-rehabilitative tool
• Quick survey of BCI research community
PHYSIOLOGICAL BASIS OF BCIS
Signal Acquisition Modalities

- **EEG**
  - Easy and safe
  - Limited resolution
  - Limited frequency range

- **ECoG**
  - Higher resolution
  - Possible risk
  - Unknown long-term stability

- **Spikes and LFPs**
  - Highest resolution
  - Possible risk
  - Unknown long-term stability
EEG: Sensorimotor Rhythm

- Combination of $\mu$ and $\beta$ rhythm over the Rolandic region
- This is an idling rhythm
- Modulation:
  - Amplitude is decreased during executed movement or motor imagery
  - Returns to baseline after executed movement or motor imagery ends

Wolpaw et al. 2002
ECoG – ERD/ERS and high-\(\gamma\)

- Desynchronization of \(\alpha\) and \(\beta\) bands during finger movement
- Increase in power of high \(\gamma\) bands during finger movement

Miller et al. 2009
ECoG – Trajectory Prediction

- ECoG signals during finger movement can further be decoded to reconstruct movement trajectory.
- Preservation with motor imagery needs to be further studied.

Kubanek et al. 2009
Microelectrodes

- Microelectrodes can record individual neurons or local field potentials
- Neurons in motor cortex appear to be directionally tuned for arm trajectory
BCI AS A NEURO-PROSTHESIS
State of the Art

The BrainGate trial at Brown University

- Considered the most advanced BCI in the world
- 2 subjects with quadriplegia were able to control a 6-degrees of freedom robotic arm to perform goal oriented tasks
- Problem:
  - Implantation of the BrainGate device is invasive
  - Recording degrades overtime and is expected to fail
  - Trajectory not smooth

Reach and grasp by people with tetraplegia using a neurally controlled robotic arm. 
ECoG-based BCIs

• If microelectrode array signals are unstable, is there another alternative?
• ECoG may be a potential source of signal for trajectory control of individual joints of the arm and hands
State of the Art

University of Pittsburg 30-day ECoG Trial

• Brain-control of a 3D cursor is mapped to the robotic arm

• Limitation is that this only performs reaching tasks

http://clinicaltrials.upmcphysicianresources.com/bci/
Decoding individual joints would potentially enable finer control of an upper limb prostheses.

Current studies report *some* ability to decode finger trajectories offline, unknown for other joints.

No translation to online BCI operation with this scheme yet.
UCI ECoG-BCI Study

Feedback

ECoG Signals

ECoG Signal Decoder

Award 1134575, PIs: Nenadic, Do
BCI-Control of Ambulation

- Loss of gait function is typically seen after SCI
  - Results in prolonged sitting and reduced physical activity, which leads to many medical co-morbidities
- Still no way to restore able-bodied-like ambulation after SCI
- BCIs can potentially restore able-bodied-like ambulation after SCI
Control in Able-Bodied Individuals

• EEG recorded during 10 mins of alternating idle/walk motor imagery

• EEG prediction model generated:
  • FFT (2 Hz bins)
  • Dimensional reduction (classwise principal component analysis\(^1\) and Approximate Information Discriminant Analysis\(^2\))
  • Bayesian Classifier

• In online BCI operation, subjects use walking motor imagery to control avatar
  – Walk along linear path
  – Stop and dwell for 2 seconds at 10 designated points along the way

BCI-Controlled Walking Avatar Control by Subjects with SCI

Subject with Paraplegia Uses BCI to Control a VR Avatar

T8 ASIA B SCI Subject (11 years post injury)  C5, Syrinx, (14 years post onset)
BCI-Robotic Gait Orthosis Control

• Next step is to translate from virtual reality to a physical device to further explore the feasibility of BCI-controlled ambulation

• A treadmill-suspended robotic gait orthosis (RoGO), such as the Lokomat (Hocoma, Switzerland), facilitates easy and safe initial testing
Brain-Computer Interface Controlled Robotic Gait Orthosis

- 1 able bodied subject
- EEG recorded during 10 mins of alternating idle/walk motor imagery, EEG prediction model then generated using CPCA\(^1\) and AIDA\(^2\)
- BCI interfaced with robotic gait orthosis (Lokomat)
- Subject asked to using walking motor imagery control robotic gait orthosis in alternating 1 min cues of idle/walk (over 5 mins total)
  - 5 trials performed
  - EMG monitored to establish “brain-control” and rule out “cheating”

Results – Offline Decoding of Walking Motor Imagery

BCI-Controlled Robotic Gait Orthosis

Time Course of Online BCI-RoGO Operation

A representative online session:
• Blue blocks: instructional cues to attempt dorsiflexion
• Red blocks: epochs of BCI-RoGO dorsiflexion states
• Black trace: corresponding gyroscope trace
• Gold/Teal/Purple: EMG for quads/tibialis anterior/gastrocnemius

Quadriceps EMG Power Spectrum

http://youtu.be/W97Z8fEAQ7g
Results

<table>
<thead>
<tr>
<th>Trial</th>
<th>X-Corr (lag in sec.)</th>
<th>Omissions</th>
<th>False Alarms (duration)</th>
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</thead>
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<tr>
<td>1</td>
<td>0.771 (10.25)</td>
<td>0</td>
<td>1 (12.0)</td>
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<tr>
<td>2</td>
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<td>1 (5.3)</td>
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<tr>
<td>4</td>
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<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0.870 (12.00)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- Average cross-correlation between cues and BCI response is 0.81±0.06 (p<10^{-5}) over 5 trials
- No omissions
- No false alarms by the end of 5 sessions
Future Direction

• Testing in additional able-bodied subjects followed by SCI subjects
• Eventual transition to control of free, over-ground lower extremity prostheses:
  – robotic exoskeleton
    • Cauda equina, conus medullaris, muscular dystrophy
  – functional electrical stimulation systems
    • Spinal cord injury
Wireless EEG to BCI Computer

Commands transmitted wirelessly to microcontroller

Portable EEG system

EEG signals from subject

Wireless Microcontroller

Parastep Stimulator Module

Relay

RJ45 cable to stimulator

Stimulation signal to FES electrodes

Subject ambulating with FES

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Subject ambulating with FES

Award #: 1160200, PIs: Nenadic, Do
BCI as Neuroprostheses- Conclusion

• Upper and lower extremity prostheses to restore basic movements after neurological injury may be possible

• Control is still very basic at this point, but continued research can potentially improve upon smoothness and increase degrees of freedom
BCI AS A REHABILITATIVE TOOL
Problem

• For the remainder of stroke, SCI, or TBI patients who are affected by partial paralysis, physiotherapy only provides a limited amount of neurological improvement

• Hence novel means must be designed to further improve neurological outcomes

• BCI-controlled functional electrical stimulation (FES) systems may be one such novel approach
Coupling activation of post-stroke cortex with electrical stimulation of the peripheral neuromuscular system may induce Hebbian learning mechanisms to provide lasting neurological and functional gains beyond that of conventional therapy.
BCI-FES for Neuro-rehabilitation

- This study describes the feasibility of such a system for foot drop due to stroke
- Stroke subjects with foot drop were recruited
- 10 minutes of training data acquired from 64 channel EEG during alternating epochs of attempted foot dorsiflexion and idling
EEG Decoding Model

• EEG decoding model generated using following algorithm
  – FFT (power calculated over 2 Hz bins)
  – Dimensional Reduction (with classwise Principal Components Analysis\(^1\) and Approximate Information Discriminant Analysis\(^2\))
  – Bayesian Classifier
• Decoding algorithm will classify novel EEG as either Idling or Dorsiflexion classes
• Online, the decoding algorithm detects EEG changes associated with attempted (but ineffective) foot dorsiflexion and the BCI system delivers electrical stimulation to elicit foot dorsiflexion

FES Device

- A neuromuscular stimulation unit (interfaced with the computer via a microcontroller) provided FES\(^1\)
  - FES electrodes were placed over the tibialis anterior muscle

Online BCI Operation

- Subjects are given alternating 10-sec “Idle” and “Move” cues for 200 secs
  - In response, subjects must idle or attempt dorsiflexion
  - BCI-FES response is recorded
Results - Video

Subject with Foot Drop due to Stroke Operates BCI-FES System

http://youtu.be/pfBoWRClrG8
Results - Online BCI Operation

<table>
<thead>
<tr>
<th>Session</th>
<th>Cross-correlation</th>
<th>Lag Time (sec)</th>
<th>Omissions</th>
<th>False Alarms</th>
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<td>3</td>
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<td>Average</td>
<td>0.60</td>
<td>1.83</td>
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</tbody>
</table>

A representative online session:
- Blue blocks: instructional cues to attempt dorsiflexion
- Red blocks: epochs of BCI-FES dorsiflexion states
- Black trace: corresponding goniometer trace

BCIs as Rehabilitation Tool - Conclusion

• BCI-FES therapy is feasible in stroke patients, but will need to be formally tested in a stroke population to determine safety and efficacy.

• Stroke patients may have non-classical motor representation, which necessitates data-driven BCI decoding approaches.
SURVEY OF BCI RESEARCH COMMUNITY
Other BCI-FES Systems

Pfurtscheller et al. 2003
3D Cursor Control with EEG-BCI

McFarland et al. 2010
Wheelchair control with EEG-BCI

Millan et al. 2009
Video Games

Playing the Game
“Pong” with EEG

Neuroelectrical Imaging and BCI Lab (NEILab)
Fondazione Santa Lucia, Roma, Italy
http://www.neilab-fsl.it/

BCI 2000
Conclusion

• BCI technology may work as neuro-prostheses:
  – Still need to define practical applications that will solve neurological problems and can potentially translate to the bedside
  – Permanent solutions that work 24/7 and are stable over years
  – Smooth and high accuracy control
Conclusion

• BCI technology may also work neuro-rehabilitative tools
  – Still need to formally prove safety and efficacy
  – Still need to implement in a practical manner
UC Irvine Brain Repair Center

• **UCI’s Brain Repair Clinic** will systematically deliver neuro-rehabilitation interventions to improve neurological and functional outcomes after stroke. In a focused intervention, this clinic will:
  – Monitor and treat post-stroke depression
  – Screen for medications that worsen stroke outcome
  – Prescribe PT/OT/ST in conjunction with pharmacological agents

• We would appreciate your referrals of ischemic stroke patients who are:
  – Age over 14
  – More than 1 week after ischemic stroke onset

• **Patients can be referred by calling Rosie Serrato at 714-456-2332.**
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