Interfaces To The Nervous System: Devices And Applications

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Outline of Presentation

• Device: Peripheral Nerve Interface: Utah Slanted Electrode Array

• Applications
  — Restoring Mobility
    • Restoration of Stance
  — Control of Prosthetic Arm
  — Bladder Control

• Future Directions
Peripheral Nerves: The Utah Slanted Electrode Array

- Focal stimulation of axons.
- Electrode tips ~ same size as axons.
- Electrode tips abut axons.
- No fiber > 200 μ from electrode tip.
- High electrode-count arrays possible.
- Arrays integrate with tissue.
- Makes stable interface, minimal influence of motion.
Surgical Implantation of Electrode Array

Automated, simple, reproducible
“Plug & Play”, push-button operation
A key feature for clinical implementation!

1 insertion = 100 electrodes
< 200 usec (little tissue compression)
Restoring Mobility
Sites for Neuroprosthetic Interventions

Peripheral Nervous System

Sensors

Muscles

Spinal Cord

Peripheral Nerves

Cerebral Cortex

Sensory Neuroprosthesis

Injury

Motor Neuroprosthesis

S1

M1
Getting control signals from CNS

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M1

Andy Schwartz
John Donoghue
Krishna Shenoy
Miguel Nicolelis
Single unit recordings w/ UEA from human cortex

Bradley Greger and Paul House
Control by volitional thought

- Cyberkinetics, Inc.
- FDA granted IDE.
- 5 subjects.
- UEA implanted in MI.
- Subject controls computer cursor via his volition.
- No complications.

Matt Nagel
Leigh Hochburg
John Donoghue
Reanimating skeletal muscles

Sensory Neuroprosthesis

Cerebral Cortex

Peripheral Nervous System

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Muscles

Normann Clark Miller

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Cat Stance

Using USEAs to stimulate hind limb extensors

Getting the paralyzed out of their wheel chairs
Why use USEAs for stimulation of peripheral nerves? Advantages

• 1 implant accesses many muscles.
  – Independent access to flexors and extensors.
• 1 implant accesses many individual motor units.
• Physiological force recruitment mechanisms.
• Fatigue resistant force generation.
Surgical Access to Nerves

Sciatic Nerve (triceps surae)

Femoral Nerve (quadriceps)

Muscular Branch (Hamstrings)

4 mm x 4mm USEA fits nerve well. Access is not complex.
Sciatic Nerve Anatomy

Chronic Histology
5 Month Post Implantation

Custom made, thin silicone containment cuff

Acute Histology
## Enhanced, Selective Access to Multiple Muscles and Motor Units

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B/TE = biceps femoris (thigh)
P = peroneus brevis
MG = medial gastrocnemius
LG = lateral gastrocnemius
S = soleus
F = flexor hallucis longus
P = plantaris
E = extensor digitorum longus
T = tibialis anterior

- 9 different leg muscles selectively accessed via a *single* USEA implanted in cat sciatic nerve
- Low stimulation thresholds: 1-10 uA

Almut Branner et al.
Selectivity between Muscles

Two separate electrodes: One exciting Gastrocnemius, and one exciting soleus

Almut Branner et al.
Single electrode stimulation of sciatic nerve:
Produces either Tremor or Fatigue (you chose!)

Continuous record (1sec)

**Low frequency stimulation produces tremor in force.**

Mean Force (90 sec)

**However, low frequency stimulation delays onset of fatigue**

McDonnell et al.
Interleaved multielectrode Intrafascicular Stimulation: Minimizes Fatigue and Tremor

- Motor unit 1
- Motor unit 2
- Motor unit 3
- Motor unit 4

Muscle

Peripheral nerve
- Motoneuron 1
- Motoneuron 2
- Motoneuron 3
- Motoneuron 4

Electrode

- Elect 1
- Elect 2
- Elect 3
- Elect 4

Interleaved Stimulation
- Elect 1
- Elect 2
- Elect 3
- Elect 4

Individual motor unit stimulation = XHz, Net muscle stimulation = 4XHz

Simultaneous Stimulation
- Elect 1
- Elect 2
- Elect 3
- Elect 4

Individual motor unit stimulation = 4XHz, Net muscle stimulation = 4XHz
Multi-Electrode Interleaved Stimulation of four electrodes in sciatic nerve

Continuous record (1sec)  Mean Force (90 sec)

- Interleaved stimulation of multiple electrodes:
  - Produces minimal tremor.
  - Greater fatigue-resistance than simultaneous stimulation.
Cat Stance

- Cat anesthetized.
- Positioned in cantilevered trough.
- ~ ¾ of cat’s weight counterbalanced with spring.
- Unilateral nerve sequential stimulation 5 electrodes.
- 40 Hz, 1.3 volt, pulse width modulation.
Three-Joint Stance: 
*Concurrent* Activation of Ankle, Knee, & Hip

- Graceful, controlled sit-to-stance (-to-sit)
- Reasonably parameter tolerant
- *Multiple* electrodes
Fatigue: interleaved vs. synchronous stimulation

6 DoF force plate under foot

Interleaved Stimulation

Synchronous Stimulation

Note: Movie sped up X 3
Conclusions

- Platform developed for automated stimulation of hundreds of penetrating microelectrodes.
- Simple surgical access to nerves of legs.
- Automated algorithms for electrode/muscle mapping, stimulation independence estimation, and stimulus parameter estimation (strength and phasing).
- ‘Normal’ appearing stance achieved.
- Interleaved stimulation produces greater fatigue resistance than synchronous stimulation.
Getting Sensory Feedback

Peripheral Nervous System

Sensory Neuroprosthesis

Normann Stein Weber

Spinal Cord

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Experimental Set-up

Magnetic Field Sensors (6 degrees of freedom)

Measure $x$, $y$, $z$ of sensors. Compute polar coordinates of manipulated ankle ("R" and Theta).
Recordings from DRG (L6 and L7)

2-5x10 arrays

Simultaneous Acute Recordings from >100 Units
>80 correlate w/ kinematics

10 seconds of data
Raster Plots and Leg Kinematics Versus time
Estimations for Random Motion

Radial coordinates

Solid = measured values, Dotted = predicted values

Correlation Coefficients
Distance = 0.88
Orientation = 0.96

Neural recordings & algorithm provide a highly accurate descriptor of limb position
Talking to the Brain

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The Next Generation Arm Prosthesis

DARPA

Dr. Gregory Clark
Our Goal

- Osteointegrated implant
  - Direct skeletal attachment
  - Universal, break-away binding
  - Management of infection
  - Connectors

(Kandel et al., 2000)
Our Goal

- **Osteointegrated implant**
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  - Next generation prosthetic arm
  - Actuators
  - Sensors

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• Neural Interface
  – Motor control

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- **Neural Interface**
  - Motor control
  - Sensory feedback

(Kandel et al., 2000)
Warwick’s Experiment

The application of implant technology for cybernetic systems.
The final application: Bladder Control in the SCI or geriatric patient

Heather A.C. Wark
Utah’s approach to bladder control

• Implant Utah Slanted Electrode Array in the pudendal nerve.

• Some electrodes will target afferent (sensory) fibers initiating bladder contraction.

• Other electrodes will target efferent (motor) fibers controlling external urinary sphincter.

Will this approach really work?
Bladder contractions evoked w/ electrical stimulation of pudendal nerve via USEA

Sphincter EMG activity

Bladder pressure

Electrical stimuli

Faster time scale
Restoration of Continence:
Selective **Low Frequency** stimulation of EUS efferents

Incontinence produced by transection of one pudendal nerve.
Efferent nerve block w/ high frequency stimulation

- USEA in canine sciatic nerve
- Cuff electrode also around sciatic nerve proximal to USEA
  - Calf muscle excited once/second with cuff electrode
  - Calf muscle twitches recorded with force transducer
- 2 kHz stimuli on 6 electrodes targeting calf muscle block twitches
EMG Responses During High Frequency USEA Block

Cuff Proximal on Sciatic Nerve, USEA Distal to Cuff
Voiding by detrusor stim & EUS block

Trials 1, 2, 4: Det 1min (33Hz) and Eus 10sec (2kHz)
Trial 3: Control
Future Directions

Wireless Recording & Stimulating Arrays

Reid Harrison (chip design),
Florian Solzbacher (systems integration),
et al.
Problem: Wires and Connectors Major Problem!

• Infection risk, from break in skin
• Tethering forces
• Electrically noisy
• Wire breakage
Wireless Recording & Stimulating Arrays

- Packaging & encapsulation
- Power coil
- Integrated circuit & SMDs
  - 100 amplifiers or stimulators
  - DSP
  - Telemetry
- Array electrodes
Wireless Recordings from Sciatic Nerve

Greg Clark and Reid Harrison
New Array Architectures using EDM

Electrodes > 5mm long

200 μ spacing

EDM – electro discharge machining
Problems for Tomorrow

• Increasing biocompatibility & longevity of implant systems
• Obtain FDA Investigational Device Exemptions (IDEs)
• Human experimentation
  • Deafness – Auditory nerve stimulation
  • Epilepsy
  • Parkinson’s Disease
  • Chronic, Clinical Depression
  • Pacing of Heart & Diaphragm
  • Chronic Pain Relief
  • Laryngeal Reanimation
  • Bowel Control
  • Paraplegic Walking
The Path to Clinical Markets

This is the real challenge!
The End

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