Upper Extremity Neuroprosthetics

Douglas T. Hutchinson, M.D.
Associate Professor
Orthopaedics

Associate Professor
Bioengineering
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<th>Team-U of Utah</th>
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<td><strong>Greg Clark, PhD</strong></td>
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<td><strong>Douglas T Hutchinson, MD</strong></td>
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<td><strong>Dave Warren, PhD</strong></td>
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<td><strong>Heather Wark, BS</strong></td>
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<td><strong>Dave Page, BS</strong></td>
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<td><strong>Christopher Duncan, MD</strong></td>
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Neuroprosthetics

Rx:

SCI
UEA
CP
BPP
NPP
Spinal Cord Injury (SCI)

Prosthetic Limbs

Limb intact, signals missing

Signals intact, limb missing

Peripheral Nervous System

Sensors

Muscles

Peripheral Nerves

Injury

Spinal Cord

S1

M1

Sensory Neuroprosthesis

Cerebral Cortex

Motor Neuroprosthesis
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
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.
Macroreplantation

- Team
- Survival 30-80%
- Complications high including death
- Functional outcome variable
Summary-Replantations

- Results even in the worst scenarios better than failure
- Despite some cases where function poorly returned
- KEY= Sensation somewhat recovers and therefore they like it and use it
- If we had a good sensate functional prosthesis............
Not Replantable
Iraq/Afghanistan War

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

*Result = many healthy amputees*
Amputation
In some ways this huge medical advance has been spurred on by the inability of the prosthesis to function and be tolerated well.

**WHY?**

- SENSATION

Yet sensation recovery poor so far in transplants.
Connection

- Osseointegrated implant
- Break-away binding
- Infection control

Bloebaum/Bachus/Kubiak U of Utah
Branemark Sweden
Prosthetic Limb

- Lighter materials
- Waterproof
- More degrees of freedom
- More motors
- Actuators, sensors
2 DARPA Arms

JHU-APL Arm

DEKA Arm System
Vanderbilt University
Multi Grasp Prosthetic Hand
Sensory Feedback
C.N.S.

Direct connection
Peripheral nerve connection
The Utah Electrode Array
Direct CNS Control
Conclusion

- Brain plasticity – can be retrained
- Cortical representation of amputated limb can ‘come back’
- Using brain or intact peripheral nerve reasonable
Peripheral Control

- Muscle
- Peripheral nerve
Myoelectrics

- 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

Manipulandum
Switch Closures

Time, sec

0 5 10 15 20 25 30 35 40
IMES: REAL TIME X-RAY VIDEO
Peripheral Nerve Interface?
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
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
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
Nerve Stump Connection

- LIFEs - Europe - limited # "hit or miss"
- Nerve Cuffs - Case Western
  Proven longevity of 2 years
  Whole nerve, less specific
- Arrays - U of Utah
CNS penetrating microelectrodes

EEG

Decode Quality (bits/second)

Invasiveness of Neural Interface

PNS – Cuff Electrodes

PNS – Intrafascicular Electrodes

PNS – Utah Slant Electrode Array

EEG

EMG
I told Doc he can do whatever he wants to my arm, but he ain’t messing with my head.”

Muscle Memory, Ben McGrath. New Yorker, July 30, 2007. Photograph by Martin Schoeller
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
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
2012

- IRB approved Human studies
  - Up to 1 month chronic implantation
  - Nerve stump histology
  - Still percutaneous

- 3 volunteers completed, 4 arrays placed and recovered
Median nerve stump width 11.5mm
Chronic Human USEA Implant

Trocar Surgical Method to Pass USEA to nerve
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
Chronic Human USEA Implant

USEA implanted into median nerve and contained with organic nerve wrap

Neuroma
Can we record action potentials over time?

APs recorded on electrode 20 for 4 weeks
Can stimulation evoke somatosensation?

Yes!
Stimulation delivered via single electrodes evokes discrete percepts.
97 USEA electrodes evoke percepts

- Median n. USEA
- Ulnar n. USEA
Subject can use USEA-evoked percepts to guide movements (closed-loop control)

S3 correctly identified whether achieved targets were ‘close’ or ‘far’ in 41/47 trials ($p<0.001$, binomial test), with no visual feedback.
**GOAL:** Restore Sensorimotor Function after Upper-limb Loss

**APPROACH:** Record from and stimulate residual arm nerves with Utah Slanted Electrode Arrays (USEAs)

1. **Movement**
   - Stimulation activates subject’s sensory nerve fibers (200-µs biphasic pulses at 200 Hz, 200-ms train)

2. **Sensation**
   - Subject feels phantom fingers
   - Information transmitted to CNS

3. **Closed-loop Control**
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.
Human Histology

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
RESULTS- human studies

- No clinical sequelae from surgeries
  - no clinically relevant nerve or muscle damage
  - preop phantom sensations about same postop
  - 1 infection cut short time but end= same
131 different percepts → compared to 18 via other neural interfaces
- Proprioceptive and cutaneous percepts
- Percepts are stable over short term
- Percepts are enjoyable and provide a useful feedback signal for prosthetic hand
- Motor control achievable (pts love it!)
PROBLEMS

- Poor overall penetration of nerve by array
- Longevity of neural interface
- Perc. wires a big issue - need wireless!
- Integration of signals/decodes need to become more user friendly and adjustable
Human USEA Implant--Coverage

Median Nerve
### P201302 Ulnar

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- **53/100 electrodes definitely or probably in fascicular space**
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- **27/100 electrodes definitely or probably in fascicular space**
U of U Research 2015
Where do we go now?
The Defense Advanced Research Projects Agency (DARPA) is building a new generation of prosthetics that can be moved with thoughts alone, and can feel the warmth of touch.
DARPA- Haptix

- We made the cut!
- 5-7 more human volunteers over 5 years
- Up to 1 year studies
- Send patient home with self adjusting wireless system with both motor control and sensation
- Neural control vs muscle control
- Arrays vs cuffs
Advantages of Wireless Technology

- Reduced risk of infection
- Reduced tethering forces
- Improved long-term recording/stimulation?
- Enhanced cosmetics
2-3 USEA implants
Radial (Ext.) and Median (Flex.)
Ulnar and Median?
Ulnar only?
Hold Hand Still
During Free-Form
Full-Hand Decode

Subject P2014-01
Muscle electrodes

- From Ripple Inc. – research park
- 4 electrodes per wire
- Soon to be wireless (MIRA)
GOAL: Restore Sensorimotor Function

1. Movement

- Stainless steel helically coiled leads in silicone tubes
- Stainless steel electrodes
- Polymer lead fixation anchors
Systematic Approach to Final Wireless System

(wireless) Stimulation And Recording Arrays (SARAs; Ripple)

(wireless) Myoelectric Implantable Recording Array MIRA (Ripple)
FUTURE APPLICATIONS
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?
THANK YOU!
Decoding Individuated Finger Flexions with Implantable MyoElectric Sensors (IMES)

Justin J. Baker¹, Dimitri Yatsenko¹, Jack F. Schorsch², Glenn A. DeMichele³, Phil R. Troyk⁴, Douglas T. Hutchinson¹, Richard F. ff. Weir², Gregory Clark¹, and Bradley Greger¹

¹University of Utah ²Rehabilitation Institute of Chicago ³Sigenics Inc. ⁴Illinois Institute of Technology

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 LOCATION + FUNCTION

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

<table>
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<tr>
<th>Muscle</th>
<th>Function</th>
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<td>Flex index (#2)</td>
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<td>FDP-superficial</td>
<td>Flex #3,#4, (#1-if 3 + 4 are flexed)</td>
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<td>FDS</td>
<td>Flex middle finger (#3)</td>
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<td>Thumb flex</td>
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THE BEHAVIORAL TASK

THUMB

INDEX

MIDDLE

DISPLAY

RELAXED

FLEX

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

TRAINING

TESTING: predictability 95%
CONTROLLING VIRTUAL HAND
SUMMARY

• 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

Neuroma
3. TA4 Systems Test: Human peripheral nerve

- Isolated action potential firing correlated with index and middle finger movements 

![Spike Raster](image1)

- Electrodes: 20 (blue), 44 (green)

- Force: index (blue), middle (green)
3. TA5 Sensory Feedback: Human peripheral nerve

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

Animal Studies

- UU Faculty
  - R Normann, B Greger, G Clark
  - D Hutchinson, P House, K Horch, S Meek
- MD/PhD student
  - H Wark
- Postdoctoral Fellow
  - D Warren
- Graduate Students
  - N Ledbetter, S Towns, J Perry, K Gunalan, B Dowden, A Wilder, S Hiatt, J Baker, B Christensen
- Technicians
  - R Macchione, Q Ruan, K Nelson, T Taylor
- Northwestern U. Med. School
  - L Miller, J Ko, C Ethier, E Oby

Wireless Recording & Stimulation

- Chip Development
  - Reid Harrison et al.
- System Integration & Encapsulation
  - Florian Solzbacher et al.

External Interface (Beltpack)
- Shane Guillary et al.; Ripple, LLC

VIE
- Loeb et al., USC
- Beaty, Bishop et al., JHU-APL

IMES
- Weir, Troyk, Schorsch et al.; RIC & Sigenics

Funding
- DARPA BAA 05-26 (Neuroprosthetic arm; GC)
- R01-NS039677 (SCI, nerve stim for stance; RN)
- HHSN265200423621C (Wireless Cx array; FS)
- R01-NS053603 (LM)
8 Electrodes
“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)

Roy D. Bloebaum, Ph.D.
Kent N. Bachus, Ph.D.
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
Do Residual Nerves Remain Viable After Amputation?

Dhillon et al., 2004
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
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

400 μm pitch

1.2 mm
Integrated Wireless Recording Array

- Packaging & encapsulation
- Power coil
- Integrated circuit & SMDs
  - 100 Amplifiers
  - DSP
  - Telemetry
- Array electrodes
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.
316 SS ELECTRODE

RETENTION BARB

.08

.04

.16

SILICONE TUBE

38 AWG 316 SS STRANDED WIRE
7 STRAND, HELICAL COILED

L

∅ .06
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!
Summary

- Brain plasticity
- Chronic nerve stumps viable
- We have Improved mechanical arms
- Need osseosintegration
- Neural control