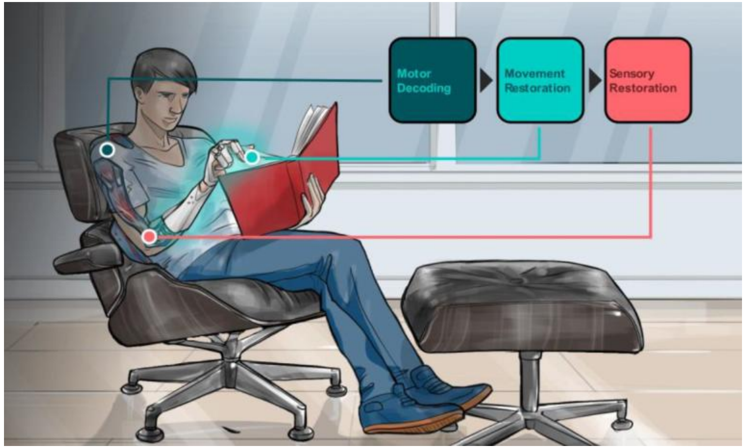
QUIZ

Start

Sensory restoration via nerve stimulation



Solaiman Shokur,

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Neuro-X, EPFL, Geneva

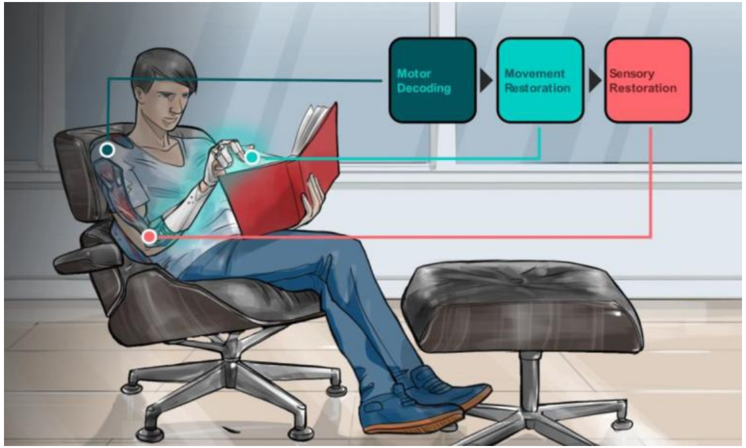
HHRI 2025

Outline

Week 11: How we perceive the world via touch

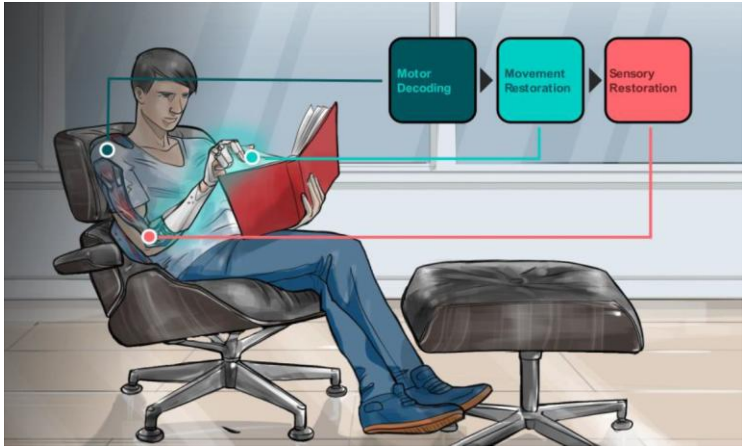
How to give haptic feedback?

- Week 13: Interfacing with the skin
- Today: Interfacing with the Peripheral Nervous System
- Week 15: Interfacing with the Central Nervous System

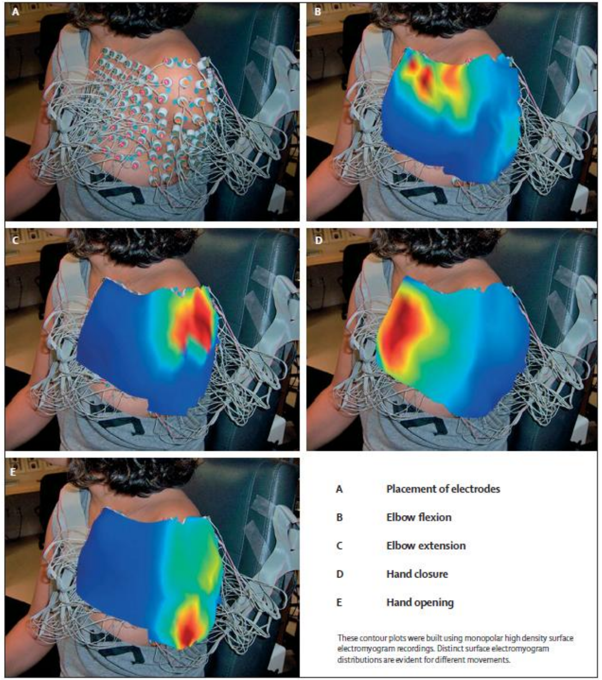


Outline

- Today: Interfacing with the Peripheral Nervous System
  - Prosthetic limbs
  - Motor decoding
    - EMG,
    - Targeted muscle and sensory reinnervation
  - Sensory feedback
    - Nerve organization
    - Electrodes to interface with the PNS
    - Restoring touch and proprioception sensations via implantable solutions
    - Thermal feedback

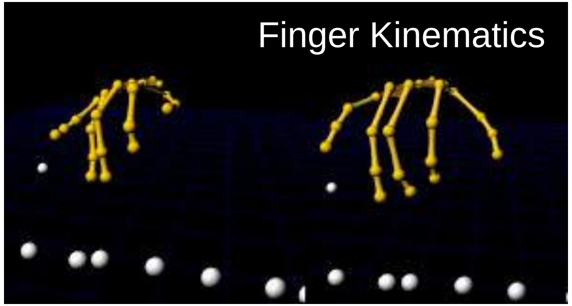


EPFL

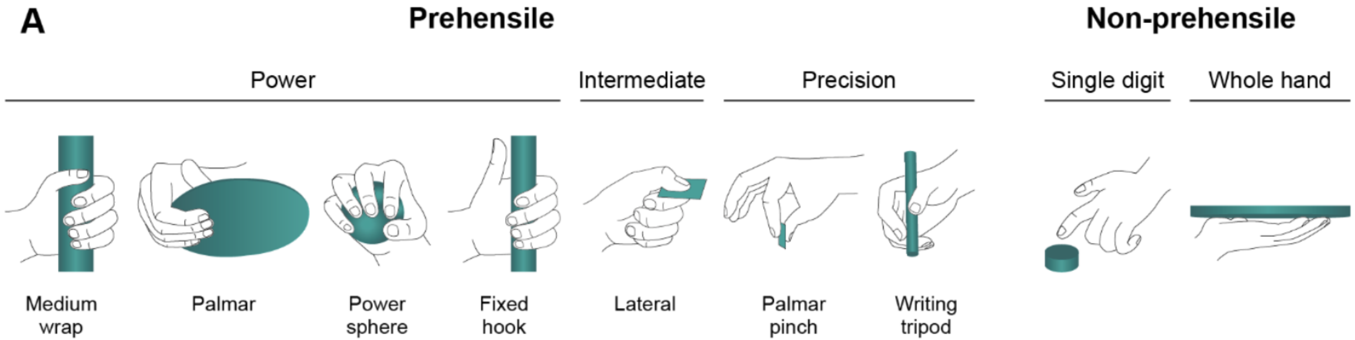


Motor decoding

What to decode



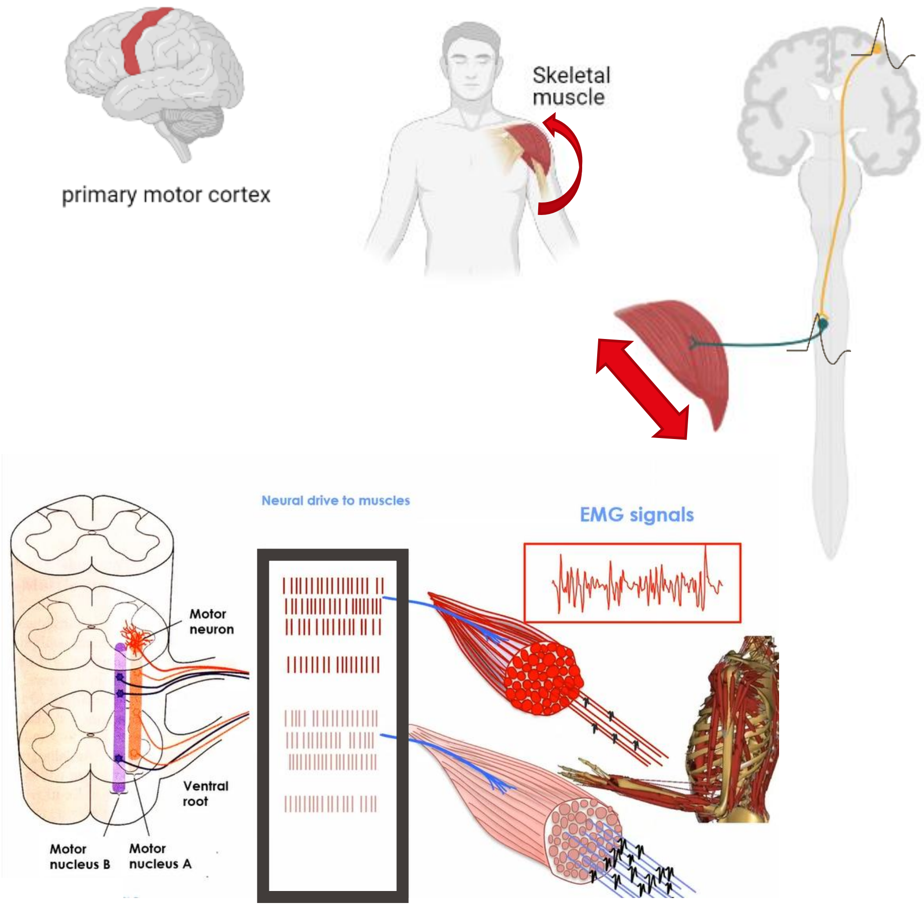
Grasping types



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

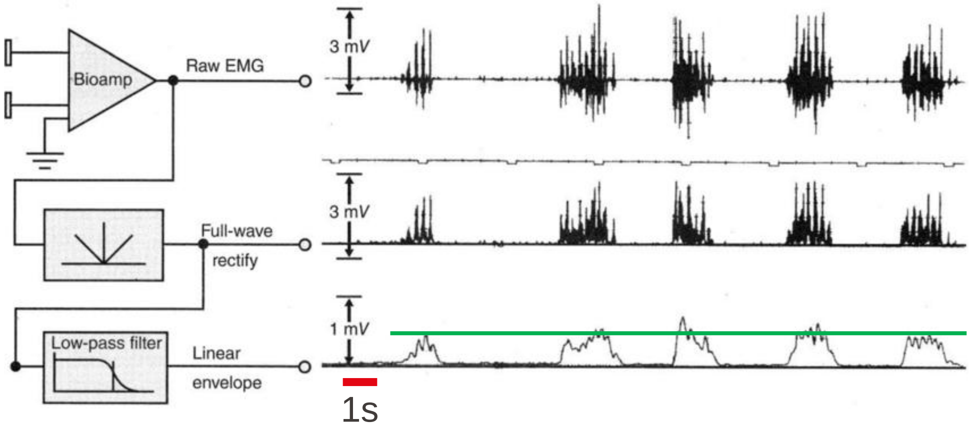
EMG signals

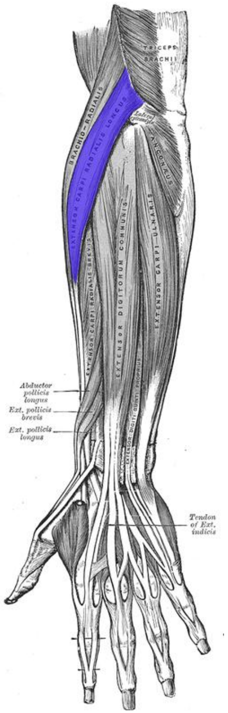
- Motor Neuron + muscle fiber that it supplies = motor unit
- The summation of these potentials is termed motor unit action potentials (MUAP) and is responsible for the muscle contraction.
- EMGs measure the MUAP



Electromyography (EMG) decoding: basic approach

Extensor carpi radialis longus muscle (wrist extension)





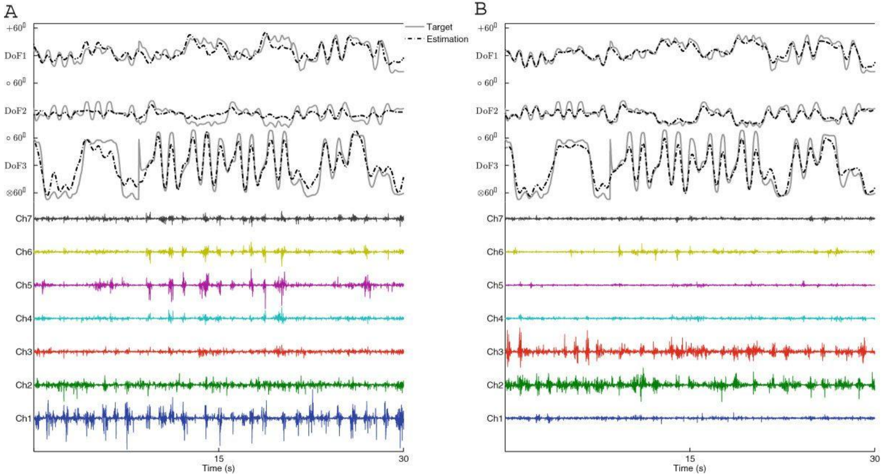
Thresholding

EMG decoding: basic approach

- The majority of commercially available robotic prosthetic hands (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

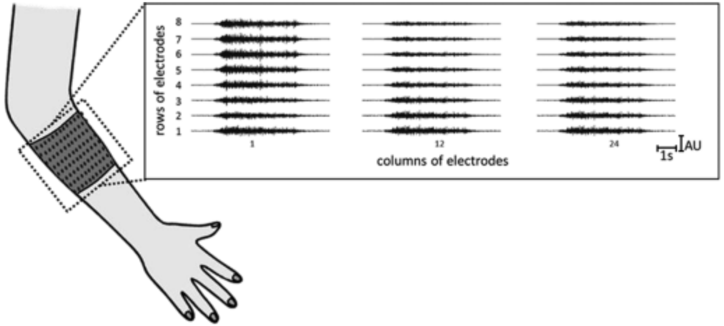
- Using machine learning approach (artificial neural network, ANN): proportional and simultaneous control of 3 DoFs of the wrist joint (flexion/extension, radial/ulnar deviation, and pronation /supination).



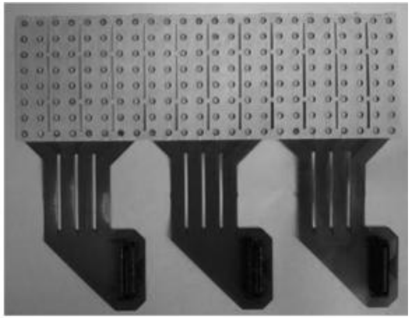
Jiang, Ning, et al. "EMG-based simultaneous and proportional estimation of wrist/hand kinematics in uni-lateral trans-radial amputees." *Journal of neuroengineering and rehabilitation* 9.1 (2012): 42.

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)

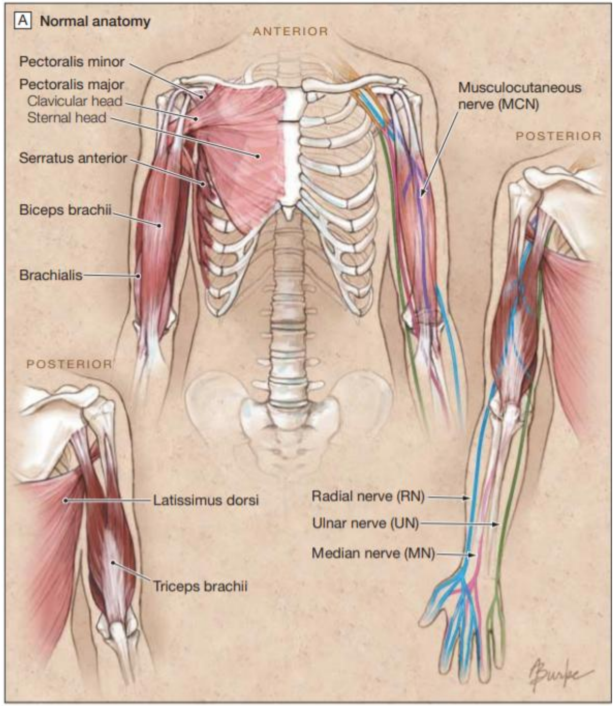


(b)

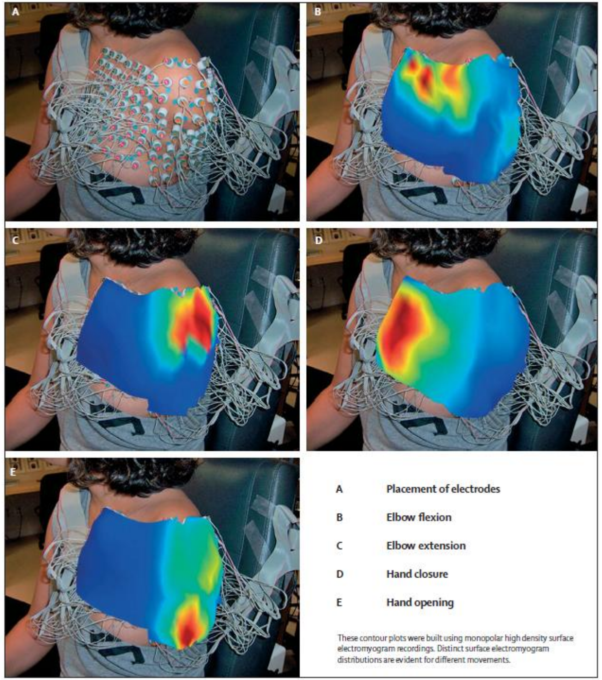
Stango, Antoniettaet al. "Spatial correlation of high density EMG signals provides features robust to electrode number and shift in pattern recognition for myocontrol." IEEE Transactions on Neural Systems and Rehabilitation Engineering 23.2 (2014): 189-198.

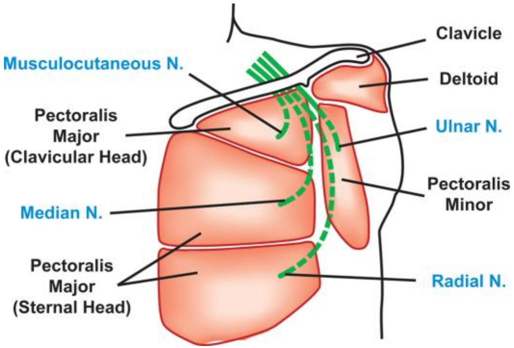
Improve intuitiveness for prosthetic users: targeted muscle reinnervation (TMR)

- 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





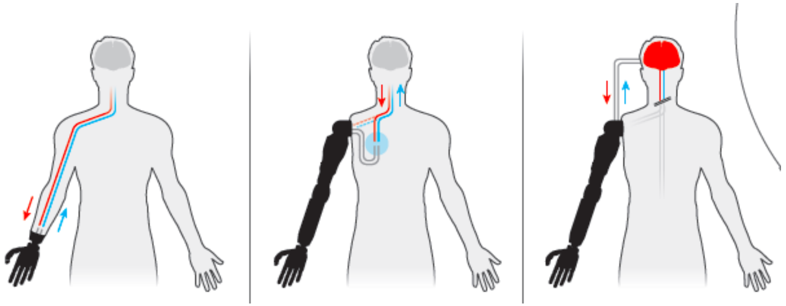
Muscles could be used as *bioamplifiers*

- 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 the 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

EPFL

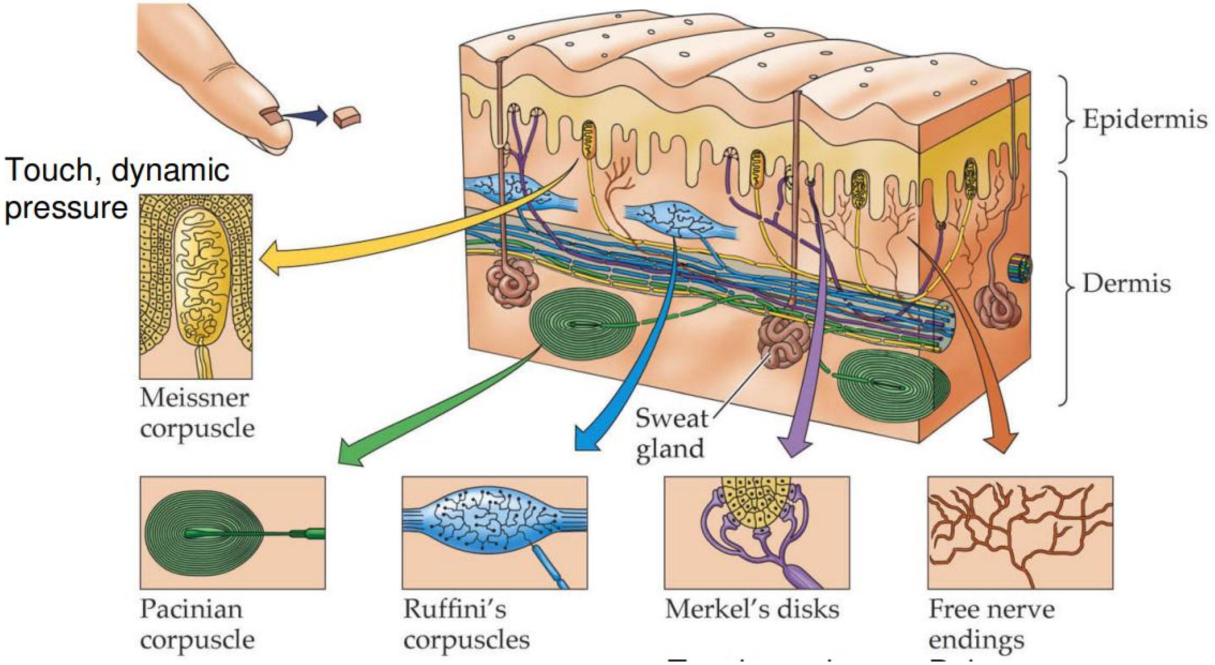


Kwok, Nature, 2013

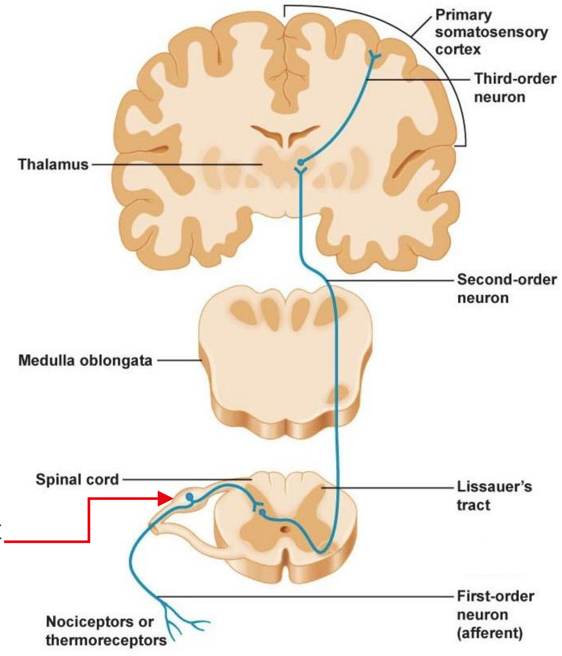
Sensory feedback

Nerve organization

Previously in HHRI: receptors in glabrous skin

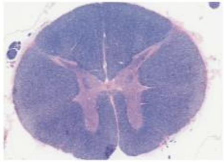


Nerve organization

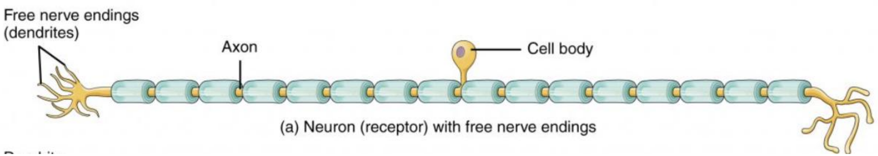


dorsal root
ganglion

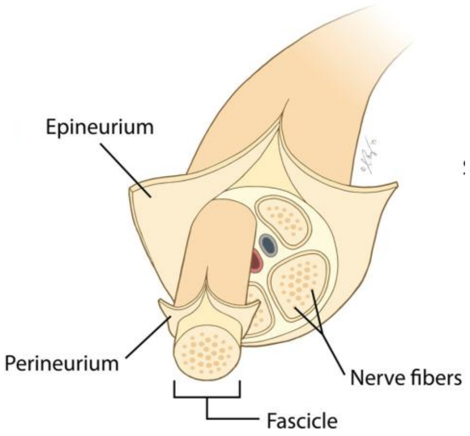
Dorsal

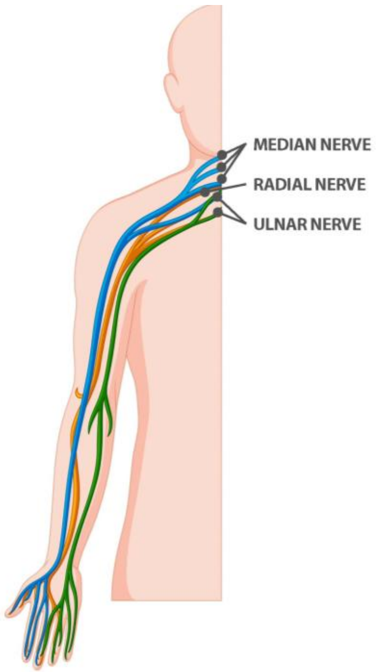


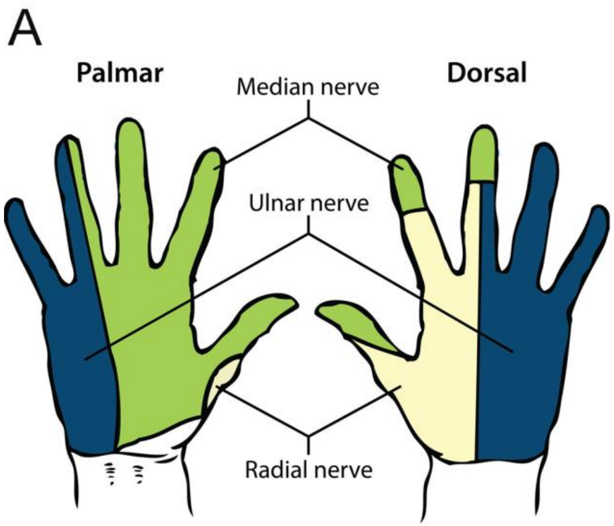
Ventral



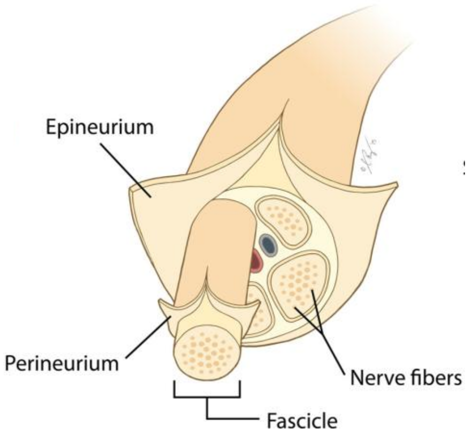
Structure of the nerve







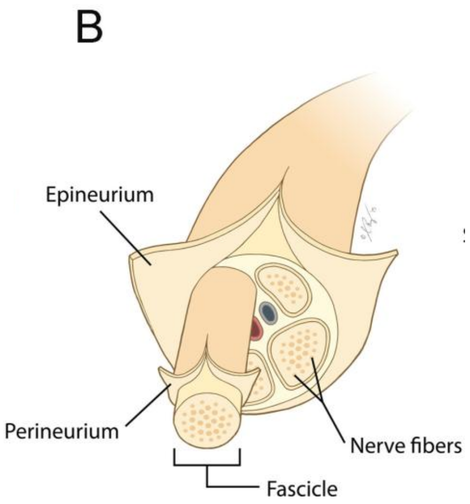
Structure of the nerve

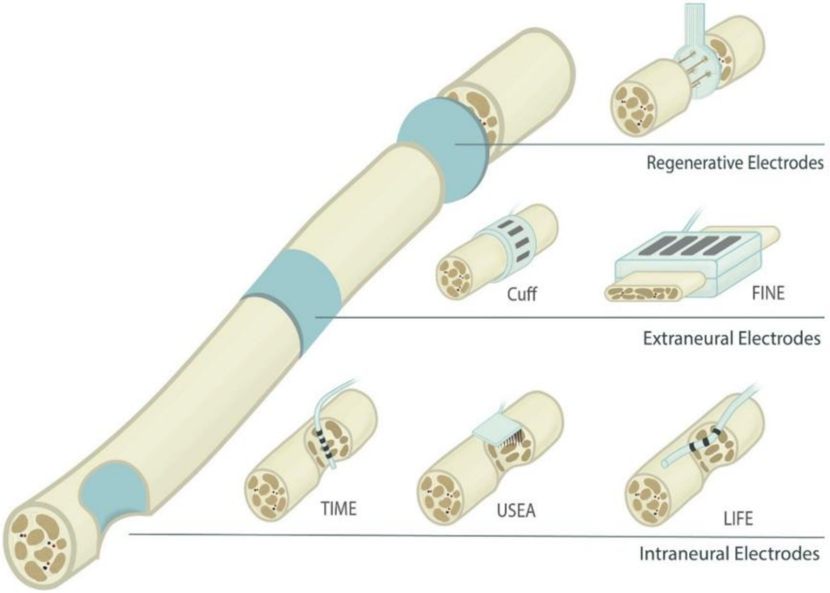


Fiber type	Fiber size (μm)	Function
Aα	12–20	Somatomotor, proprioception
Aβ	5–12	Touch, pressure
Aγ	3–6	Muscle spindle
Aδ	2–5	Pain and temperature
B	<3	Preganglionic autonomic
C	0.4–1.2 (unmyelinated)	Postganglionic autonomic, pain, temperature

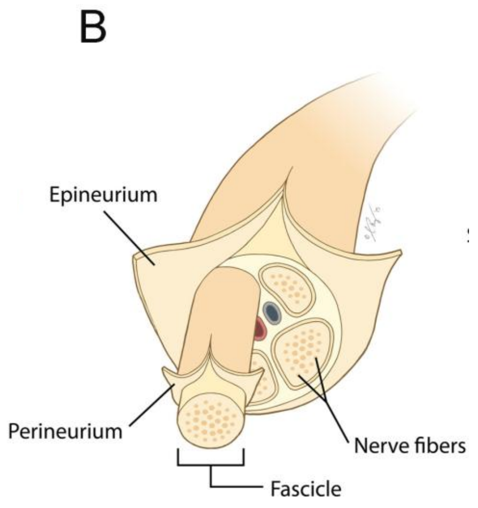
Adapted from Snell (2010).

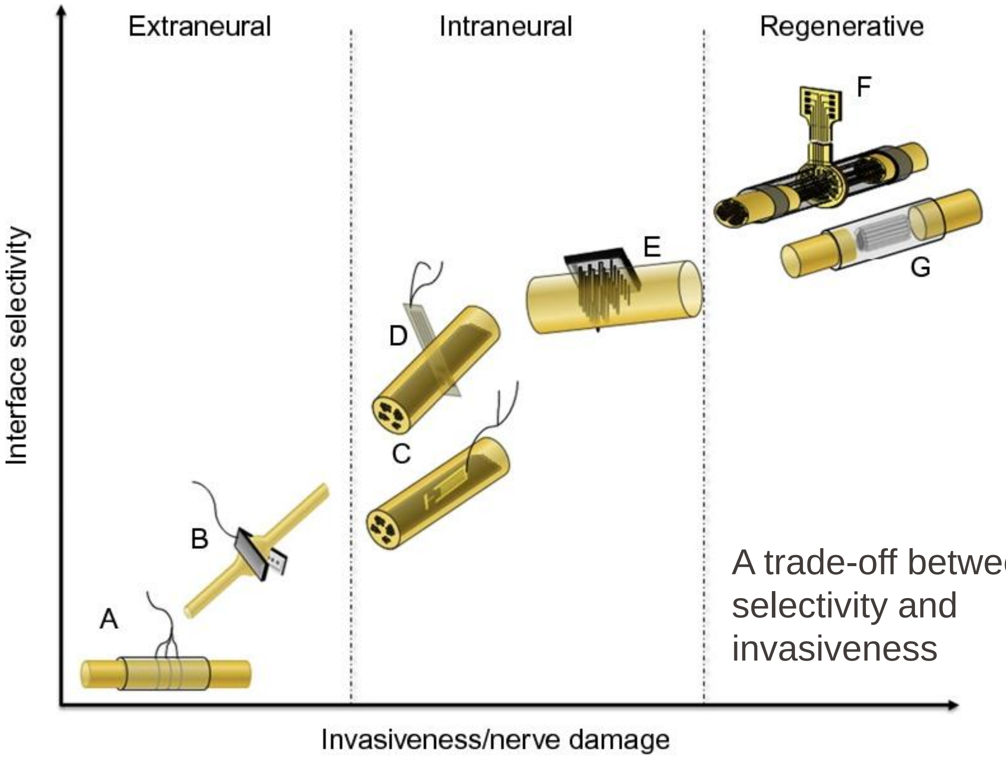
Peripheral neural interfaces





Peripheral neural interfaces

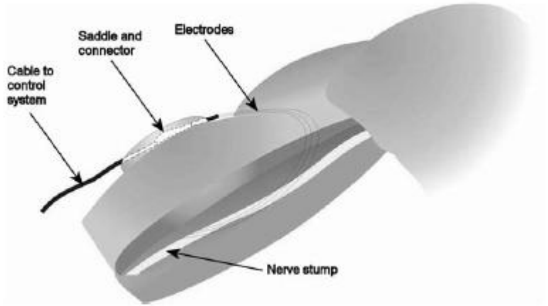


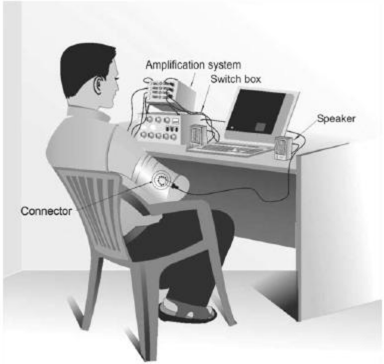


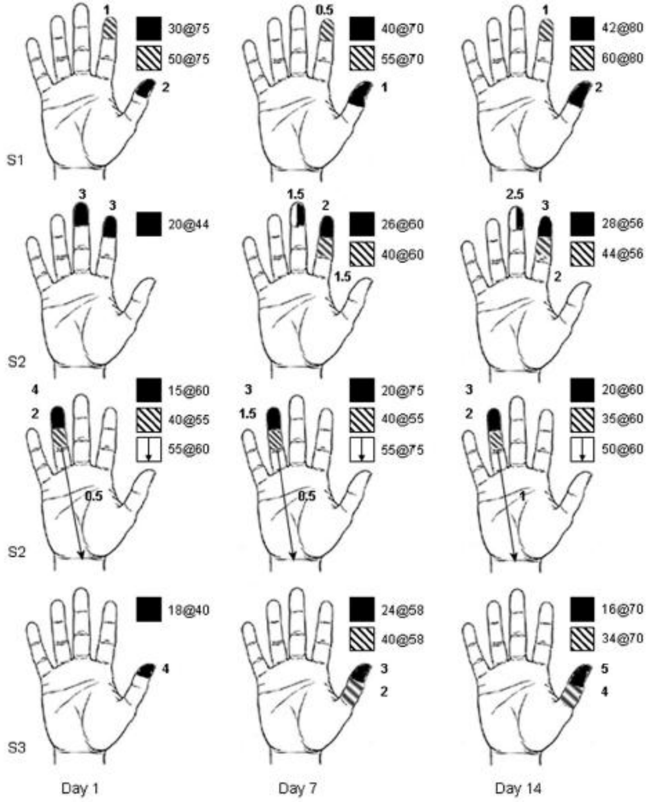
A trade-off between selectivity and invasiveness

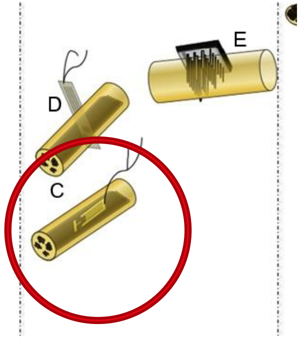
Boretius, T., Badia, J., Pascual-Font, A., Schuettler, M., Navarro, X., Yoshida, K., & Stieglitz, T. (2010). A transverse intrafascicular multichannel electrode (TIME) to interface with the peripheral nerve. Biosensors and Bioelectronics, 26(1), 62-69.

Example of intraneural stimulation





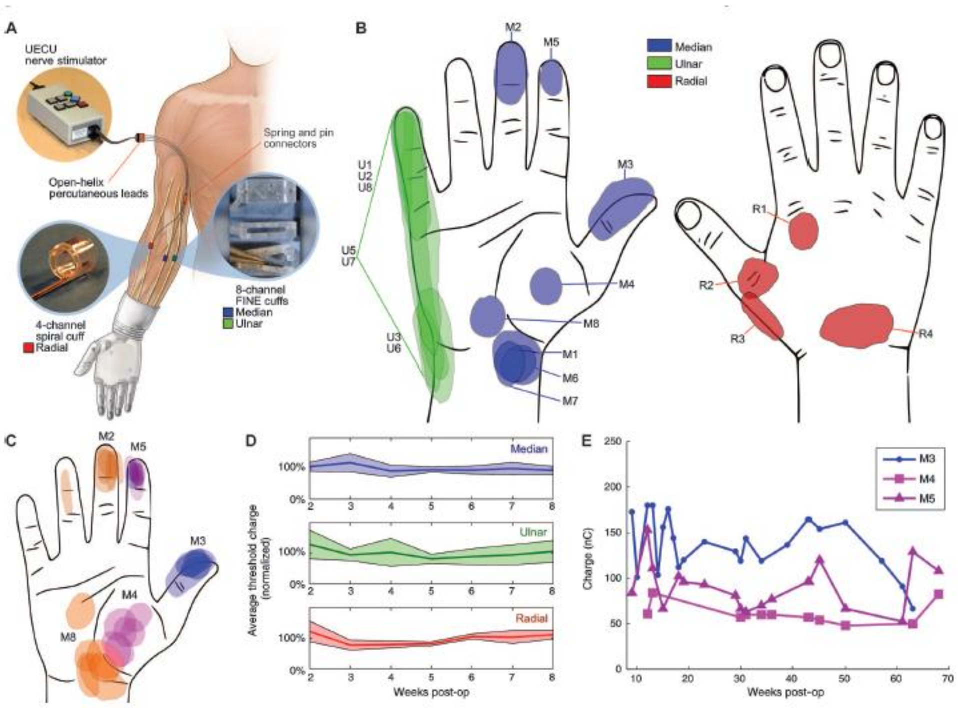


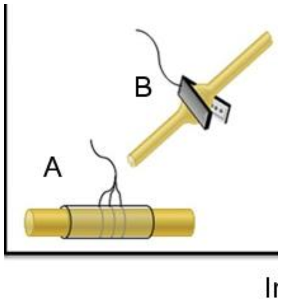


LIFE electrode

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

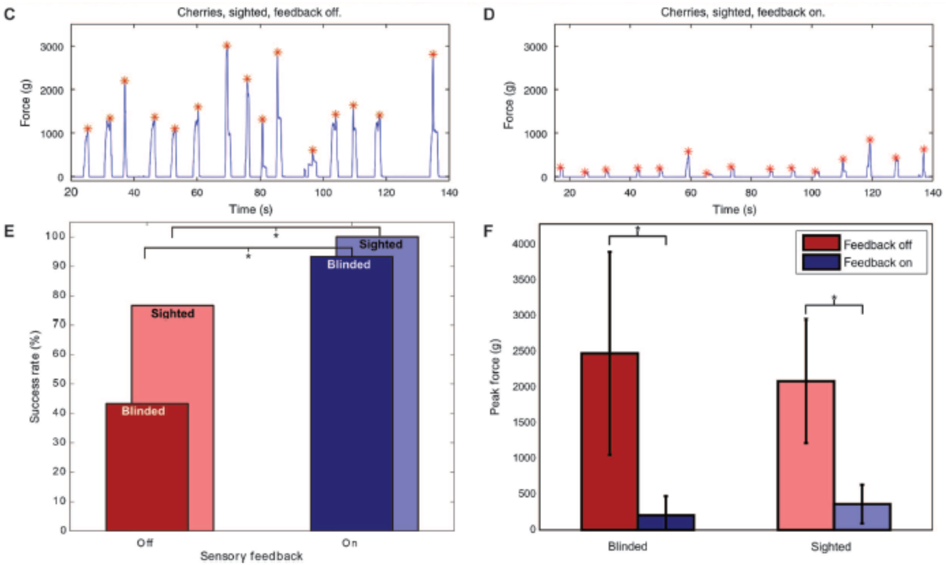


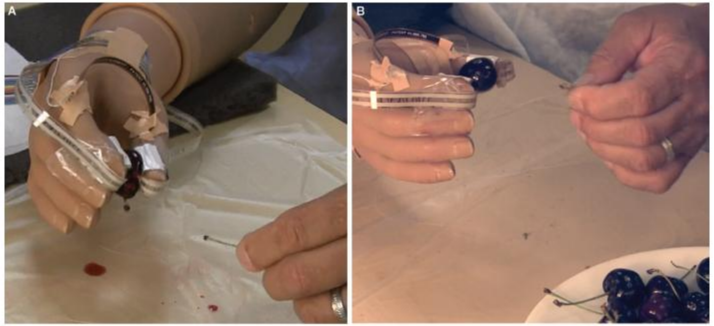


CUFF and
FINE electrodes

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

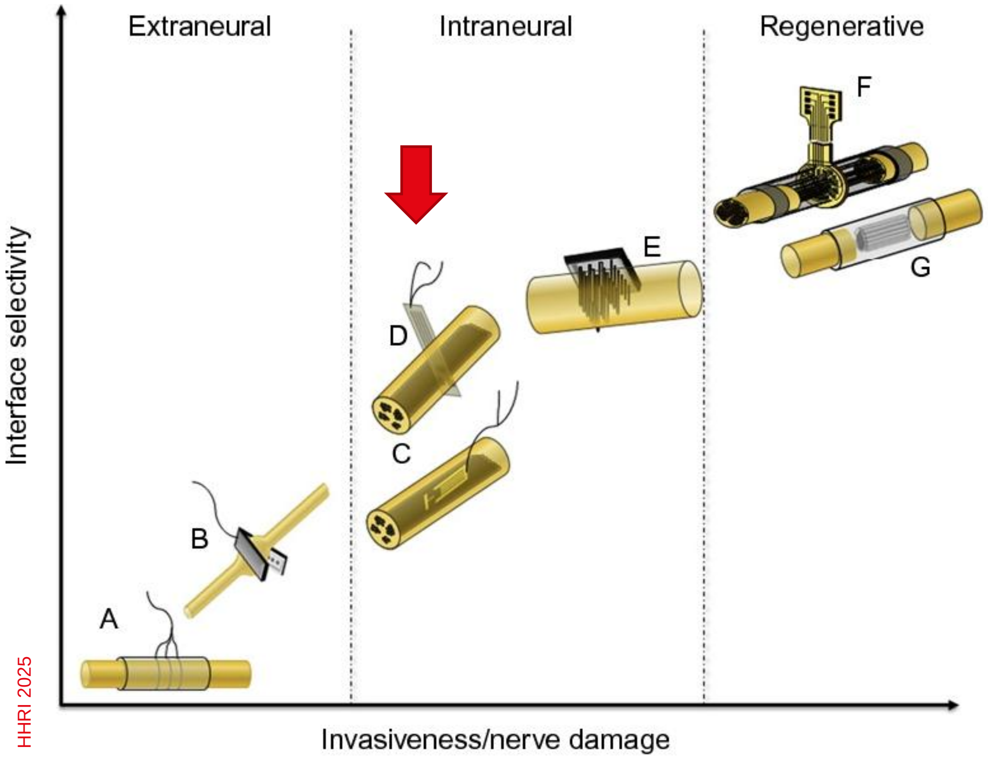




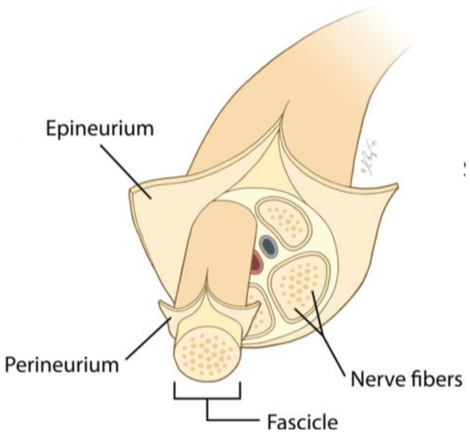
Improvement in a functional task when sensory feedback was present.

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



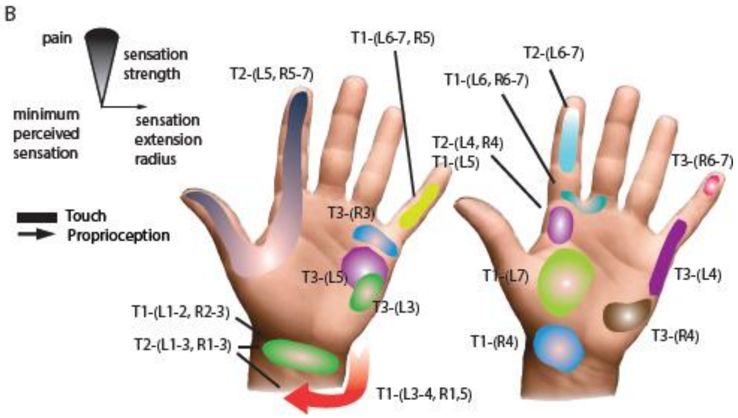
Transverse Intrafascicular
Multichannel Electrode (TIME)

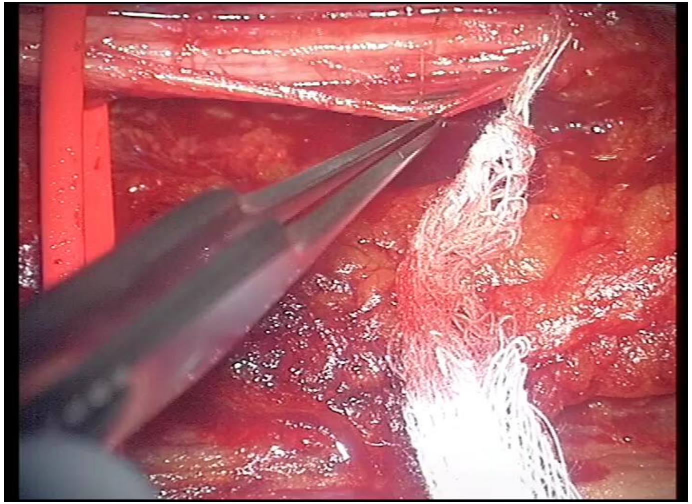


Boretius, T., Badia, J., Pascual-Font, A., Schuettler, M., Navarro, X., Yoshida, K., & Stieglitz, T. (2010). A transverse intrafascicular multichannel electrode (TIME) to interface with the peripheral nerve. Biosensors and Bioelectronics, 26(1), 62-69.

Bidirectional neuro controlled hand prostheses

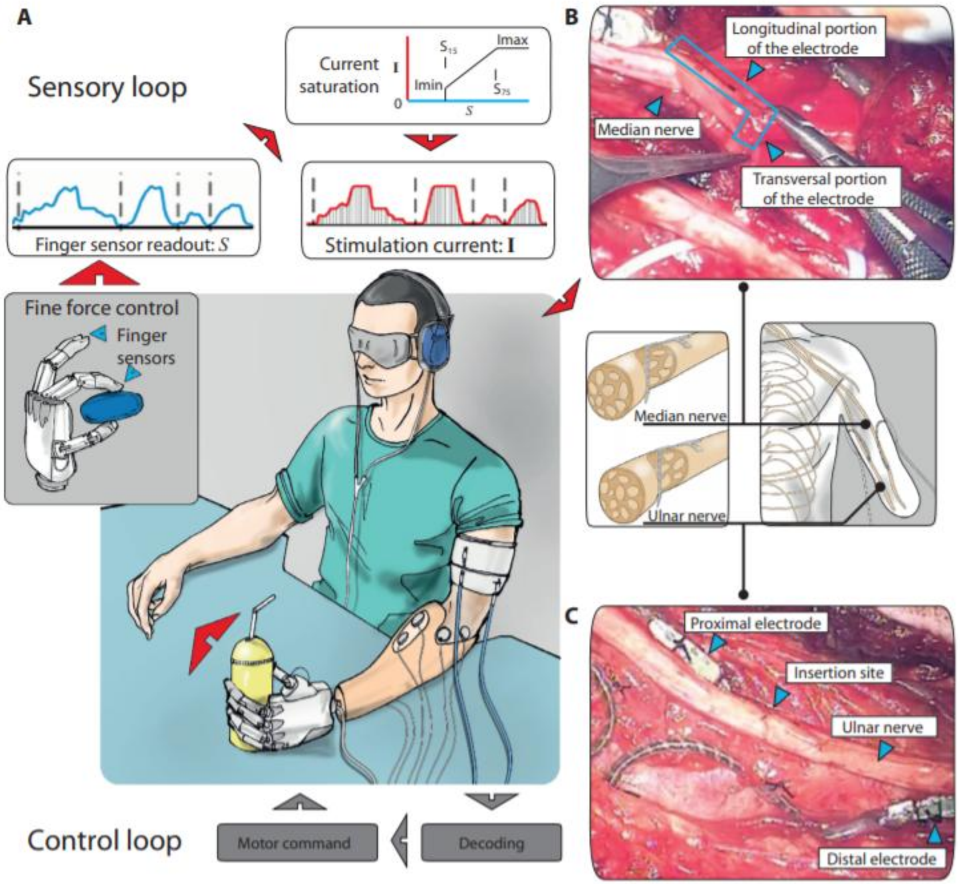
- Four week implant in a 35-year-old man, from Denmark with a trans-radial amputation in 2004 (fireworks accident)
- Two TIMEs in the median and two in the ulnar nerve





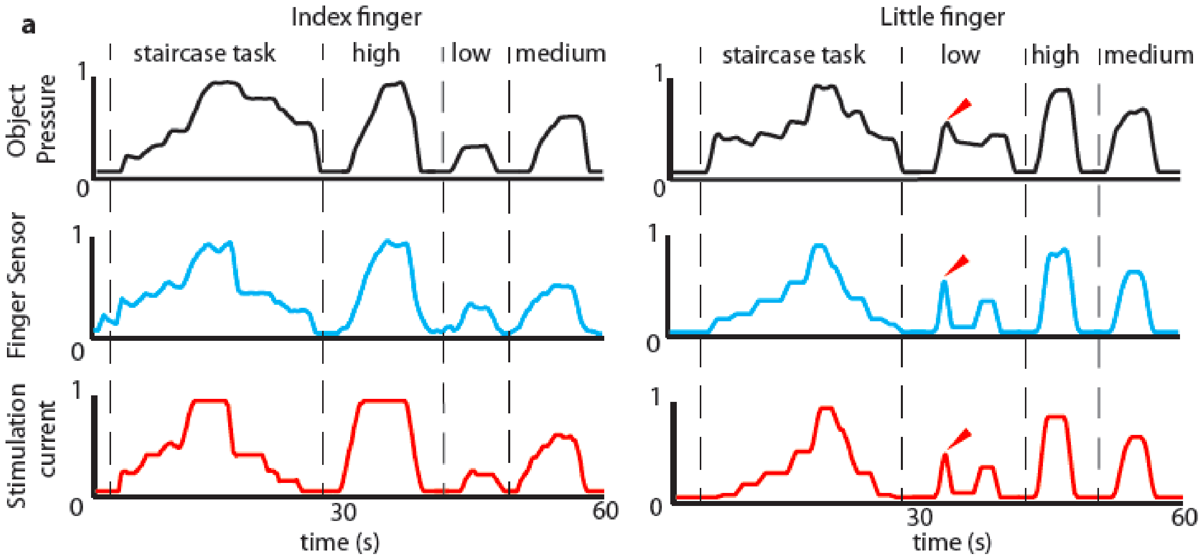
TIME electrodes

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.



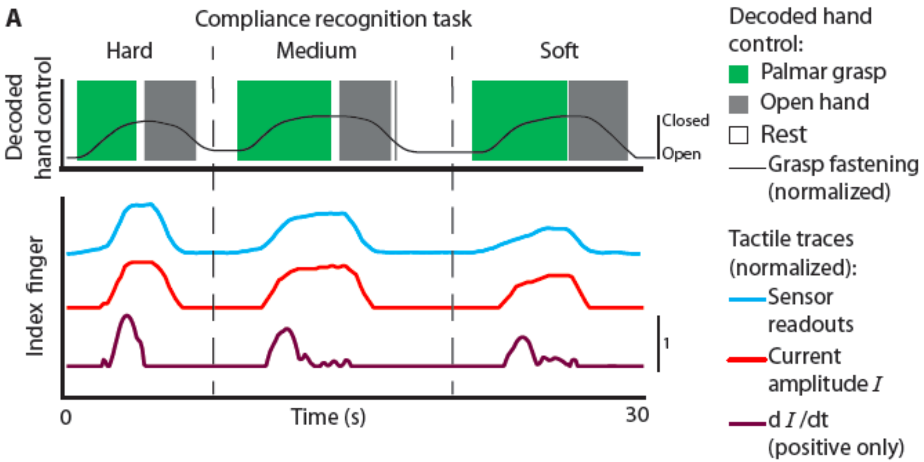
Test the possibility for the subject to use the sensory information during closed-loop control and manipulation experiments

Selection of grasping force levels

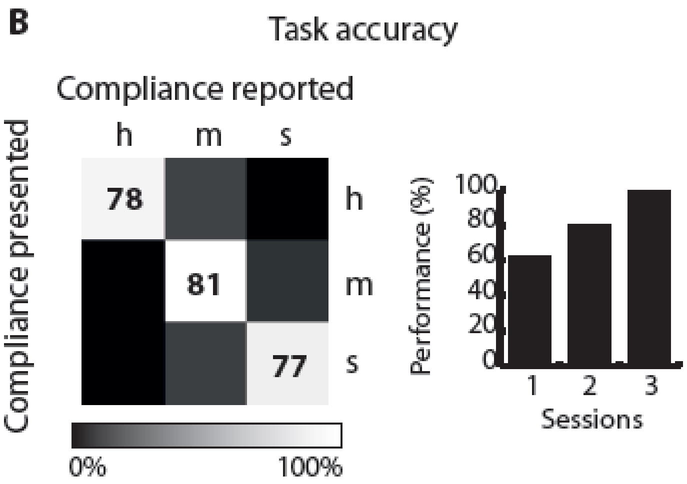


Raspopovic, S., Capogrosso, M., Petrini, F. M., Bonizzato, M., Rigosa, J., Di Pino, G., ... & Micera, S. (2014). Restoring natural sensory feedback in real-time bidirectional hand prostheses. Science translational medicine, 6(222), 222ra19-222ra19.

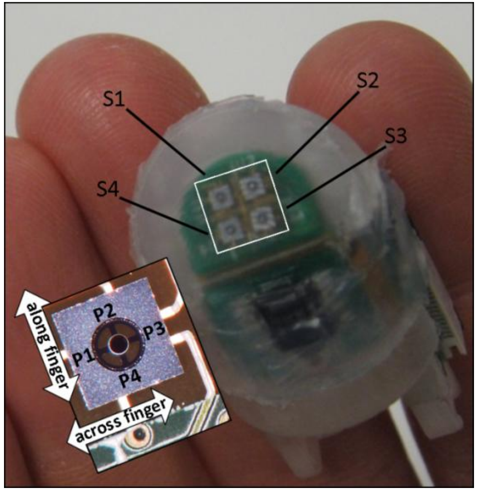
Compliance recognition

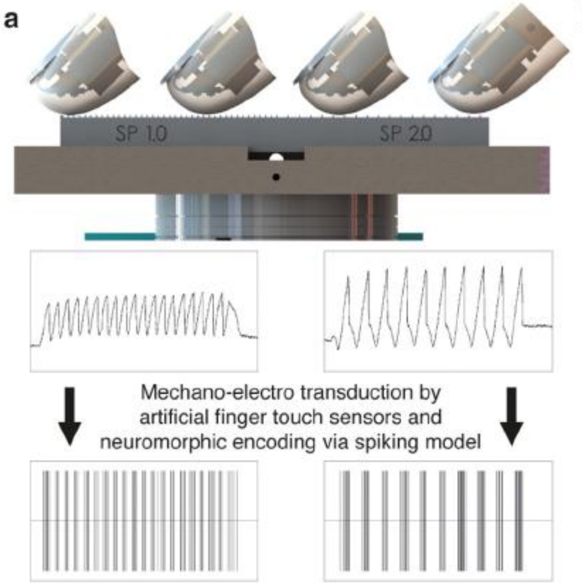


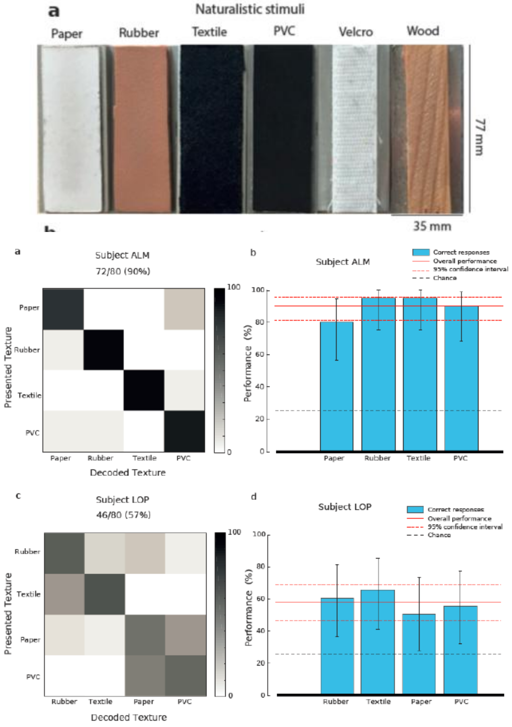
Three objects with different stiffness properties



Detecting texture via FA-type stimulation

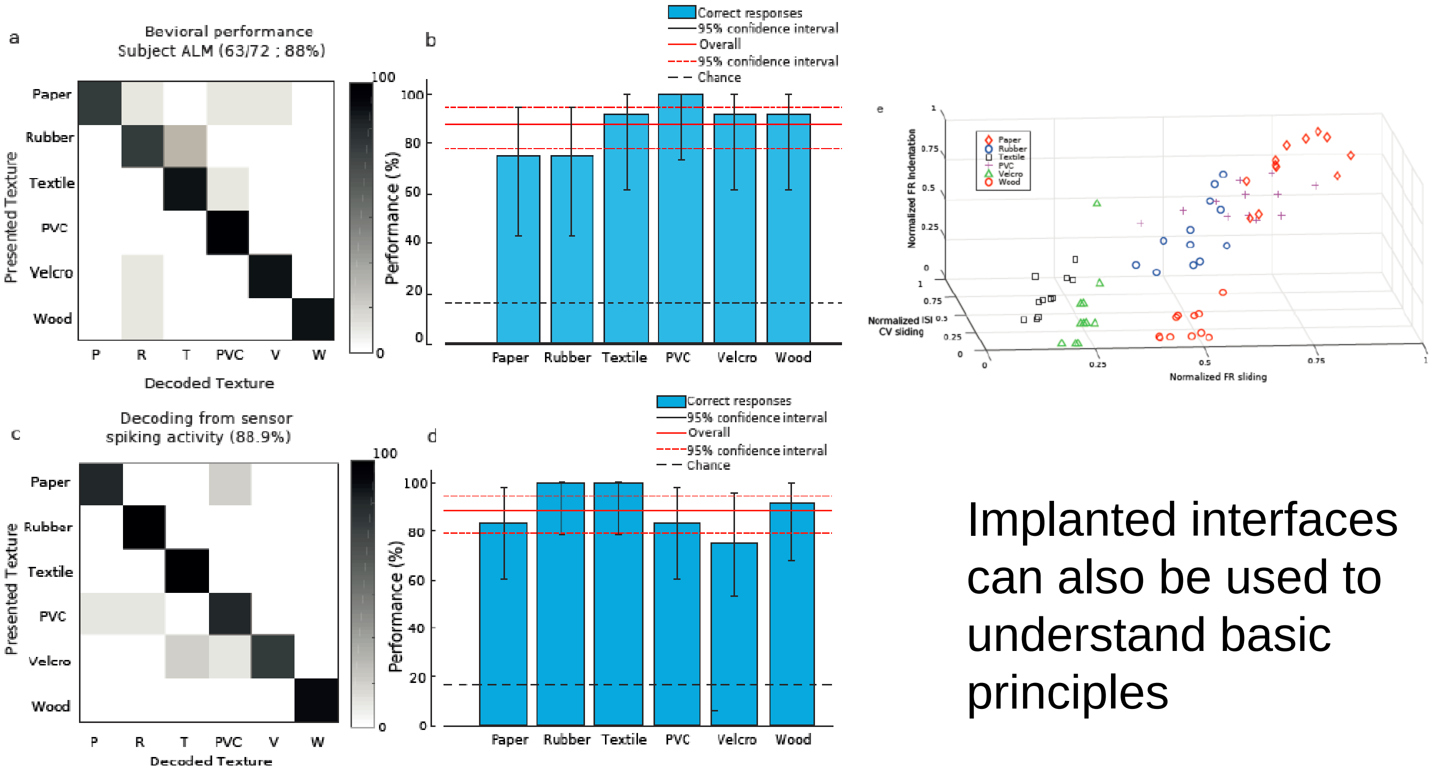






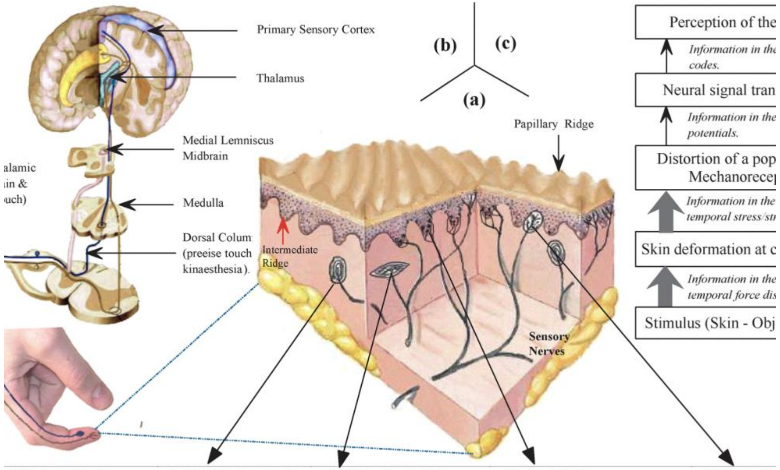
Oddo, C. M., Raspopovic, S., Artoni, F., Mazzoni, A., Spigler, G., Petrini, F., ... & Micera, S. (2016). Intraneural stimulation elicits discrimination of textural features by artificial fingertip in intact and amputee humans. elife, 5, e09148.

Restoring detection of real textures



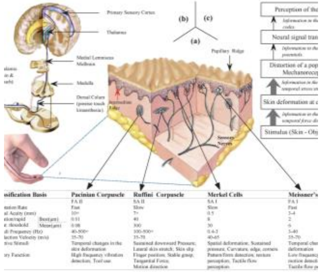
Implanted interfaces can also be used to understand basic principles

Human touch system



ssification Basis		Pacinian Corpuscle	Ruffini Corpuscle	Merkel Cells	Meissner's
		FA II	SA II	SA I	FA I
tation Rate		Fast	Slow	Slow	Fast
al Acuity (mm)		10+	7+	0.5	3-4
ation/rapid	Best(μm)	0.01	40	8	2
it. threshold	Mean(μm)	0.08	300	30	6
uli Frequency (Hz)		40-500+	100-500+	0.4-3	3-40
luction Velocity (m/s)		35-70	35-70	40-65	35-70
tive Stimuli		Temporal changes in the skin deformation	Sustained downward Pressure; Lateral skin stretch; Skin slip.	Spatial deformation; Sustained pressure; Curvature, edge, corners.	Temporal char deformation
ory 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 motion detecti Tactile flow pe

Biomimetic encoding strategy



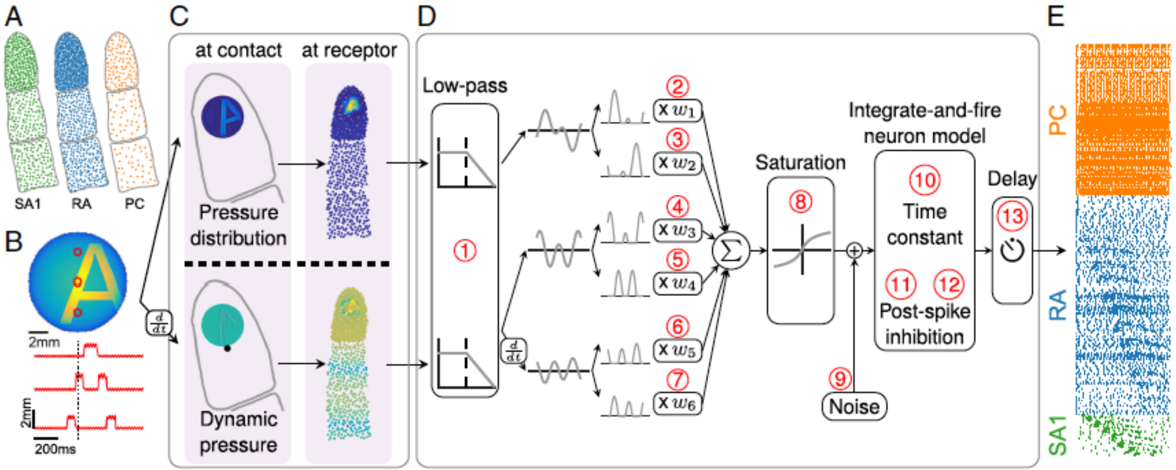
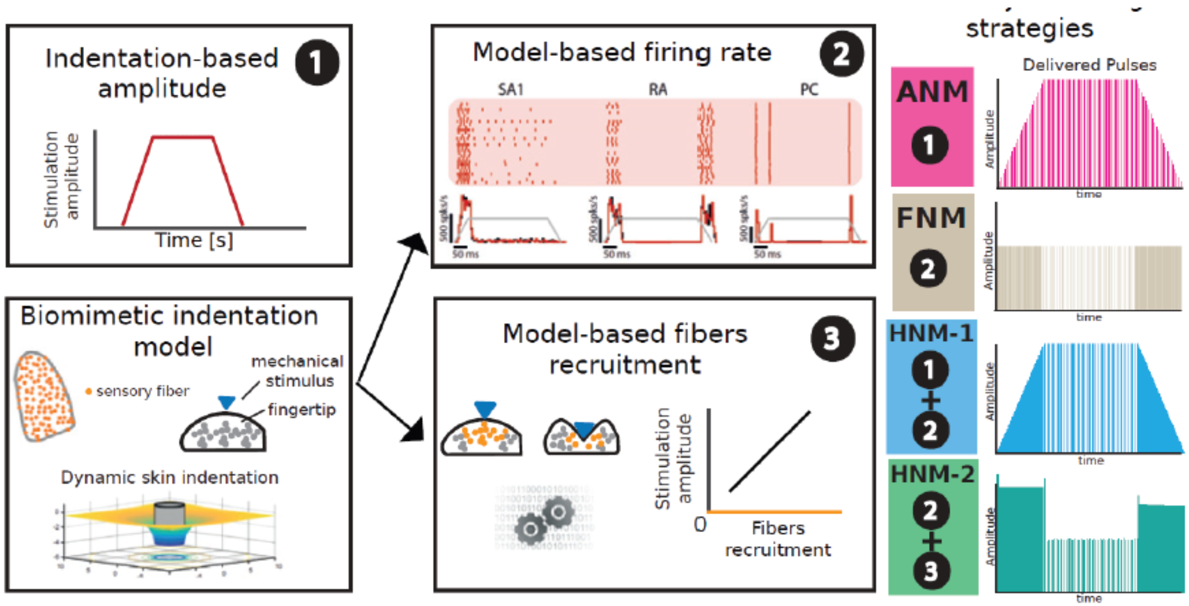


Fig. 1. Overview of the model. (*A*) Receptors are distributed across the skin given the known innervation densities of SA1, RA, and PC afferents. (*B*) The stimulus—in this case, a vibrating embossed letter A scanned across the skin—is defined as the time-varying depth at which each small patch of skin (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.

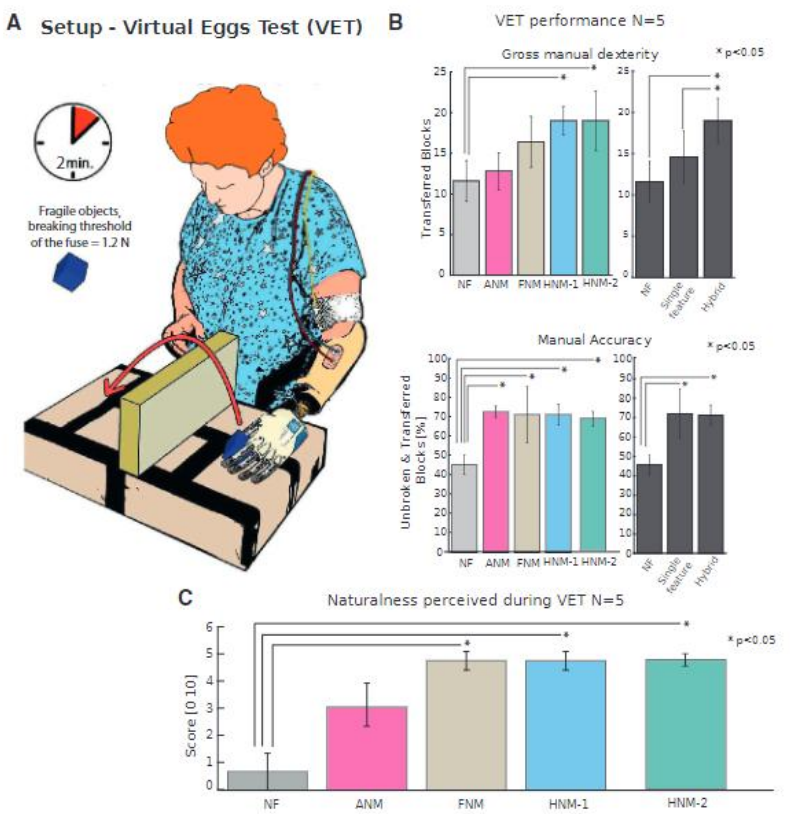
Saal et al., PNAS, 2017

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.

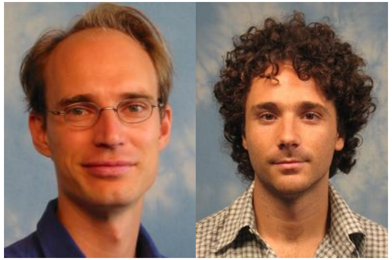
Biomimetic encoding strategy



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

The biomimetic approaches were judged more natural

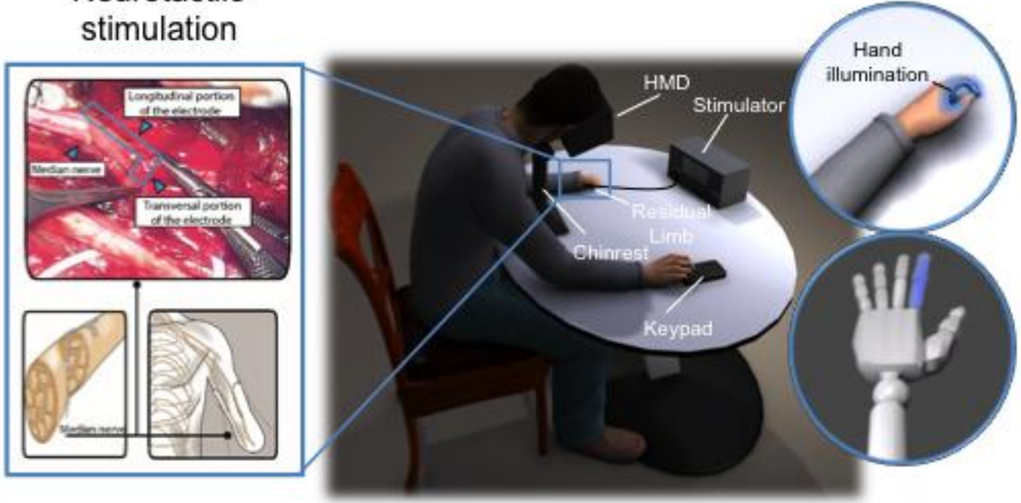
Embodiment



O. Blanke G. Rognini

Illumination and virtual stimuli as shown on HMD

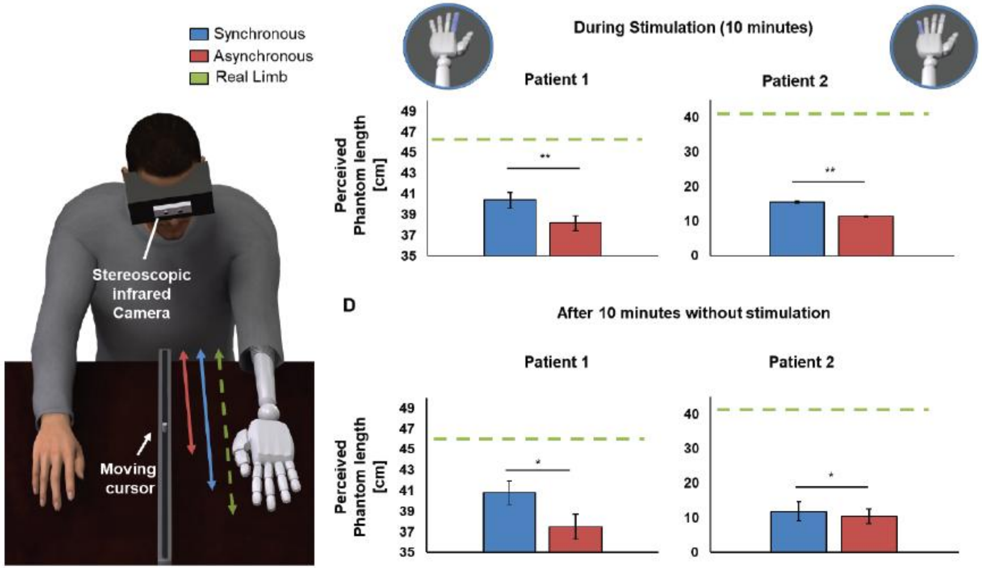
Neurotactile stimulation



Patient 1 (artificial hand)

Patient 2 (prosthetic hand)

Sensory feedback

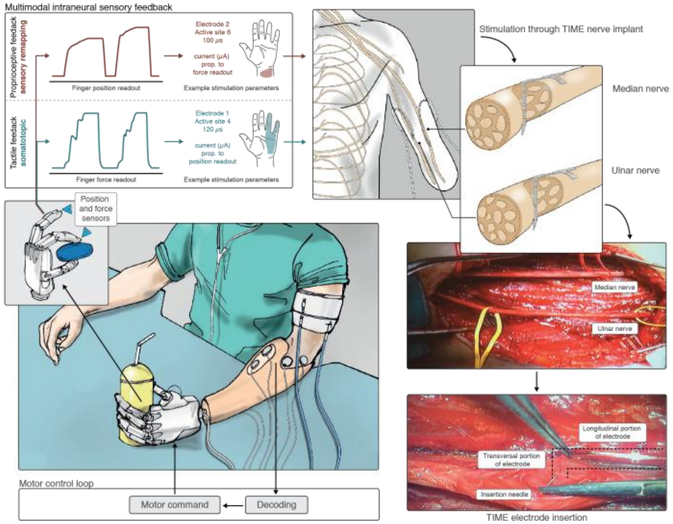


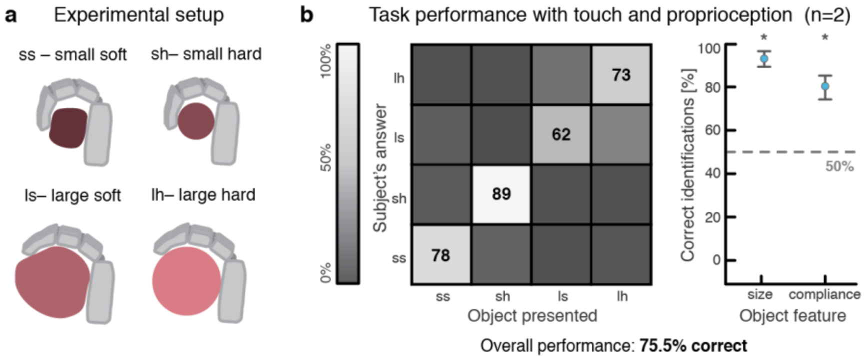
Synchronous Tactile feedback (via intraneural stimulation) and Visual feedback (illumination of the region corresponding to phantom touch) feedback increased prosthesis embodiment and reduced the telescoping effect (perception that limb is shorter).

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

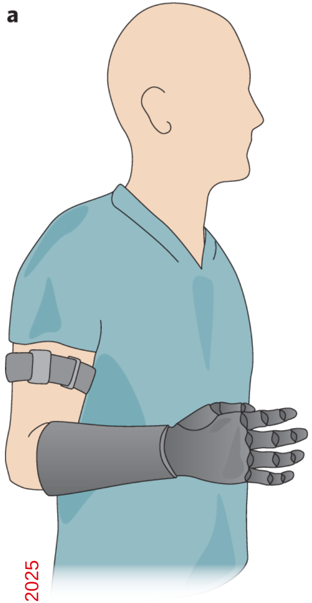
“Multimodal” sensory feedback

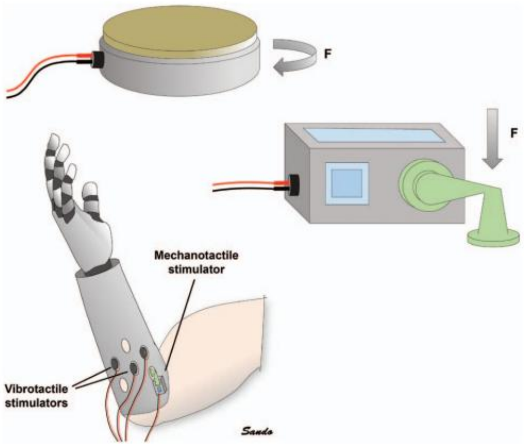


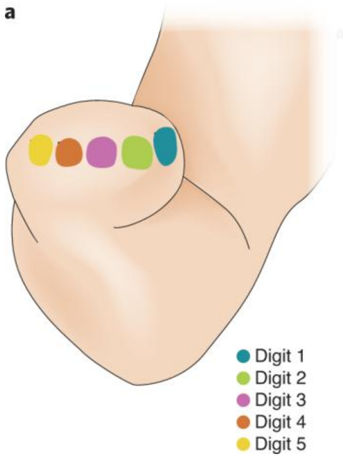


D’Anna, Edoardo, et al. "A closed-loop hand prosthesis with simultaneous intraneural tactile and position feedback." Science Robotics 4.27 (2019): eaau8892.

Tactile feedback via non-invasive solutions

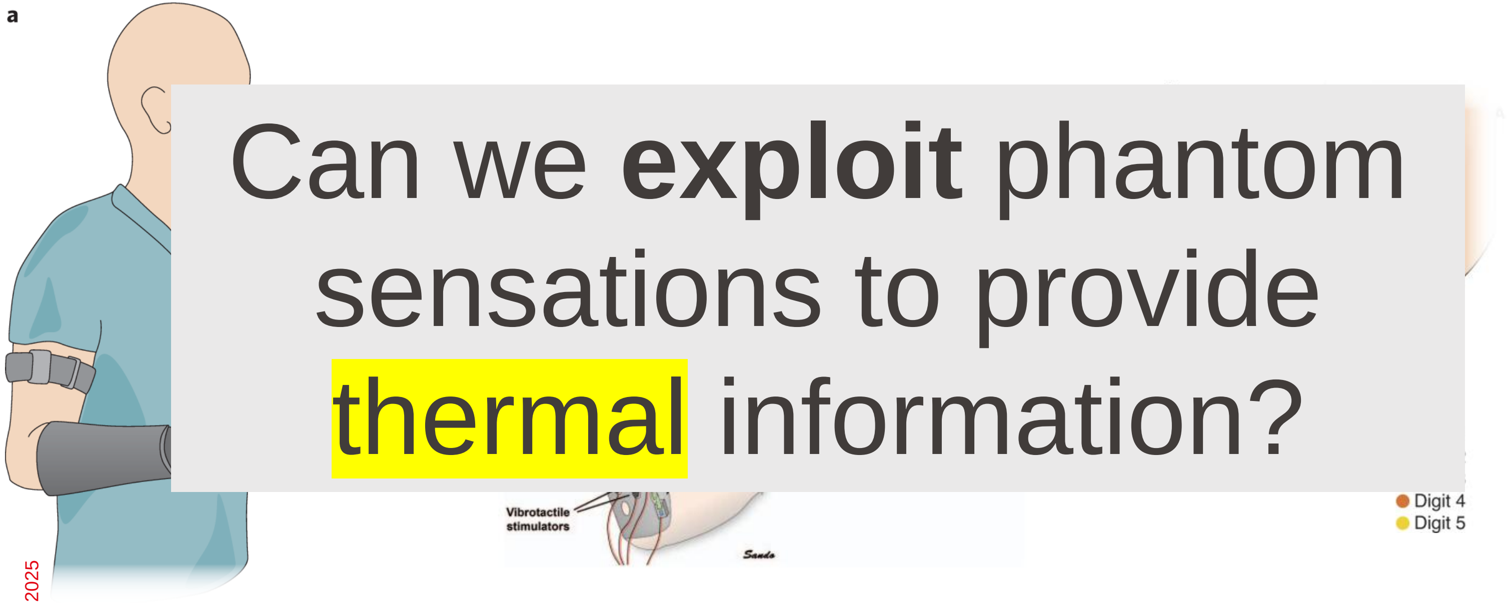






Bensmaia, S. J., Tyler, D. J., & Micera, S. (2020). Restoration of sensory information via bionic hands. Nature Biomedical Engineering, 1-13.

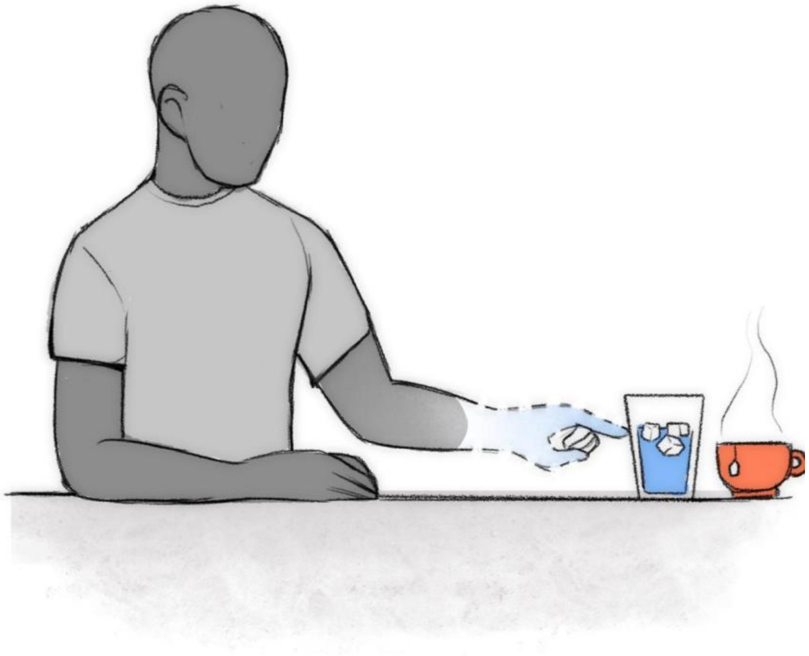
Tactile feedback via non-invasive solutions



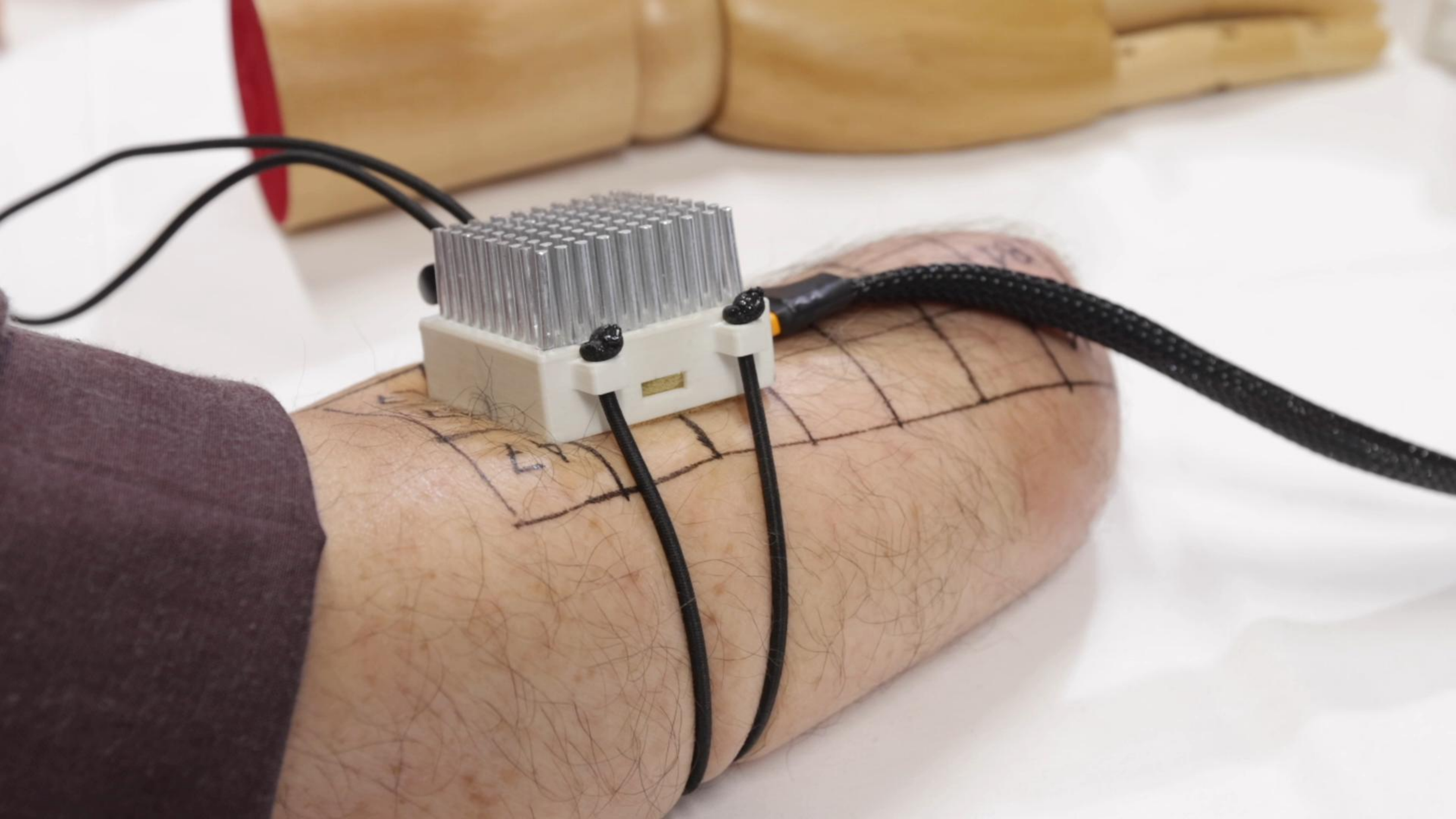
Can we **exploit** phantom sensations to provide thermal information?

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

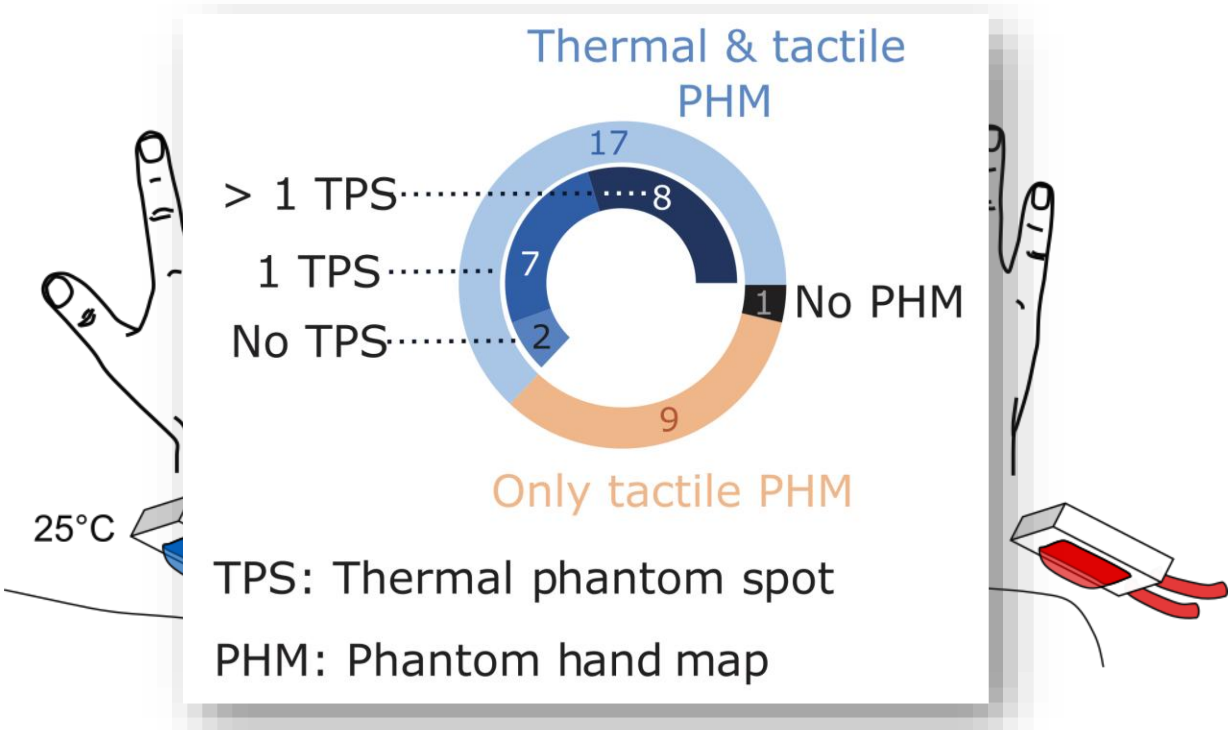
Why thermal feedback?



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

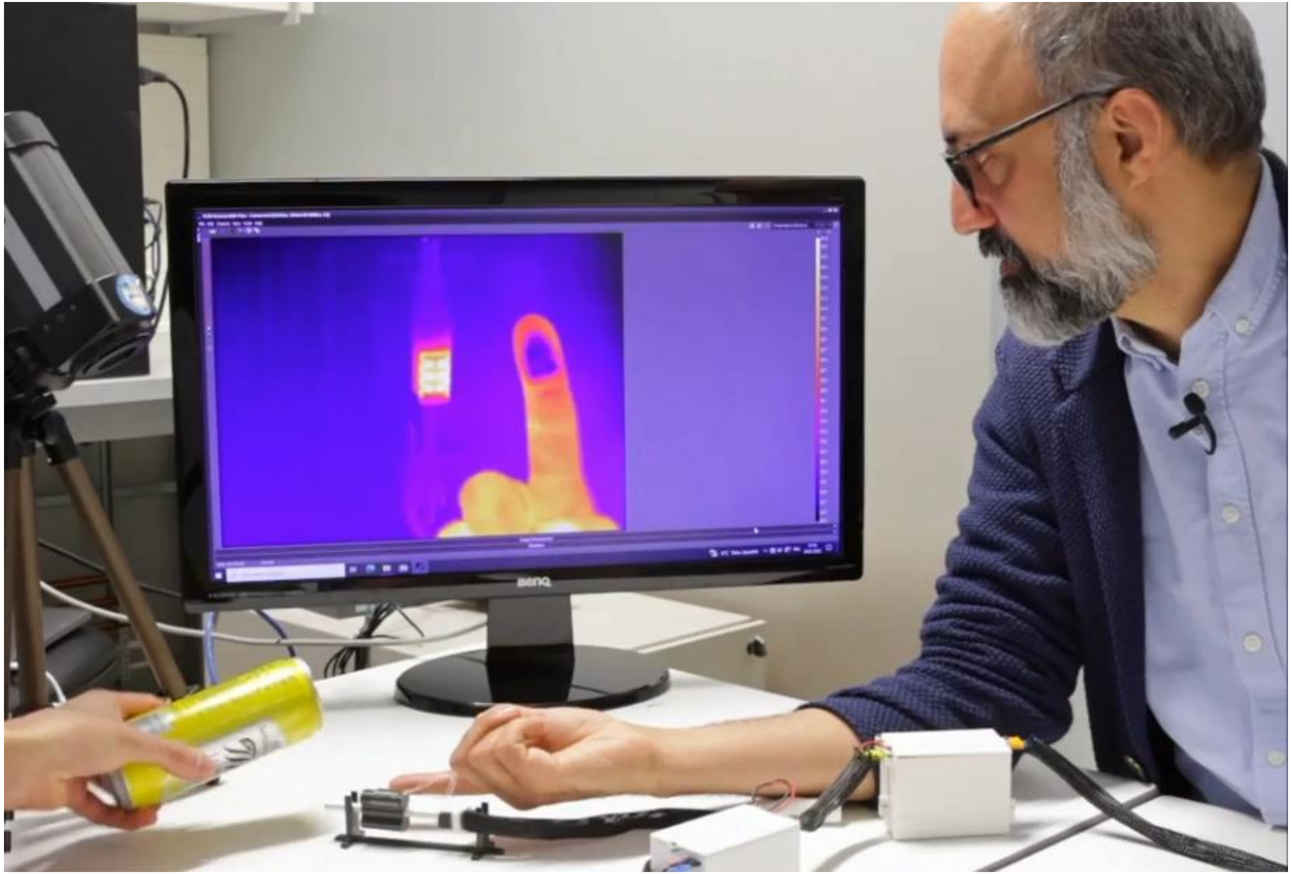


Phantom tactile and thermal maps



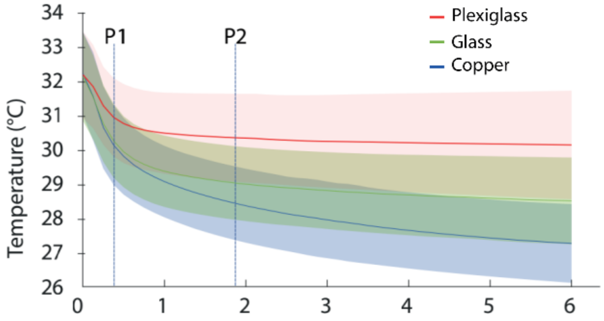
F. Iberite, J. Muheim, O. Akouissi, S. Gallo, G. Rognini, F. Morosato, A. Clerc, M. Kalff, E. Gruppioni, S. Micera*, S. Shokur*. Restoration of natural thermal sensation in upper-limb amputees (2023). Science.

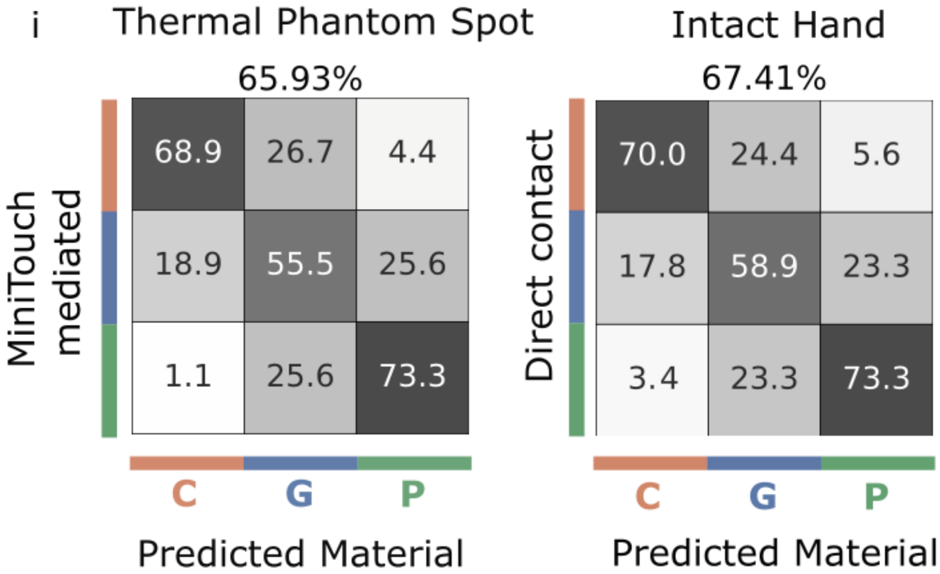
Wearable solution



Iberite et al. 2023

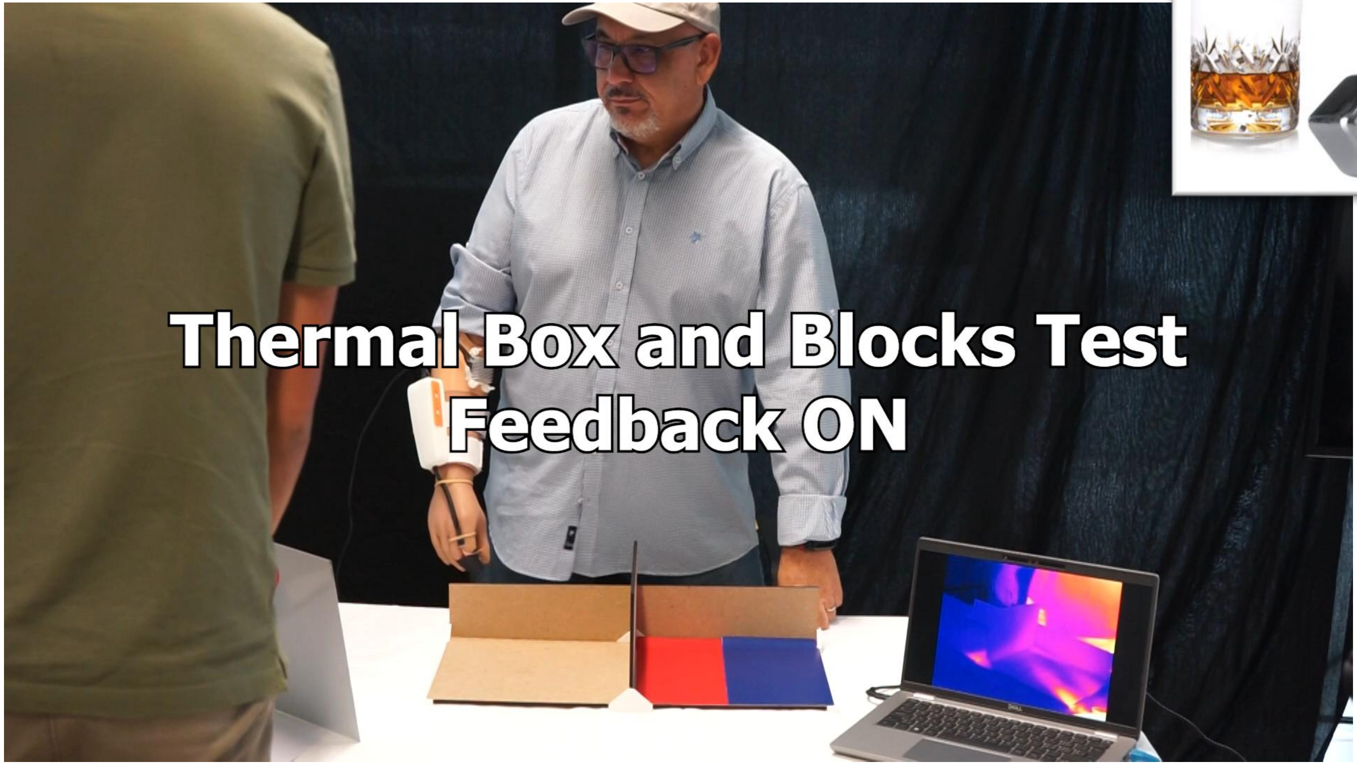
Material detection





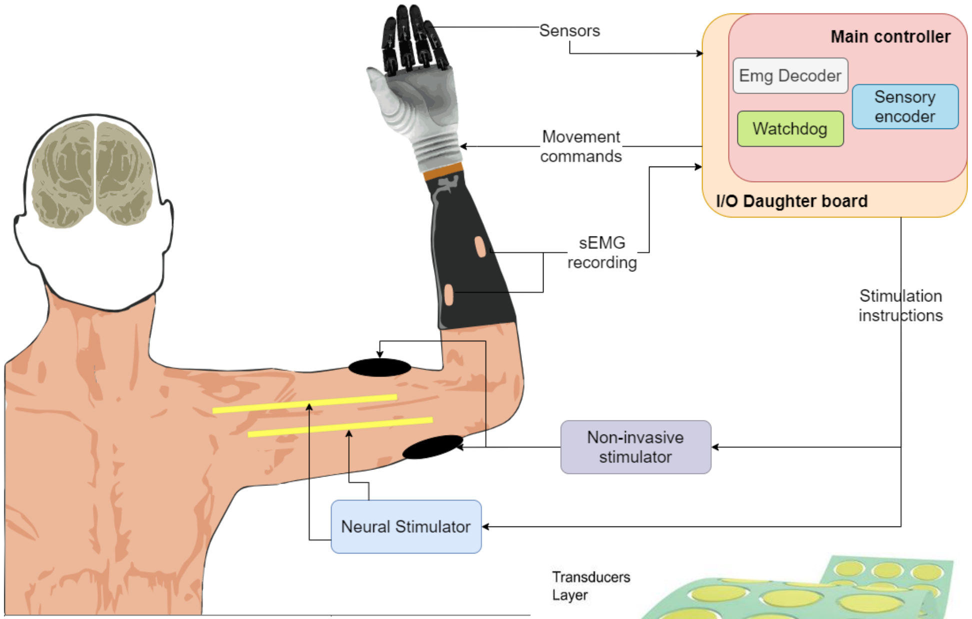
Iberite et al. 2023

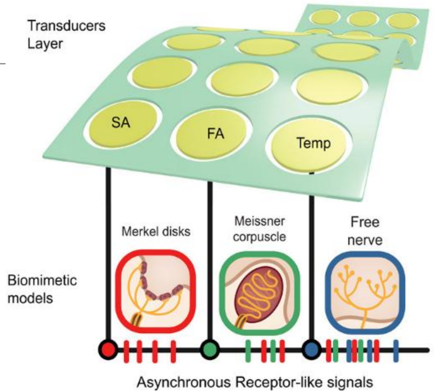
Sensory motor tasks with real-time feedback

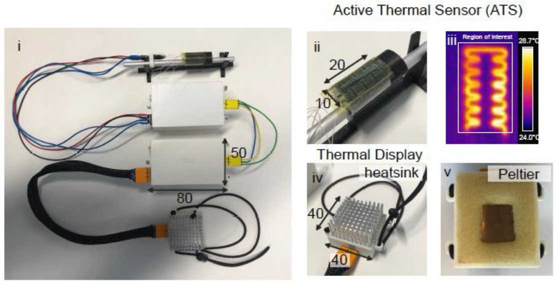


Muheim et al. 2024

NEXT STEP – Going chronic at home

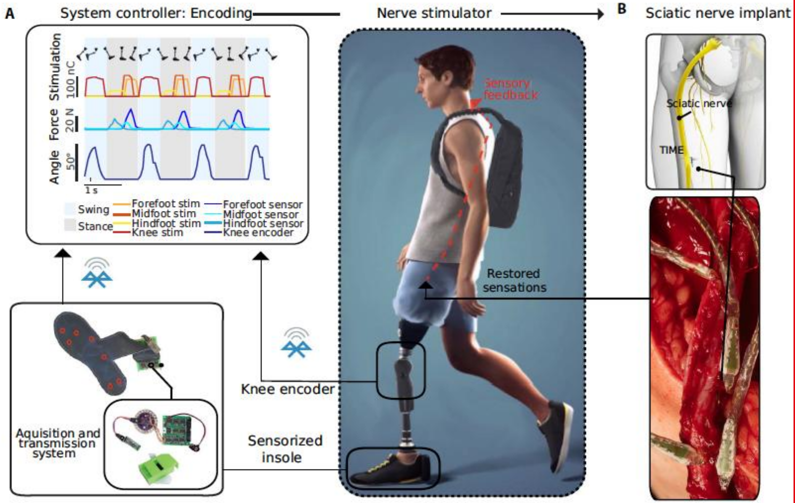




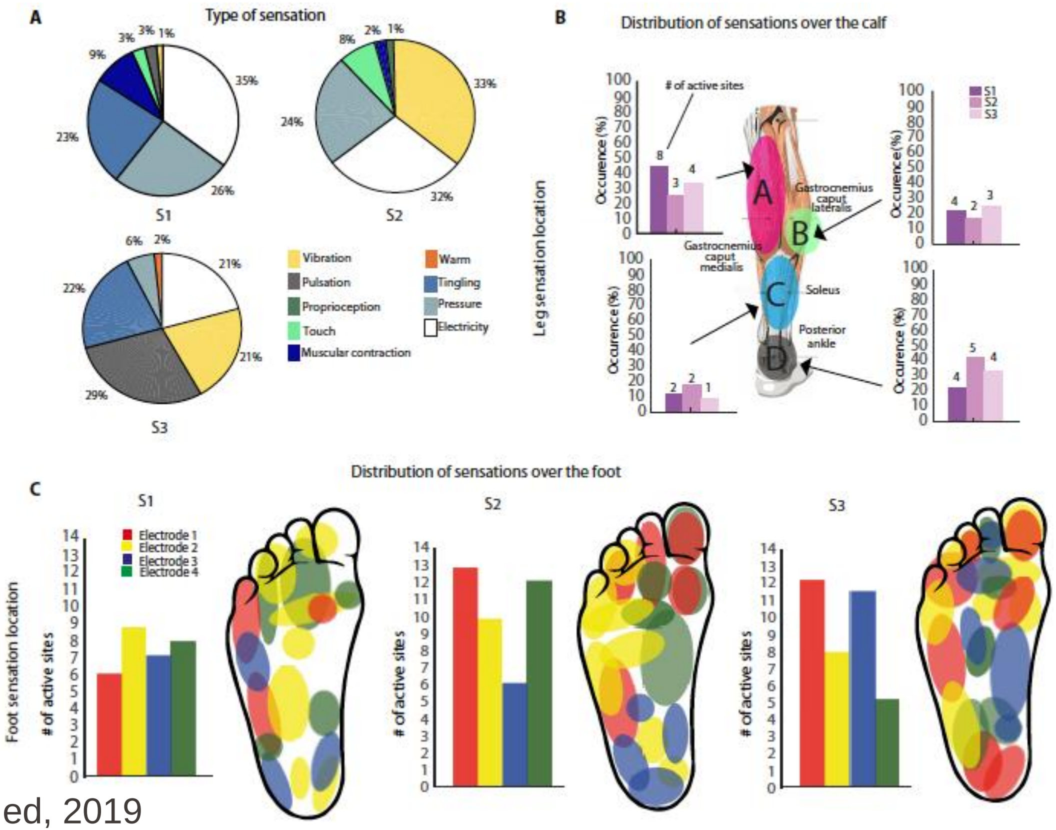


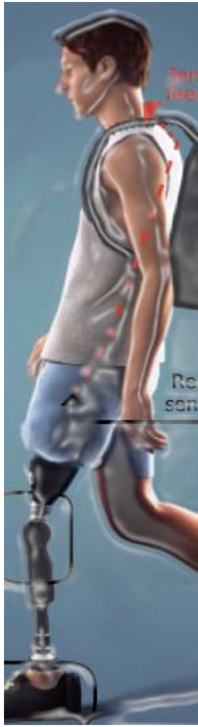
EPFL

Lower limb bionics



Bidirectional neurocontrolled leg prostheses
Sensory feedback



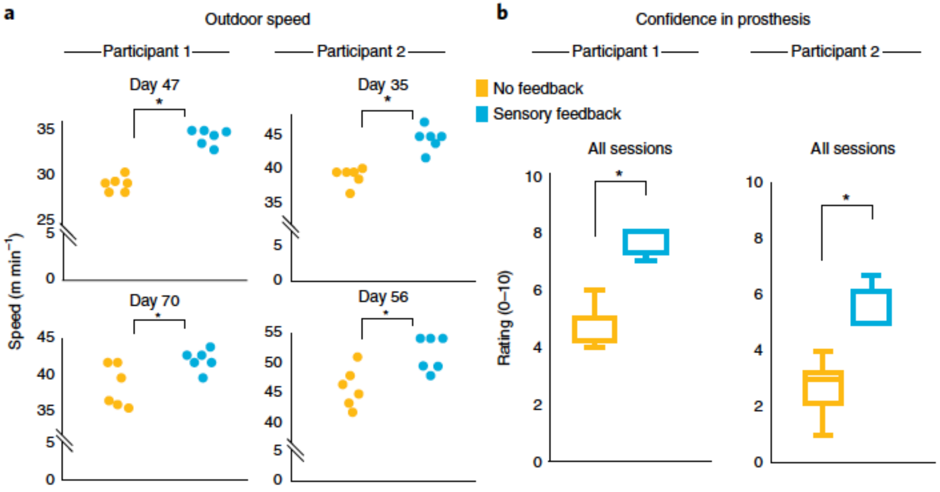


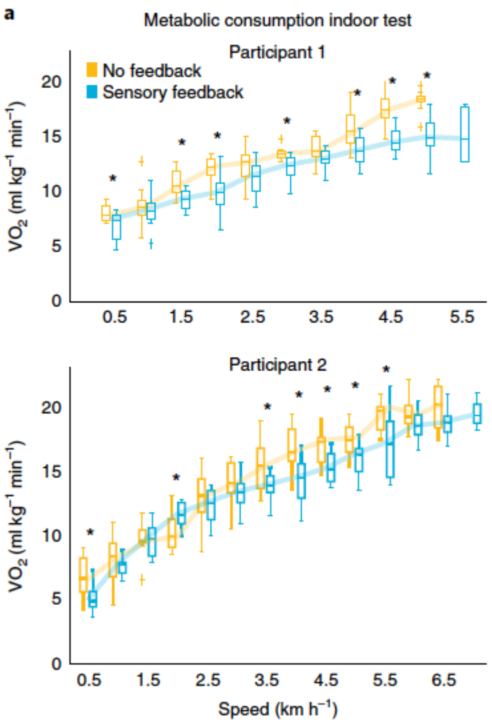
Petrini et al.,
Science Trans Med, 2019

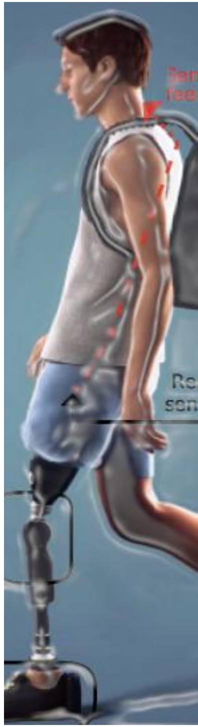
EPFL

Bidirectional neurocontrolled leg pro

Sensory feedback







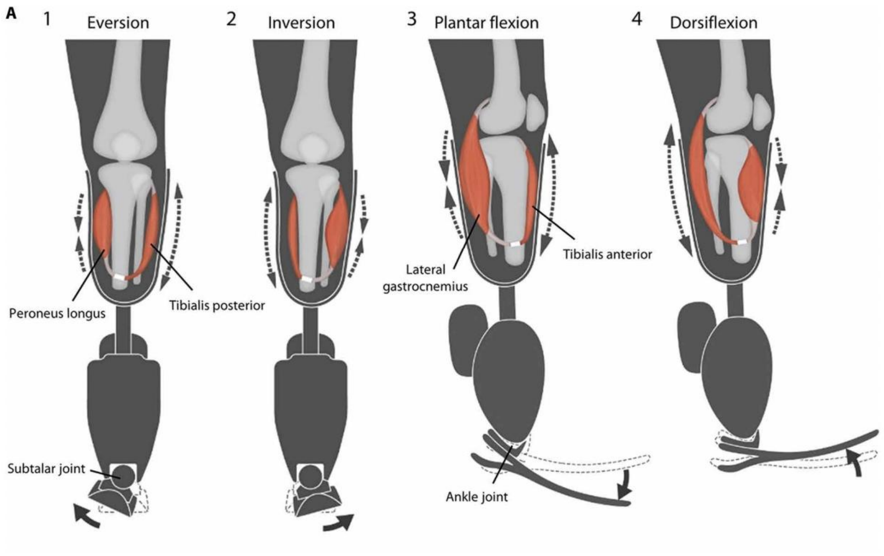
Walking speed and self-reported confidence increased while mental and physical fatigue decreased for both participants

Participants exhibited reduced phantom limb pain with neural sensory feedback.

Petrini et al., Nature Medicine, 2019

Agonist-antagonist myoneural interface

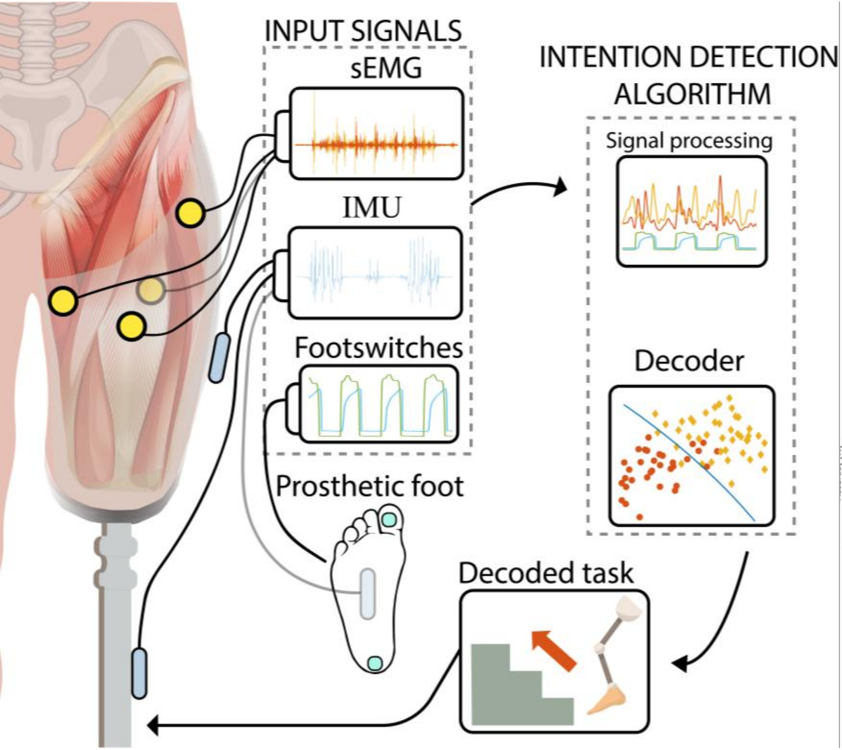
- As a methodology of improving efferent (neural pathways that relay commands from the central nervous system to a muscle or other end organ) prosthetic control and providing afferent proprioceptive sensation, we present an agonist-antagonist myoneural interface (AMI)
- An AMI is made up of an agonist 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.

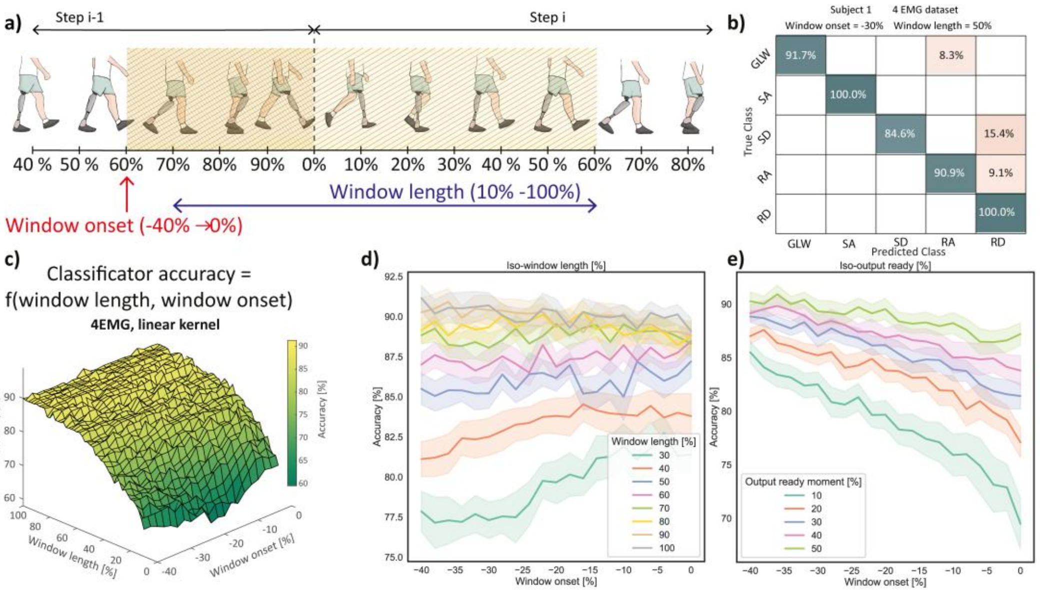


Clites et al., Science Trans Med, 2018

Bidirectional neurocontrolled leg prostheses

Bidirectional neurocontrolled leg prostheses





Bidirectional neurocontrolled leg prostheses
Sensory feedback