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Scuola Superiore Sant'Anna

La protesi "bionica": collegare il sistema nervoso ad un arto artificiale

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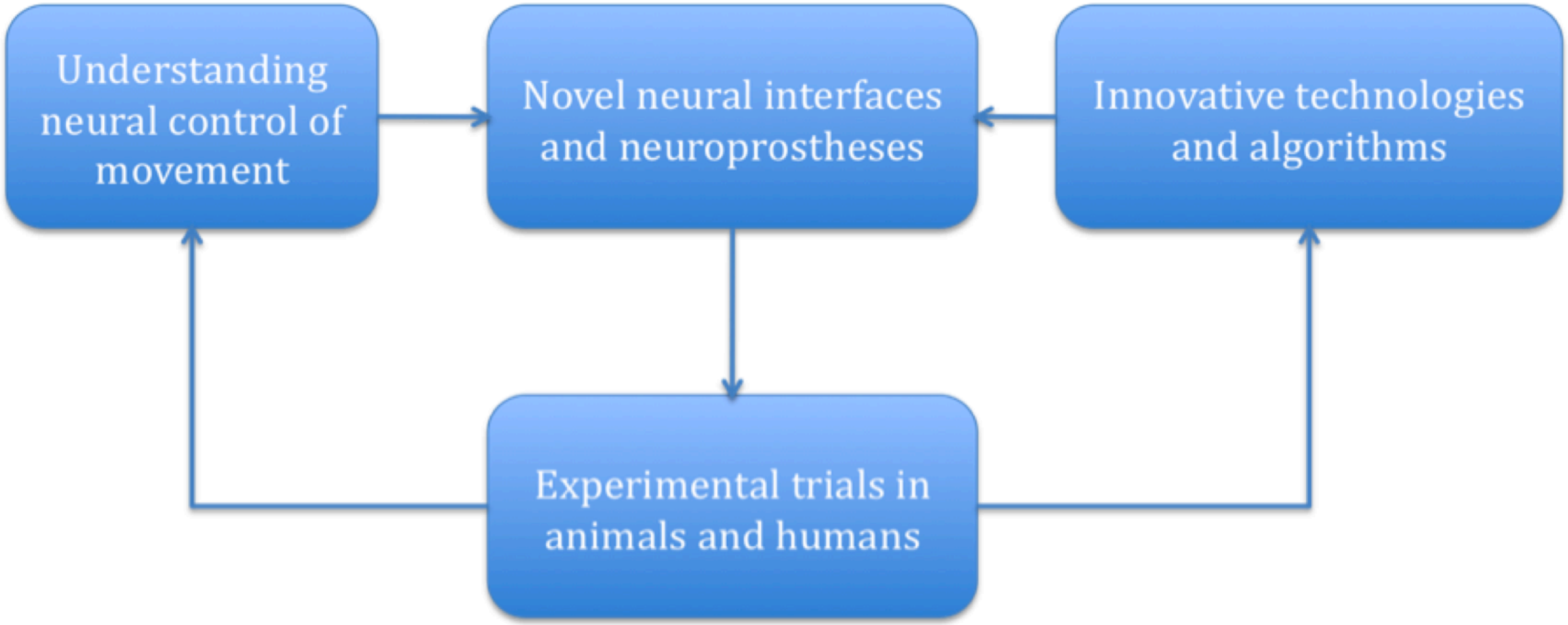
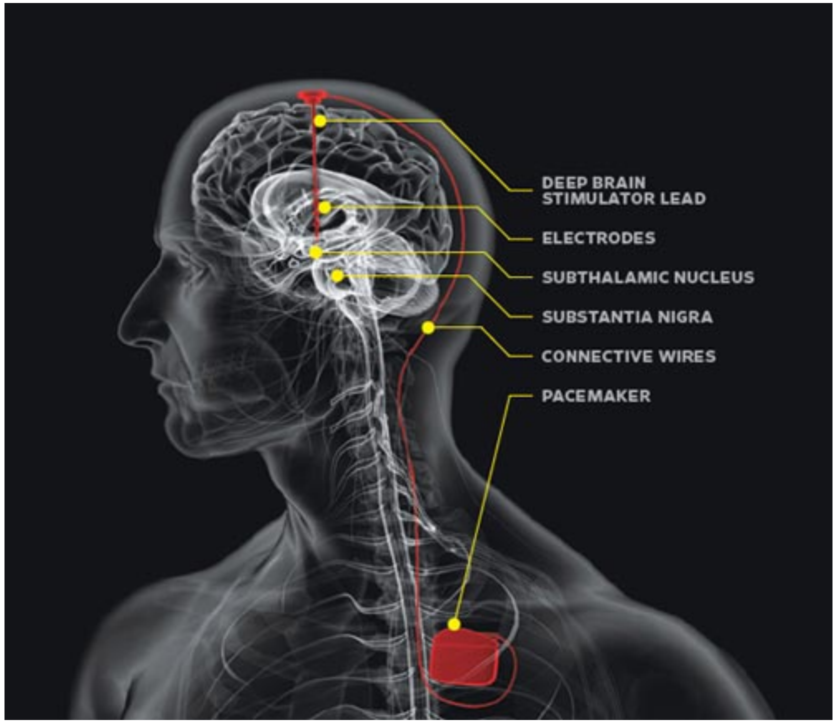
Neuroprosthetics (or NeuroTechnologies)

Neuroprosthetics is a discipline related to neuroscience and engineering concerned with developing devices ("**neural prostheses**"), which can substitute or restore a motor, sensory, or cognitive functions that might have been damaged as a result of an injury or a disease

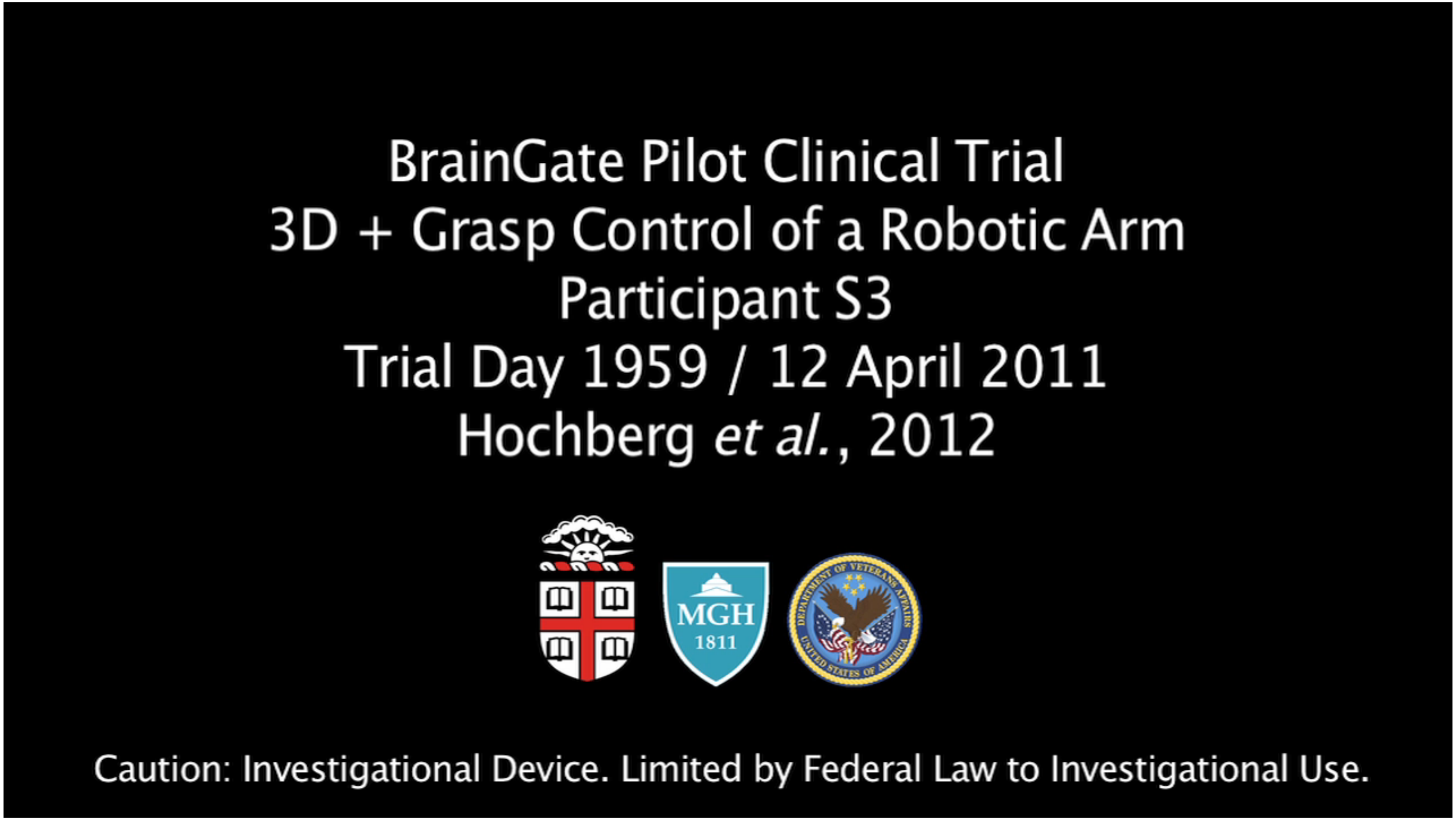


Cochlear implants

Deep Brain Stimulation for Parkinson

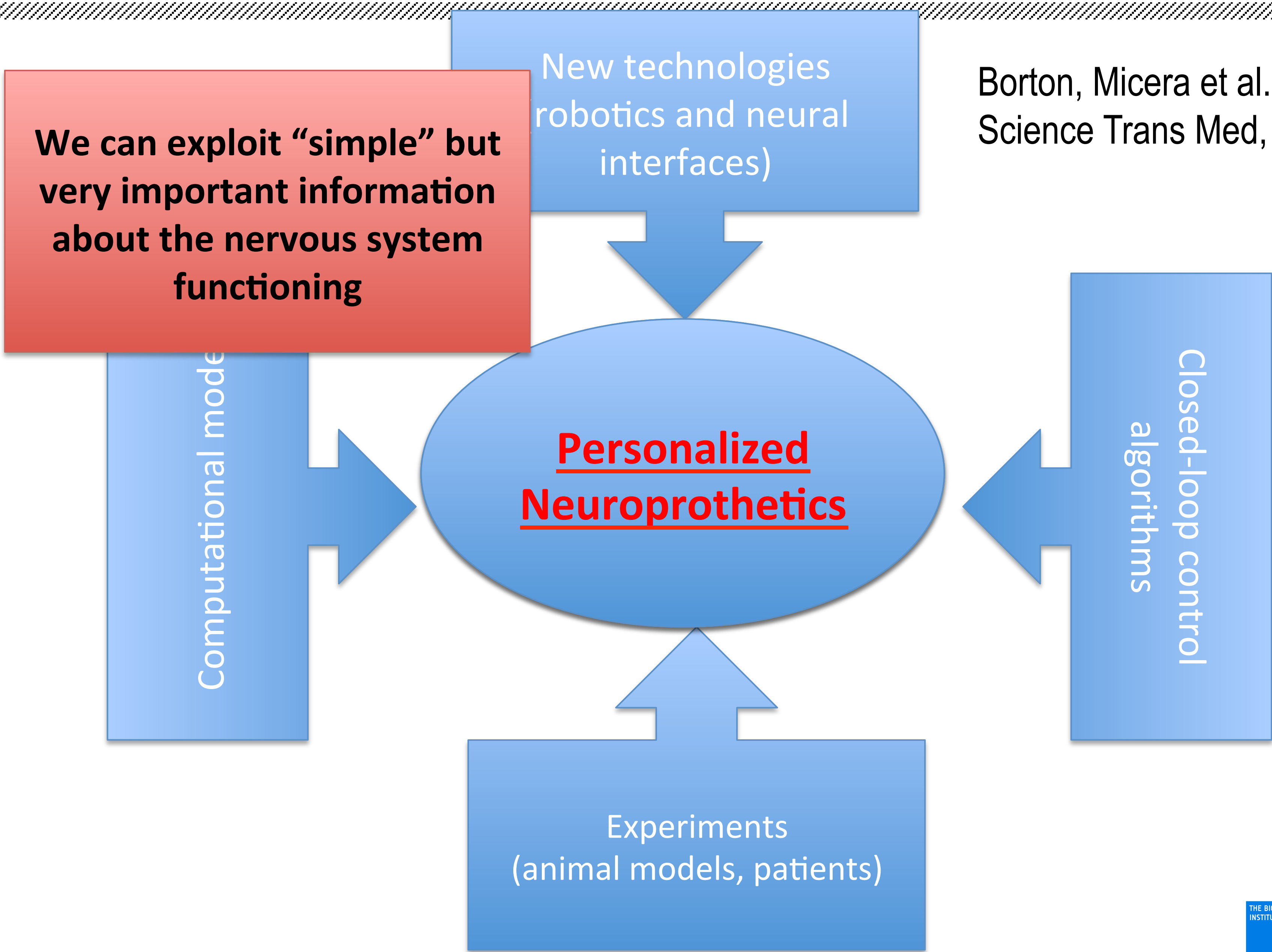


Cortical control of robotic systems



Personalized Neuroprosthetics

Borton, Micera et al.,
Science Trans Med, 2013

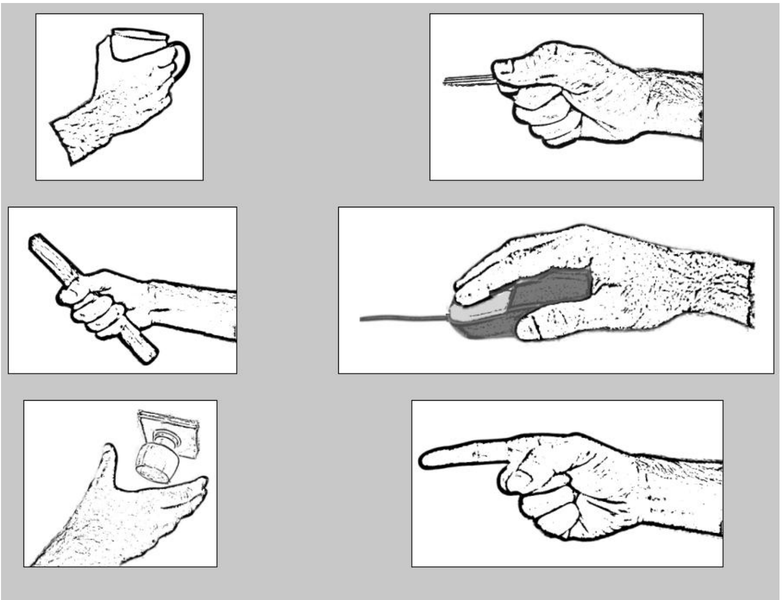


Take home message #1

Neuro-modulation can allow amazing results…potentials are UNLIMITED

The human hand

- Capable of both delicate and precise manipulation and powerful grasping of heavy objects
- Combination of a large number of degrees of freedom, proprioceptive and exteroceptive sensors



Hand prostheses for amputees

- Limited dexterity
- No sensorization
- Complex control strategies
- Perceived as a foreign body

OUR dream…

The « Stealth » Paradox

?

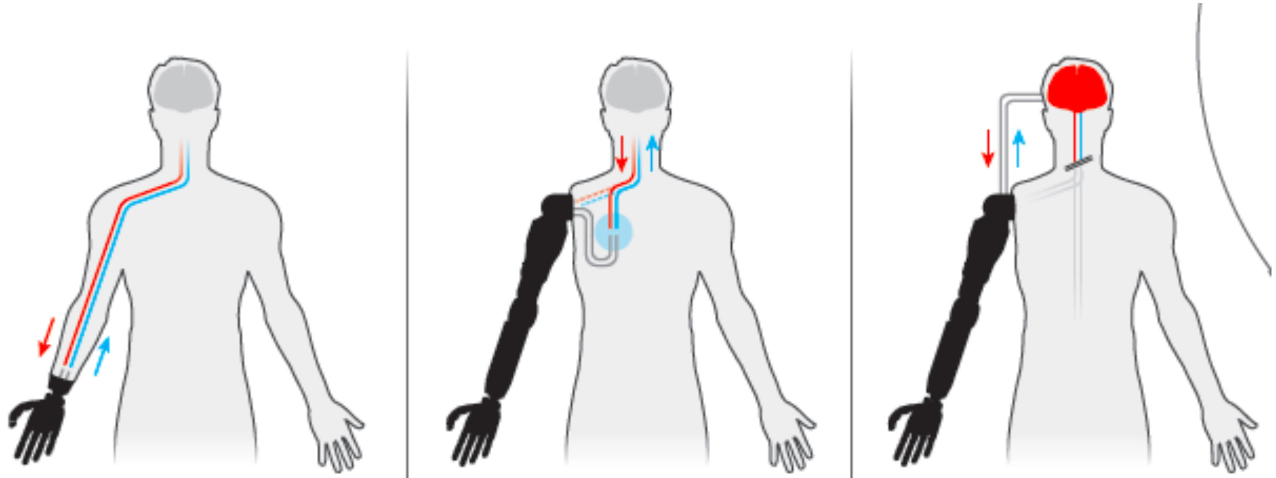
After the Second World War two stealth plains have been found…how to repair the not functioning one trying to understand how the working out can function

Take home message #2

This is really an ill-posed problem

Sensory feedback

Real-time, and natural feedback from the hand prosthesis to the user is essential in order to enhance the control and functional impact of prosthetic hands in daily activities, prompting their full acceptance by the users

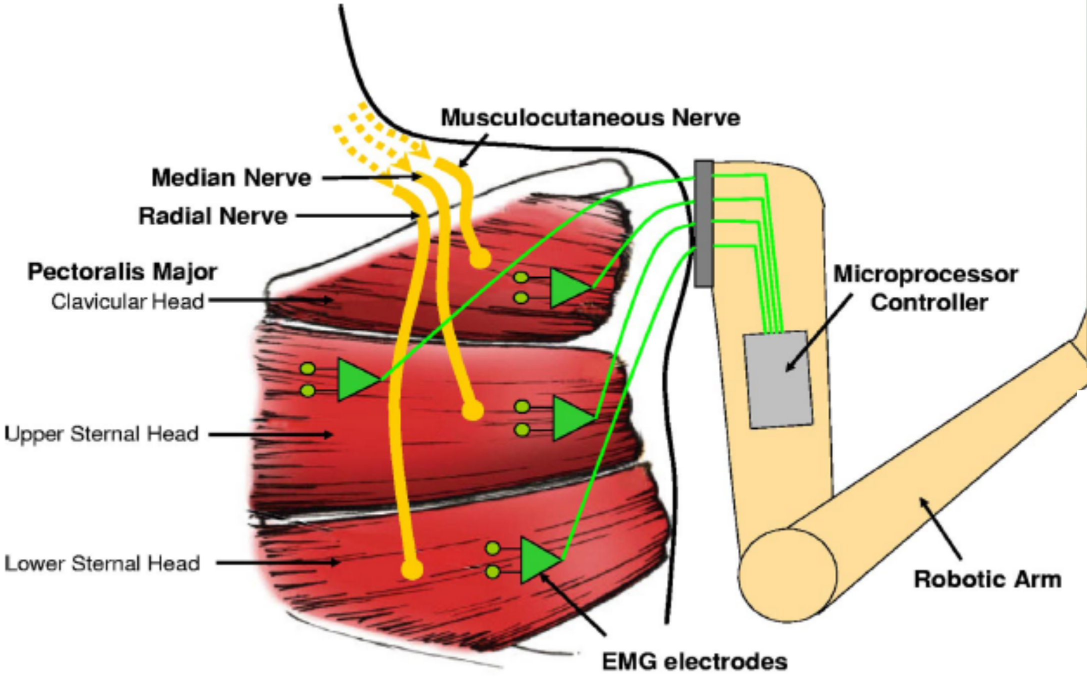


Use the remaining nerves
Electrical leads from the prosthetic's sensors stimulate nerves in the person's stump that once served the real limb.

Move the nerves
Re-routed nerves grow new endings into muscle and skin, where external devices translate signals going to and from the prosthesis.

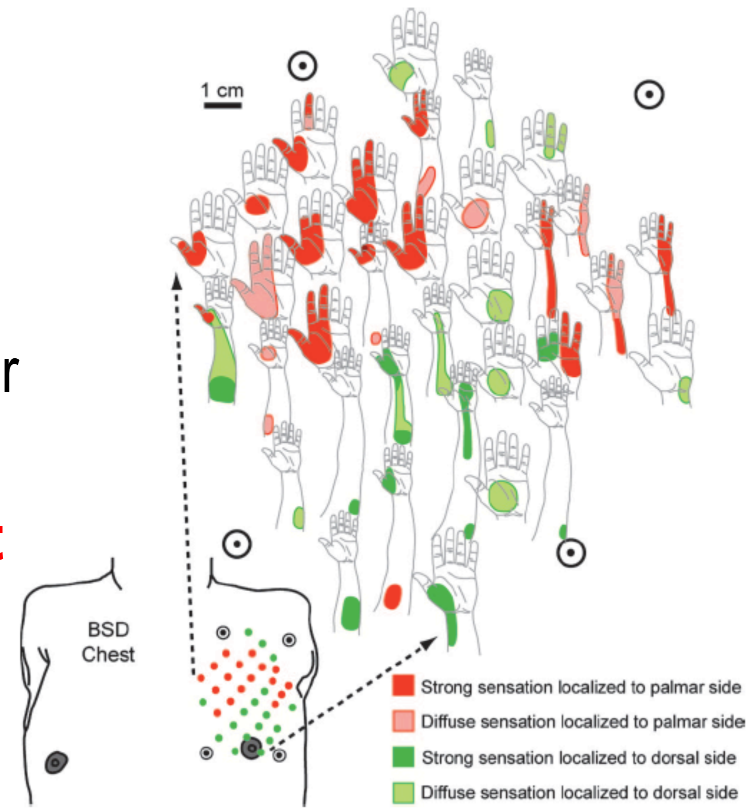
Stimulate the brain
Sensory signals are routed around a severed spinal cord and into the brain, where they produce sensations by direct stimulation of the cortex.

Targeted Muscle Reinnervation

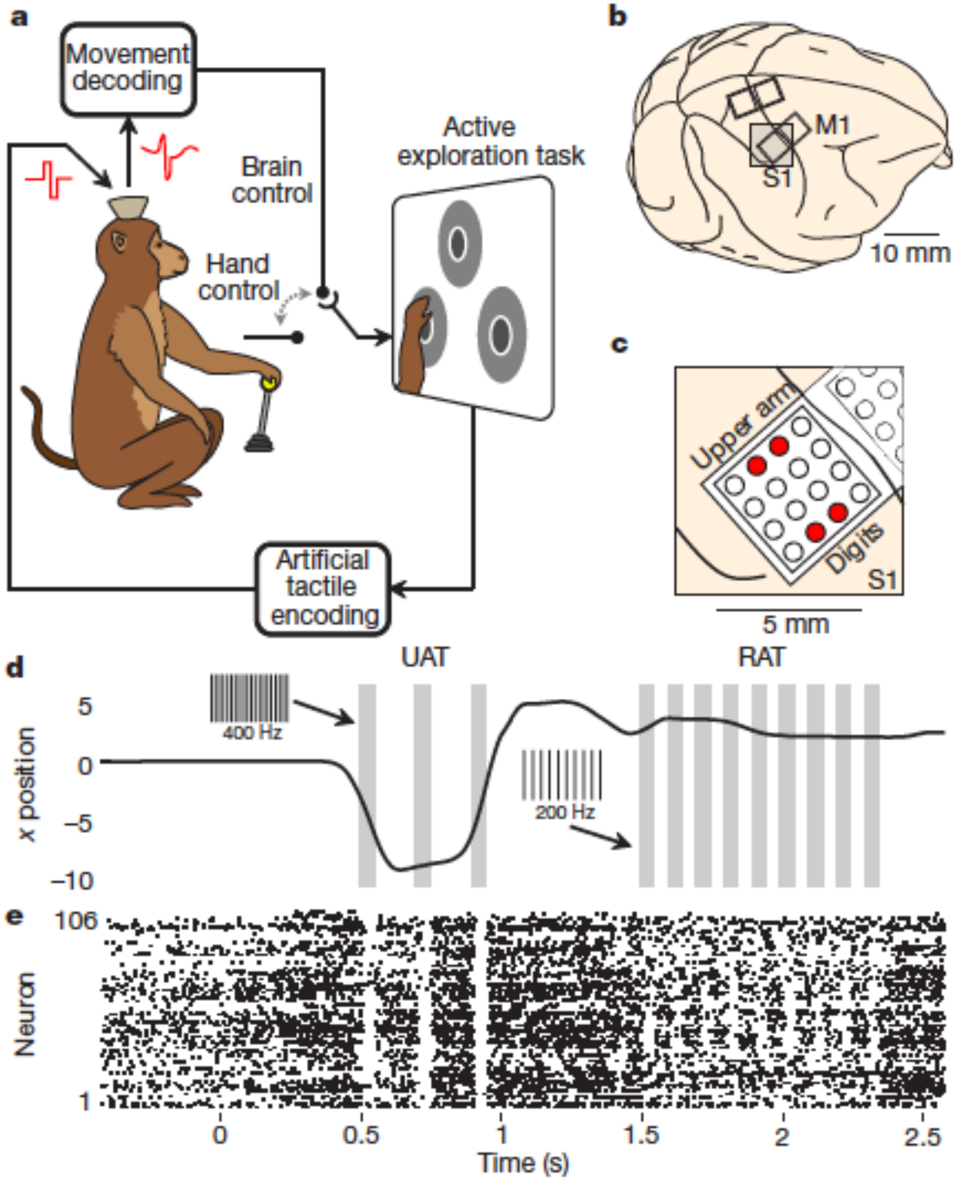


- Very interesting solution but more suitable for proximal (shoulder) amputations
- **Sensory feedback is possible but difficult to be daily usable**

Kuiken et al., 2007, 2008



Intracortical sensory feedback



Intracortical sensory feedback is possible but the performance are still limited

O'Doherty et al., 2011

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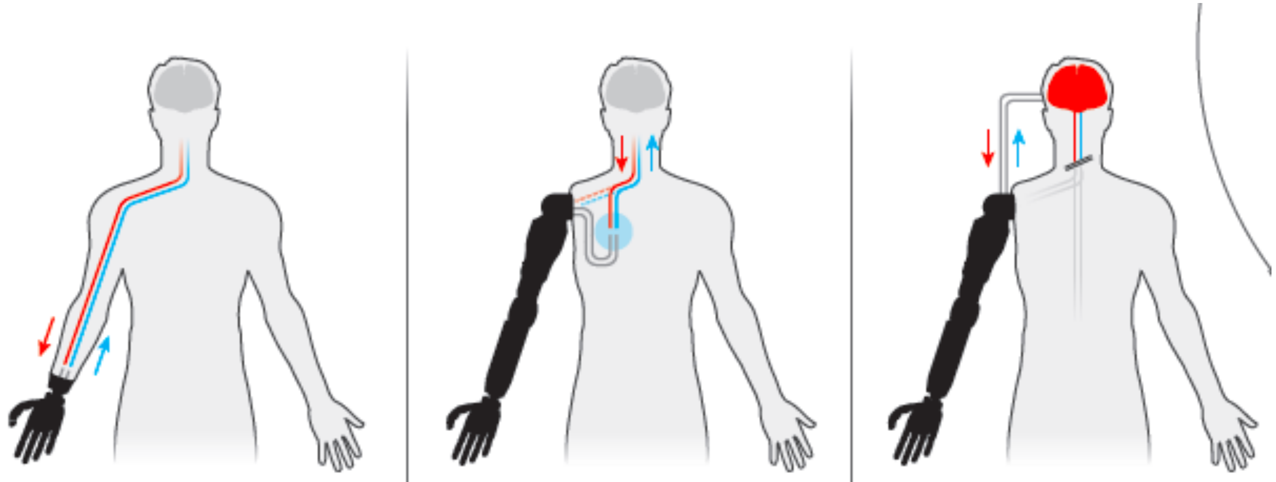

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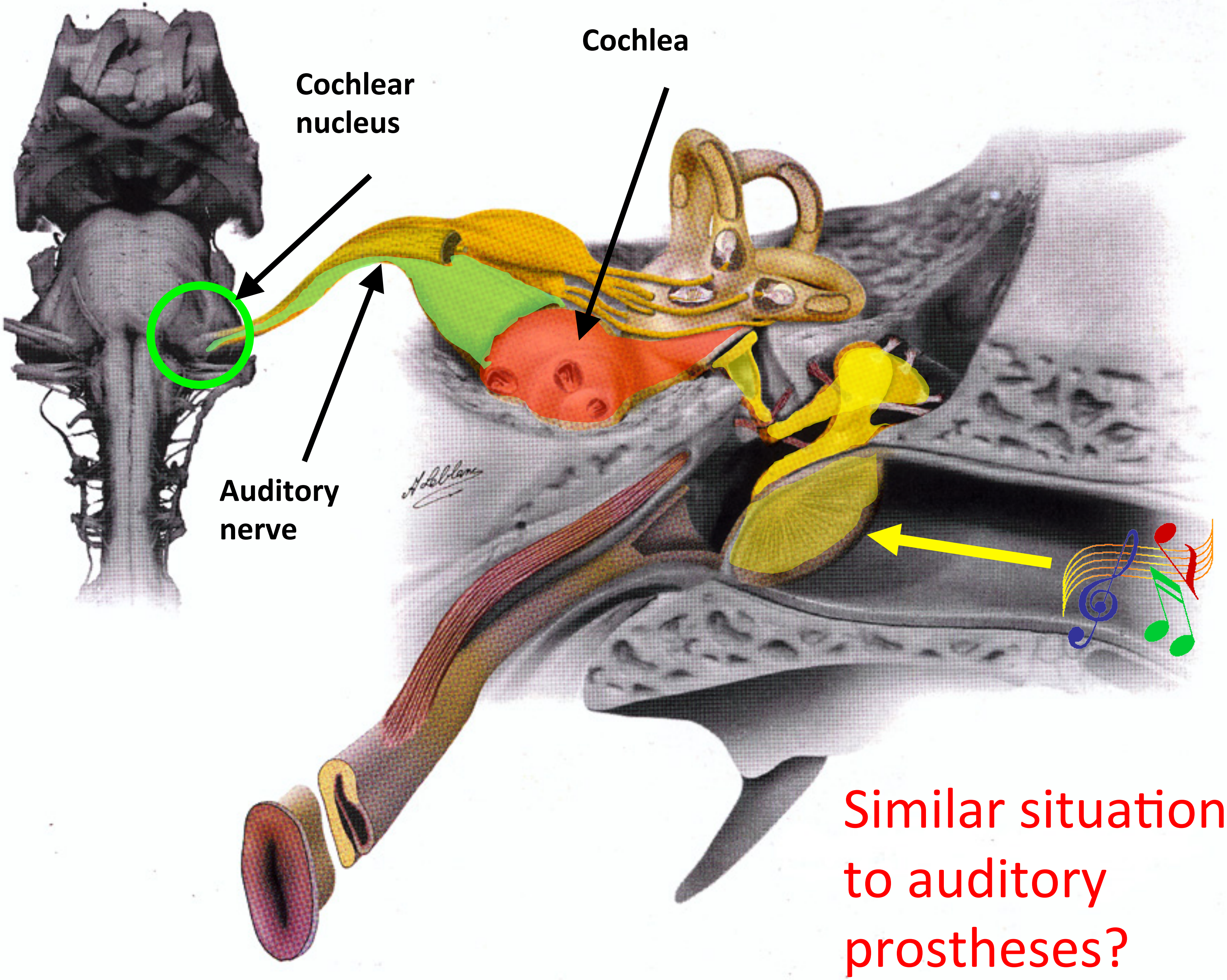
Stimulate the brain
Sensory signals are routed around a severed spinal cord and into the brain, where they produce sensations by direct stimulation of the cortex.

Maybe we should use the existing neural structures when possible

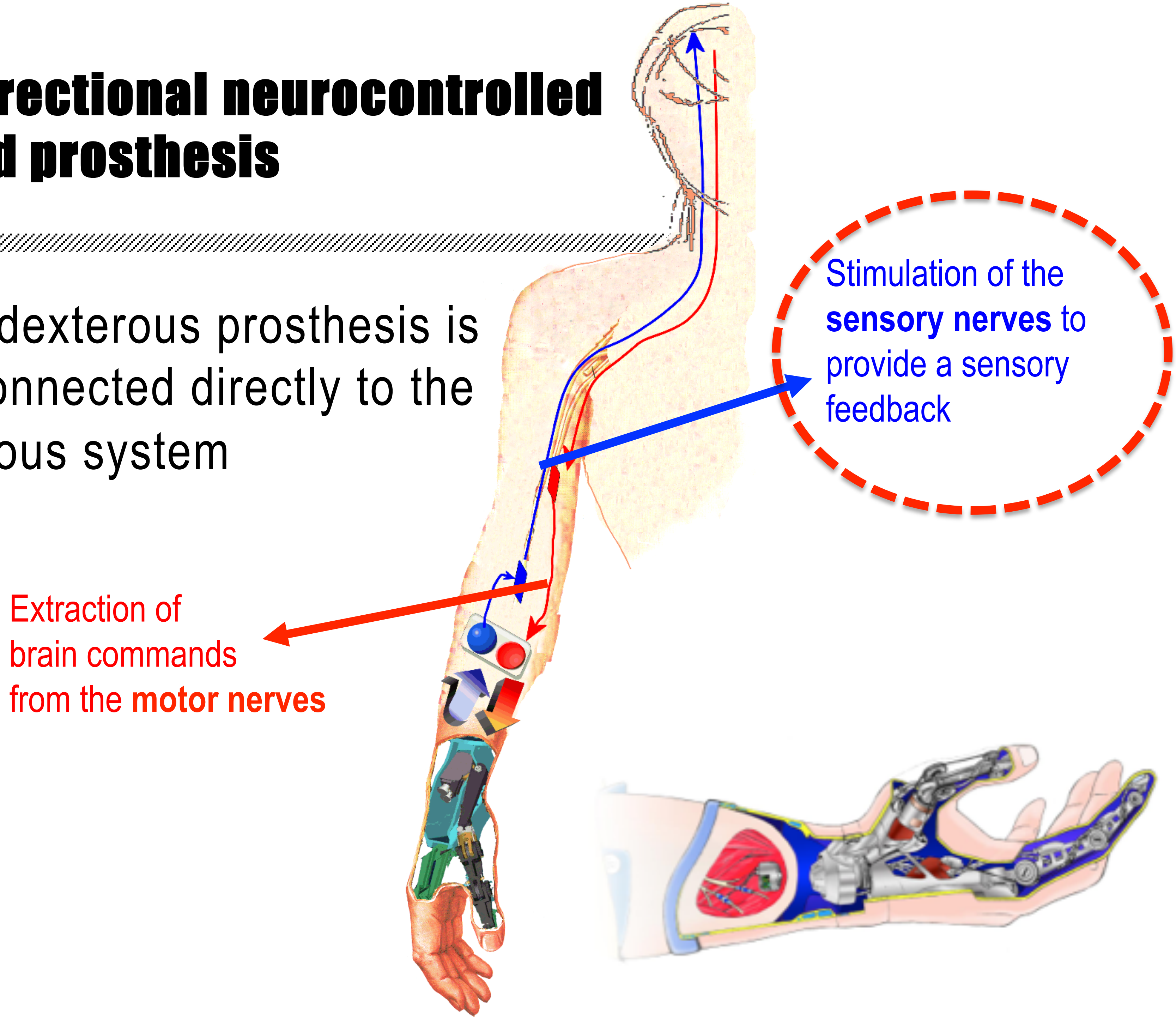
Take home message #3

Do not give up your ideas!

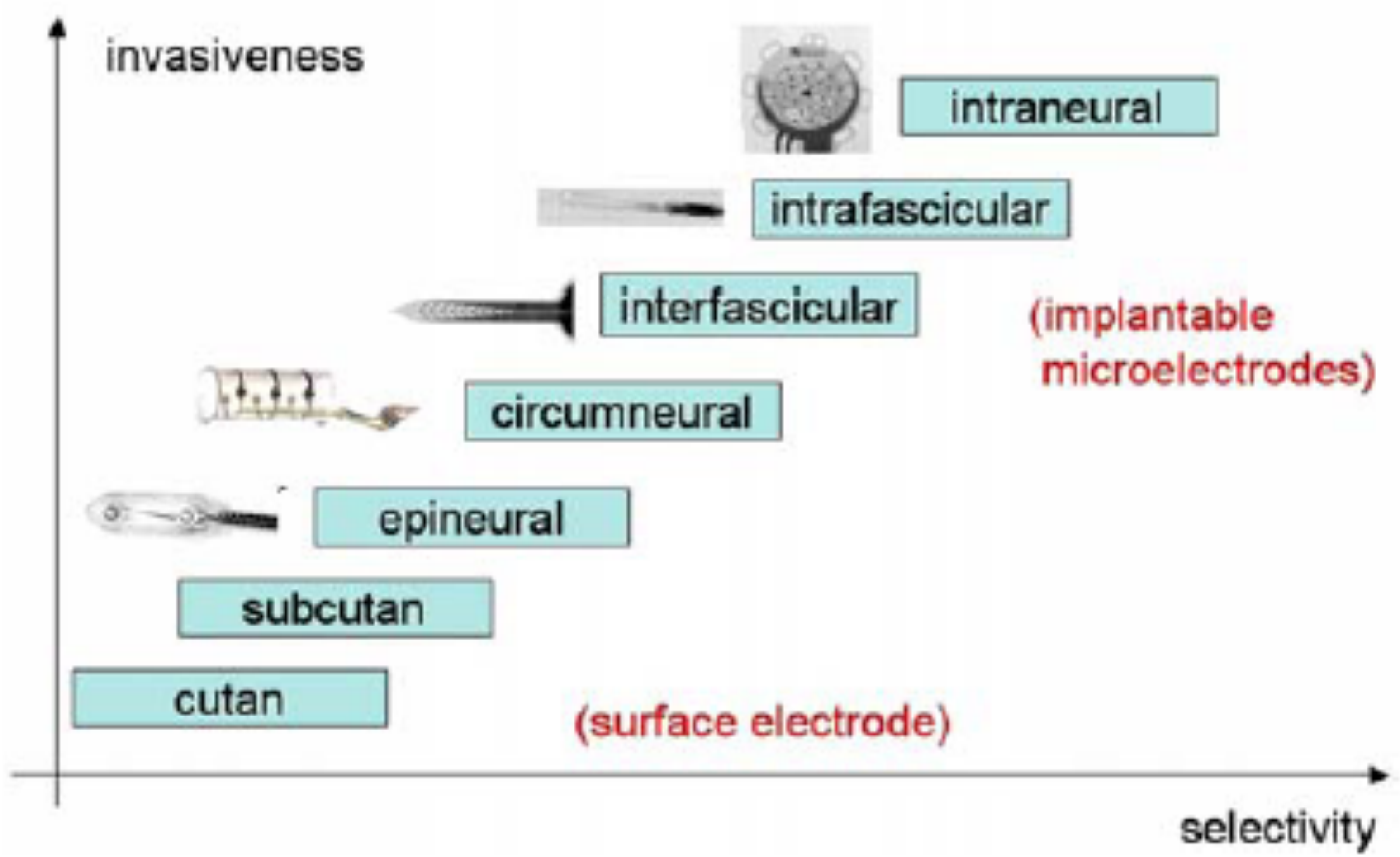

Cochlea
Cochlear
nucleus
Auditory
nerve
Similar situation
to auditory
prostheses?

Bidirectional neurocontrolled hand prosthesis

The dexterous prosthesis is re-connected directly to the nervous system



Implantable PNS electrodes

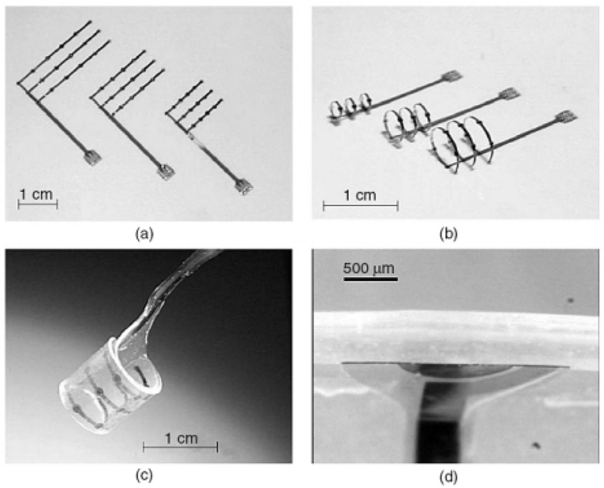


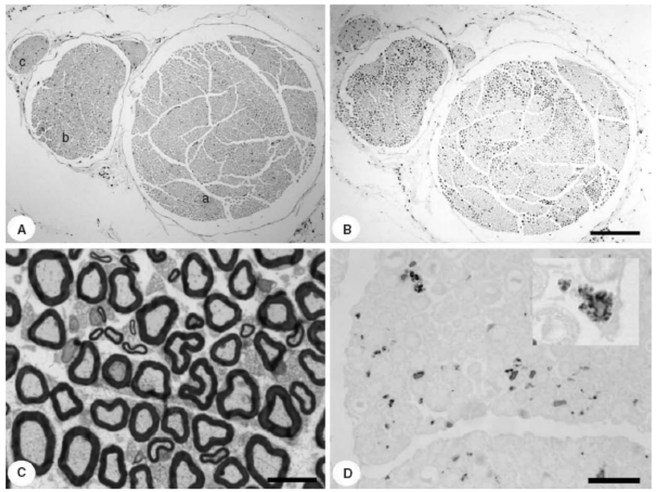
Take home message #4

It could be a loooooong way

Cuff electrodes

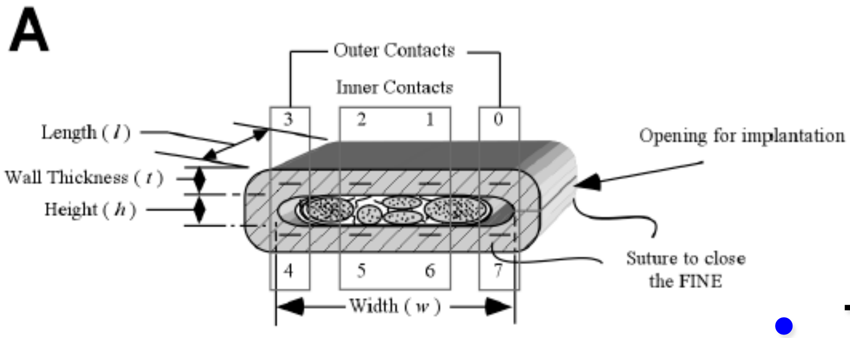
- Cuff electrodes are composed of an insulating tubular sheath that completely encircles the nerve and contains electrode contacts exposed at their inner surface that are connected to insulated lead wires
- They are less prone to damage the nerve and easier to implant

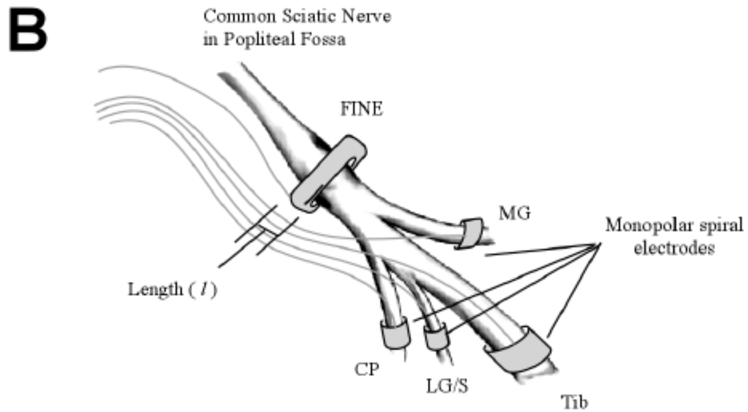




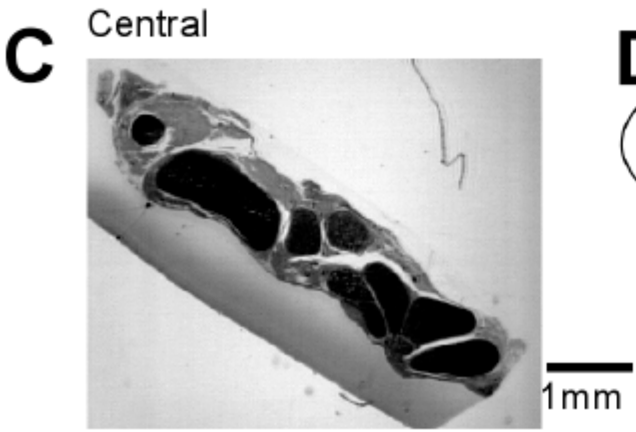
Stieglitz et al., IEEE Eng Med Biol Mag, 2005

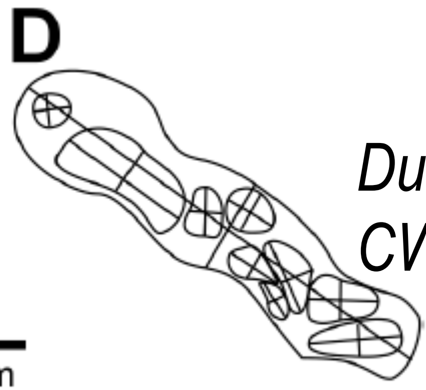
FINE electrodes





- They can provide an increased selectivity
- More channels
- More “favorable” anatomy
- Advanced signal processing
- However, **the selectivity could still be limited** especially for the delivery of sensory feedback





Durand, Tyler, and colleagues, CWRU

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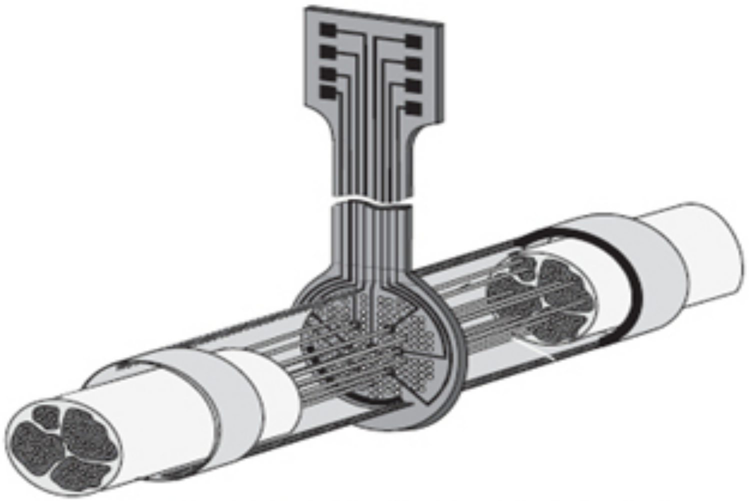
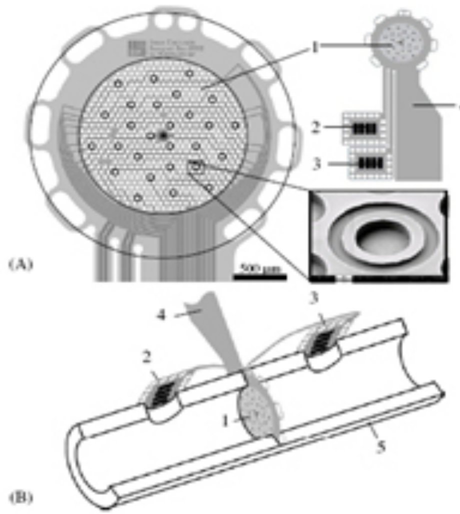
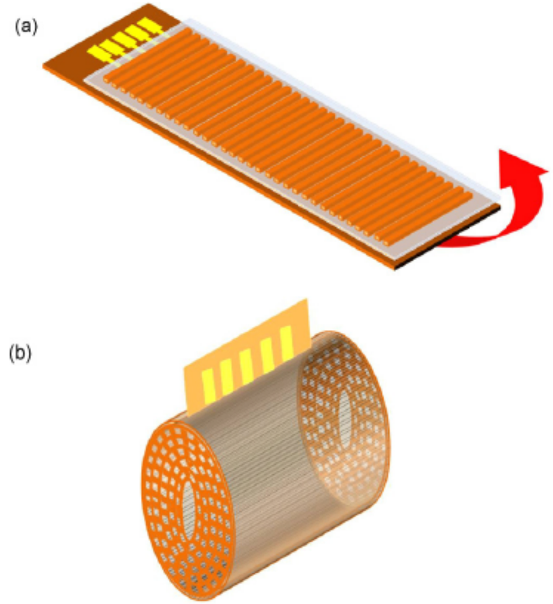
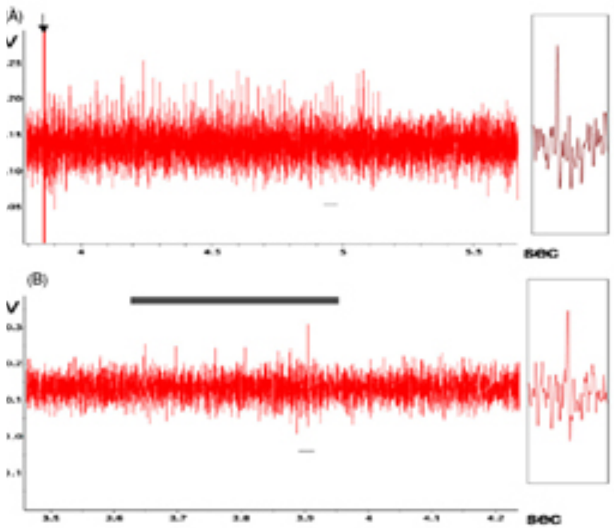
Regenerative electrodes



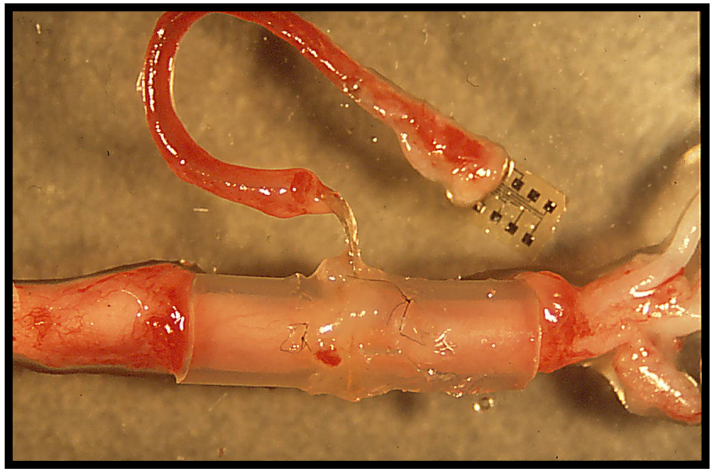






Dario, Micera et al., 1998
Rodriguez, Navarro et al., 2000
Ramachandran, Navarro et al., 2006
Lacour et al., 2013

Regenerative electrodes

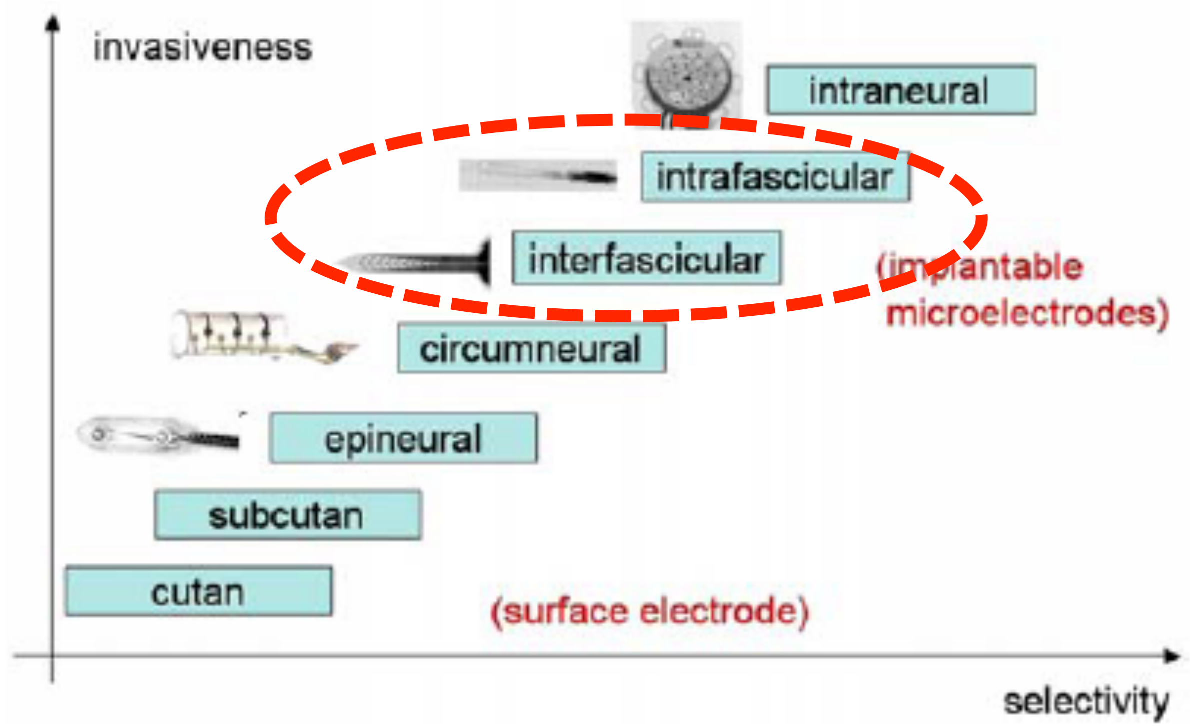


Nerve regenerated through the regenerative electrode

- Regeneration was limited in comparison with nerves repaired with a silicone guide without sieve electrode (obstacle to regeneration)
- Maintenance of regenerated axons is difficult in the absence of distal targets organs, as in amputed limbs

Lago, Navarro et al. Biomaterials 2005

Implantable PNS electrodes

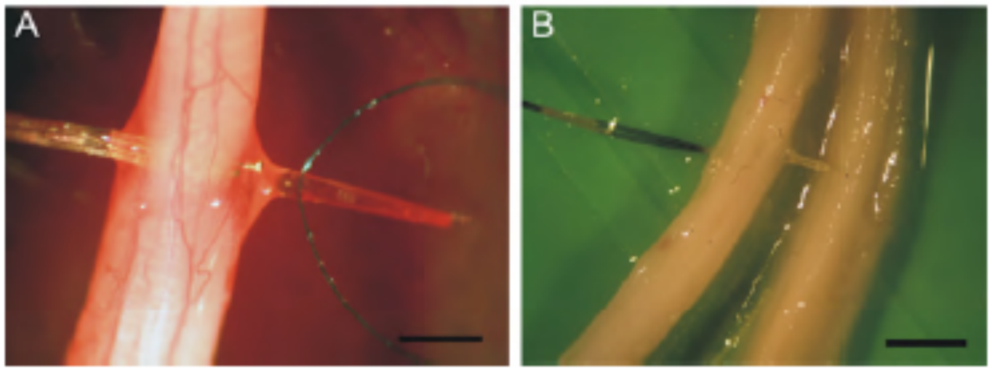


Intraneural electrodes seem to represent a good trade-off between high selectivity and reduced invasiveness

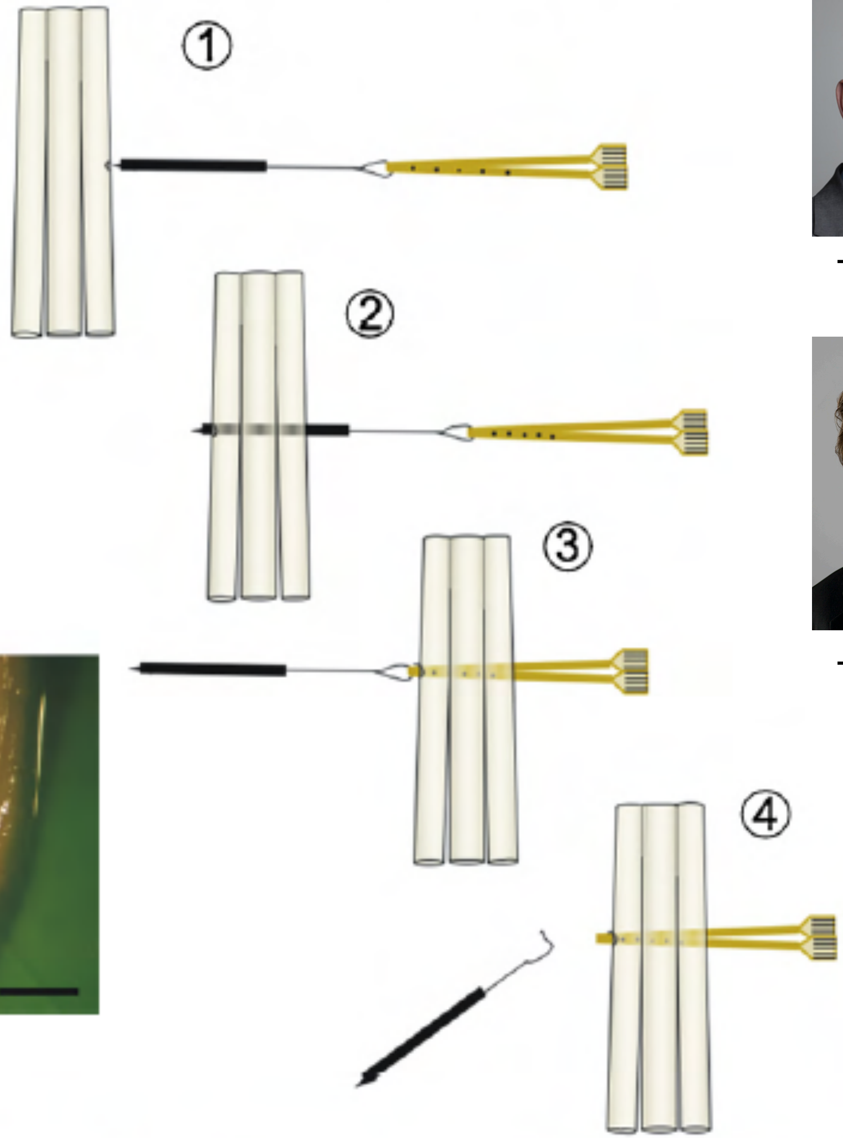
Micera, et al., IEEE T-NSRE, 2008

Transveral Intrafascicular Multichannel Electrode (TIME)

- A novel electrode design that transversally penetrates the peripheral nerve
- Intended to selectively activate subsets of axons in different fascicles within the nerve



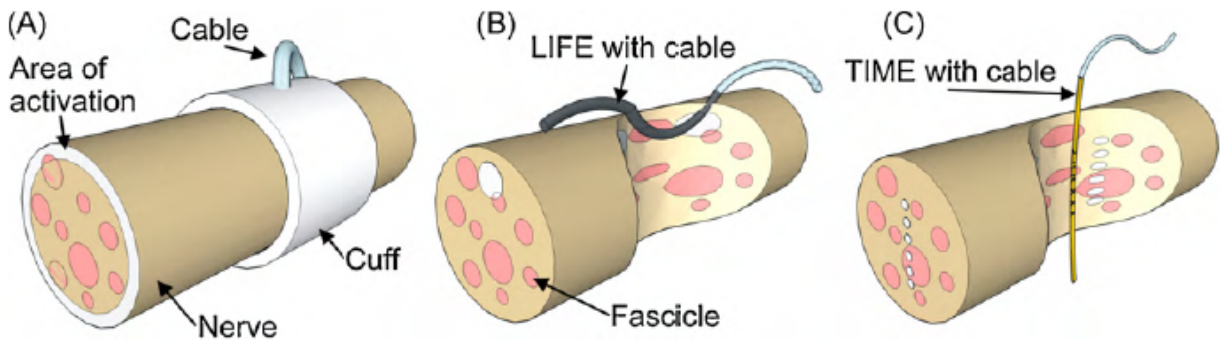
Boretius, et al., Biosensors and Bioelectronics, 2010



T. Stieglitz

T. Boretius

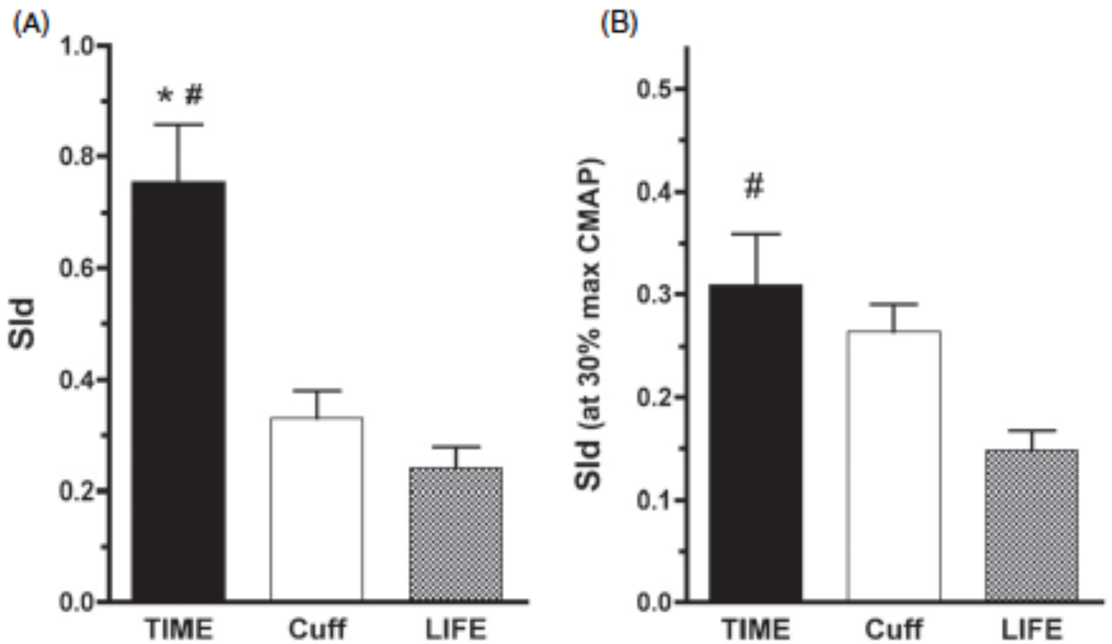
Transveral Intrafascicular Multichannel Electrode (TIME)



X. Navarro

Very good selectivity when compared with other solutions

Badia, et al., J Neural Eng, 2011



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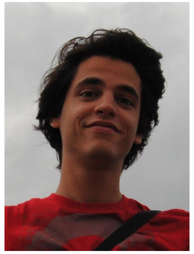
Short-term implant of TIMEs in an amputee

P.M. Rossini

S. Raspopovic

M. Capogrosso



M. Bonizzato

- 35 year old man, from Denmark
- trans-radial amputation in 2004 (fireworks accident during family celebration)

- Subjects resistant to pharmacological therapy and with no neuropathies (evaluated by Electroneurography) or other systemic diseases affecting brain/spinal cord/nerves

- Subjects with no neuropsychiatric disorders, evaluated by neuropsychological and psychiatric tests (WAIS-R, CES-D, MMPI-2)

- FOUR week implant

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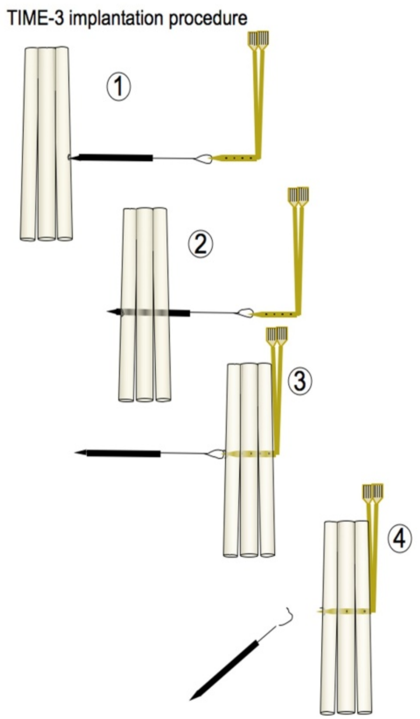
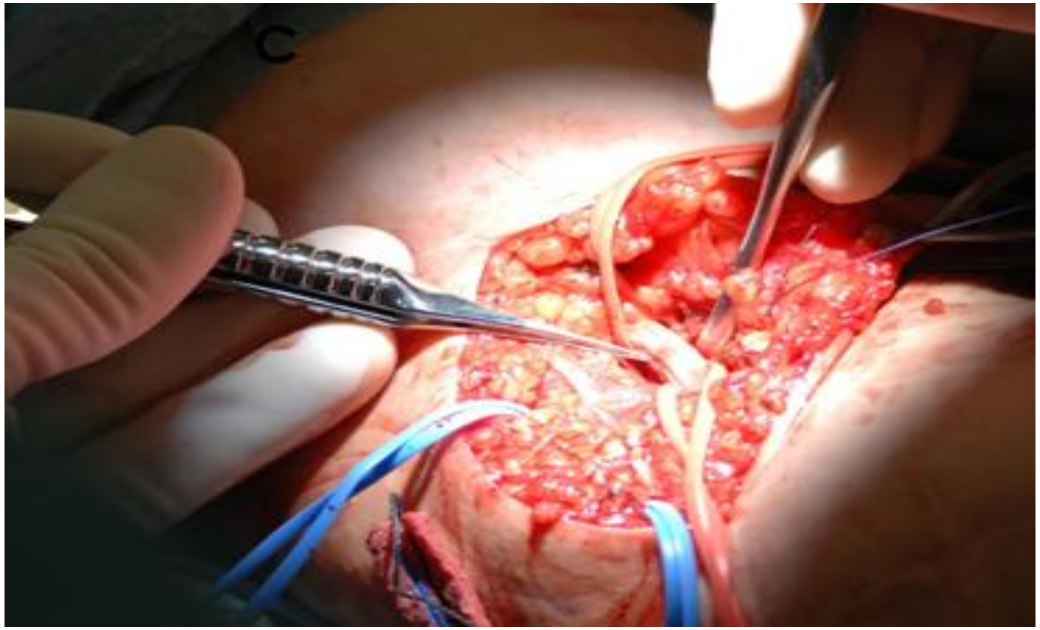
TIME implant

- **Nerves to implant:**
  - ✓ Median nerve
  - ✓ Ulnar nerve

- **Number of electrodes:**
  - ✓ 2 for each nerve





▪**Surgical technique:**

✓General anesthesia
✓skin incision (medial edge of the biceps muscle-15 cm)
✓Exposition of the ulnar and median nerves
✓epineural microdissection
✓TIME electrodes inserted under surgical microscope using a guiding needle
✓8-0 suture used to fix the electrodes to the epineurium
✓Subcutaneous pockets

Force and manipulation control using sensory feedback

- The stimulation protocol was designed and articulated in two phases:
  - Threshold and upper limit detection and subjective mapping of sensation location, type and strength
  - Implementation of closed-loop control strategies

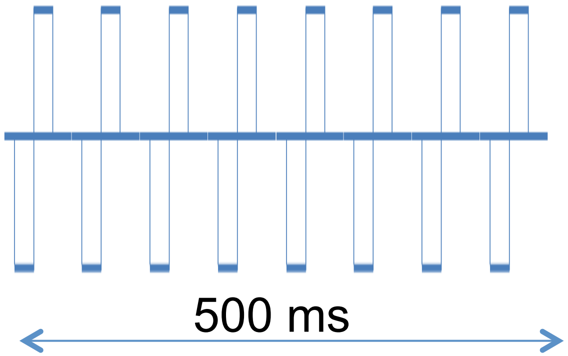
Force and manipulation control using sensory feedback

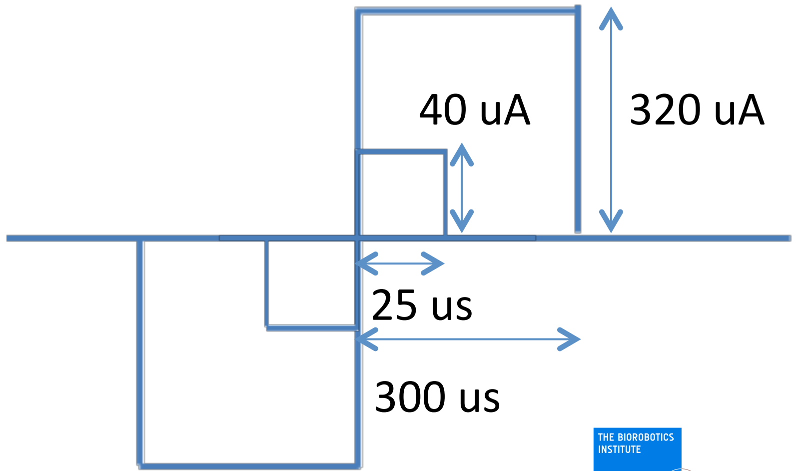

S. Raspopovic


F. Petrini

The stimulation was delivered as follows:

- ✓ Symmetric biphasic pulsed trains lasting 500 ms were delivered through every channel (referred to the correspondent ground, e.g. T2L2-T2LG) for all the electrodes
- ✓ Cathodic waves (the first phase was always of negative polarity)
- ✓ The pulse width and amplitude were increased respectively from 25 to 300 us (with steps of 25 us) and from 40 to 320 uA (with steps of 20 uA): the delivered charge resulted to be in the range 1-96 nC
- ✓ The frequency of the biphasic pulses was 50 Hz (empirically tested to be the most pleasant one for the patient)

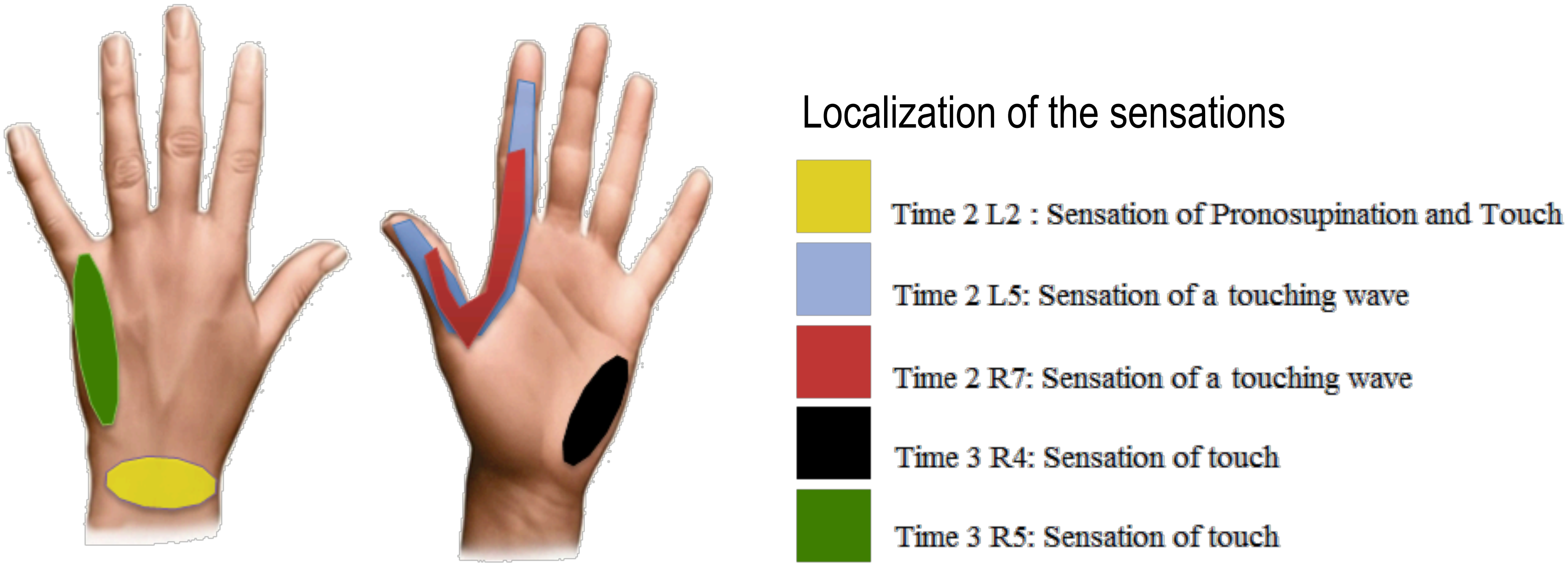




Characterization of the sensations provided

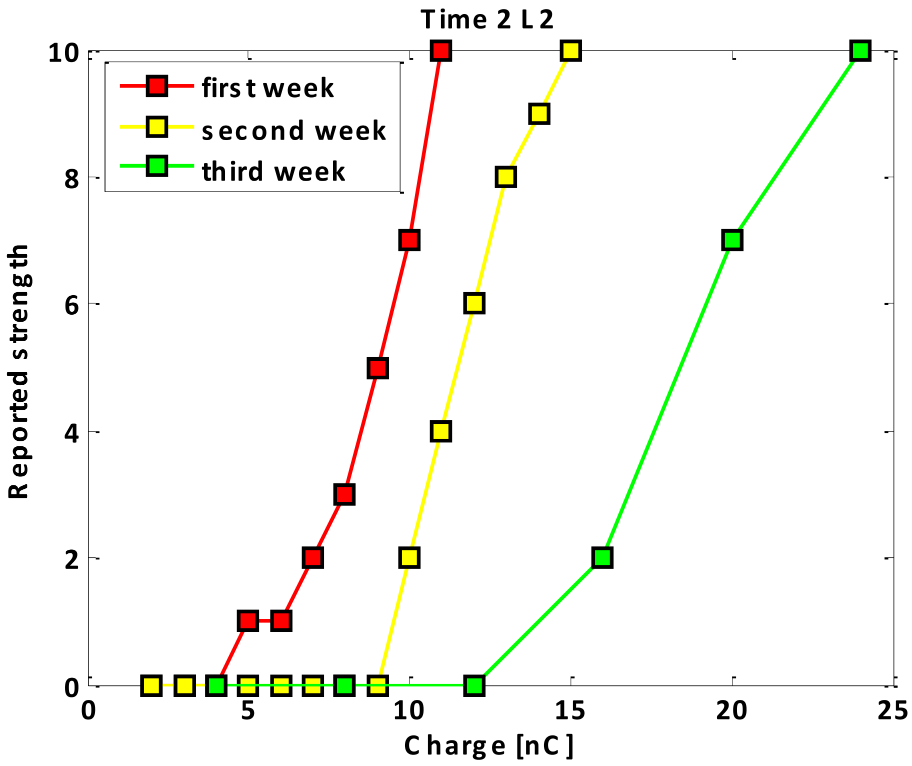
Results:

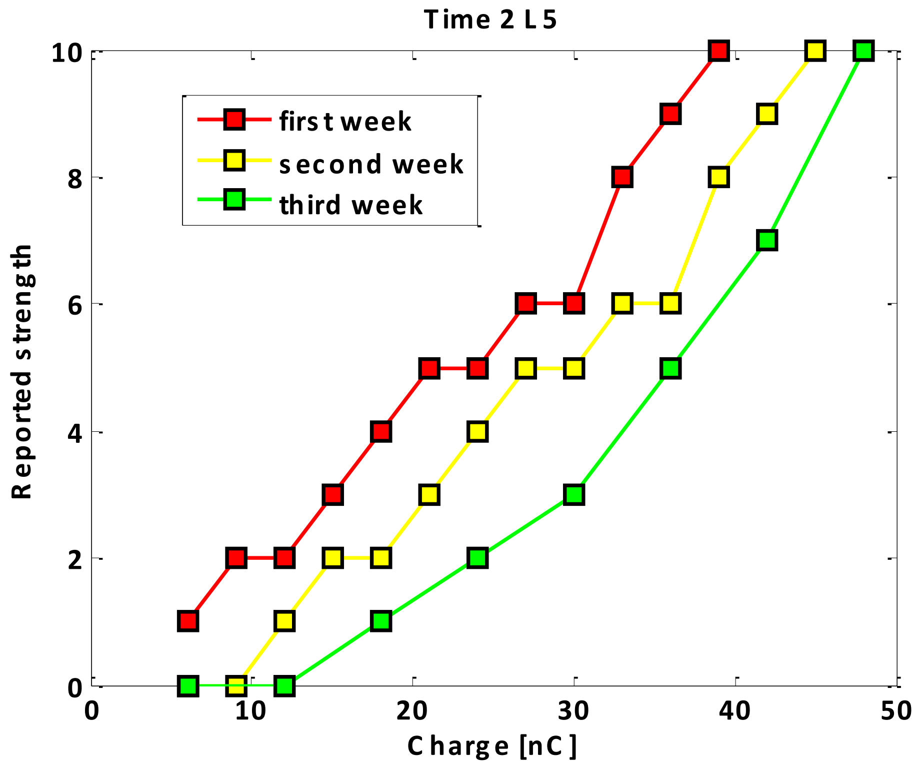
1. the patient reported a large variety of sensations: waving on the skin, touch, pressure, hot/cold, proprioception, vibration
2. the reported sensations were prevalently localized on palm, thumb, index and little finger of the missing hand/fingers



Characterization of the sensations provided

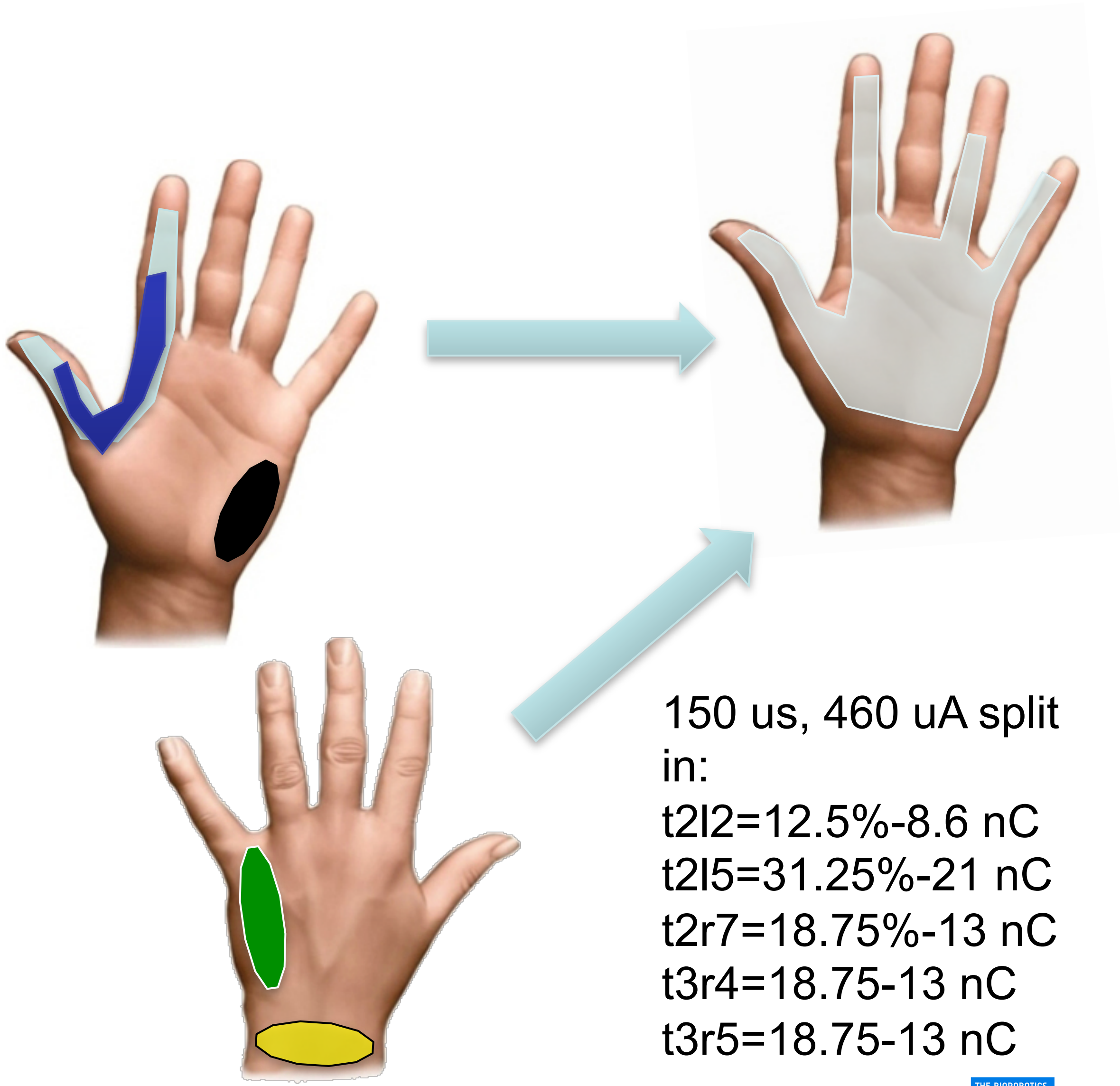
Injected charge-Reported sensation strength





Characterization of the sensations provided

- We discovered that by stimulating simultaneously different electrode channels, sensations different from the original ones could be elicited



150 us, 460 uA split in:
t2l2=12.5%-8.6 nC
t2l5=31.25%-21 nC
t2r7=18.75%-13 nC
t3r4=18.75-13 nC
t3r5=18.75-13 nC

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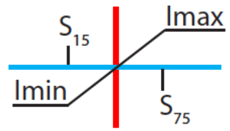
Closed-loop control based on sensory feedback

- Test the possibility for the subject to use the sensory information during closed-loop control and manipulation experiments

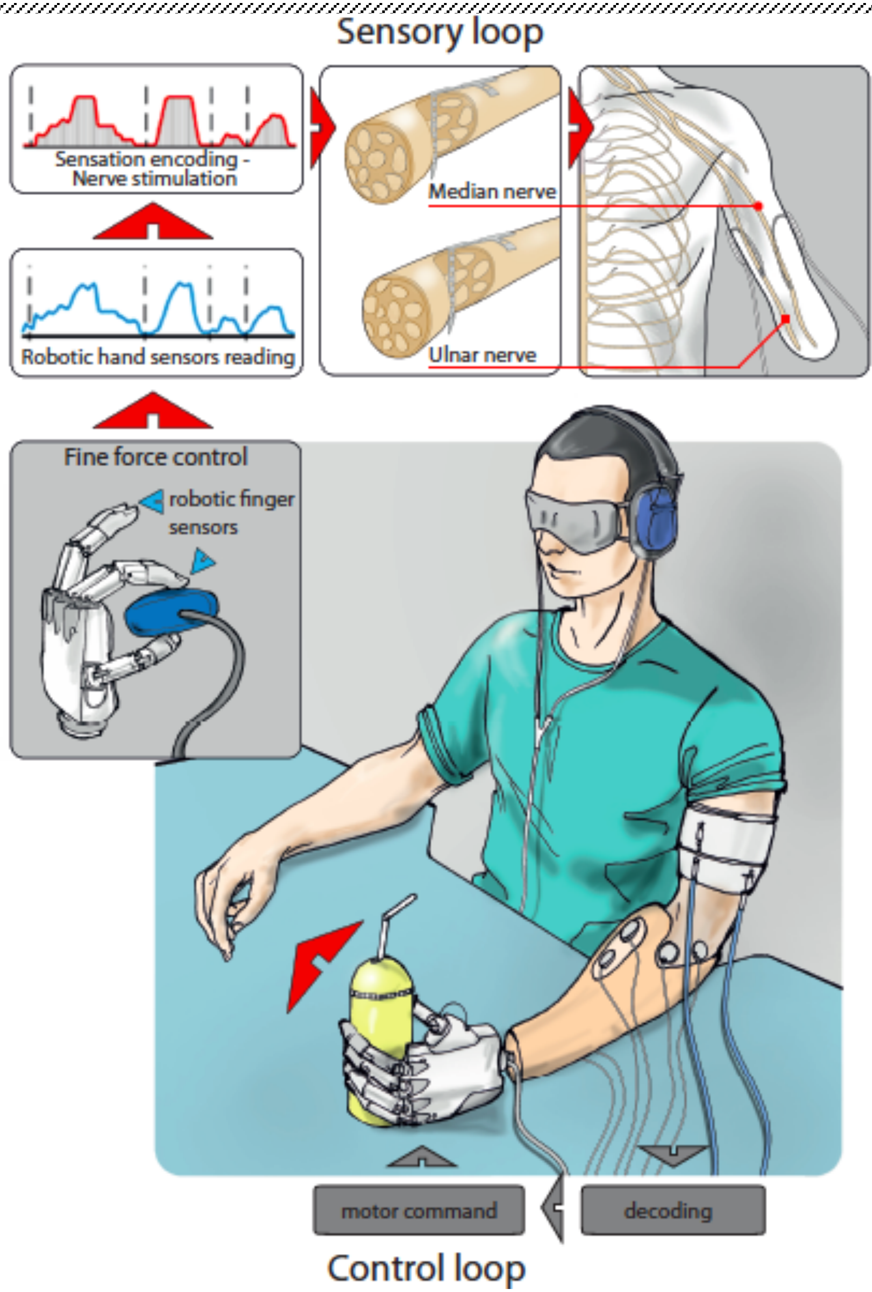
Current saturation



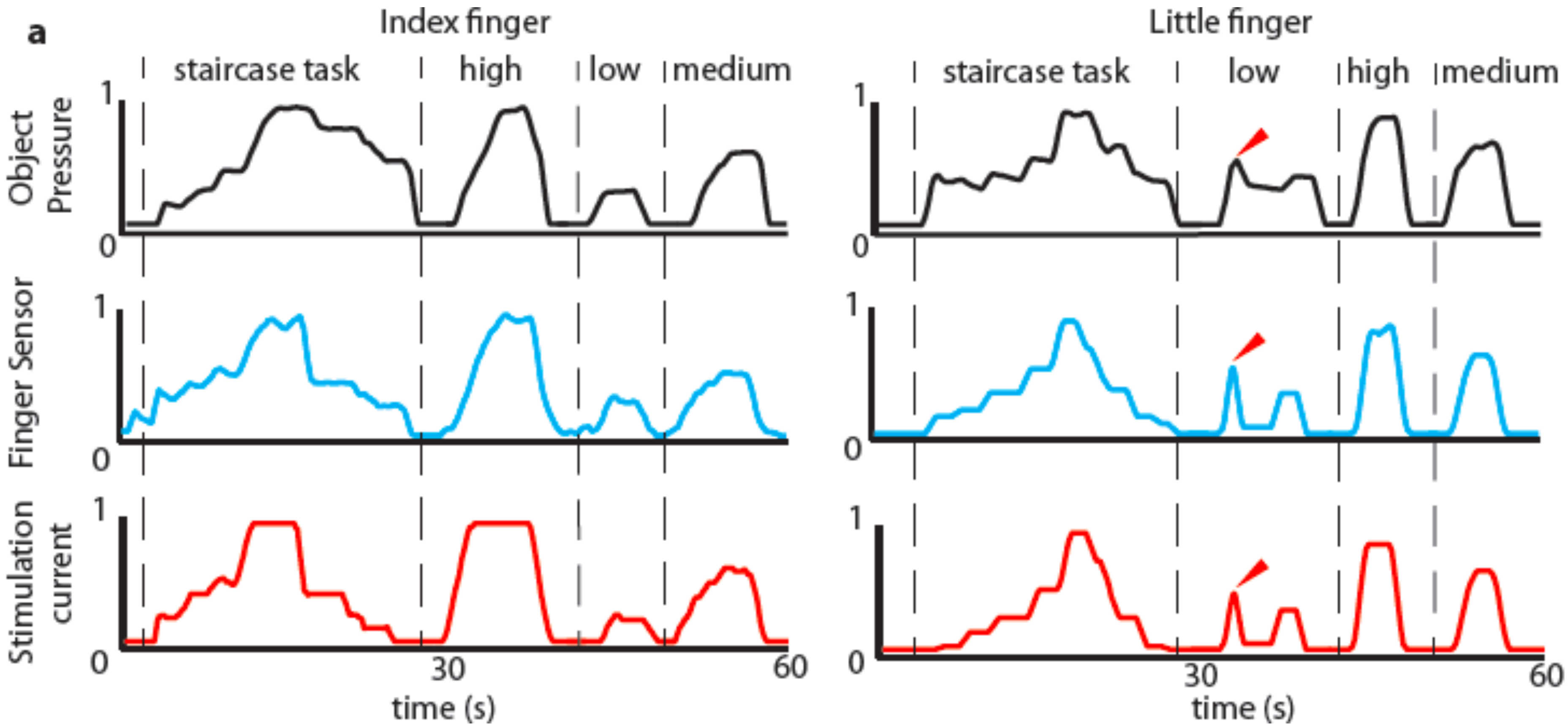
$$\mathbf{I} = (\mathbf{I}_{\mathbf{max}} - \mathbf{I}_{\mathbf{min}}) \cdot \frac{(S - S_{15})}{(S_{75} - S_{15})} + \mathbf{I}_{\mathbf{min}}$$

Current/Sensor relationship

Azzurra dexterous hand
(Prensilia srl)



Selection of grasping force levels



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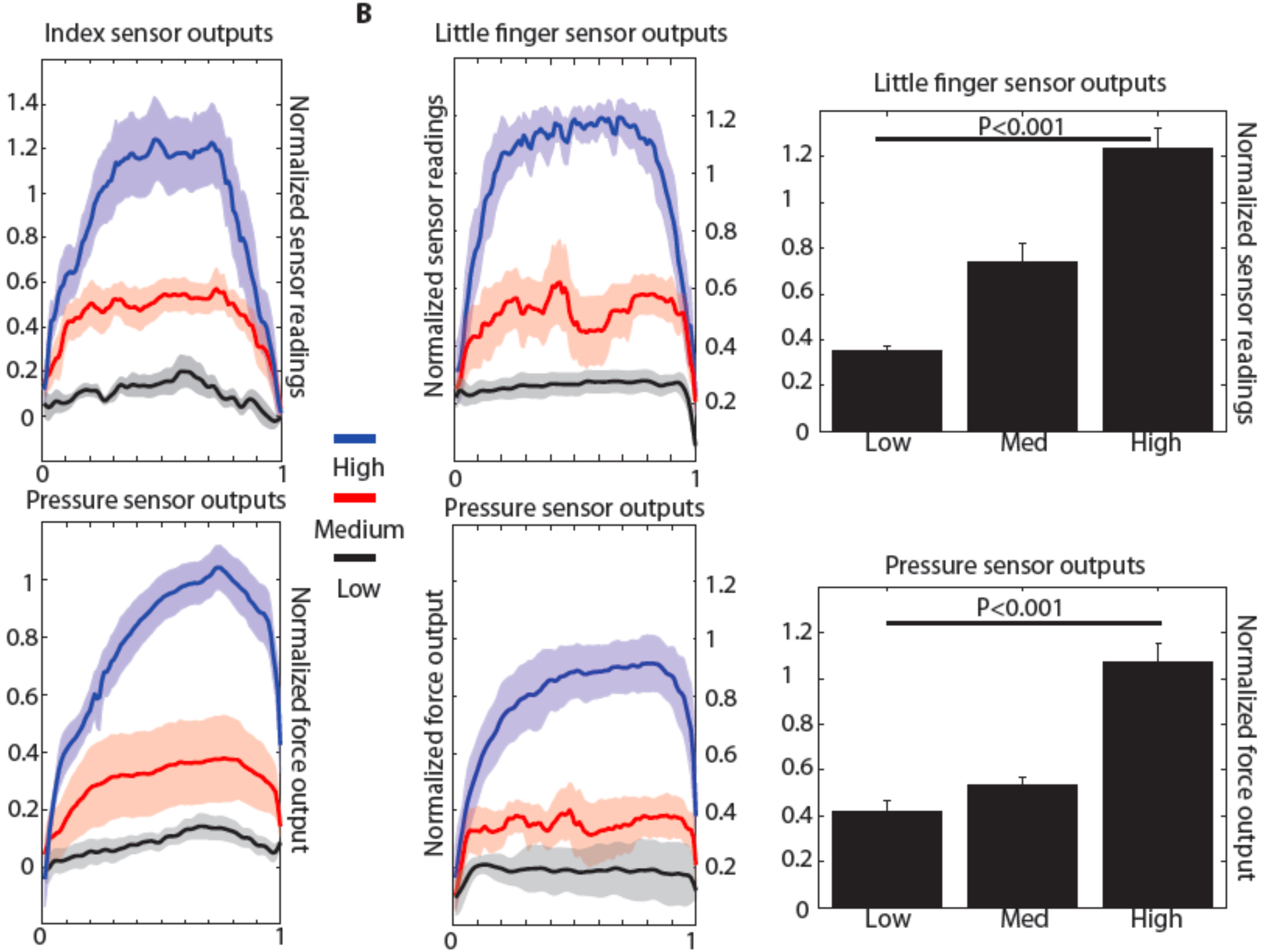
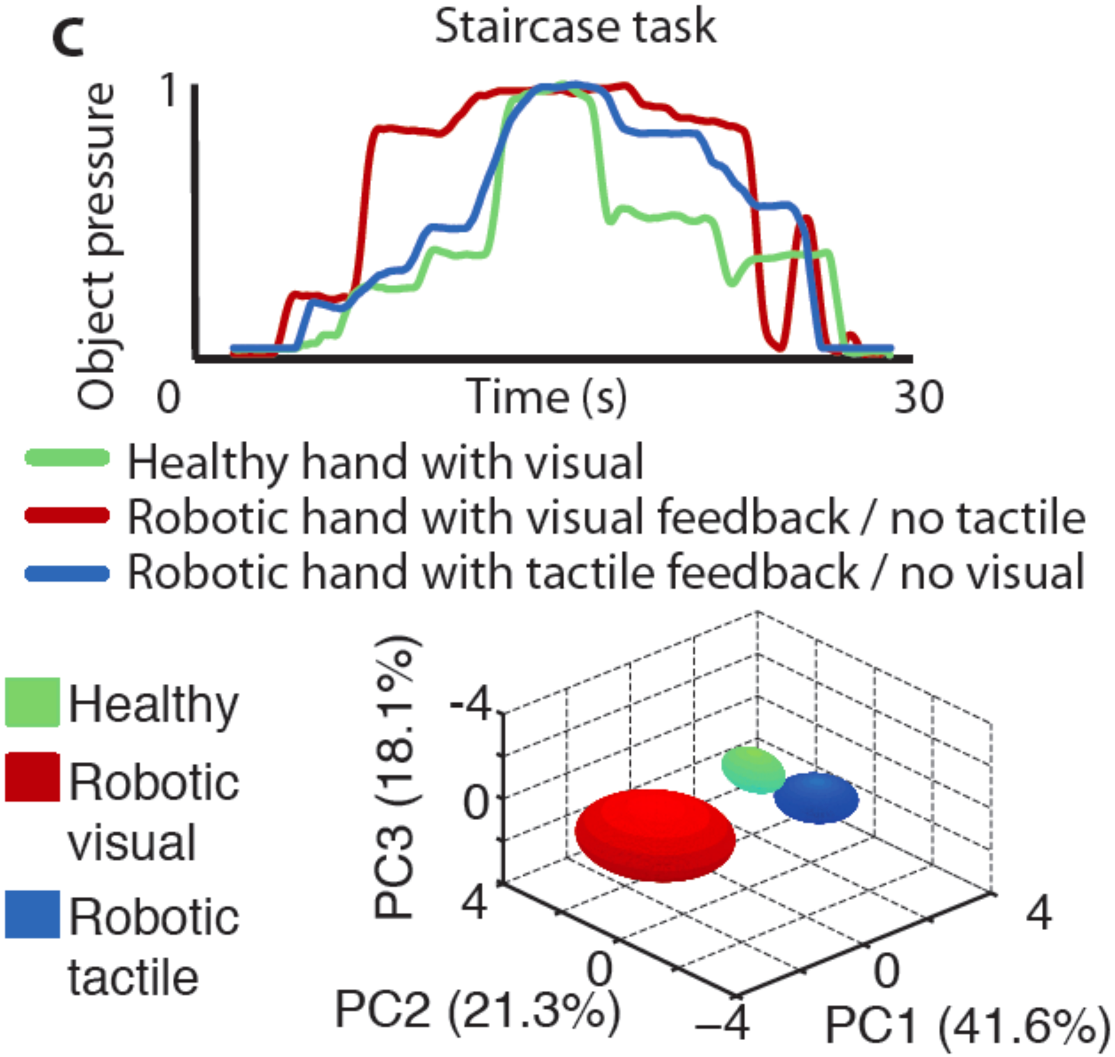


Modulation of grasping force

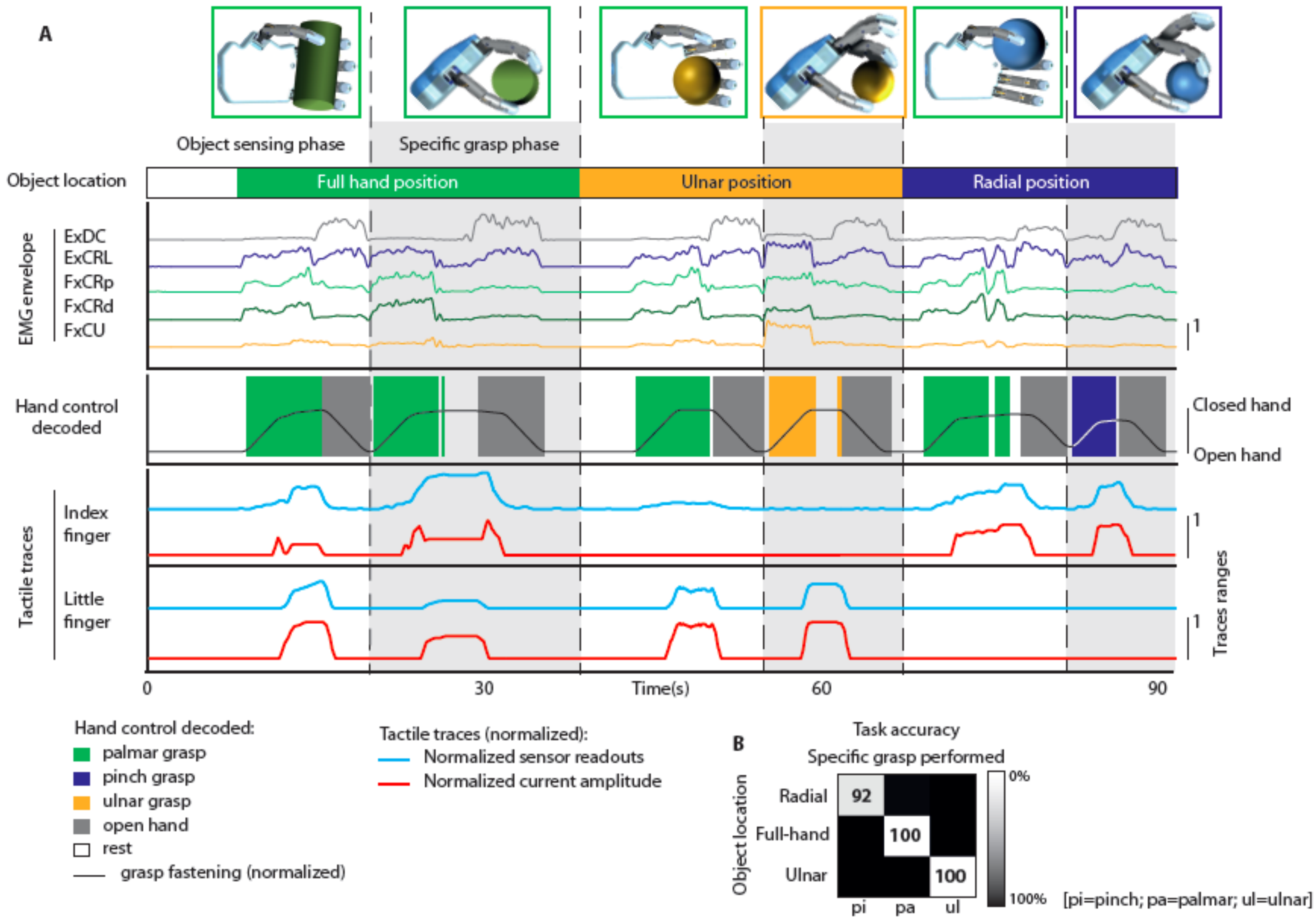


The artificial sensory feedback allowed the user to achieve performance close to the natural ones

Take home message #5

Sometimes dreams can become real

Grasping recognition



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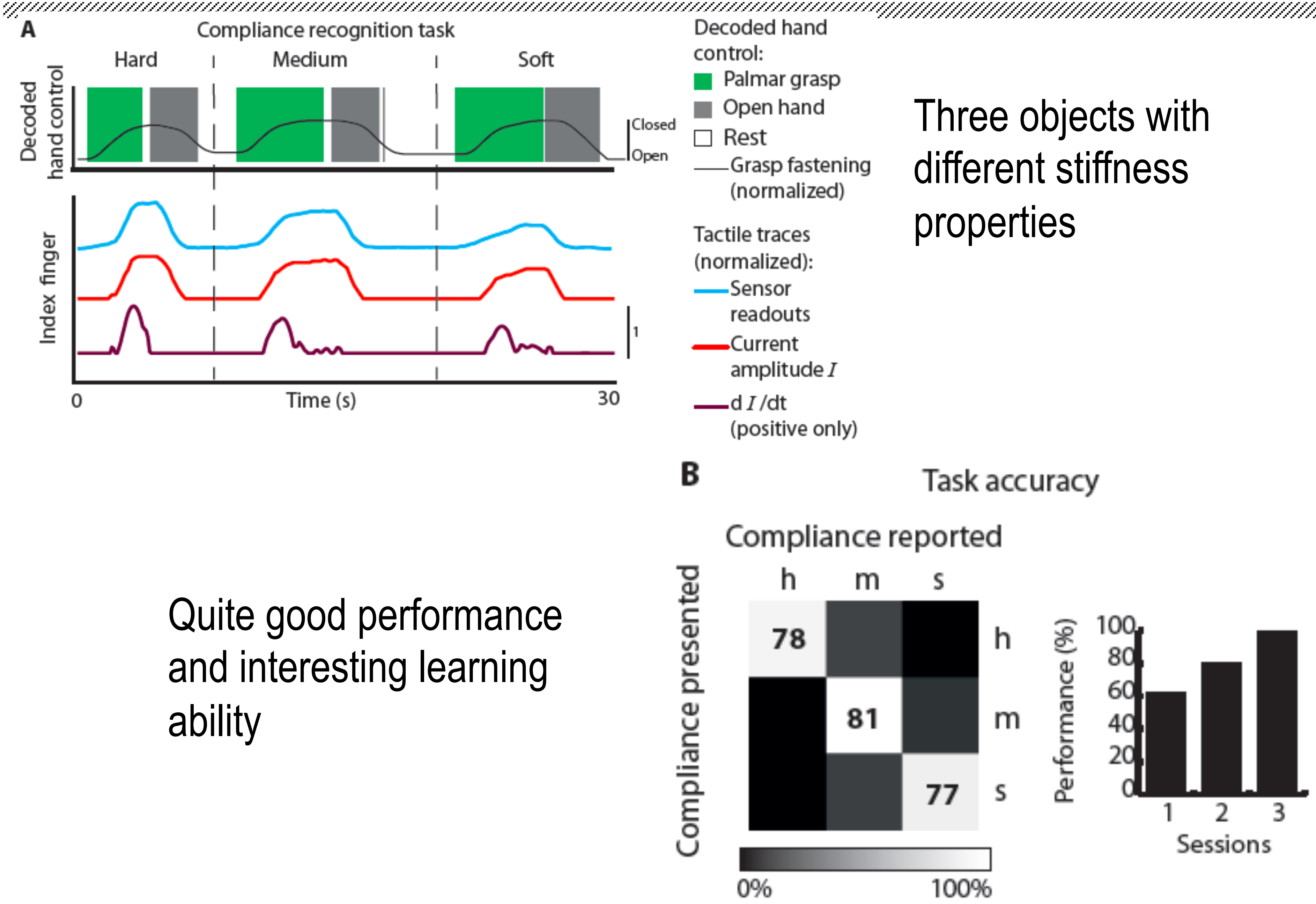
Compliance recognition

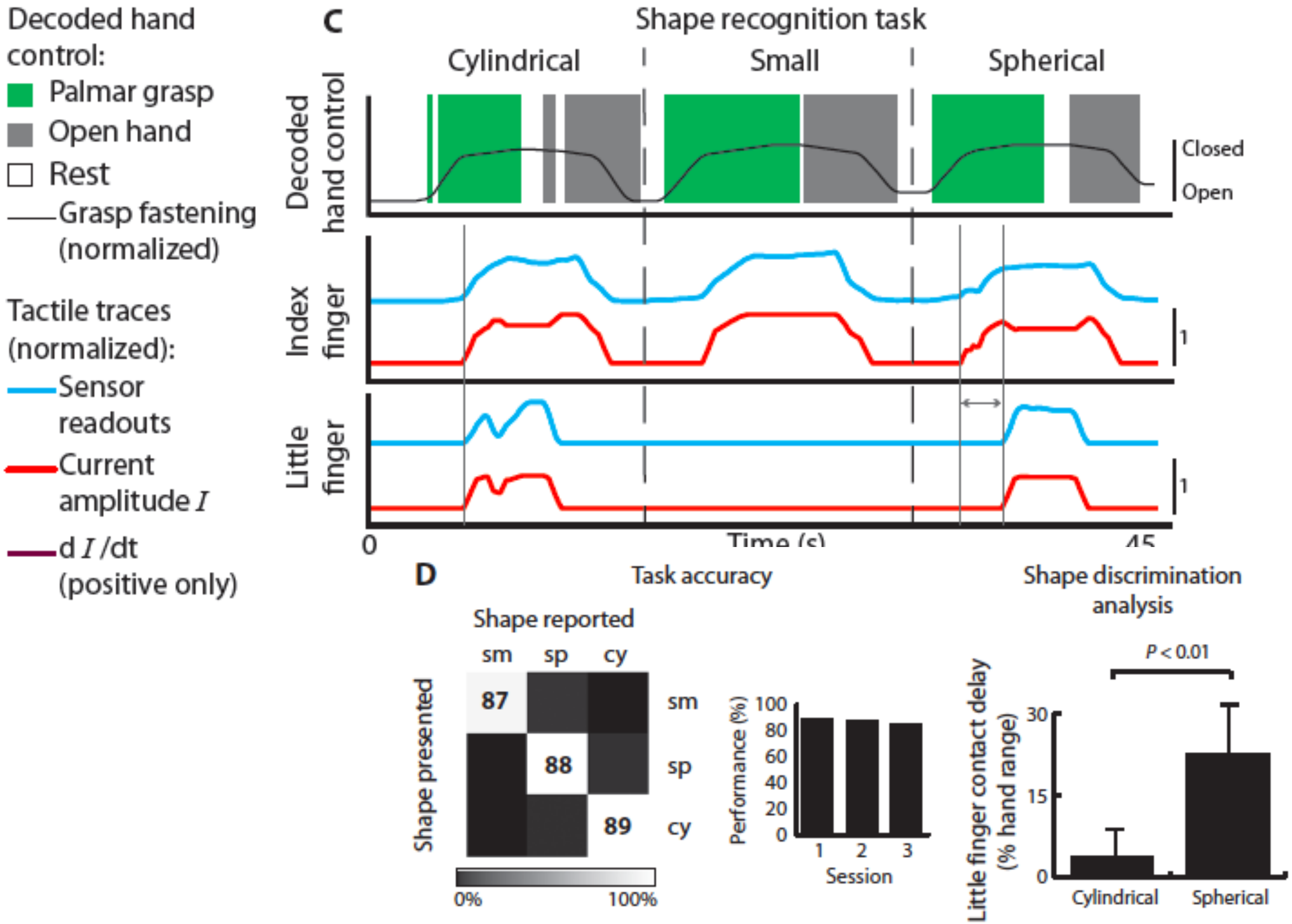


Three objects with different stiffness properties

Quite good performance and interesting learning ability

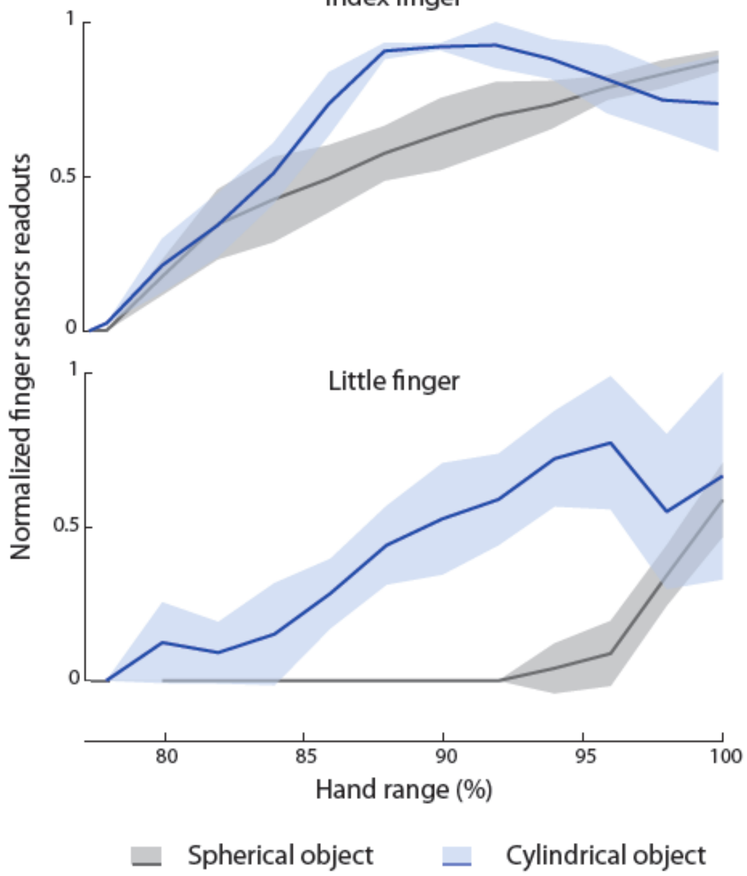
SENSING COMPLIANCE: HARD

Shape recognition

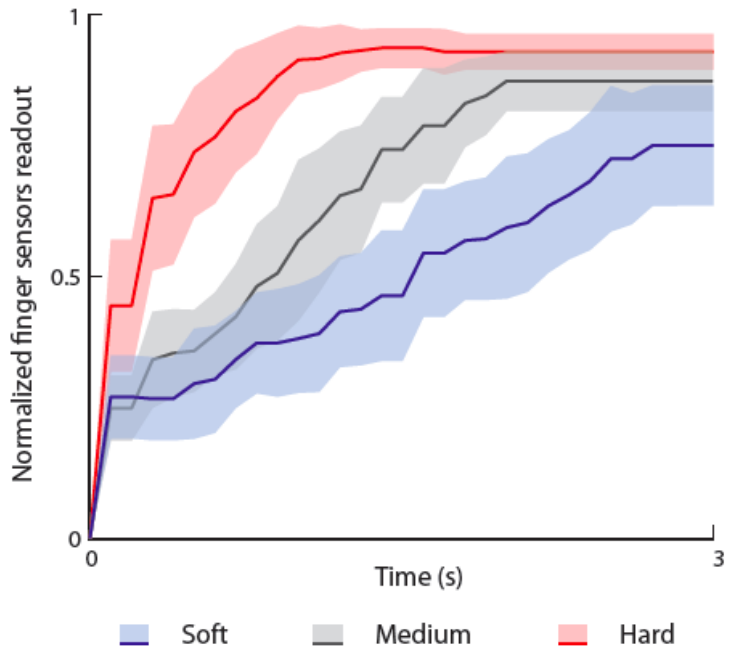


Why this is possible?

Shape recognition



Compliance recognition



Different force profiles were provided to the users using the afferent stimulation
→ this is **NOT** on-off sensation!

Next step: long-term clinical study

CHUV (Lausanne)

AUOP (Pisa)

Gemelli (Rome)

Conclusions

- It is possible to restore a natural sensory feedback using TIME electrodes
- The user is able to easily integrate the information into motor control strategies
- The potentials and limits of this approach must be clearly defined in the next future

Take home message #6

This is just the onset of the story

Thanks to DENNIS!

FOR MORE INFORMATION

silvestro.micera@sssup.it