Brain-Computer Interfaces to Replace or Repair the Injured Central Nervous System.

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Three approaches to restore movement

1. Replace: Brain control of muscle stimulation
2. Replace & Repair: Intra-Spinal Stimulation
3. Repair: Brain-triggered spinal stimulation

Three approaches to restore movement

Brain control of muscle stimulation

Control signals recorded from motor cortex…
...trigger functional electrical stimulation (FES) delivered to paralyzed muscles

Recording from human motor cortex

100-electrode array

Monkeys use brain activity to control a robotic arm for self-feeding

Activity decoded from groups of neurons to control end-point of a robot arm in 3-dimensions

Control robotic arm 5 years after implant

Serial 2D task + Grasp/Tilt accomplished with 3 (or 13) neurons
Connecting cortical neurons to control muscle stimulation

Directional tuning of motor cortex neurons - decoding

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Human subjects learn non-intuitive muscle control

Monkeys learn random decoder equally well

Train single neurons to control muscle stimulation
1. Cell activity during wrist movement

2. Direction tuning sets visual feedback

Visual feedback of cell rate with targets oriented in preferred direction

3. Monkey controls cursor with neuron

Monkeys can maintain cell activity for prolonged periods

Neurons can be trained to produce or suppress activity for sustained periods of time

Moritz & Fetz, J Neural Engineering 2011

Monkey controls 2D cursor directly using only 2 neurons

Monkey directly controls 3D cursor using only 3 neurons

Moritz & Fetz, J Neural Engineering 2011
Brain-controlled muscle stimulation

- Cell activity directly converted to muscle stimulation (FES)
- Wrist muscles temporarily paralyzed by nerve block

Moritz et al., Nature 2008

Model of reversible paralysis

Catheters deliver anesthetic to nerves

Moritz et al., Nature 2008

Cortical control of muscle stimulation

Cortical neurons move cursors on computer screen
Cortical neurons trigger FES of paralyzed muscles via standard or miniature computer

Moritz et al., Nature 2008

Brain-control of muscle stimulation

Monkeys match 5 levels of wrist torque using cortically-controlled FES
Only 5-10% of torque can be produced without stimulator

Moritz et al., Nature 2008

Cell tuning does not predict control of FES

- Tuned neurons initially control cursor faster
- The brain learns to use all neurons equally well to control FES with practice
- Feedback triples population of useful neurons

Moritz et al., Nature 2008

Can other cortical areas be used to control FES?

- MCA stroke → arm paresis
- Neurons in somatosensory cortex can be controlled equally well
- Record from spared cortex for control? (e.g., leg area or cortex contralateral to injury)

Moritz & Fetz, J Neural Engineering 2011
Outline: Intra-Spinal Stimulation

1. Replace: Brain control of muscle stimulation
   2a. Replace: Intra-Spinal Stimulation

Advantages of spinal stimulation

- More natural recruitment order of motor units (Mushahwar & Horsch, 2000)
- Elicit functional muscle synergies or reflex circuits from single stimulating electrodes, reducing number of electrodes & controllers
  - Evoke complete stepping movements in spinal cats with only 4 electrodes (Mushahwar et al. 2002)

Spinal stimulation evoked movements

Hand or arm movements were evoked at 76% of stimulation sites

Example: Intra-spinal microstimulation

Synergies evoked by spinal stimulation

Simultaneous flexion of fingers & thumb was the most common synergistic movement evoked

Movements of the digits were most commonly evoked

Replace: Spinal stimulation

- Hand and arm movements are readily evoked throughout cervical spinal cord.
- Synergist muscles are commonly co-activated by spinal stimulation.
- Perhaps brain-controlled spinal stimulation is the ideal neuroprosthesis to restore hand & arm function

Mushahwar et al., J Neural Eng (2007)
Outline: Intra-Spinal Stimulation

1. Replace: Brain control of muscle stimulation
   2b. Repair: Intra-Spinal Stimulation

Epidural stimulation promotes movement

- Case Study: 23-year-old man with paraplegia from a C7–T1 subluxation
- ASIA – B: abnormal sensation present below the lesion, but no motor function of trunk or leg muscles
- Multisite epidural electrode array over L1-S1
- Therapeutic stimulation duration 40-120 min per session
- 7 months of stimulation paired with movement training (standing, stepping, etc.)

Harkema et al., Lancet 2011

Without Epidural Stimulation

Attempts of voluntary movements (leg, ankle, and toe) without epidural stimulation

Harkema et al., Lancet 2011

With Epidural Stimulation ON

Voluntary movements (leg, ankle, and toe) with epidural stimulation (4 V, 30 Hz)

Harkema et al., Lancet 2011

Intra-spinal stimulation for sustained recovery?

- Epidural stimulation on cord dorsum activates sensory afferents
- Intra-spinal stimulation in ventral horn activates spinal motor neurons and interneurons
- Intra-spinal stimulation may promote sustained recovery of function after incomplete spinal cord injury

Mushahwar et al., J Neural Eng (2007)

Three approaches to restore movement

1. Replace: Brain control of muscle stimulation
2. Replace & Repair: Intra-spinal microstimulation
3. Repair: Brain-triggered spinal stimulation
Synchronizing cortical sites leads to stronger connections

Promoting repair of functional connections after injury

Stimulation may guide repair of connections via LTP & Hebbian plasticity

Neurons recorded from motor cortex

Brain-triggered spinal stimulation

Intact motor system

Brain-triggered spinal stimulation

Incomplete spinal cord injury

Summary: BCI to restore movement

1. Replace: Monkeys can use arbitrary neurons to control muscle stimulation and move a paralyzed arm. Could alternative brain areas be used for control following stroke?

2. Replace: Spinal stimulation can evoke forelimb movements & functional muscle synergies. Is BCI-controlled ISMS the ideal combination for limb reanimation?

3. Repair: Spinal stimulation enhances recovery after injury. Can synchronous stimulation collaborate with stem cells to promote spinal cord regeneration?
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