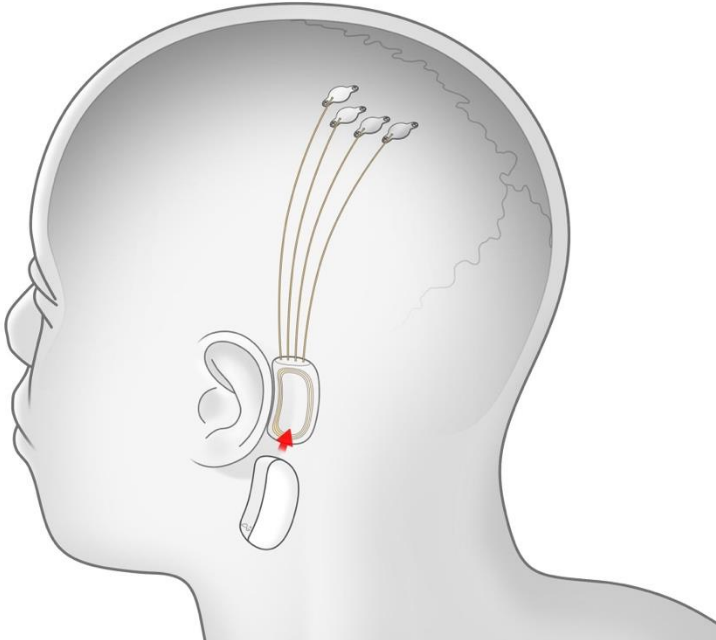
# Bionic artificial limbs
Translational neuroengineering

Dr. Solaiman Shokur
Prof. Silvestro Micera
Translational Neural Engineering lab, EPFL



# Bionic artificial hand

# The Motivation

- The loss of the upper limb is a traumatic event that changes the **quality of life** radically
- Reduction of
  - Ability in **reaching**, **grasping, and manipulation**
  - Ability to sense through the sense of touch
  - **Gesture** (communication)

- Causes:
  - Vascular deficiencies
    - Peripheral arterial disease
    - Diabetes (10% of people with diabetes have a foot ulcer)
  - Trauma:
    - Car Accident
    - Work accidents
  - Land mines
- Estimate of 0.1% to 0.5% of world population with amputation
- There are more than 1 million annual limb amputations globally

**Few innovations** in the past 50 years

Actual prostheses **do not satisfy** amputees' requirements and are very different from the natural model

# The big challenges

## Hand Prosthesis

How to design and develop a **more functional** and **naturally controlled prosthetics hand**?

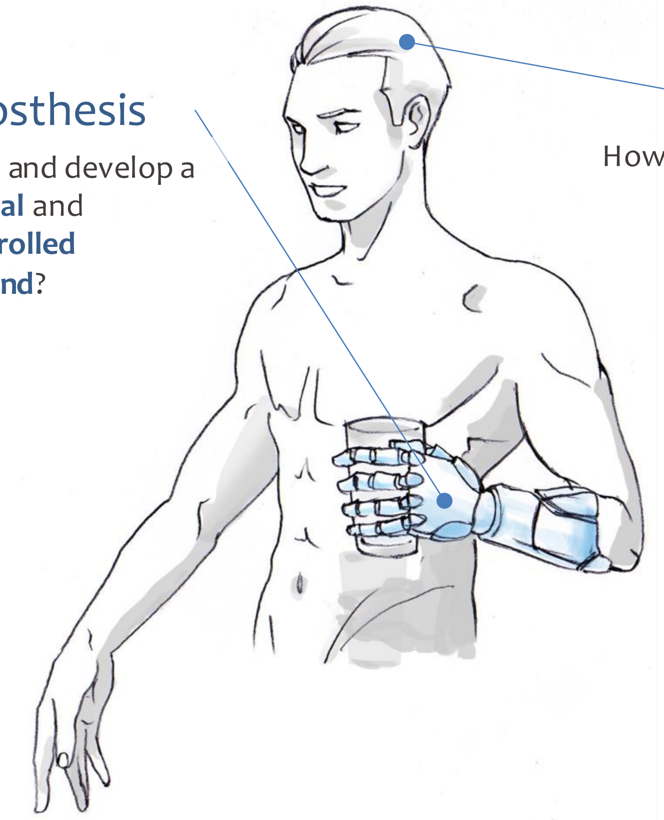
Dexterity

Functionality

Reliability

…

…



## Human Prosthesis Interface

How to **control** this dexterity?

Sources

Cognitive Effort

Reliability

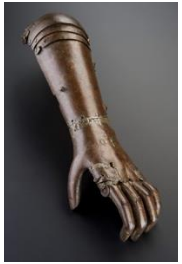
…

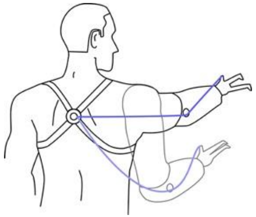
…

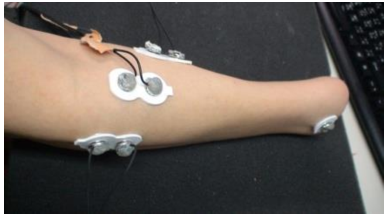
# Existing solutions for the action



- Prosthetic Hands
  - Passive
    - Cosmetic
  - Active
    - Body-powered
    - Robotic Prosthetic hands







# Examples of robotic prosthetic hands


Be bionic hand
Ottobock (GE)

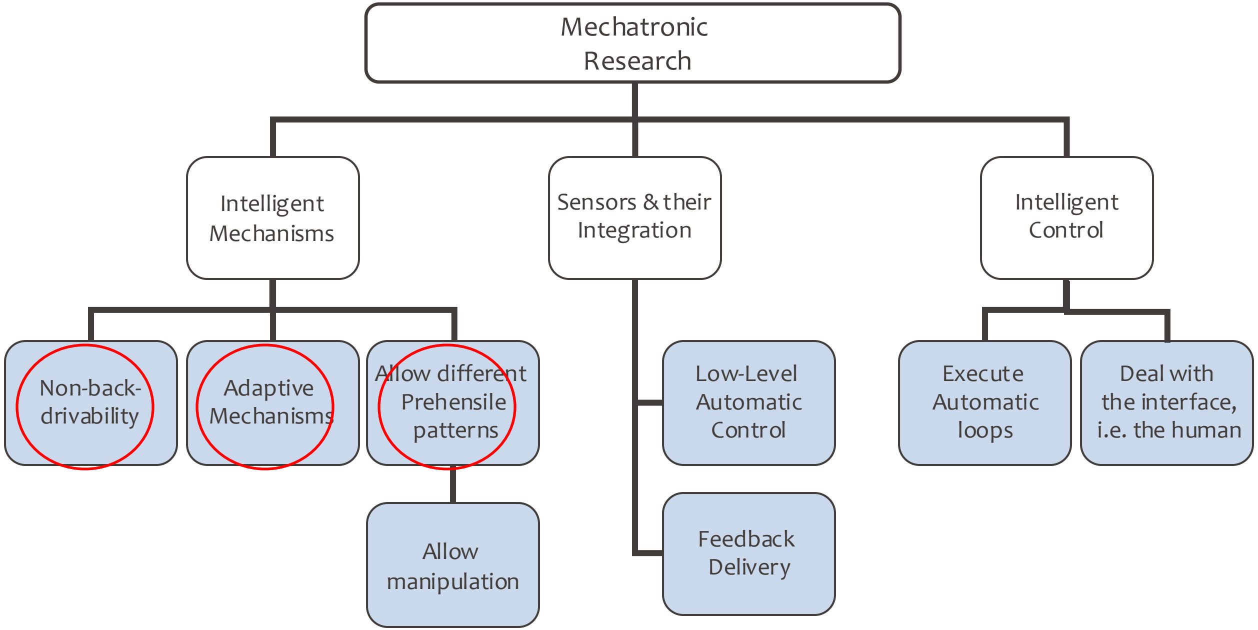
IH2 Azzura Hand
Prensila (IT)

Open Bionics
Hero arm

Hannes Hand
IIT (IT)


Darpa Prosthetic
Hand (USA)

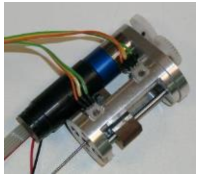
# Key issues

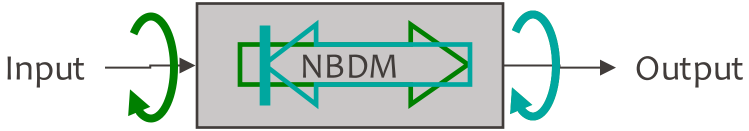

Mechatronic Research
Intelligent Mechanisms
Sensors & their Integration
Intelligent Control
Non-back-drivability
Adaptive Mechanisms
Allow different Prehensile patterns
Allow manipulation
Low-Level Automatic Control
Feedback Delivery
Execute Automatic loops
Deal with the interface, i.e. the human

# Mechatronic

## Design issues: non back drivability

Mechanisms wherein motions generated by the input (motor) drive are transmitted to the output (i.e. fingers) and wherein motions originated from the output are blocked






In a prosthesis it allows to maintain the grasp once the power supply is switched off

Non back drivable transmission = Power saving!= key in prosthetics!

Lead Screw

Worm Gear

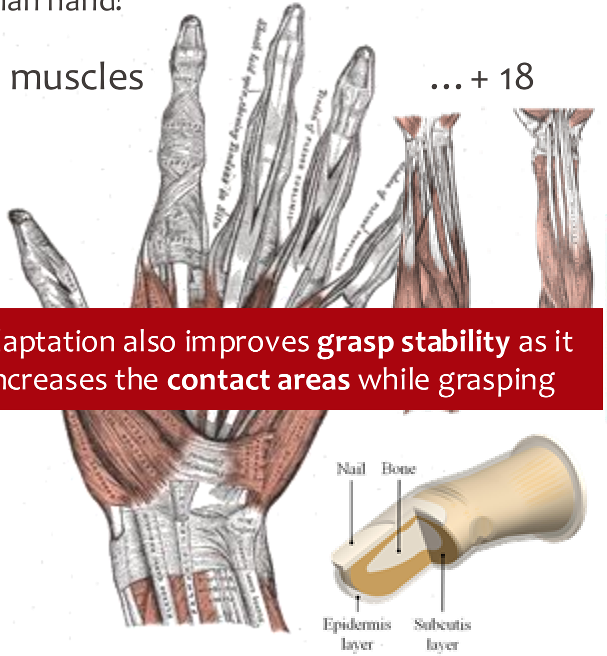
Gear heads with high reduction rate

Brakes/ clutches

# Mechatronic
## Design issues: adaptability

**Problem:** It's an hard task to **design, actuate, and control** a self-contained artificial hand with a number of degrees of freedom (DoF) equal or close to those in the biological human hand!

22 muscles … + 18



Adaptation also improves **grasp stability** as it increases the **contact areas** while grasping

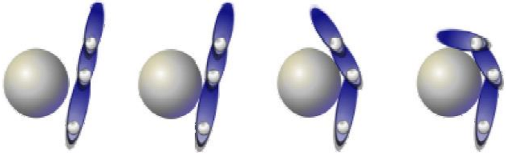


Phalanx adaptation mechanisms

Possible solutions (to simplify the problem):

- Cut DoFs; Rigidly couple DoFs;
- Implement adaptable mechanisms.

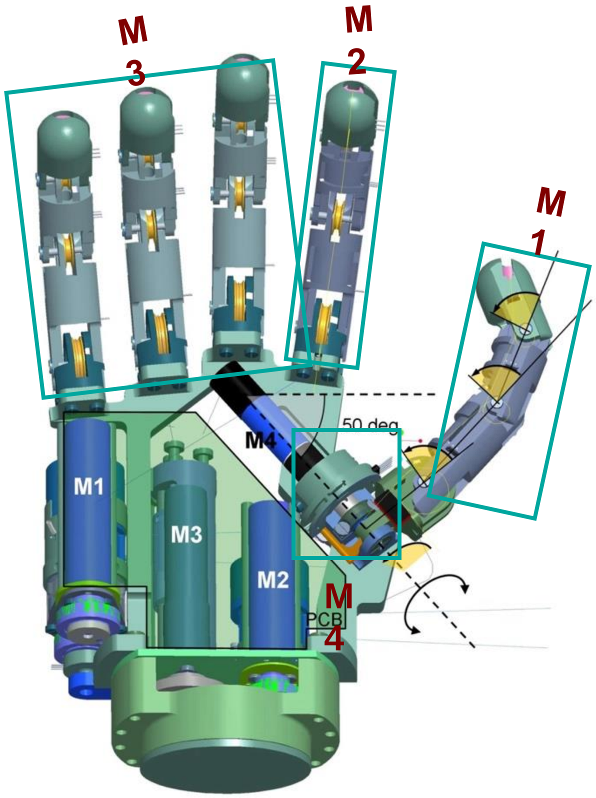

Hand adaptation mechanisms



Finger adaptation mechanisms

**Underactuated mechanisms**

# Case Study




## The SmartHand prototype

### The SmartHand at glance

**Mechanical Spec**

| | |
|---|---|
| Weight | 600 gr |
| Size | Human inspired |
| Degrees of freedom | 16 |
| Degrees of actuation | 4 |
| Full flexion speed | <1.5 s |
| Tendon max active force | 45 N |
| Grasp force (Cyl, Lat, Lift) | <30,<5,100 N |

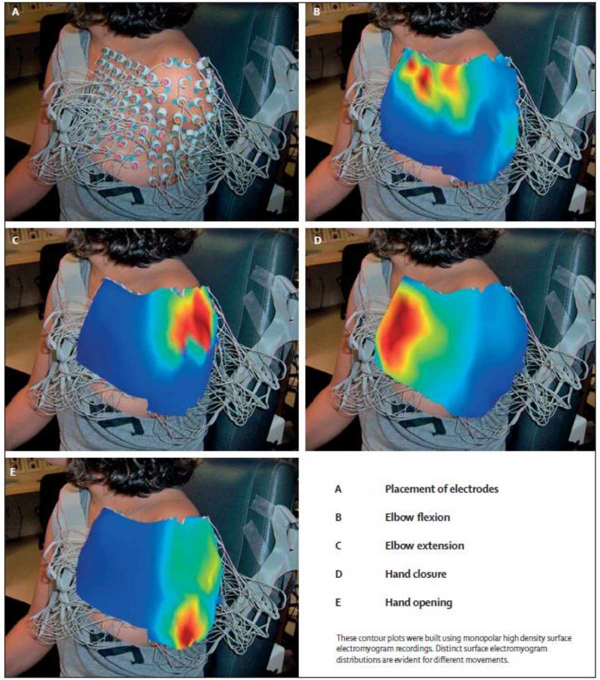
**Sensory System**

| | |
|---|---|
| Position (digital encoder) | 4 |
| Position (Joint Hall sensors) | 15 |
| Position (Potentiometer) | 2 |
| Tension Sensors (strain gauges) | 5 |
| Limit switch (digital) | 8 |

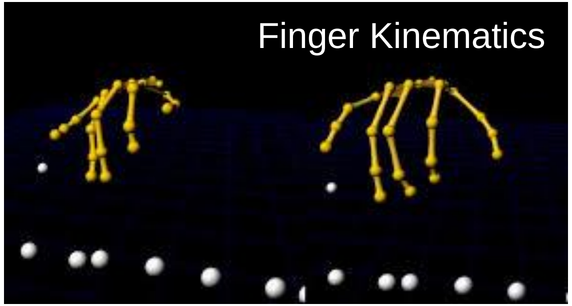
**Electrical Spec**

| | |
|---|---|
| Power req. | 12V /3A |
| Control loops | Position and tension (1 kHz) |
| Reading delays | < 1 ms |
| Total preset grasps | 10 (programmable) |
| Communication | RS232 / USB |

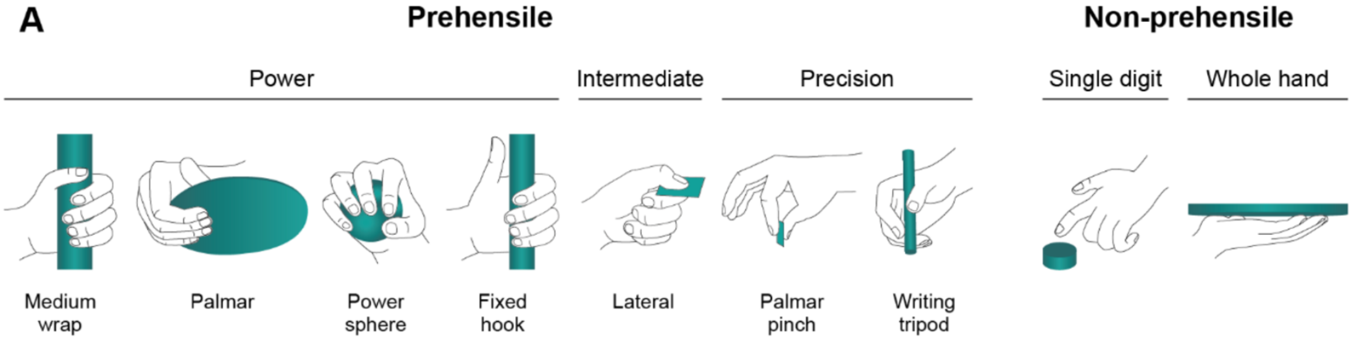
# Motor decoding



# What to decode



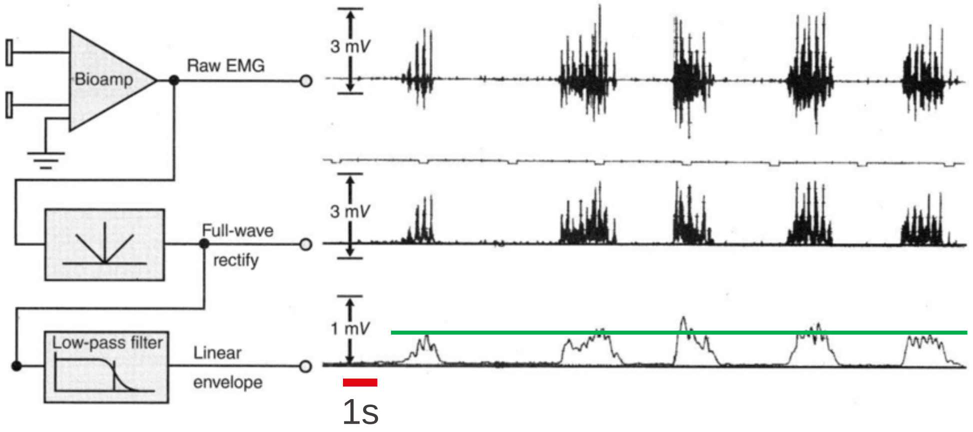

Grasping types



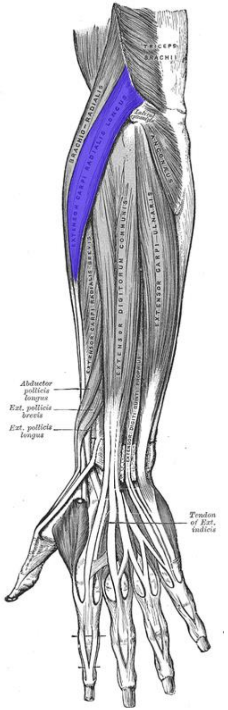

Feix, Thomas, et al. "The grasp taxonomy of human grasp types." *IEEE Transactions on human-machine systems* 46.1 (2015): 66-77.

# Electromyography (EMG) decoding: basic approach

Extensor carpi radialis longus muscle (wrist extension)




Thresholding

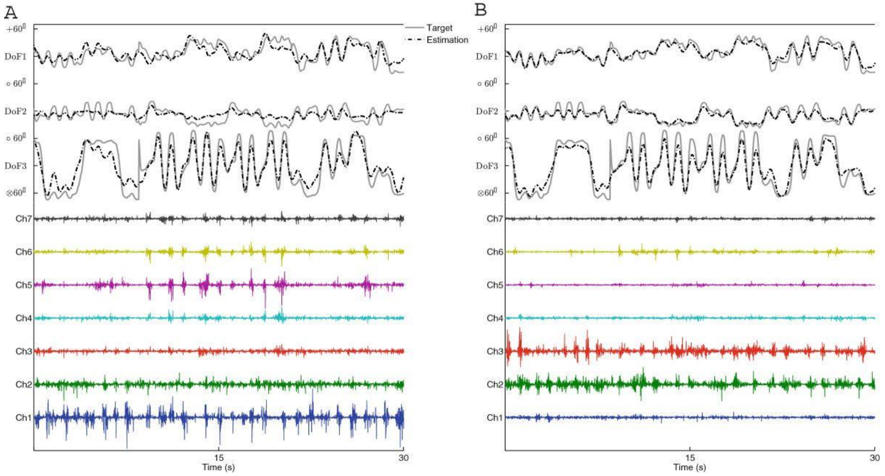


# EMG decoding: basic approach

- The majority of commercially available RPHs use threshold-based sEMG decoding over a few surface electrodes
- Generally, control of 1 DoF
- Sometimes more DoF, by cycle through different types of grasps:
  - Non intuitive
  - Cannot be used for multi DoF

# EMG decoding: machine learning approach

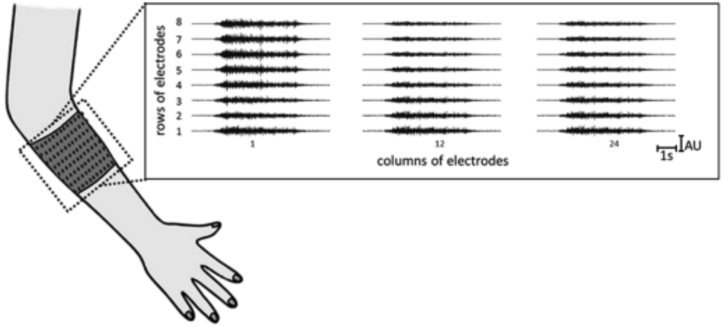
- Using machine learning approach (artificial neural network, ANN): proportional and simultaneous control of 3 DoFs of the wrist joint (flexion/extension, radial/ulnar deviation, and pronation /supination).



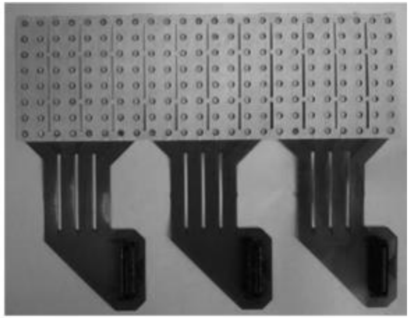

Jiang, Ning, et al. "EMG-based simultaneous and proportional estimation of wrist/hand kinematics in uni-lateral trans-radial amputees." *Journal of neuroengineering and rehabilitation* 9.1 (2012): 42.

# High density EMG

- In general, robustness and reliability of classical pattern recognition systems are influenced by **electrode shift during don and doff**, and by the presence of **malfunctioning channels**
- HD EMG grid of electrodes is an ensemble of sensors that records data spatially correlated.
- The variogram is a function that describes the spatial correlation between observations.




(a)



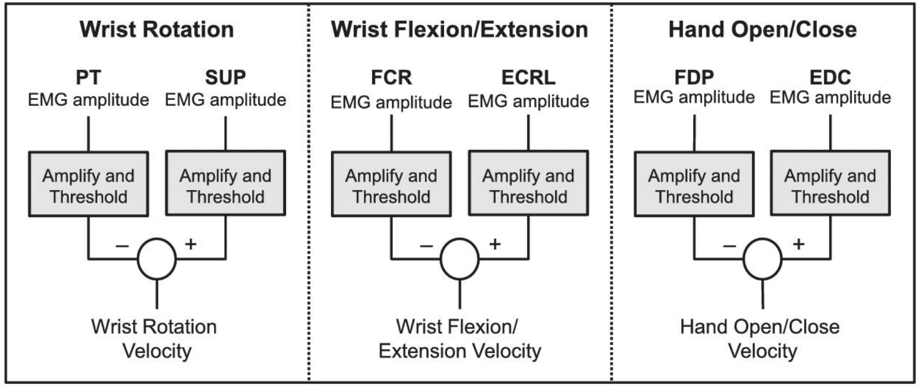
(b)



Stango, Antoniettaet al. "Spatial correlation of high density EMG signals provides features robust to electrode number and shift in pattern recognition for myocontrol." IEEE Transactions on Neural Systems and Rehabilitation Engineering 23.2 (2014): 189-198.

# Intramuscular EMG (iEMG) control

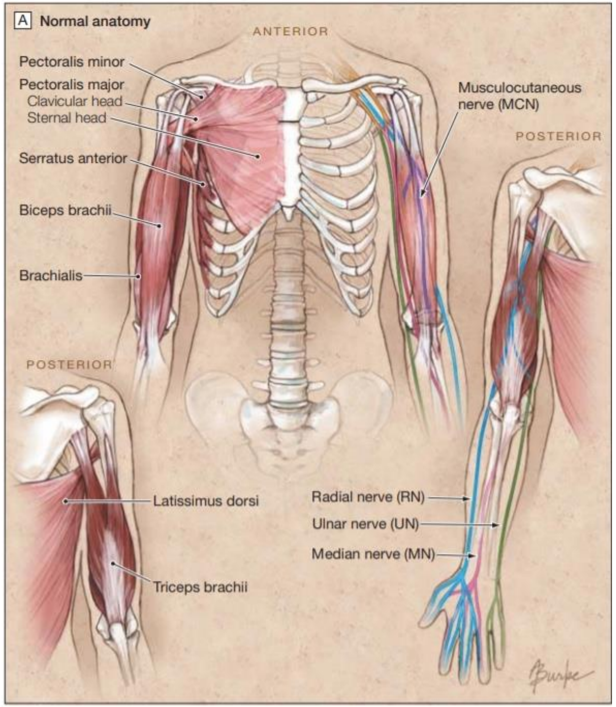
- Clinically available myoelectric control strategies do not allow simultaneous movement of multiple degrees of freedom (DOFs)
- The use of implantable devices that record intramuscular EMG signals could overcome this constraint
- Intramuscular EMG signals can be recorded using percutaneous fine wire electrodes inserted using needles
- The use of iEMG can allow to use proportional control (but of course also pattern recognition)



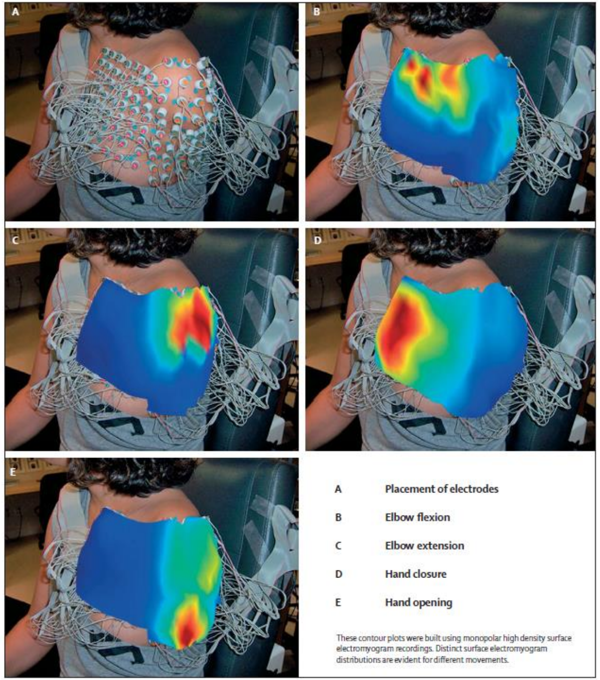

Smith et al., 2014

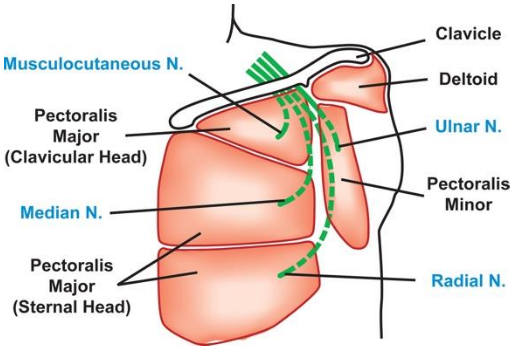
# Improve intuitiveness for prosthetic users: targeted muscle reinnervation (TMR)

- Years after amputation, severed nerves still carry information about movements.
- **But**, these nerves no longer have muscle effectors → this important neural information is unavailable via classic EMG recording.
- **Solution**: nerves severed because of arm amputation could be surgically transferred to **spare** 'target' muscles i.e., muscles rendered biomechanically redundant after loss of the arm. This technique is called **Targeted muscle Reinnervation (TMR)**



# Targeted muscle Reinnervation



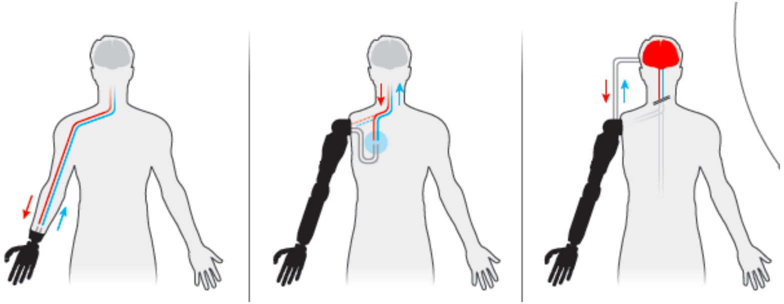

Muscles could be used as *bioamplifiers*

- After reinnervation, contraction of target muscles and EMG signal generation occurs in response to neural control information intended for the missing limb.
- Example: The patient wants to close their missing hand, the transferred median nerve causes depolarization of its target muscle, generating EMG signals that are used to close the prosthetic hand.
- This results in a faster, easier and more intuitive control of the prosthesis control.



Kuiken, Todd A., et al. "Targeted reinnervation for enhanced prosthetic arm function in a woman with a proximal amputation: a case study." The Lancet 369.9559 (2007): 371-380.


MOTHERBOARD

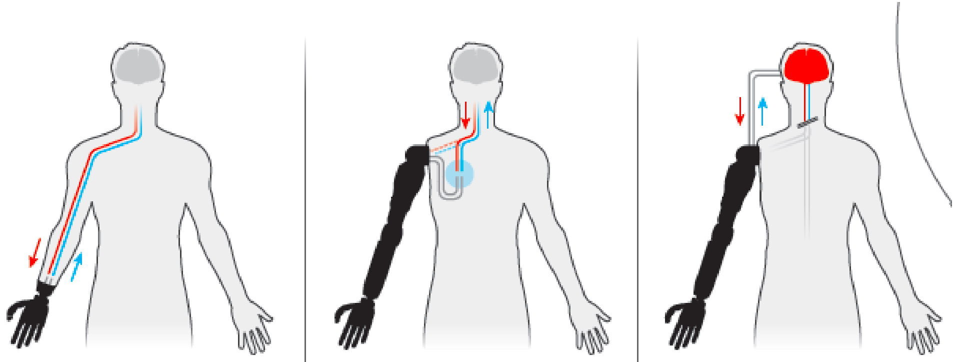


Kwok, Nature, 2013

# Sensory feedback

# 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*

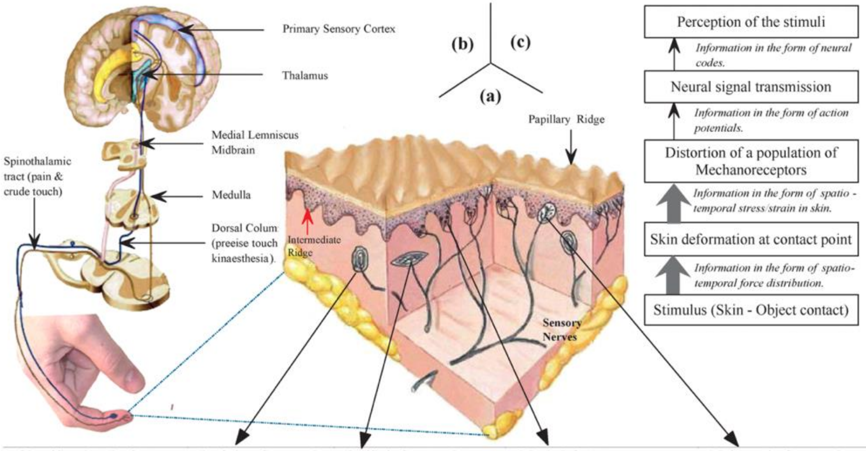
Re-routed nerves grow new endings into muscle and skin, where external devices translate signals going to and from the prosthesis.

*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.

Kwok, Nature, 2013

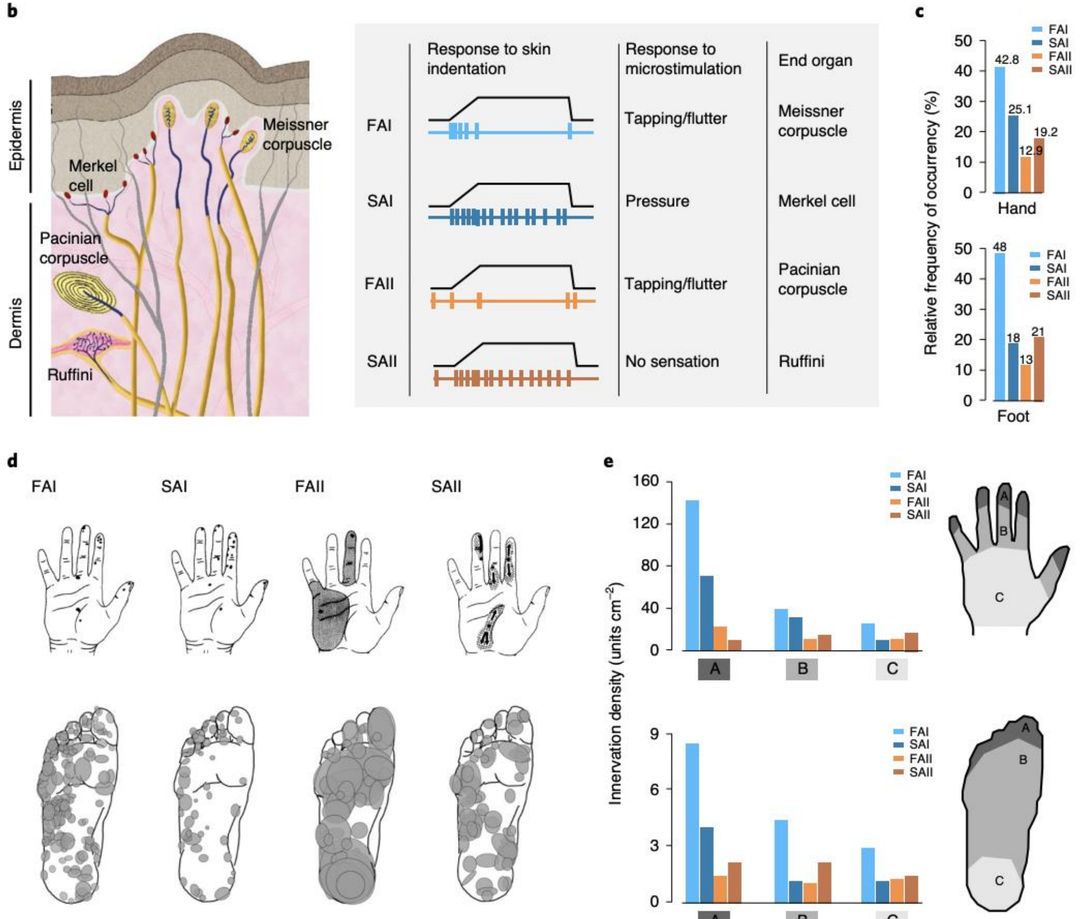
# Human touch system



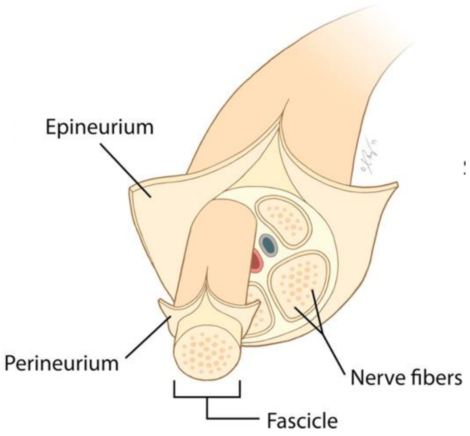

| Classification Basis | | Pacinian Corpuscle | Ruffini Corpuscle | Merkel Cells | Meissner's Corpuscle |
|---|---|---|---|---|---|
| Type | | FA II | SA II | SA I | FA I |
| Adaptation Rate | | Fast | Slow | Slow | Fast |
| Spatial Acuity (mm) | | 10+ | 7+ | 0.5 | 3-4 |
| Vibration/rapid indent. threshold | Best(μm) | 0.01 | 40 | 8 | 2 |
| | Mean(μm) | 0.08 | 300 | 30 | 6 |
| Stimuli Frequency (Hz) | | 40-500+ | 100-500+ | 0.4-3 | 3-40 |
| Conduction Velocity (m/s) | | 35-70 | 35-70 | 40-65 | 35-70 |
| Effective Stimuli | | Temporal changes in the skin deformation | Sustained downward Pressure; Lateral skin stretch; Skin slip. | Spatial deformation; Sustained pressure; Curvature, edge, corners. | Temporal changes in skin deformation |
| Sensory Function | | High frequency vibration detection; Tool use. | Finger position; Stable grasp; Tangential Force; Motion direction | Pattern/form detection; texture perception; Tactile flow perception. | Low frequency vibration & motion detection; Grip control; Tactile flow perception. |

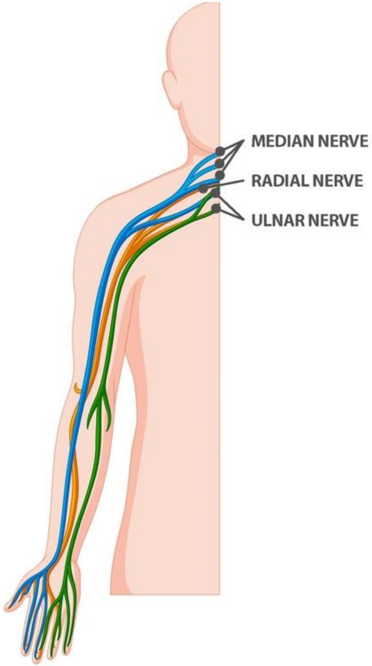
- During object manipulation and tactile exploration, the glabrous skin of the hand undergoes complex spatiotemporal mechanical deformations, which in turn, drive very precise spiking responses in individual afferents
- Coarse object features, such as edges and corners, are reflected in spatial patterns of activation in slowly adapting type I (SA1) and rapidly adapting (FA) fibers, which are densely packed in the fingertip
- At the same time, interactions with objects and surfaces elicit high-frequency, low-amplitude surface waves that propagate across the skin of the finger and palm and excite vibration-sensitive Pacinian (PC) afferents all over the hand

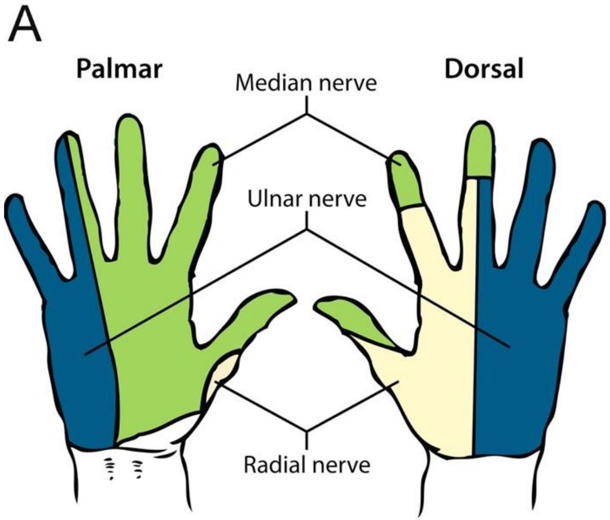
# Human touch system



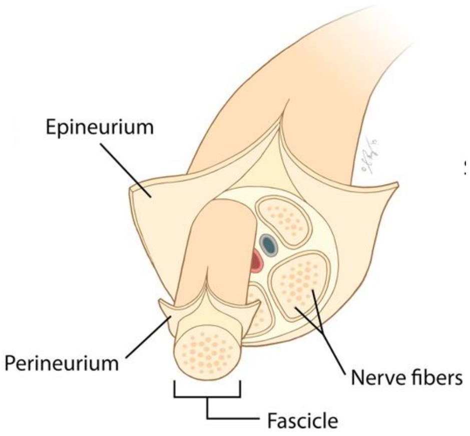
# Structure of the nerve



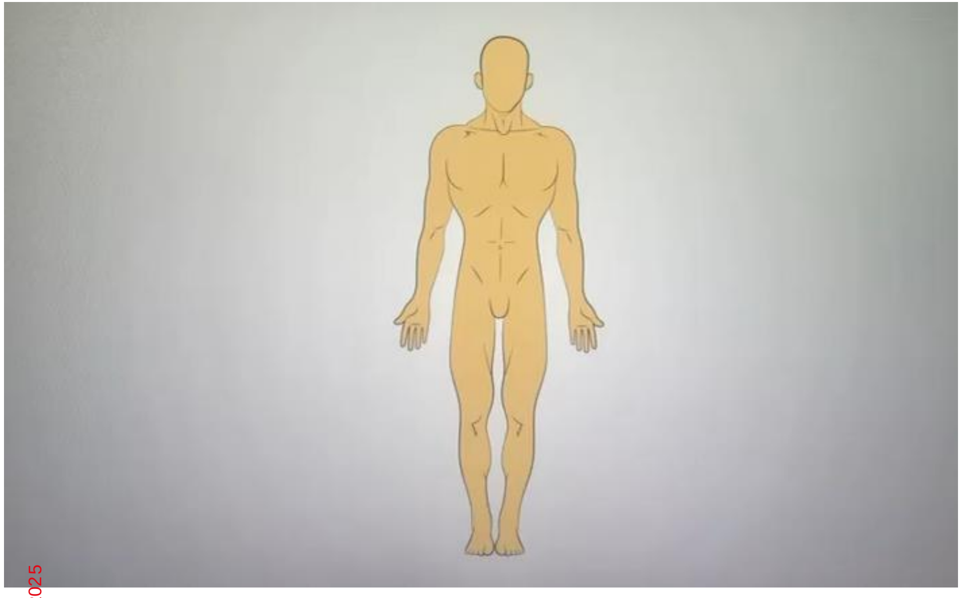
# Structure of the nerve

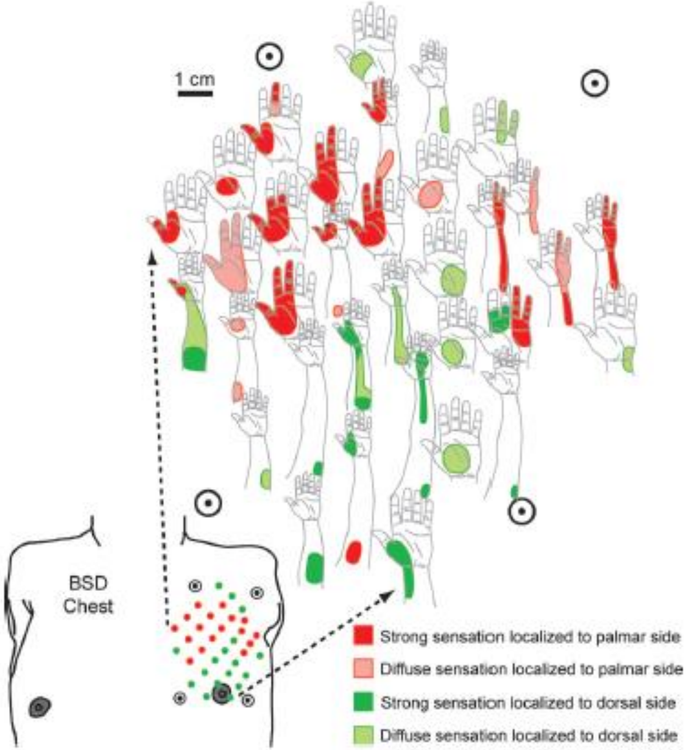



| Fiber type | Fiber size ($\mu$m) | Function |
|---|---|---|
| A$\alpha$ | 12–20 | Somatomotor, proprioception |
| A$\beta$ | 5–12 | Touch, pressure |
| A$\gamma$ | 3–6 | Muscle spindle |
| A$\delta$ | 2–5 | Pain and temperature |
| B | <3 | Preganglionic autonomic |
| C | 0.4–1.2 (unmyelinated) | Postganglionic autonomic, pain, temperature |

*Adapted from Snell (2010).*

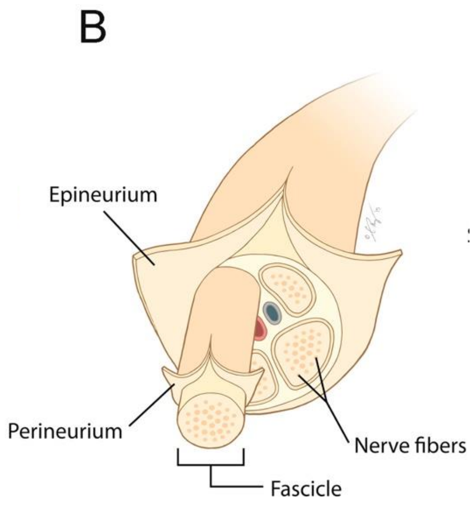
# Targeted Sensory Reinnervation

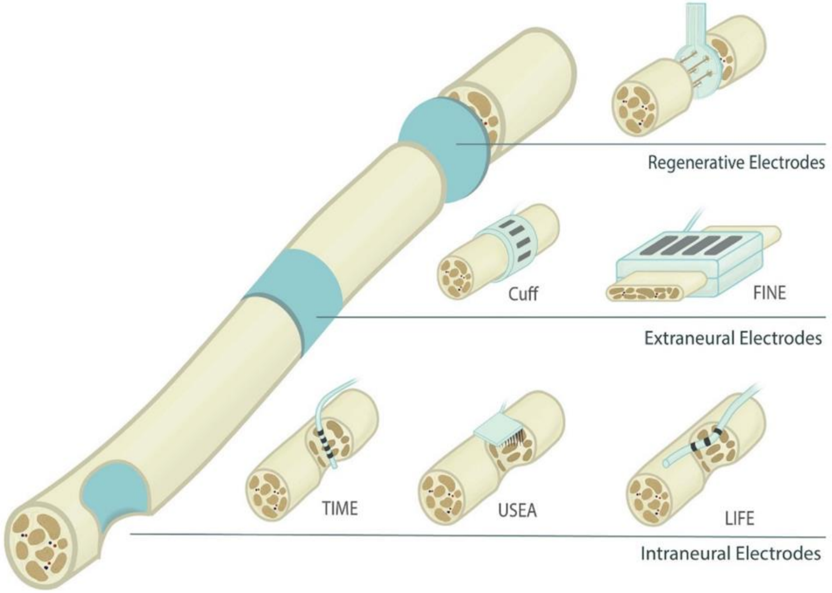




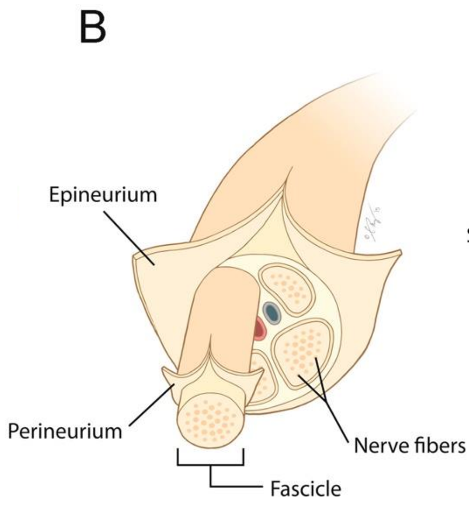

Kuiken et al., 2007, 2008, Gardetto 2025

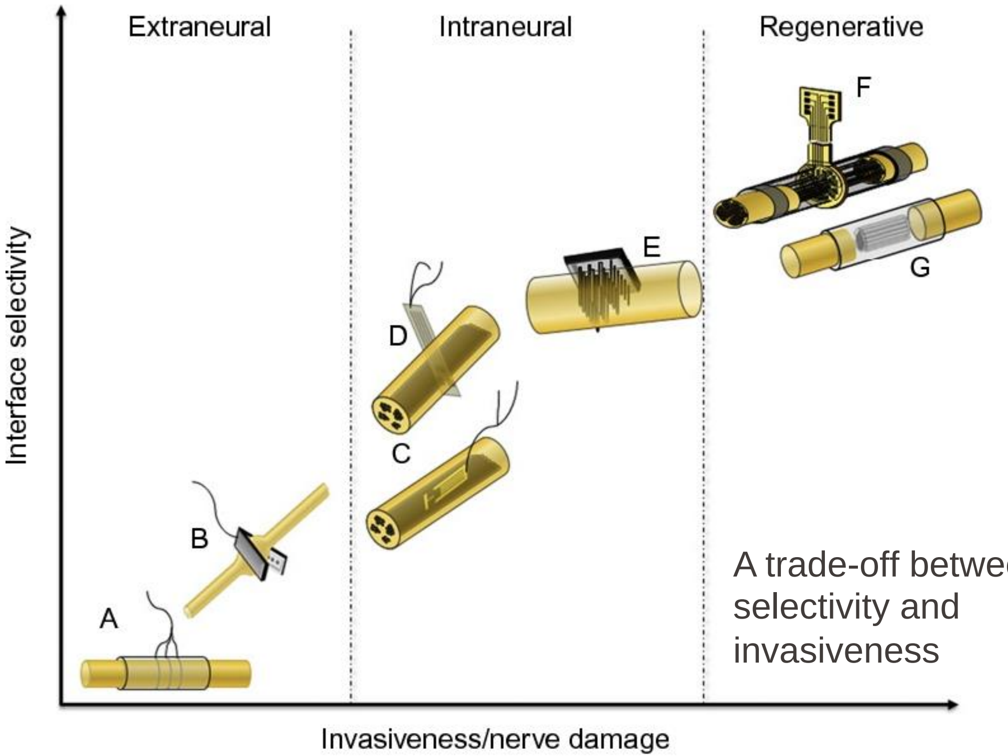
# Peripheral neural interfaces



# Peripheral neural interfaces



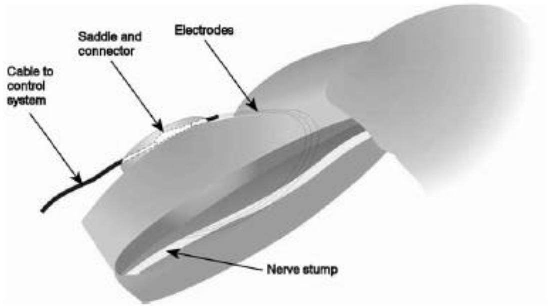



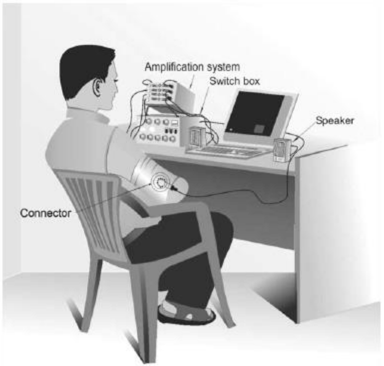

A trade-off between selectivity and invasiveness

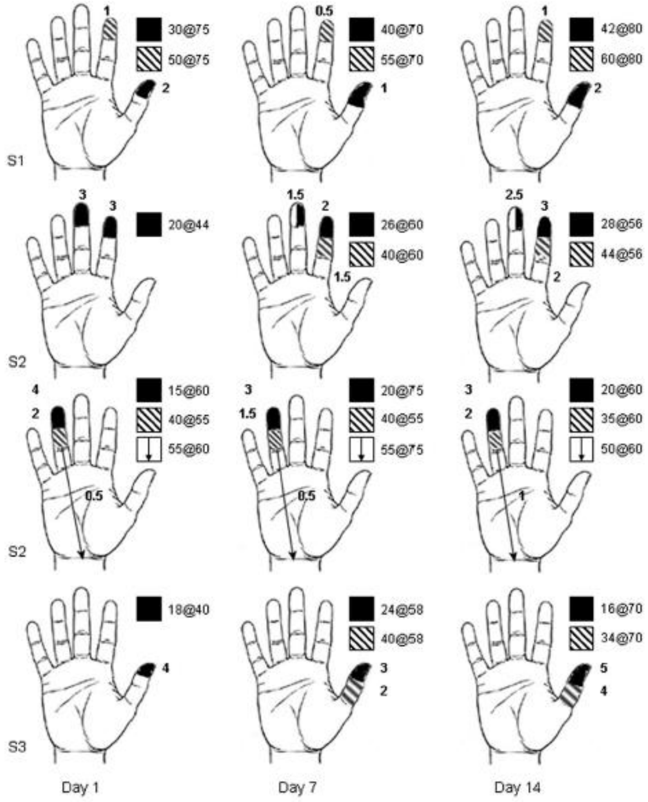


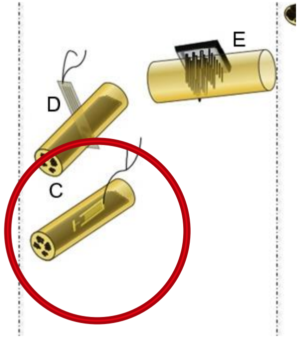
Boretius, T., Badia, J., Pascual-Font, A., Schuettler, M., Navarro, X., Yoshida, K., & Stieglitz, T. (2010). A transverse intrafascicular multichannel electrode (TIME) to interface with the peripheral nerve. Biosensors and Bioelectronics, 26(1), 62-69.

# Example of intraneural stimulation



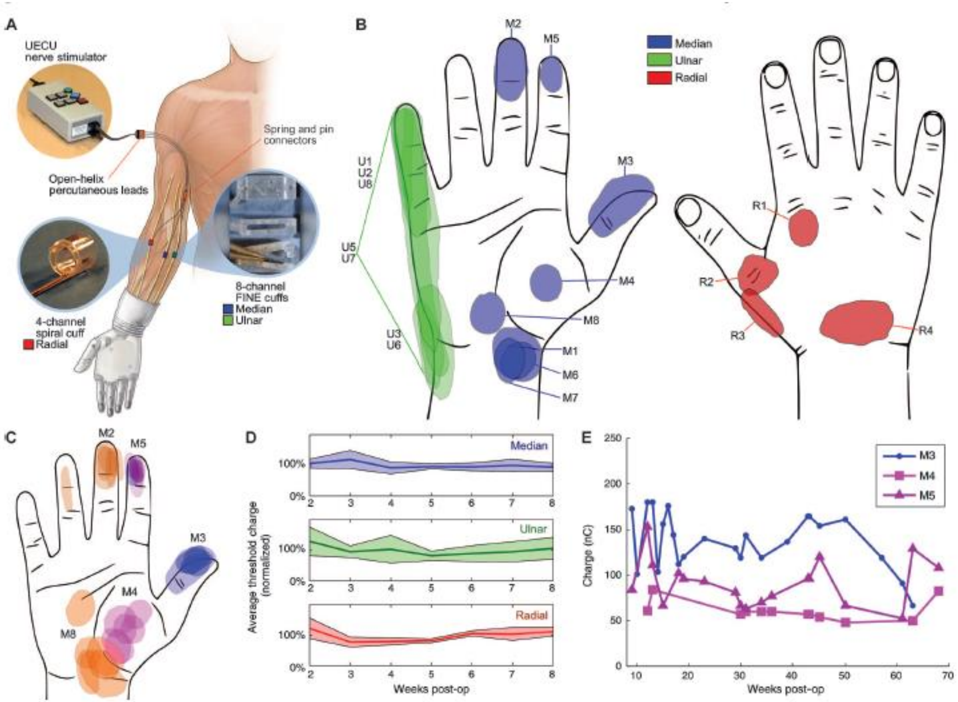



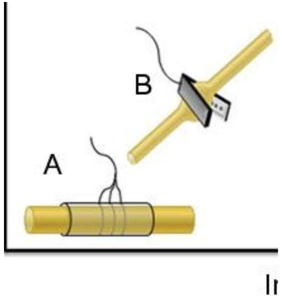

LIFE electrode

03/03/2025

Dhillon, G. S., & Horch, K. W. (2005). Direct neural sensory feedback and control of a prosthetic arm. IEEE transactions on neural systems and rehabilitation engineering, 13(4), 468-472.

# Example of extraneural stimulation



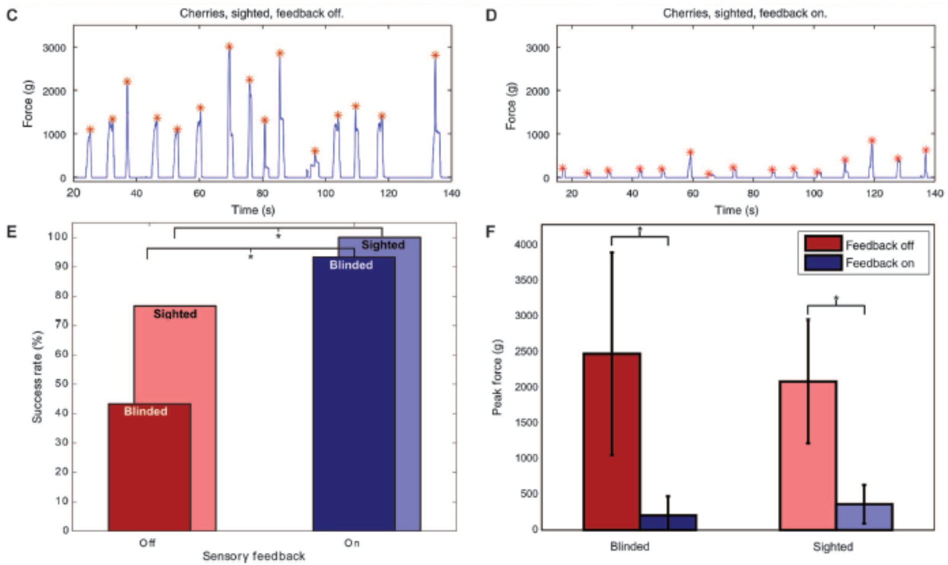



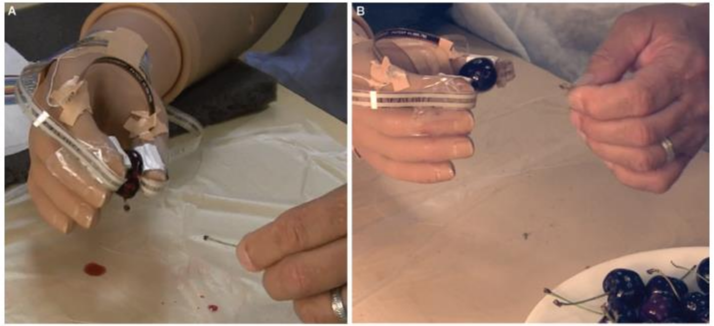

CUFF and
FINE electrodes



Tan, D. W., Schiefer, M. A., Keith, M. W., Anderson, J. R., Tyler, J., & Tyler, D. J. (2014). A neural interface provides long-term stable natural touch perception. Science translational medicine, 6(257), 257ra138-257ra138.

# Example of extraneural stimulation



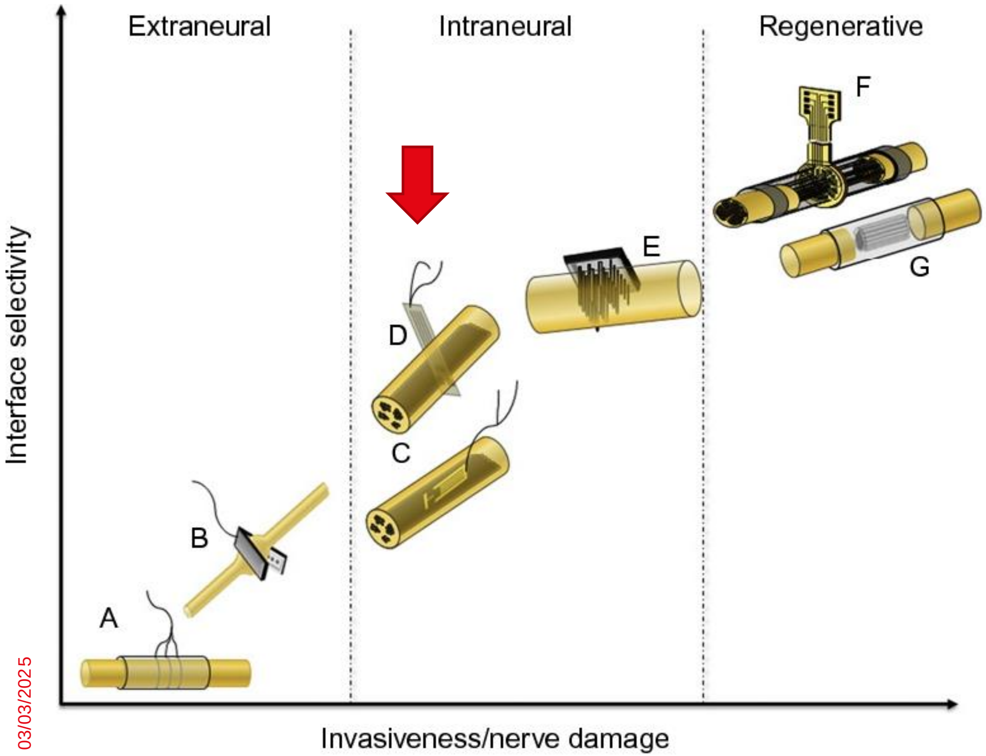



Improvement in a functional task when sensory feedback was present.

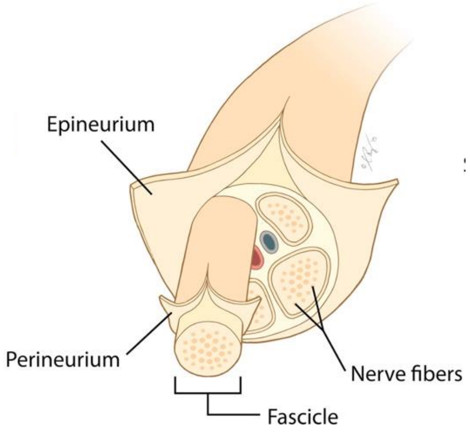
03/03/2025

Tan, D. W., Schiefer, M. A., Keith, M. W., Anderson, J. R., Tyler, J., & Tyler, D. J. (2014). A neural interface provides long-term stable natural touch perception. Science translational medicine, 6(257), 257ra138-257ra138.

EPFL




Transverse Intrafascicular **Multichannel** Electrode (TIME)



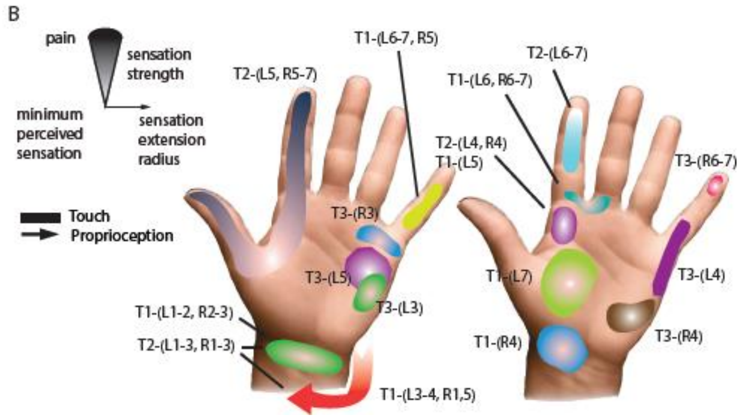


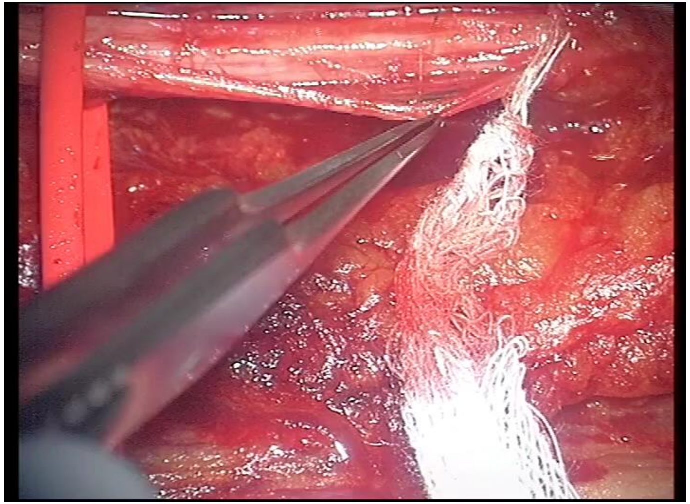

Boretius, T., Badia, J., Pascual-Font, A., Schuettler, M., Navarro, X., Yoshida, K., & Stieglitz, T. (2010). A transverse intrafascicular multichannel electrode (TIME) to interface with the peripheral nerve. Biosensors and Bioelectronics, 26(1), 62-69.

EPFL

# Bidirectional neuro controlled hand prostheses

- Four week implant in a 35-year-old man, from Denmark with a trans-radial amputation in 2004 (fireworks accident)
- Two TIMEs in the median and two in the ulnar nerve



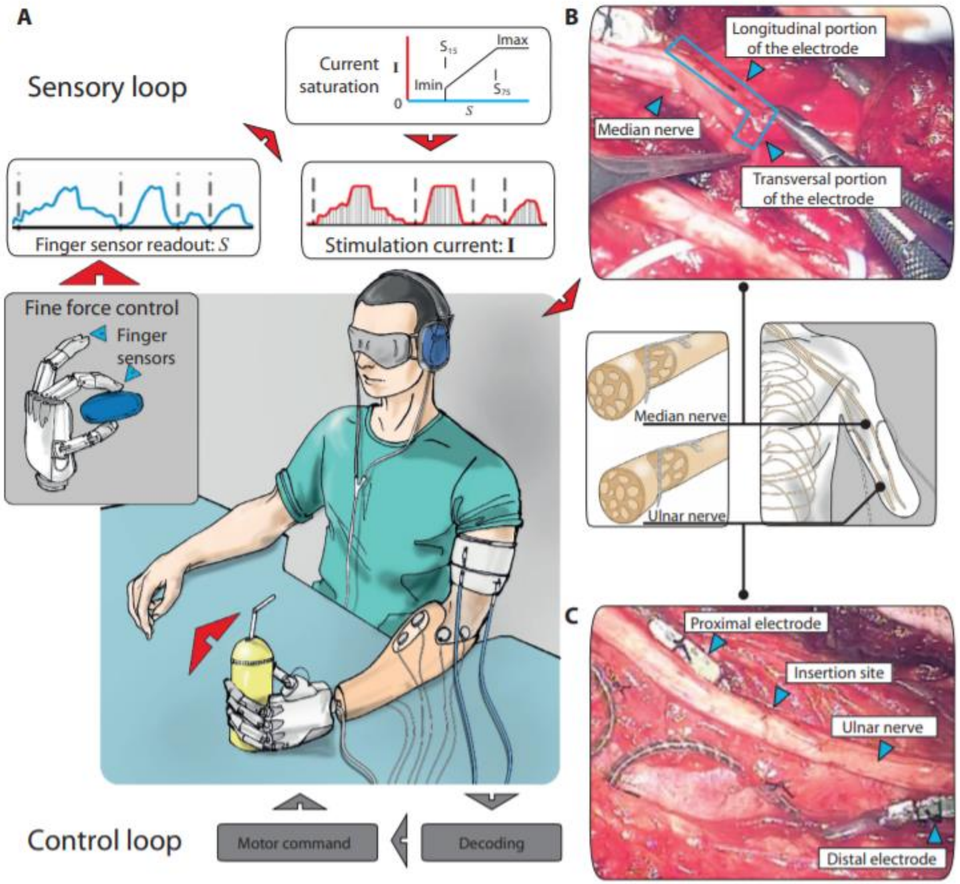



TIME electrodes



Raspopovic, S., Capogrosso, M., Petrini, F. M., Bonizzato, M., Rigosa, J., Di Pino, G., ... & Micera, S. (2014). Restoring natural sensory feedback in real-time bidirectional hand prostheses. Science translational medicine, 6(222), 222ra19-222ra19.

EPFL



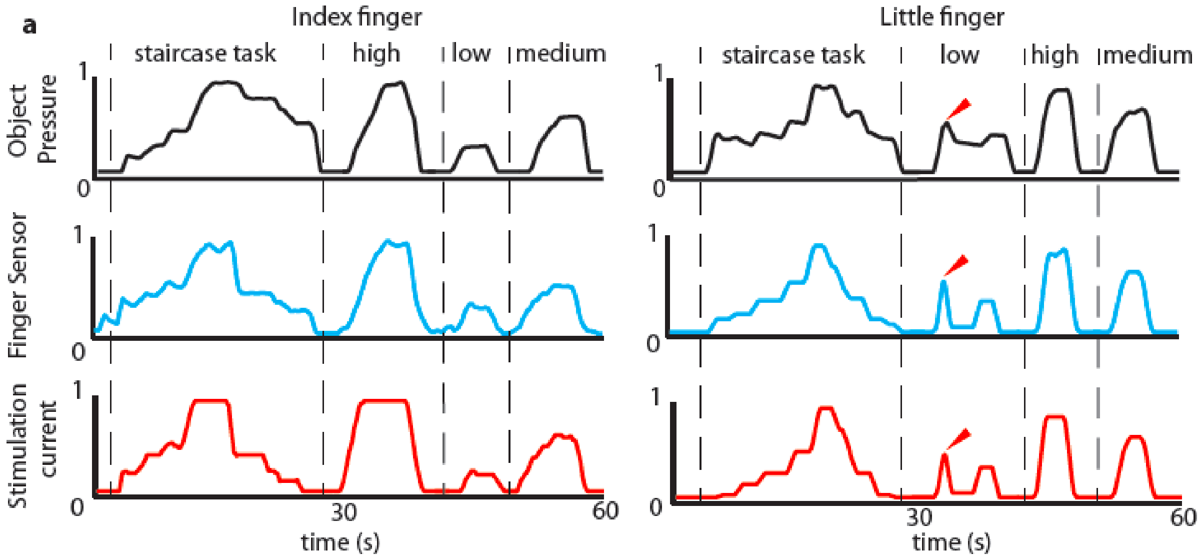

Test the possibility for the subject to use the sensory information during closed-loop control and manipulation experiments



Solaiman Shokur

# Selection of grasping force levels

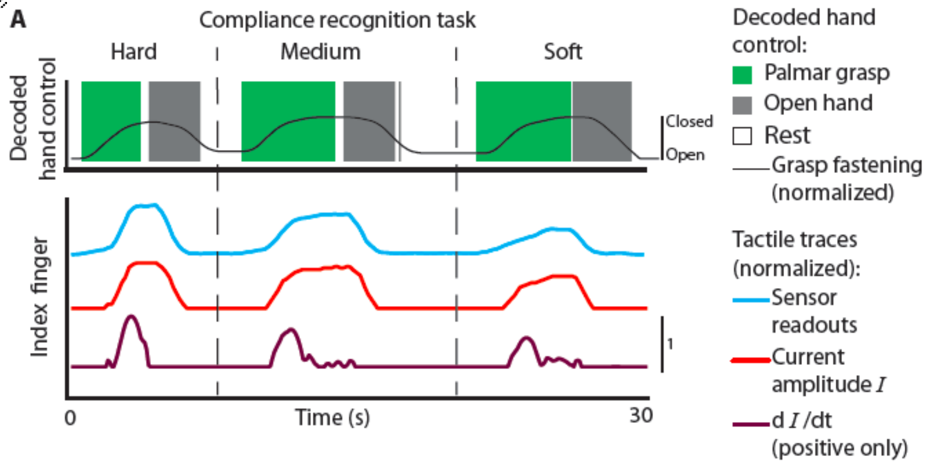




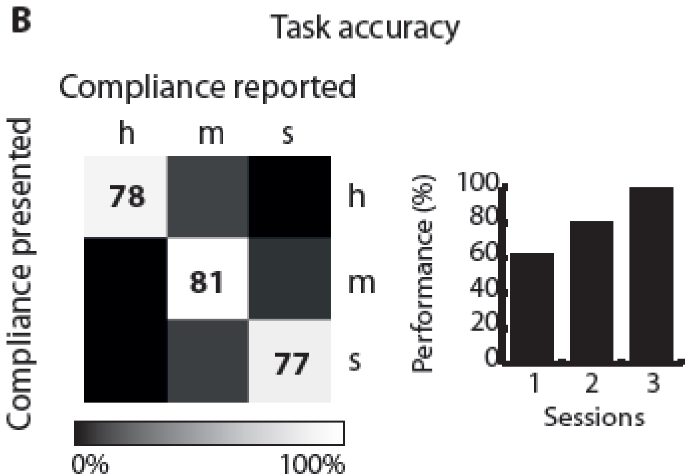



Raspopovic, S., Capogrosso, M., Petrini, F. M., Bonizzato, M., Rigosa, J., Di Pino, G., ... & Micera, S. (2014). Restoring natural sensory feedback in real-time bidirectional hand prostheses. Science translational medicine, 6(222), 222ra19-222ra19.

# Compliance recognition

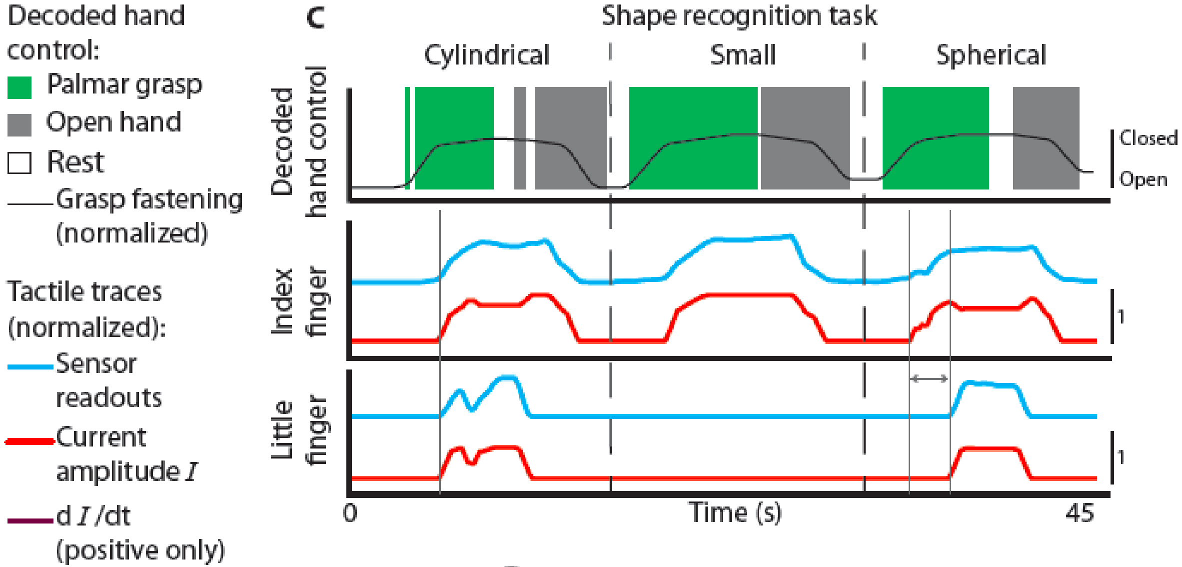


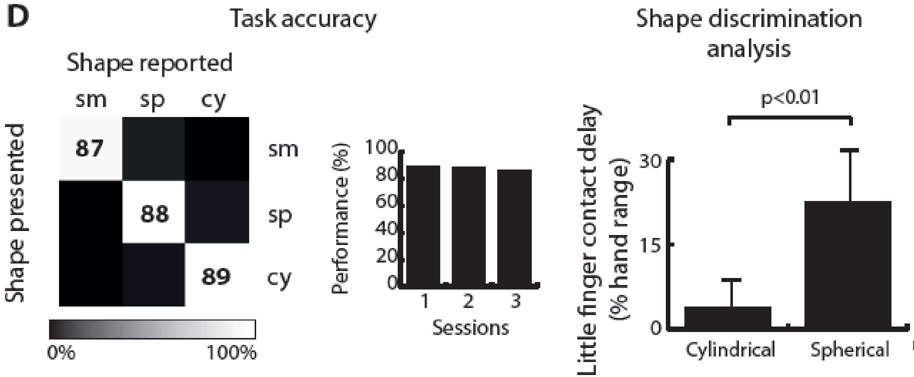

Three objects with different stiffness properties




Quite good performance and interesting learning ability

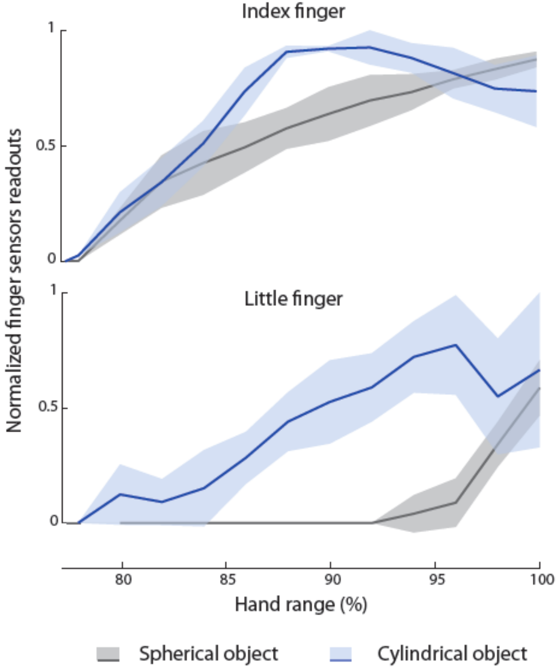
# Shape recognition



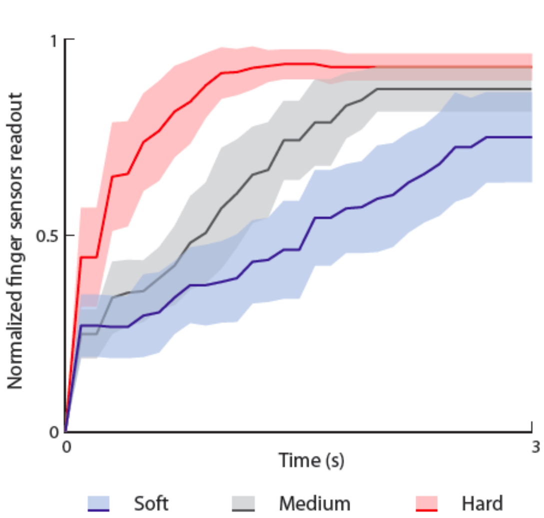



# Why this is possible?

Shape recognition

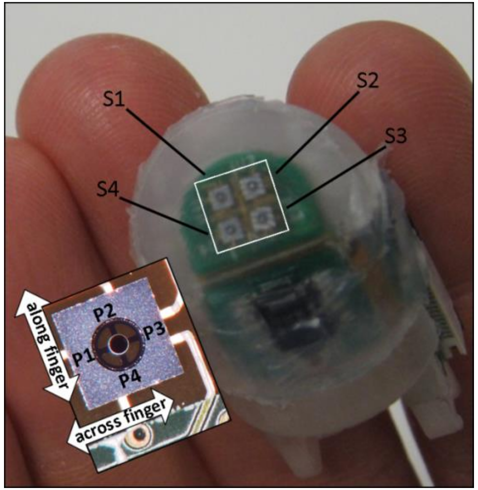


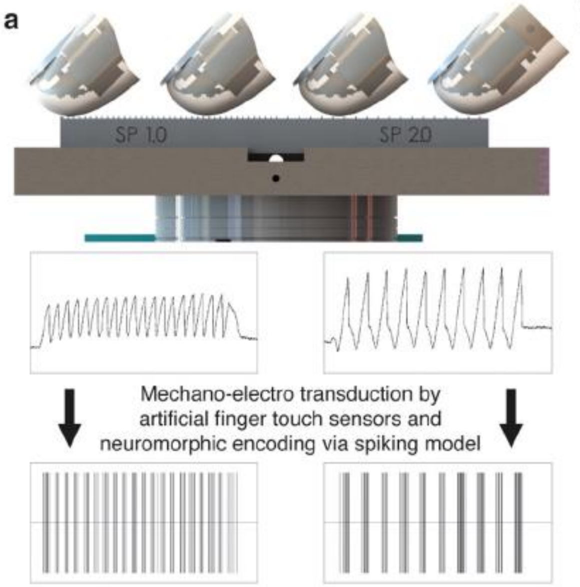

Compliance recognition

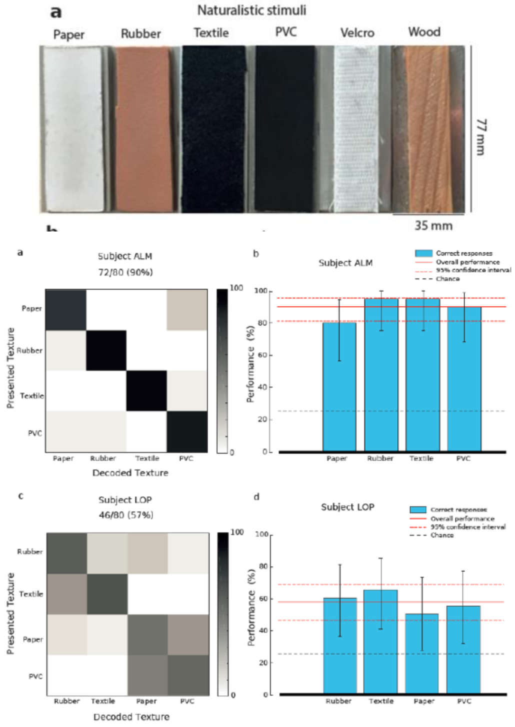



- Different force profiles were provided to the users using the afferent stimulation → this is **NOT** on-off sensation!

# Detecting texture via FA-type stimulation



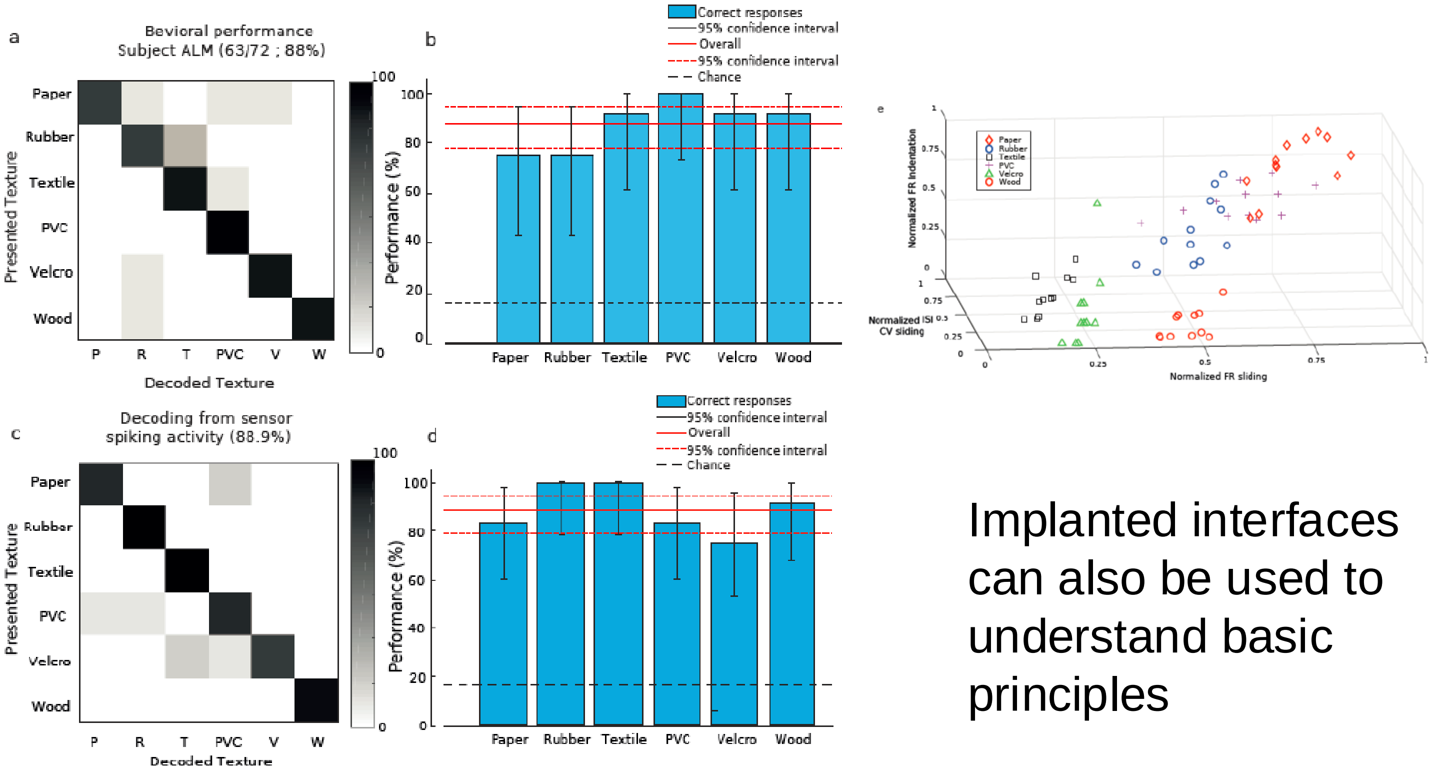





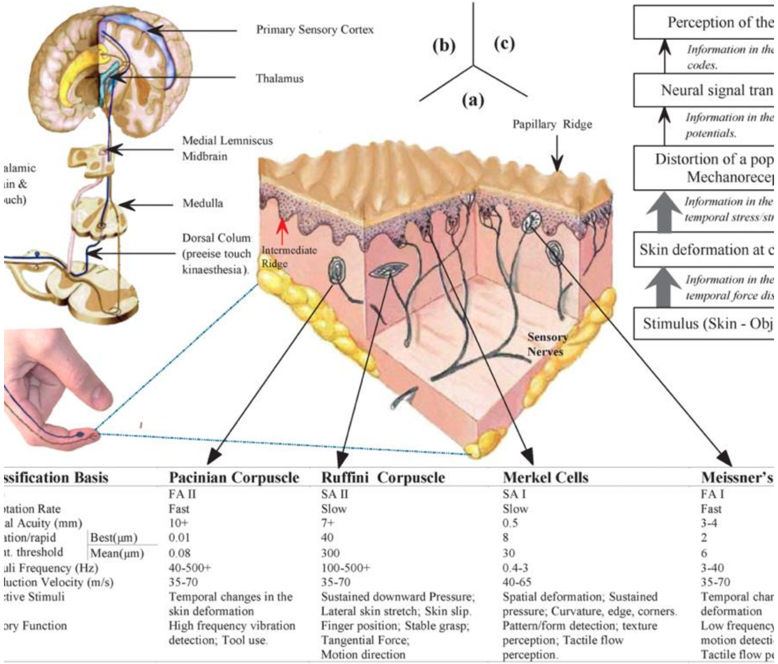

Oddo, C. M., Raspopovic, S., Artoni, F., Mazzoni, A., Spigler, G., Petrini, F., ... & Micera, S. (2016). Intraneural stimulation elicits discrimination of textural features by artificial fingertip in intact and amputee humans. elife, 5, e09148.

# Restoring perception of real textures

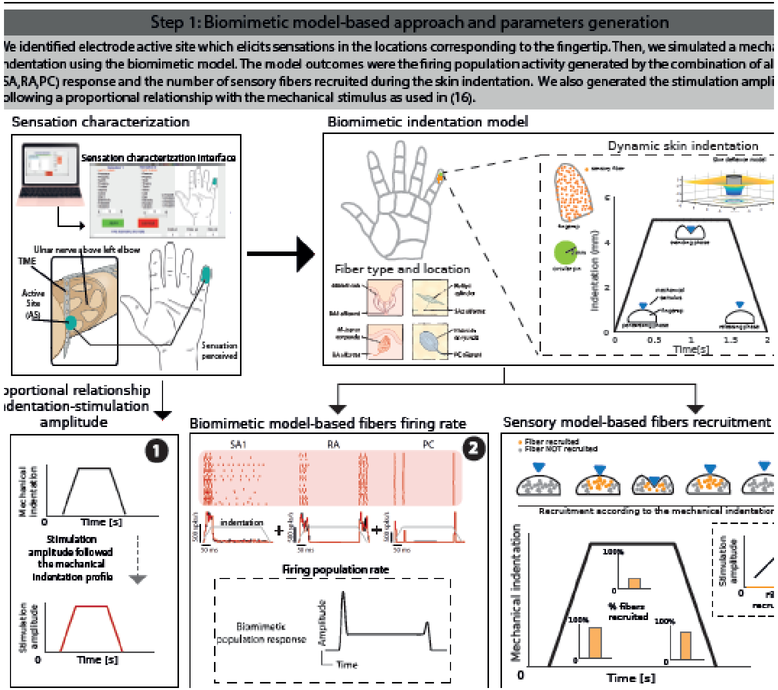



Implanted interfaces can also be used to understand basic principles

# Human touch system




# Biomimetic encoding strategy



EPFL

# Biomimetic encoding strategy

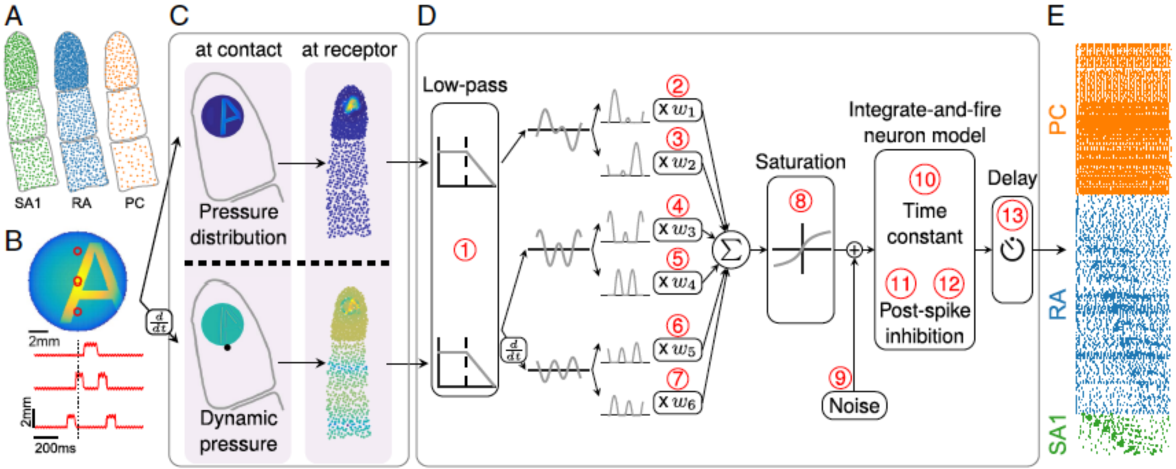
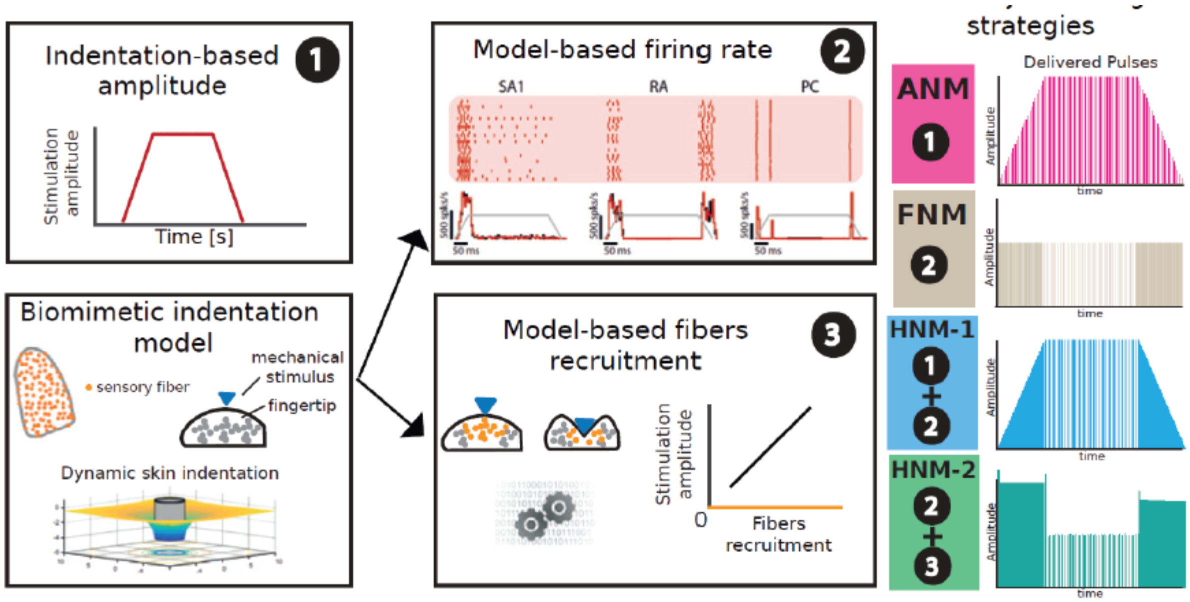



**Fig. 1.** Overview of the model. (*A*) Receptors are distributed across the skin given the known innervation densities of SA1, RA, and PC afferents. (*B*) The stimulus—in this case, a vibrating embossed letter A scanned across the skin—is defined as the time-varying depth at which each small patch of skin (here dubbed a pin) is indented (with a spatial resolution of 0.1 mm). The traces in *Lower* show the time-varying depth at the three locations on the skin indicated by the red dots in *Upper*. (*C*) The mechanics model relies on two parts: (*Upper*) modeling the distribution of stresses using a quasistatic elastic model and (*Lower*) modeling dynamic pressure and surface wave propagation. *Left* shows the surface deformation of the skin, and *Right* shows the resulting pattern of stresses at the location of the receptors. (*D*) The spiking responses are determined by leaky IF models using different sets of up to 13 parameters (marked in red numbers) for individual SA1, RA, and PC afferents fit based on peripheral recordings to skin vibrations. Adapted from ref. 71. (*E*) The output of the model is the spike train of each afferent in the population. Raster of the response of the afferent population sampled as in *A* to the stimulus shown in *B* (only active afferents are included). Note that the SA1s (in contact) only encode the spatial aspect of the stimulus, that the PCs encode from the whole finger phase-lock with the 200-Hz vibration, and that the RAs show mixed spatial and vibration responses.

Saal et al., PNAS, 2017

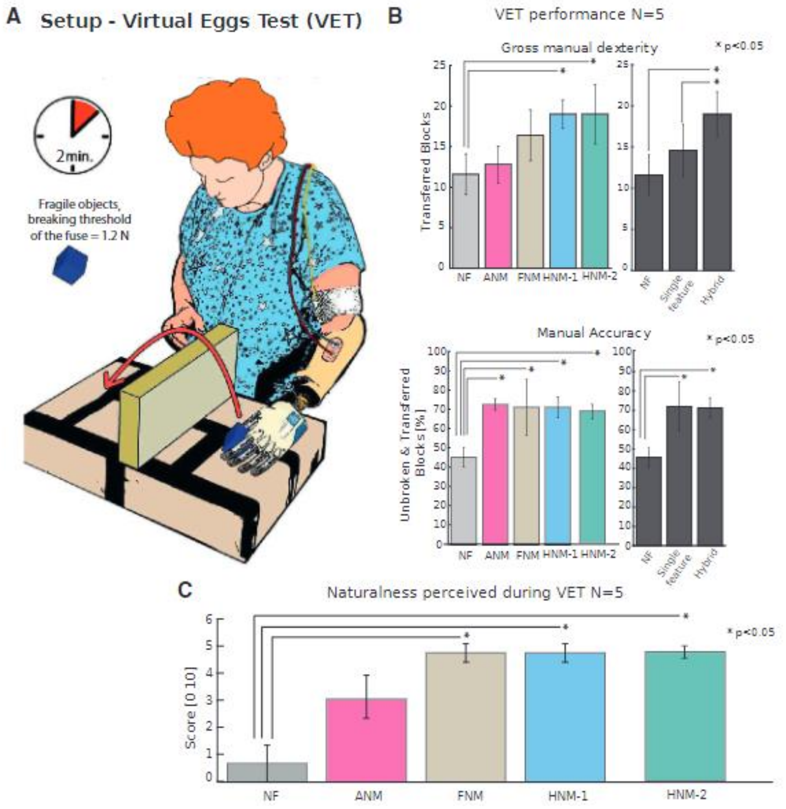
# Biomimetic encoding strategy






Valle, Giacomo, et al. "Biomimetic intraneural sensory feedback enhances sensation naturalness, tactile sensitivity, and manual dexterity in a bidirectional prosthesis." Neuron 100.1 (2018): 37-45.

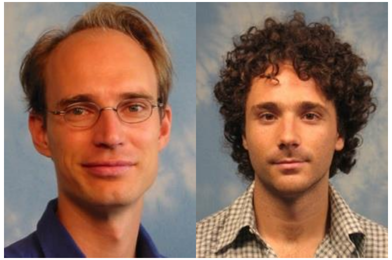
# Biomimetic encoding strategy




The two hybrid models are better to perform the virtual egg task.

The biomimetic approaches were judged more natural

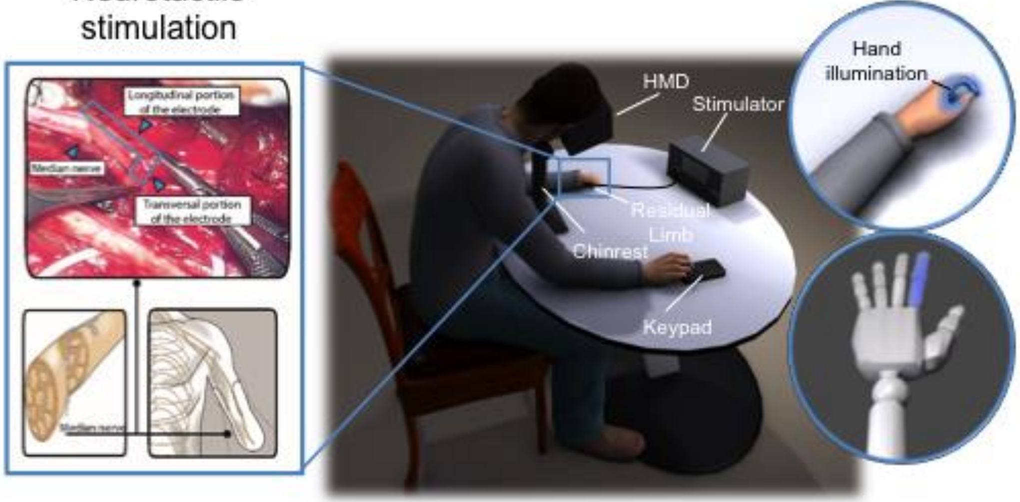
# Embodiment



O. Blanke G. Rognini

Illumination and virtual stimuli as shown on HMD

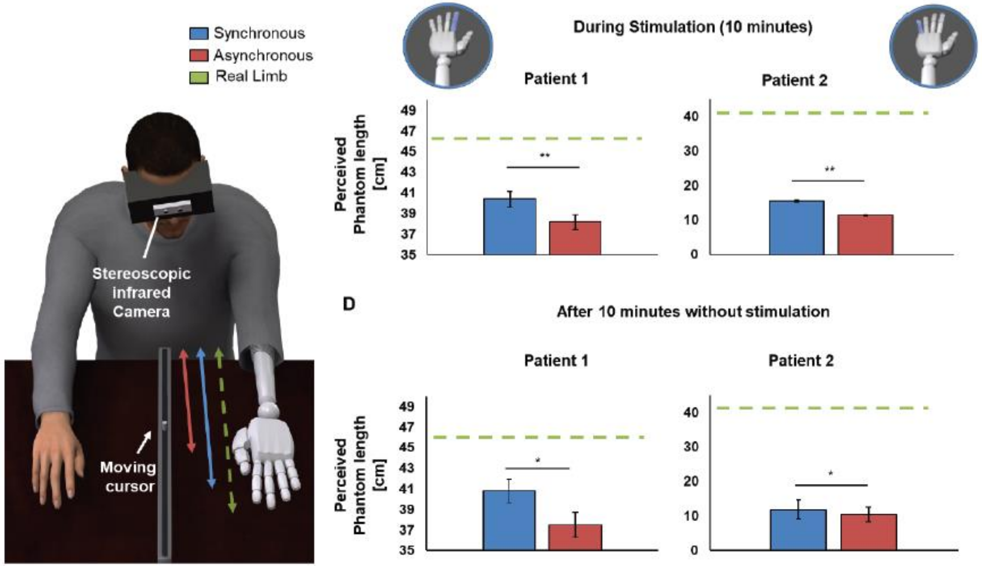
Neurotactile stimulation




Patient 1 (artificial hand)

Patient 2 (prosthetic hand)

# Sensory feedback

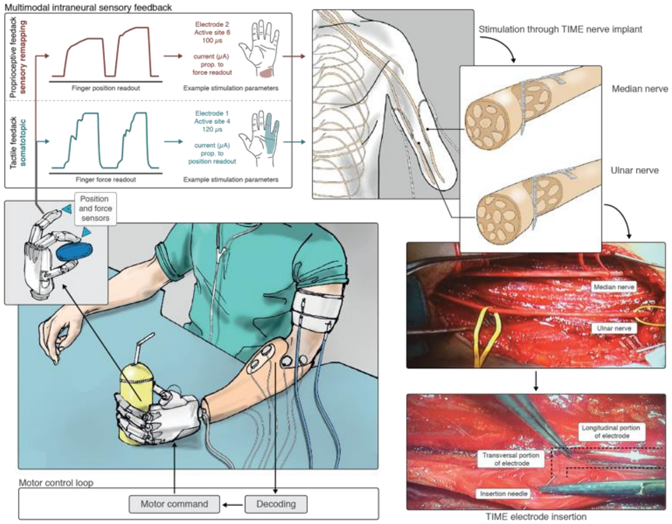


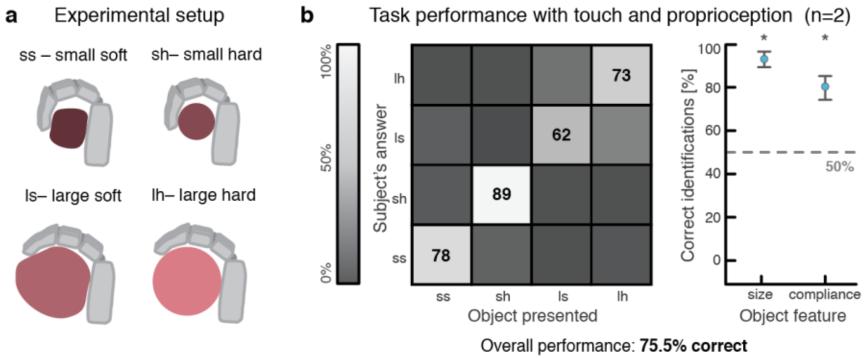

Synchronous Tactile feedback (via intraneural stimulation) and Visual feedback (illumination of the region corresponding to phantom touch) feedback increased prosthesis embodiment and reduced the telescoping effect (perception that limb is shorter).



Rognini, Giulio, et al. "Multisensory bionic limb to achieve prosthesis embodiment and reduce distorted phantom limb perceptions." Journal of Neurology, Neurosurgery & Psychiatry 90.7 (2019): 833-836.

# Bidirectional neurocontrolled hand prostheses
## “Multimodal” sensory feedback

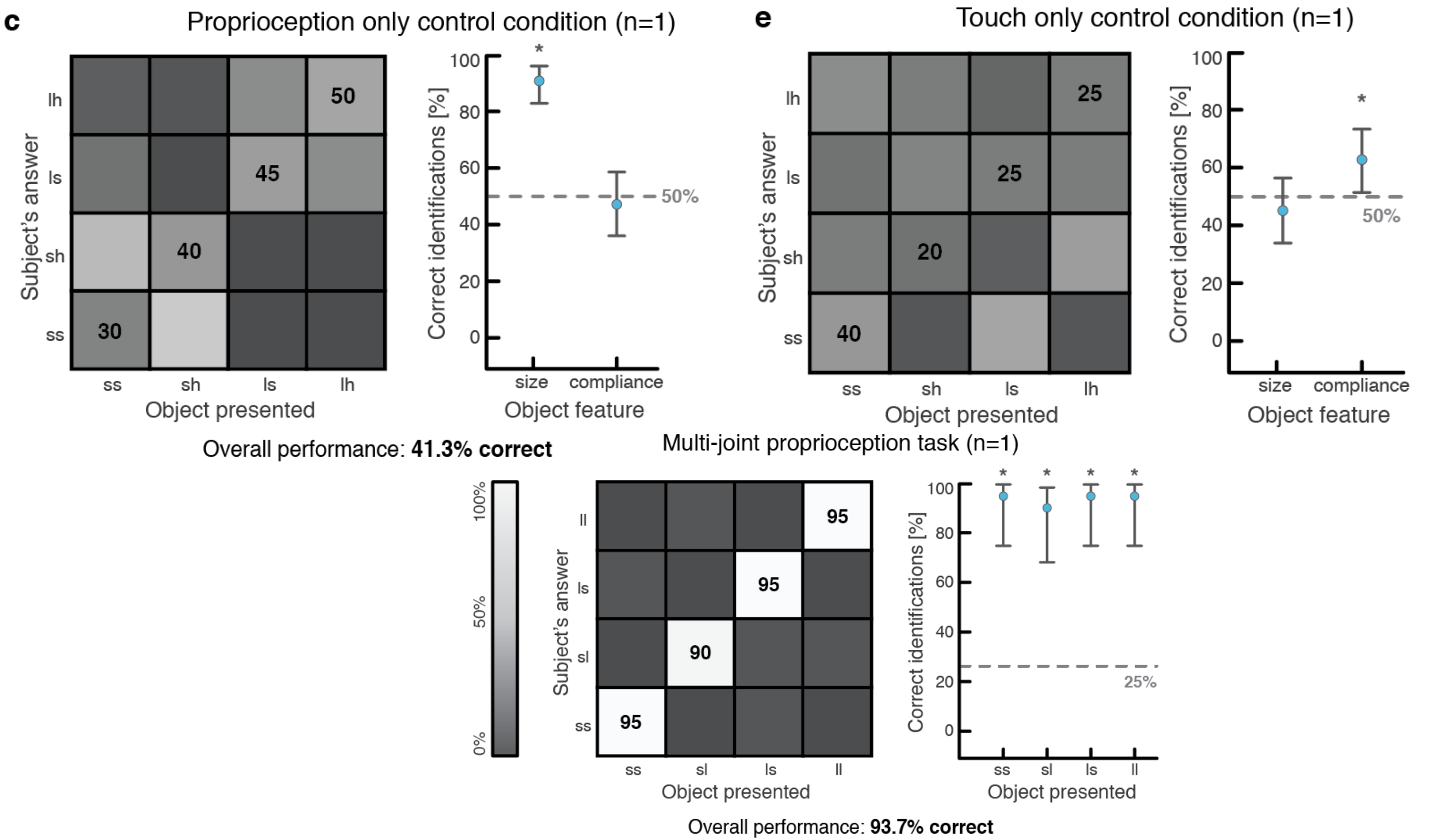




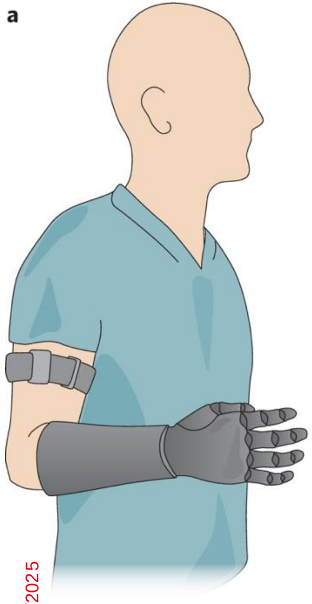

D’Anna, Edoardo, et al. "A closed-loop hand prosthesis with simultaneous intraneural tactile and position feedback." Science Robotics 4.27 (2019): eaau8892.

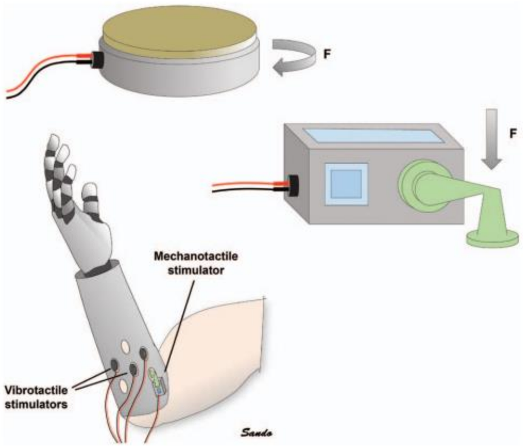
# Restoration of proprioception and tactile feedback

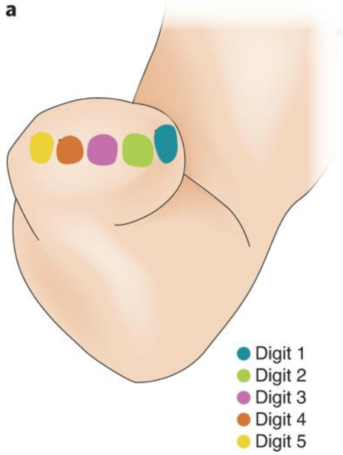



D'Anna, Edoardo, et al. "A closed-loop hand prosthesis with simultaneous intraneural tactile and position feedback." Science Robotics 4.27 (2019): eaau8892.

# Tactile feedback via non-invasive solutions



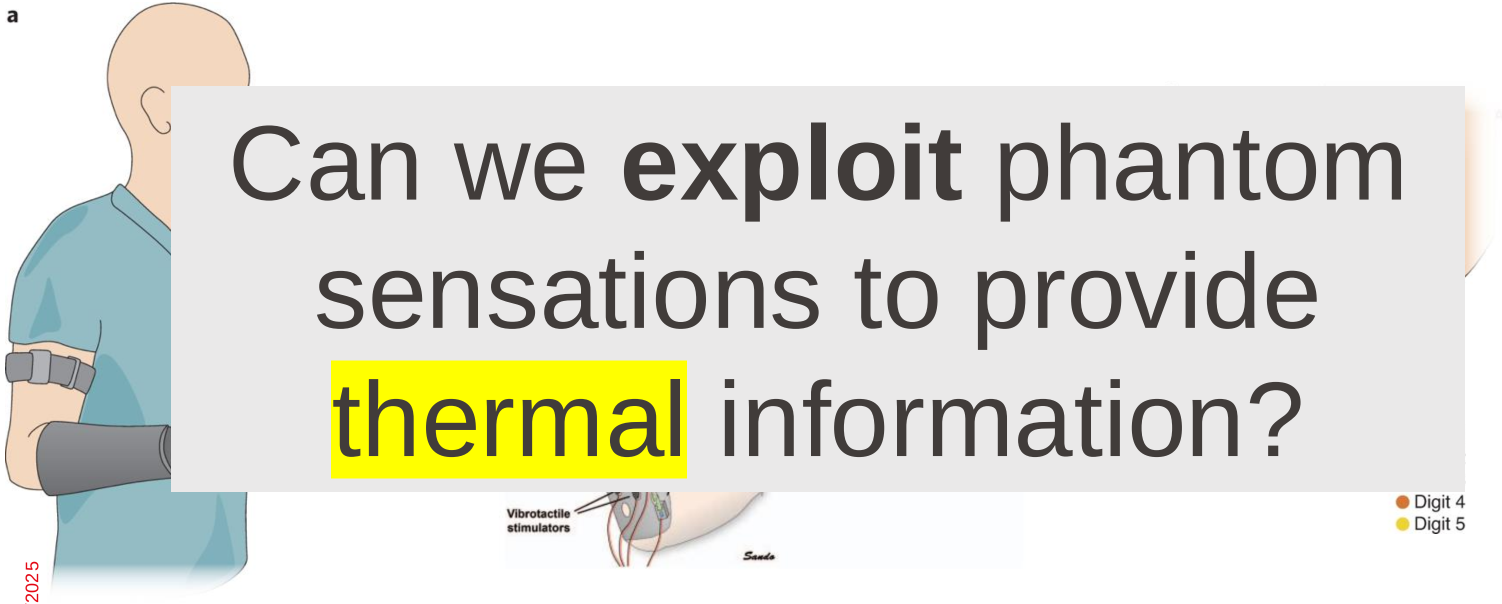






Bensmaia, S. J., Tyler, D. J., & Micera, S. (2020). Restoration of sensory information via bionic hands. Nature Biomedical Engineering, 1-13.

# Tactile feedback via non-invasive solutions

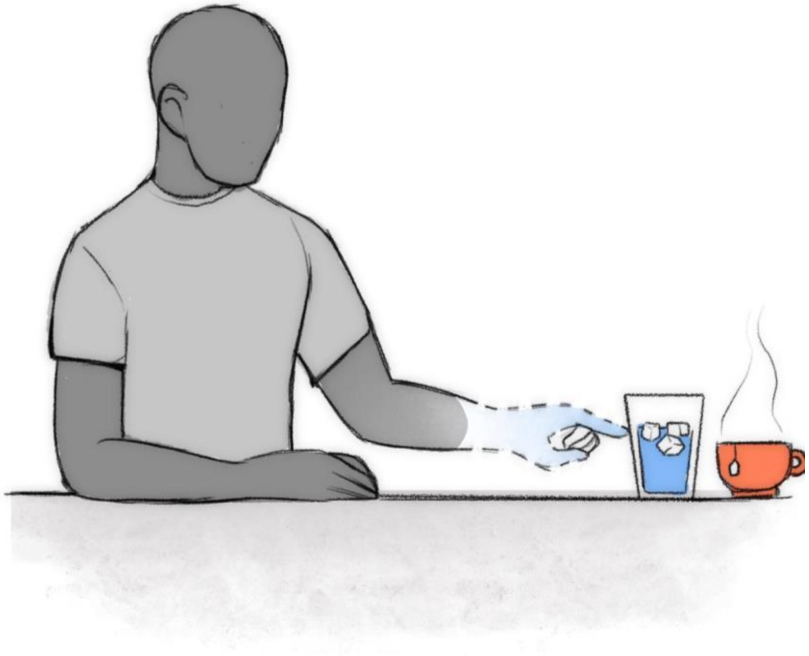



Can we **exploit** phantom sensations to provide thermal information?



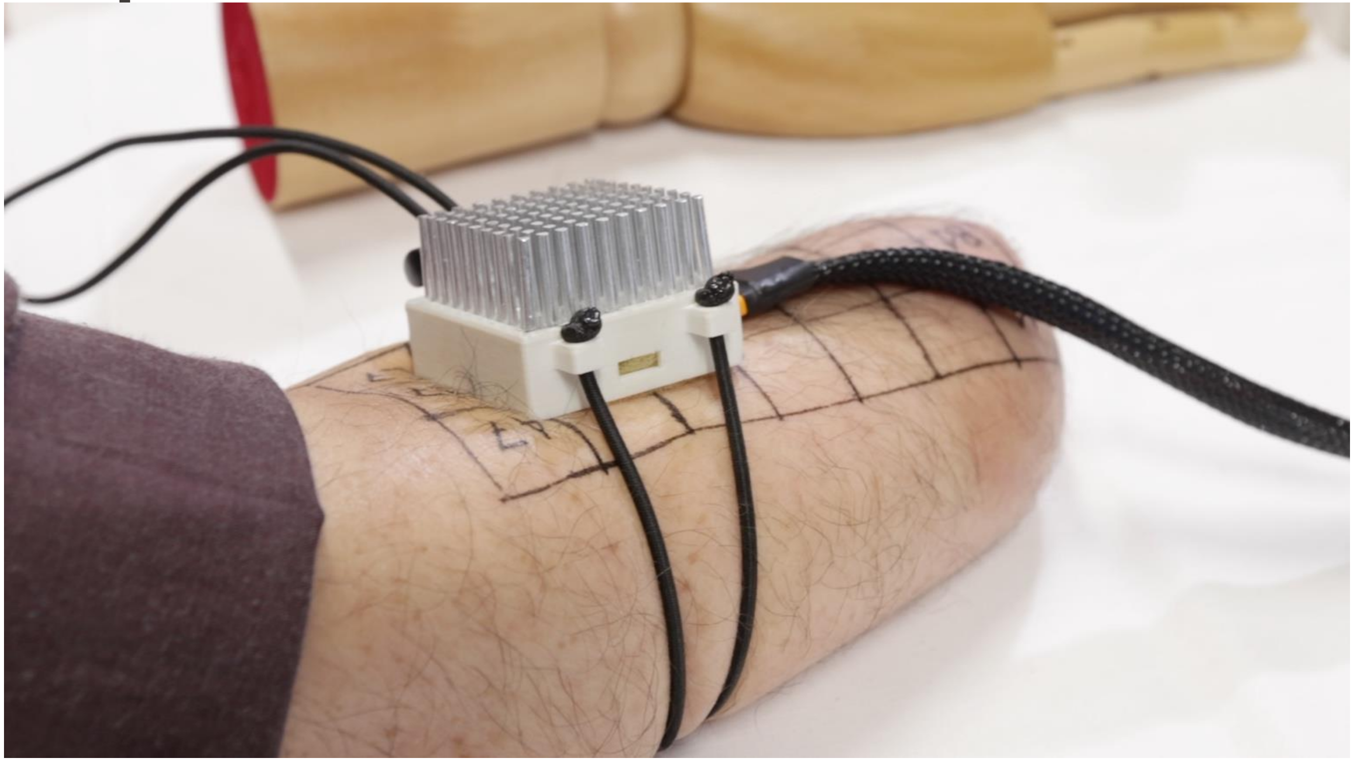
Bensmaia, S. J., Tyler, D. J., & Micera, S. (2020). Restoration of sensory information via bionic hands. Nature Biomedical Engineering, 1-13.

# Why thermal feedback?



- Convey thermal information
  - Cold, warm, dangerously hot
- More complex modalities:
  - **Material** detection
  - **Moisture** detection
  - Contact with a **body**
- **Social** and **affective** aspects of touch

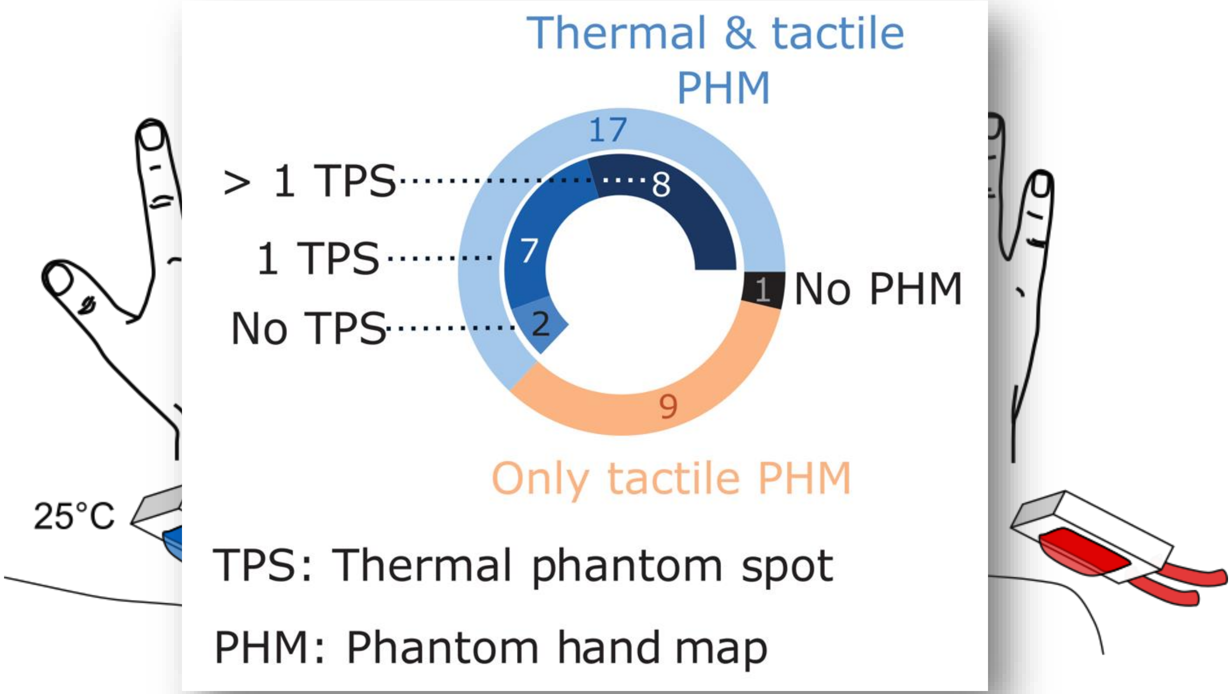
# Phantom tactile and thermal maps





F. Iberite, J. Muheim, O. Akouissi, S. Gallo, G. Rognini, F. Morosato, A. Clerc, M. Kalff, E. Gruppioni, S. Micera*, S. Shokur*. Restoration of natural thermal sensation in upper-limb amputees (2023). Science.

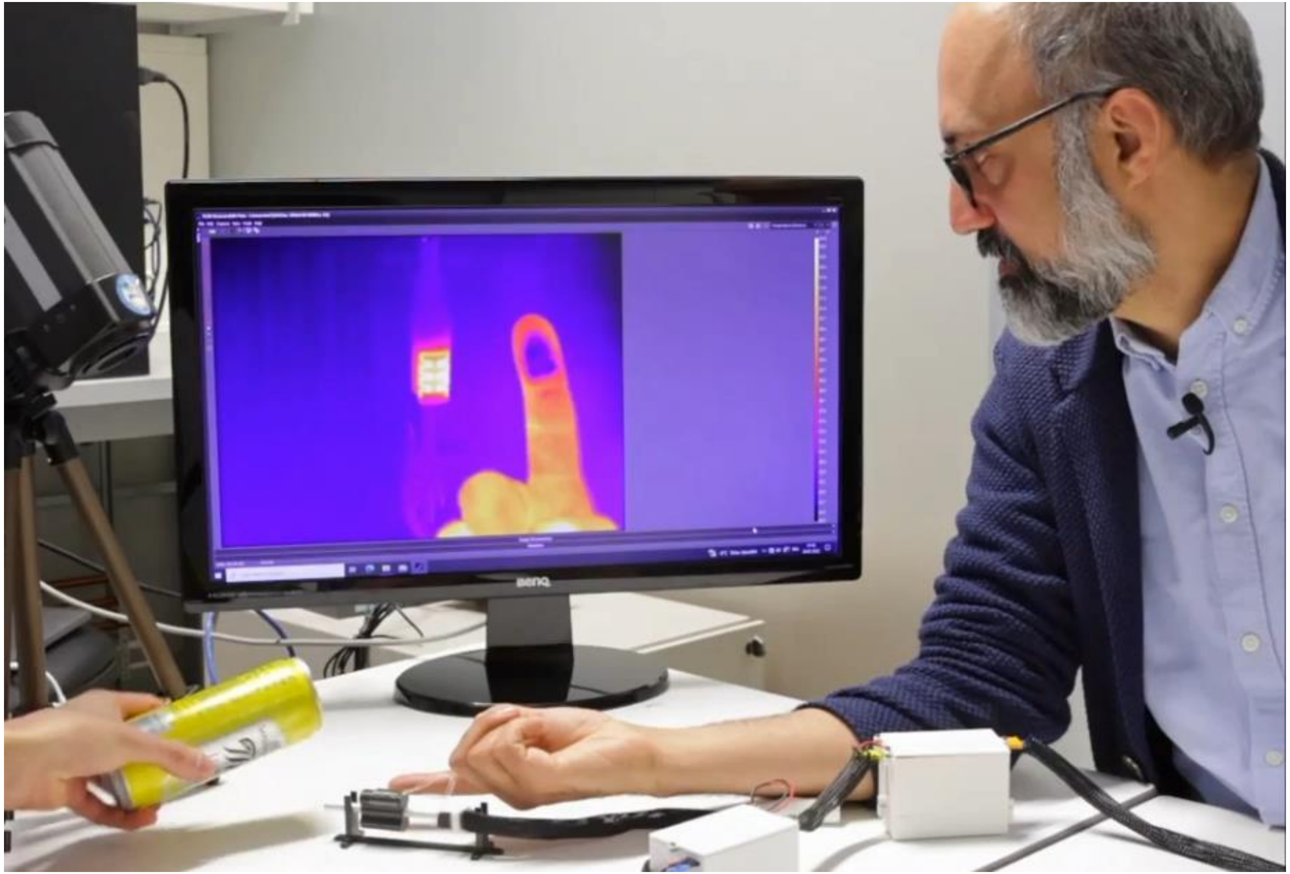
# Phantom tactile and thermal maps





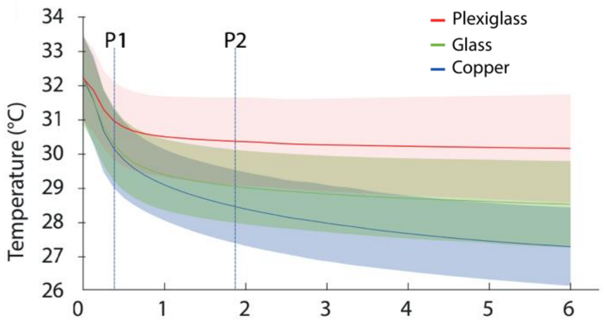

F. Iberite, J. Muheim, O. Akouissi, S. Gallo, G. Rognini, F. Morosato, A. Clerc, M. Kalff, E. Gruppioni, S. Micera*, S. Shokur*. Restoration of natural thermal sensation in upper-limb amputees (2023). Science.

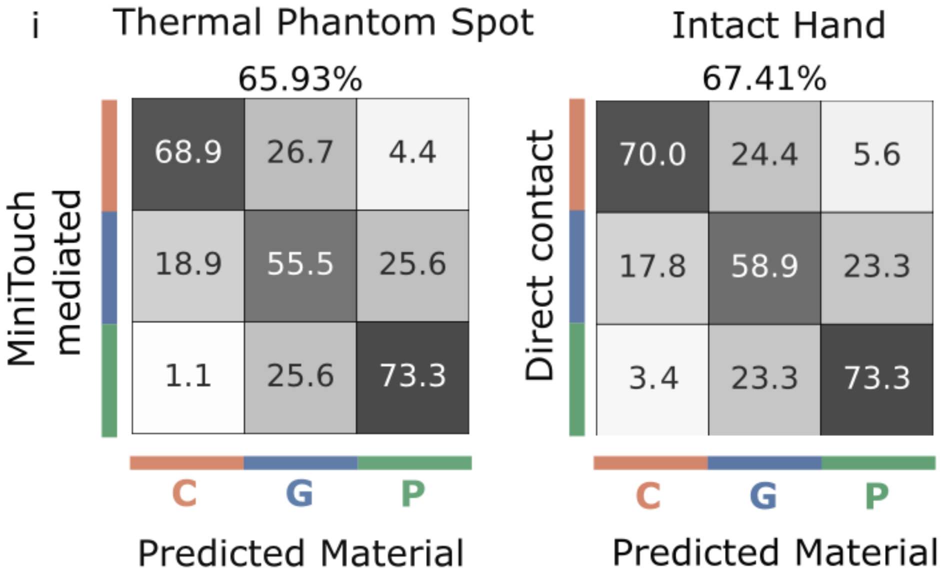
# Wearable solution




Iberite et al. 2023

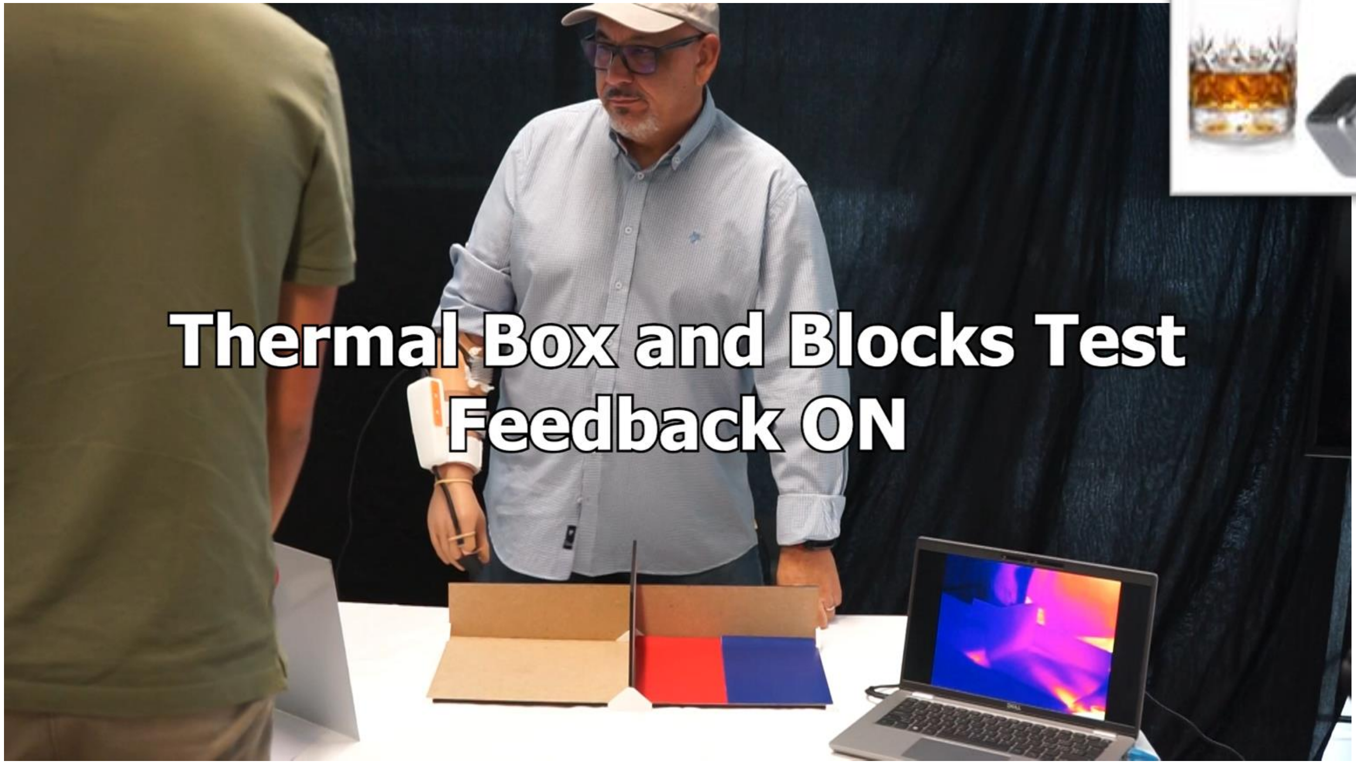
# Material detection



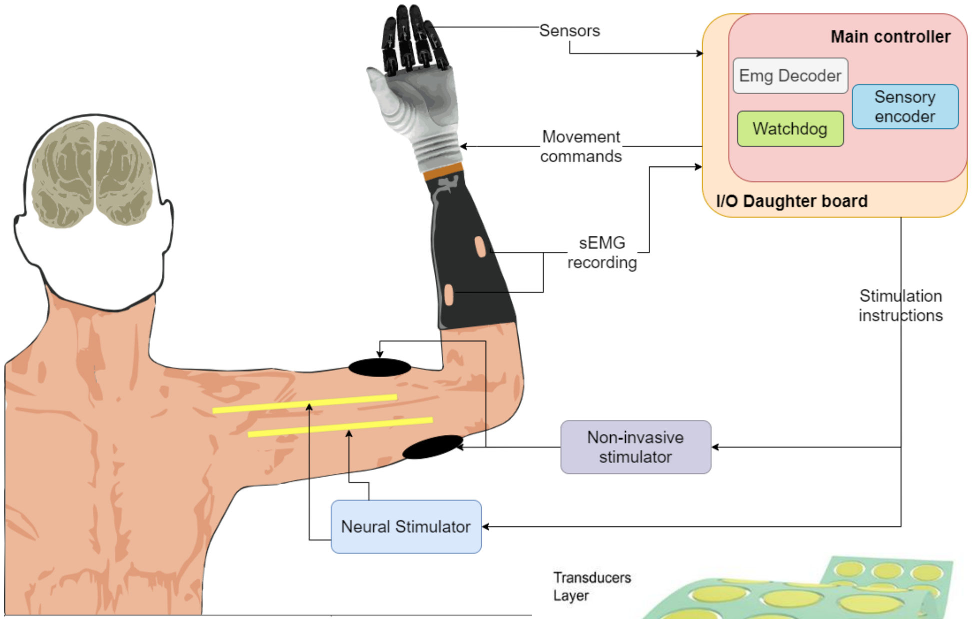

Iberite et al. 2023

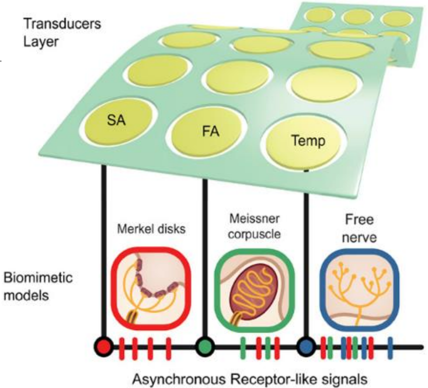
# Sensory motor tasks with real-time feedback



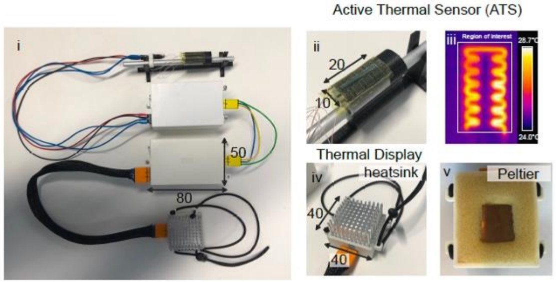

Muheim et al. 2024

# NEXT STEP – Going chronic at home

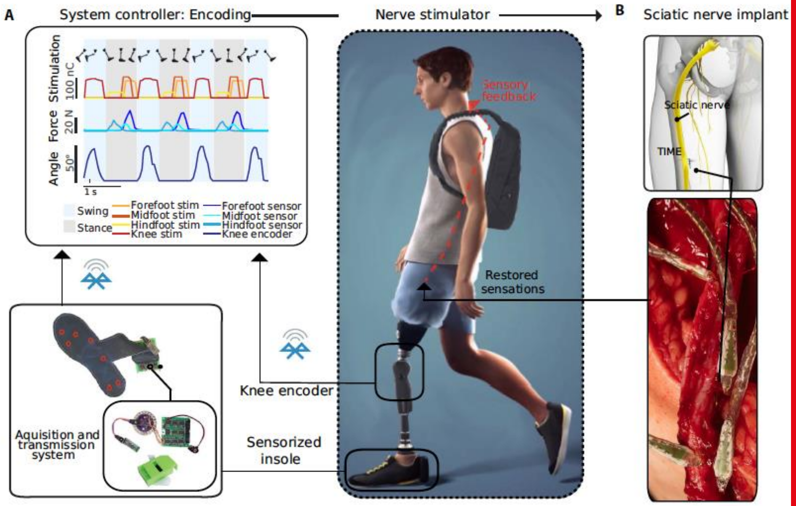




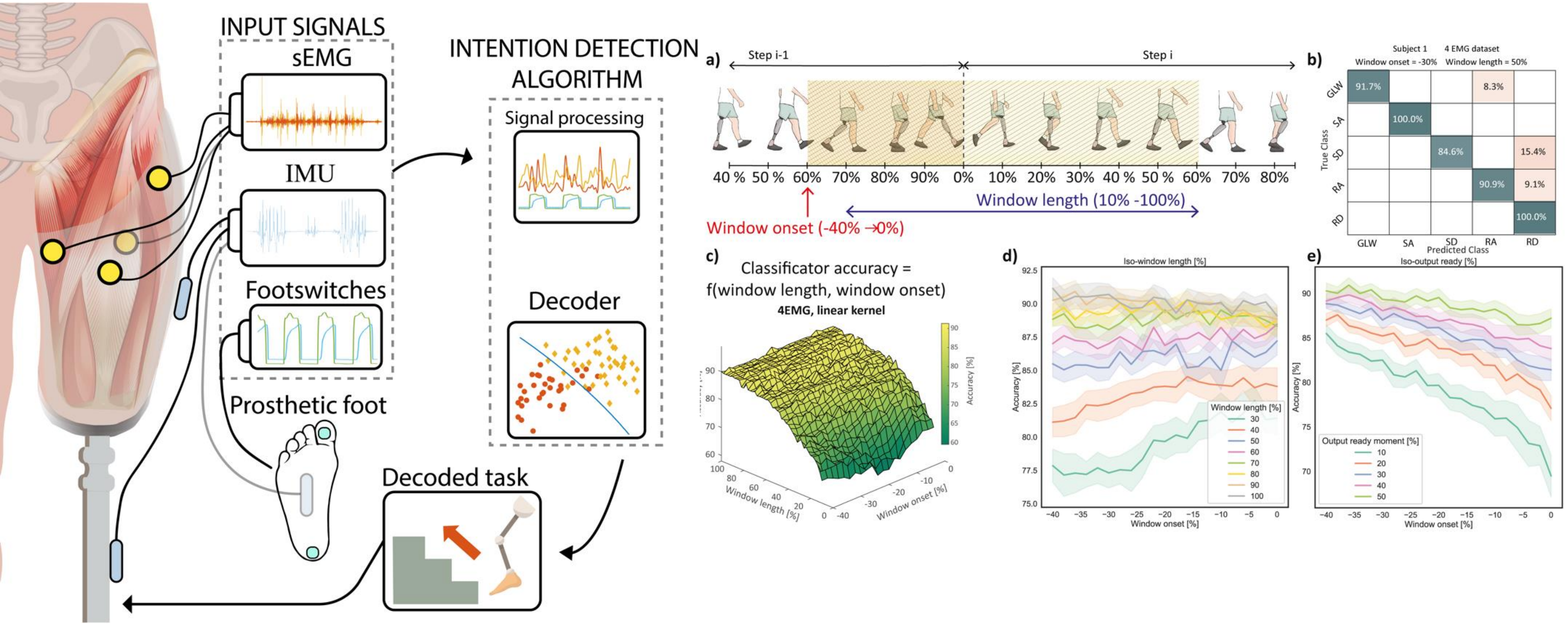


# Lower limb bionics

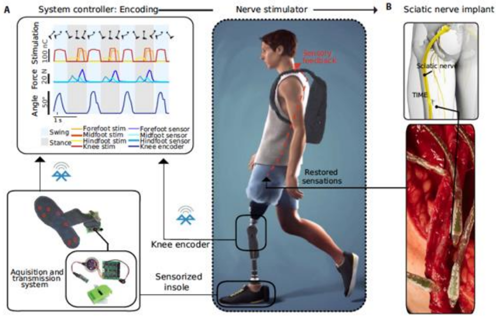


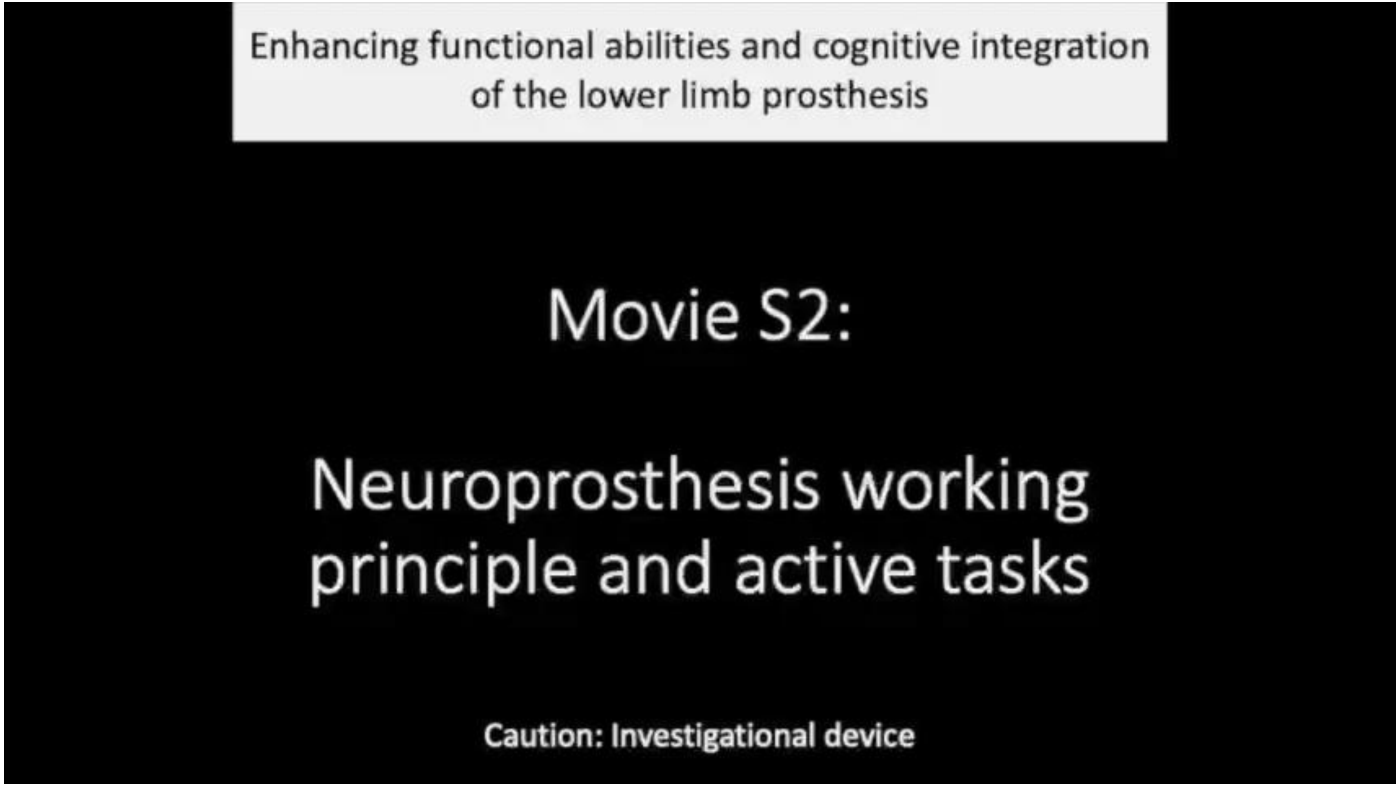
# Bidirectional neurocontrolled leg prostheses


# Bidirectional neurocontrolled leg prostheses



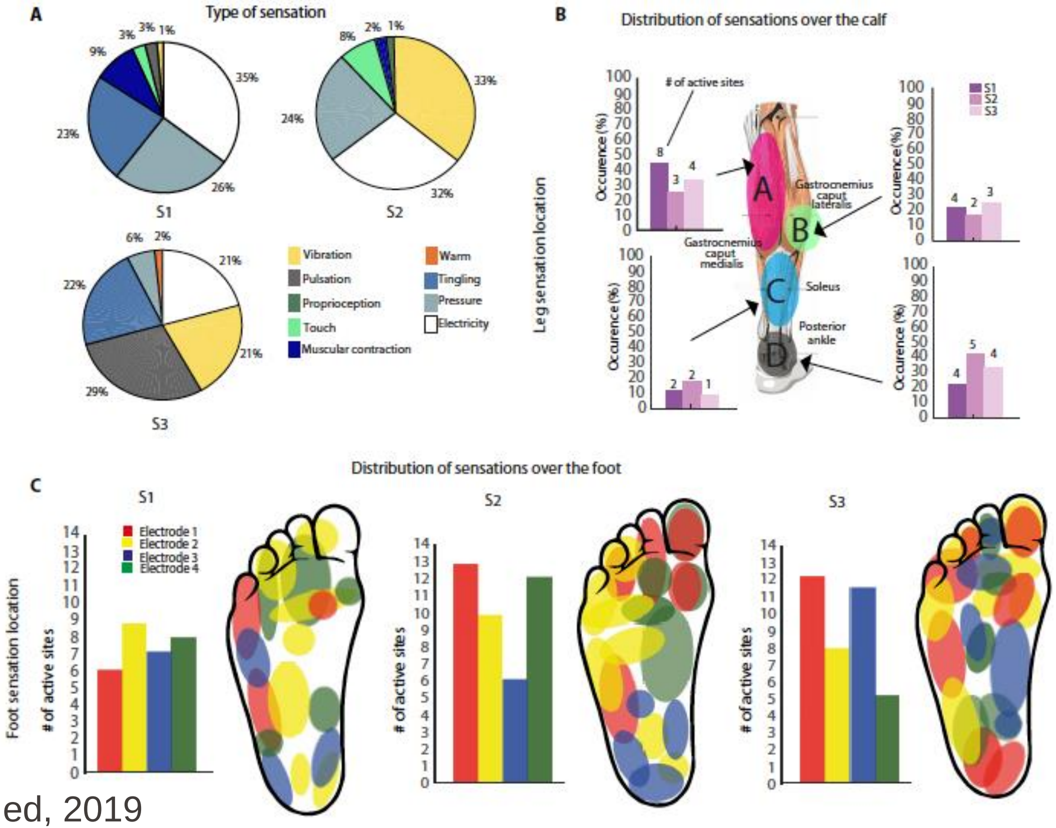
# Bidirectional neurocontrolled leg prostheses
## Sensory feedback



# Bidirectional neurocontrolled leg prostheses

## Sensory feedback

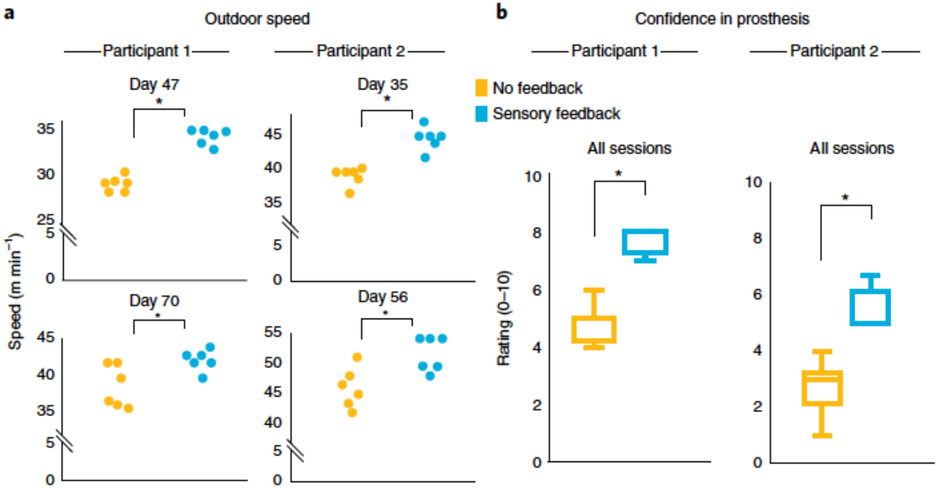


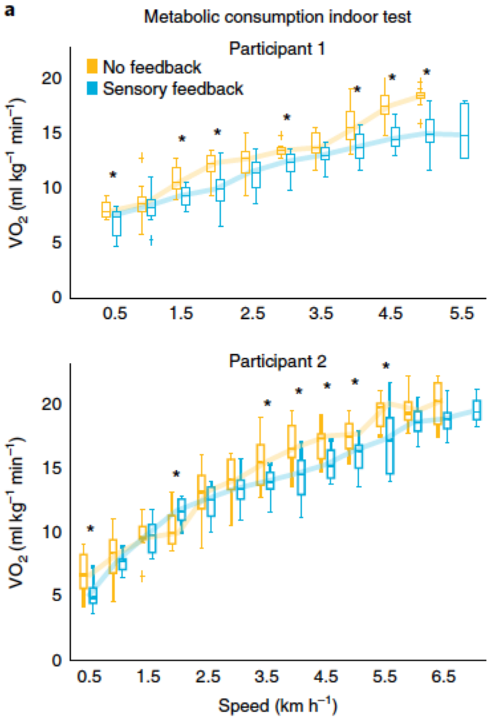

Petrini et al.,
Science Trans Med, 2019

EPFL

# Bidirectional neurocontrolled leg

## Sensory feedback



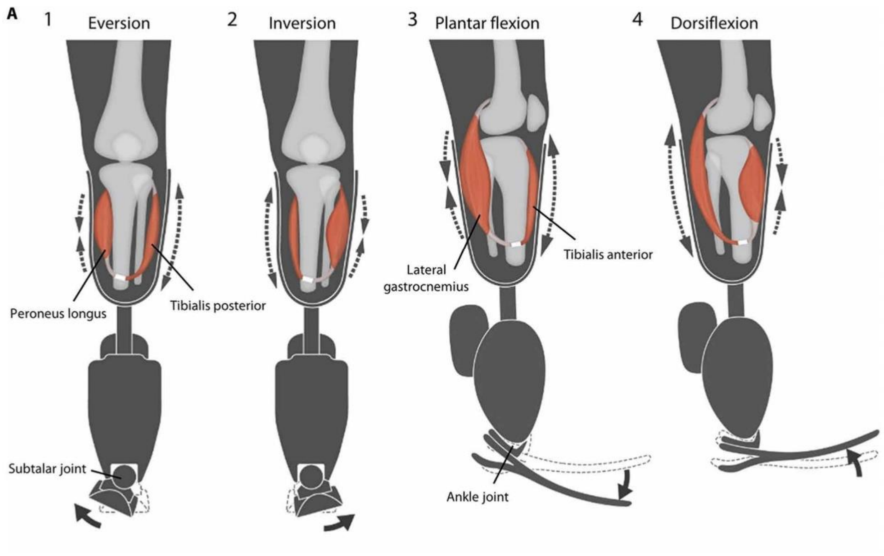

Walking speed and self-reported confidence increased while mental and physical fatigue decreased for both participants

Participants exhibited reduced phantom limb pain with neural sensory feedback.

Petrini et al., Nature Medicine, 2019

# Agonist-antagonist myoneural interface

- As a methodology of improving efferent (neural pathways that relay commands from the central nervous system to a muscle or other end organ) prosthetic control and providing afferent proprioceptive sensation, we present an agonist-antagonist myoneural interface (AMI)
- An AMI is made up of an agonist and an antagonist muscle tendon connected mechanically in series: When the agonist contracts, the antagonist is stretched and vice versa
- The purpose of an AMI is to control and interpret proprioceptive feedback from a bionic joint.

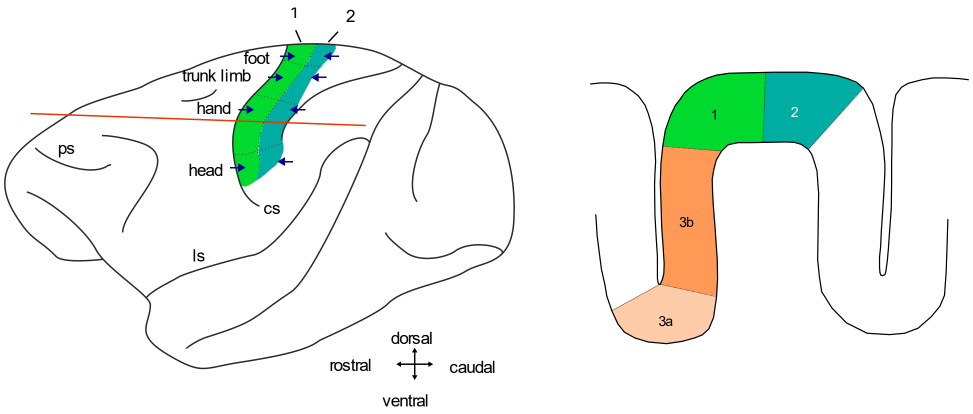



Clites et al., Science Trans Med, 2018

EPFL

# Sensory feedback via brain stimulation

# Cortical anatomical organization for Primary Somatosensory Cortex (NHP)

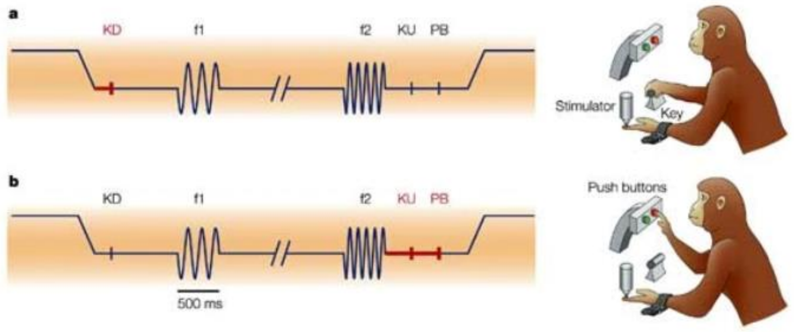


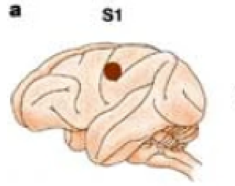

- Neurons in area 3a respond primarily to joint movements. Proprioceptive afferents are multimodally processed in this region.
- Neurons in areas 3b and 1 respond to light touch. Phase-locked responses to vibrations are primarily seen in area 3b, they gradually disappear in area 1 and area 2.

cs: central sulcus; ips: intraparietal sulcus; pcd: precentral dimple; asu: arcuate sulcus; ps: principal sulcus; ls: lateral sulcus; BA: Brodmann area. Modified from (James et al., 2007; Pons et al., 1985, 1987).

# Sensory feedback cortical mechanisms

- Test with nonhuman primates (NHP) showed that the sensation of flutter is produced with mechanical vibrations in the range of 5–50 Hz
- The stimulus activates neurons in S1 that somatotopically map to the site of stimulation.
- A subset of neurons in area 3b— those with quickly adapting properties— are strongly entrained by periodic flutter vibrations, firing with a probability related to the input frequency
- Hence, quickly adapting neurons provide a dynamic representation of such flutter stimuli.



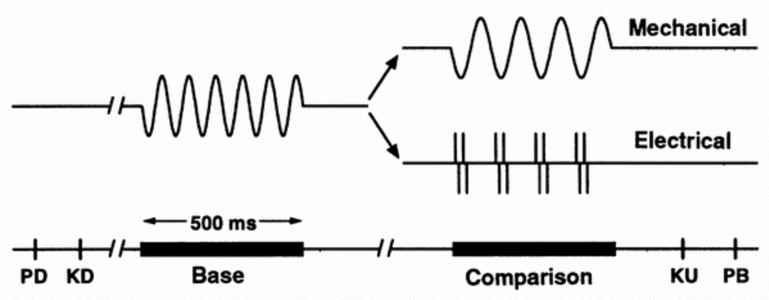






Romo, R., Hernández, A., Zainos, A., & Salinas, E. (1998). Somatosensory discrimination based on cortical microstimulation. Nature, 392(6674), 387–390. https://doi.org/10.1038/32891

# Intracortical micro stimulation

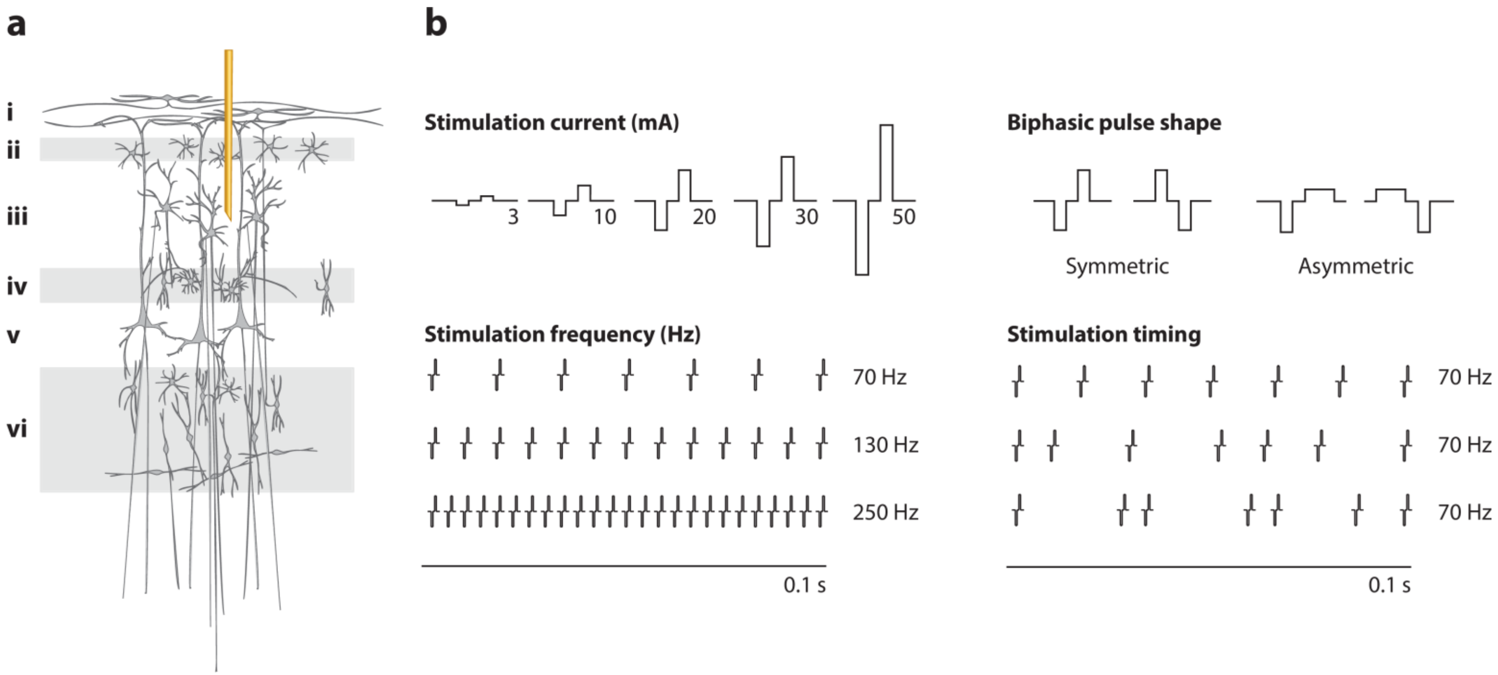
- **Method**:
  - Microelectrodes implanted into area 3b of S1
  - Biphasic current pulses (lasted 0.2 ms, with 0.05 ms between phases), amplitude 65 µA and 100 µA
- **Results:** Animals reliably indicated whether electrical signal was higher or lower than that the mechanical signal
- **Conlcusion:** the neural code underlying the sensation of flutter can be manipulated.






Romo, R., Hernández, A., Zainos, A., & Salinas, E. (1998). Somatosensory discrimination based on cortical microstimulation. Nature, 392(6674), 387–390. https://doi.org/10.1038/32891

# Cortical anatomical organization for Primary Somatosensory Cortex (NHP)




Dadarlat MC, et al. 2023
*Annu. Rev. Biomed. Eng.* 25:51–76

03/03/2025

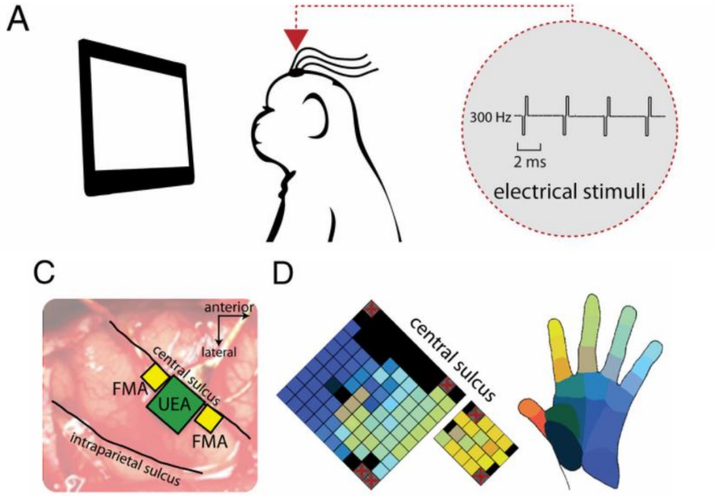
Romo, R., Hernández, A., Zainos, A., & Salinas, E. (1998). Somatosensory discrimination based on cortical microstimulation. Nature

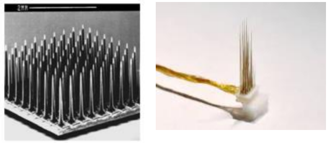
EPFL

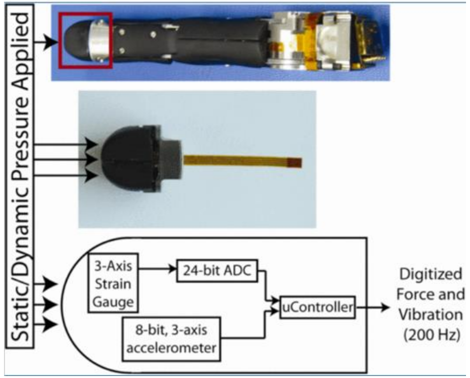
# Encoding via ICMS

Bensmaia Lab
RESEARCH IN SOMATOSENSORY NEUROSCIENCE AND NEUROPROSTHETICS

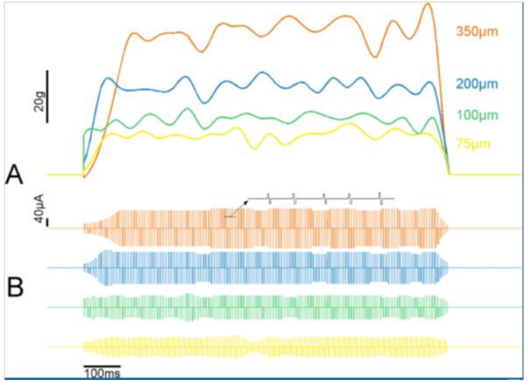
THE UNIVERSITY OF CHICAGO






Pressure sensors on the finger-tip of a prosthetic hand

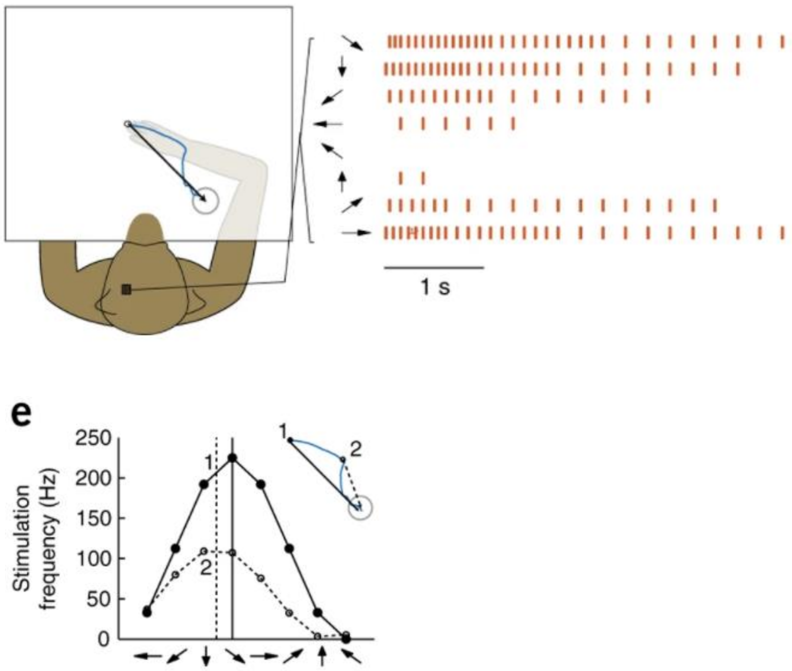



Conversion from time-varying force to ICMS pulse trains of varying amplitude. (A) Time-varying force output of the prosthetic finger on four detection trials with four different amplitudes. (B) Resulting electrical stimulation pulse trains



Kim, Sungshin, et al. "Behavioral assessment of sensitivity to intracortical microstimulation of primate somatosensory cortex." Proceedings of the National Academy of Sciences 112.49 (2015): 15202-15207.

# Sensory encoding using a learning-based ICMS approach

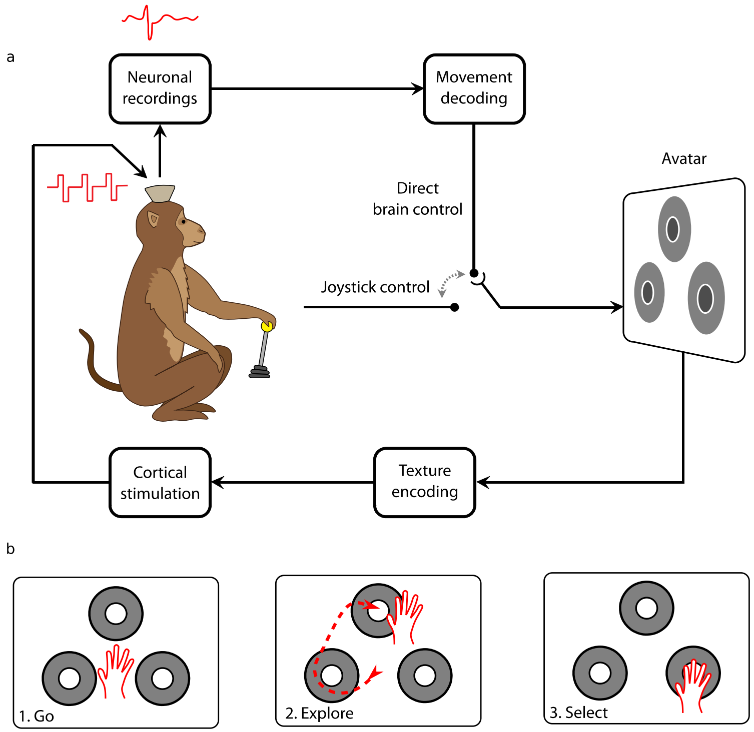


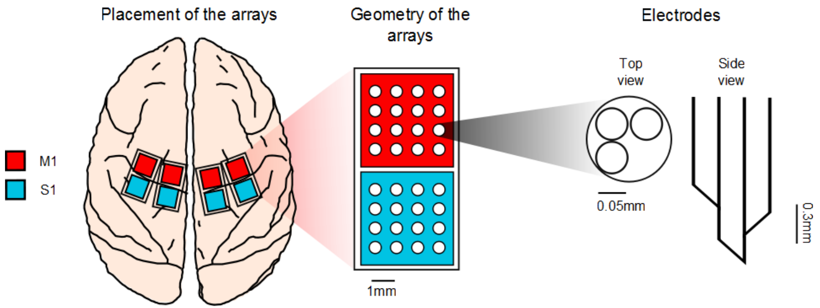

- Stimulation on 8 electrodes.
- Non-biomimetic approach, but rather a learning-based approach
  - Spatiotemporal correlations between a visual signal and novel artificial signal in a behavioral context would be sufficient for a monkey to learn to integrate the new modality.
- Provide continuous information about the hand state during reaching via ICMS
- **Result**: artificial kinesthetic feedback can be efficiently learned by the monkey and can provide rich insights for directing movements.



Dadarlat, M. C., O'doherty, J. E., & Sabes, P. N. (2015). A learning-based approach to artificial sensory feedback leads to optimal integration. Nature neuroscience, 18(1), 138-144.

# Bidirectional brain machine interface



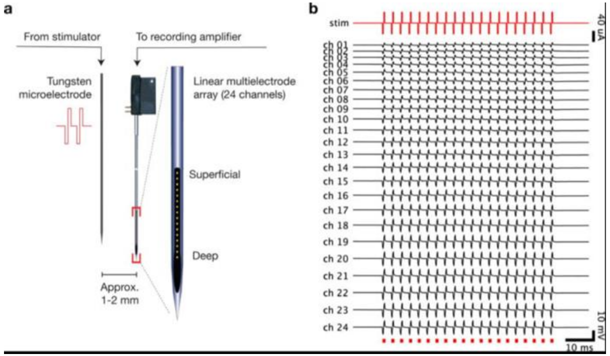






O’Doherty, J. E., Lebedev, M. A., Ifft, P. J., Zhuang, K. Z., Shokur, S., Bleuler, H., & Nicolelis, M. A. (2011). Active tactile exploration using a brain–machine–brain interface. *Nature*, *479*(7372), 228-231.

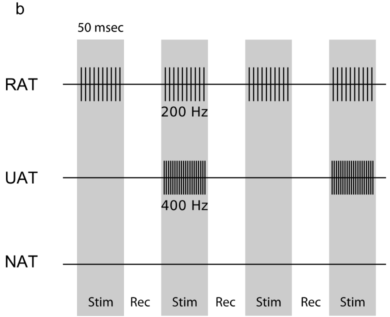
# Stimulation paradigm

**Problem**
Complex signal artifact during the stimulation periods -> corrupts the signals recorded in the motor cortex

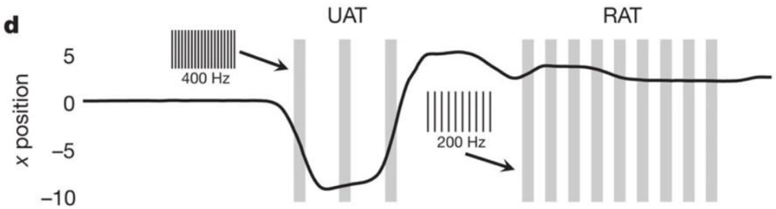



O'Shea, D. J., & Shenoy, K. V. (2018). ERAASR: an algorithm for removing electrical stimulation artifacts from multielectrode array recordings. Journal of neural engineering, 15(2), 026020.

**Solution** (for this study):
Multiplexing of sensory encoding and motor decoding periods

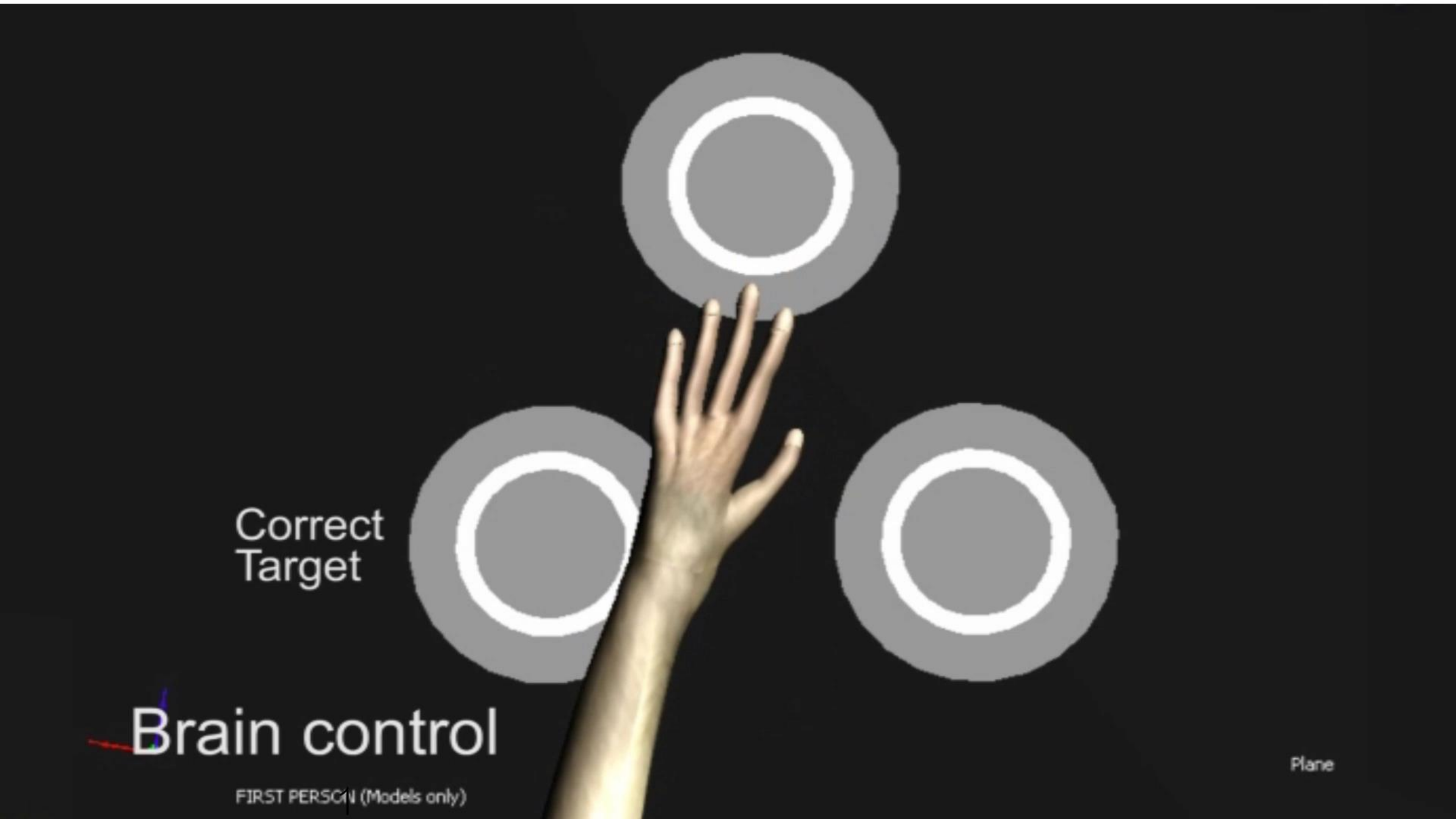



Encoding of the rewarded the unrewarded and null artificial textures

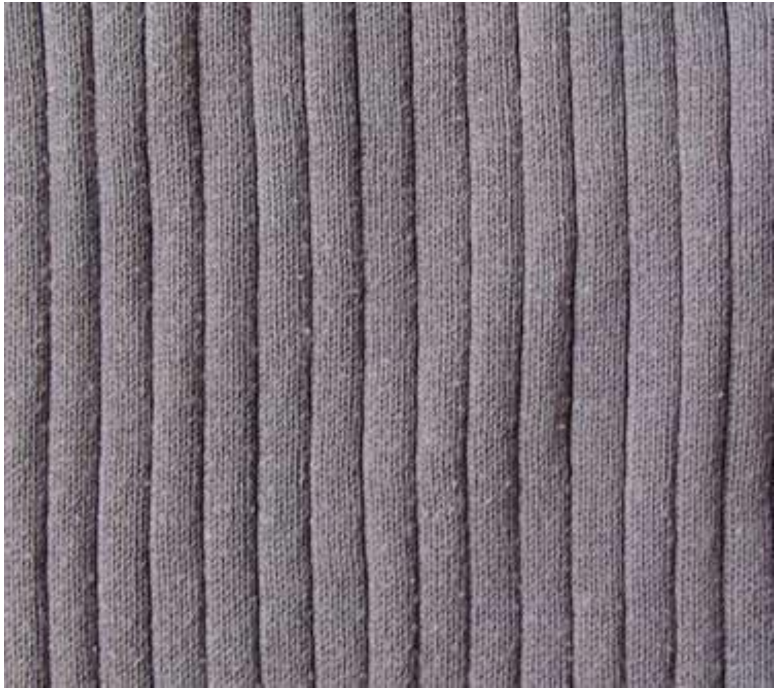


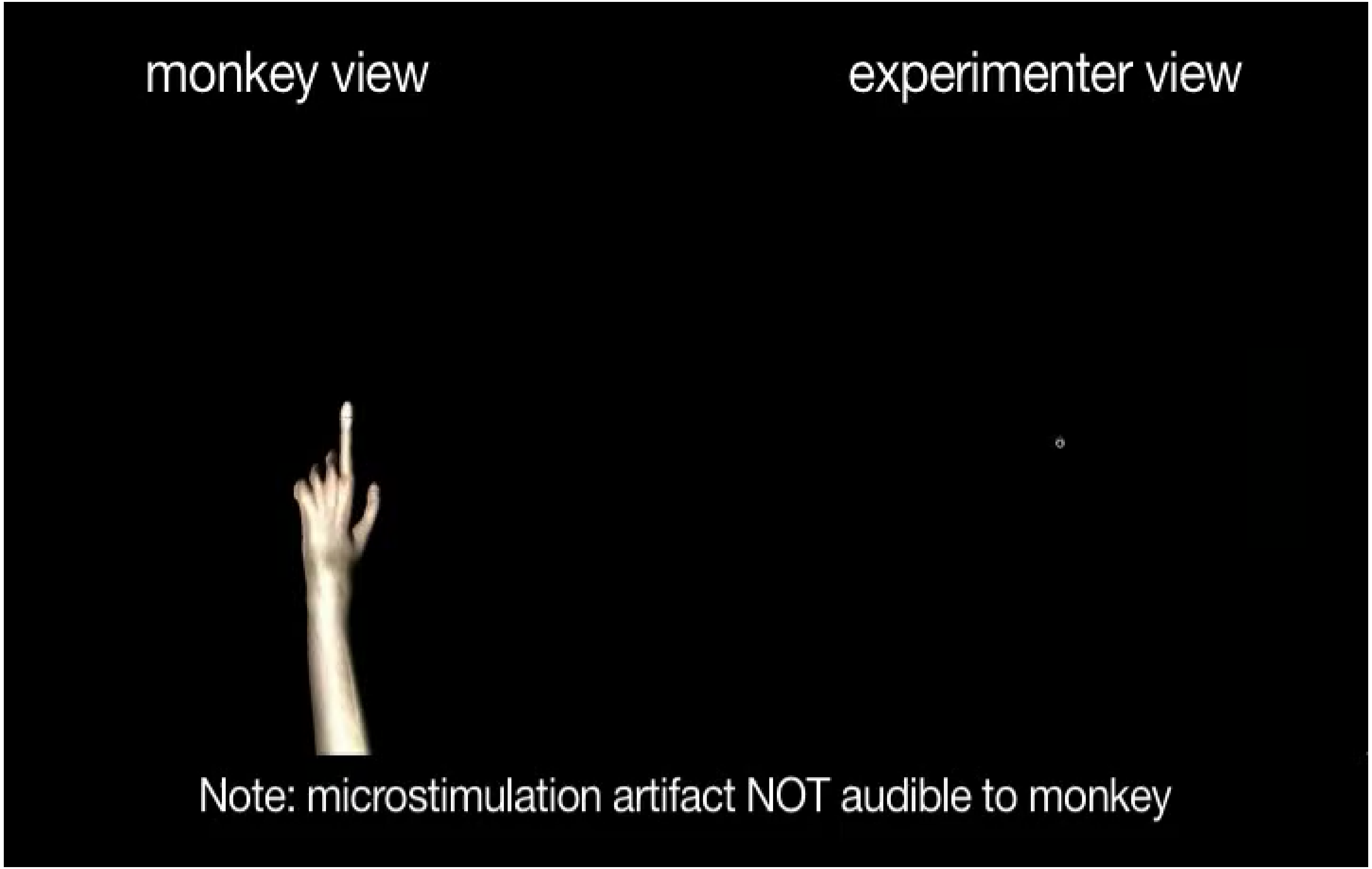



O'Doherty, J. E., Lebedev, M. A., Ifft, P. J., Zhuang, K. Z., Shokur, S., Bleuler, H., & Nicolelis, M. A. (2011). Active tactile exploration using a brain–machine–brain interface. *Nature*, *479*(7372), 228-231.


Correct
Target
Brain control
FIRST PERSON (Models only)
Plane

# Texture perception

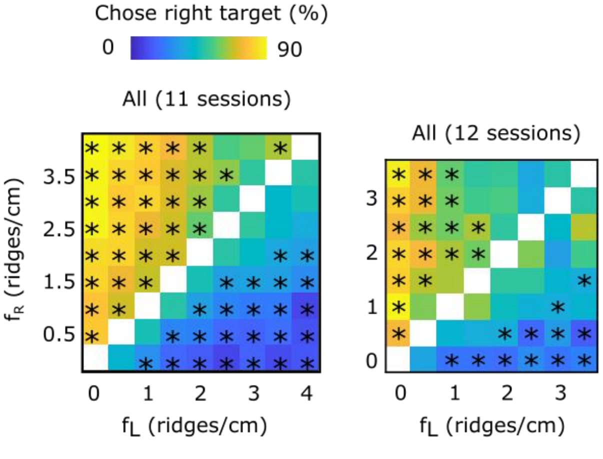





J. E. O'Doherty*, S. Shokur *, L. E. Medina, M. A. Lebedev, M. A. L. Nicolelis. Creating a neuroprosthesis for active tactile exploration of textures (2019). Proceedings of the National Academy of Sciences.

# Active tactile exploration of textures: results

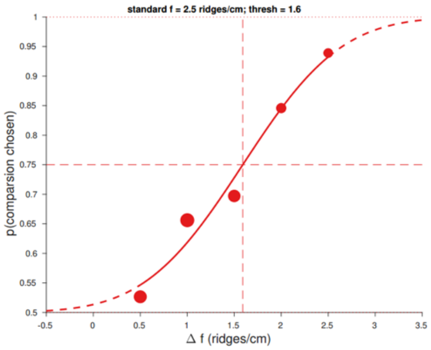
Monkeys discriminated spatial gratings based on self-generated temporal ICMS



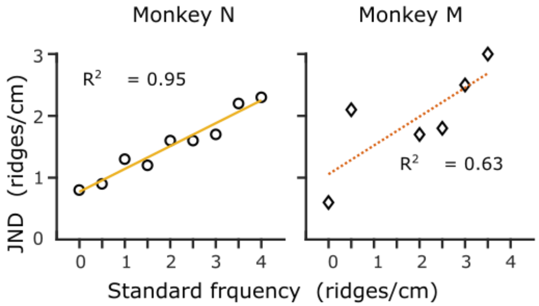

Monkey N

Monkey M

Psychometrics analysis of
Just noticeable difference (JND)

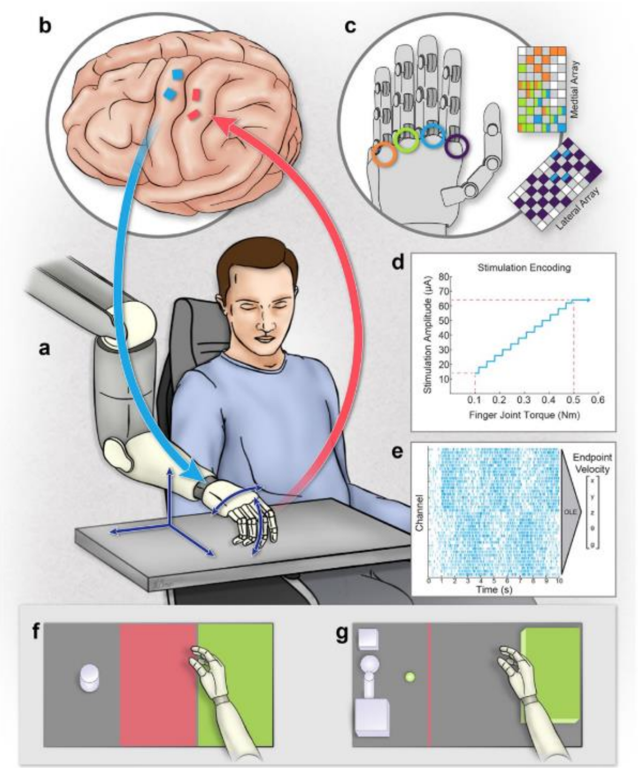



JND increases proportionally to f, consistent with the Weber–Fechner/Steven's law




J. E. O'Doherty*, S. Shokur *, L. E. Medina, M. A. Lebedev, M. A. L. Nicolelis. Creating a Neuroprosthesis for active tactile exploration of textures (2019). Proceedings of the National Academy of Sciences.

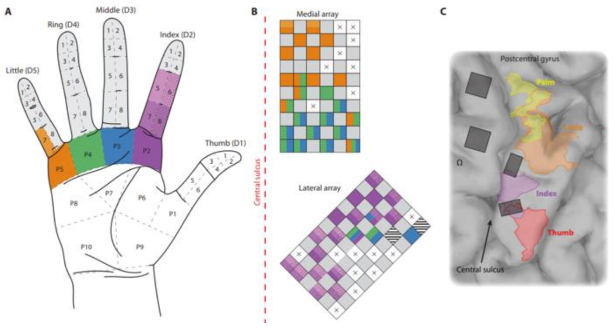
# Clinical test with implanted electrodes in Tetraplegic patients

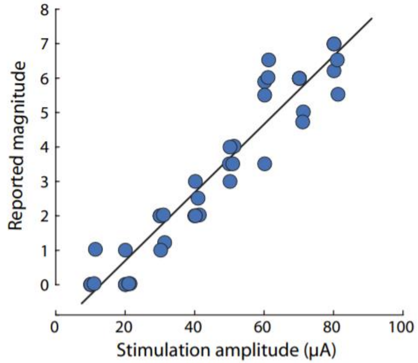



Patient:

- A 28-year-old male participant with tetraplegia
- Two microelectrode arrays implanted in area 1 of S1
- Electrode implanted in M1 as part of a larger protocol

# How does it feel ?




There is a linear relation between perceived intensity of tactile feedback and the amplitude of stimulation

**Table 1. Percept qualities evoked by intracortical microstimulation.** The number of trials evoking each response type is shown. The totals in each category (naturalness, depth, etc.) differ because the participant did not always provide a complete response for every case where he could detect a stimulus. In 79 cases, a sensation of "tingle" was described without being further described by one of the subcategories.

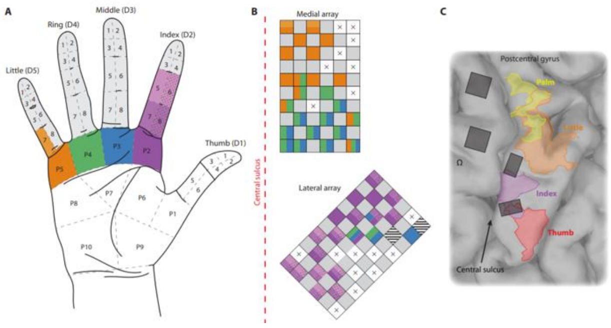
| Naturalness (250) | Depth (247) | Pain (280) | Somatosensory quality (190) |
|---|---|---|---|
| .. | ... | ........ | |
| .. | ... | ........ | |
| .. | ... | ........ | |
| .. | ... | ........ | |

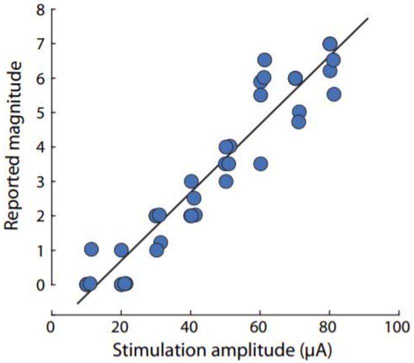


Flesher, Sharlene N., et al. "Intracortical microstimulation of human somatosensory cortex." Science translational medicine 8.361 (2016): 361ra141-361ra141.

EPFL

# How does it feel ?




There is a linear relation between perceived intensity of tactile feedback and the amplitude of stimulation

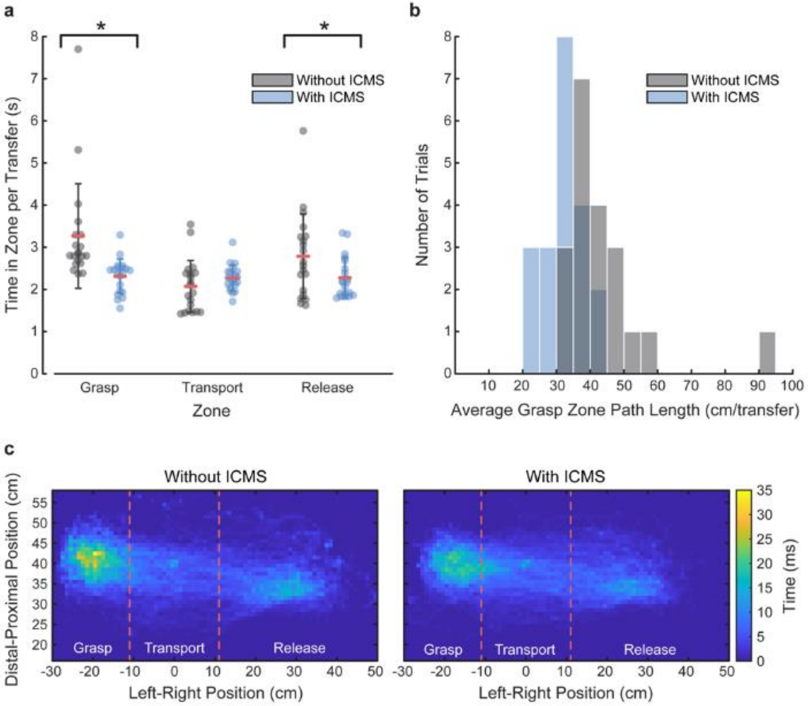
**Table 1. Percept qualities evoked by intracortical microstimulation.** The number of trials evoking each response type is shown. The totals in each category (naturalness, depth, etc.) differ because the participant did not always provide a complete response for every case where he could detect a stimulus. In 79 cases, a sensation of "tingle" was described without being further described by one of the subcategories.

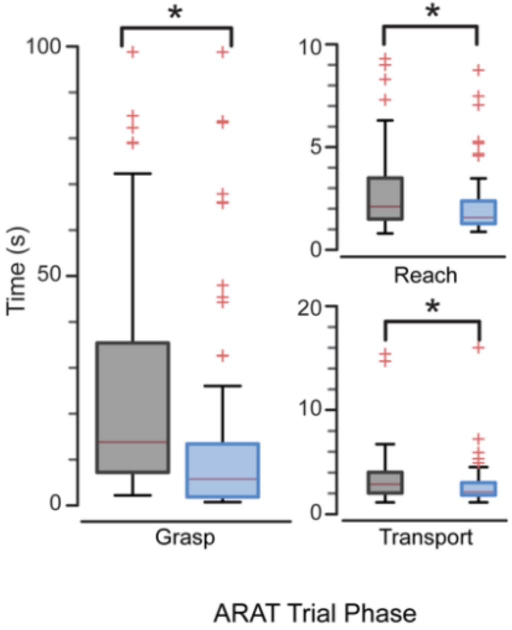
| Naturalness (250) | | Depth (247) | | Pain (280) | | Somatosensory quality (190) | |
|---|---|---|---|---|---|---|---|
| Totally natural | 0 | Skin surface | 9 | 0 (no pain) | 280 | Mechanical | Touch (2), pressure (128), sharp (0) |
| Almost natural | 12 | Below skin | 5 | 1, 2, 3 | 0 | Movement | Vibration (1), movement (0) |
| Possibly natural | 233 | Both | 233 | 4, 5, 6 | 0 | Temperature | Warm (30), cool (0) |
| Rather unnatural | 5 | | | 7, 8, 9 | 0 | Tingle (79) | Electrical (29), tickle (0), itch (0) |
| Totally unnatural | 0 | | | 10 (most pain) | 0 | | |



Flesher, Sharlene N., et al. "Intracortical microstimulation of human somatosensory cortex." Science translational medicine 8.361 (2016): 361ra141-361ra141.

# Functional improvement using a bidirectional BMI



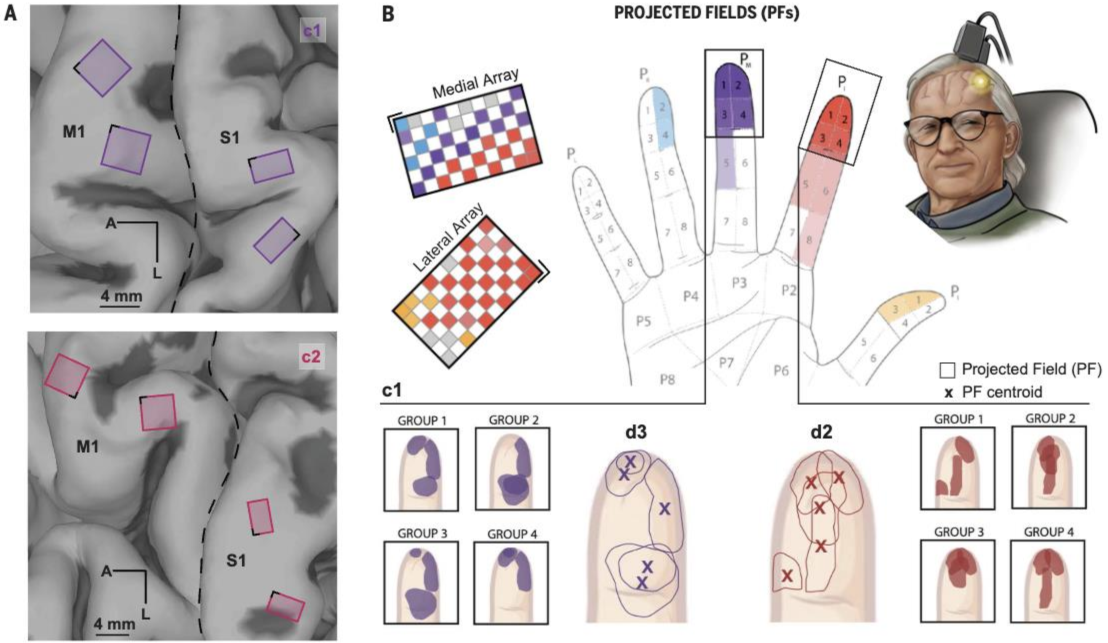




03/03/2025

Flesher, S. N., Downey, J. E., Weiss, J. M., Hughes, C. L., Herrera, A. J., Tyler-Kabara, E. C., ... & Gaunt, R. A. (2021). A brain-computer interface that evokes tactile sensations improves robotic arm control. Science, 372(6544), 831-836.

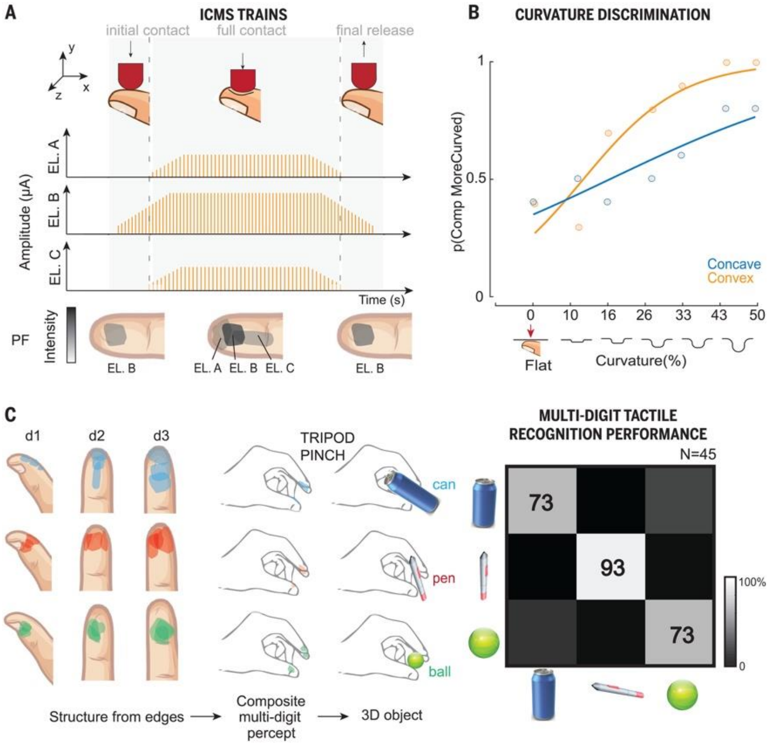
# Brain-to-machine-to-brain interface in a quadriplegic subject





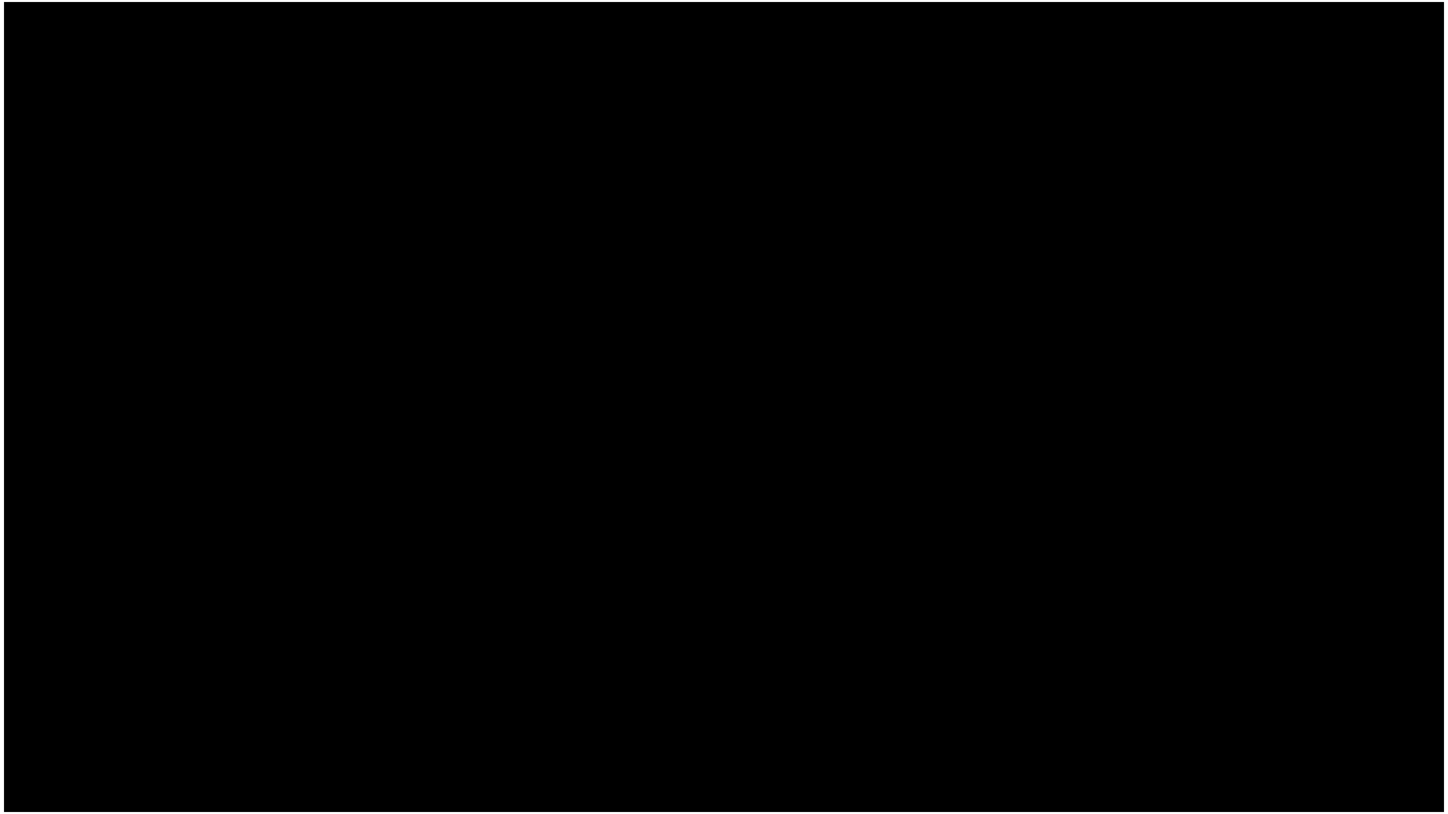

Valle, G., Alamri, A. H., Downey, J. E., Lienkämper, R., Jordan, P. M., Sobinov, A. R., ... & Bensmaia, S. J. (2025). Tactile edges and motion via patterned microstimulation of the human somatosensory cortex. Science, 387(6731), 315-322.

# Brain-to-machine-to-brain interface in a quadriplegic subject




03/03/2025

# Brain-to-machine-to-brain interface in a quadriplegic subject



# Conclusions

- Artificial limbs can be bidirectionally controlled in several ways
  - Non-invasive interfaces for decoding (EMG, EEG) and encoding (vibrators, transcutaneous electrical stimulation)
  - Invasive interfaces for decoding and encoding (ECoG, intracortical, peripheral implants)
- The choice must be done taking into account the residual skills of the subjects AND their preferences
- The different neurotechnological “tools” must be integrated accordingly