Upper Extremity Neuroprosthetics

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Geography Lesson!!
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Neuroprosthetics

Rx:

SCI
UEA
CP
BPP
NPP
Spinal Cord Injury (SCI) | Prosthetic Limbs

- Peripheral Nervous System
- Sensory Neuroprosthesis
- Spinal Cord
- Cerebral Cortex
- S1
- M1
- Muscles
- Motor Neuroprosthesis
- Signals intact, limb missing
- Signals intact, limb missing

(Sources: Kandel et al., 2000)
SCI

1) **Functional Electrical Stimulation (FES)**
   Upper Extremity (Freehand)
   Michael Keith, M.D. – Case Western

2) **Standing/Gait**
   U of Miami, Case Western, University of Utah
8 Electrodes
Freehand - Challenges

# Wires = # Muscles
Invasive
Sensory Feedback
Muscle Fatigue
Re-programming
Money
Claire Lomas Finishes London Marathon in 16 Days!
Upper Extremity Amputation
Replantation Ischemic Time

- Literature ranges 4-33 hrs.
  average =10

- Muscle death – 6 hrs.

- Capillary permeability – 2 hrs.
Macoreplantation

- Team
- Survival 30-80%
- Complications high including death
- Functional outcome variable
Not Replantable
Iraq/Afghanistan War

- Increase use of body armor
- Increase use of man made explosives

Result = many healthy amputees
Amputation
Hand Transplantation

- Louisville
- Pittsburgh
- Johns Hopkins
- Tuscon
- L.A.?
- NYC?
- Boston?
Connection

- Osseointegrated implant
- Break-away binding
- Infection control

Bloebaum/Bachus  U of Utah
Branemark  Sweden
“Development of Osseointegrated Implants for Soldiers Following Orthopaedic Extremity Trauma”

The Department of Defense
U.S. Army Medical Research and Materiel Command (USAMRMC)
Congressional Directed Medical Research Programs (CDMRP)
Prosthetic Limb

- Lighter materials
- Waterproof
- More degrees of freedom
- More motors
- Actuators, sensors
Vanderbilt University
Multi Grasp Prosthetic Hand
C.N.S.

Direct connection
Peripheral nerve connection
Direct CNS Control

If I were Rob Strauch, I would have a 60 minutes clip here!
Simple Representation of the Sensory Cortex
M1: Little and ring finger flexed together
M2: Middle finger flexed
M3: Index finger flexed
M4: Thumb in opposition towards the base of the little finger
M5: All fingers flexed together
M6: Extension of the wrist
M7: Flexion of the wrist
M8: Abduction of the fingers
M9: Adduction of the thumb
M10: Flexion of the IP joint of the thumb
Conclusion

- Brain plasticity – can be retrained
- Using intact peripheral nerve reasonable
Controller

- Muscle
- Neural

Neuroprosthetics
Myoelectricity

- Use remaining muscle to control one function of prosthesis
  - Availability
  - Gross motions
  - Retraining (not natural)
Enhanced Myoelectric Control

Fig. 1. Diagram of nerve-muscle graft procedure.
Courtesy of DEKA Research & Development and The Rehabilitation Institute of Chicago
**IMES**

- Intramuscular Electrical Stimulation
- Wireless
- Small
- Can place in specific residual muscles
Control of Individual Finger Movements via Wireless IMES EMG in Monkey

- All fingers
- Index finger alone
- All fingers
IMES: REAL TIME X-RAY VIDEO
Direct Nerve Interface

- Would allow low current input/high force output
- Patient could simply think about task
- Multiple simultaneous motions
- Sensory feedback readily available
Direct Neural Interface

Problems

1) Will the nerve stump function?
2) Infection control
3) Connection to nerves
Nerve Stump Connection
Peripheral Nerve Stimulation: Cuff Electrodes

Advantages (relative to muscle stimulation)
- Lower stimulation thresholds (1-20 mA) than muscle electrodes
- Accesses multiple muscles; relatively easy to implant

Disadvantages
- Poor muscle selectivity: activate many (even opposing) muscles
- Poor force gradation
Enhanced Force Control and Between-Muscle Selectivity

- **Force**
  - Highly controllable over full dynamic range

- **Selectivity**
  - Virtually no activation of other muscles, even at maximum forces
Extremely low-frequency stimulation

- Reduces fatigue
- Reduces potentiation
- RESULT: Maintains target force
LIFES

- Longitudinal Intrafascicular Electrical Stimulation

- Horch, Meek, Dhillon, Hutchinson
  U of Utah Bioengineering
Implanted HLIFEs in Amputee Nerve Stump

Motor Channel

Sensory Channel

Motor Channel
Do Residual Nerves Remain Viable After Amputation?

Dhillon, Horch, Hutchinson J.H.S. 2004
Do Residual Nerves Remain Viable After Amputation?

Dhillon et al., 2004
Residual Nerves Remain Viable After Amputation
Conclusion

Graded, distally referred, tactile and proprioceptive sensory feedback can be provided by intrafascicular stimulation of amputee nerve stumps.

Graded, distally referred, motor control signals can be obtained by intrafascicular recording from amputee nerve stumps.
LIFES ‘08

- NSF funded, IRB approved human volunteer experiments
- 1 incision, 2 electrodes in ulnar nerve, 4 in median nerve, just prox. to elbow
- 4 month chronic studies
- Sensation and motor output to prosthesis
The Utah Electrode Array
The Utah Slanted Electrode Array (USEA)  
10 x 10

A neuroprosthetic “smart bomb”
- Proximity and selectivity: activates only selected nerve fibers
- Multi-site: can activate many different fibers independently

Utah Slanted Electrode Array  
Intrafascicular Multielectrode Stimulation (IFMS)
Enhanced, Selective Access to Multiple Muscles and Motor Units

- 9 different leg muscles selectively accessed via a single USEA implanted in cat sciatic nerve
- Between-muscle selectivity
- Within-muscle independence
- Low stimulation currents: 1-10 uA
Sensory Feedback
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)

Impulse Inserter
CNS penetrating microelectrodes

- EEG
- EMG
- PNS – Cuff Electrodes
- PNS – Intrafascicular Electrodes
- PNS – Utah Slant Electrode Array

Invasiveness of Neural Interface vs. Decode Quality (bits/second)
USEA Studies

- 2005-2008  Cat studies for DARPA/DOD
- 2008  “walking cat”
- 2009  Non human primate at Northwestern University
USEAs in 3 Arm Nerves of Non-Human Primate
2-3 USEA implants
Radial (Ext.) and Median (Flex.)
Ulnar and Median?
Ulnar only?
2012

- IRB approved Human studies
  up to 1 month chronic implantation
  nerve stump histology
  still percutaneous

- Looking for volunteers!
Median nerve stump width 11.5mm
Chronic Human USEA Implant

Trocar Surgical Method to Pass USEA to nerve
Acute Human USEA Implant: Lower Arm

Organic nerve wrap for containment system (AxoGen Nerve Guard, AxoGen Inc)

Vascular clips close wrap

Median N.

Ulnar N.
Chronic Human USEA Implant

USEA implanted into median nerve and contained with organic nerve wrap

Neuroma
3. TA5 Sensory Feedback: Human peripheral nerve

- First evoked somatosensation using micro-stimulation via a USEA
Can stimulation evoke somatoeensation?

Yes!
Stimulation delivered via single electrodes evokes discrete percepts.

Electrode 19 Weeks 2-3
week 2, 11-14 (33uA) = blue circle
week 3, 11-19 (33uA) = red X
week 3, 11-21 (38uA) = red X
Can we record action potentials over time?

APs recorded electrode 20 for 4 weeks
Histology

Median Nerve

Electrode tracks are seen across the nerve. Note: the section was not parallel to the electrode tracks so only part of the track is seen.
Example of extra-fascicular nerve growth up two electrode tracks
Antibody Staining of Electrode Sites

Extra-fascicular nerve growth

Nerve fascicle (green = NF)
One USEA electrode penetrating into a fascicle
Advantages of Wireless Technology

- Reduced risk of infection
- Reduced tethering forces
- Improved long-term recording/stimulation?
- Enhanced cosmetics
**Integrated Neural Interface (INI)**

- Power receiving coil (Au) on polyimide with ceramic ferrite backing
- Integrated circuit with neural amplifiers or stimulation, signal processing, and RF telemetry electronics
- SMD Capacitor (0402 package)
- Utah Microelectrode Array
  - Bulk micromachined silicon with platinum tips and glass isolation between shanks
- Entire assembly coated in parylene and silicon carbide
- 1.2 mm
- 400 μm pitch
Integrated Wireless Recording Array

- Packaging & encapsulation
- Power coil
- Integrated circuit & SMDs
  - 100 Amplifiers
  - DSP
  - Telemetry
- Array electrodes
Summary

- Brain plasticity
- Chronic nerve stumps viable
- Improve mechanical arms
- Need better prosthetic interface
- Neural control
- Possibilities numerous
- Americans need to study Geography!
Future

- Verify functionality in humans long term
- Determine best surgical fixation procedure and instrumentation
- Verify appropriate histology of residual nerve
- Finalize wireless technology
- Osseous integrated interface without infection
- Put it all together!
Congenital Amputees?

- Nerve availability?
- Brain adaptability?
- Bilaterality?
Neuropathic Pain

- Giving ‘normal sensation’ to the peripheral nerve may mask/eliminate abnormal pain pathways
- Better than spinal column stimulators?
- Better than neurontin/lyrica?
Birth Plexus Palsy

- Keep muscles working while recovery occurs in first 6 months
- If recovery not proceeding then bypass injury site electronically
- Perhaps place electrodes at time of grafting
- Avoid need to graft?
Cerebral Palsy

- Utilize normal peripheral nerves and muscles controlled by other arm or normal half of brain?
- Would simple afferent or efferent stimulation decrease spasticity?
- Eliminate botox and baclofen?
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VIE
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THANK YOU!
Decoding Individuated Finger Flexions with Implantable MyoElectric Sensors (IMES)

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30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society

August 20-24, 2008
- Transmits and receives EMG signal wirelessly
- 15 x 2 mm
IMES IMPLANTATION

June 29, 2007

3 weeks post implantation

Pictures of IMES implantation during surgery
### IMES LOCATION + FUNCTION

#### Muscles where IMES were implanted and their function

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDP-deep</td>
<td>Flex index (#2)</td>
</tr>
<tr>
<td>FDP-superficial</td>
<td>Flex #3,#4,(#1-if 3 + 4 are flexed)</td>
</tr>
<tr>
<td>FDS</td>
<td>Flex middle finger (#3)</td>
</tr>
<tr>
<td>FCr</td>
<td>Wrist flexion</td>
</tr>
<tr>
<td>APL</td>
<td>Thumb abduction</td>
</tr>
<tr>
<td>EDCI</td>
<td>Extension of #4,#5</td>
</tr>
<tr>
<td>EDC</td>
<td>Extension of #2,#3</td>
</tr>
<tr>
<td>Wrist extensor</td>
<td>Wrist extension</td>
</tr>
<tr>
<td>Thenar eminence</td>
<td>Thumb flex</td>
</tr>
</tbody>
</table>
THE BEHAVIORAL TASK

- THUMB
- INDEX
- MIDDLE

RELAXED
FLEX
CUE
EMG RAW DATA

Monkey with arm in IMES coil.
DECODE TRAINING & TESTING PLOTS

TRAINING

TESTING: predictability 95%
CONTROLLING VIRTUAL HAND
• Very small individuated finger flexions can be correctly decoded using Wireless IMES EMG signals with high accuracy

• IMES remain safe and effective for 14 months post-implantation

• IMES can offer intuitive dexterous control of artificial limbs and hands after amputation
Chronic Human USEA Implant

Median N. = 11.5 mm width
3. TA4 Systems Test: Human peripheral nerve

- Isolated action potential firing correlated with index and middle finger movements
3. TA5 Sensory Feedback: Human peripheral nerve

- Somatotopic map of all evoked sensations using micro-stimulation via USEA

Experiment_20121107
Results of Evoked Sensory Percepts

By hacw

**9 of 16 electrodes stimulated evoked percepts

Stimulation: Biphasic, current-controlled with threshold of percepts evoked from 2-14 μA with 100 μs pulse-width at 200 Hz for 200ms duration
Human USEA Implant--Coverage

Median Nerve
My Father, circa 1965

“If it hurts we can cut it off and get a new one at the hardware store”