Bionic artificial limbs

Translational neuroengineering

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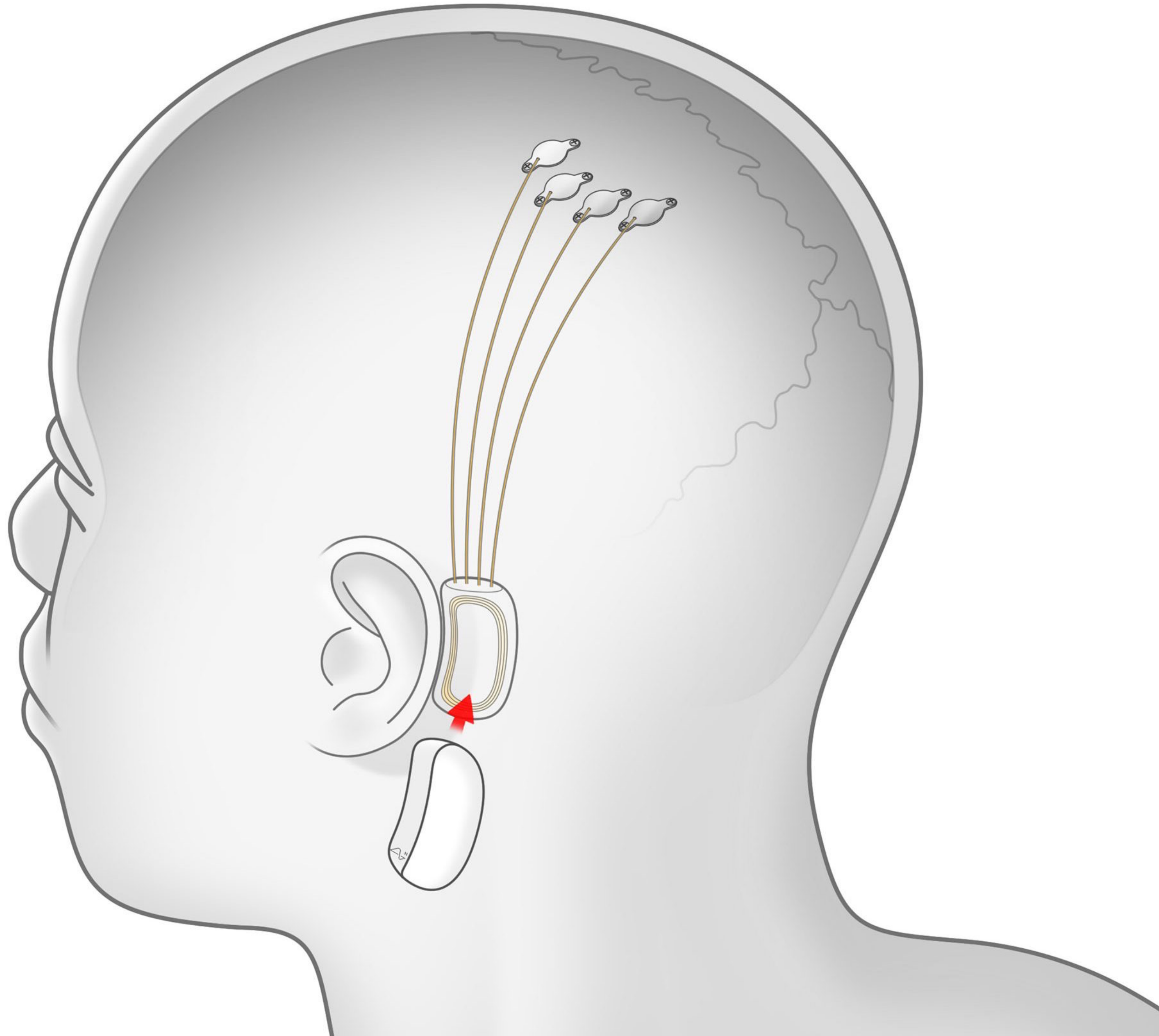
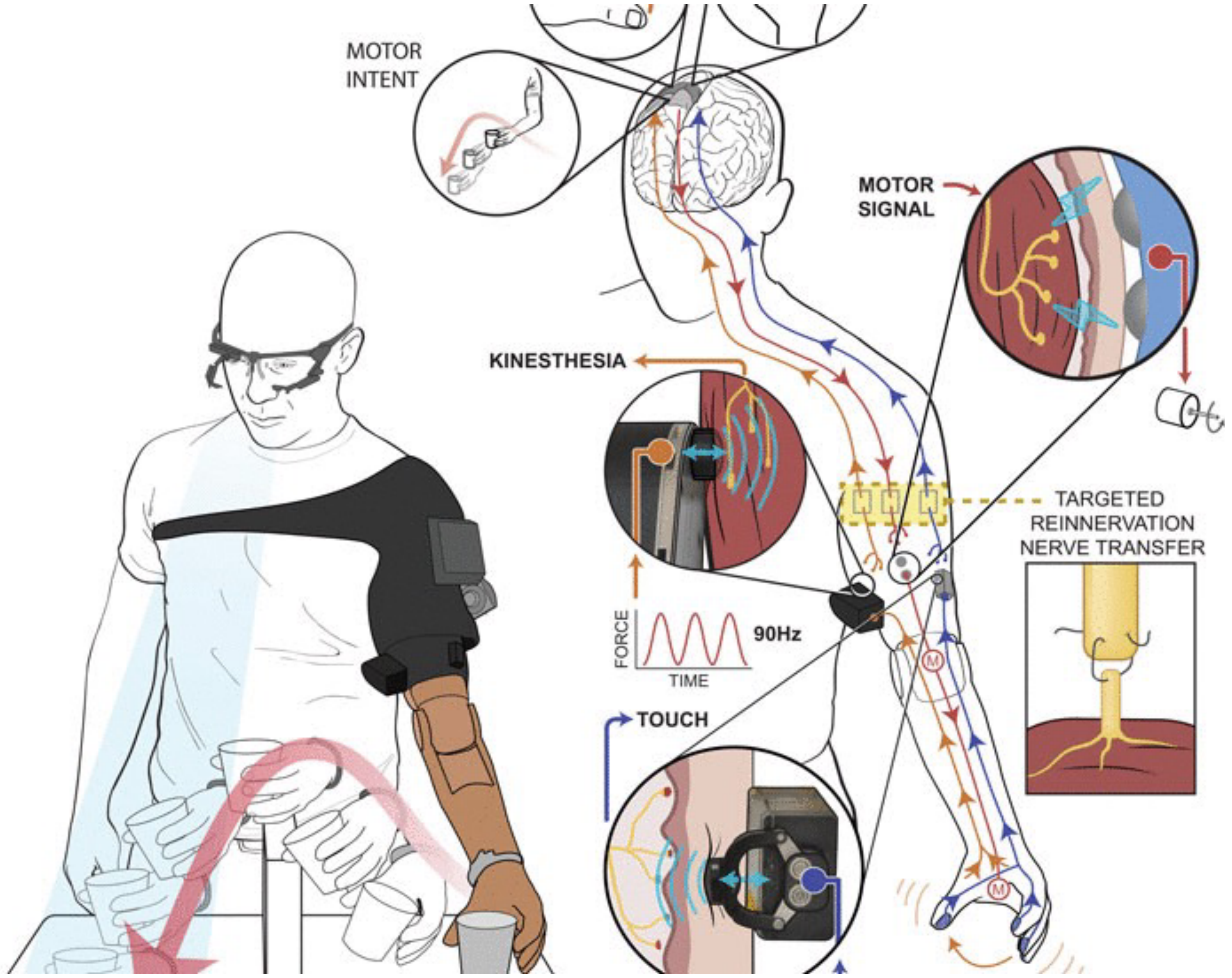
Translational NeuroEngineering




MOTOR
INTENT
MOTOR
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REINNERVATION
NERVE TRANSFER
FORCE
TIME
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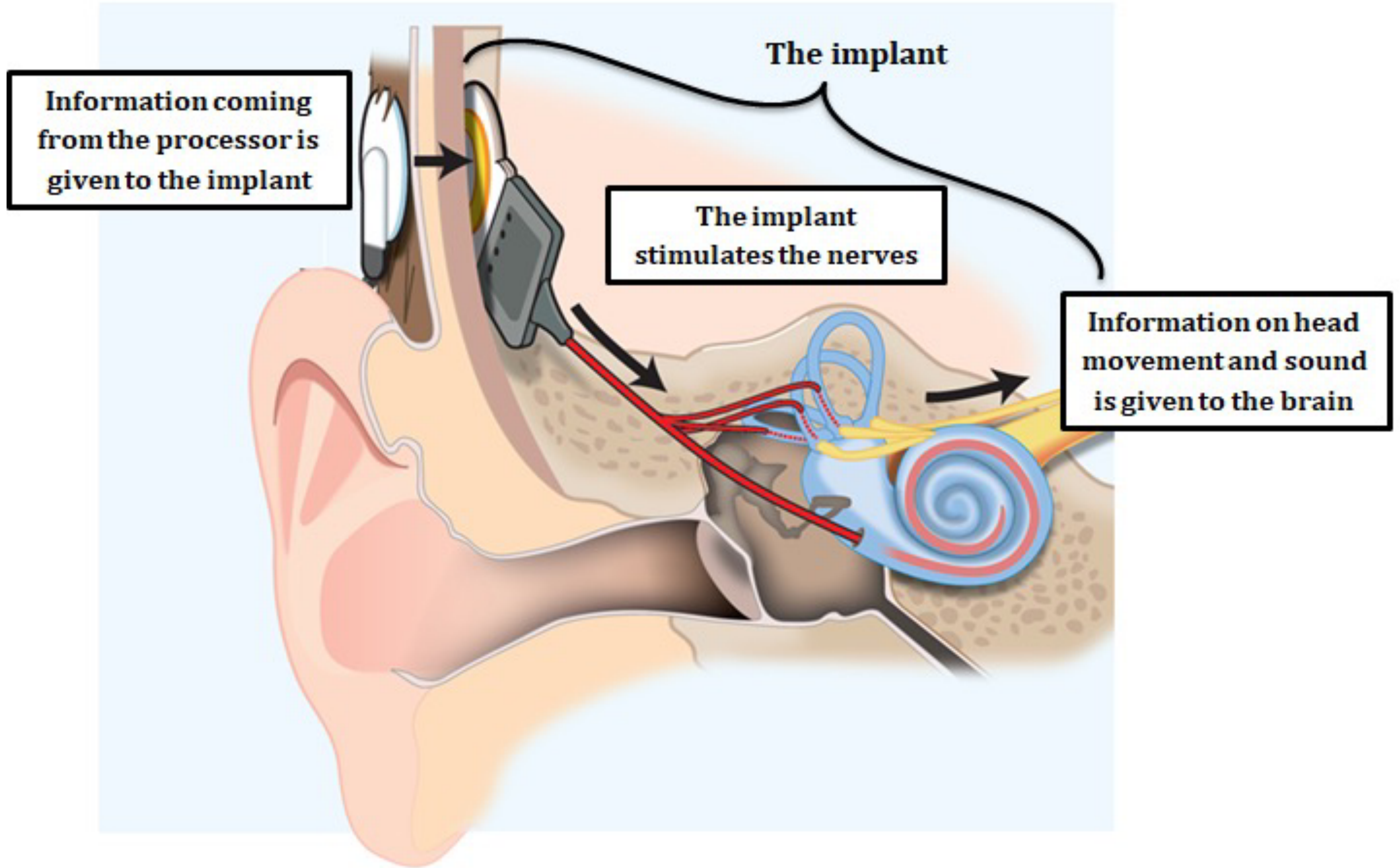
TOUCH


The implant
Information coming from the processor is given to the implant
The implant stimulates the nerves
Information on head movement and sound is given to the brain

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 in **sensing** through the sense of touch
- **Gesture** (communication)

Statistics

38% Transhumeral

31% Transradial

14% Partial hand

5% Fingers

…

…

1.7 million total number of amputees living in the U.S

65,000 upper limb amputations in the U.S. each year

27,000 hand amputation below the wrist in the U.S. each year

400 hand amputation below the wrist in Italy each year

Consequences

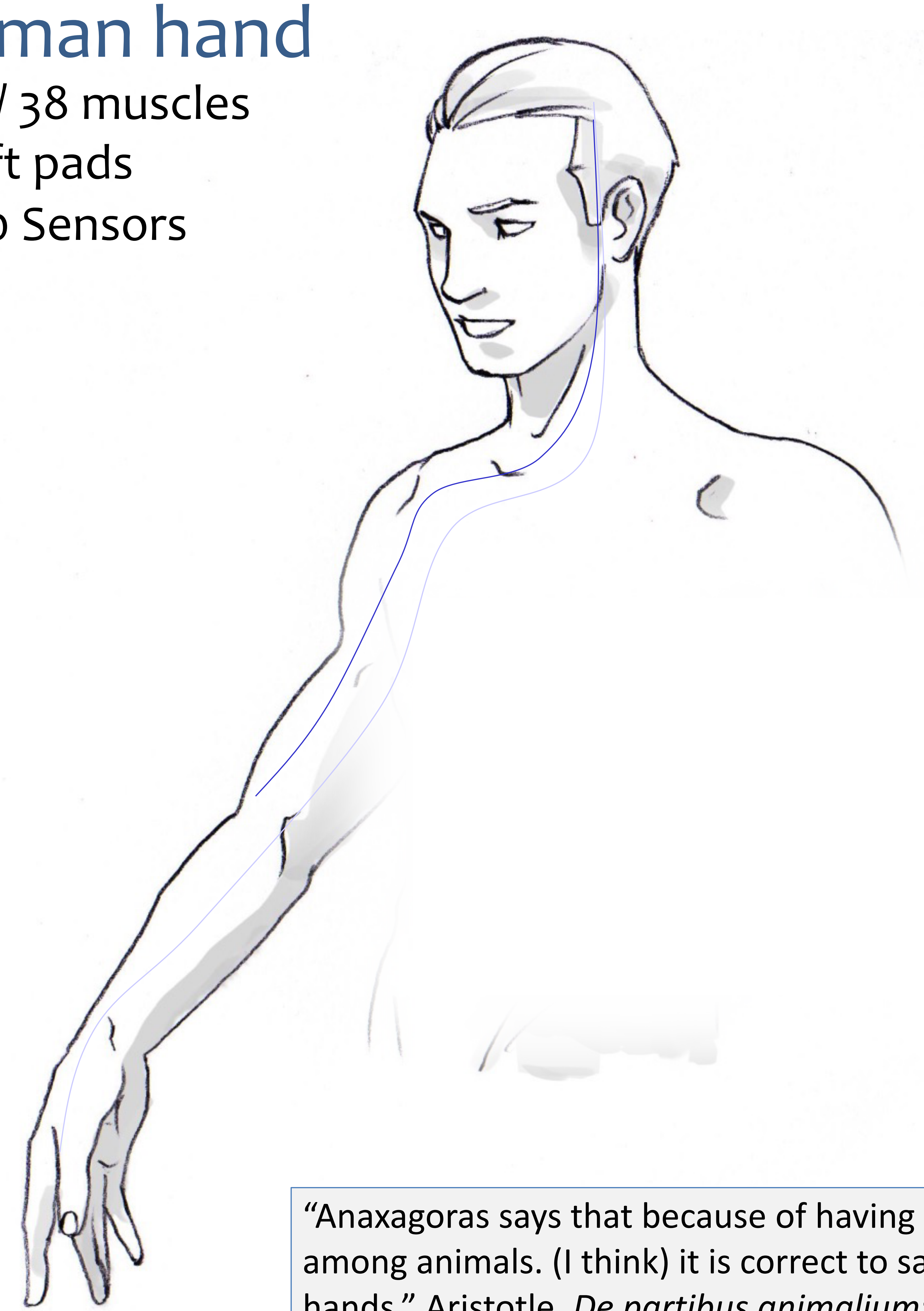
Few innovations in the past 50 years

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

The biological Model

The human hand

21 joints / 38 muscles
Soft pads
35000 Sensors



Action

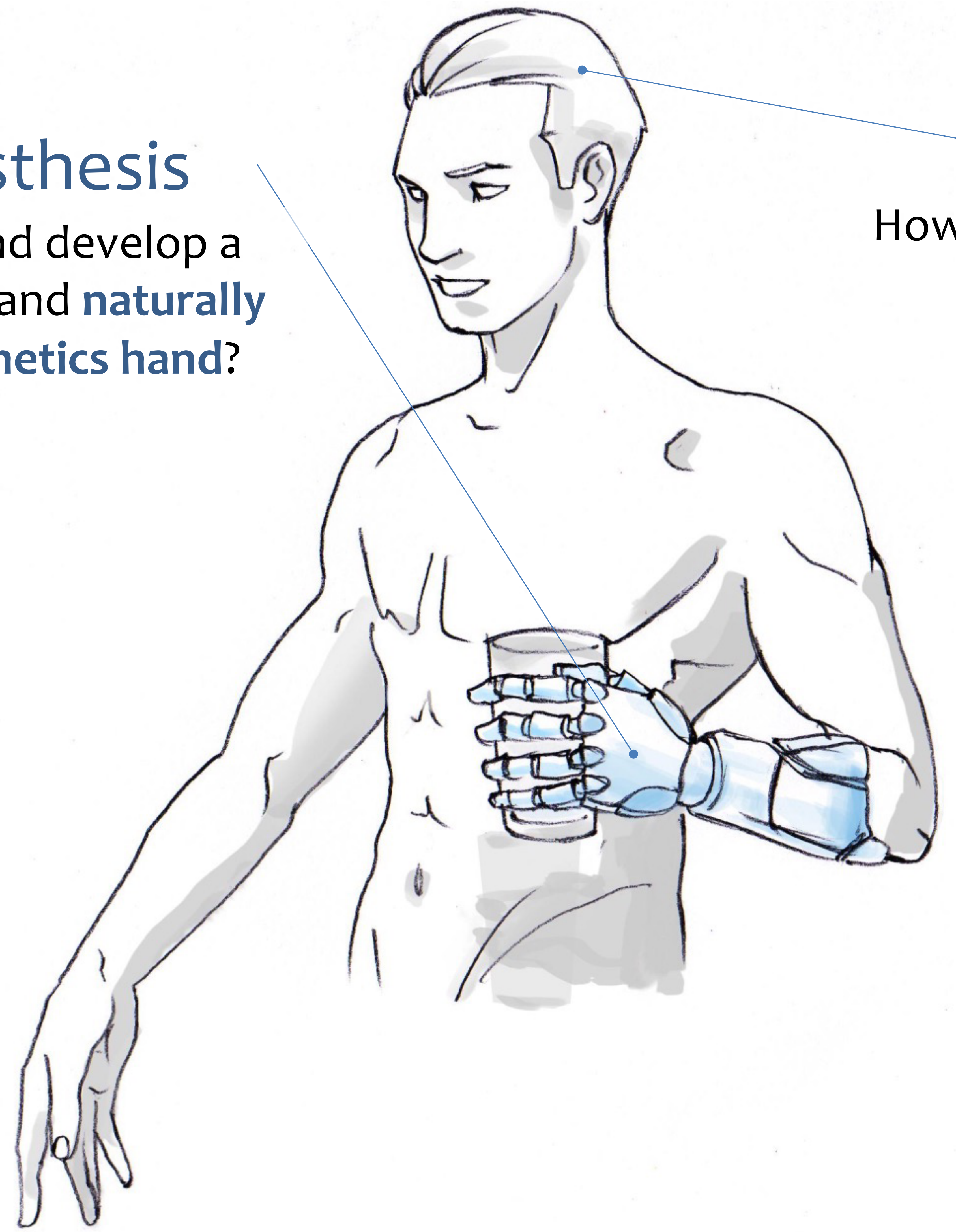
EEG – ENG - EMG

Sensation

Tactile perception
Proprioception
Pain
Temperature

"Anaxagoras says that because of having hands, man grew the most intelligent among animals. (I think) it is correct to say that because of his intelligence he has hands." Aristotle, *De partibus animalium*: 687a 7, ca. 340 BC.

The big challenges



Hand Prosthesis

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

Dexterity

Functionality

Reliability

…

…

UP Interface

How to **control** this dexterity?

Sources

Cognitive Effort

Reliability

…

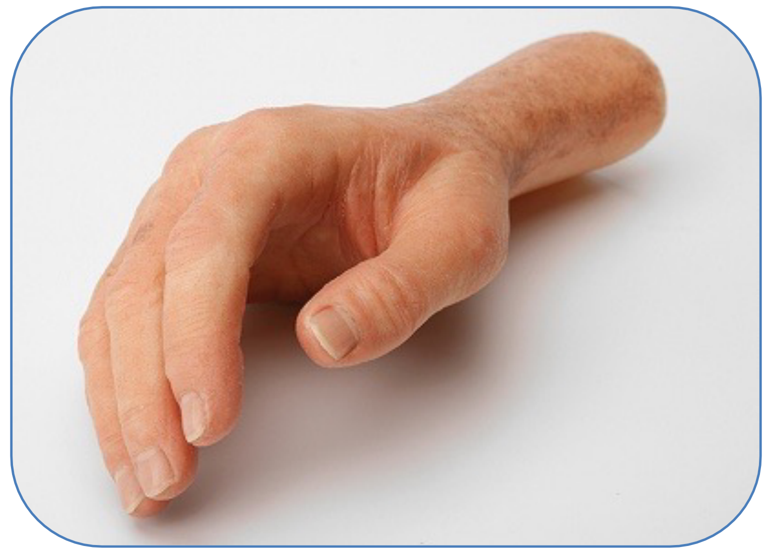
…

What can an amputee get today?

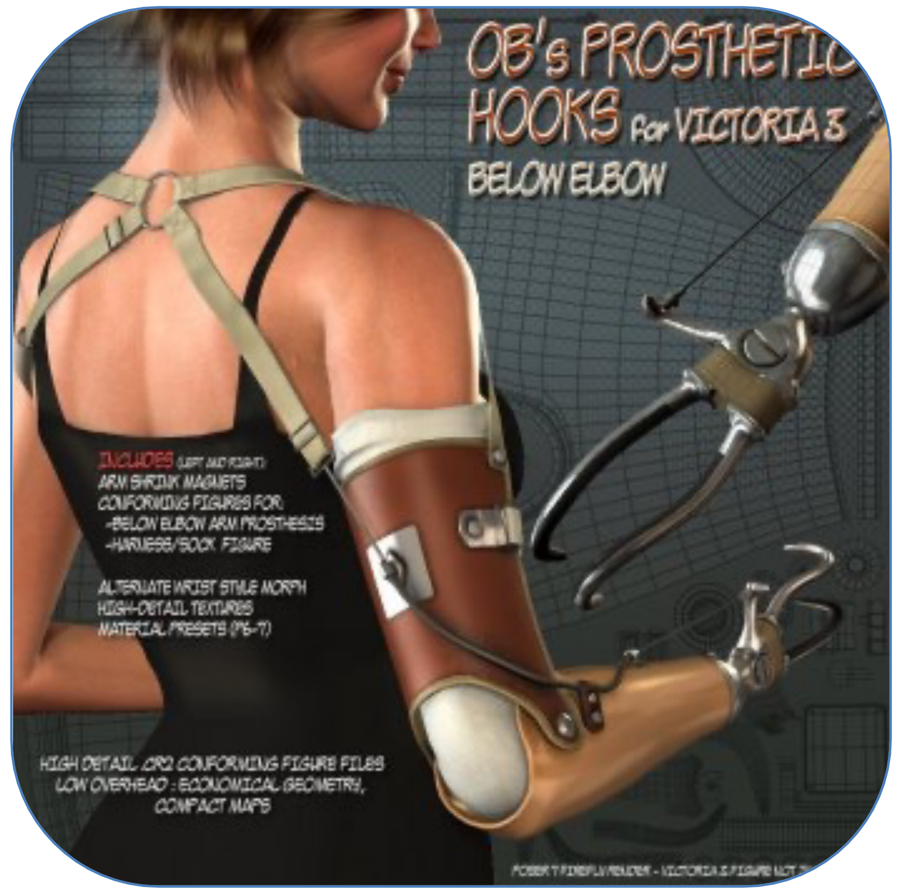
Hand Prosthesis

- Prosthetic Hands
  - Passive
    - Cosmetic
  - Active
    - Body-powered
    - Myoelectric

Cosmetic



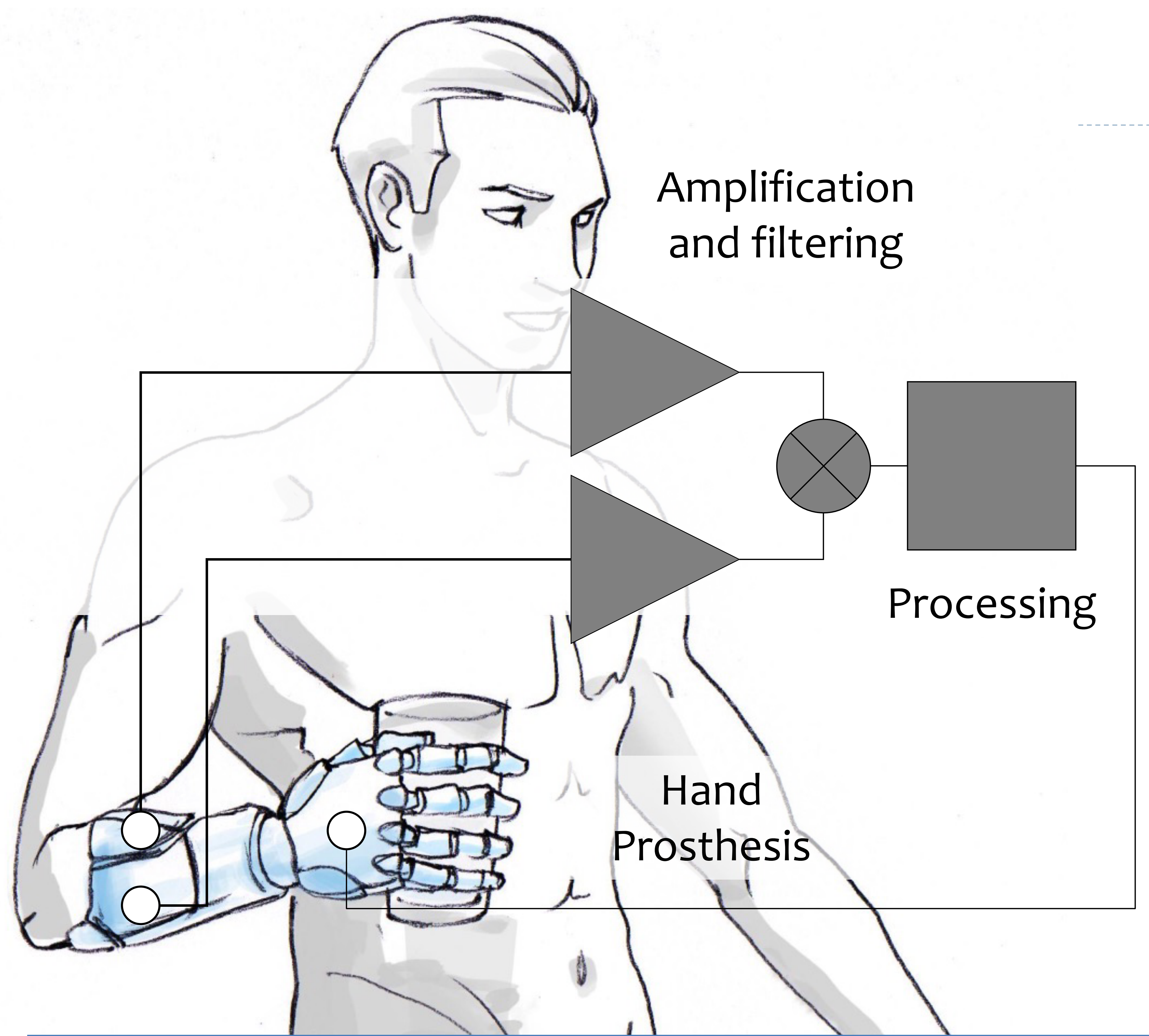
Body-powered

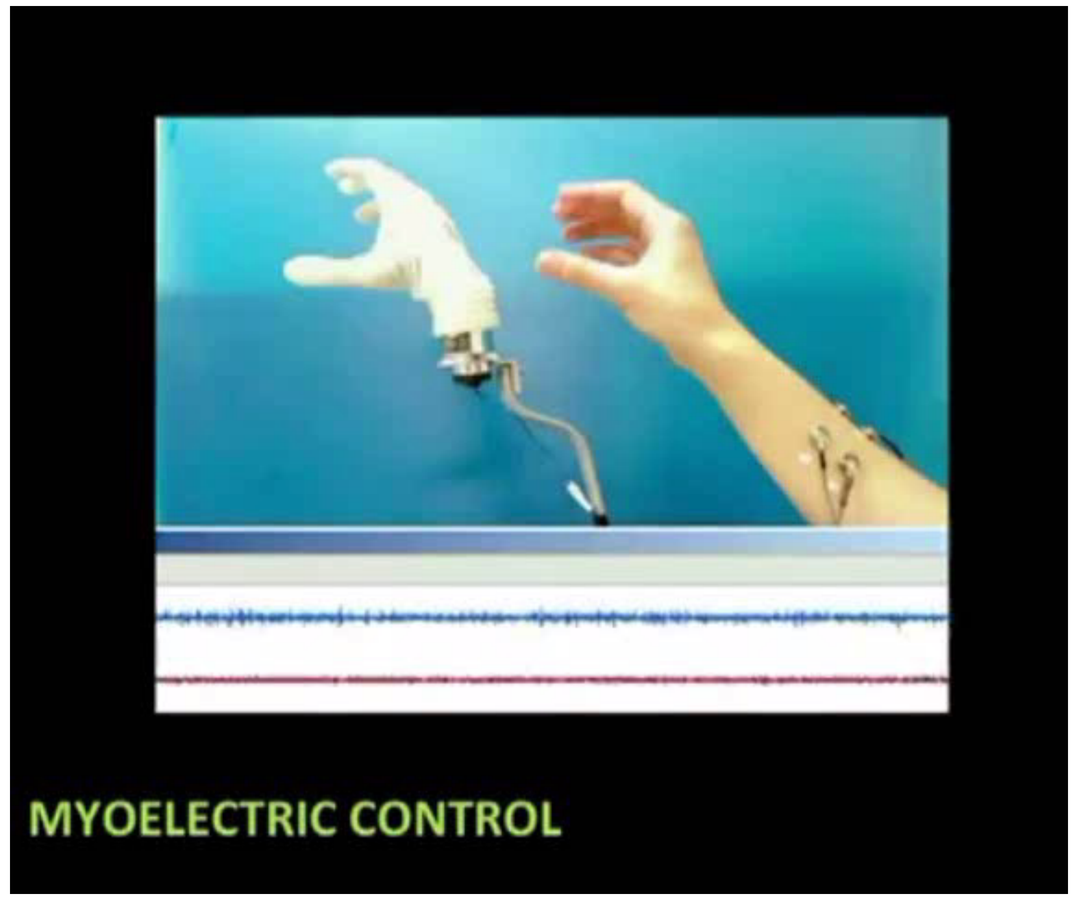


Myoelectric

What can an amputee get today?

HP Interface





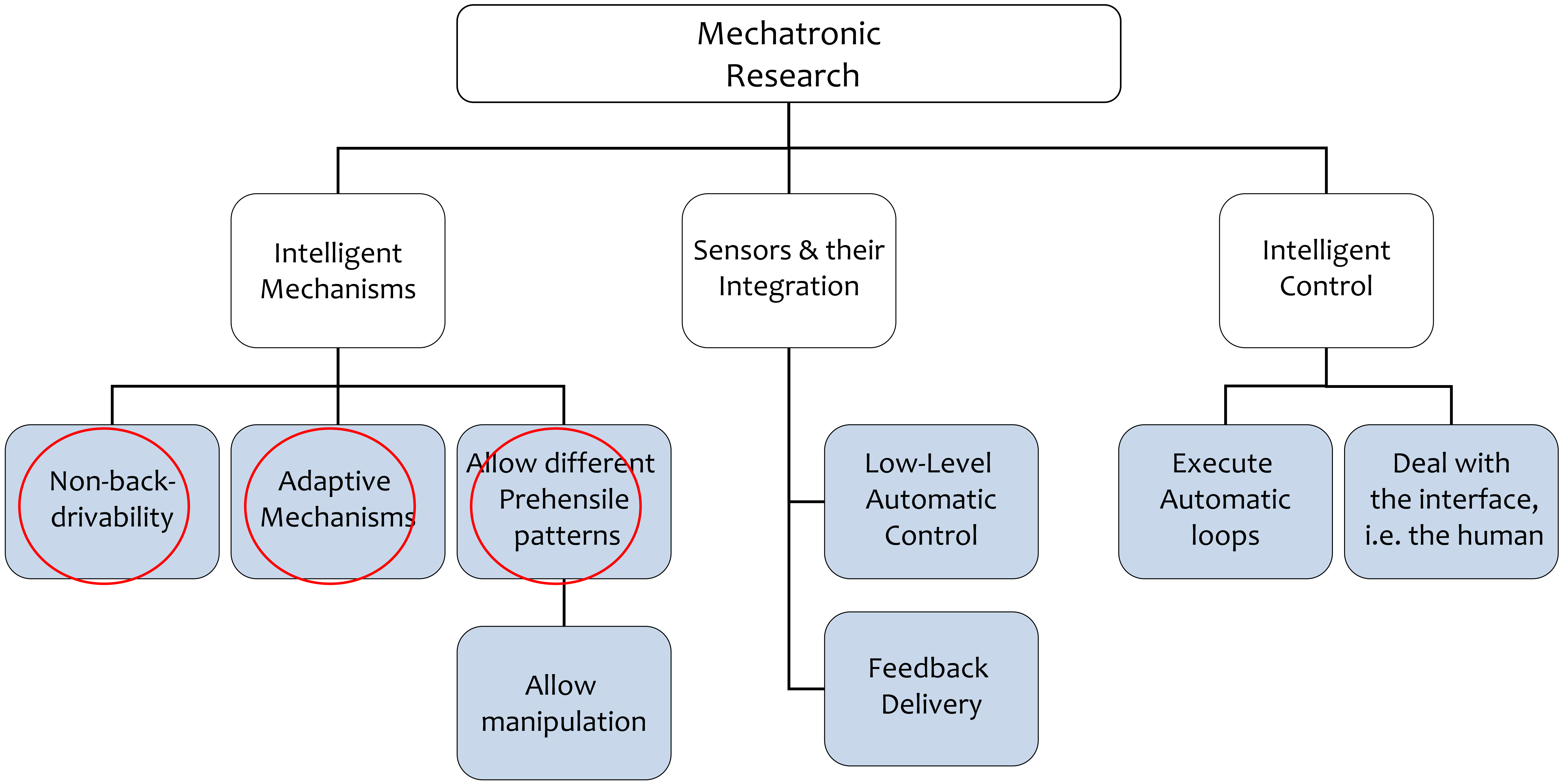
! **Multifunctional prosthesis** are usually operated as finite-state machines, hence different devices (joints) can be controlled **sequentially.**

Main issues:

- poor functionality → Very "limited" set of grasps possible (only 1 grasp!) or high cognitive effort is required
- poor cosmesis → Both static and dynamic properties
- poor controllability → No sensory feedback

30% - 50% of the users abandon their prosthesis!!!

Key issues



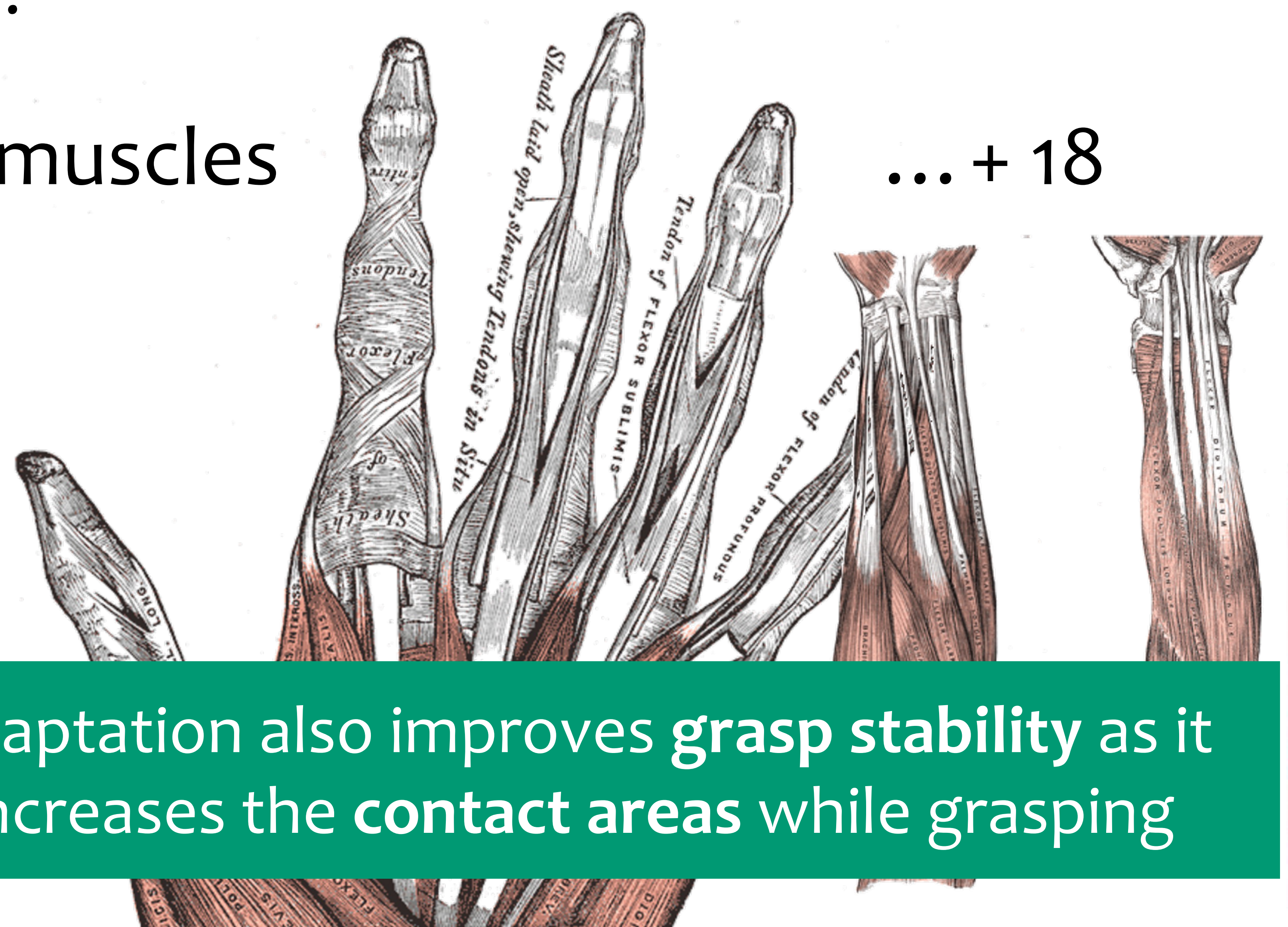
Mechatronic Research
Intelligent Mechanisms
Sensors & their Integration
Intelligent Control
Non-back-drivability
Adaptive Mechanisms
Allow different Prehensile patterns
Allow manipulation
Low-Level Automatic Control
Feedback Delivery
Execute Automatic loops
Deal with the interface, i.e. the human

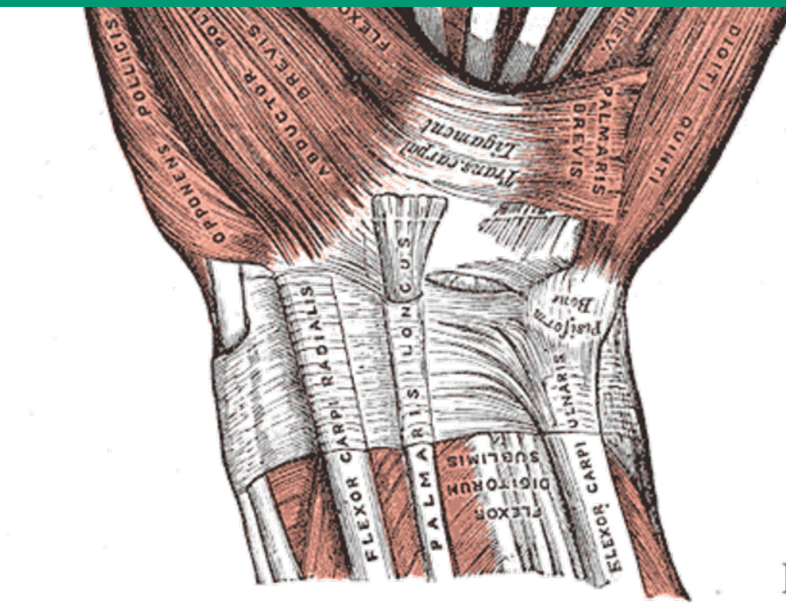
Mechatronic

Design issues: 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



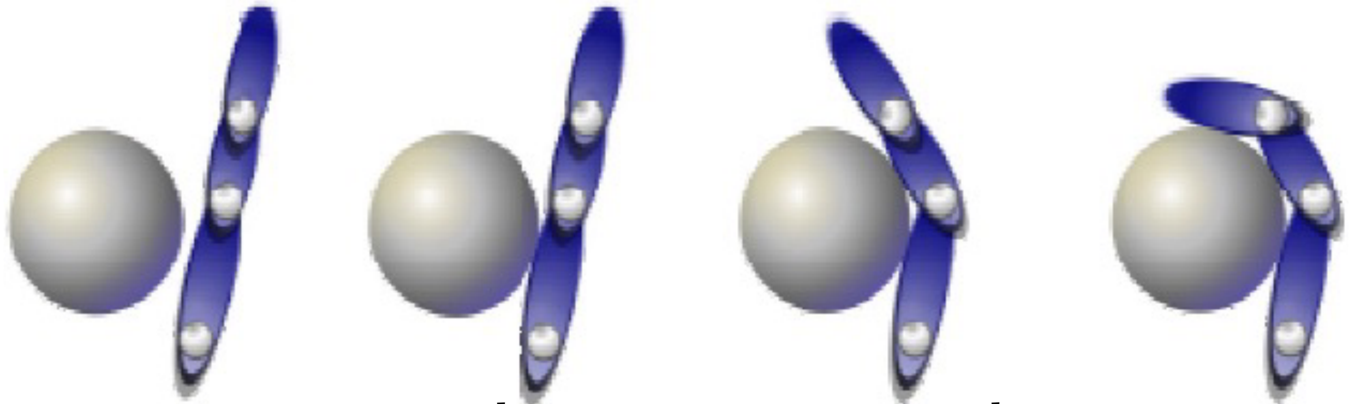


Adaptation also improves **grasp stability** as it increases the **contact areas** while grasping

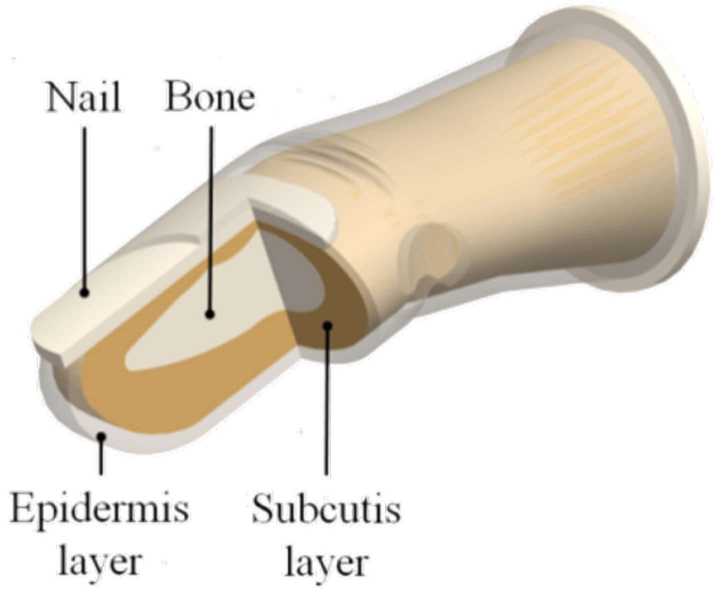
Possible solutions (to simplify the problem):

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

Hand adaptation mechanisms



Finger adaptation mechanisms

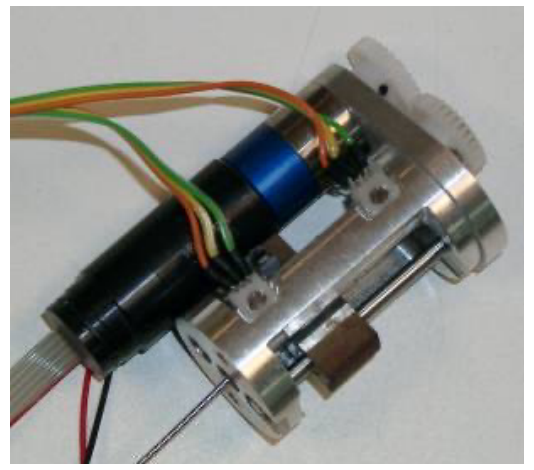


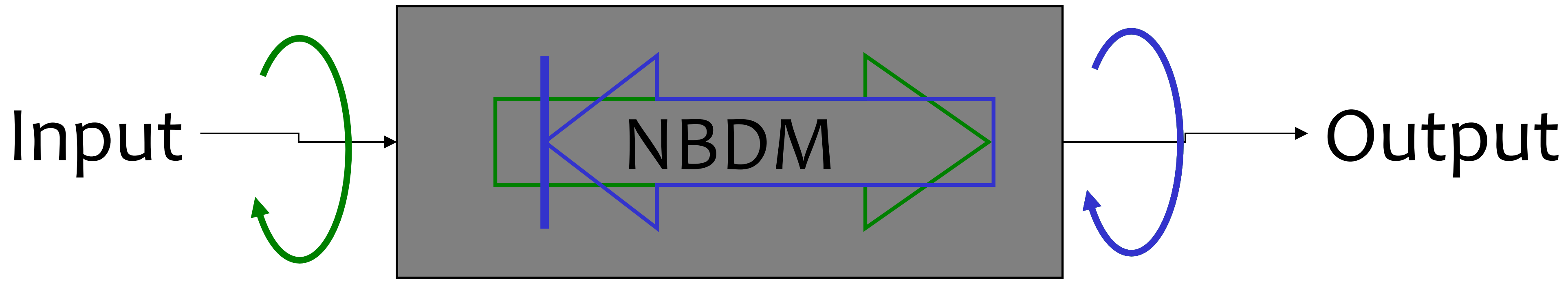
Phalanx adaptation mechanisms

Underactuated mechanisms

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

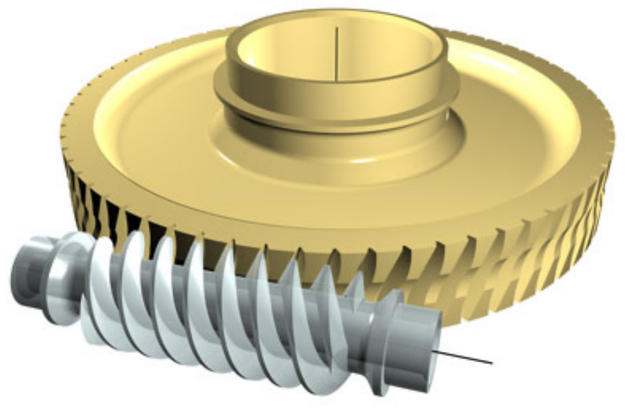




In a prosthesis it allows to maintain the grasp once the power supply is switched off

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

Lead Screw

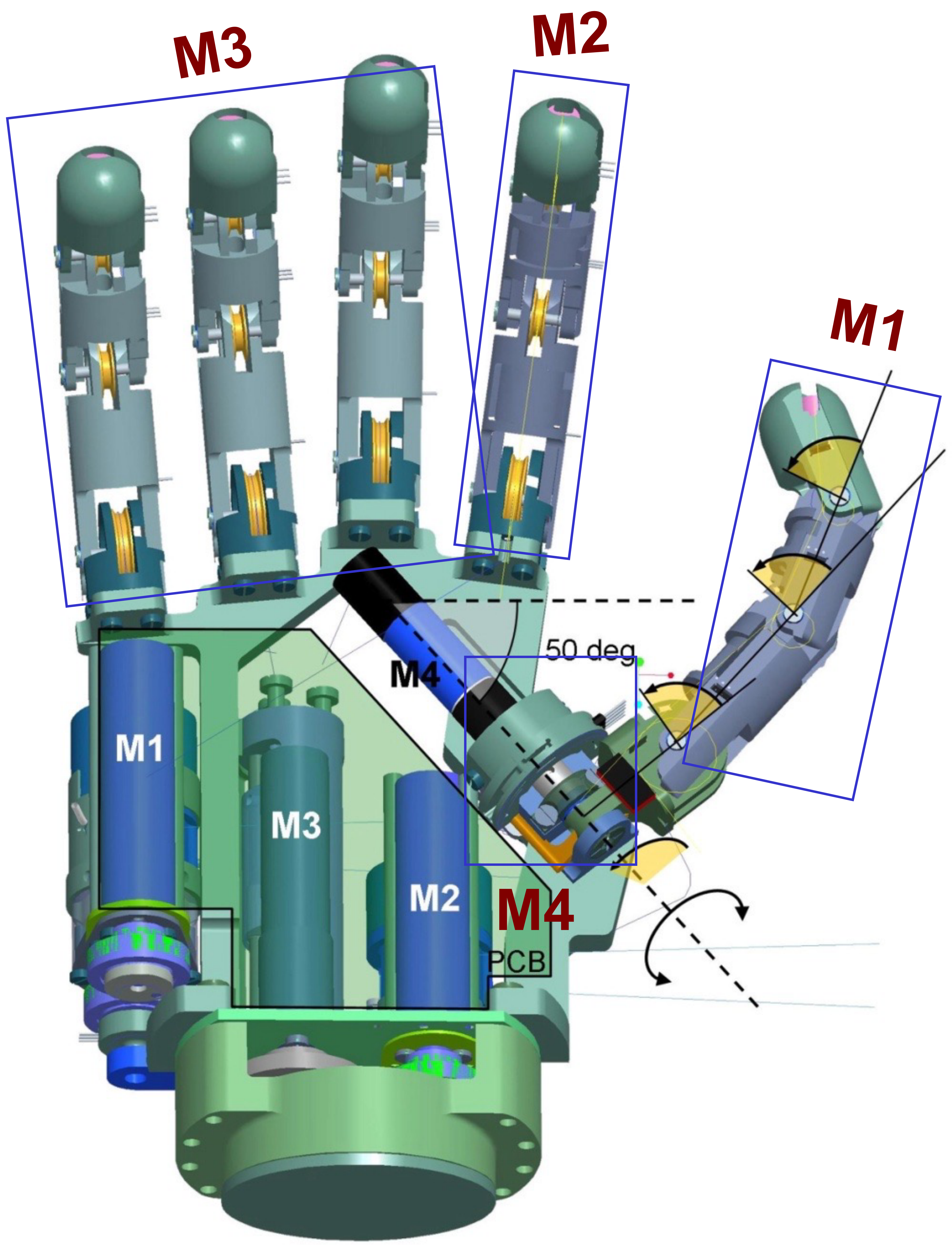


Worm Gear

Gear heads with high reduction rate

Brakes/ clutches

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

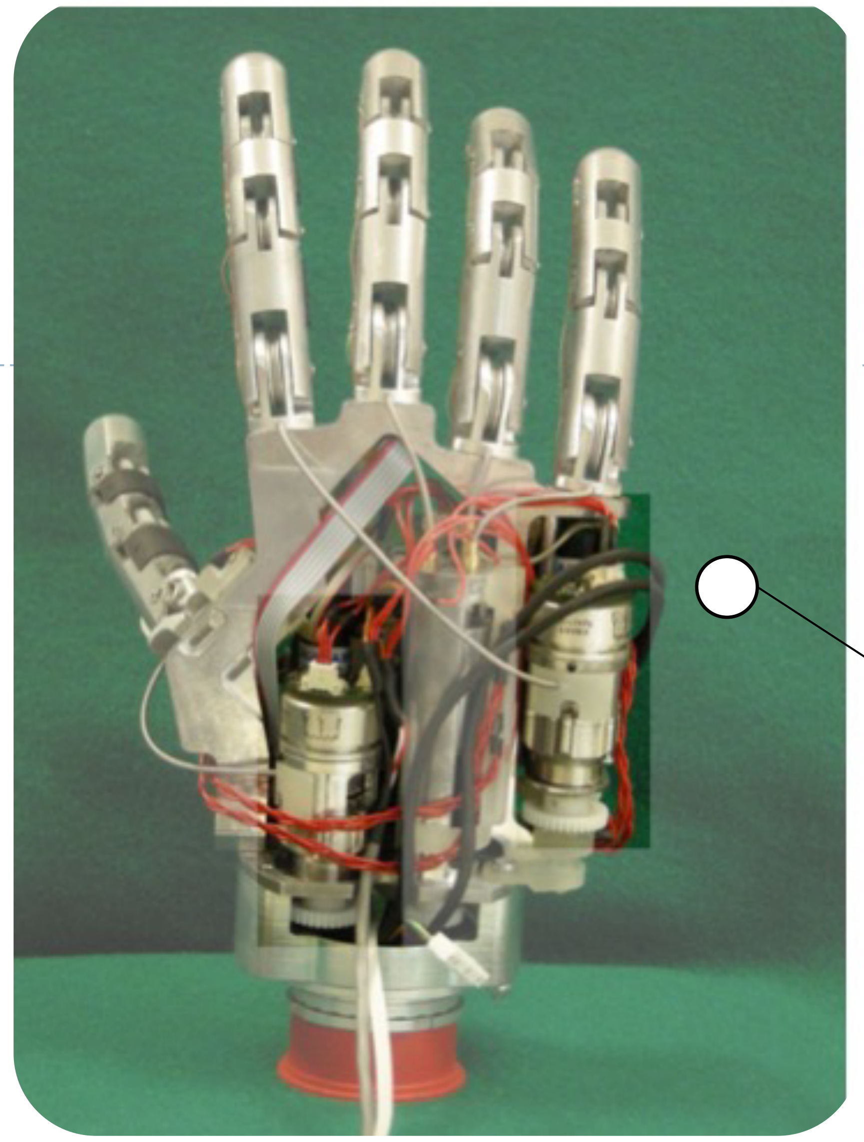
Position (digital encoder)	4
Position (Joint Hall sensors)	15
Position (Potentiometer)	2
Tension Sensors (strain gauges)	5
Limit switch (digital)	8

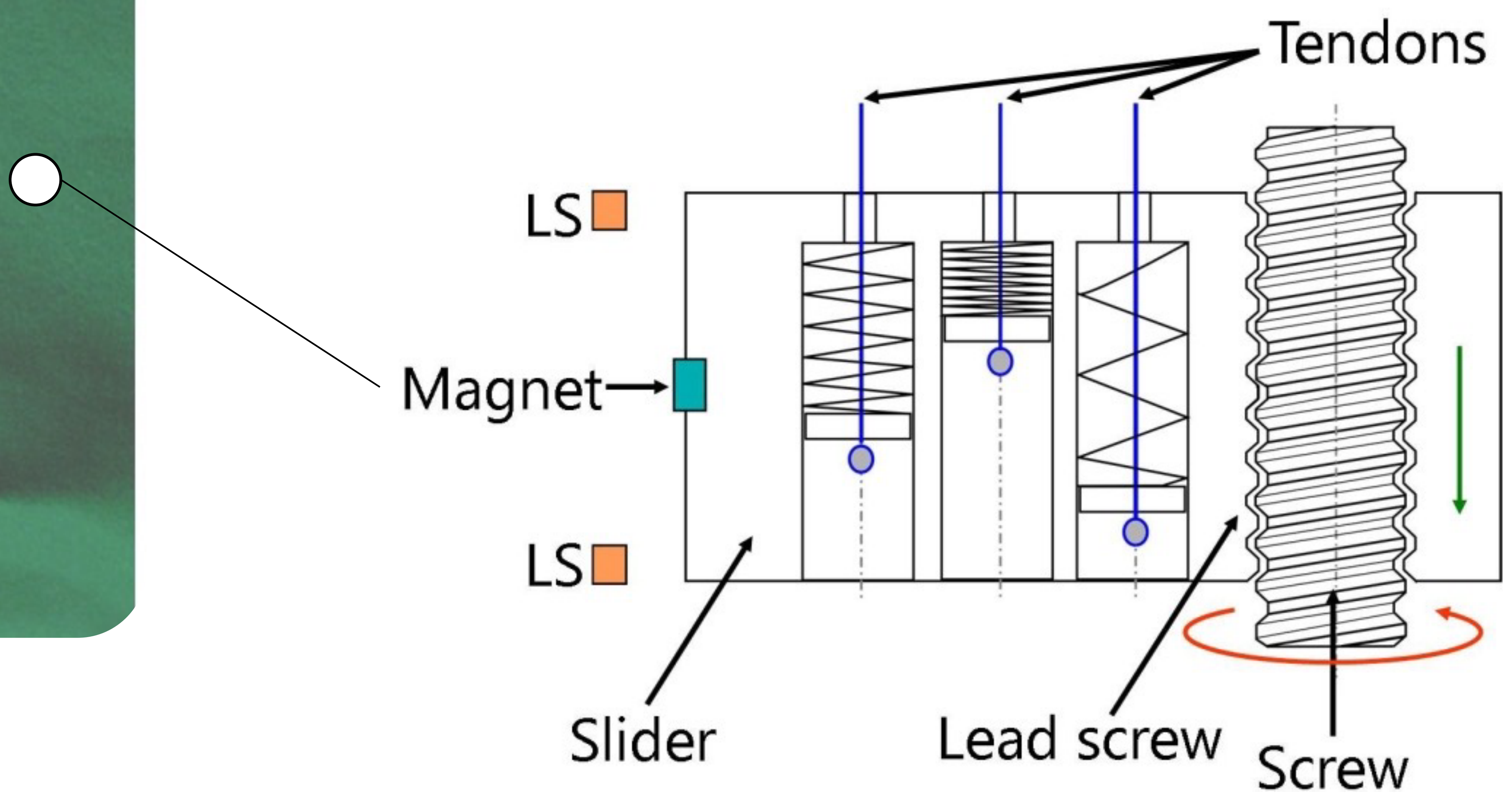
Electrical Spec

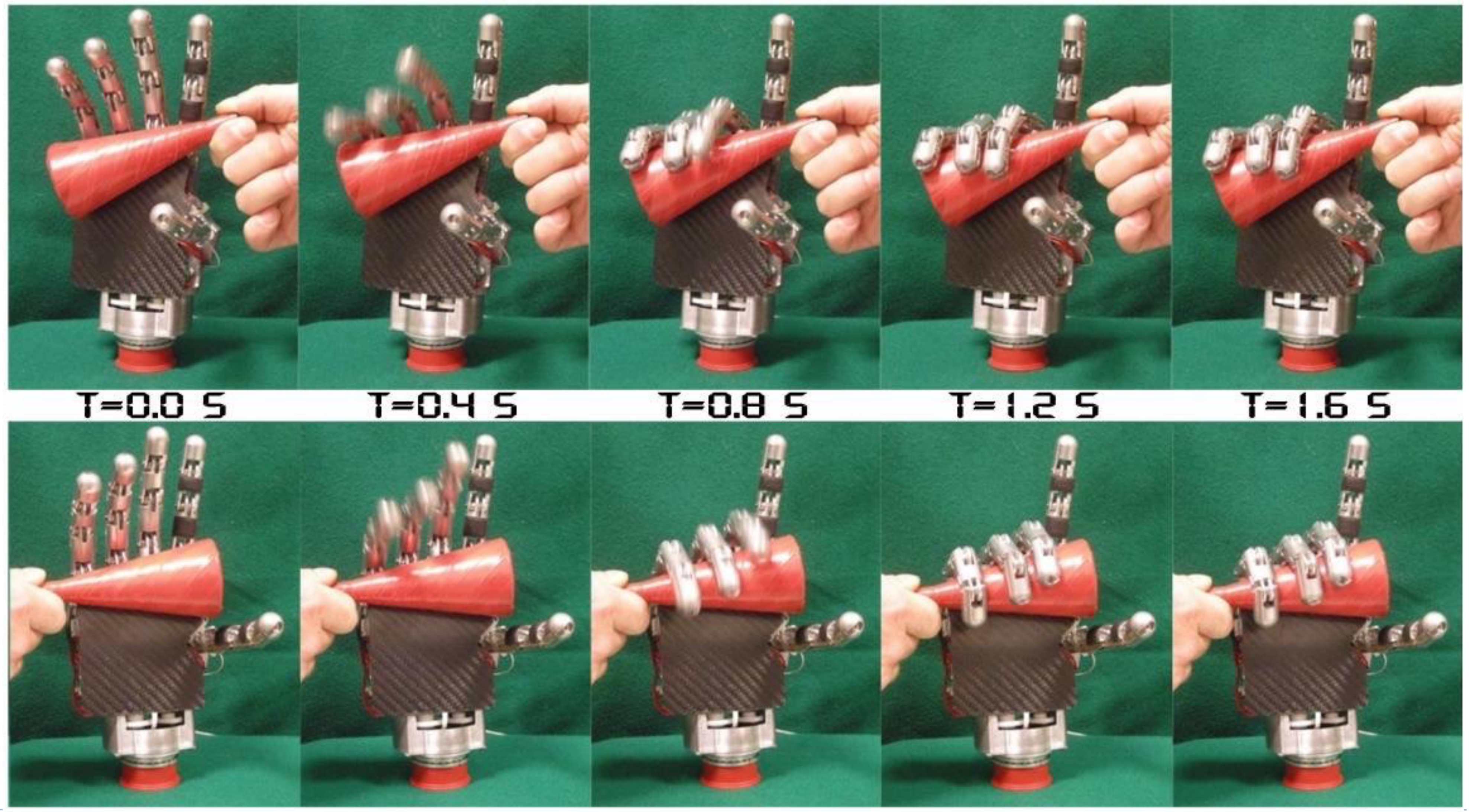
Power req.	12V /3A
Control loops	Position and tension (1 kHz)
Reading delays	< 1 ms
Total preset grasps	10 (programmable)
Communication	RS232 / USB

Case Study

The SmartHand prototype



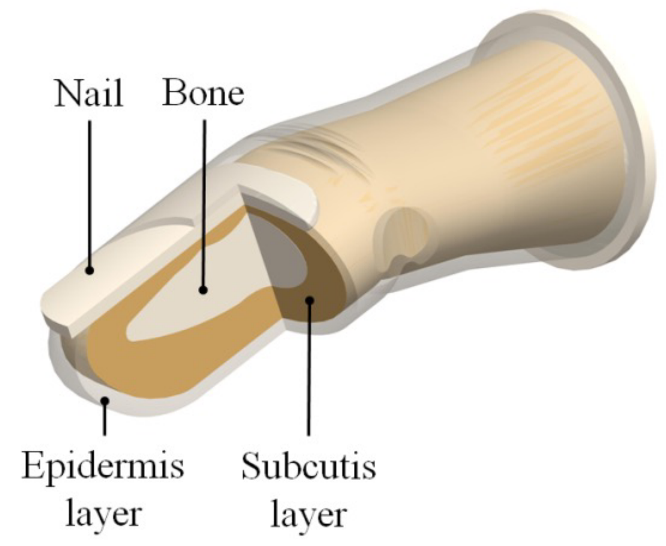




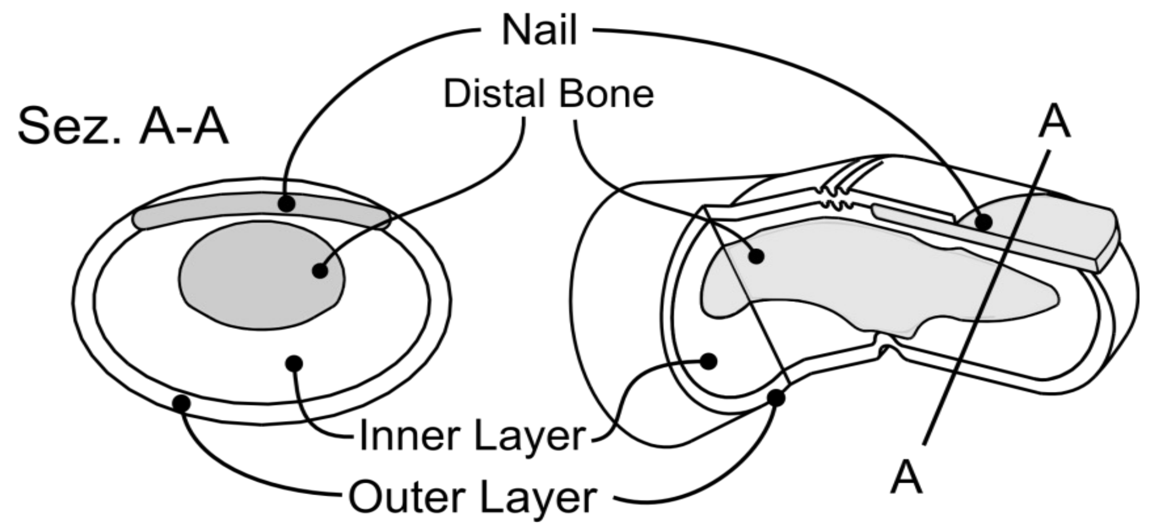
Adaptability of the last three fingers (driven by just 1 motor) on a complex surface

Case Study
The OpenHand prototype

Human finger-tips play a fundamental role during the action of fine manipulation and precision grasping of objects

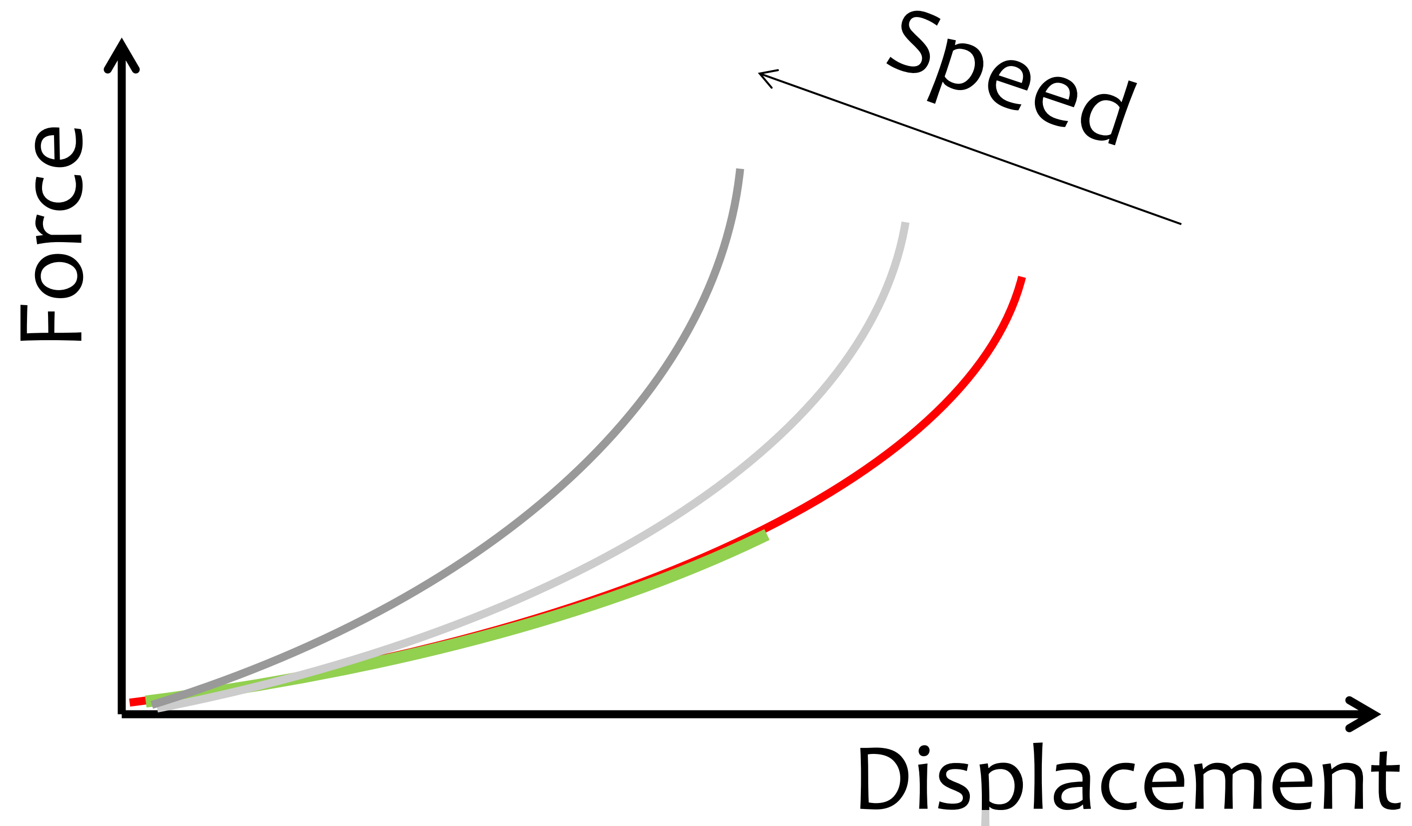


Multi-layers structure with different proprieties:
- Epidermis and subcutis layers - **Compliant materials**
- Nail and inner bone - **Stiff materials**



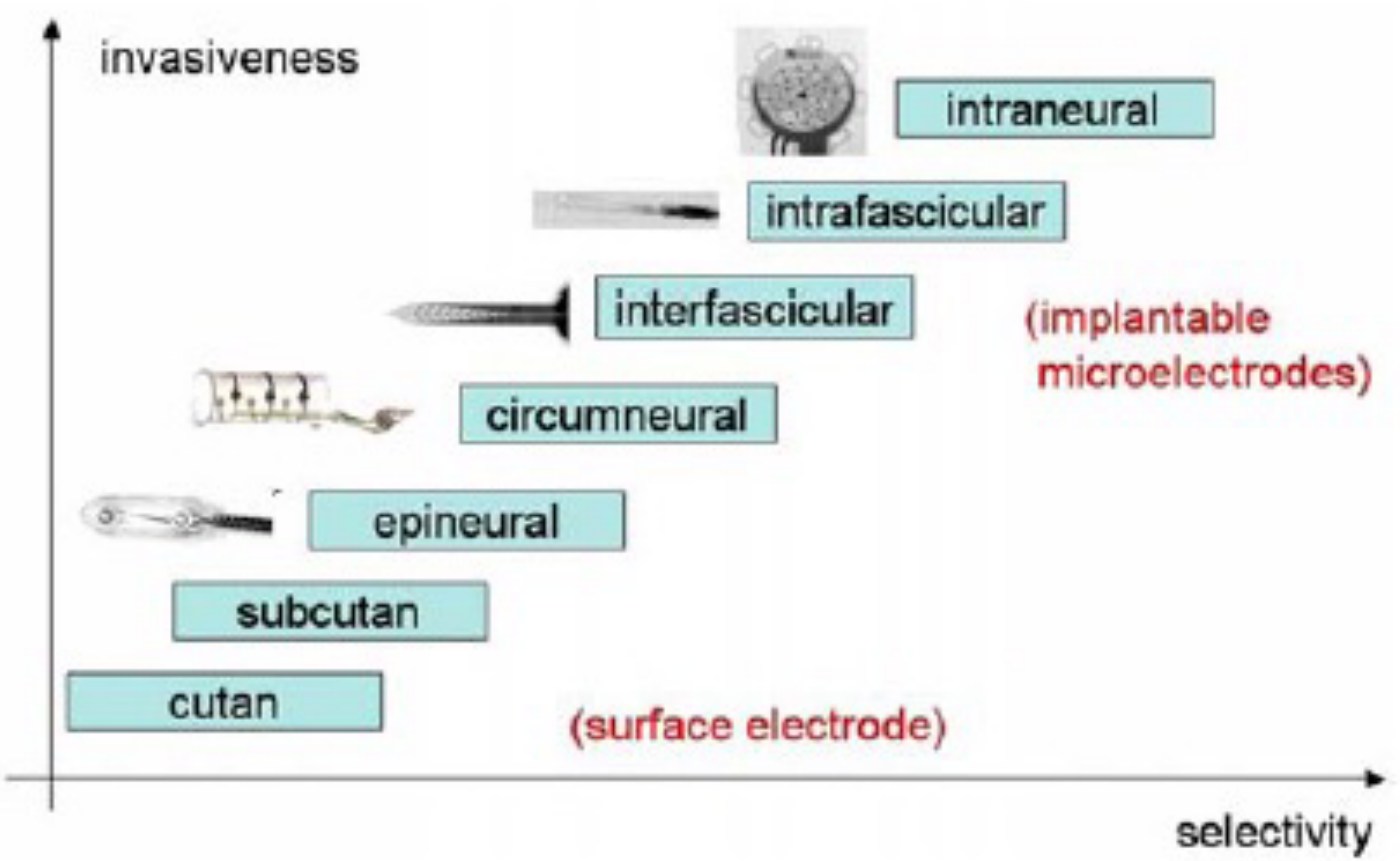
Non-linear & time-dependent characteristic:
- Low forces – Large displacements (**Compliant behavior**)
- High forces – Small displacements (**Stiff behavior**)
- Energy dissipation (**Visco-elastic behavior**)

Benefits of grasping and manipulation:
- Conformability;
- Large contact areas;
- Energy dissipation;



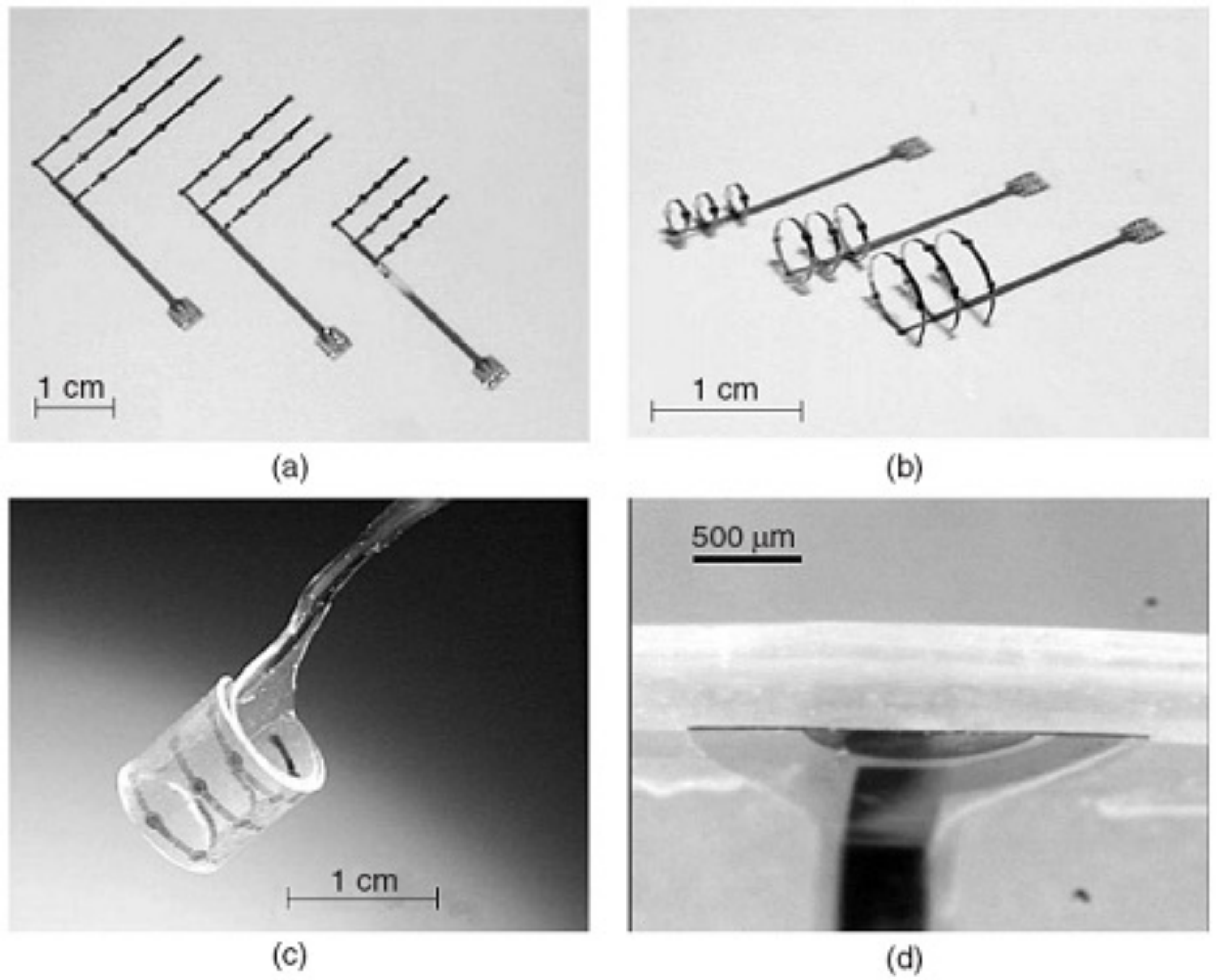
1. M. Controzzi, M. D'Alonzo, C. Peccia, C. Cipriani Design, simulation and development of a human inspired fingertip for robotic hand, to be submitted to the Journal o Bioispiration and Biomimetics
2. M. Controzzi, C. Cipriani, M. D'Alonzo, C. Peccia and M. C. Carrozza Design of an Anthropomorphic Robotic Hand with Intrinsic Actuation and Compliant Fingers, GNB 2012, Rome, Italy, June, 2012.
3. M. D'Alonzo, M. Controzzi, C. Peccia, C. Cipriani and M C. Carrozza. ``Design of biomimetic artificial fingertips and analysis of stiffness at the contact,'' GNB 2012, Rome, Italy, June, 2012.

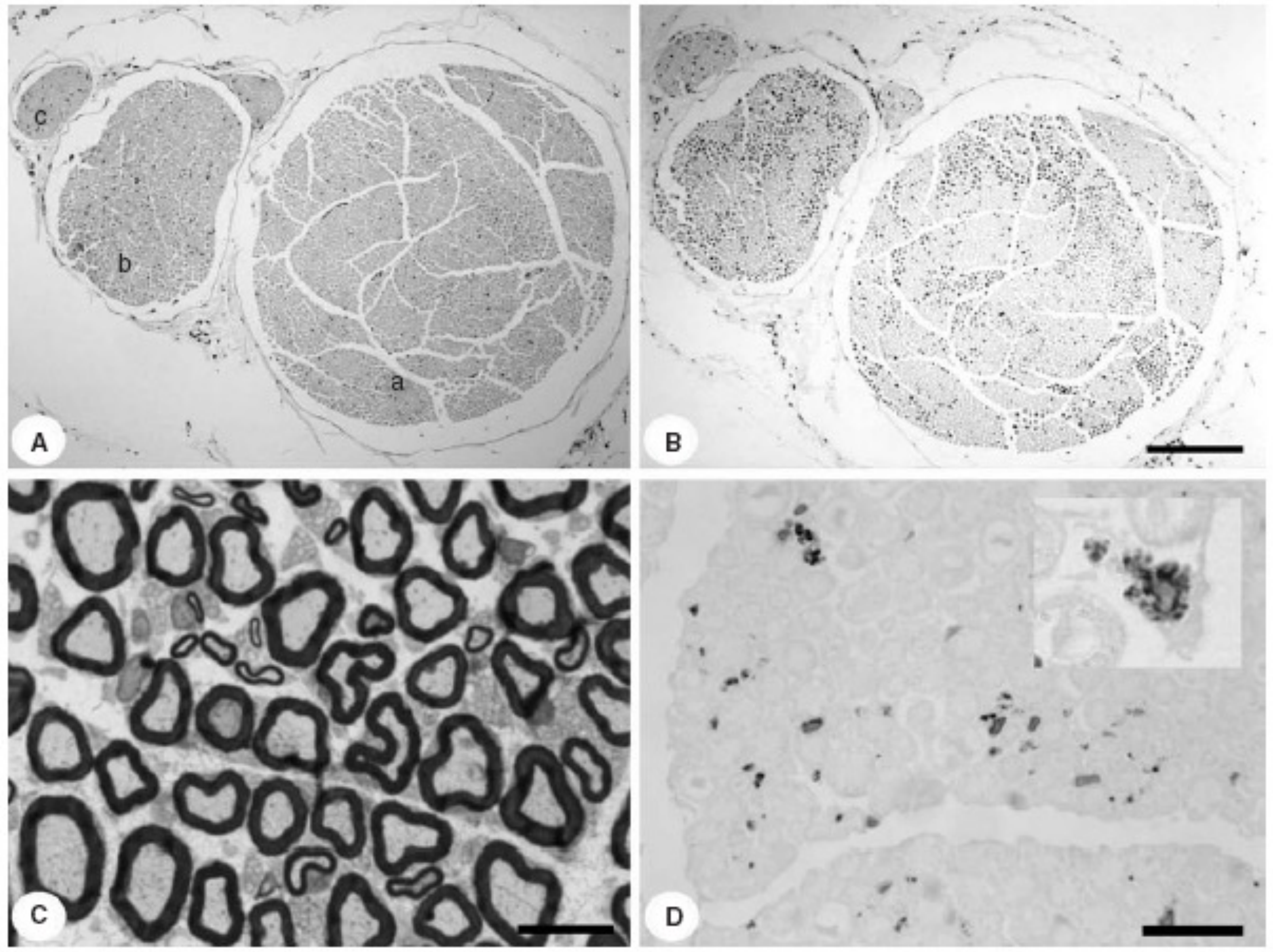
Interfaces with the PNS



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





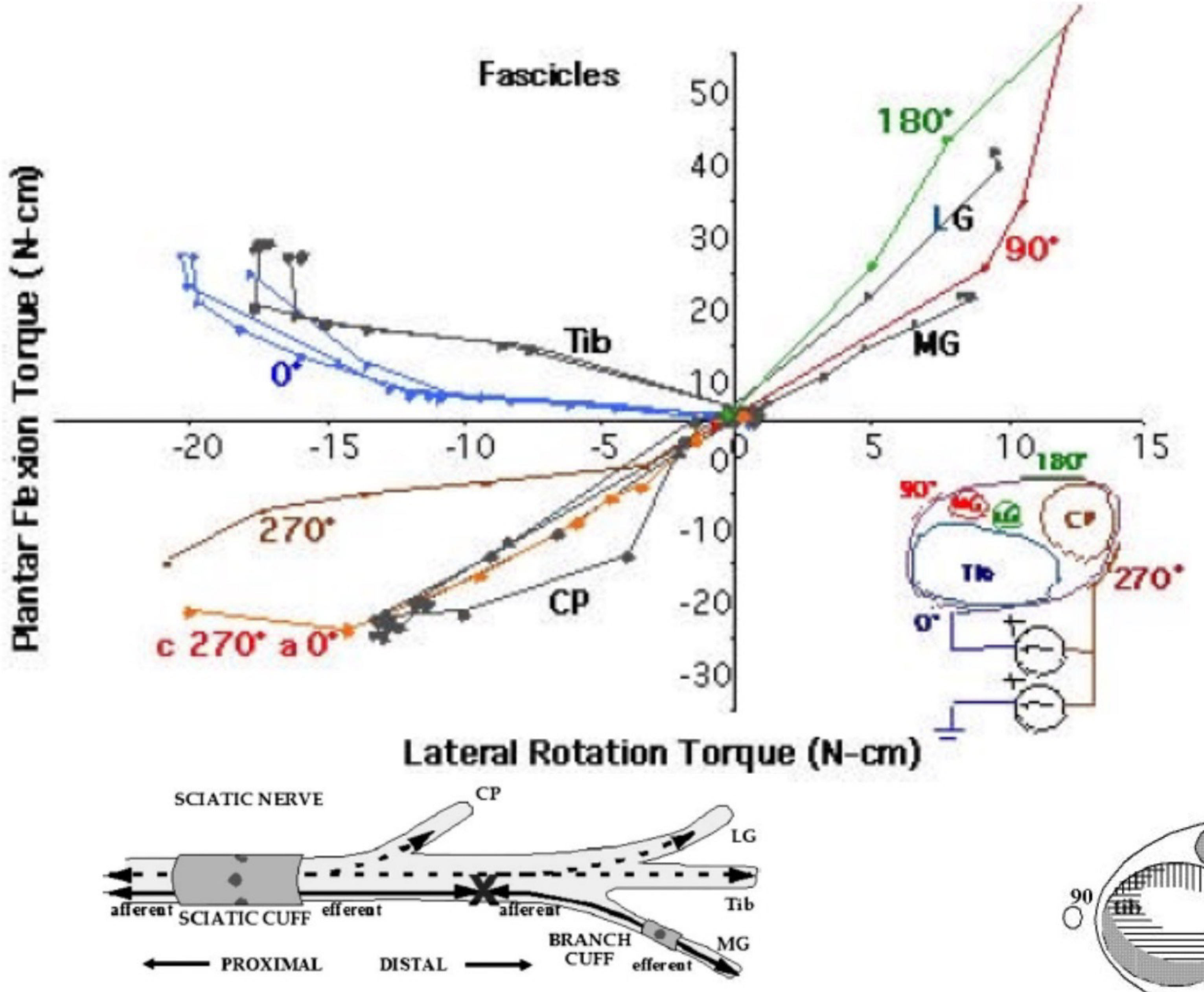


Fig. 1. Full and selective activation of an individual nerve branch was tested by using a branch cuff on the corresponding nerve branch (the MG in this example). The branch cuff was used to activate the branch nerve completely. Activation of nerve fibers serving that nerve branch, by stimulation applied to the sciatic cuff, will not change the resulting output since the branch cuff has already activated those fibers (solid lines). Activation of nerve fibers serving other nerve branches, by stimulation applied to the sciatic cuff, will propagate to different muscles and, therefore, cause a change in the resulting output (dashed lines).

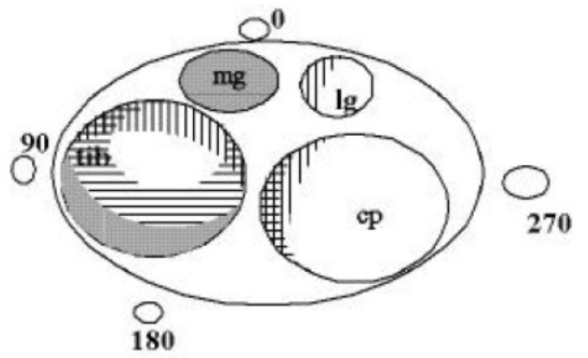
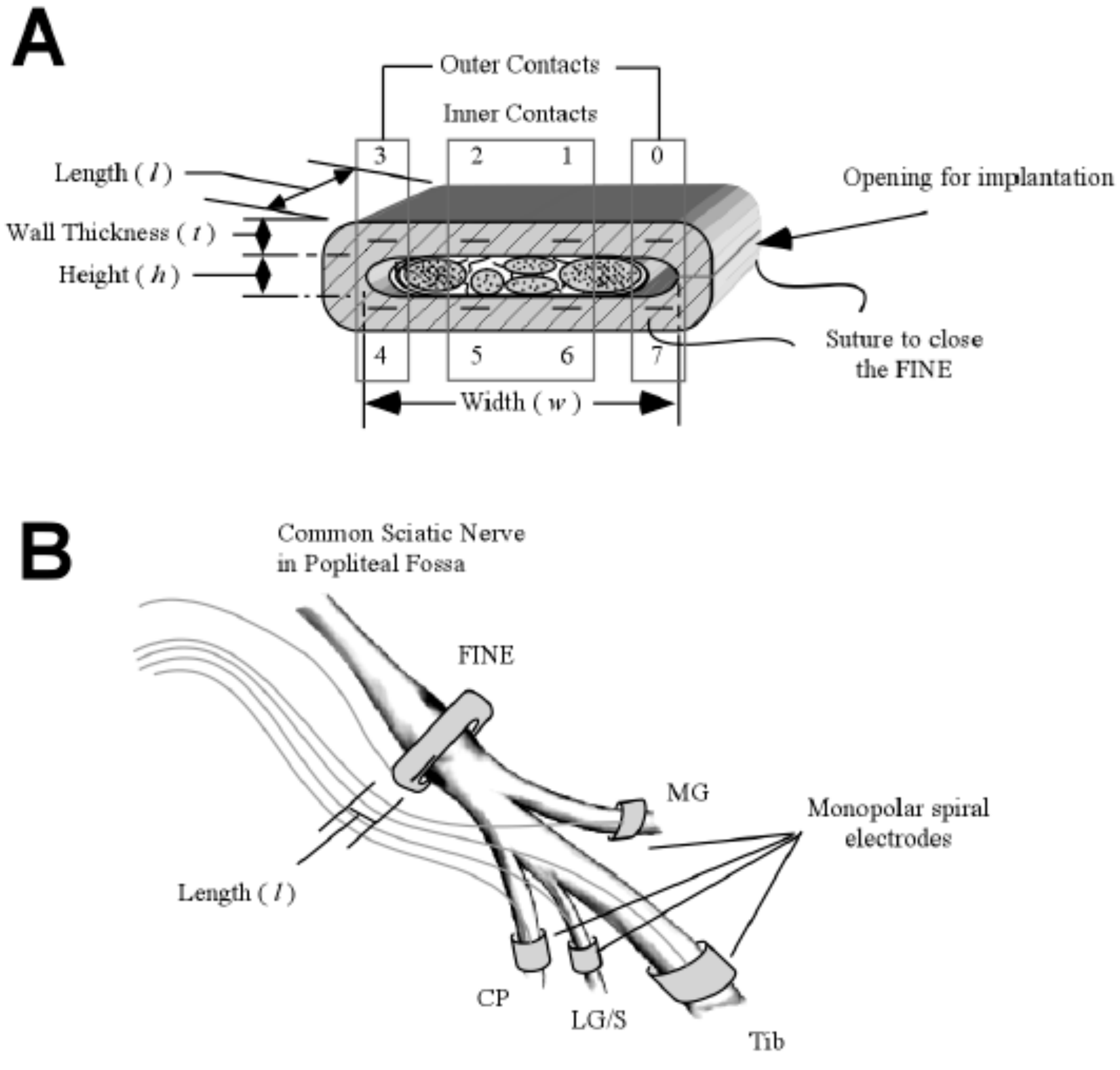
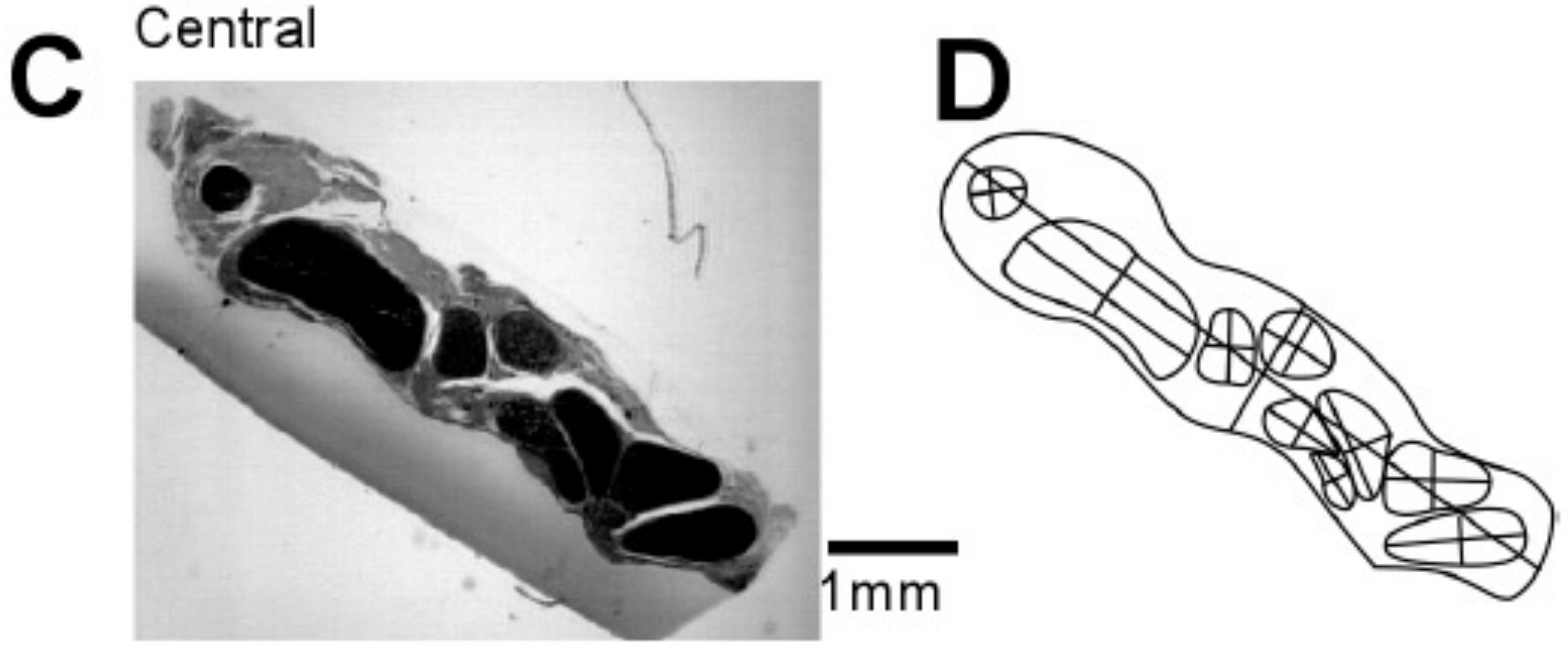


Fig. 21. Schematic representation of cat sciatic nerve containing four motor fascicles, tibial (tib), medial gastrocnemius (mg), laterial gastrocnemius (lg) and common peroneal (cp). Electrode contacts in the self-sizing spiral cuff electrode are labeled 0°, 90°, 180°, and 270°. Grayed areas represent axon populations activated when stimuli (c180°a90°) and (c0°) are separately applied. The vertically hatched areas depict axons stimulated to subthreshold levels by (c0°), and horizontal hatched areas depict axons stimulated to subthreshold levels by stimuli (c180°a90°). Regions where the two subthreshold regions overlap to create suprathreshold excitation have overlapping horizontal and vertical hatched areas.

FINE electrodes

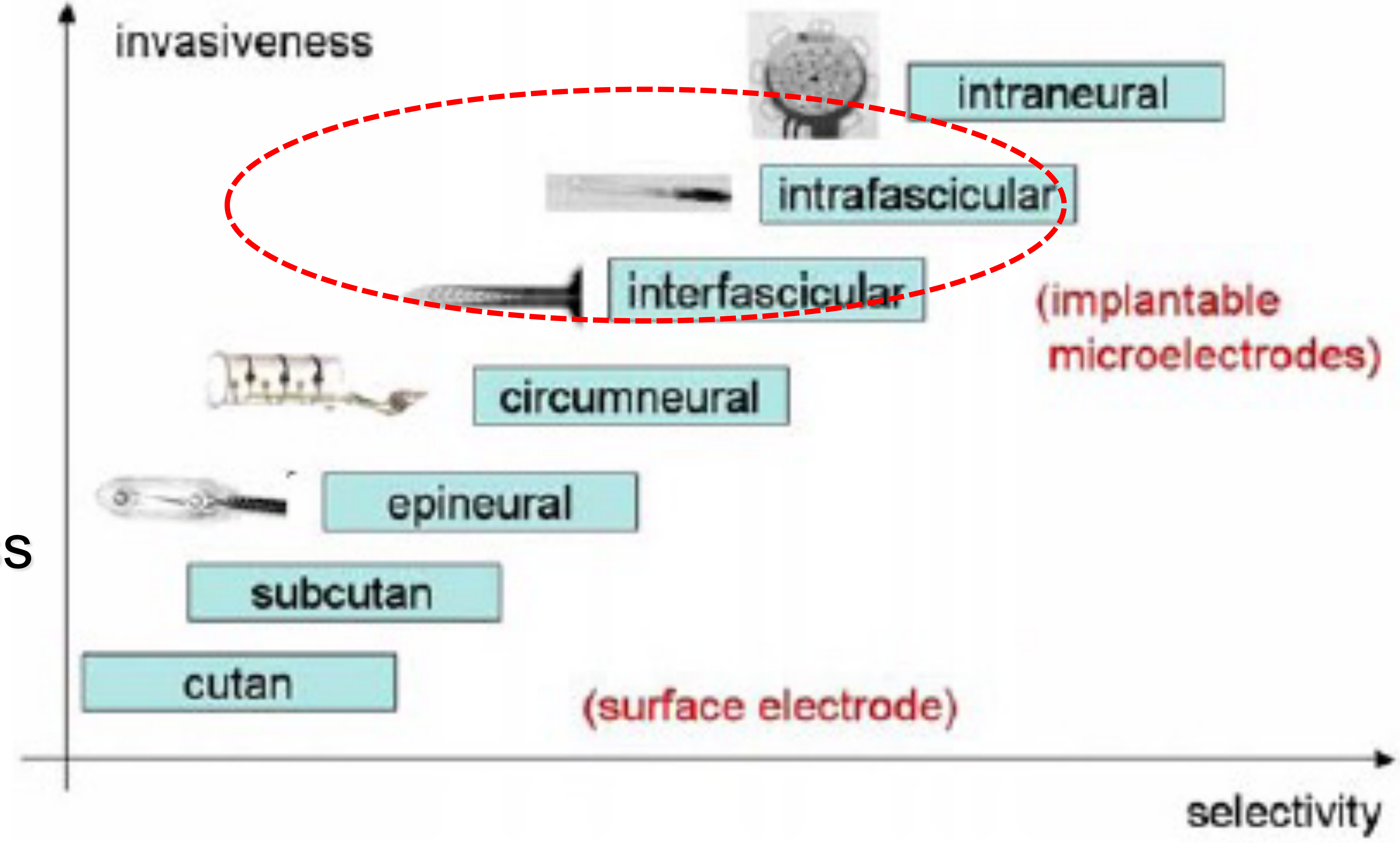
- They can provide an increased selectivity:
  - More channels
  - More “favorable” anatomy
  - Advanced signal processing
- However, the selectivity could sti be limited especially for the delivery of sensory feedback

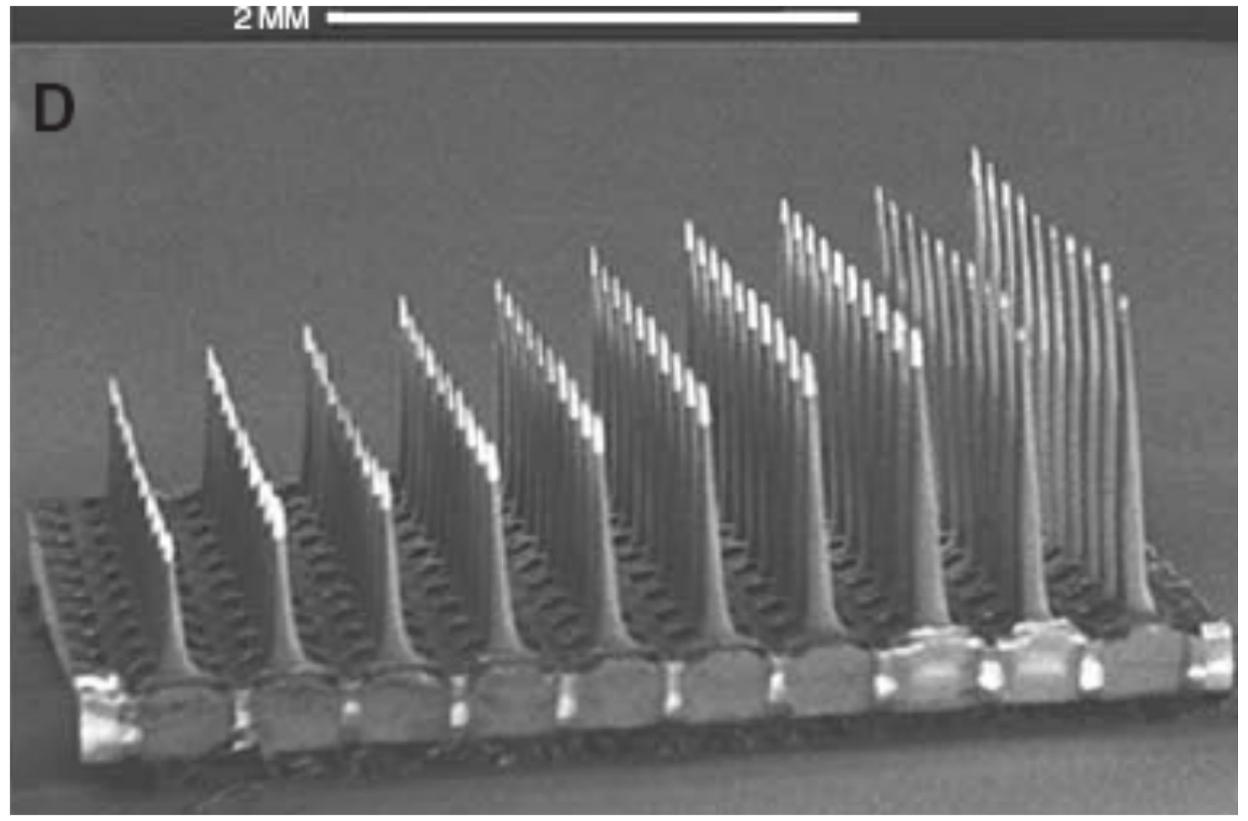




Intraneural (intrafascicular) electrodes

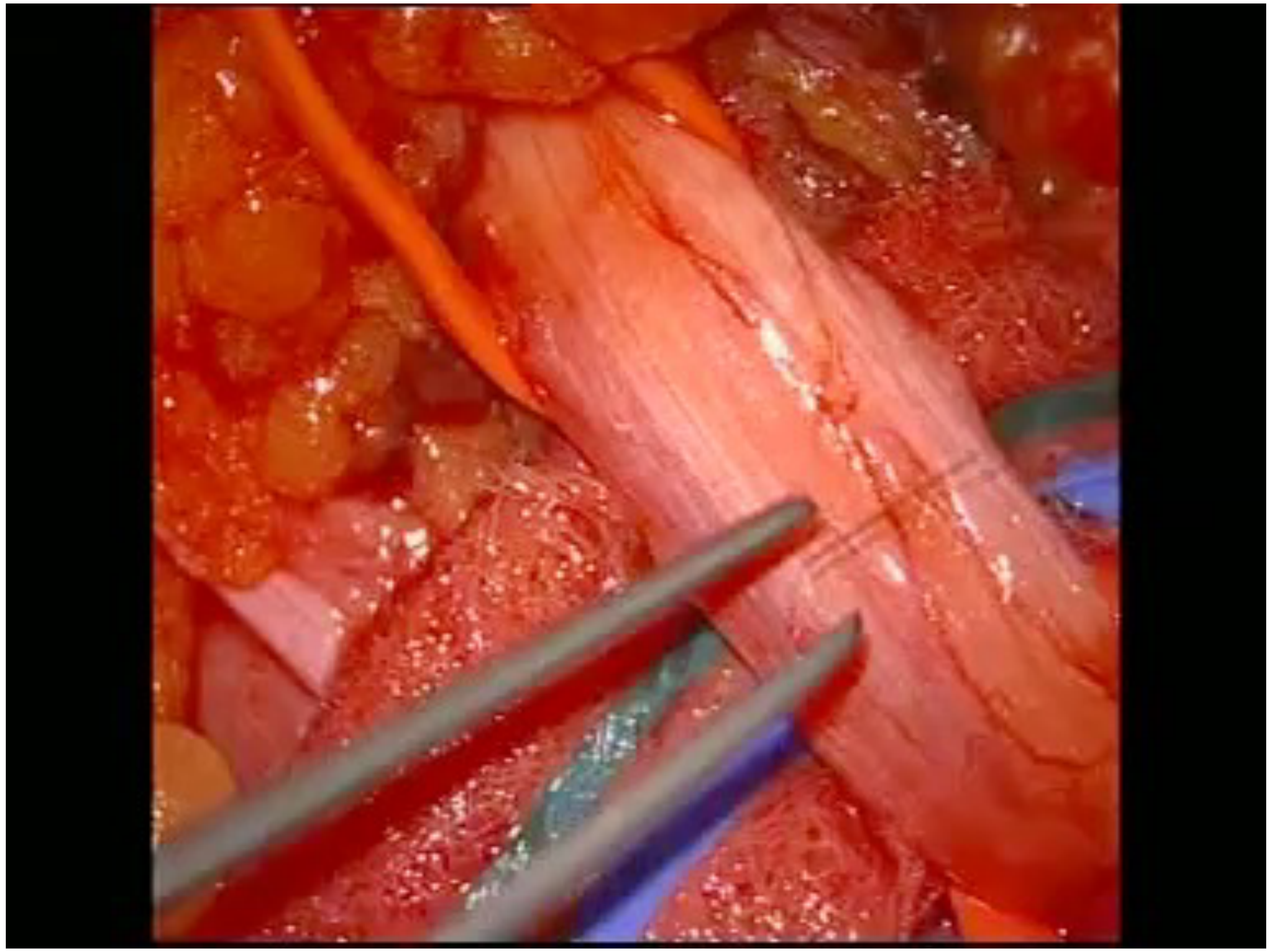
Intraneural electrodes
seem to represent a good trade-off between high selectivity and reduced invasiveness

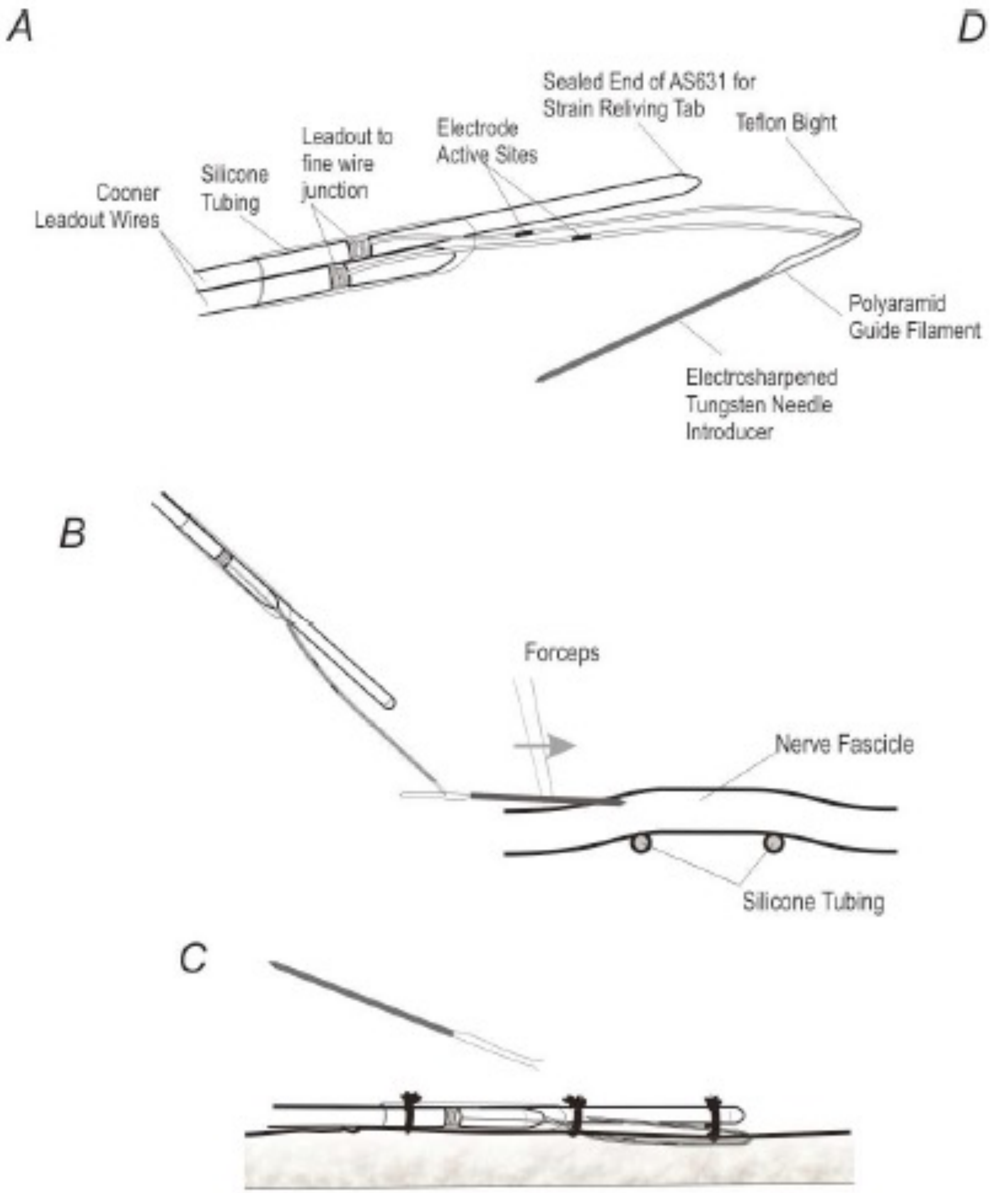




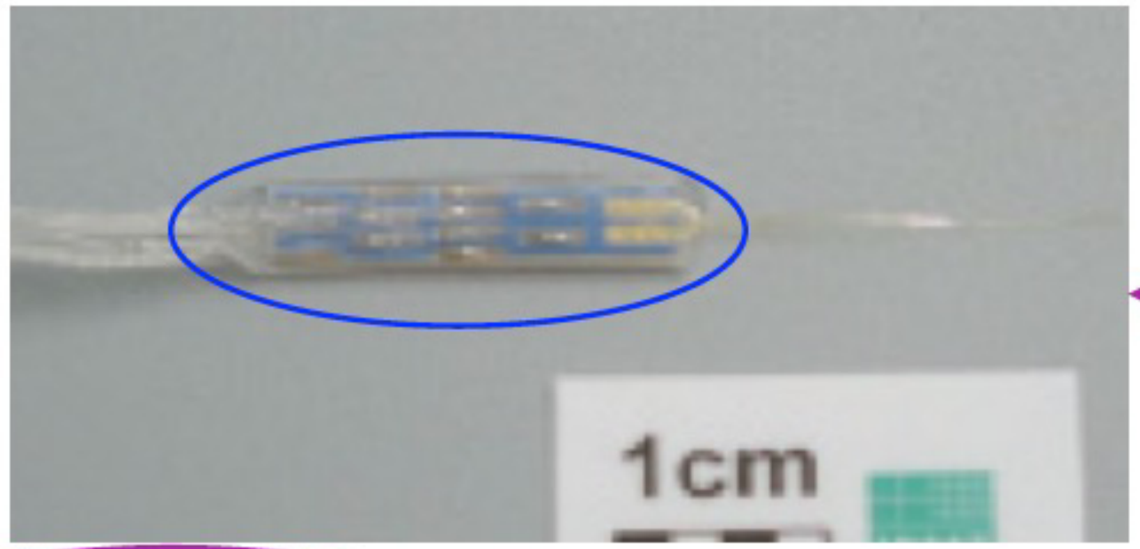
Longitudinal intrafascicular electrodes (LIFEs)

- LIFEs are relatively easy to implant
- Provide a good trade-off between reduced invasiveness and good selectivity

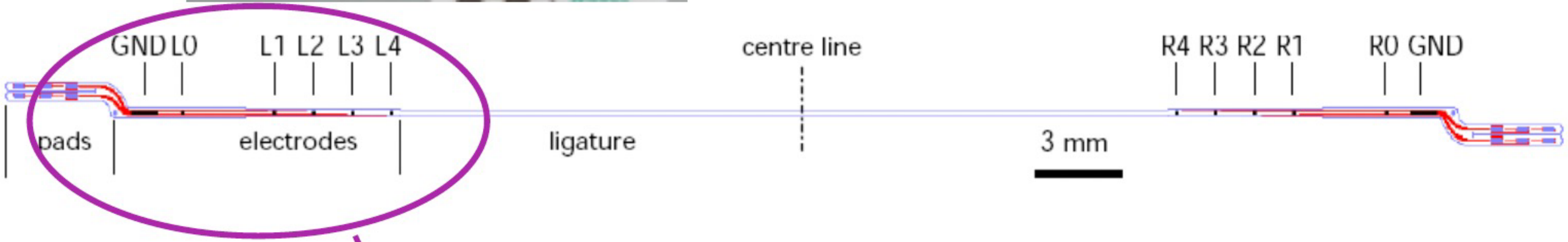


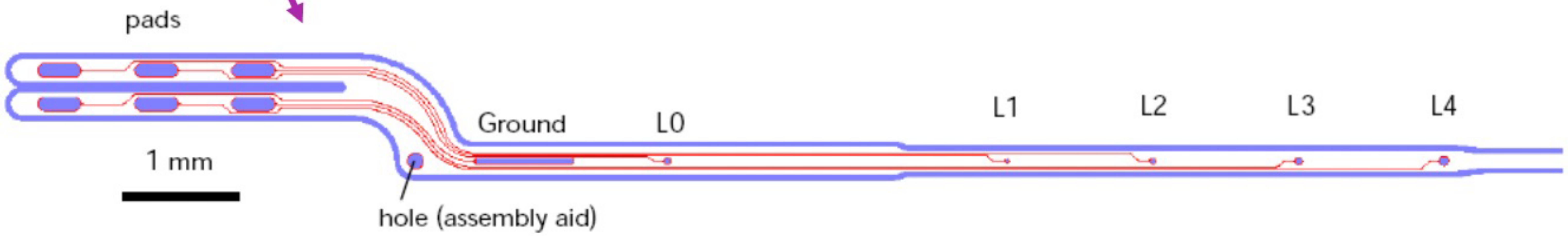


Thin-film longitudinal intrafascicular electrodes (tfLIFEs)



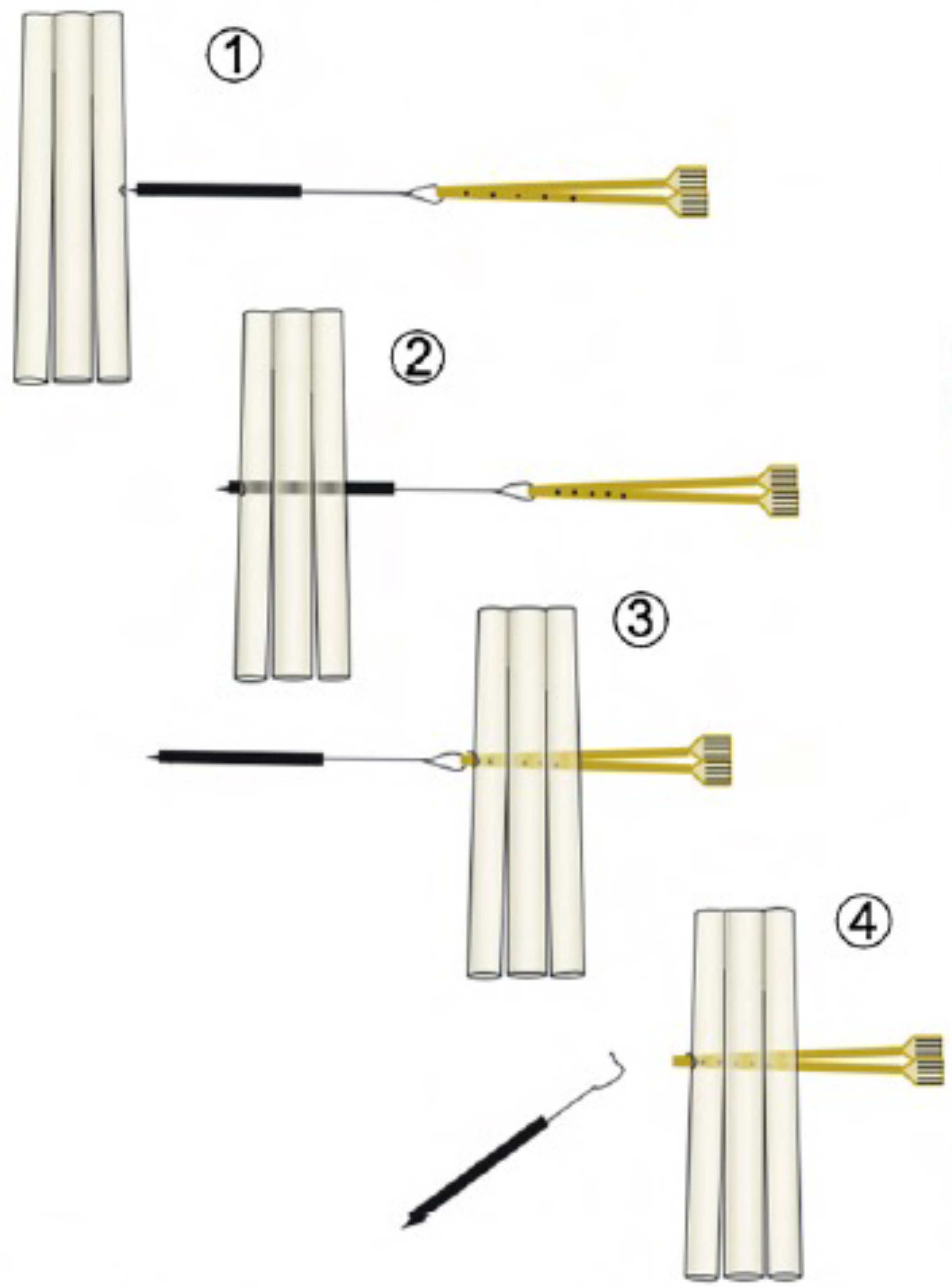
The active part of the electrode is made of a flexible polyamide thin-film 5µm thick. The polyimide acts as substrate and as insulation on which platinum tracks are sputtered

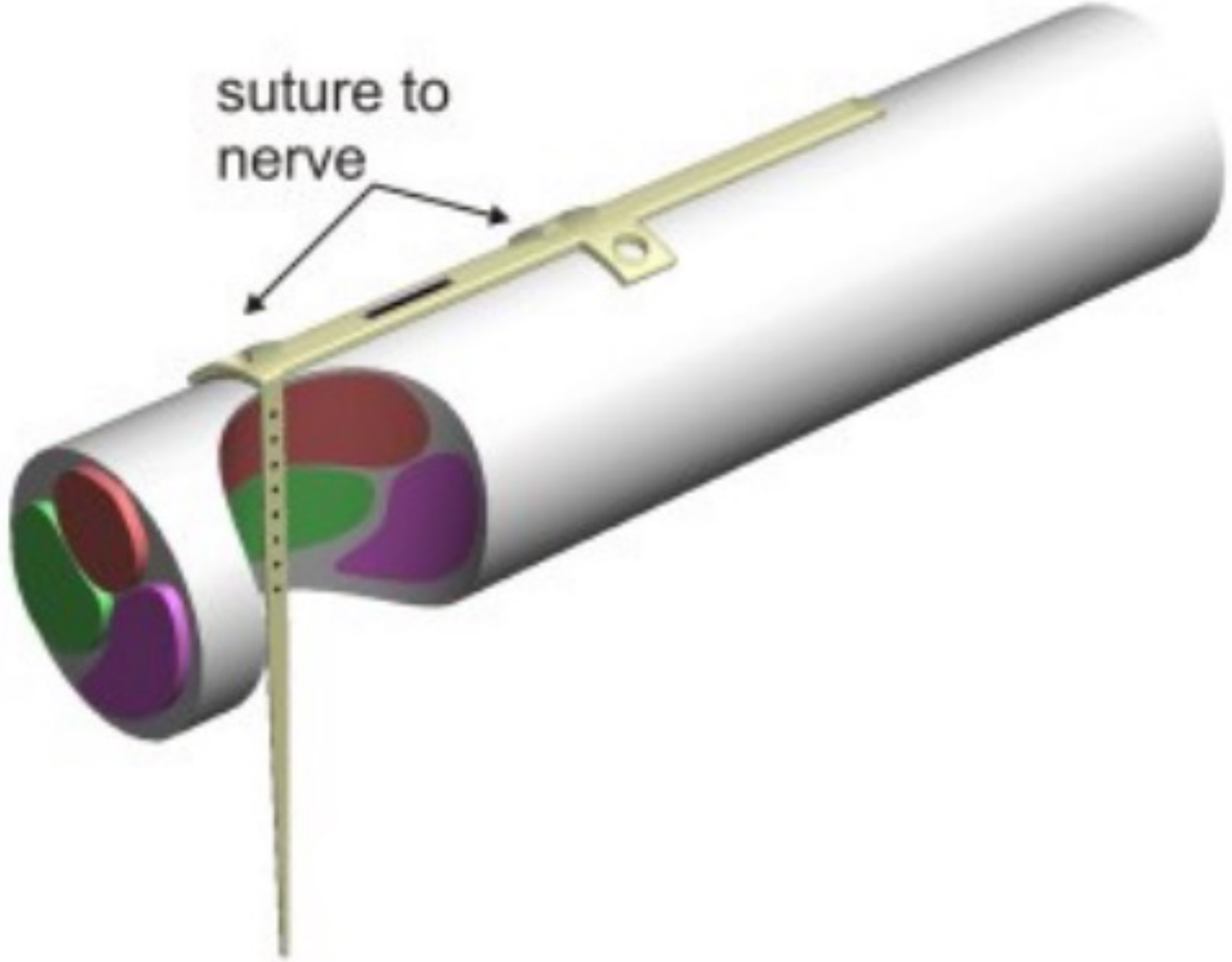


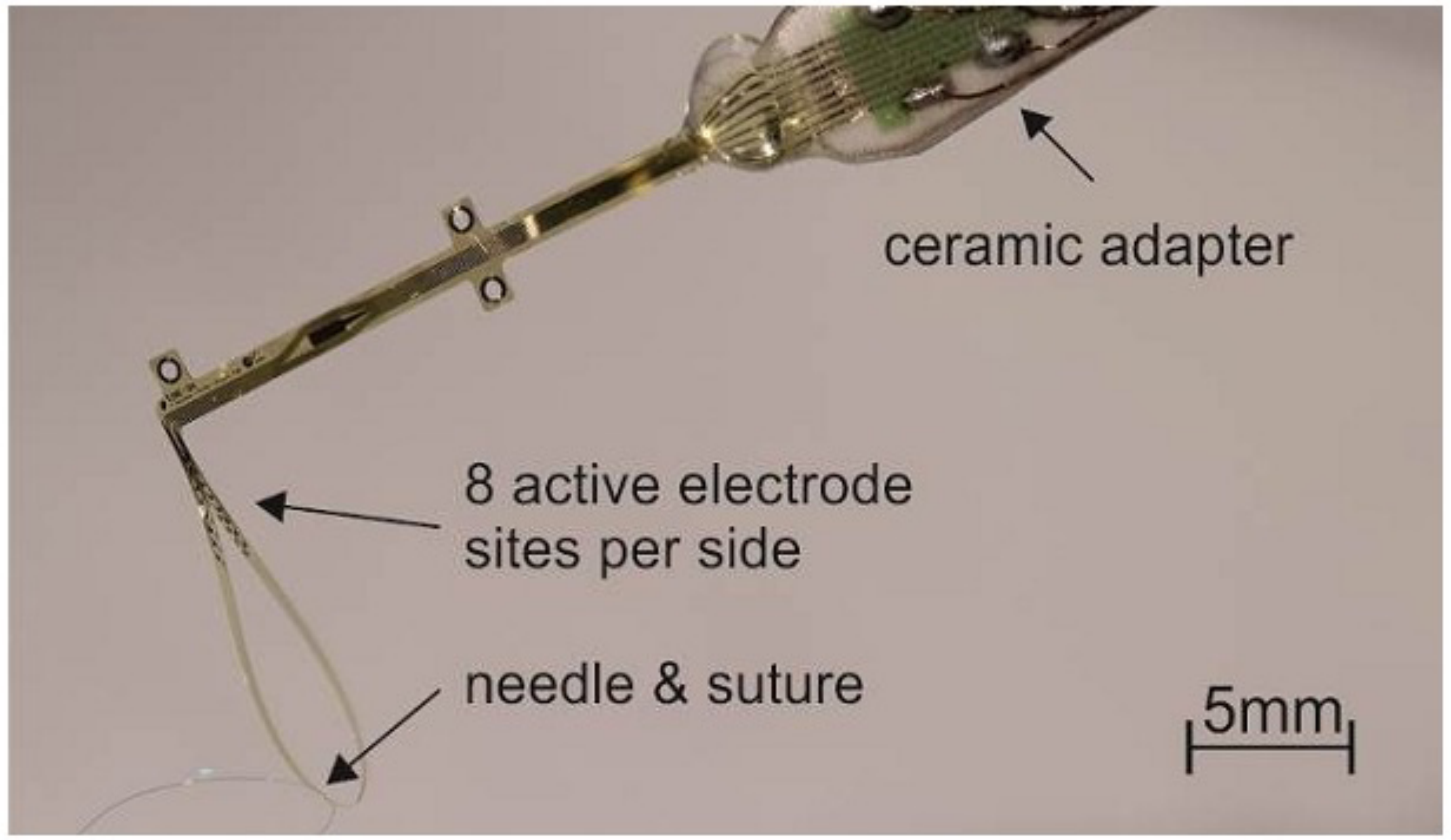


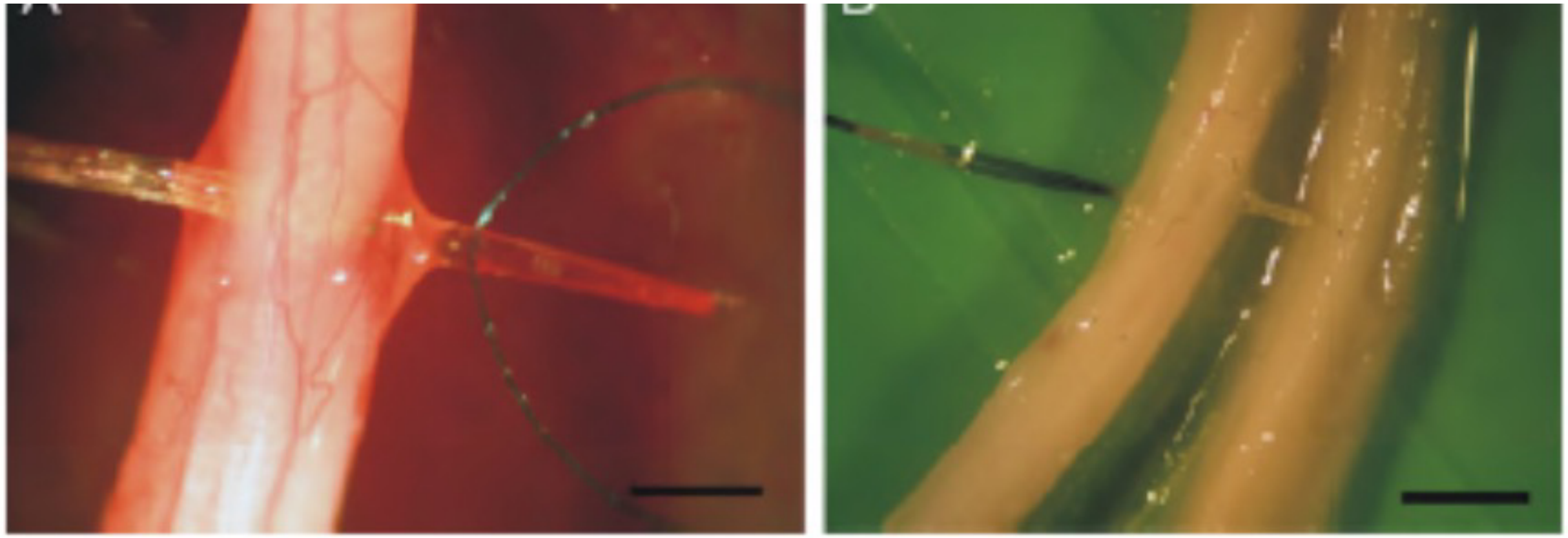
- L1-L4 and R1-R4 are electrode contacts on the left and right part of the device respectively.
- L0 and R0 are the indifferent recording reference electrodes.
- Two large ground electrodes are placed at the end of the electrode area needed for tripolar recording.

Transveral Intrafascicular Multichannel Electrode (TIME)



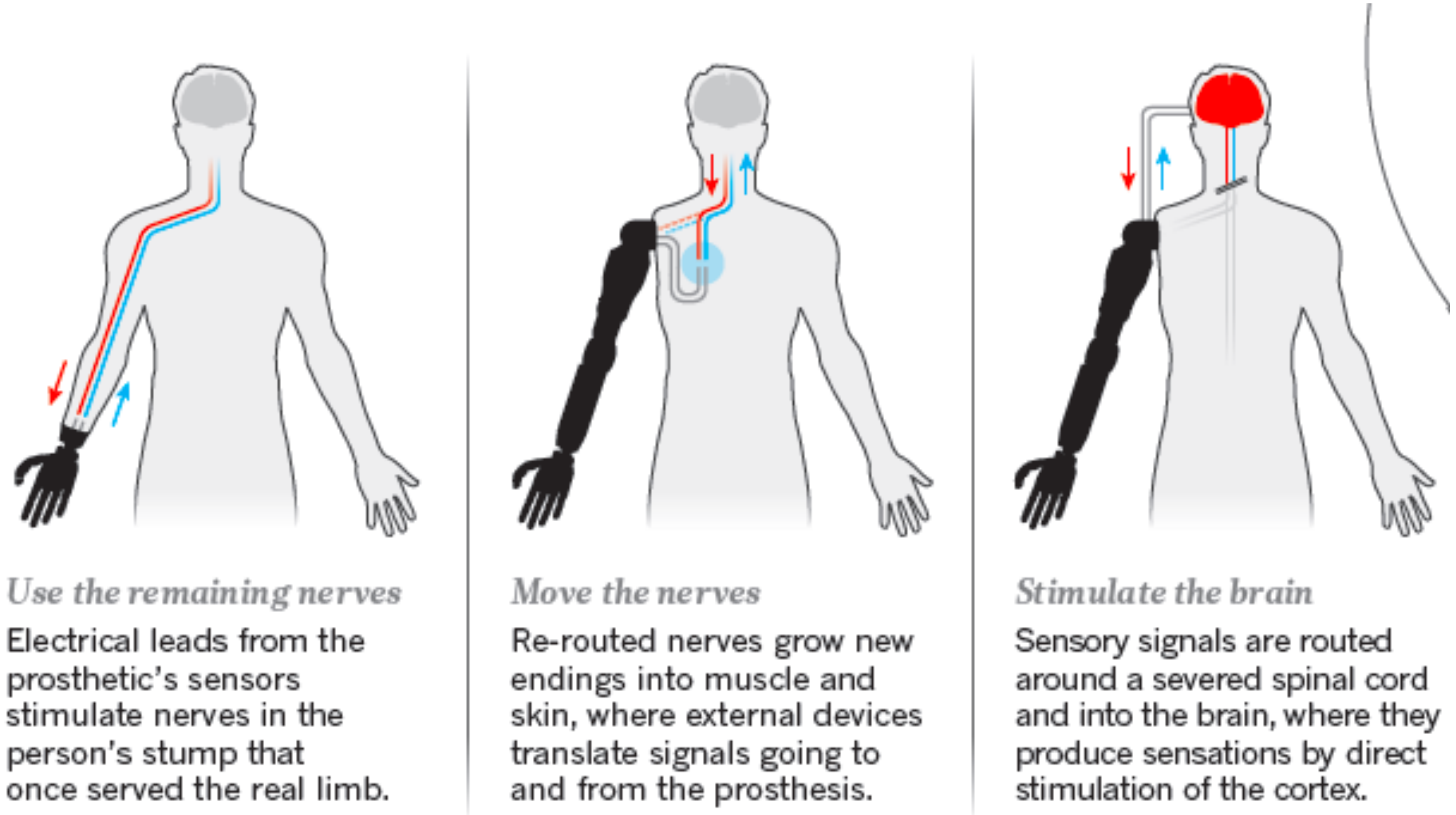






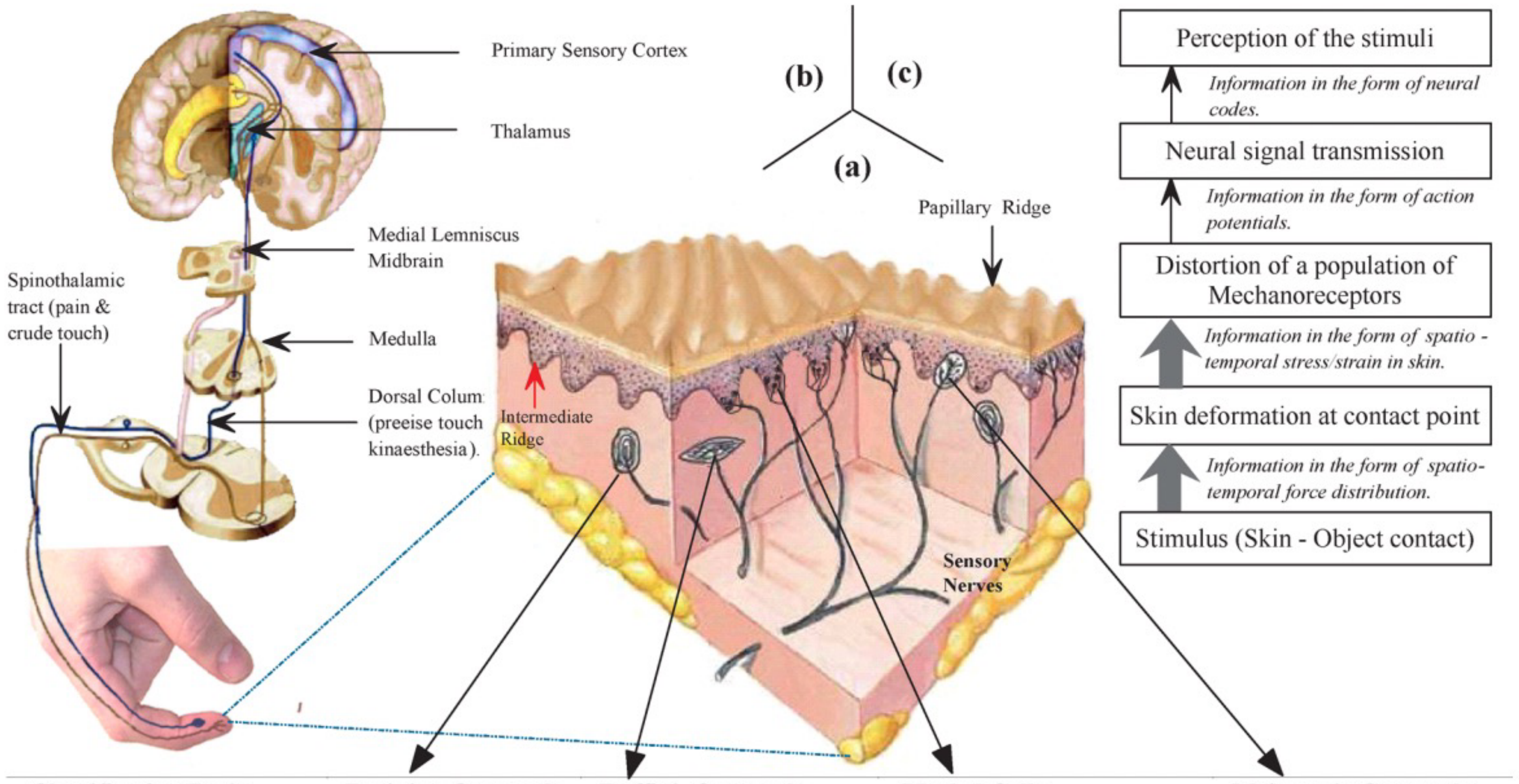
Sensory feedback

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



Kwok, Nature, 2013

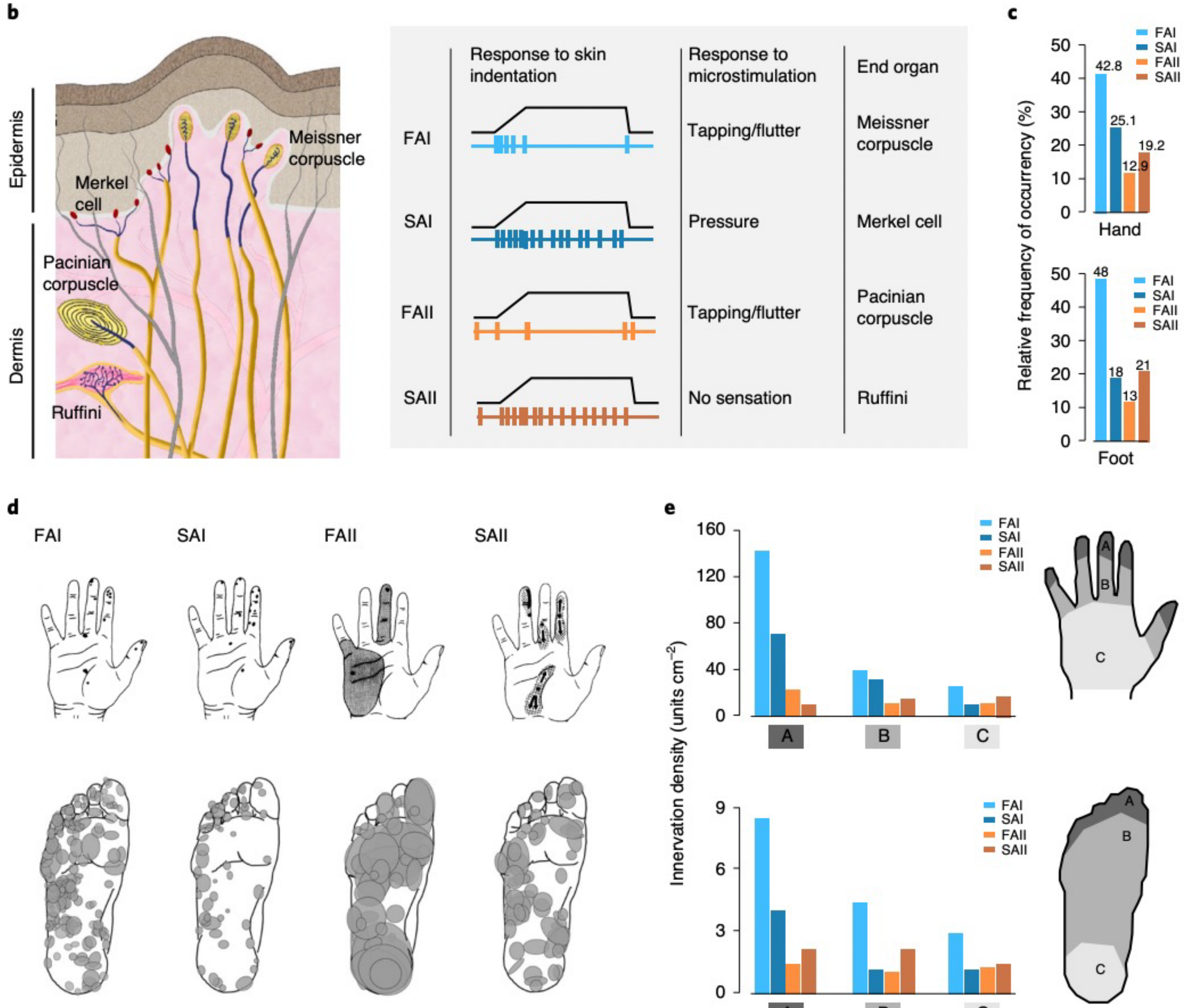
Human touch system



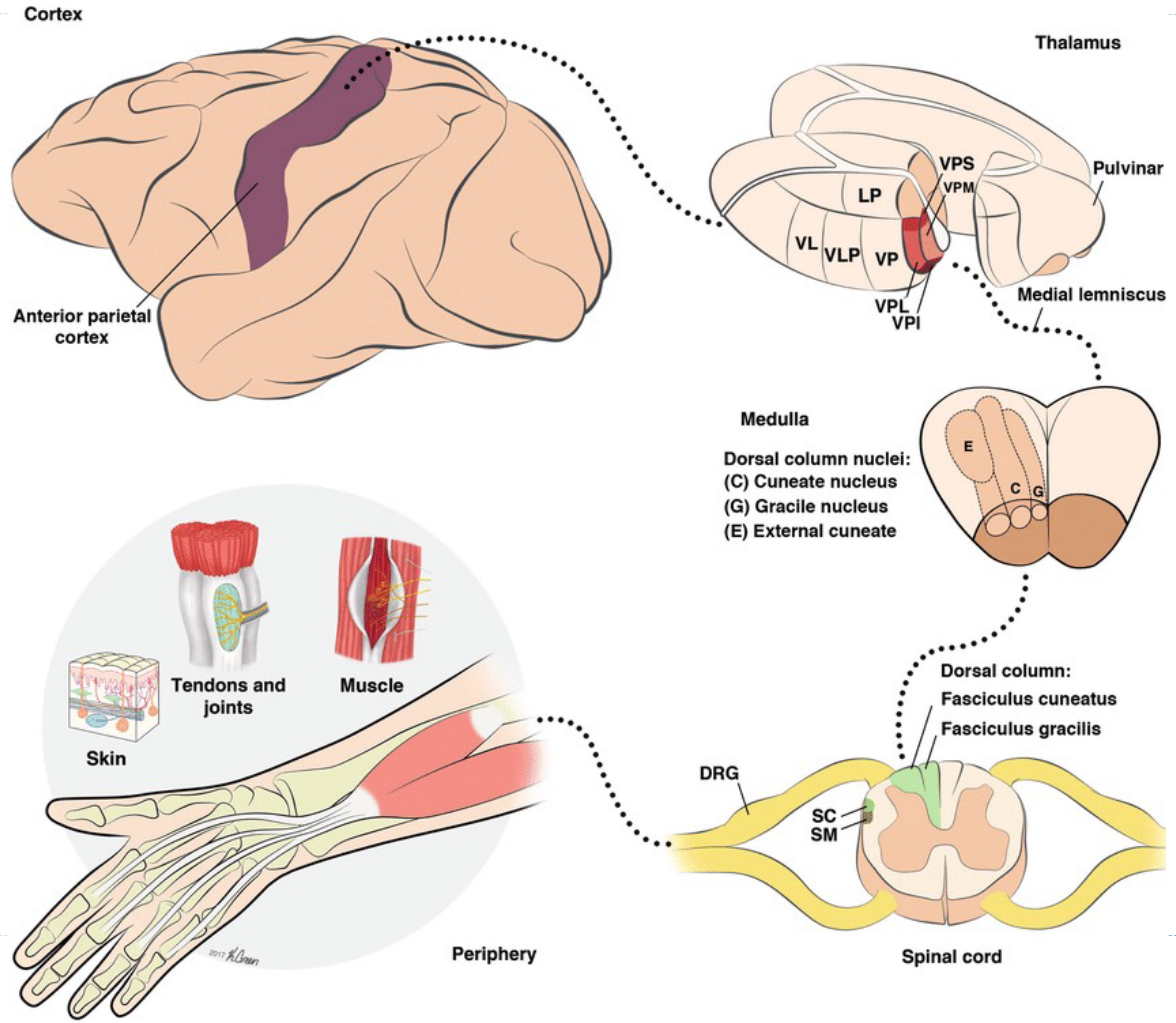
Classification Basis		Pacinian Corpuscle	Ruffini Corpuscle	Merkel Cells	Meissner's Corpuscle
Type		FA II	SA II	SA I	FA I
Adaptation Rate		Fast	Slow	Slow	Fast
Spatial Acuity (mm)		10+	7+	0.5	3-4
Vibration/rapid indent. threshold	Best(μm)	0.01	40	8	2
	Mean(μm)	0.08	300	30	6
Stimuli Frequency (Hz)		40-500+	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

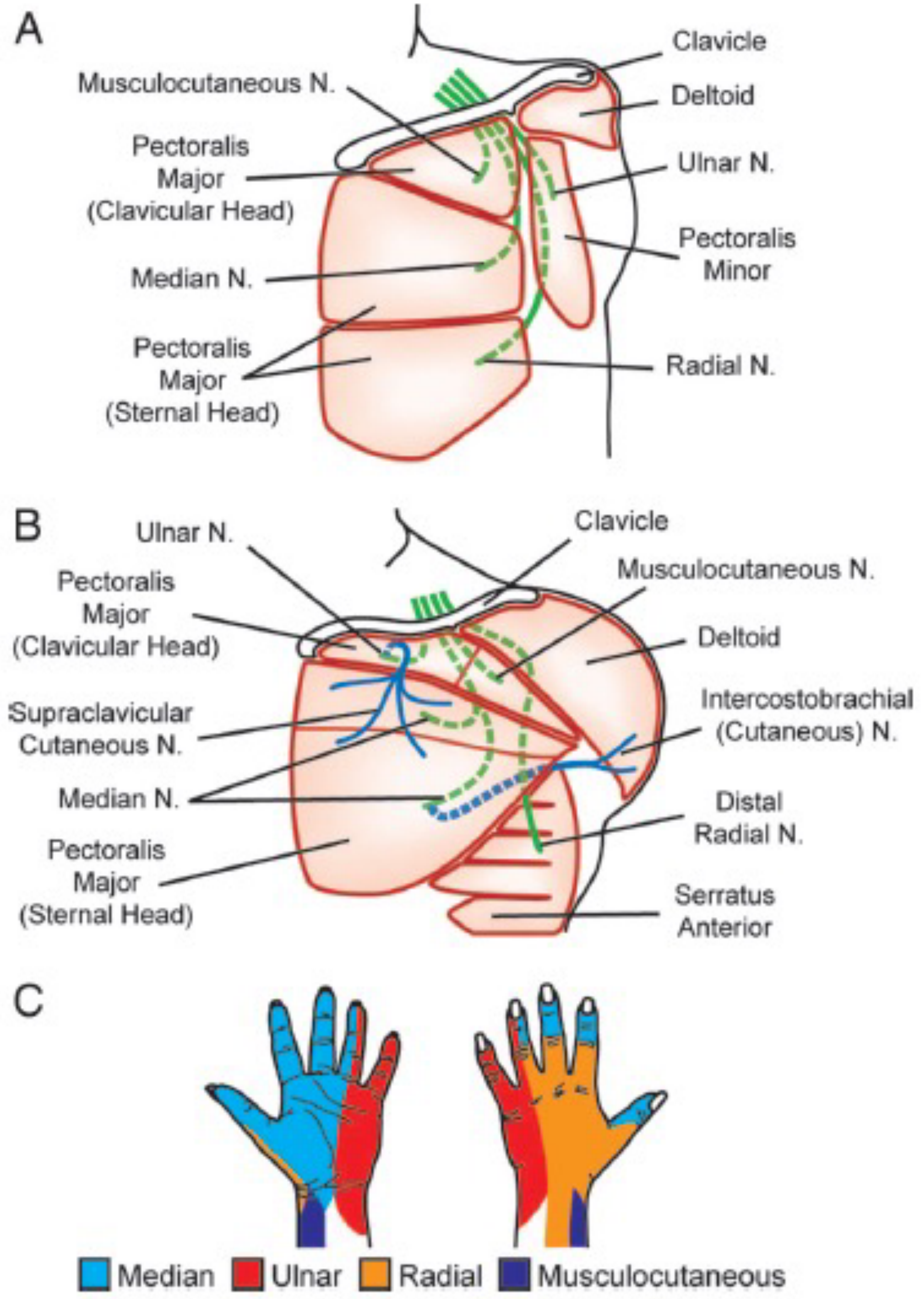
Human touch system

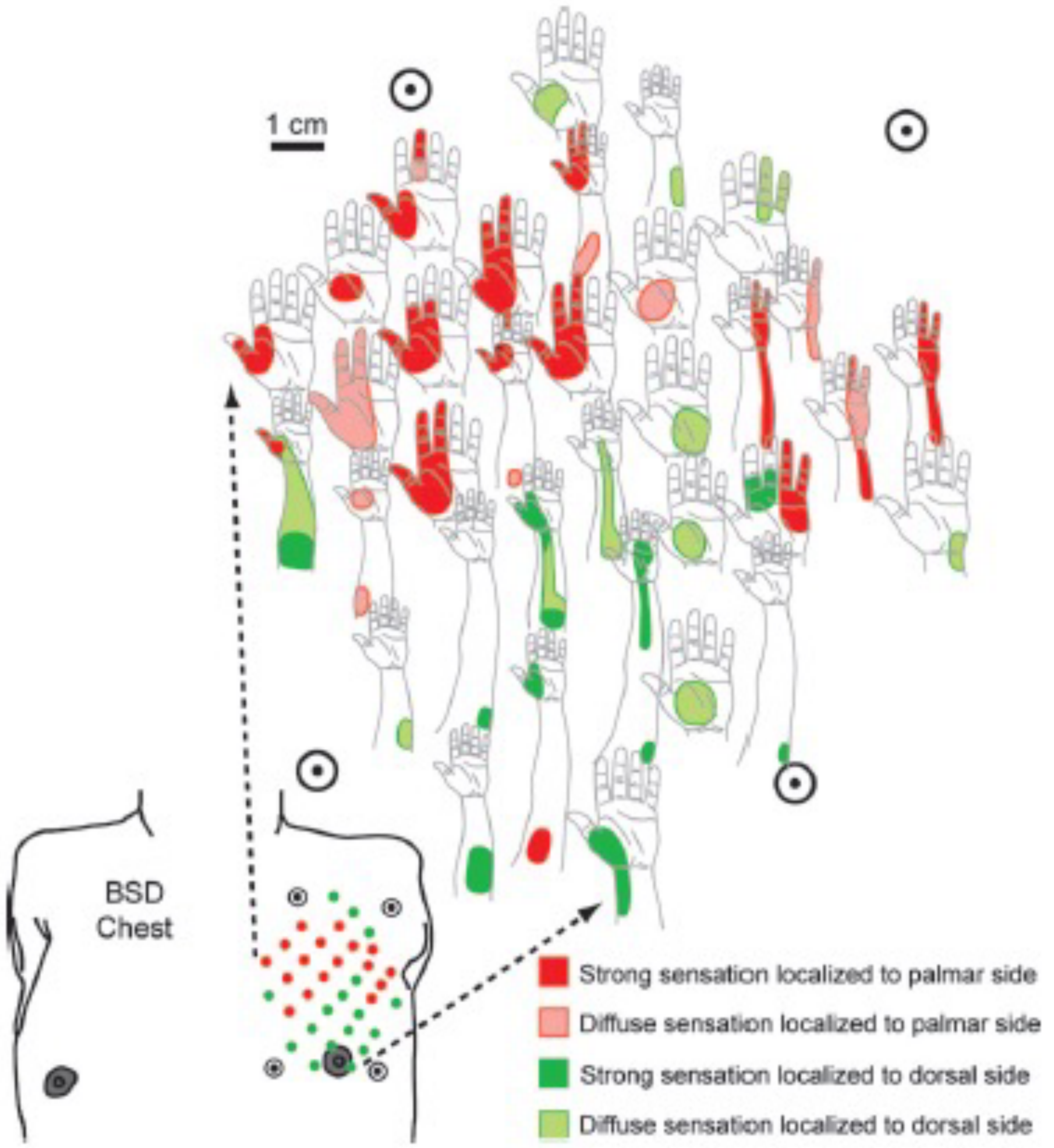


Human touch system



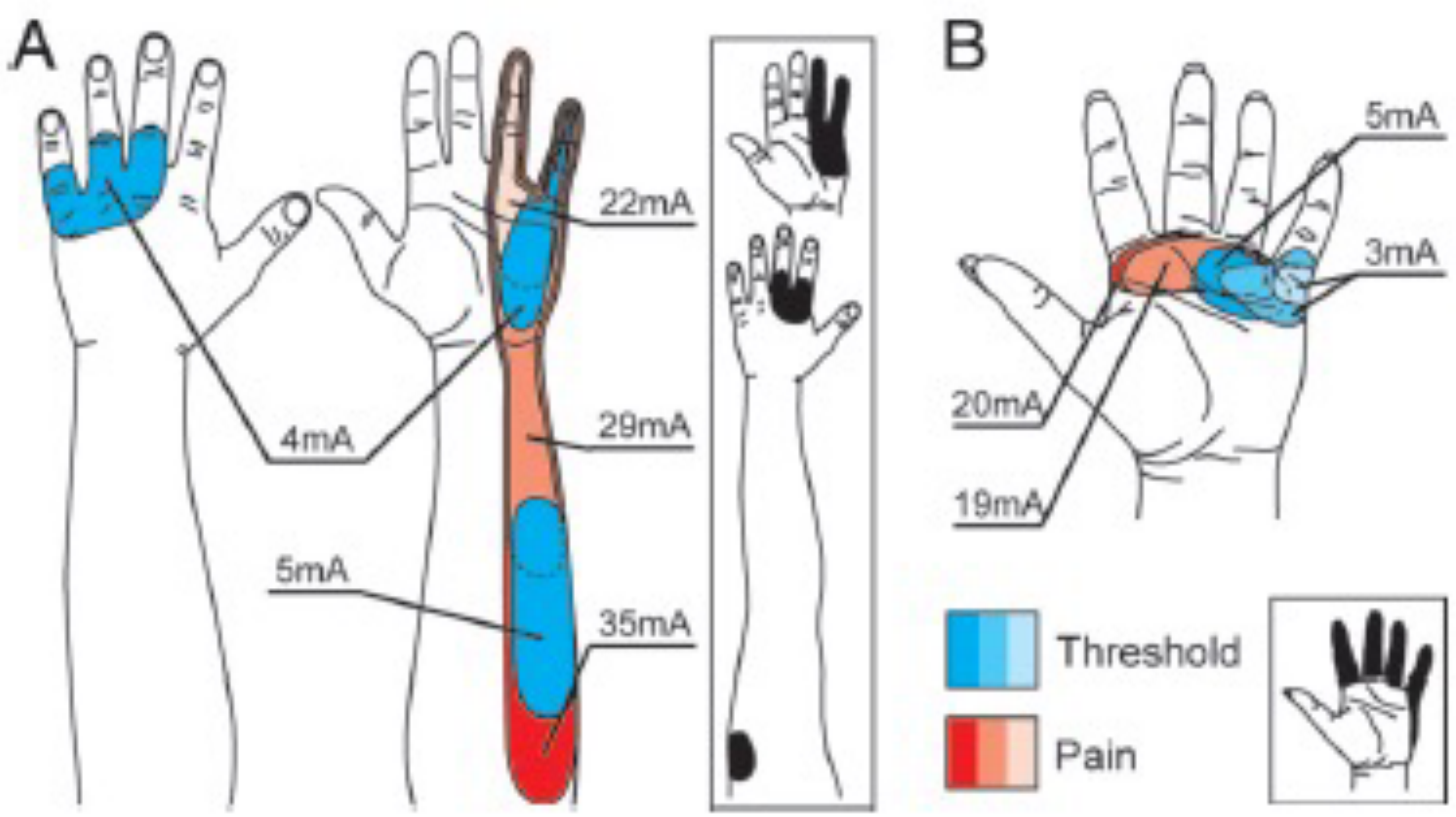
Targeted Muscle Reinnervation

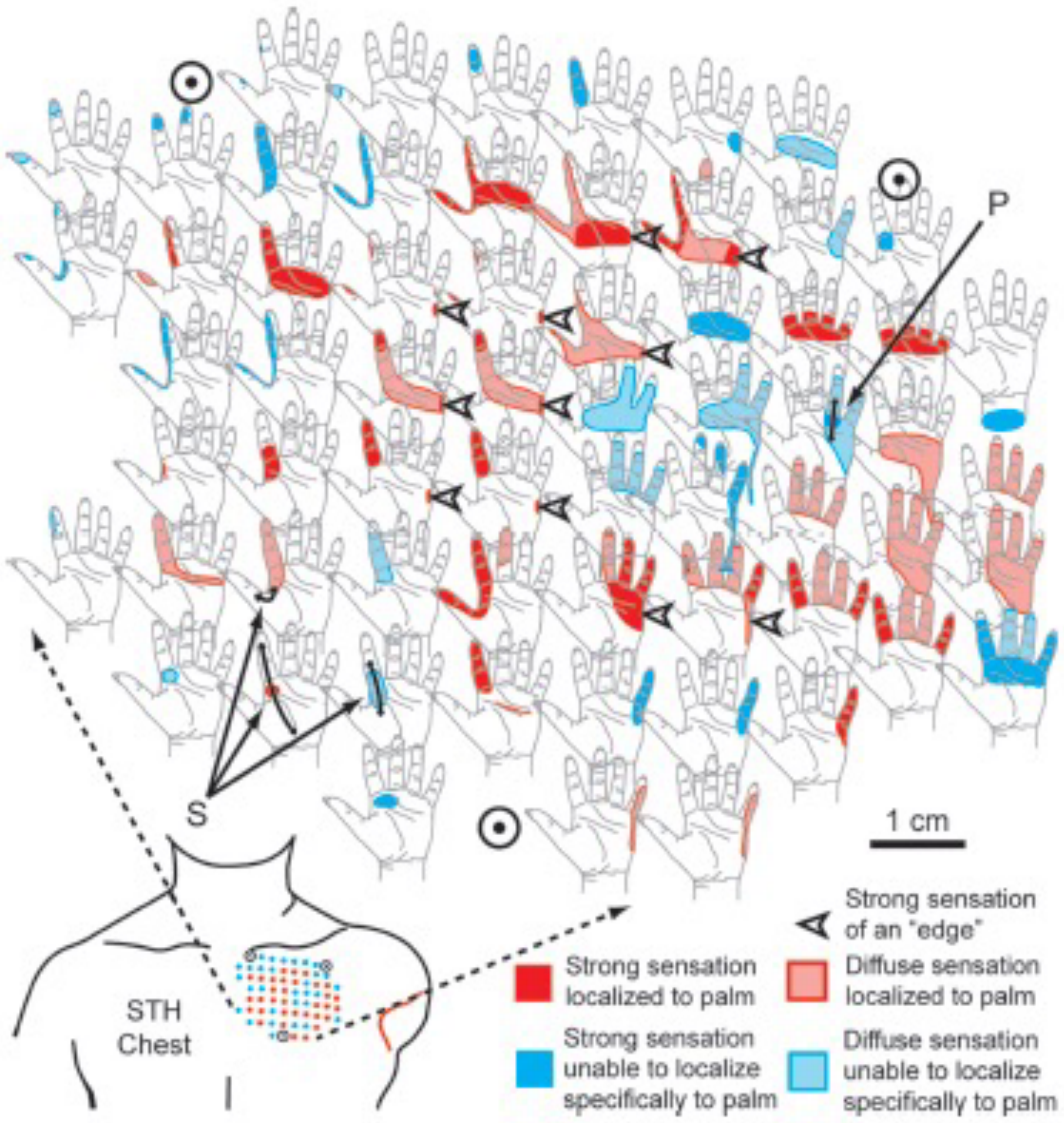




Kuiken et al., 2007, 2008

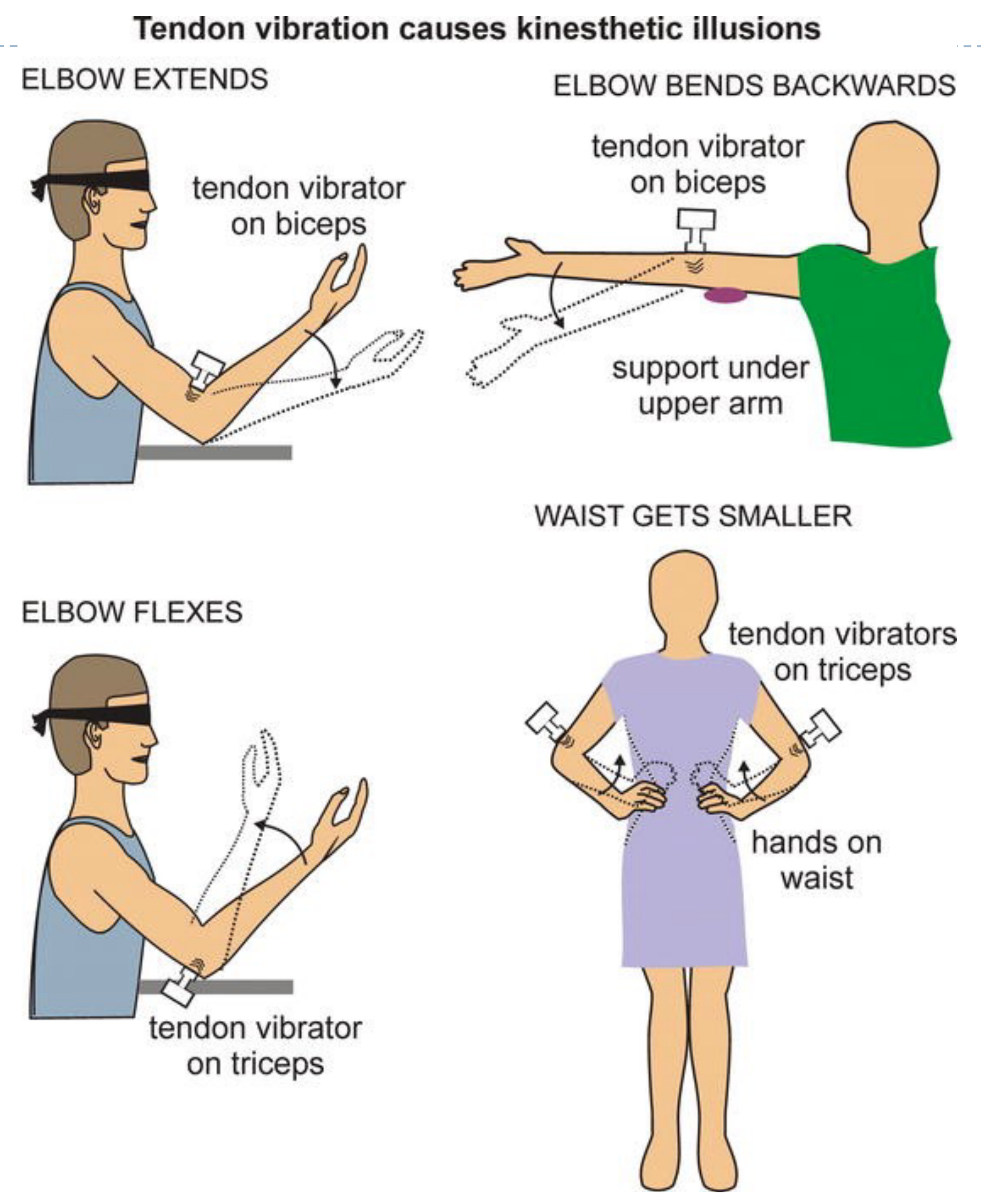
Targeted Muscle Reinnervation

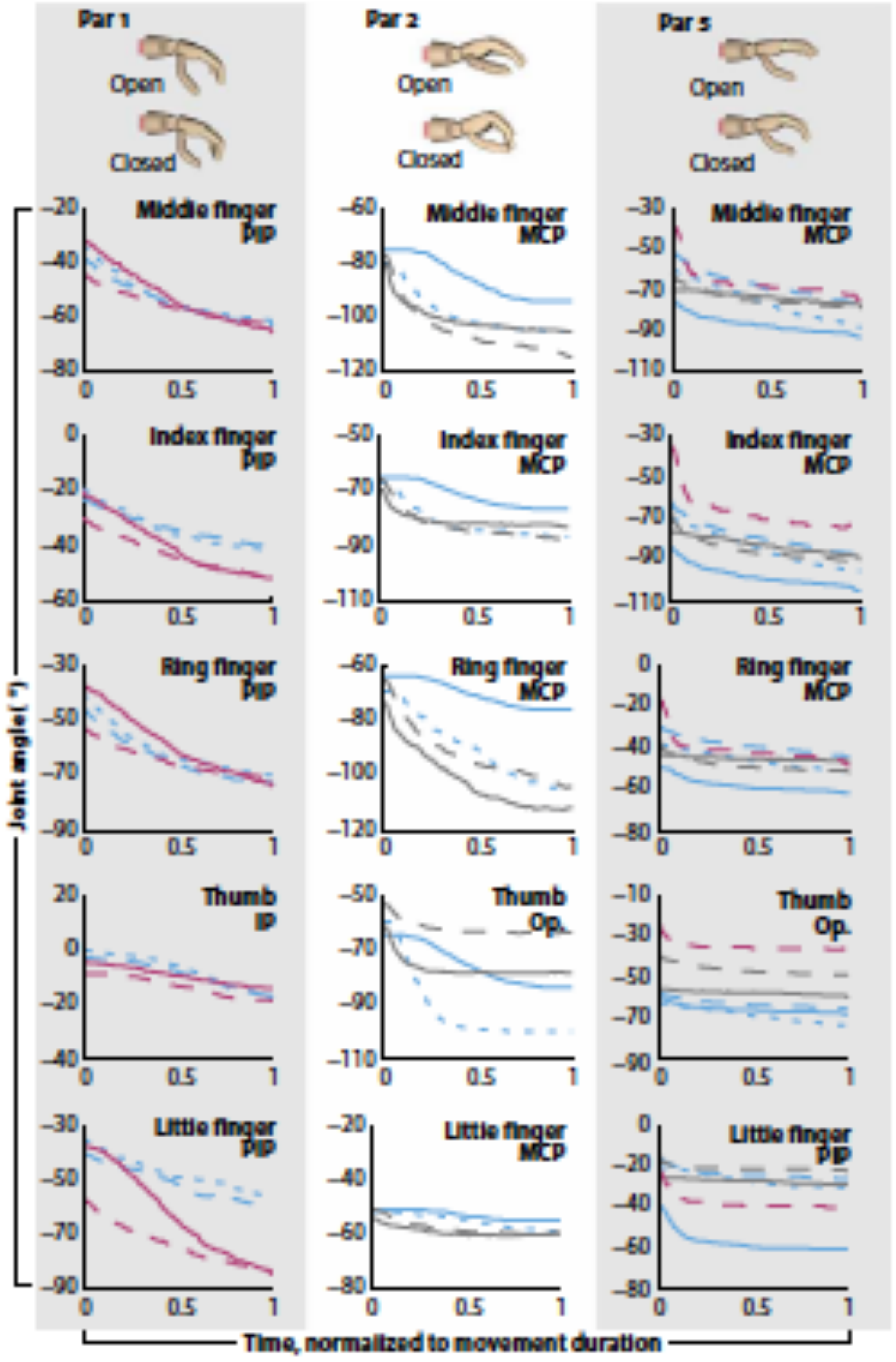


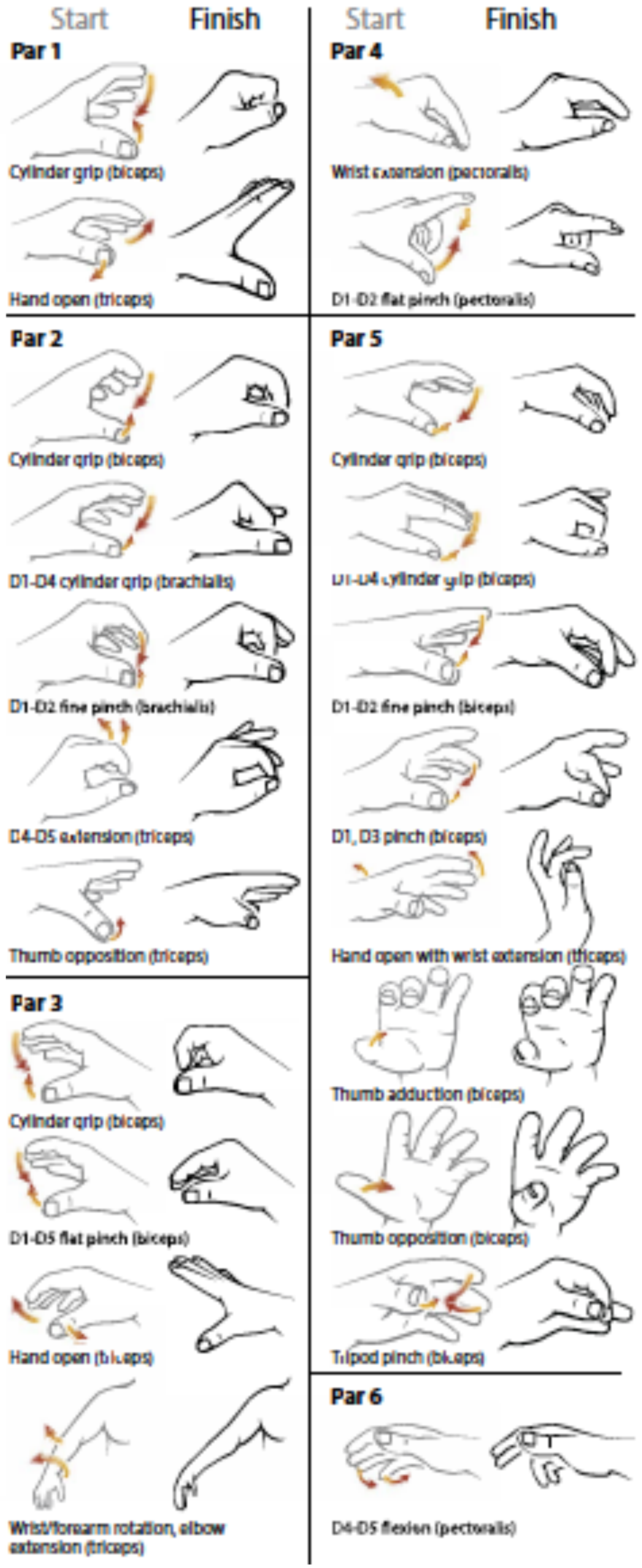


- Very interesting solution but more suitable for proximal (shoulder) amputations
- **Sensory feedback is possible but difficult to be daily usable**

TMR and proprioceptive illusion



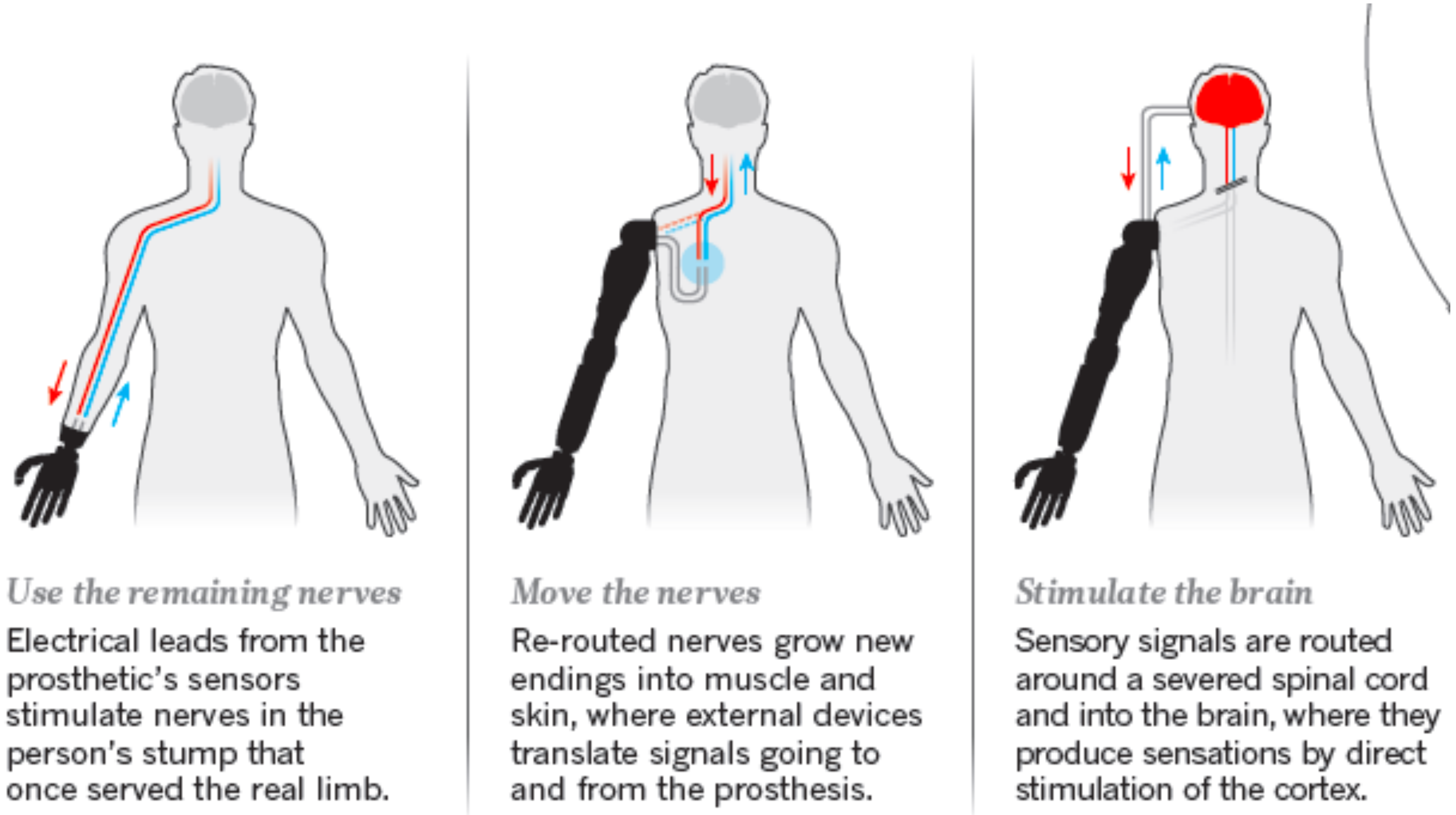




Marasco et al, STM, 2018

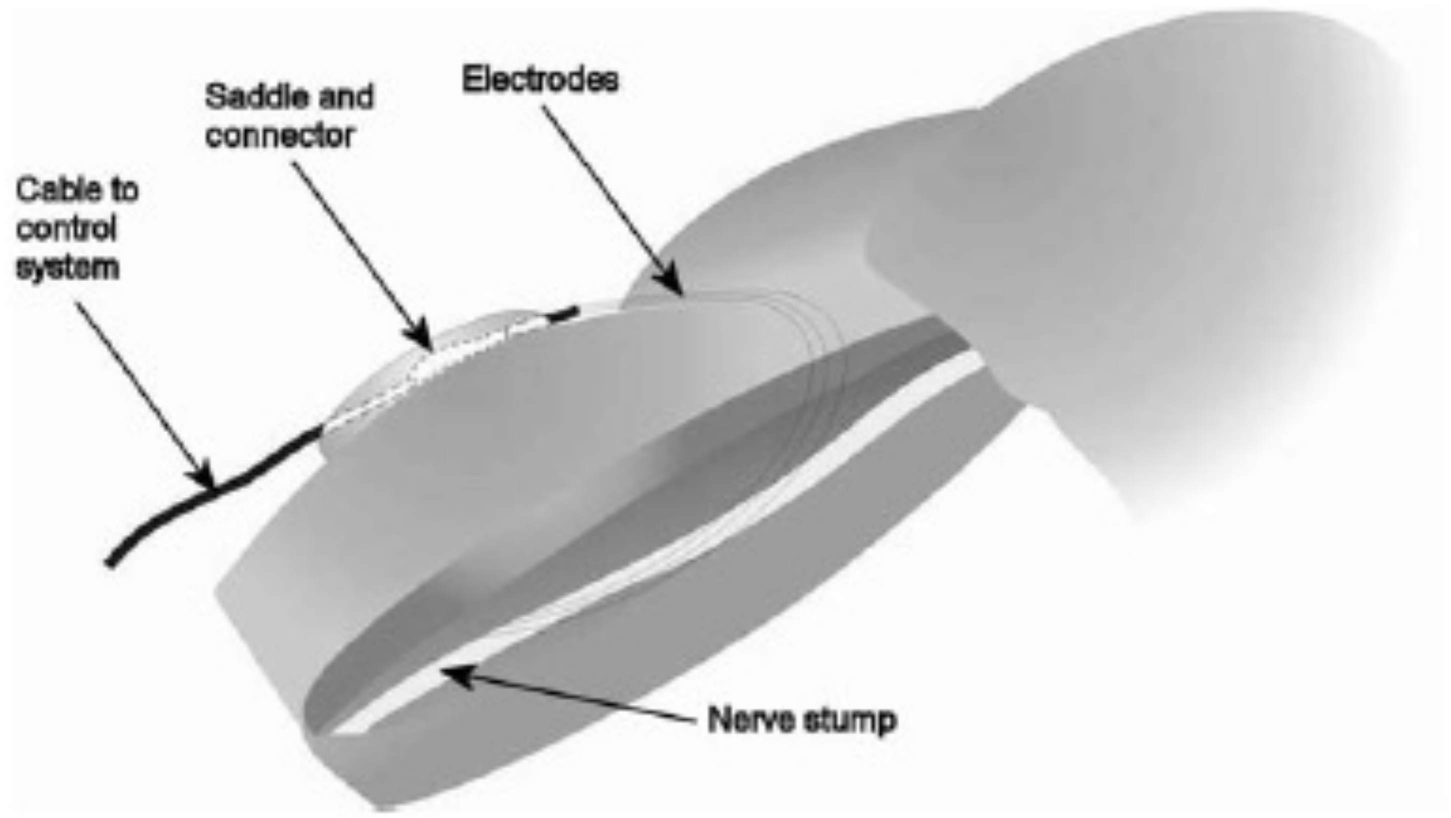
Sensory feedback

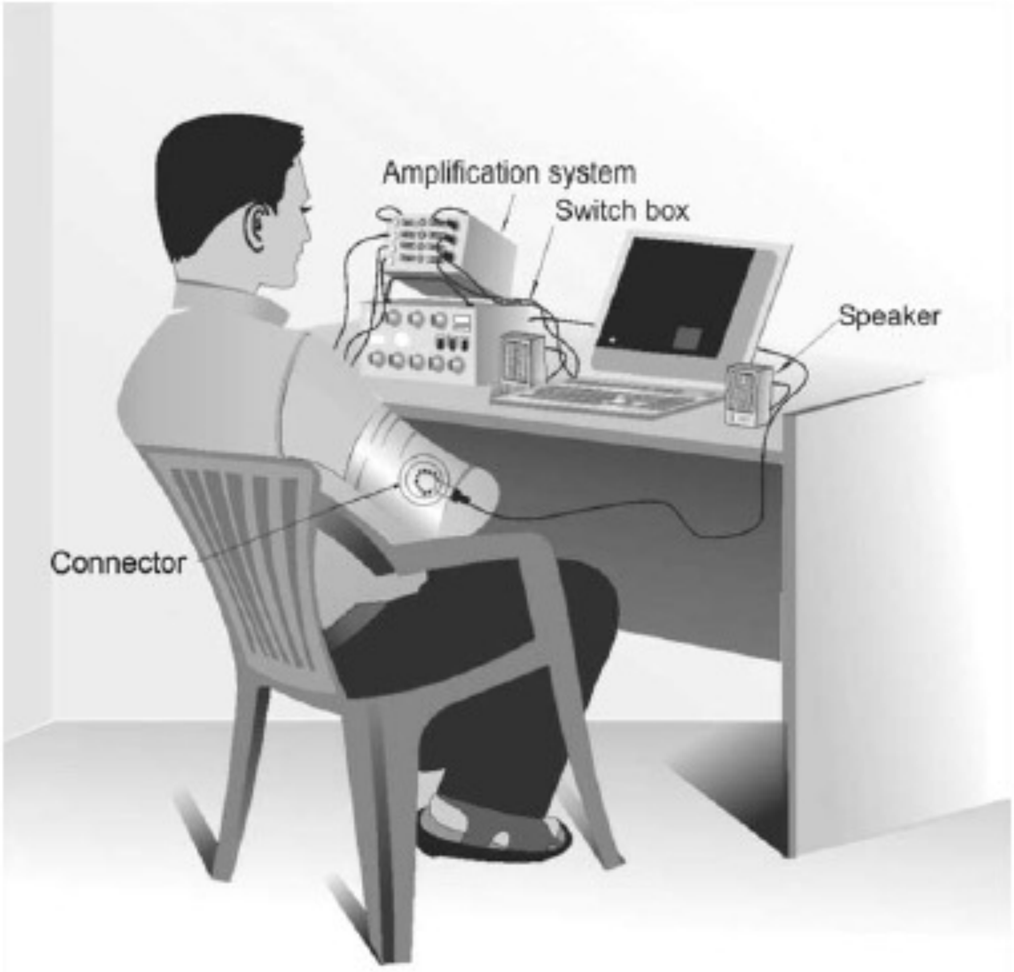
Real-time, and natural feedback from the hand prosthesis to the user is essential in order to enhance the control and functional impact of prosthetic hands in daily activities, prompting their full acceptance by the users

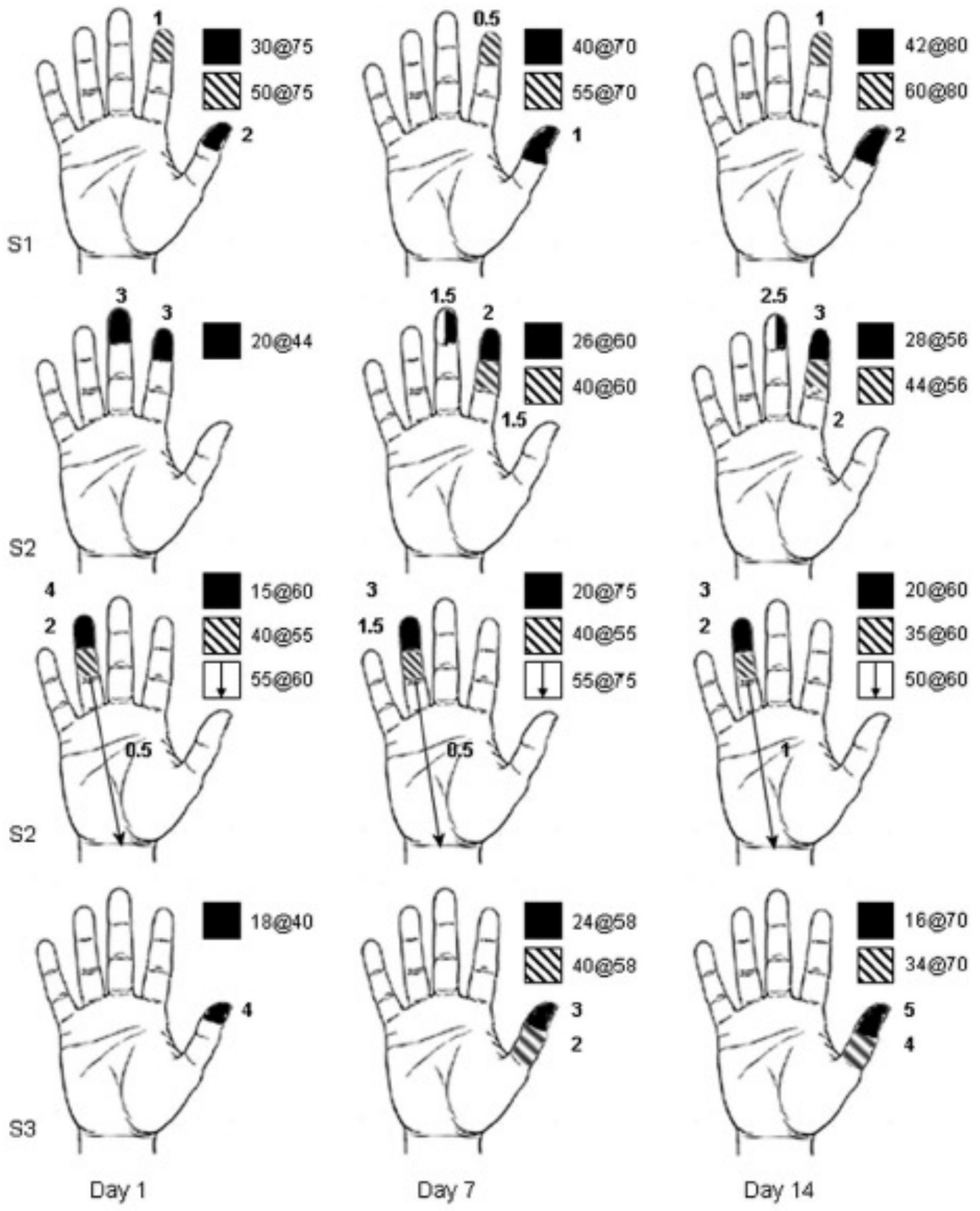


Kwok, Nature, 2013

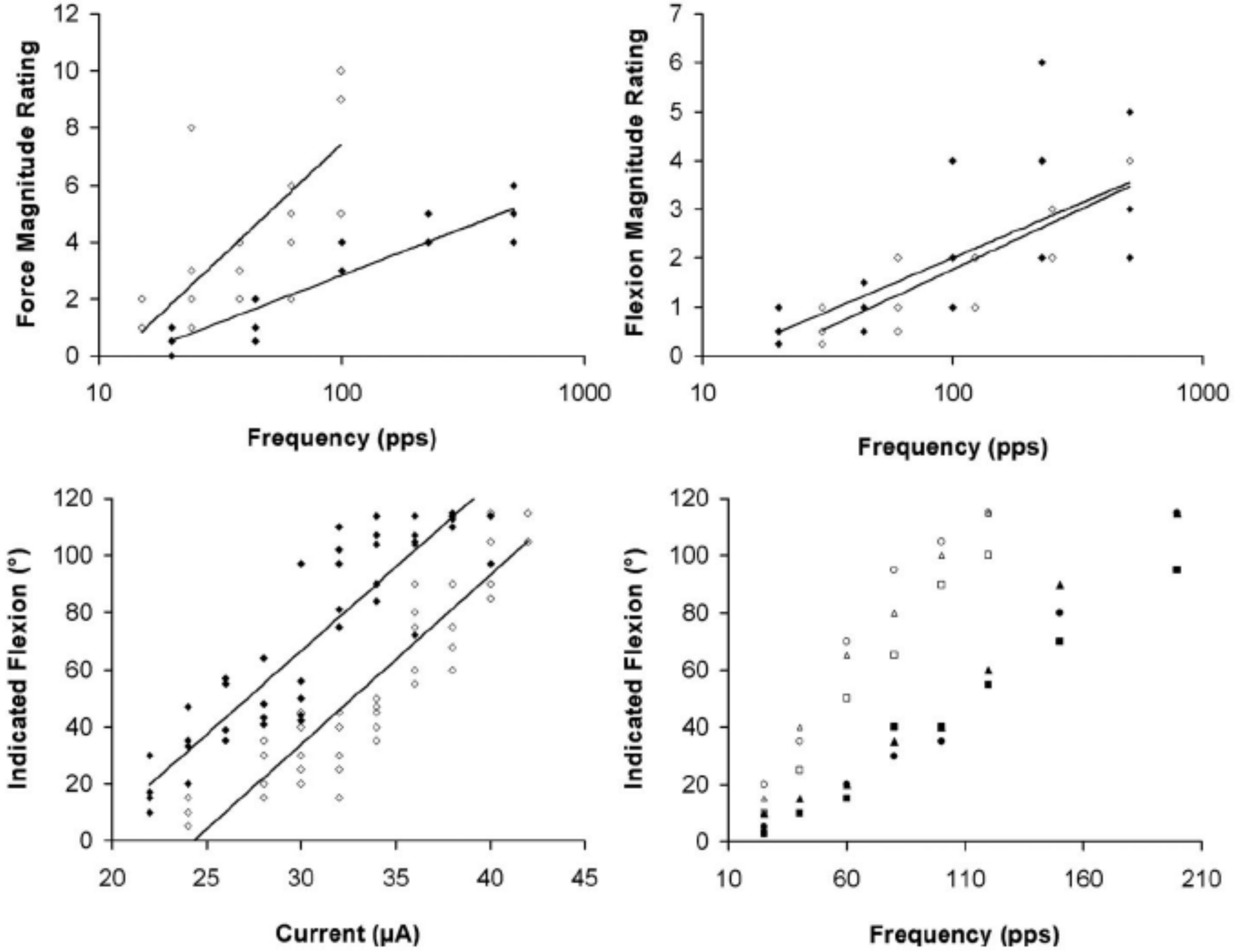
First intraneural experiment



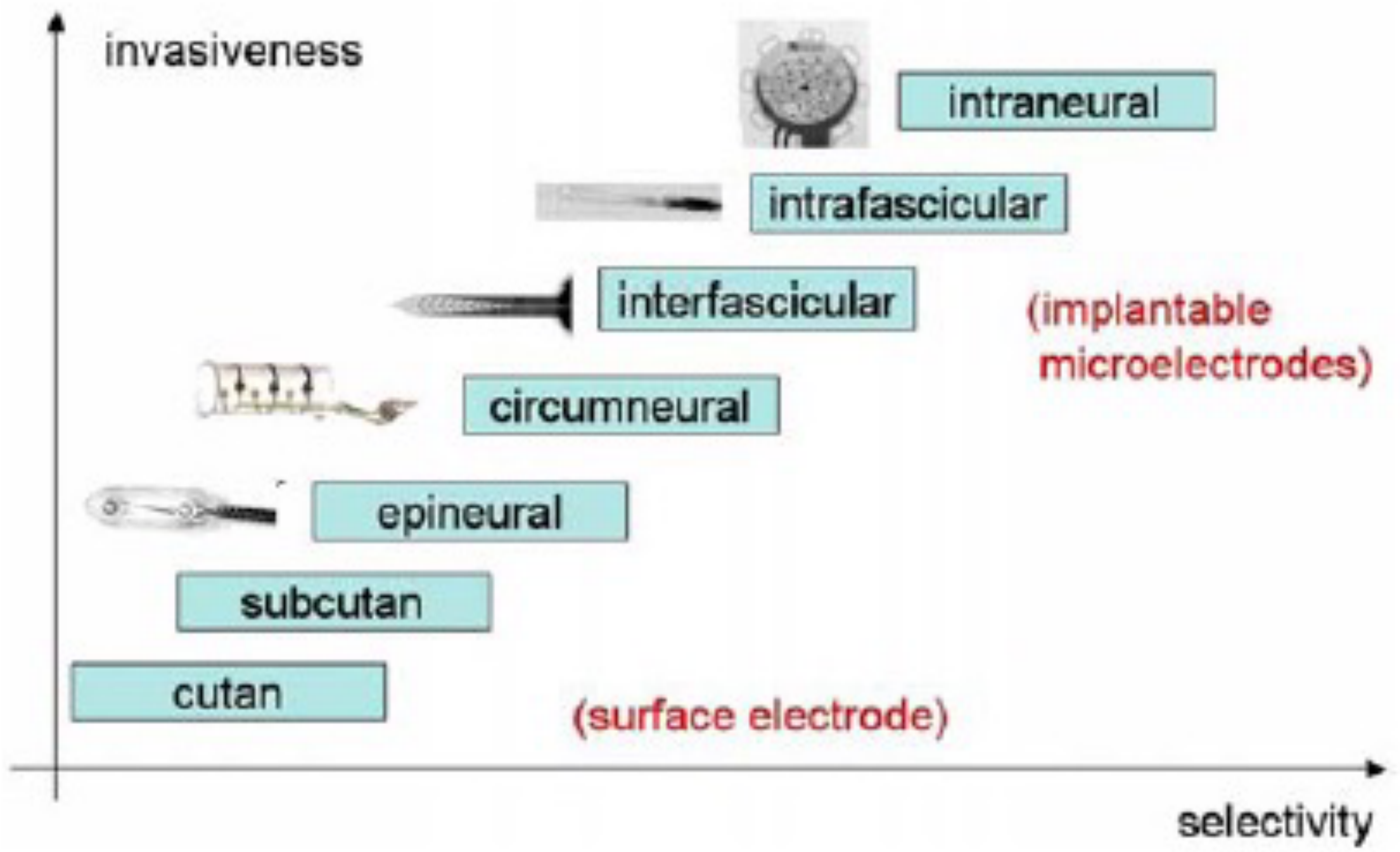




First intraneural experiment

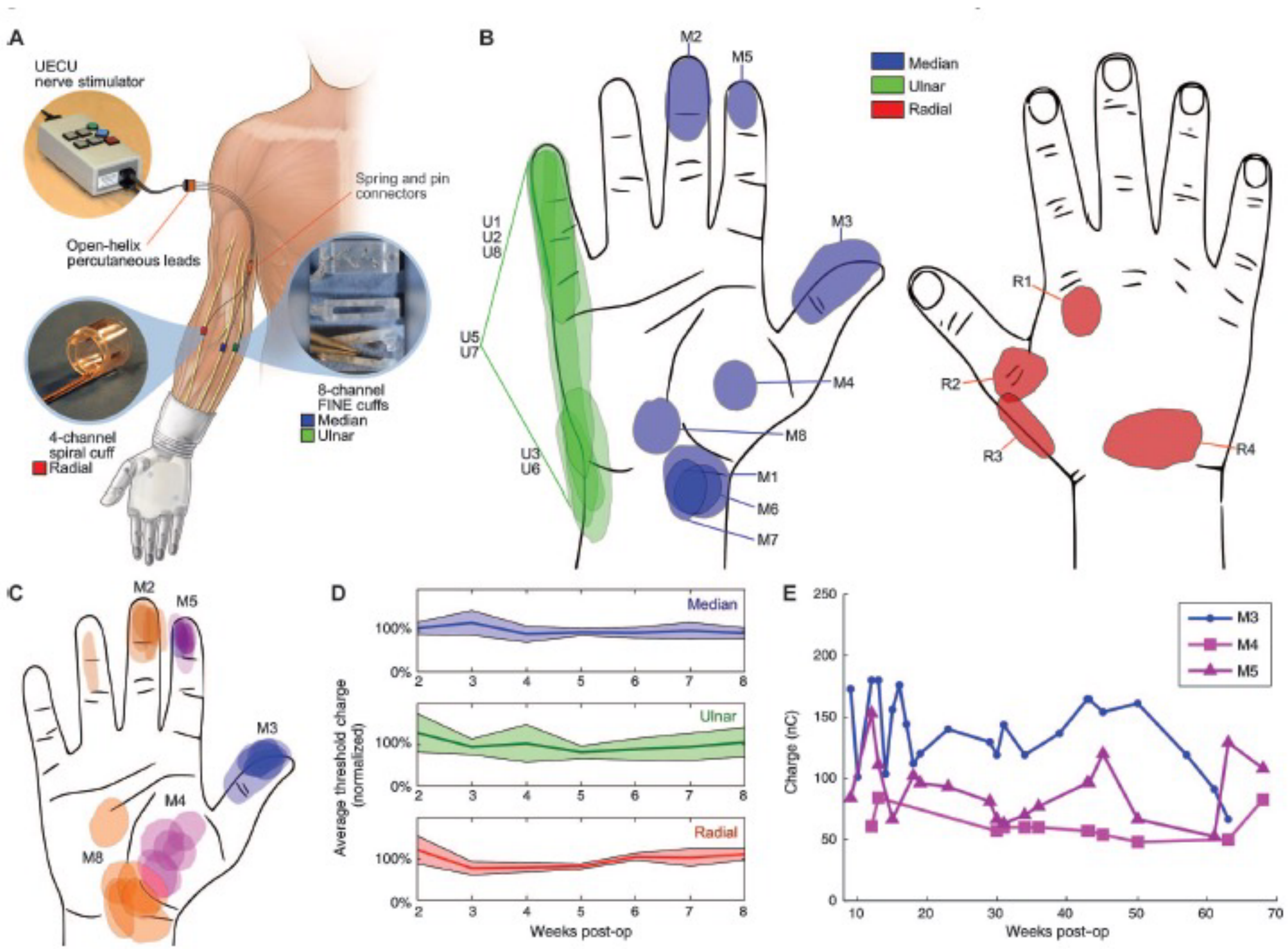


Peripheral implantable electrodes

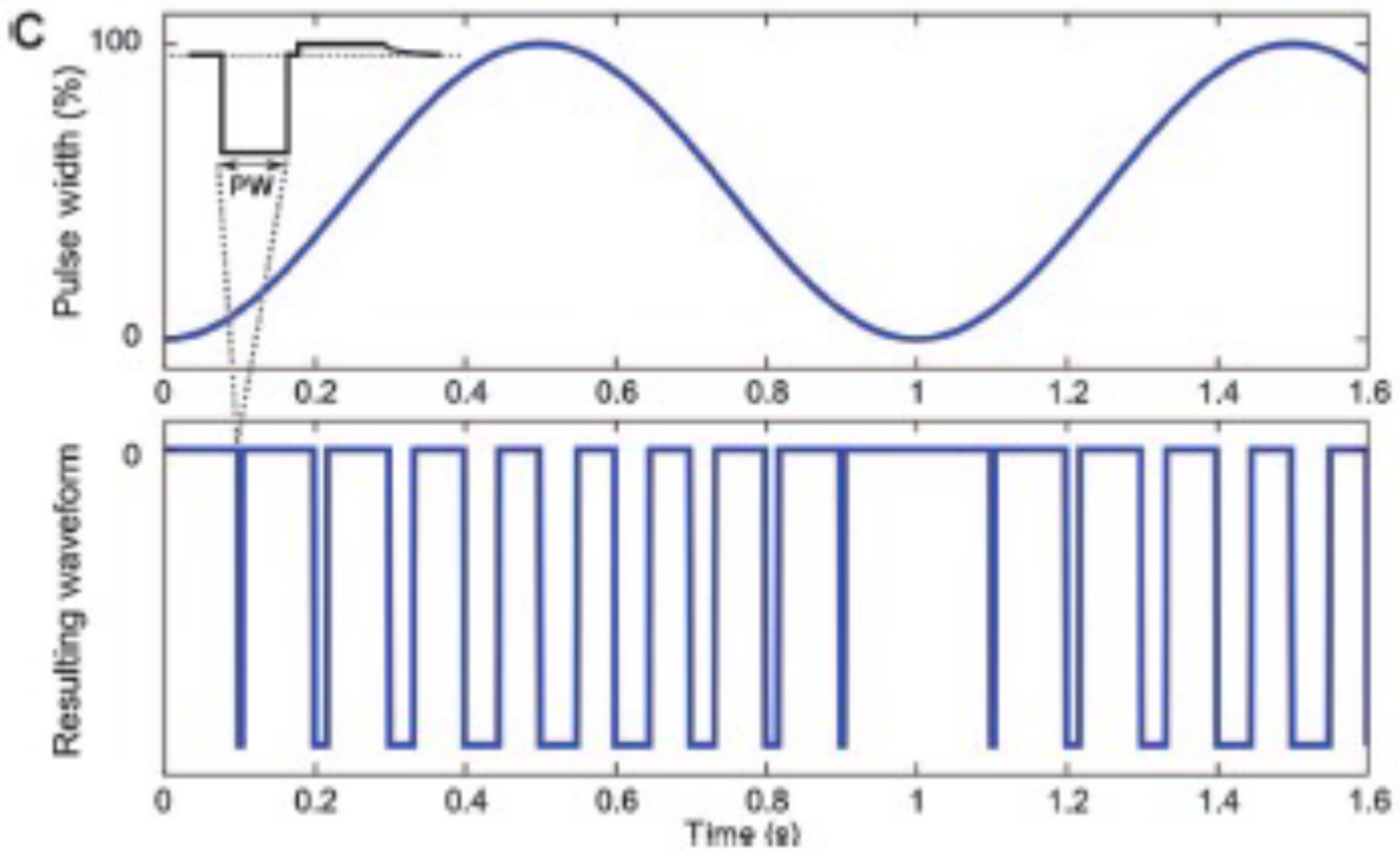


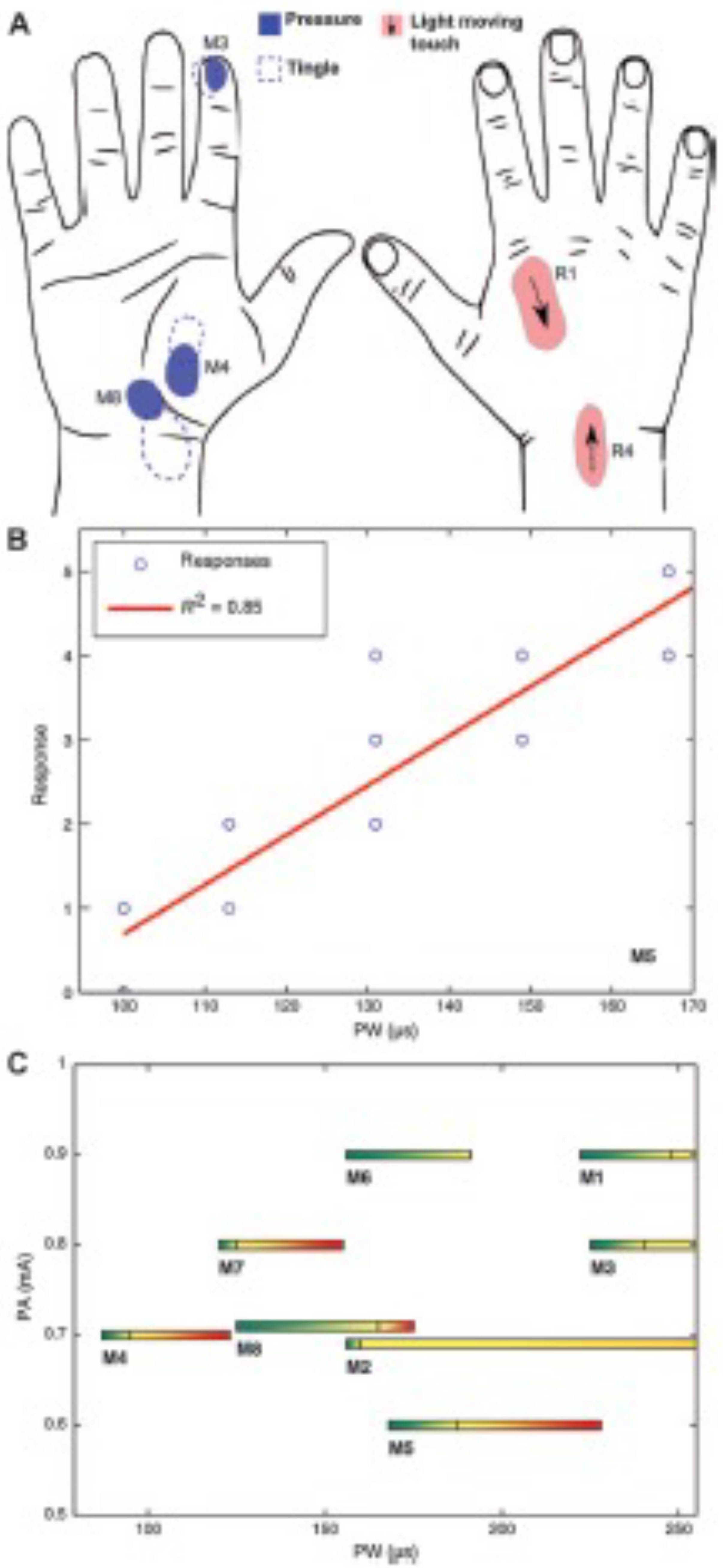
Micera et al., IEEE T-NSRE, 2008

Sensory feedback using FINE electrodes

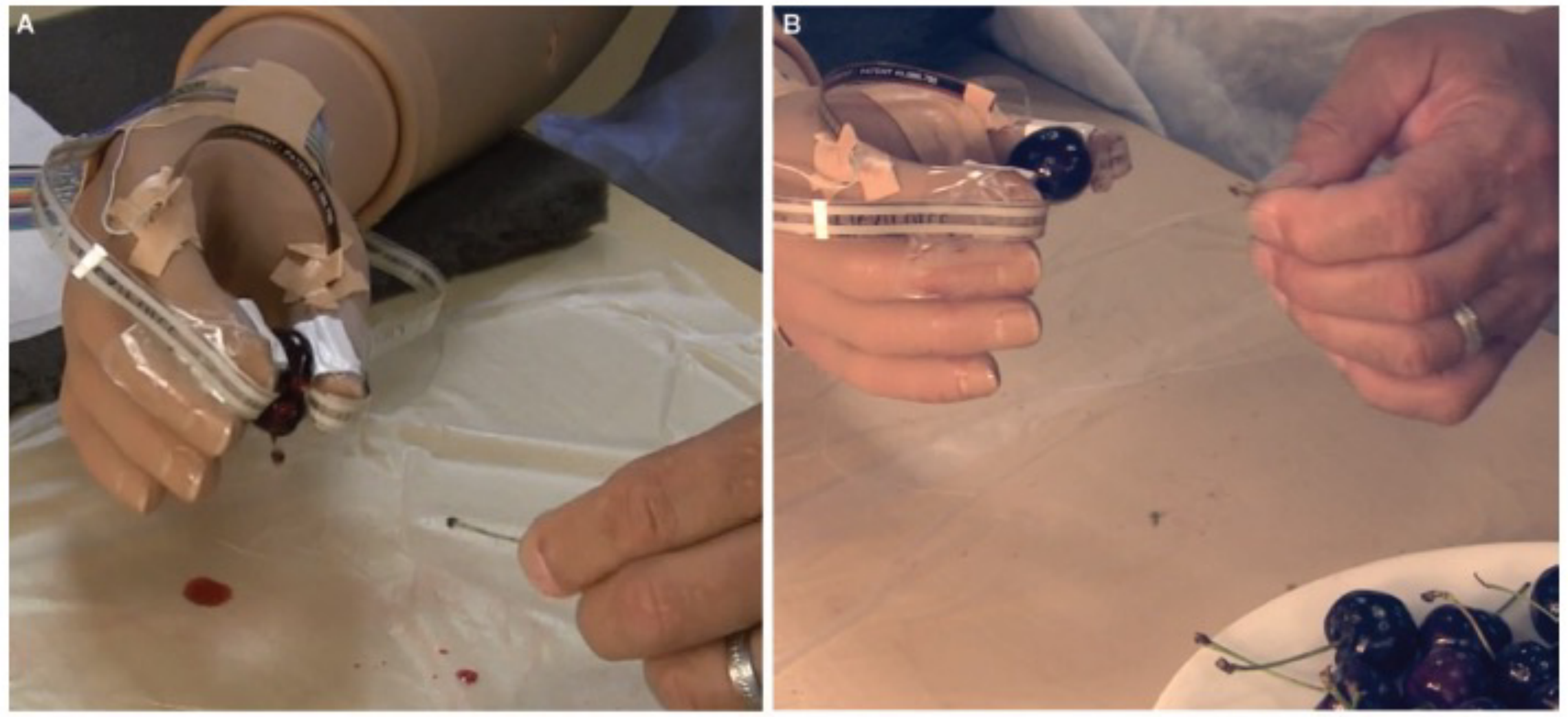


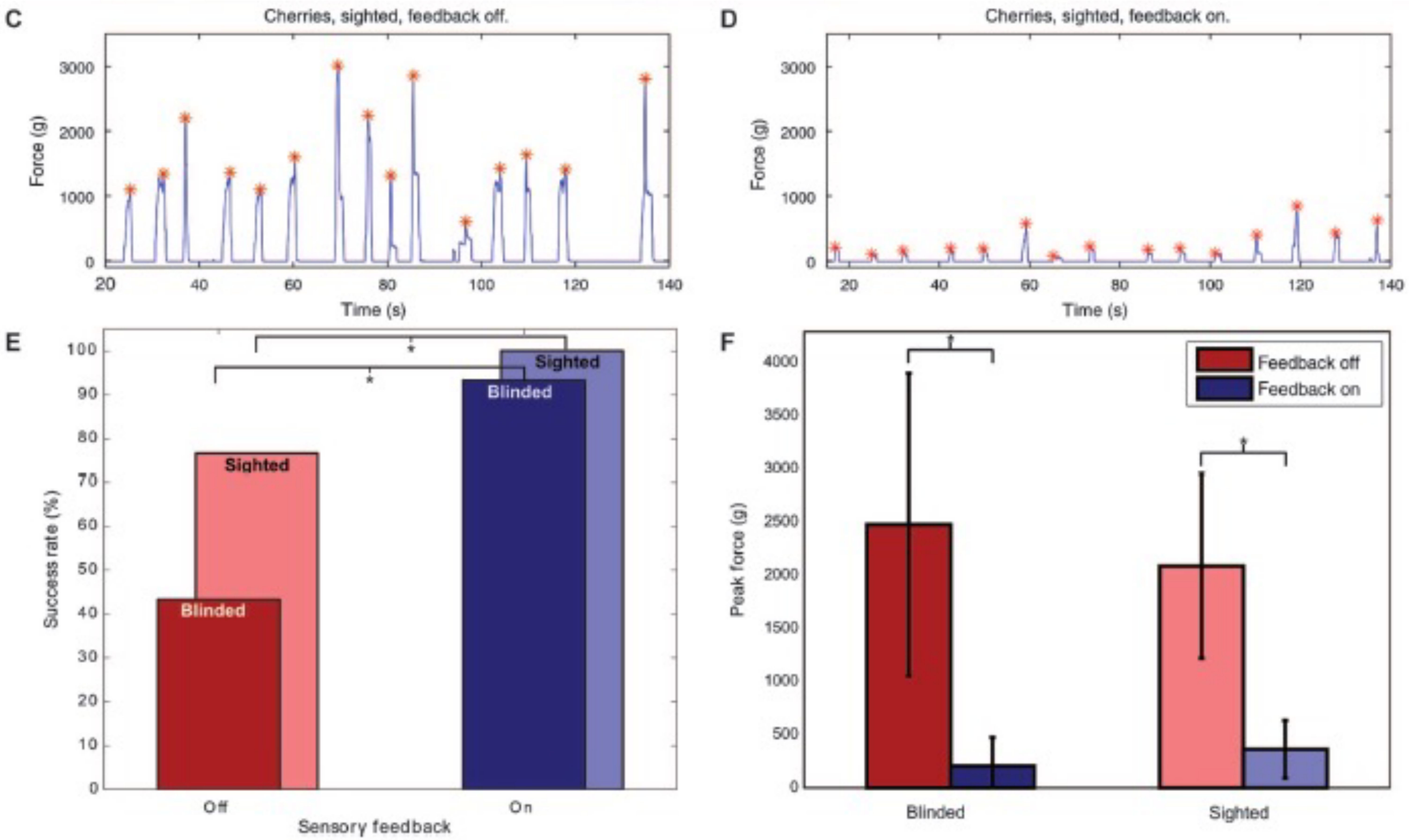
Sensory feedback using FINE electrodes





Sensory feedback



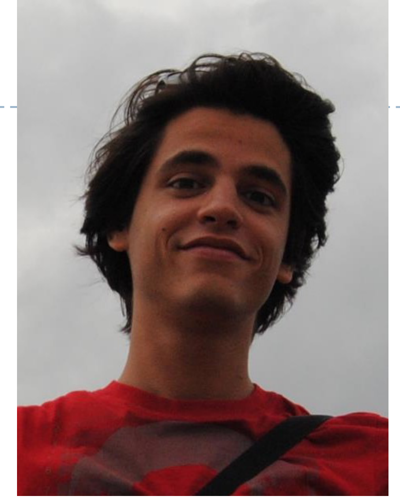


Short-term implant of TIMEs in an amputee

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

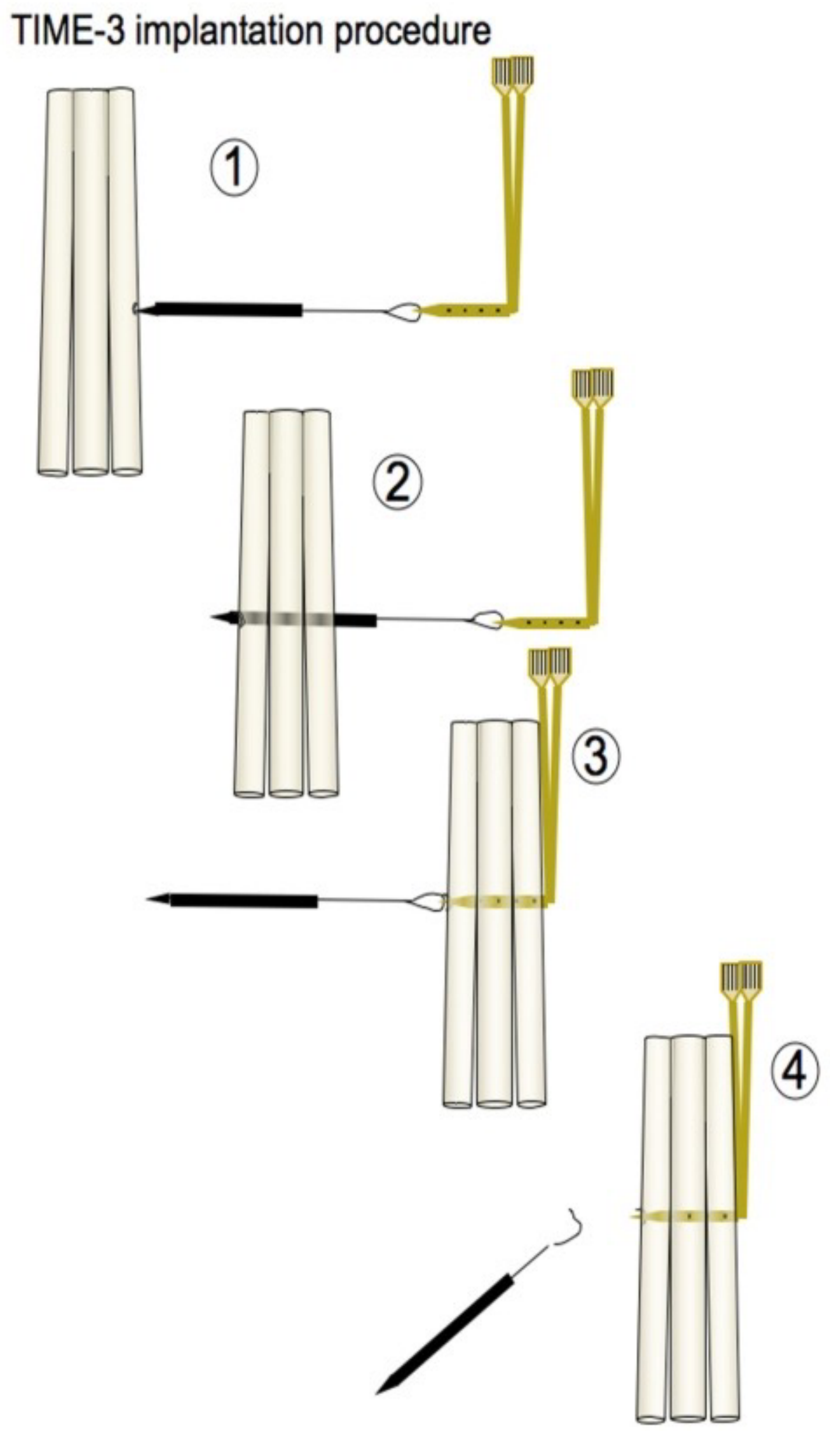
- Subjects with no neuropsychiatric disorders, evaluated by neuropsychological and psychiatric tests (WAIS-R, CES-D, MMPI-2)

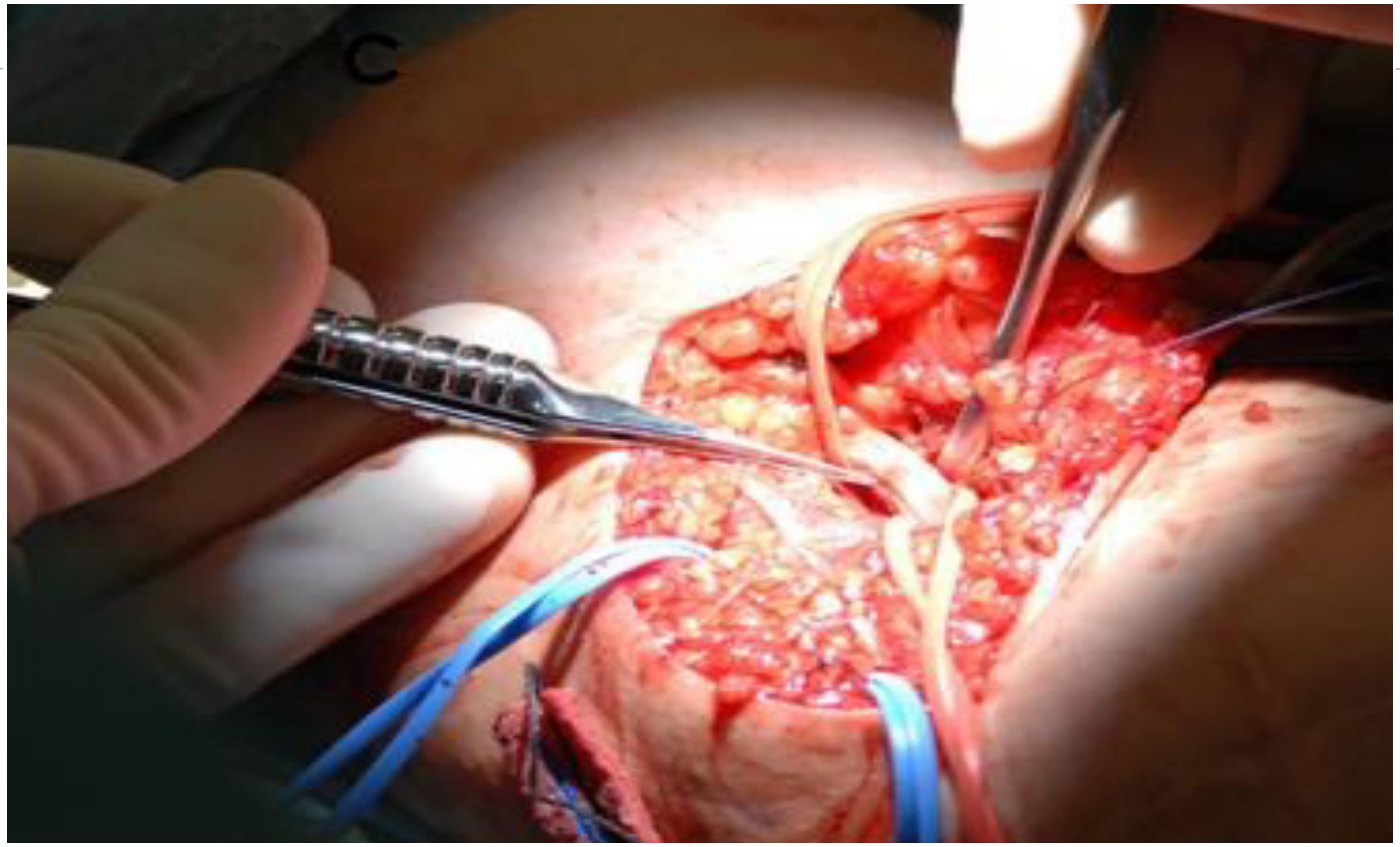
- FOUR week implant

TIME implant

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

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



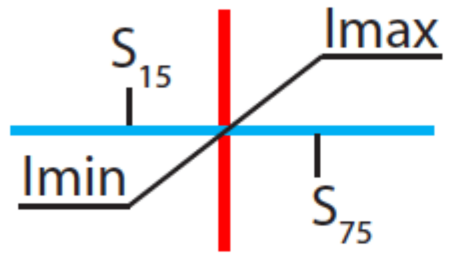


- **Surgical technique:**

✓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

Closed-loop control based on sensory feedback

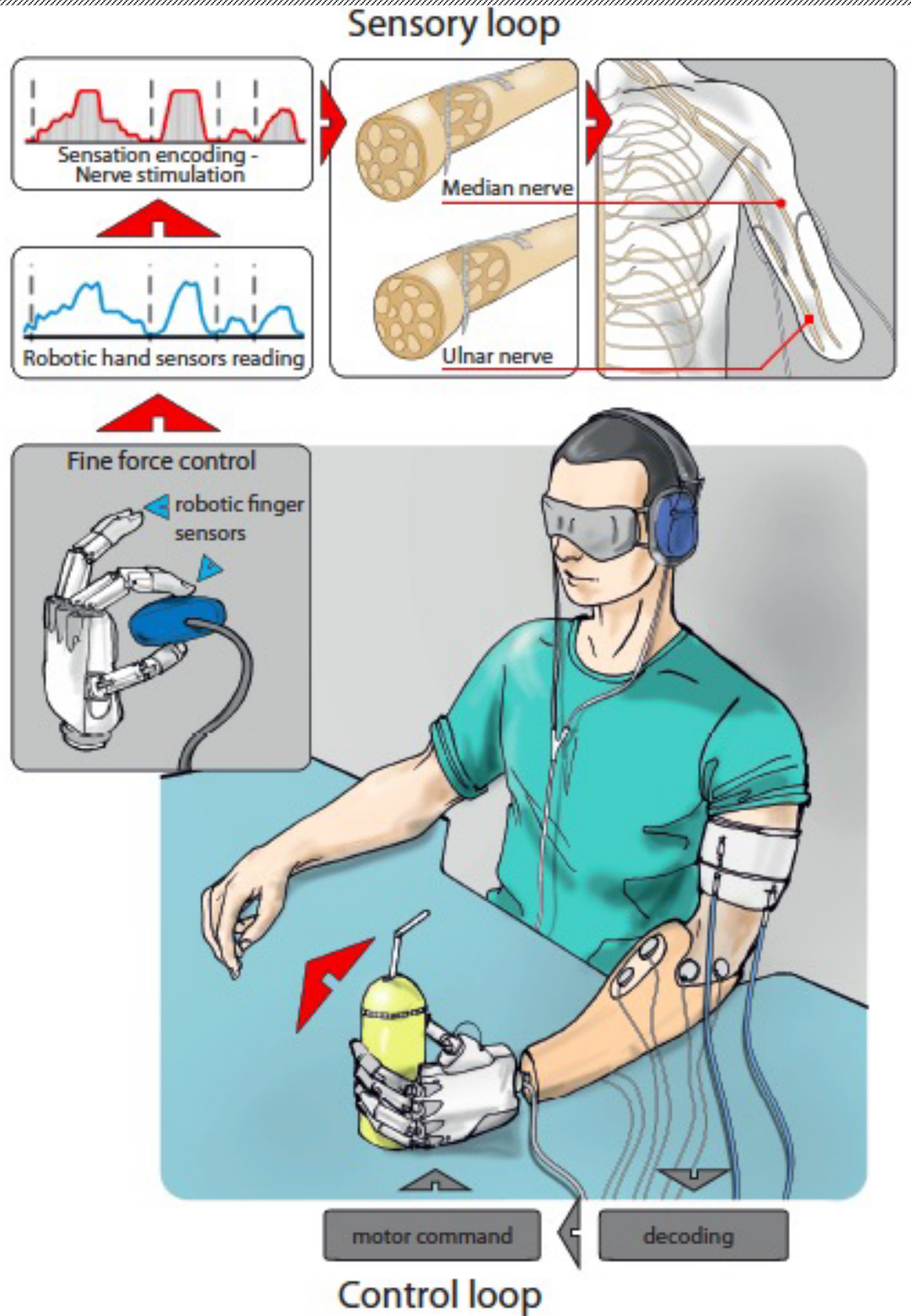
- Test the possibility for the subject to use the sensory information during closed-loop control and manipulation experiments



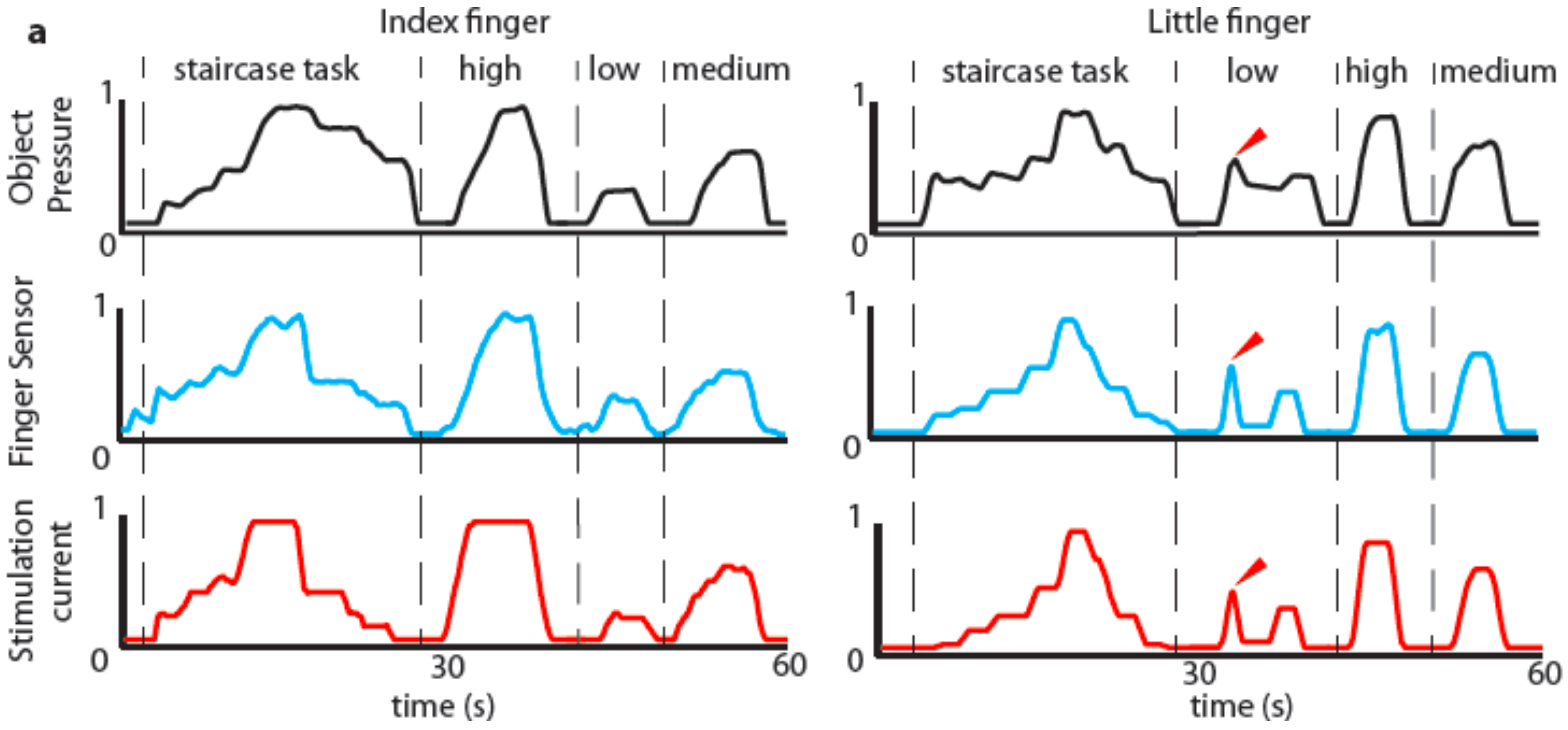
$$\mathbf{I} = (\mathbf{I}_{max} - \mathbf{I}_{min}) \cdot \frac{(S - S_{15})}{(S_{75} - S_{15})} + \mathbf{I}_{min}$$

Current/Sensor relationship

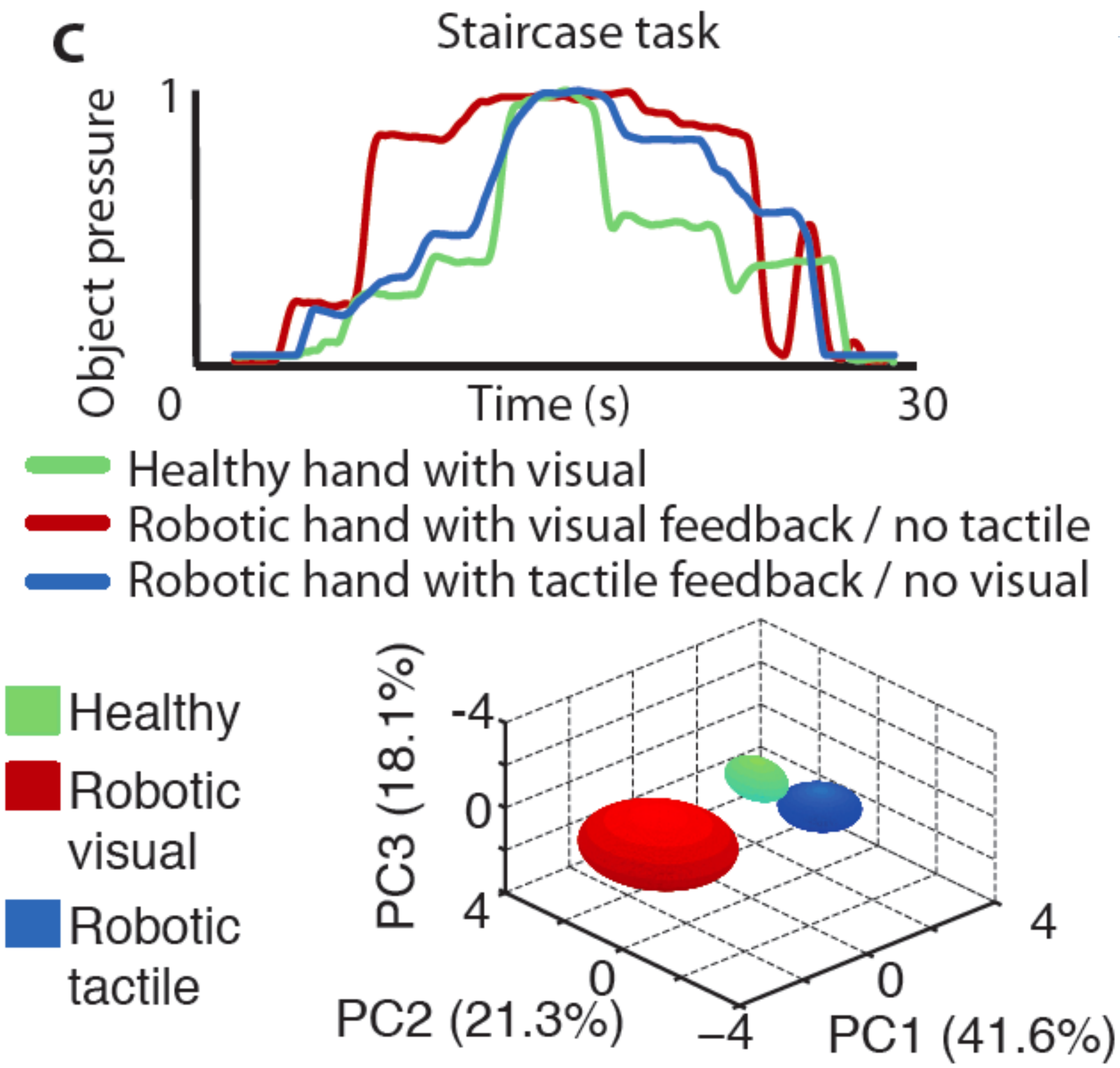
Azzurra dexterous hand (Prensilia srl)



Selection of grasping force levels

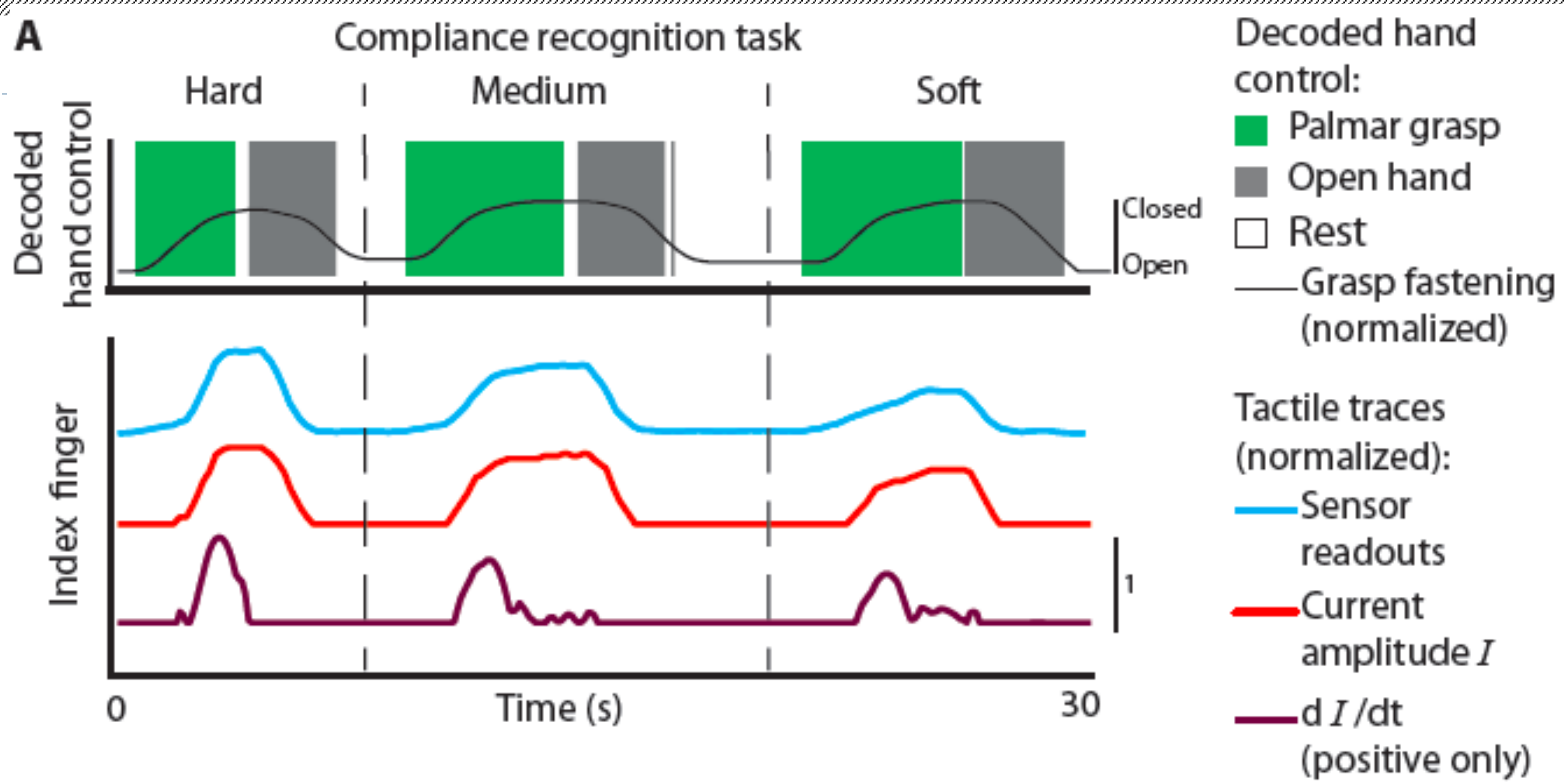


Modulation of grasping force



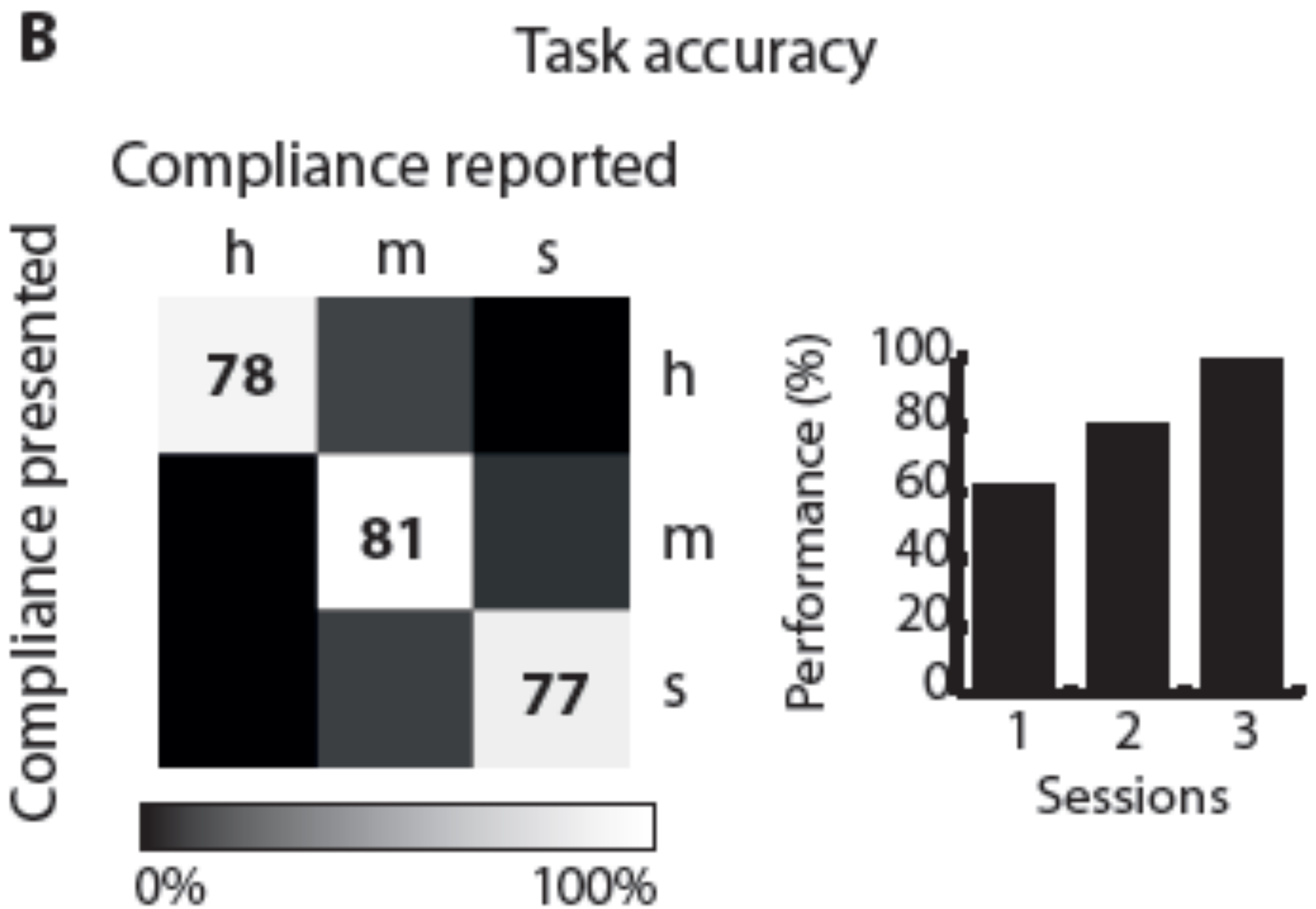
The artificial sensory feedback allowed the user to achieve performance close to the natural ones

Compliance recognition

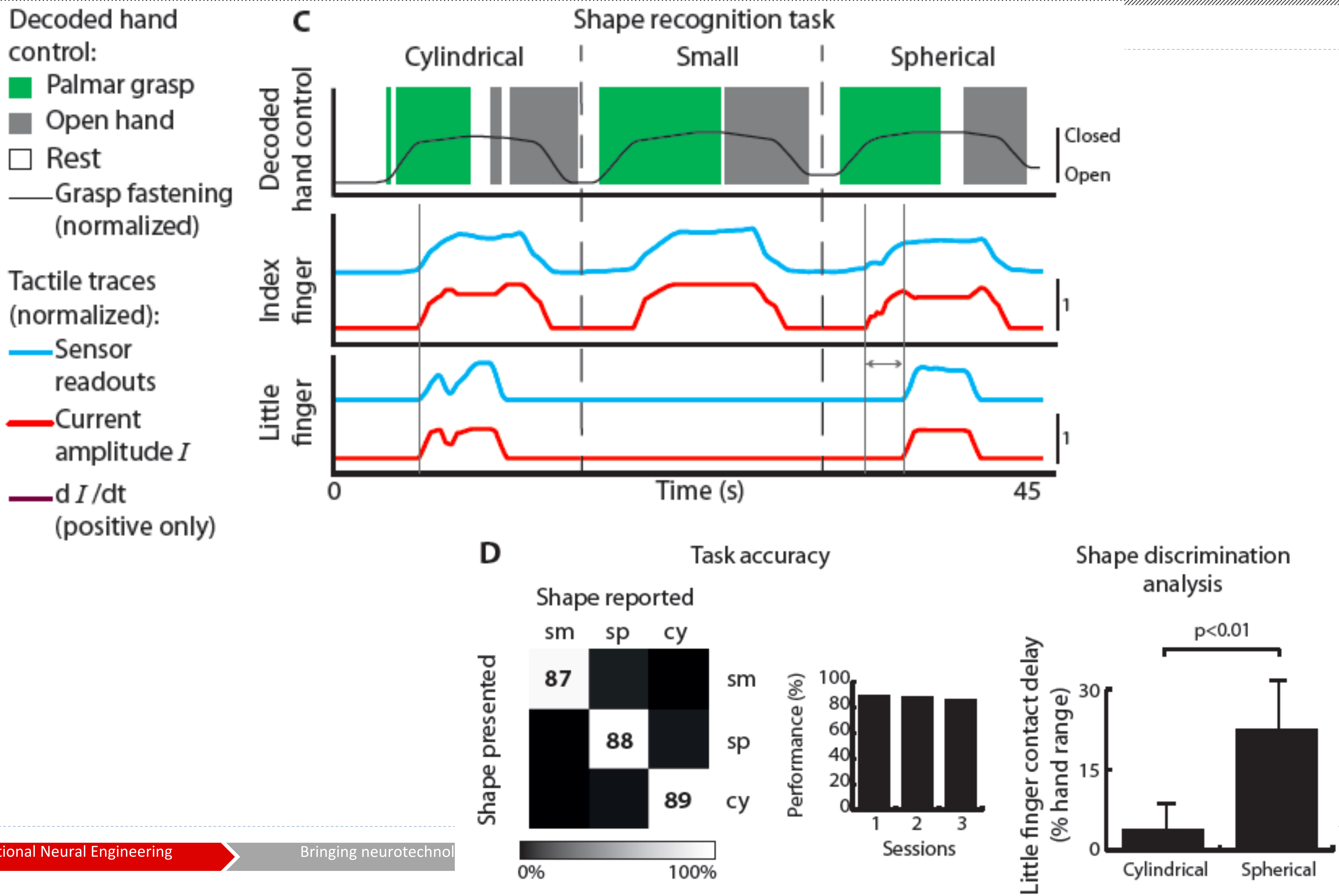


Three objects with different stiffness properties

Quite good performance and interesting learning ability

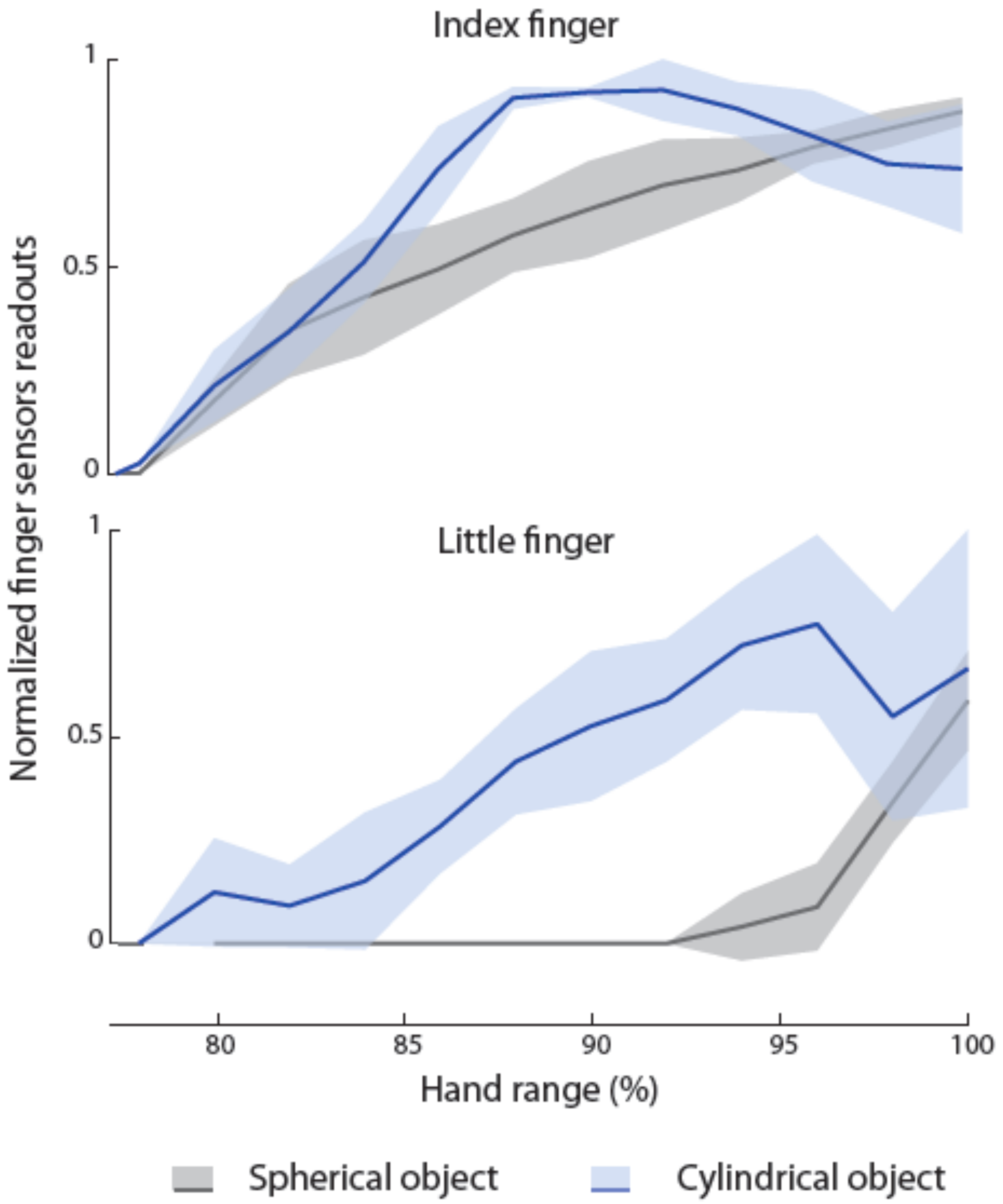


Shape recognition

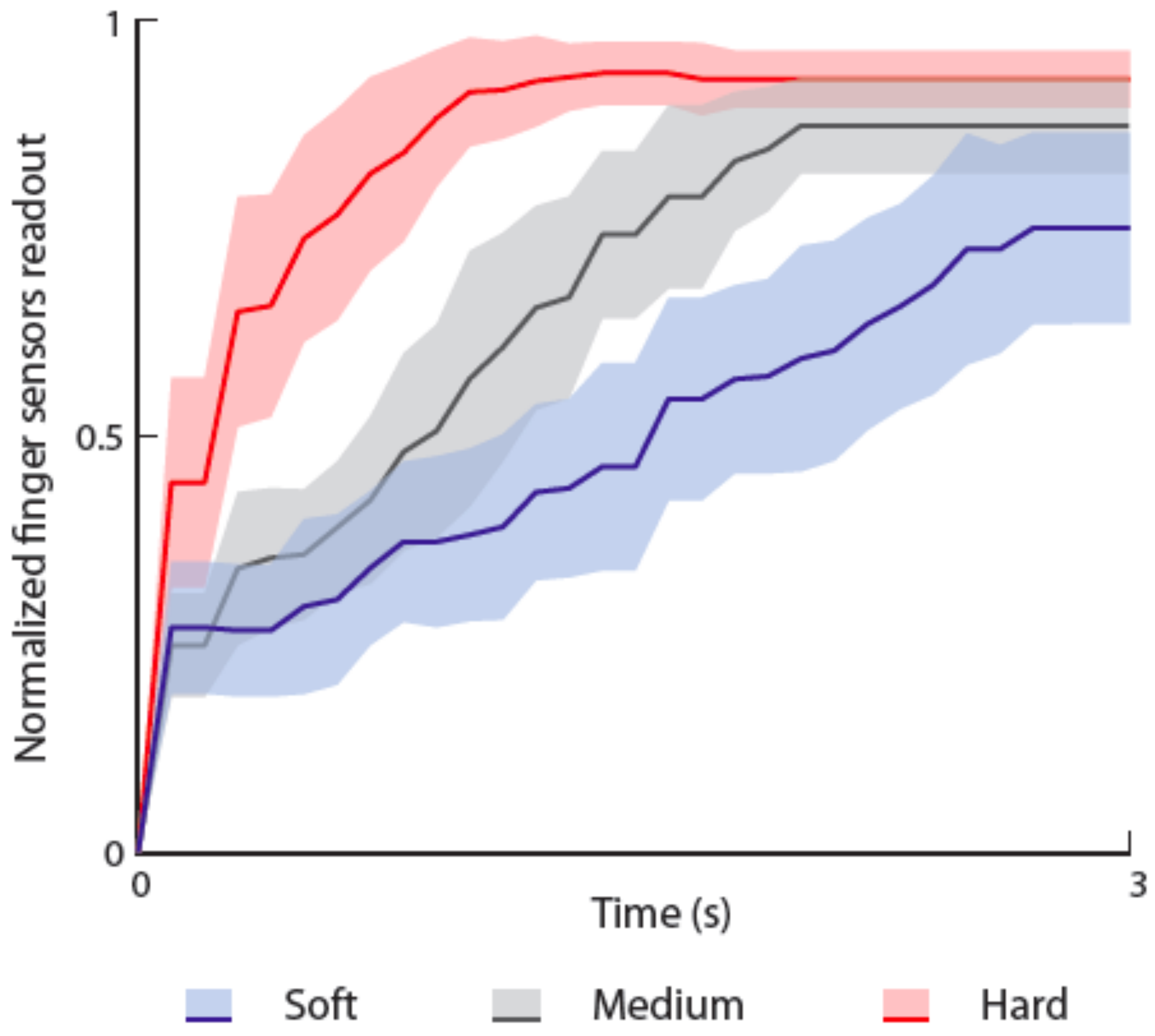


Why this is possible?

Shape recognition

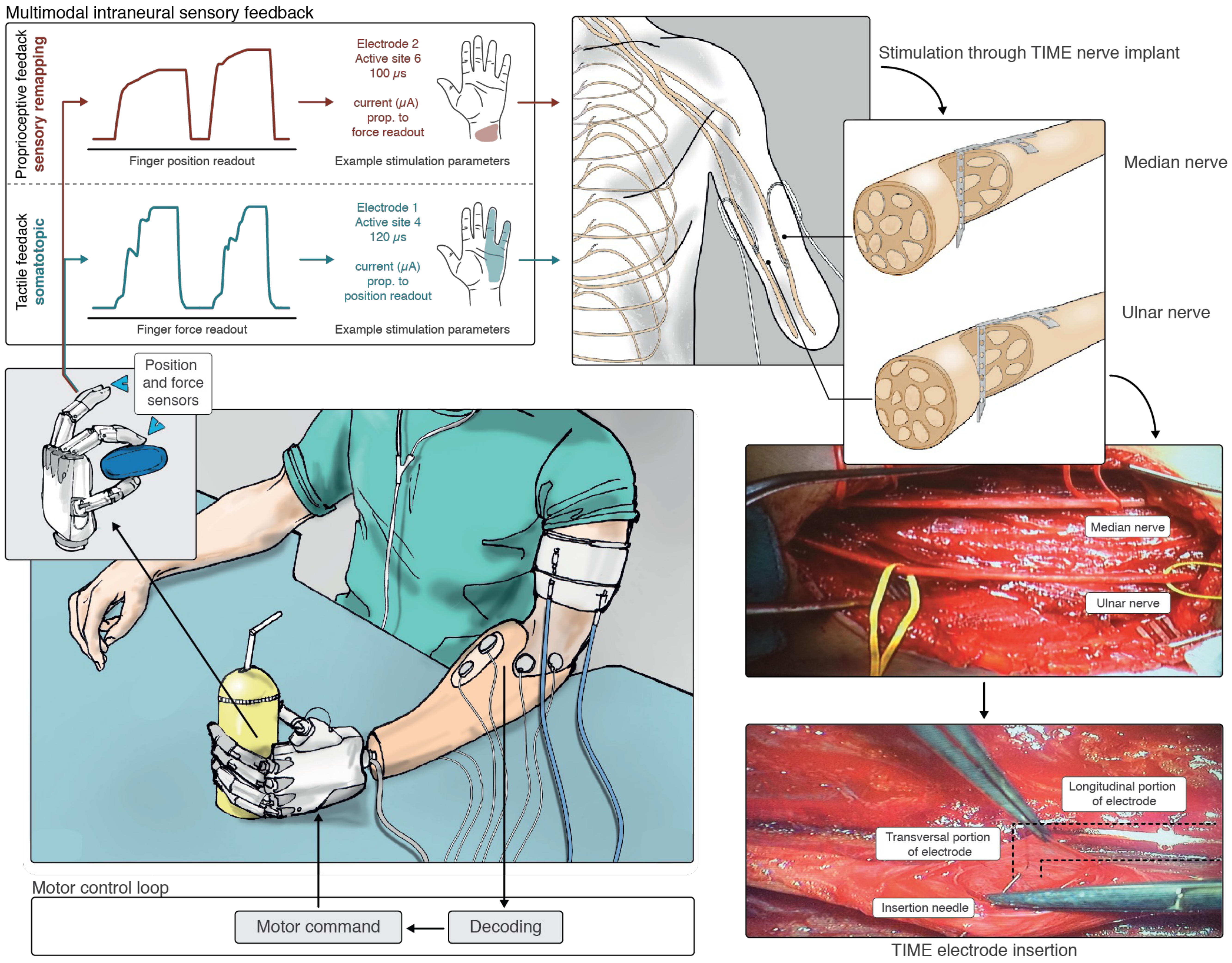


Compliance recognition

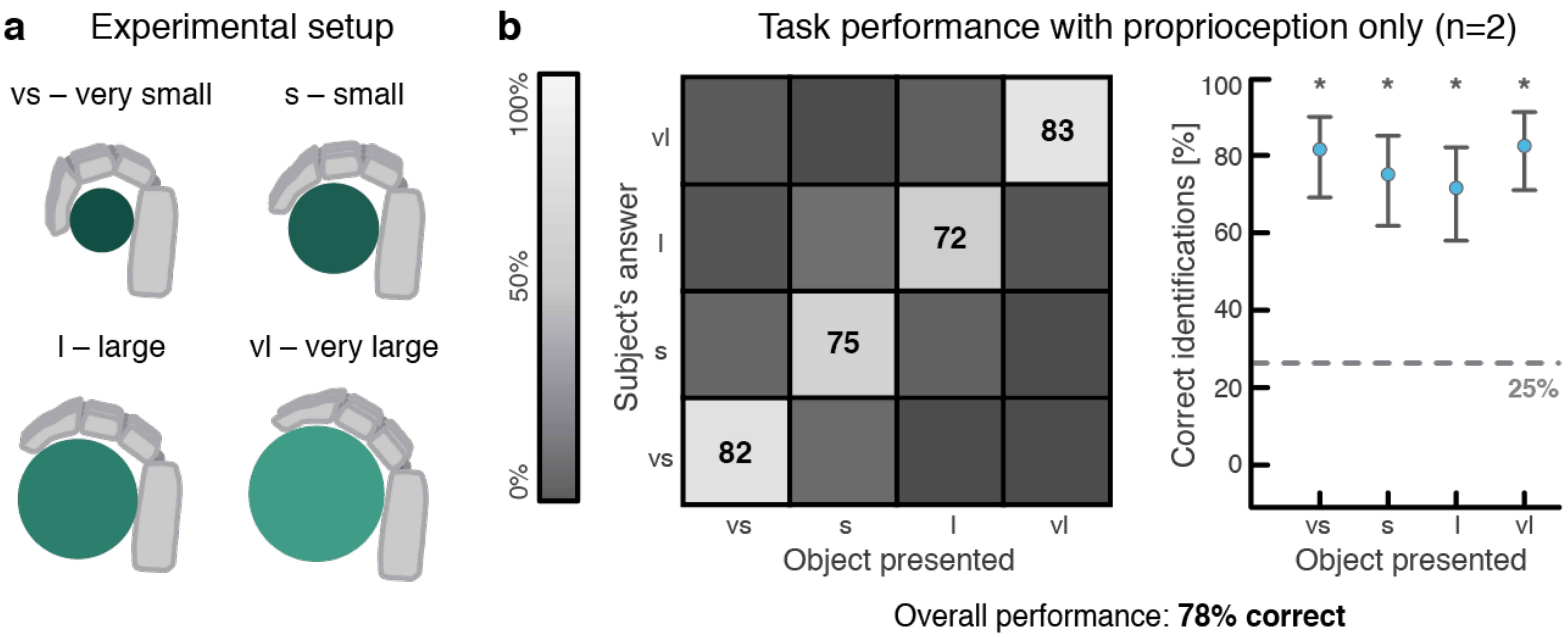


Different force profiles were provided to the users using the afferent stimulation
→ this is **NOT** on-off sensation!

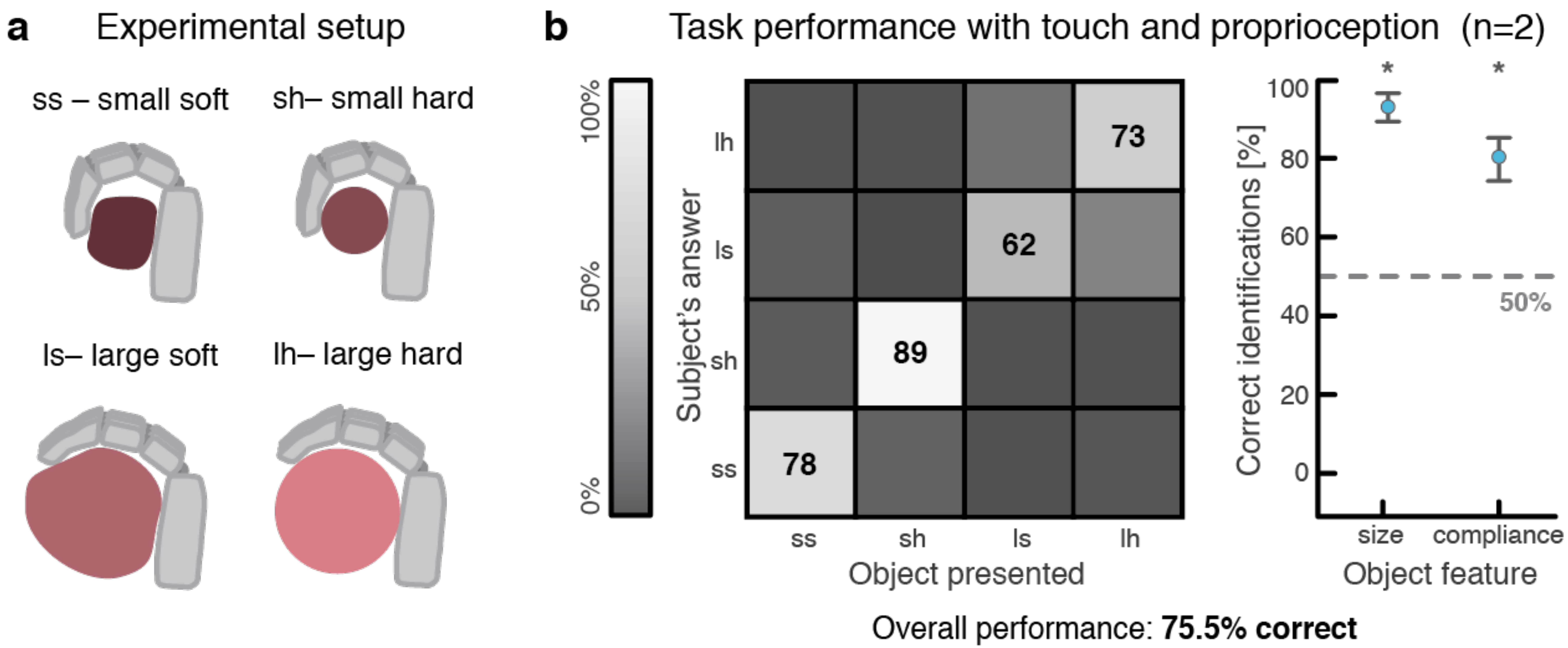
Restoration of proprioception and tactile feedback



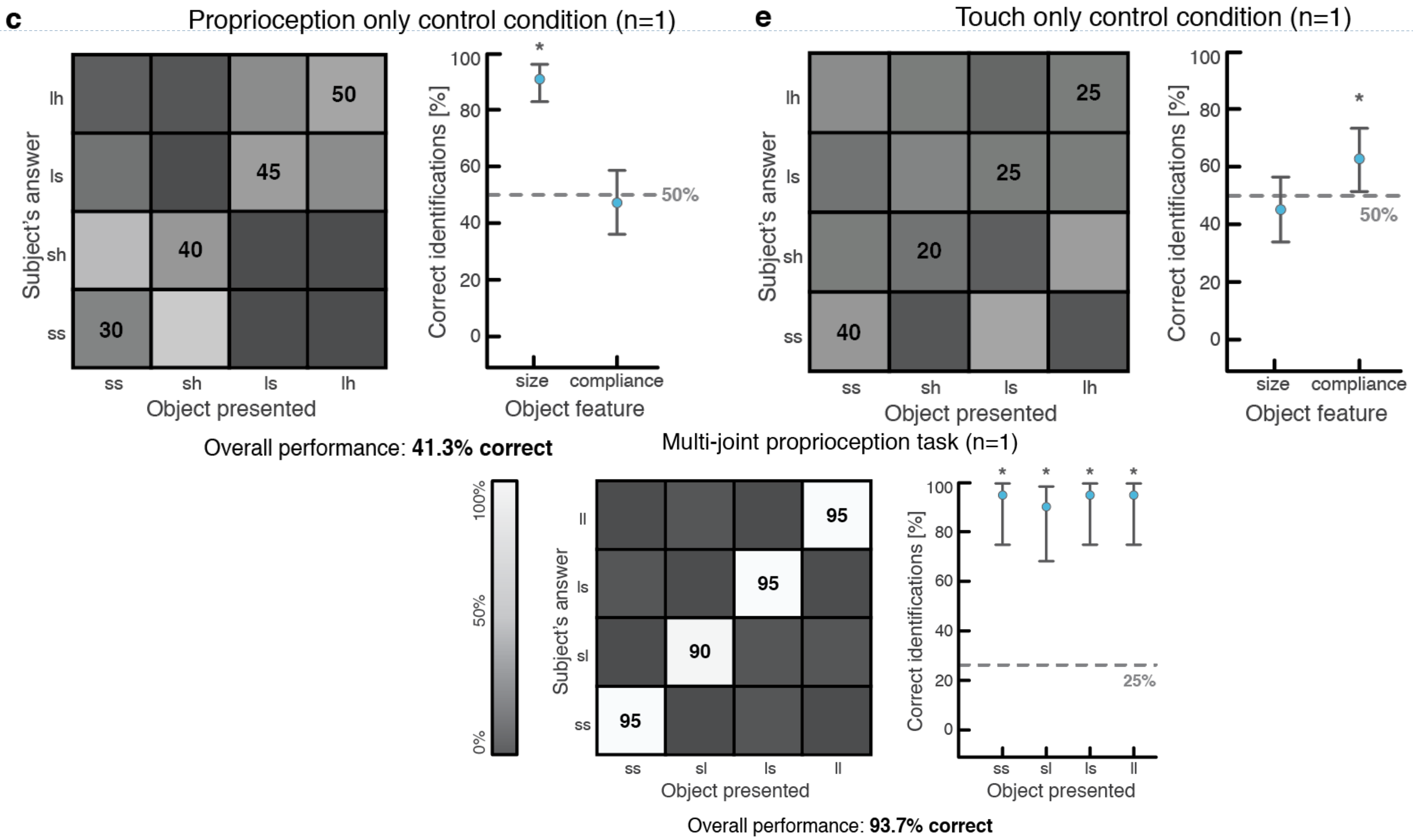
Restoration of proprioception and tactile feedback



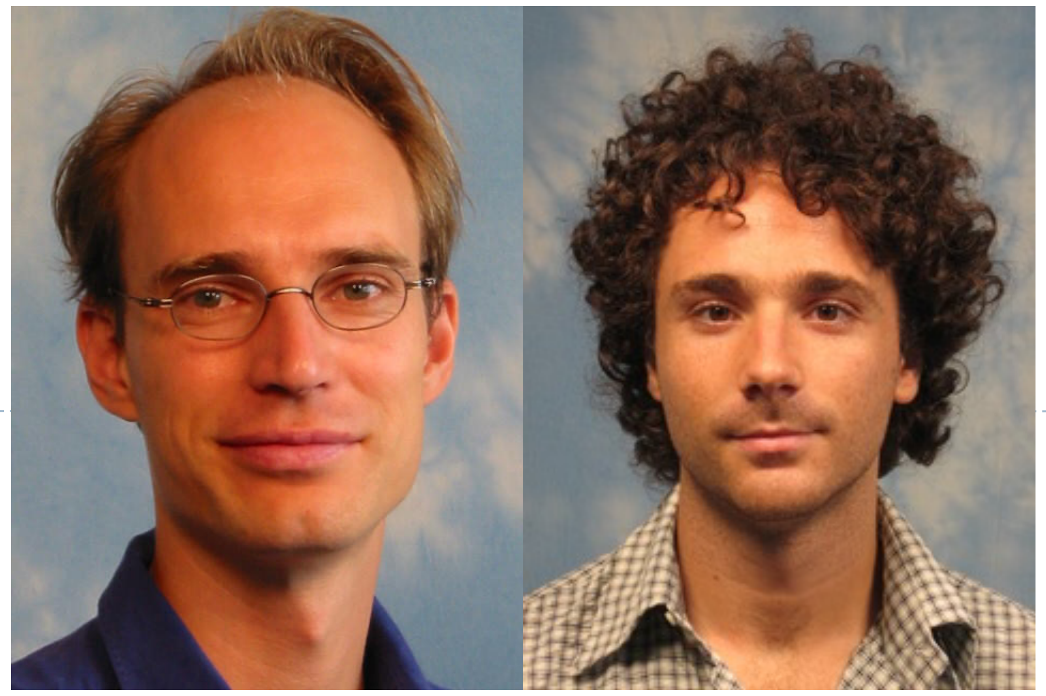
Restoration of proprioception and tactile feedback



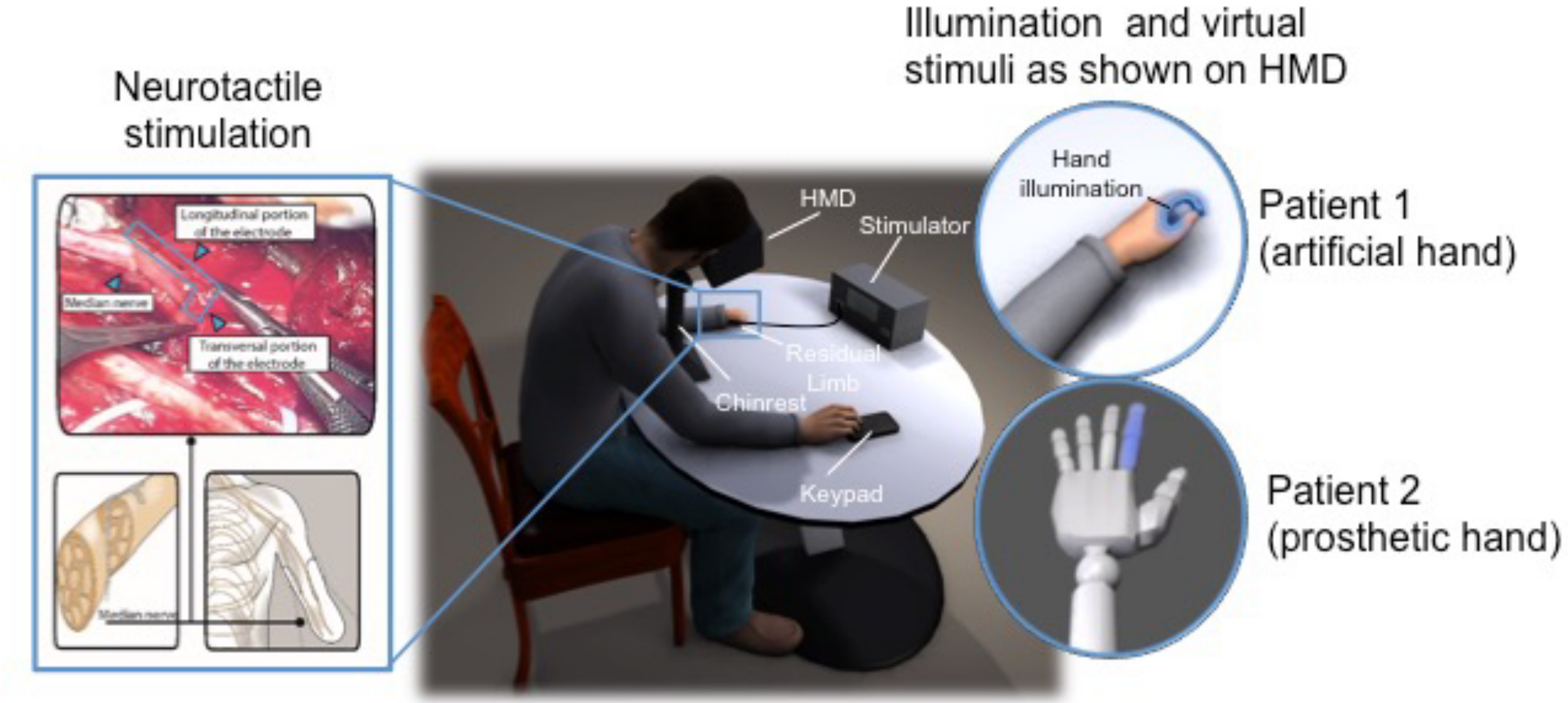
Restoration of proprioception and tactile feedback



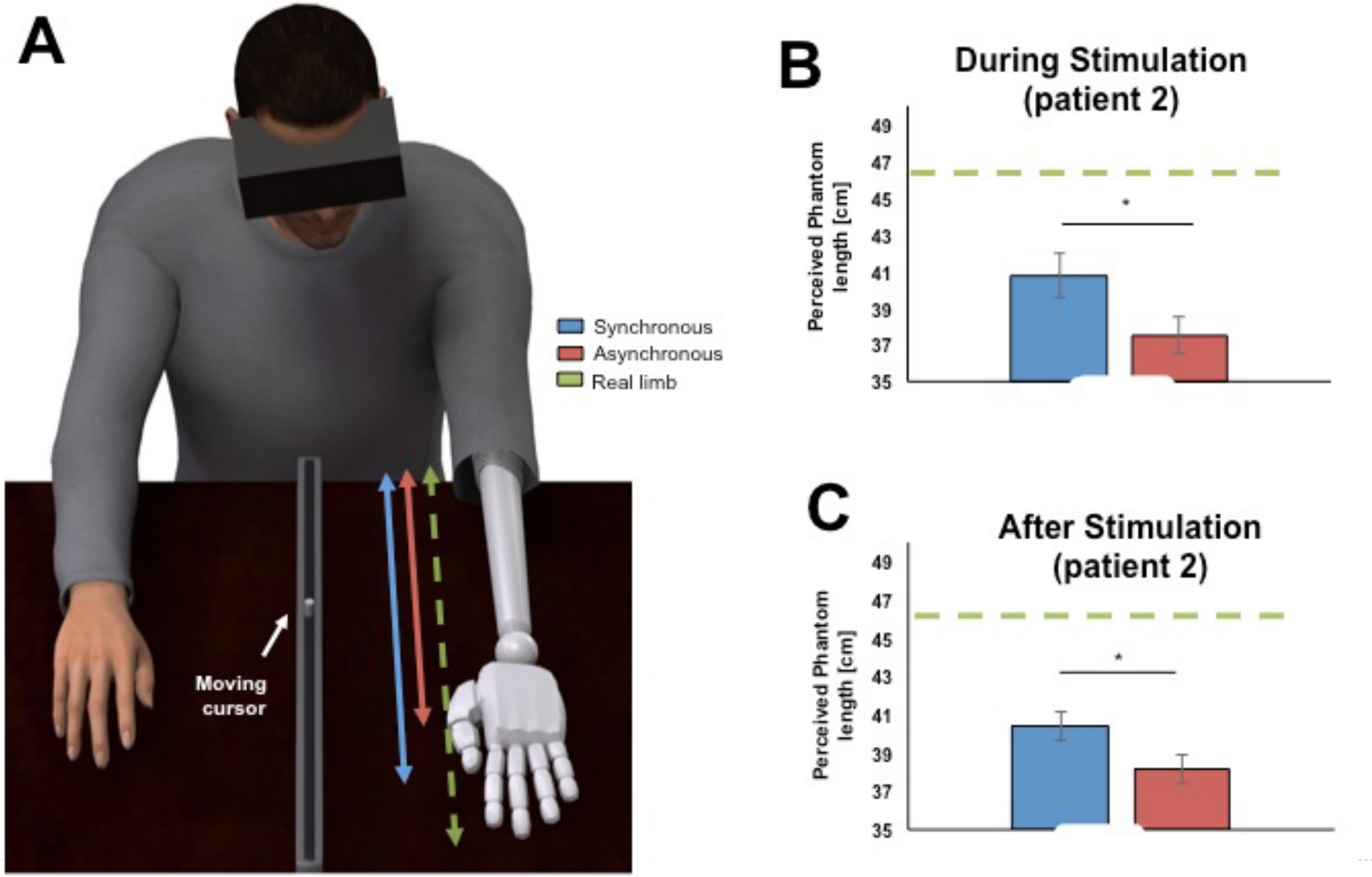
Embodiment



O. Blanke G. Rognini

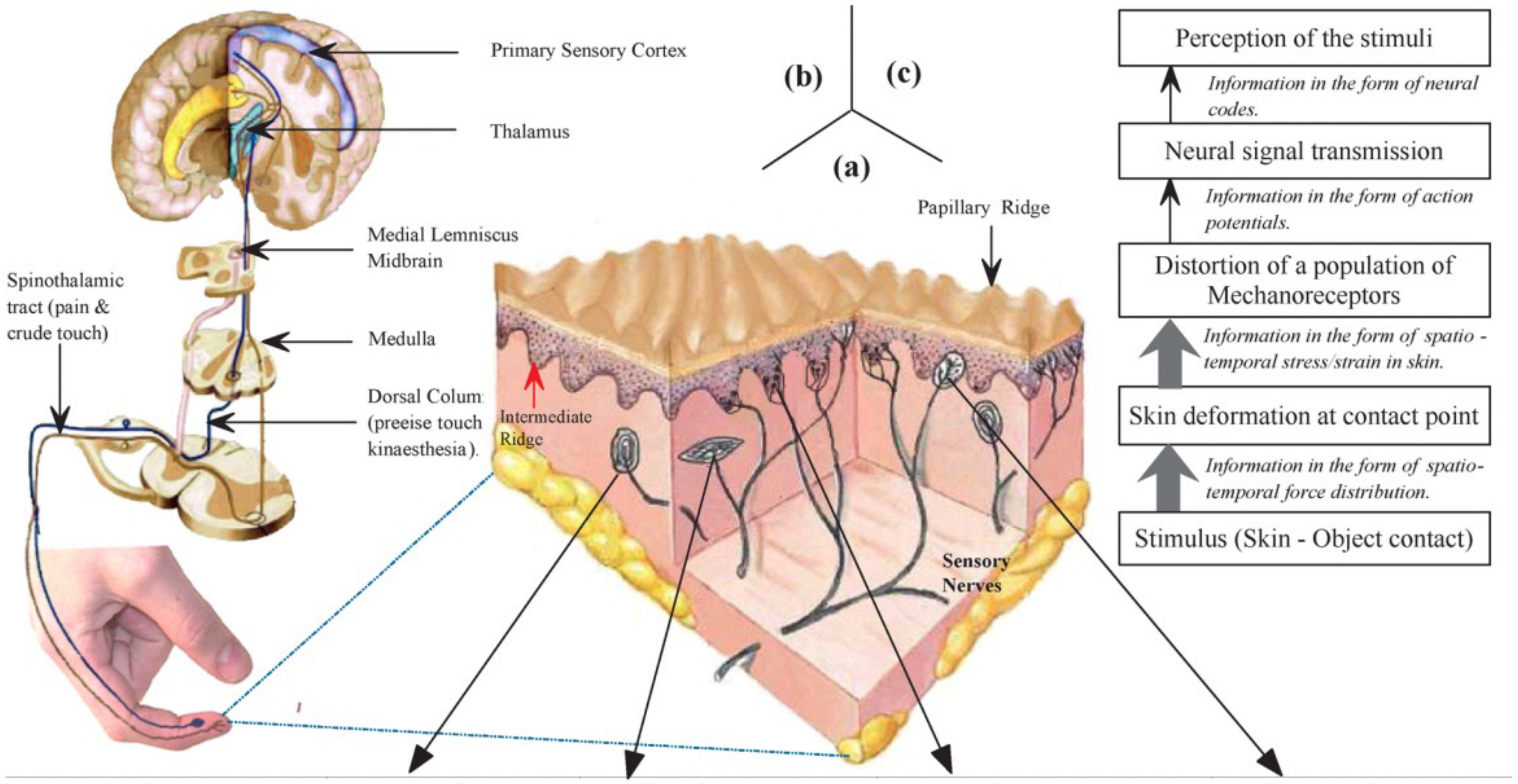


Embodiment



A
Synchronous
Asynchronous
Real limb
Moving cursor
B
During Stimulation (patient 2)
Perceived Phantom length [cm]
49
47
45
43
41
39
37
35
*
C
After Stimulation (patient 2)
Perceived Phantom length [cm]
49
47
45
43
41
39
37
35
*

Human touch system



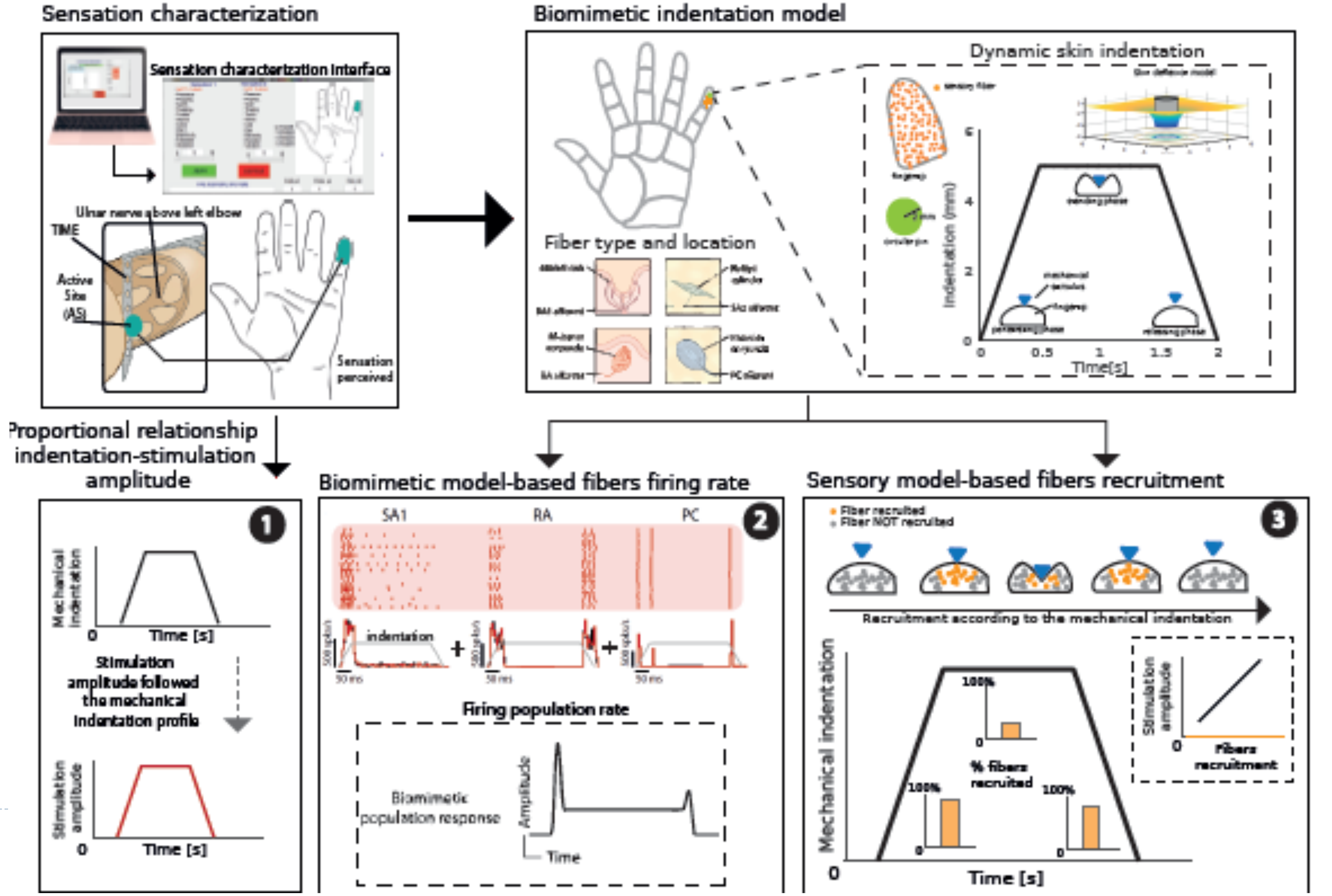
Classification Basis		Pacinian Corpuscle	Ruffini Corpuscle	Merkel Cells	Meissner's Corpuscle
Type		FA II	SA II	SA I	FA I
Adaptation Rate		Fast	Slow	Slow	Fast
Spatial Acuity (mm)		10+	7+	0.5	3-4
Vibration/rapid indent. threshold	Best(μm)	0.01	40	8	2
	Mean(μm)	0.08	300	30	6
Stimuli Frequency (Hz)		40-500+	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.

- Natural sensors fibers convey detailed information about contact events and provide us with an exquisite sensitivity to the form and surface properties of grasped objects
- 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 sur-face waves that propagate across the skin of the finger and palmand excite vibration-sensitive Pacinian (PC) afferents all over thehand

Biomimetic encoding strategy

Step 1: Biomimetic model-based approach and parameters generation

We identified electrode active site which elicits sensations in the locations corresponding to the fingertip. Then, we simulated a mechanical skin indentation using the biomimetic model. The model outcomes were the firing population activity generated by the combination of all the fibers (SA,RA,PC) response and the number of sensory fibers recruited during the skin indentation. We also generated the stimulation amplitudes following a proportional relationship with the mechanical stimulus as used in (16).



Biomimetic encoding strategy

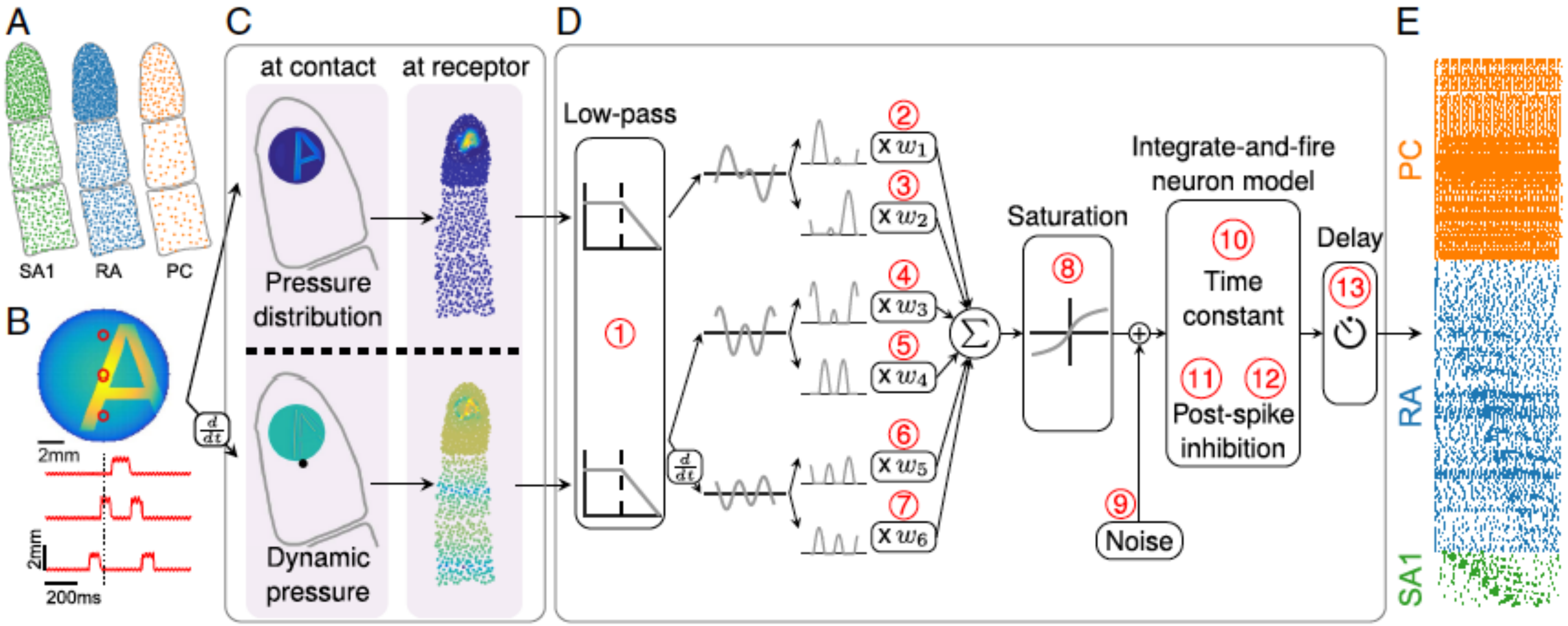
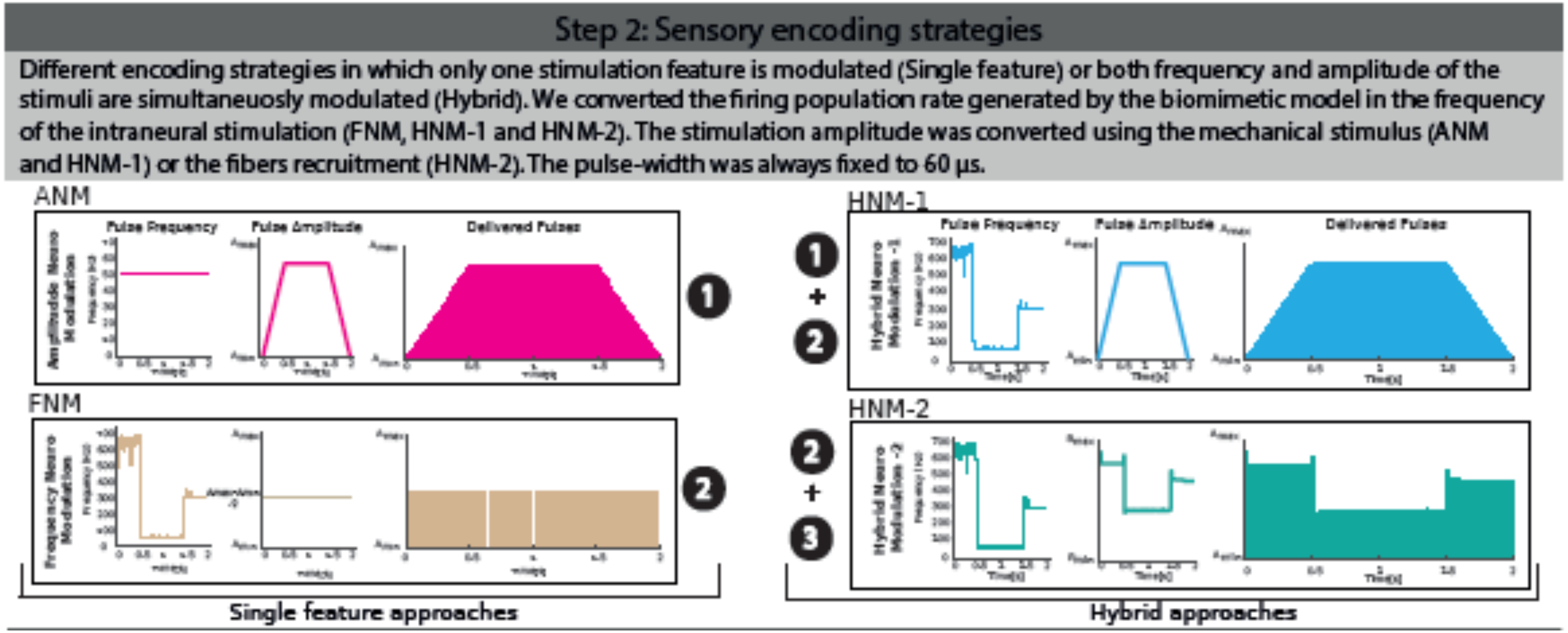


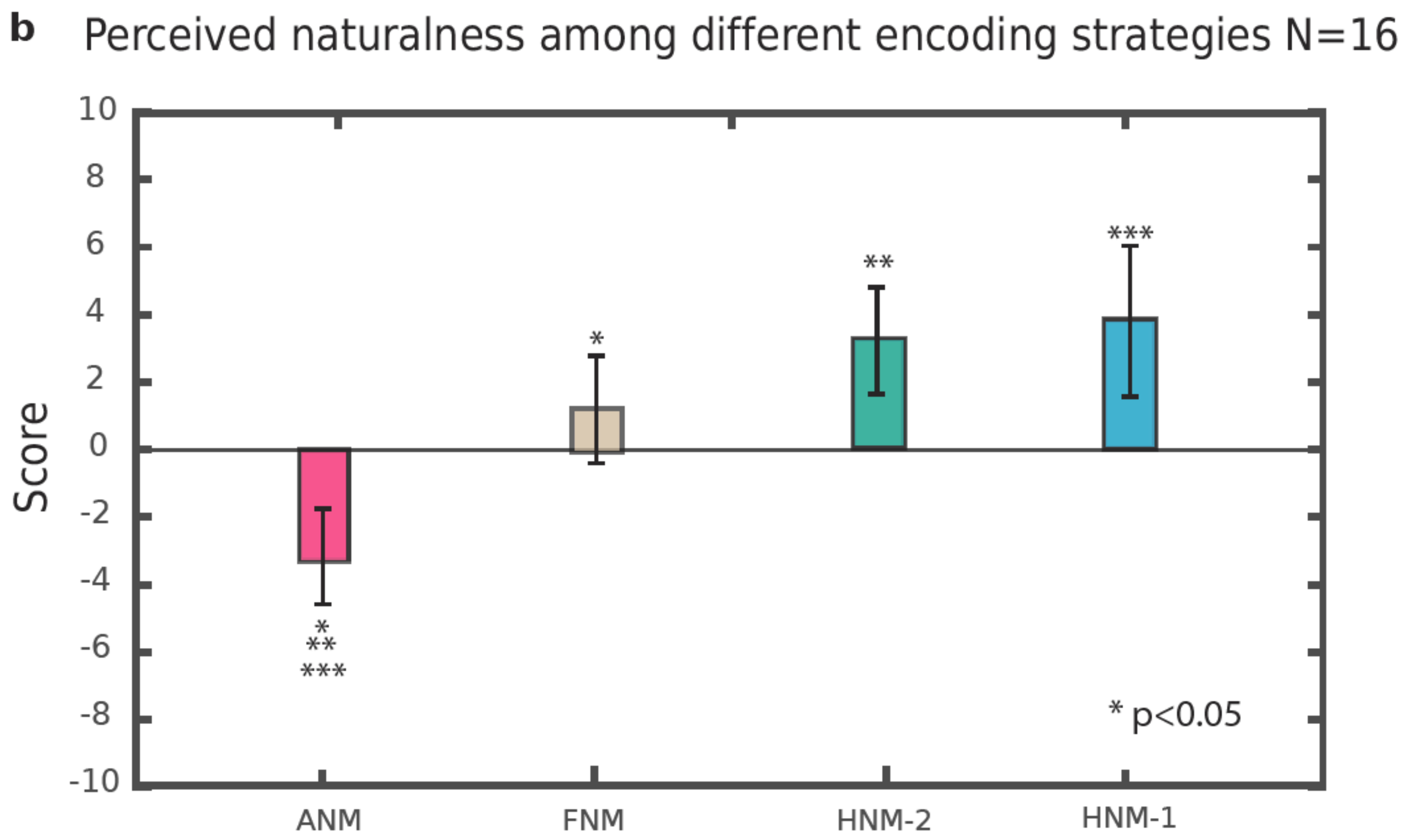
Fig. 1. Overview of the model. (*A*) Receptors are distributed across the skin given the known innervation densities of SA1, RA, and PC afferents. (*B*) The stimulus—in this case, a vibrating embossed letter A scanned across the skin—is defined as the time-varying depth at which each small patch of skin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

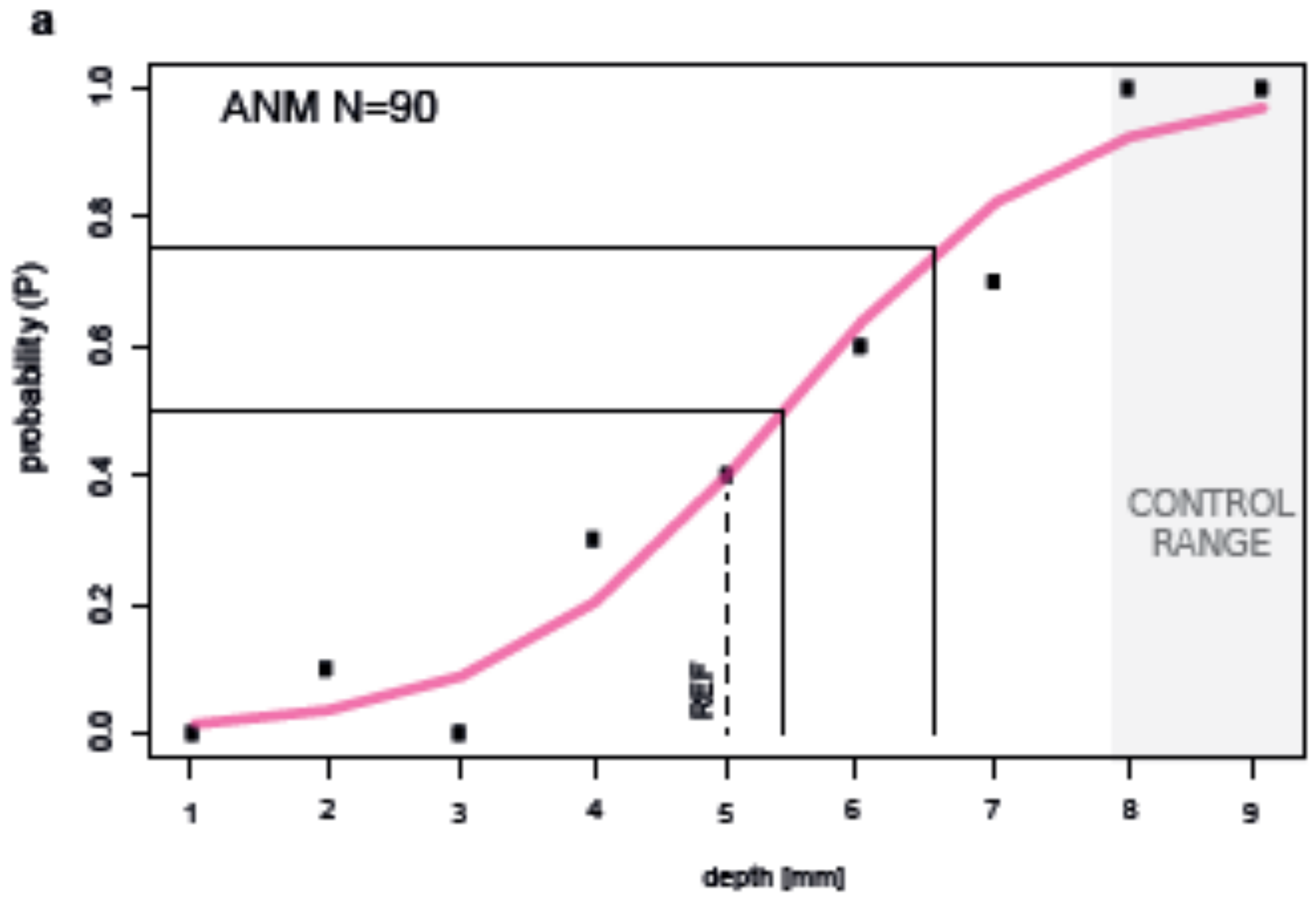
Saal et al., PNAS, 2017

Biomimetic encoding strategy



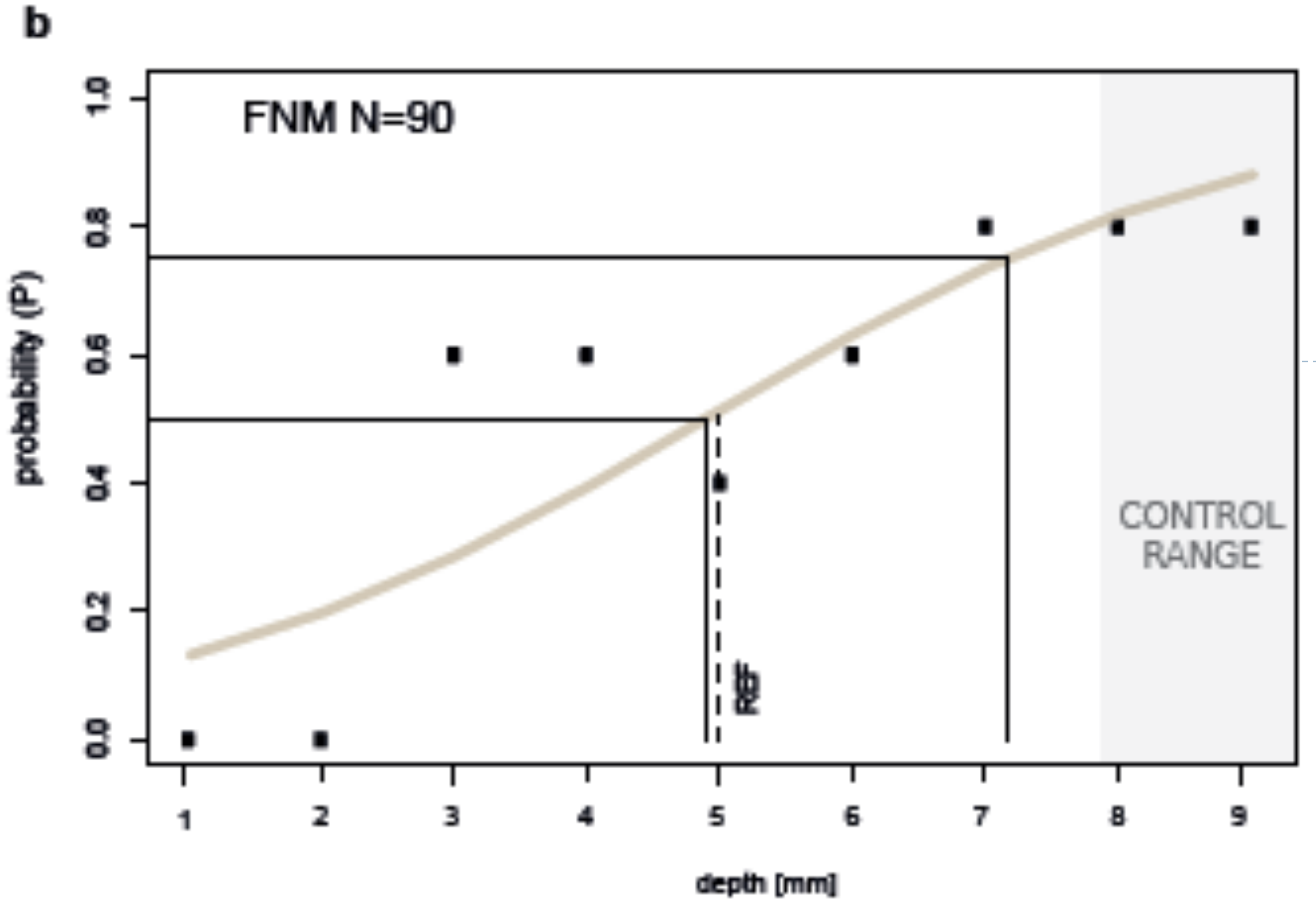
Biomimetic encoding strategy





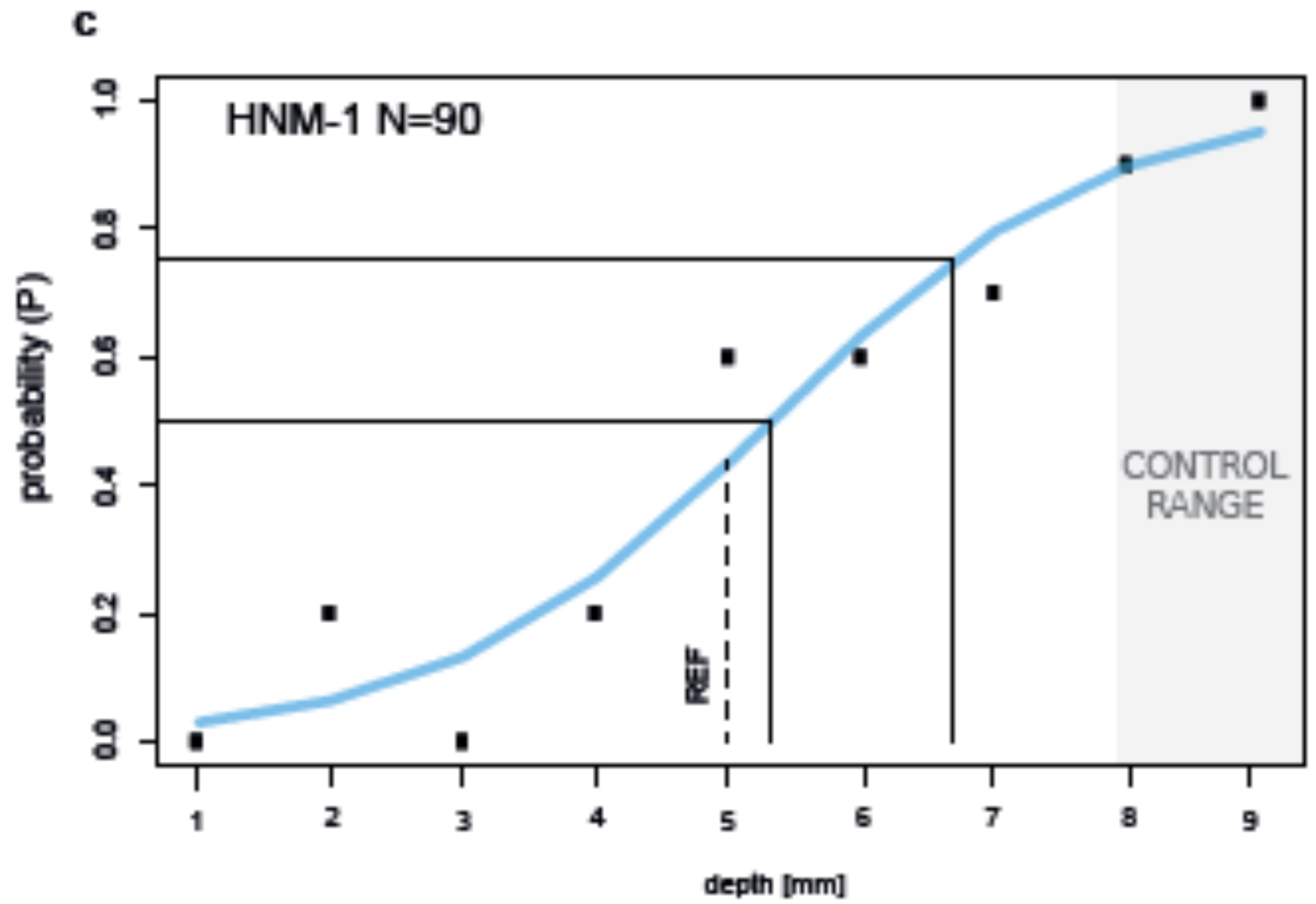
Point of Subjective Equality (PSE): **5.51** mm

Just-Noticeable Difference (JND): **1.01** mm



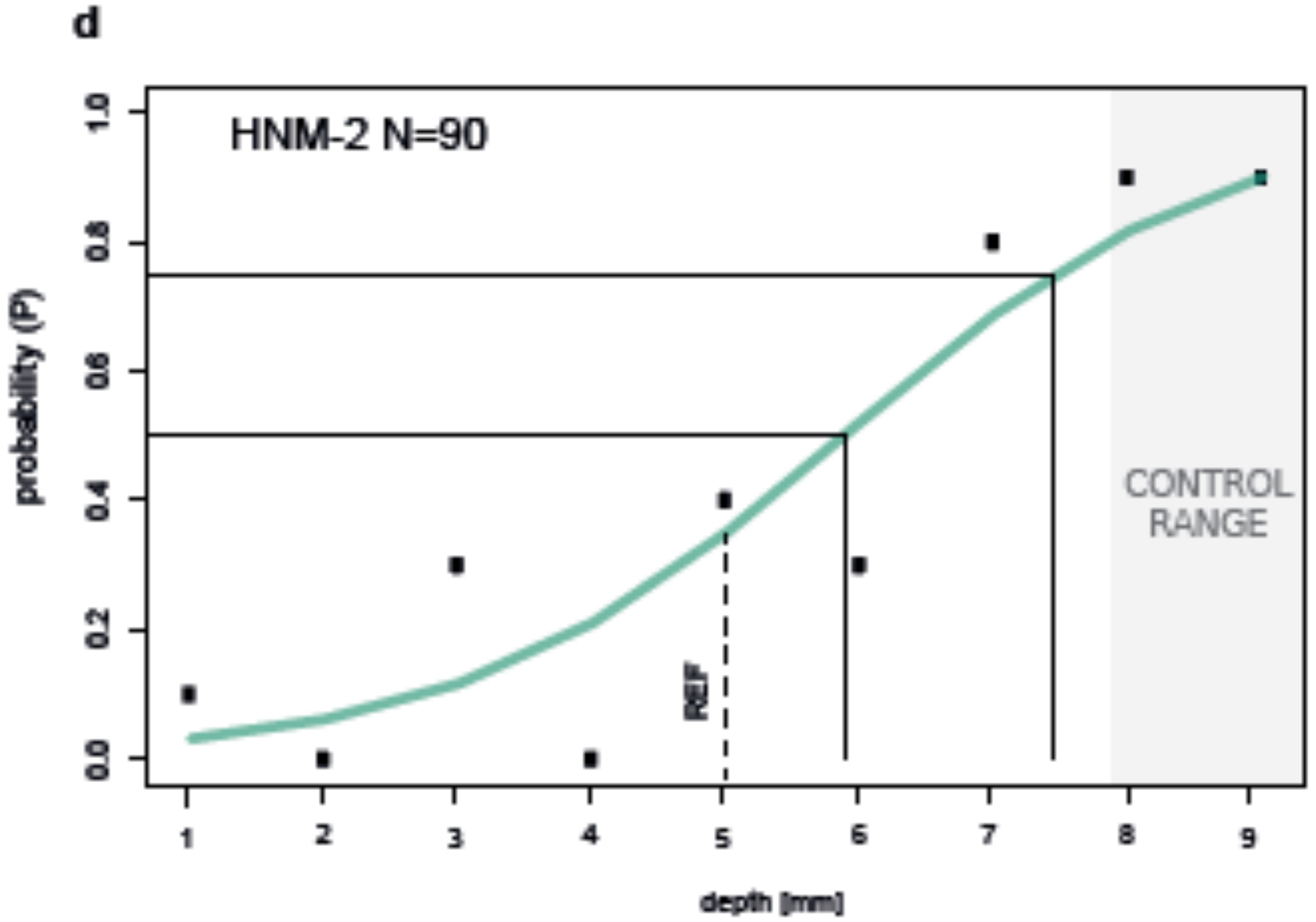
Point of Subjective Equality (PSE): **4.87** mm

Just-Noticeable Difference (JND): **2.26** mm



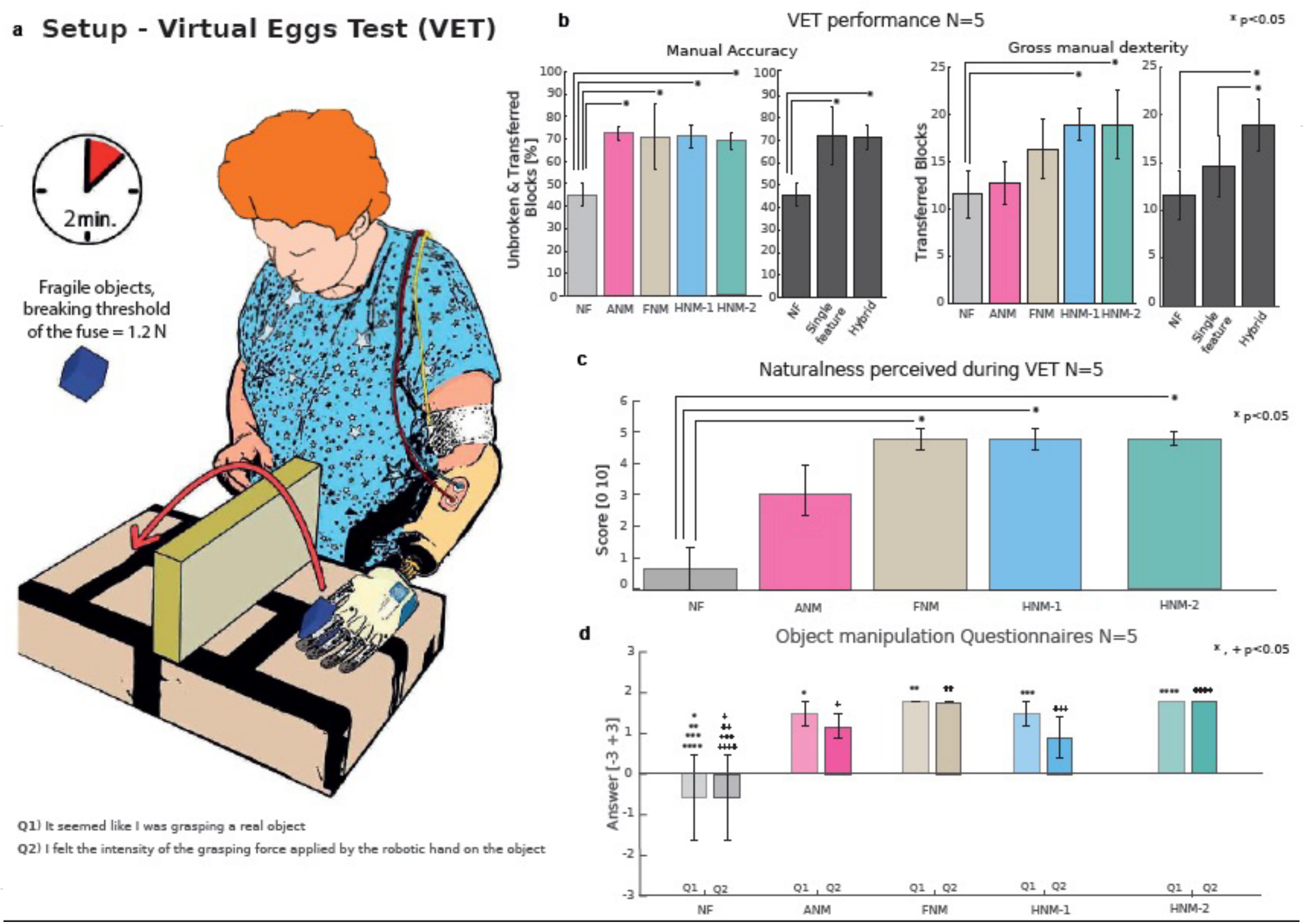
Point of Subjective Equality (PSE): **5.31** mm

Just-Noticeable Difference (JND): **1.35** mm

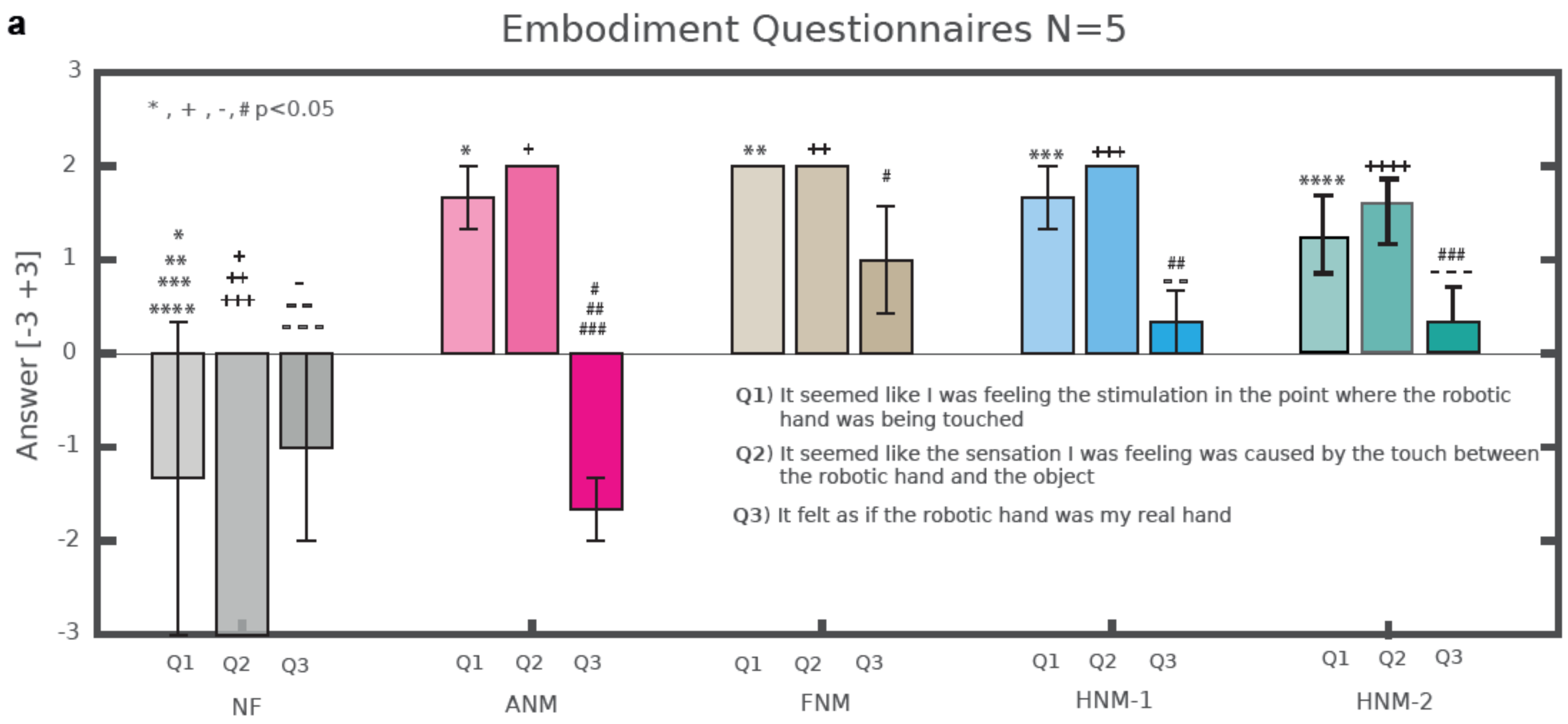


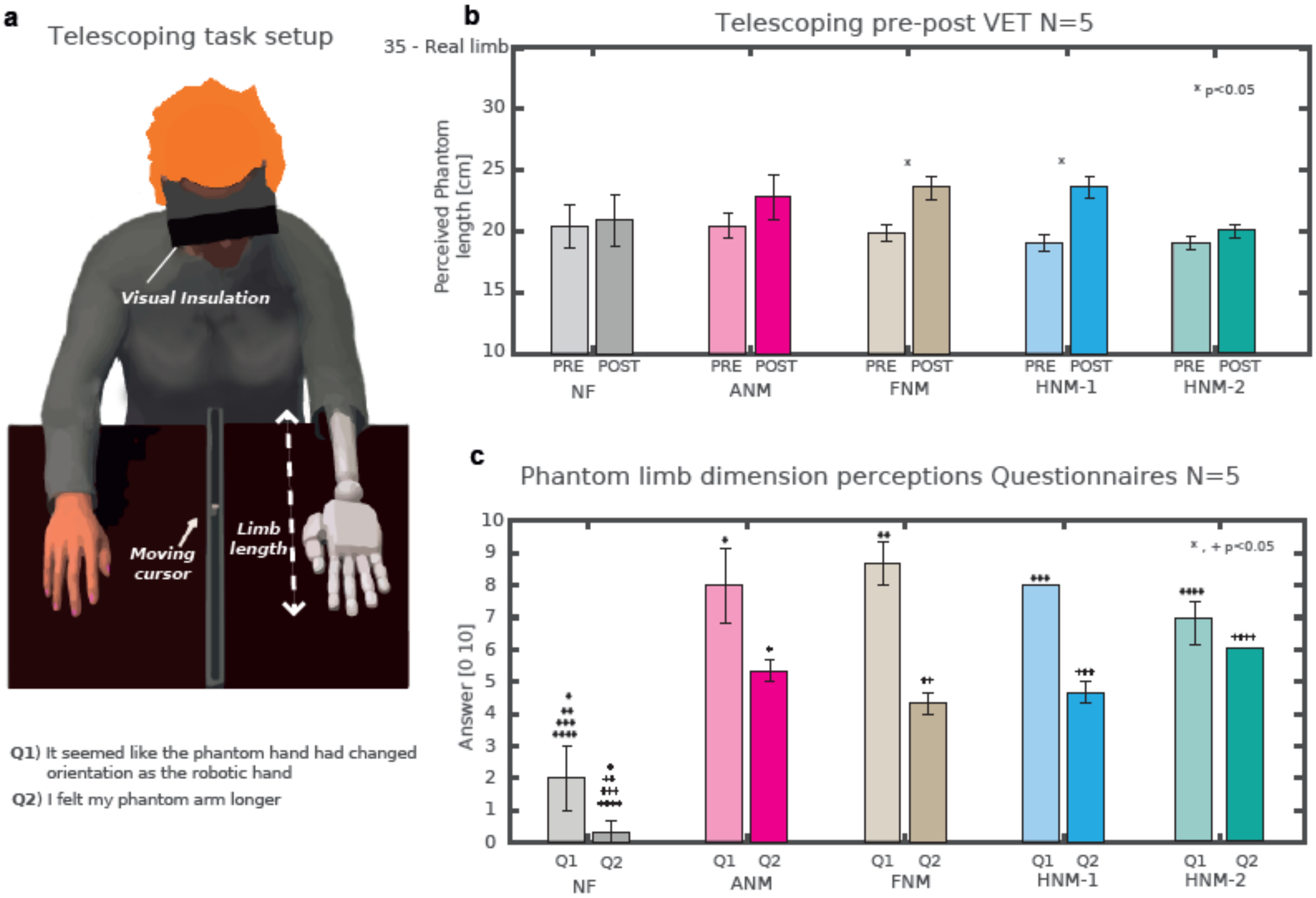
Point of Subjective Equality (PSE): **5.87** mm

Just-Noticeable Difference (JND): **1.55** mm

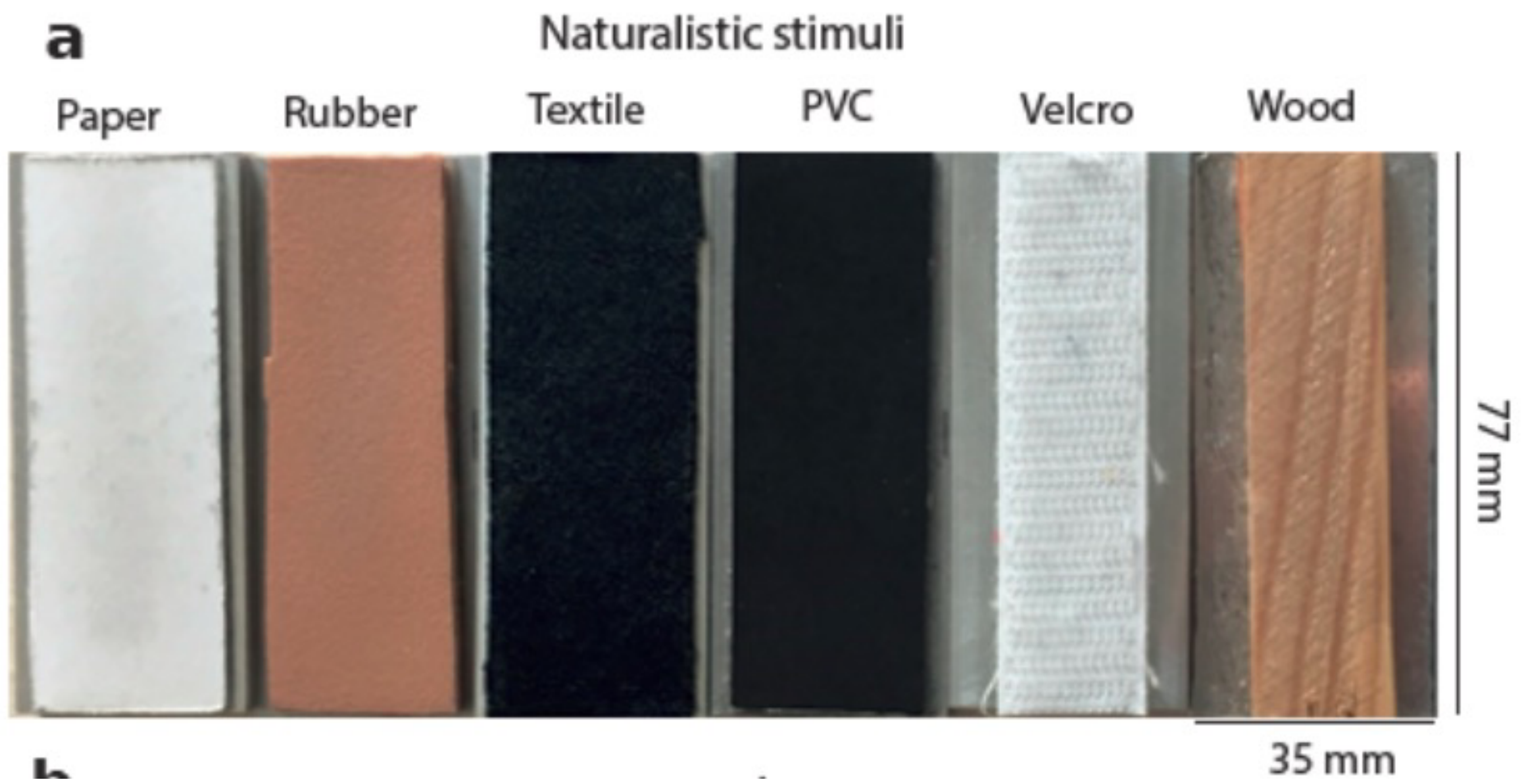

a Setup - Virtual Eggs Test (VET)
2 min.
Fragile objects, breaking threshold of the fuse = 1.2 N
Q1) It seemed like I was grasping a real object
Q2) I felt the intensity of the grasping force applied by the robotic hand on the object
b VET performance N=5
* p<0.05
Manual Accuracy
Unbroken & Transferred Blocks [%]
NF ANM FNM HNM-1 HNM-2
NF Single feature Hybrid
Gross manual dexterity
Transferred Blocks
c Naturalness perceived during VET N=5
* p<0.05
Score [0 10]
NF ANM FNM HNM-1 HNM-2
d Object manipulation Questionnaires N=5
*, + p<0.05
Answer [-3 +3]
Q1 Q2
NF ANM FNM HNM-1 HNM-2

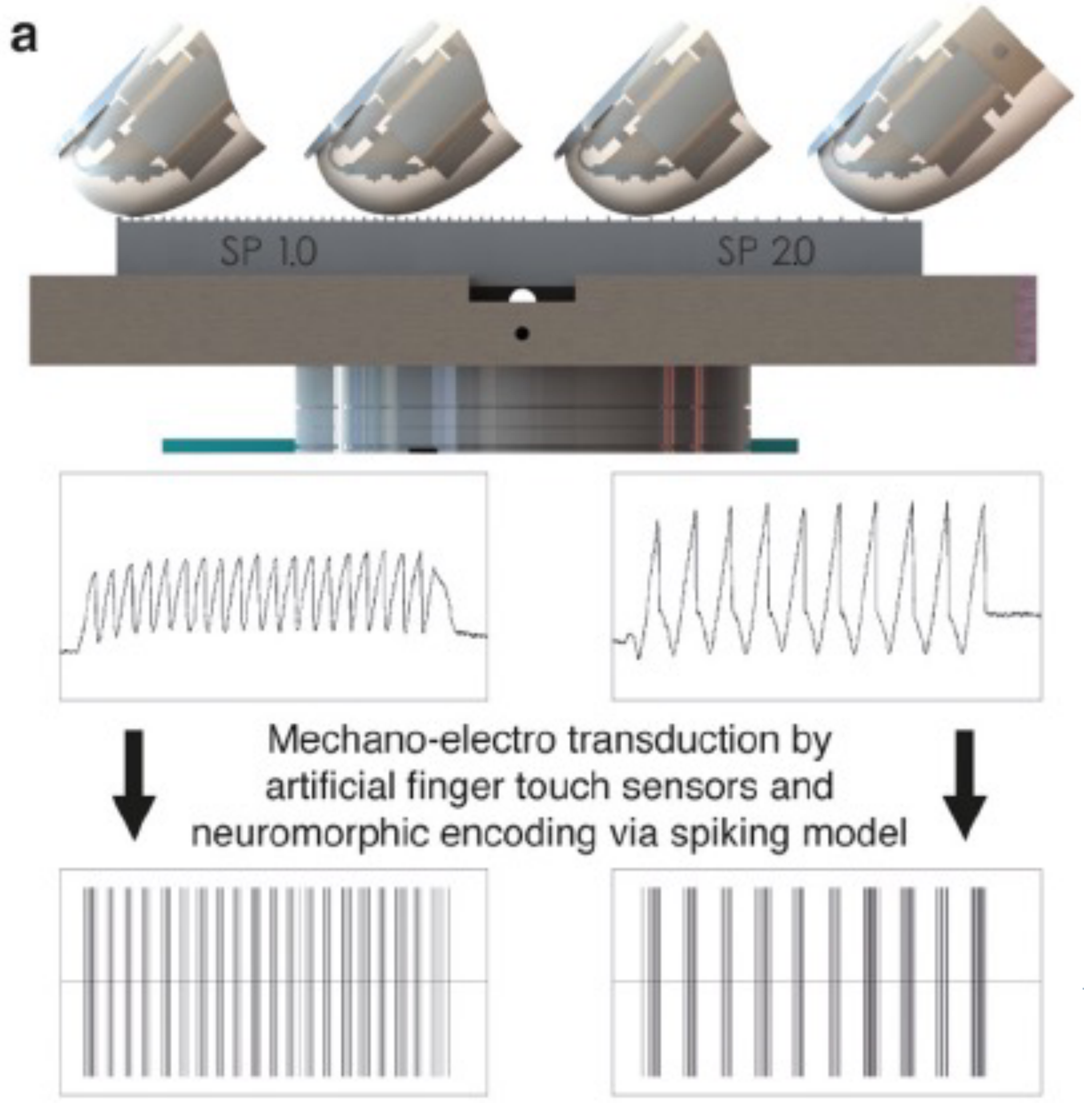
Biomimetic encoding strategy

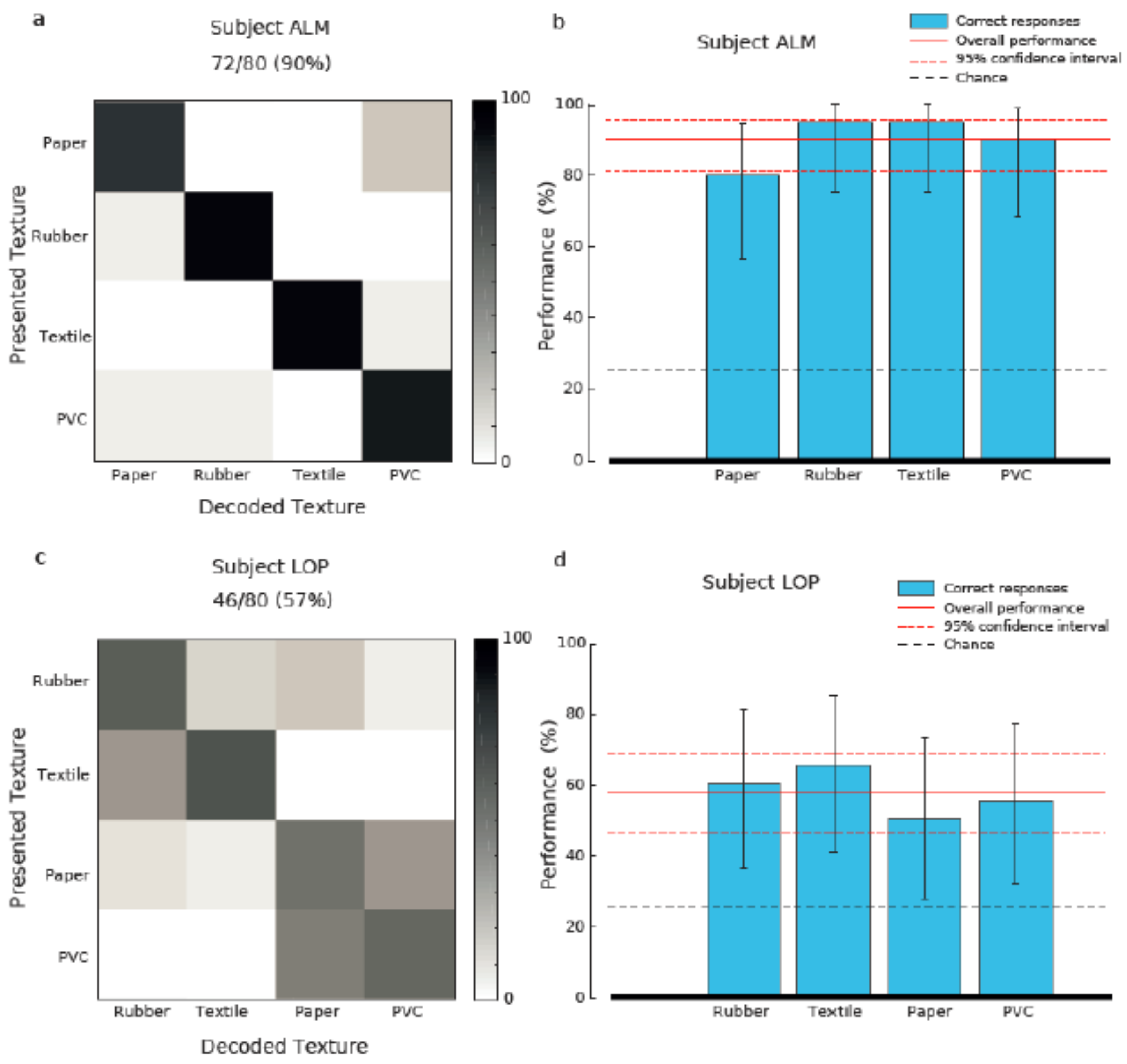



a
Telescoping task setup
Visual Insulation
Moving cursor
Limb length
Q1) It seemed like the phantom hand had changed orientation as the robotic hand
Q2) I felt my phantom arm longer
b
Telescoping pre-post VET N=5
35 - Real limb
Perceived Phantom length [cm]
x p<0.05
PRE POST
NF
ANM
FNM
HNM-1
HNM-2
c
Phantom limb dimension perceptions Questionnaires N=5
Answer [0 10]
x , + p<0.05
Q1 Q2
NF
ANM
FNM
HNM-1
HNM-2

Restoring perception of real textures



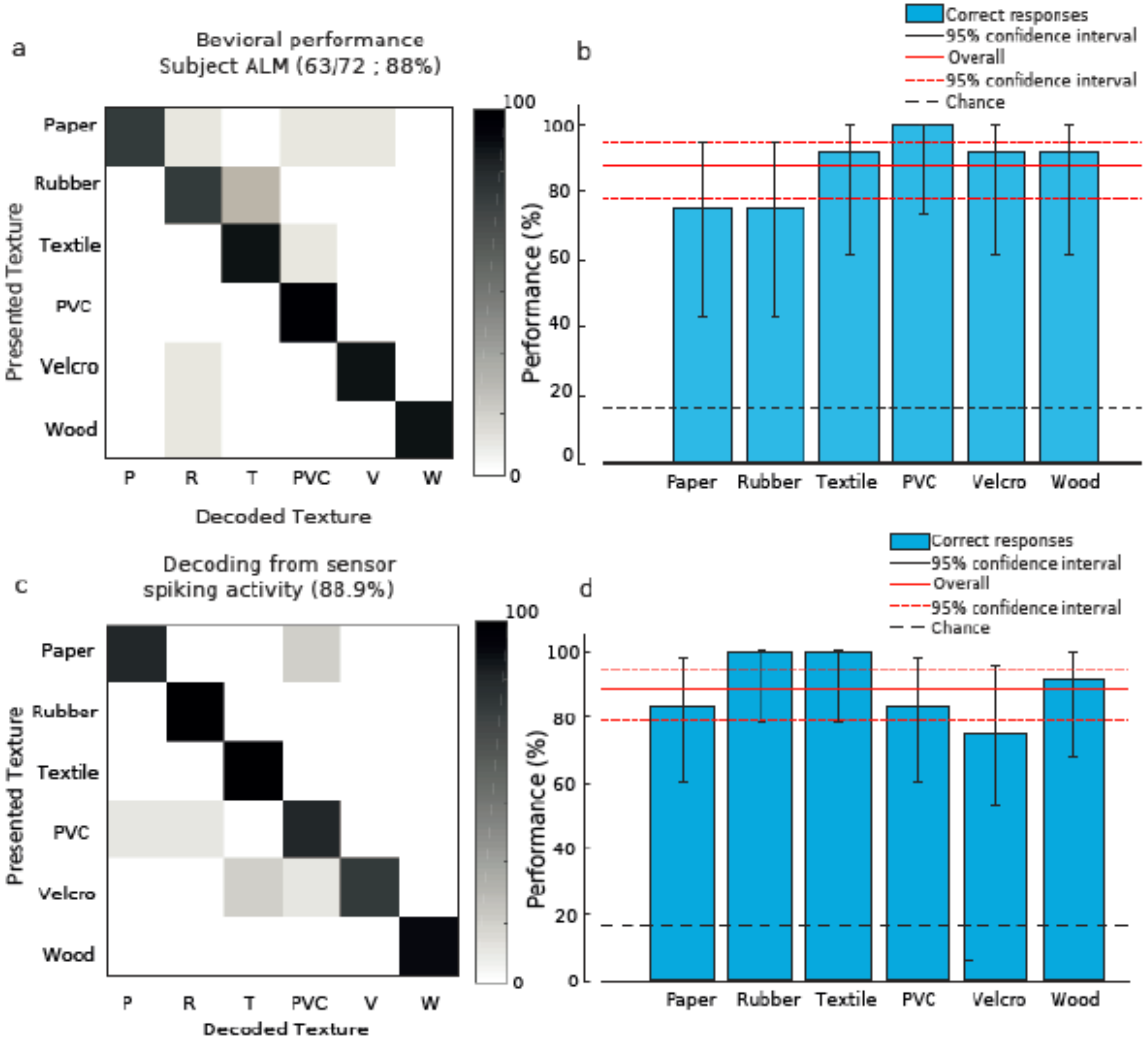


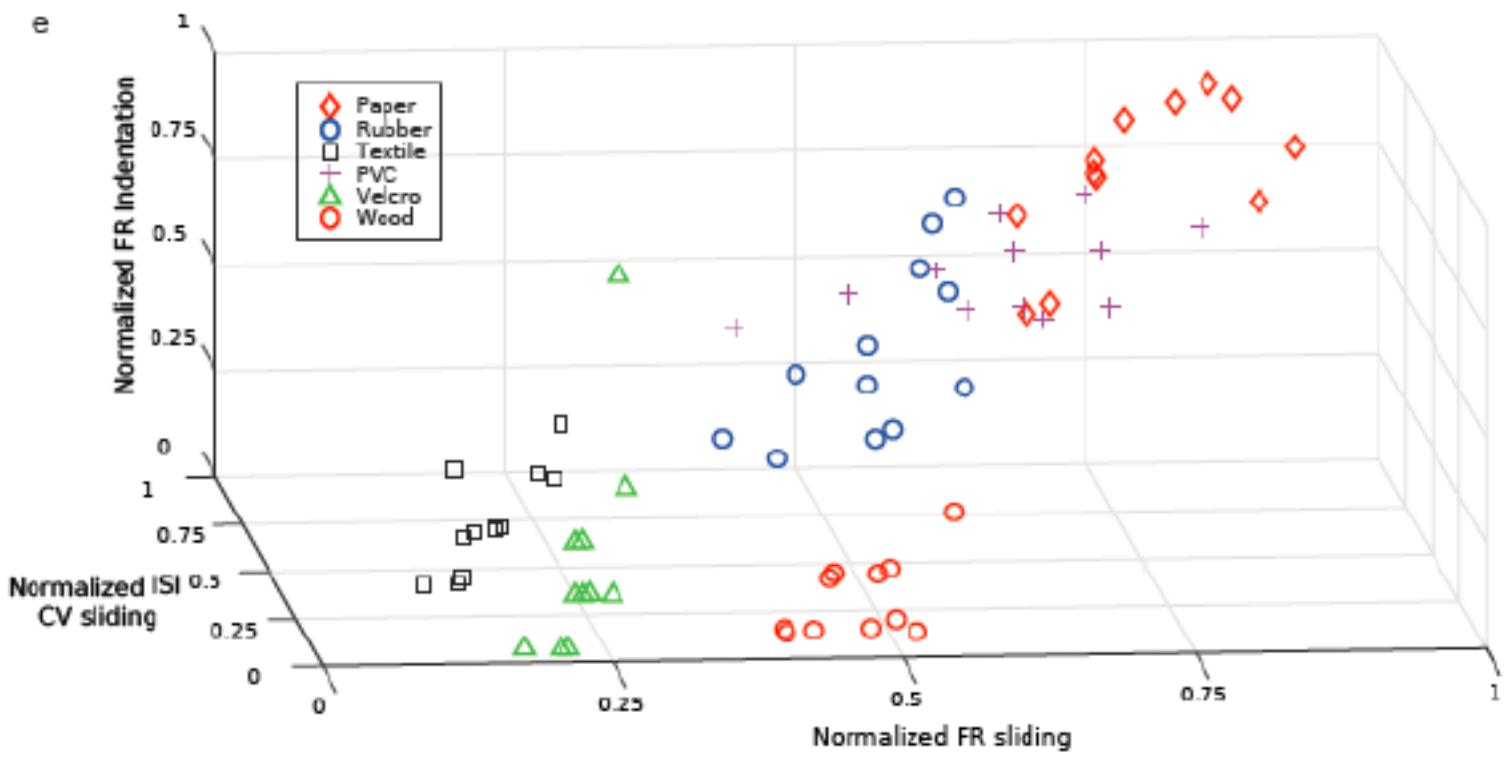


Oddo et al., eLIFE, 2016

Mazzoni et al., Sci Rep, 2019

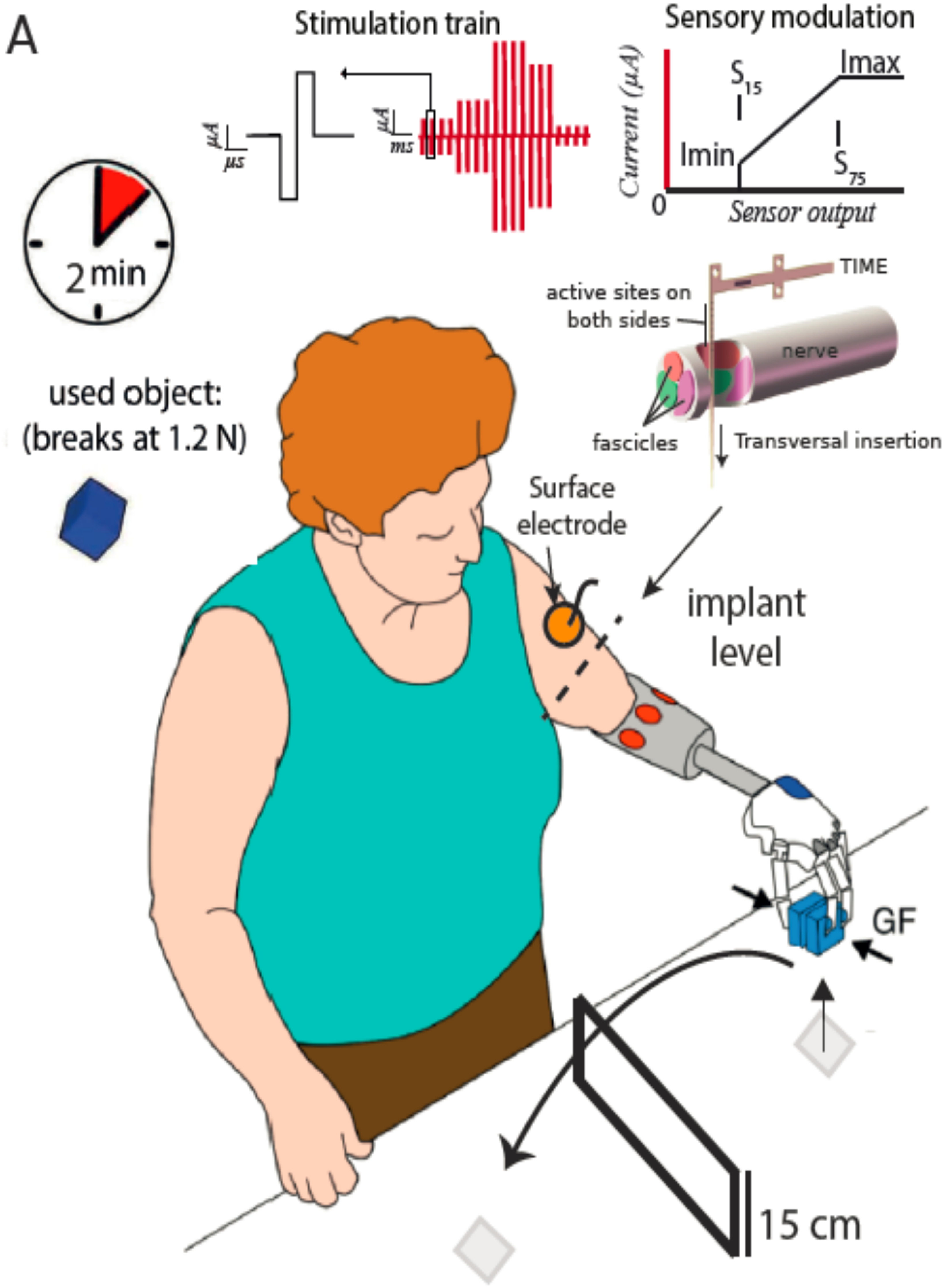
Restoring perception of real textures





Implanted interfaces can also be used to understand basic principles

Effects of cognitive load



B

Induced sensations & stimulation parameters

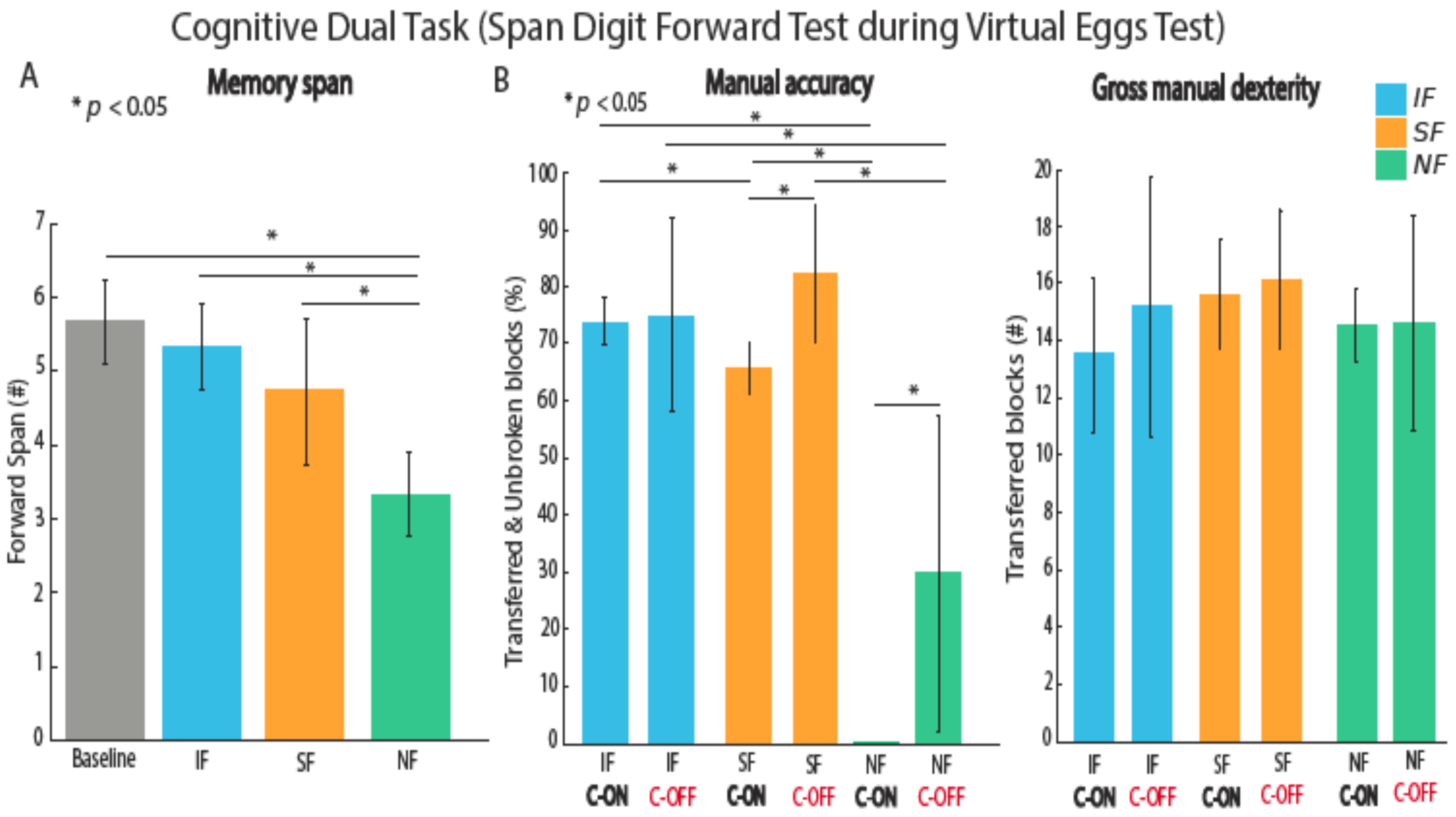
Intraneural sensory Feedback (IF)

sensation type	vibration
sensation intensity	$S_{min} = 1$, $S_{max} = 8$
electrode position	proximal part of ulnar nerve above elbow
amplitude	A_{min}=200 μA , A_{max}= 300 μA
pulse-width	80 μs
frequency	50 Hz

Superficial sensory Feedback (SF)

sensation type	electricity
sensation intensity	$S_{min} = 1$, $S_{max} = 8$
electrode position	on the skin of the left arm
amplitude	A_{min}=100 μA , A_{max}= 500 μA
pulse-width	200 μs
frequency	50 Hz

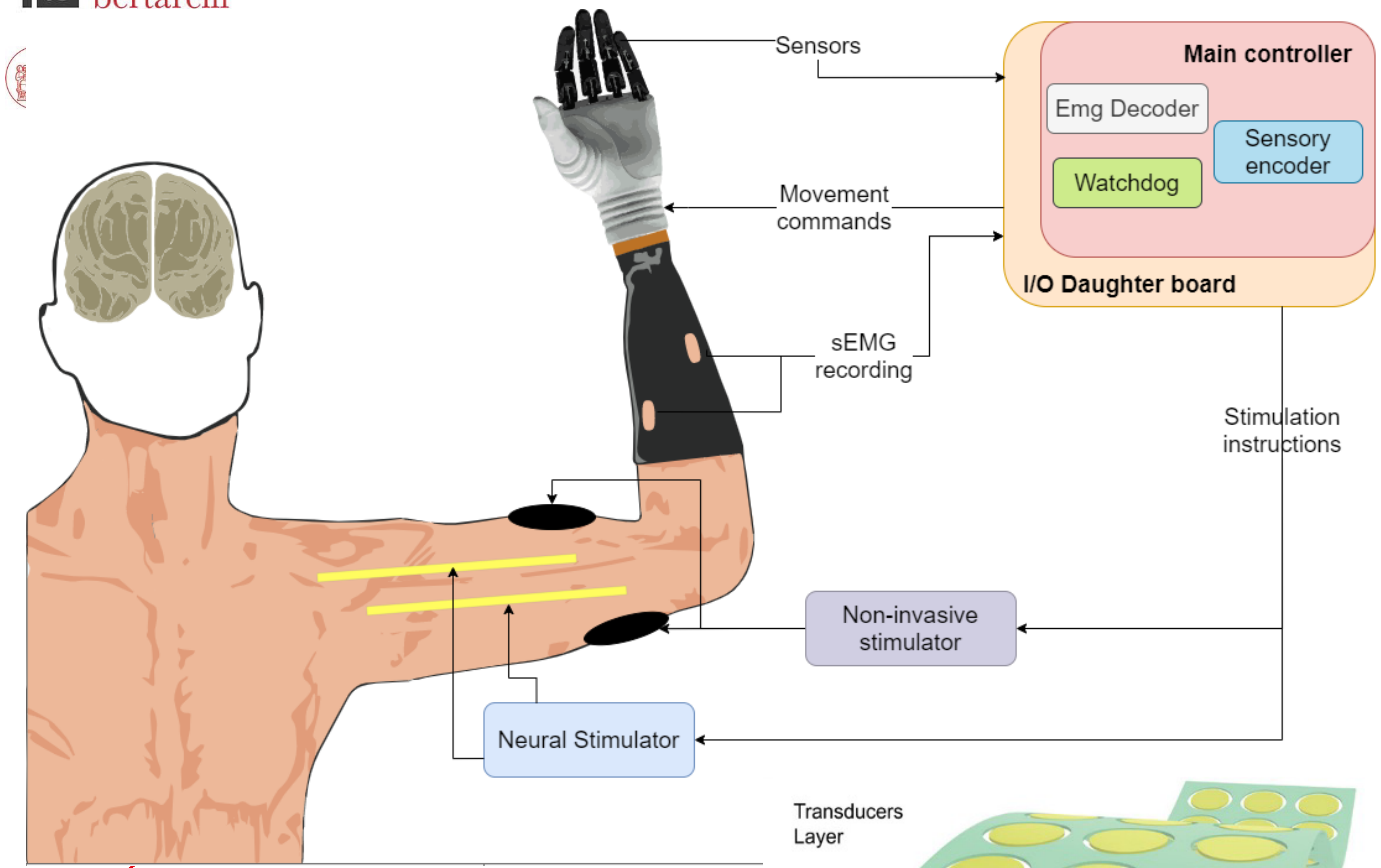
Effects of cognitive load

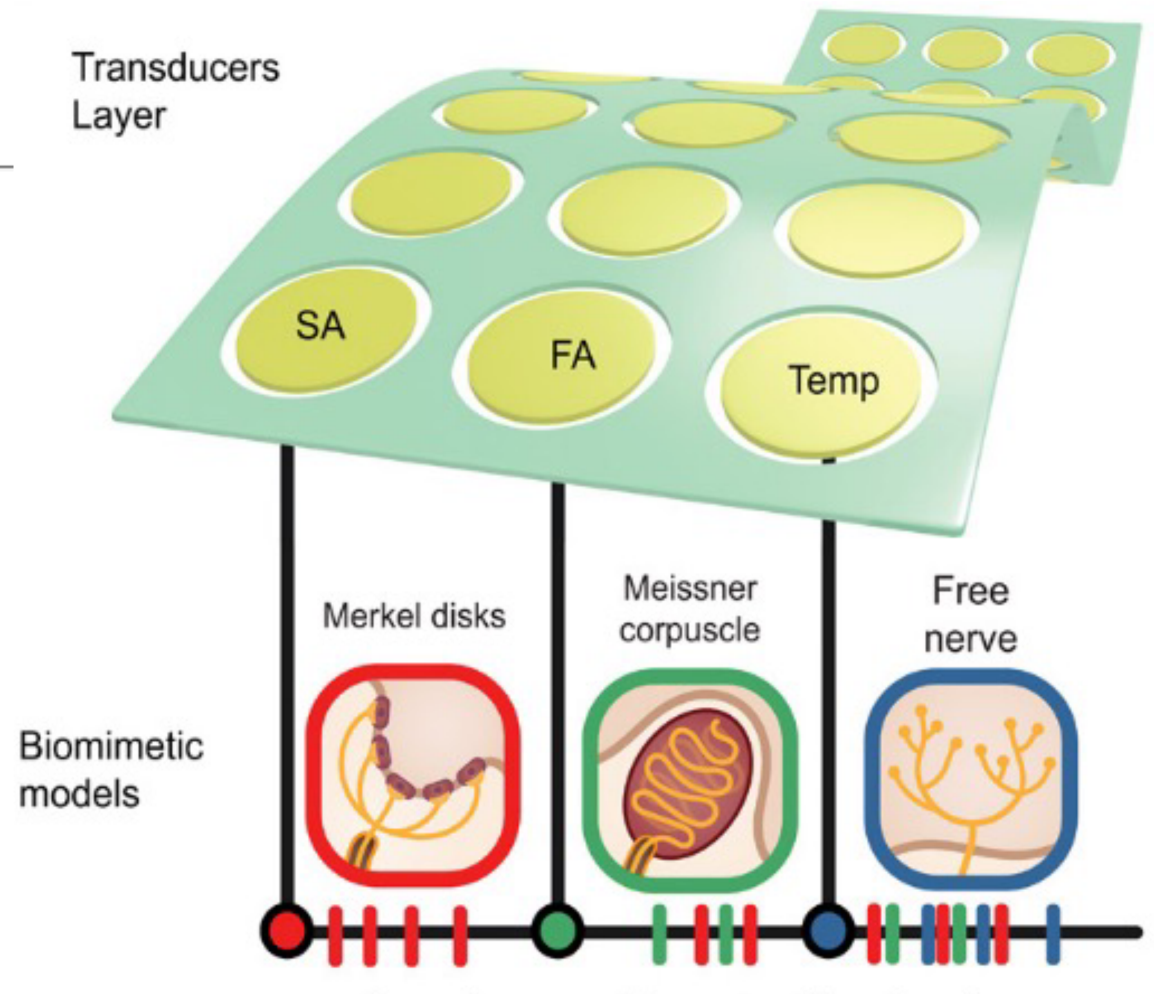


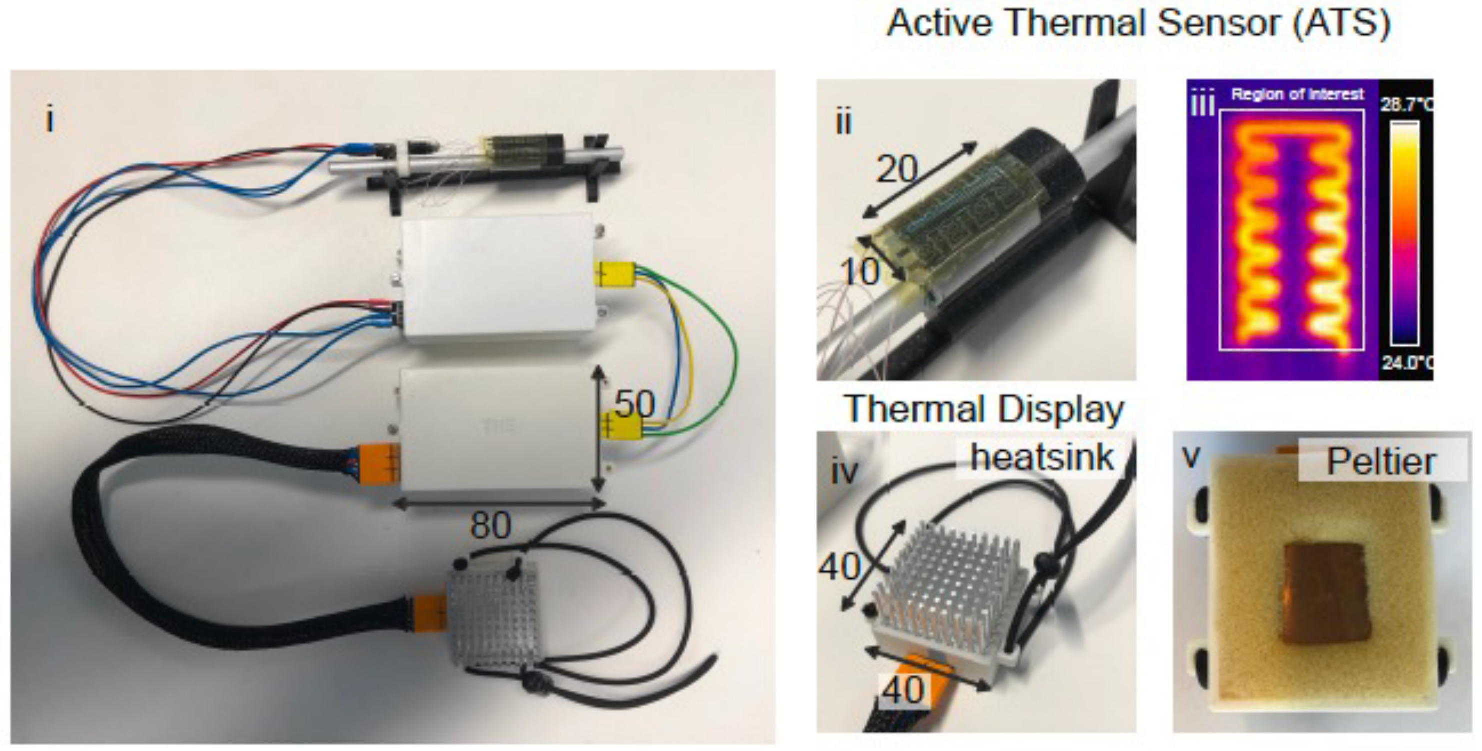
EPFL

fondation bertarelli

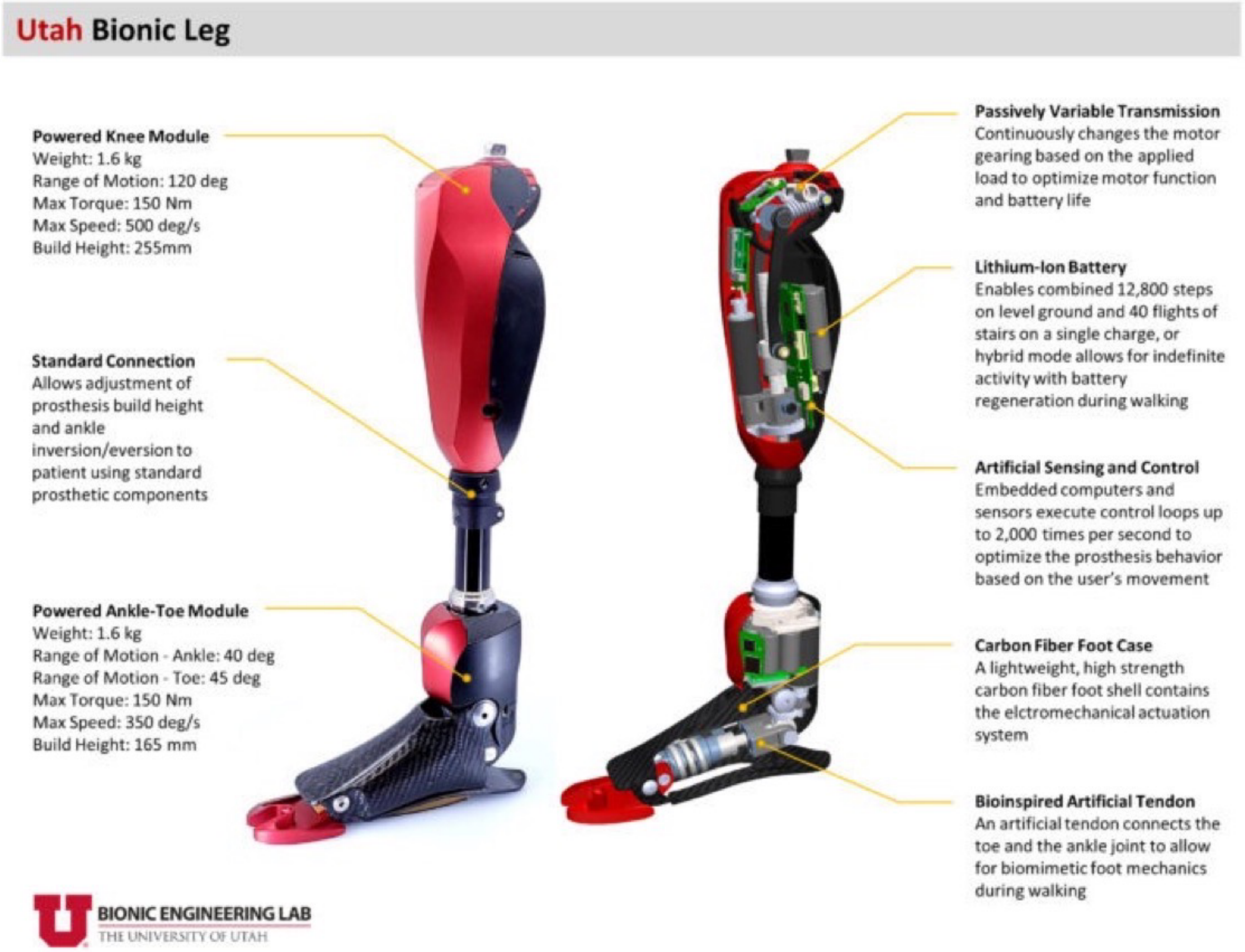
NEXT STEP – Going chronic at home







Bidirectional neurocontrolled leg prostheses

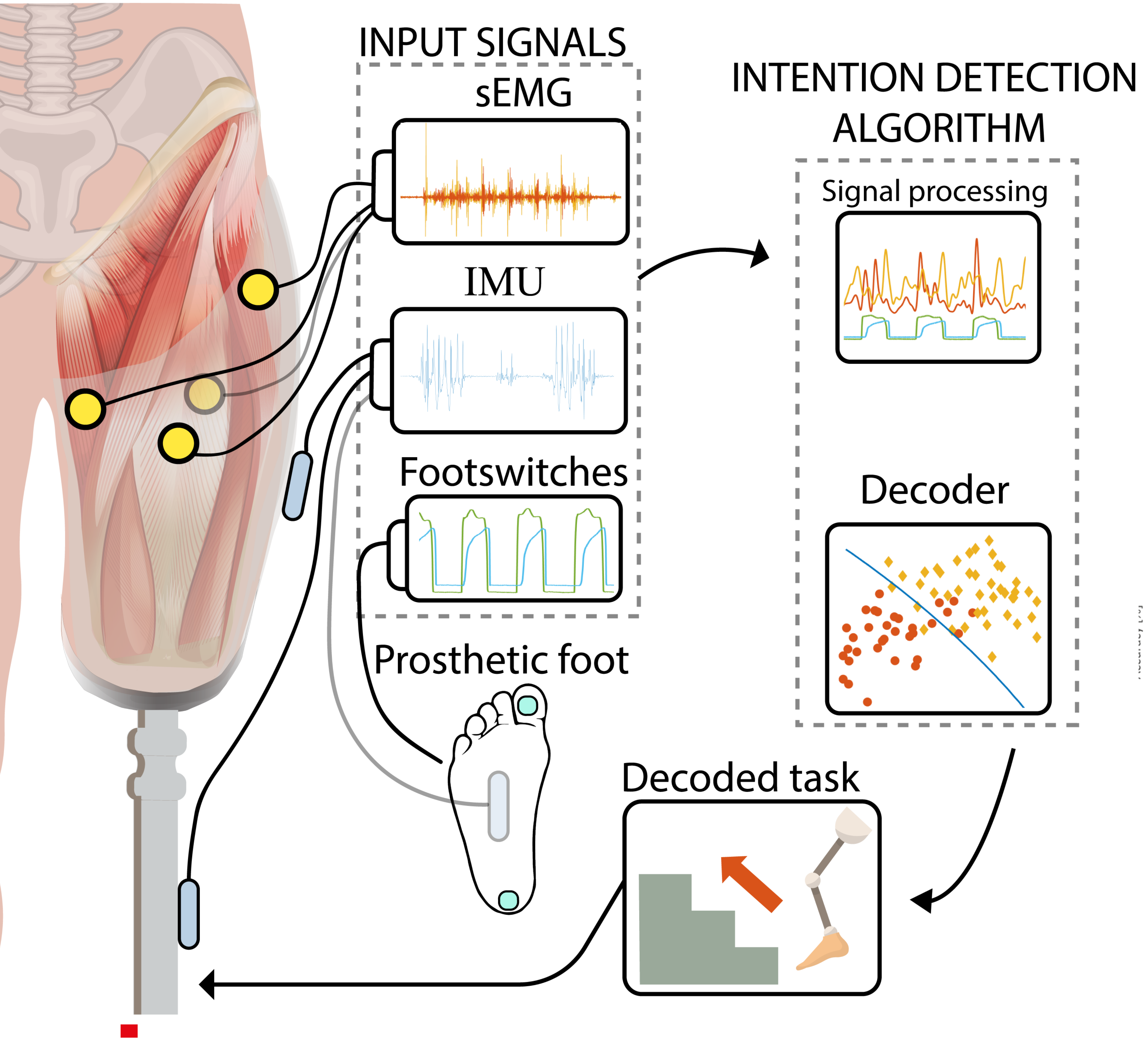


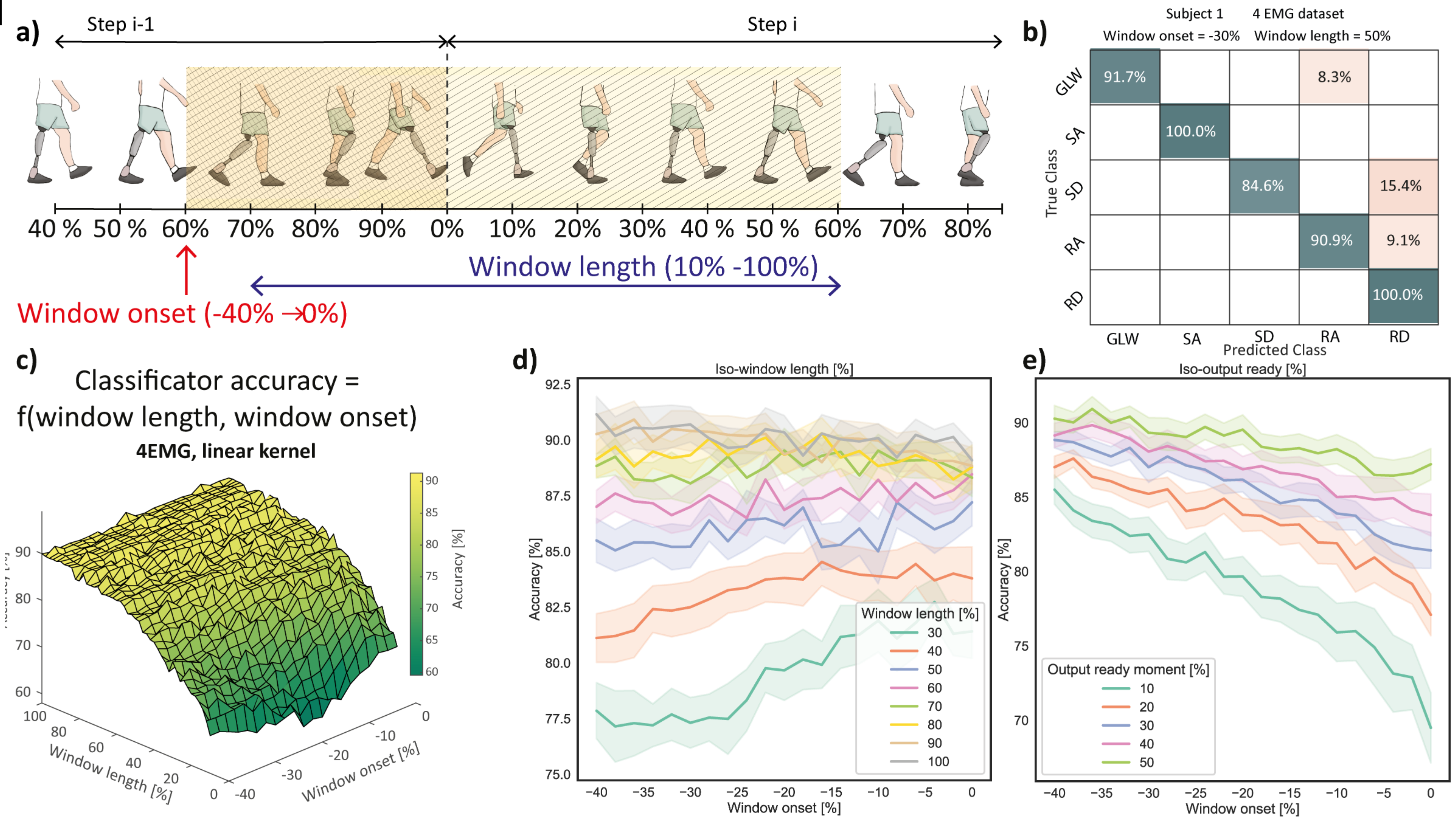
EPFL

fondation bertarelli

Sant'Anna Scuola Universitaria Superiore Pisa

Bidirectional neurocontrolled leg prostheses

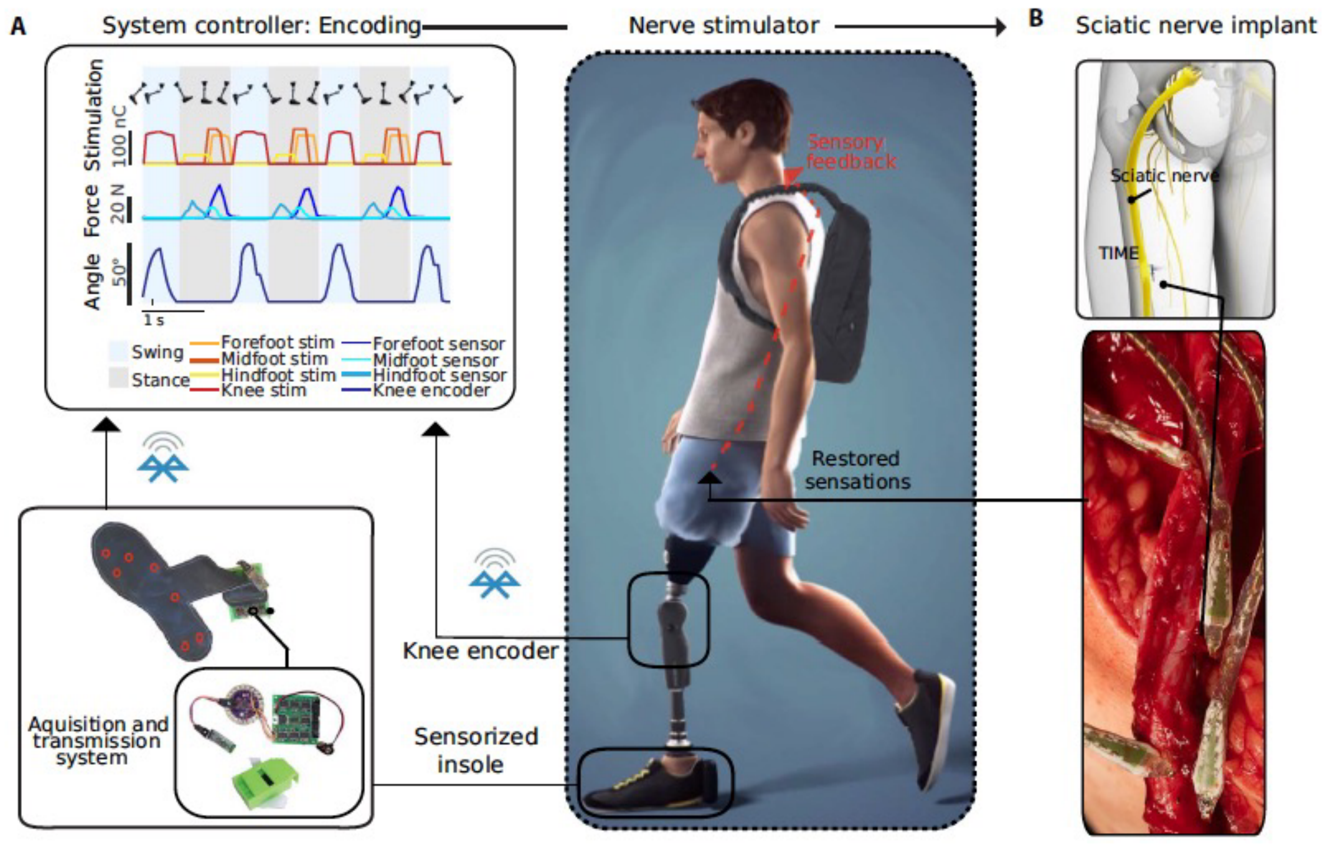


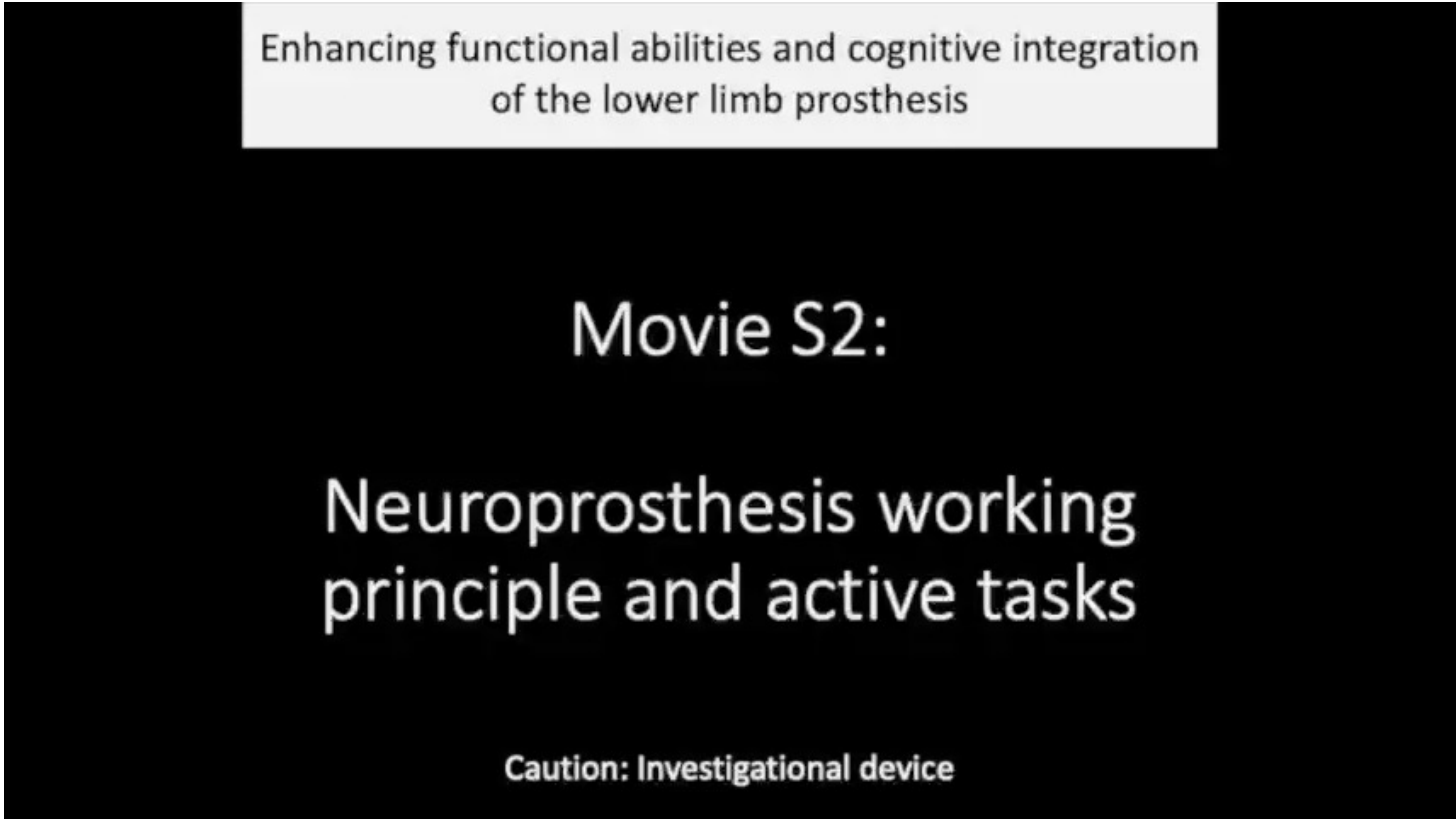


S.Micera

Bidirectional neurocontrolled leg prostheses

Sensory feedback





i4LIFE – Intraneural stim

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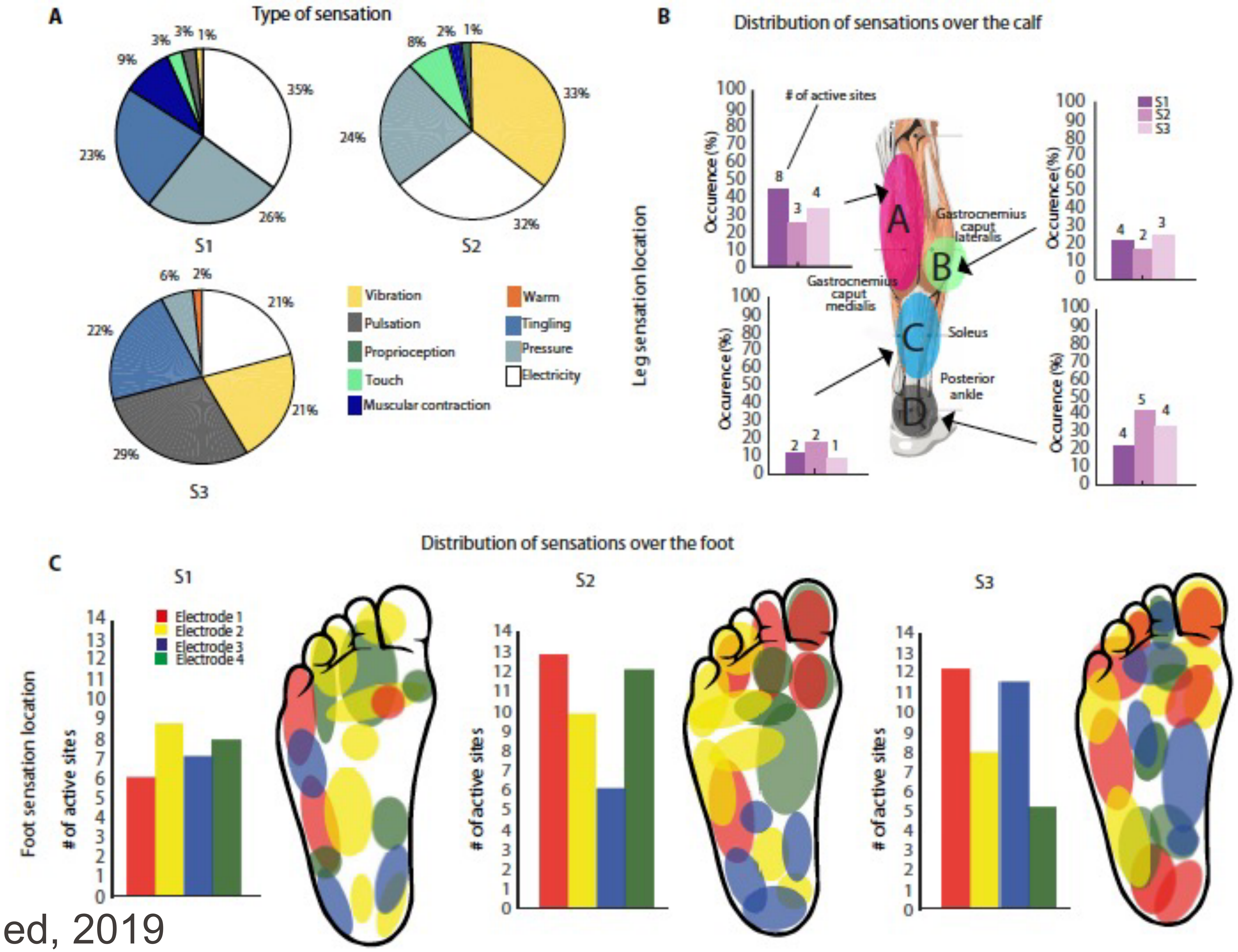
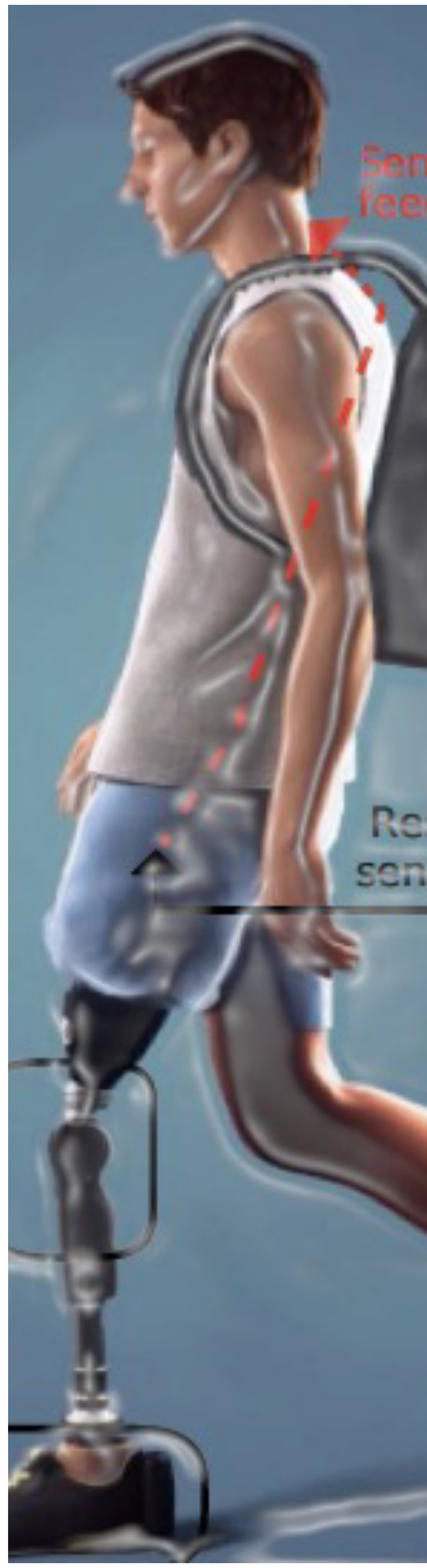
Bidirectional neurocontrolled leg prostheses
Sensory feedback



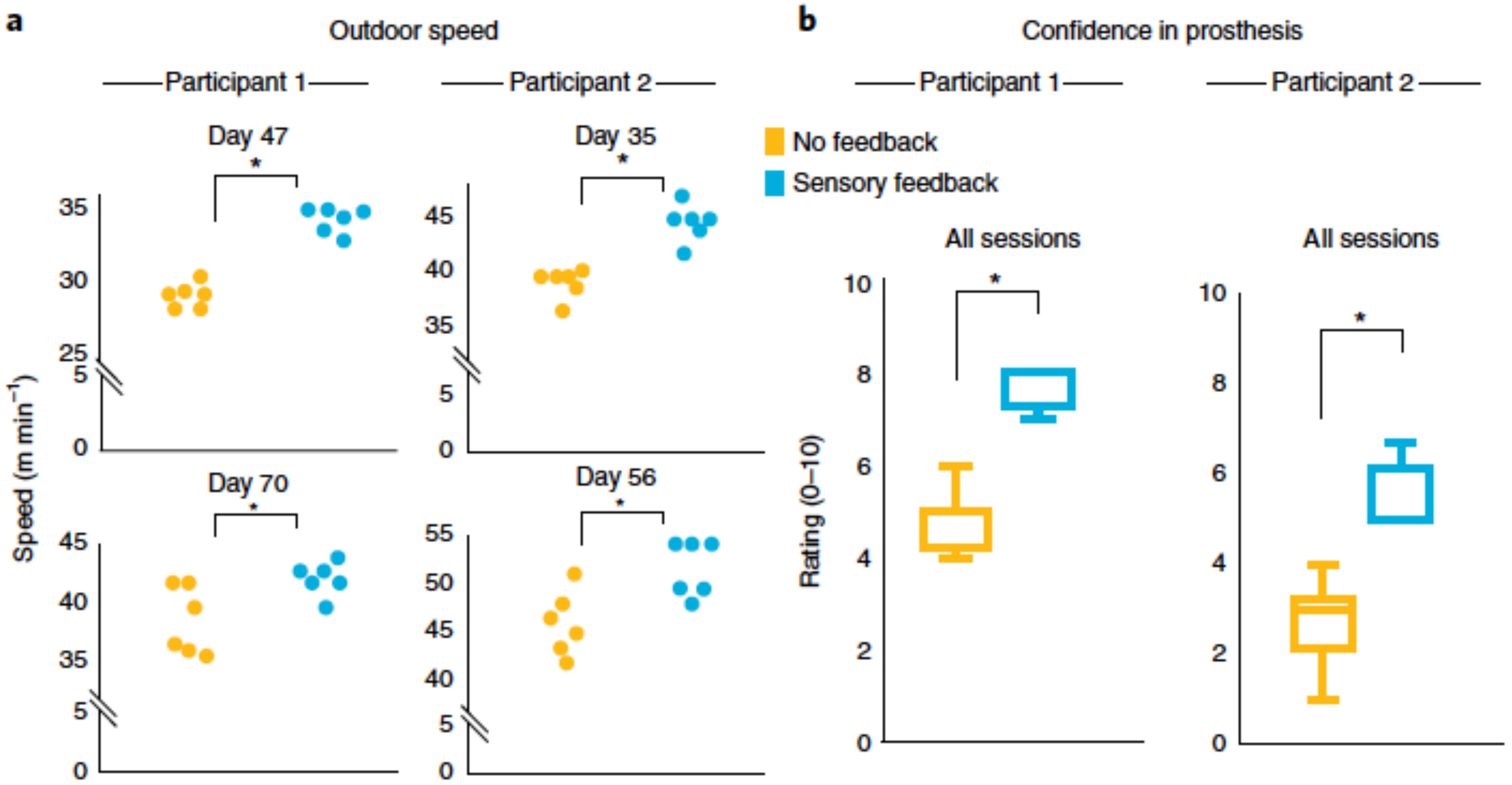


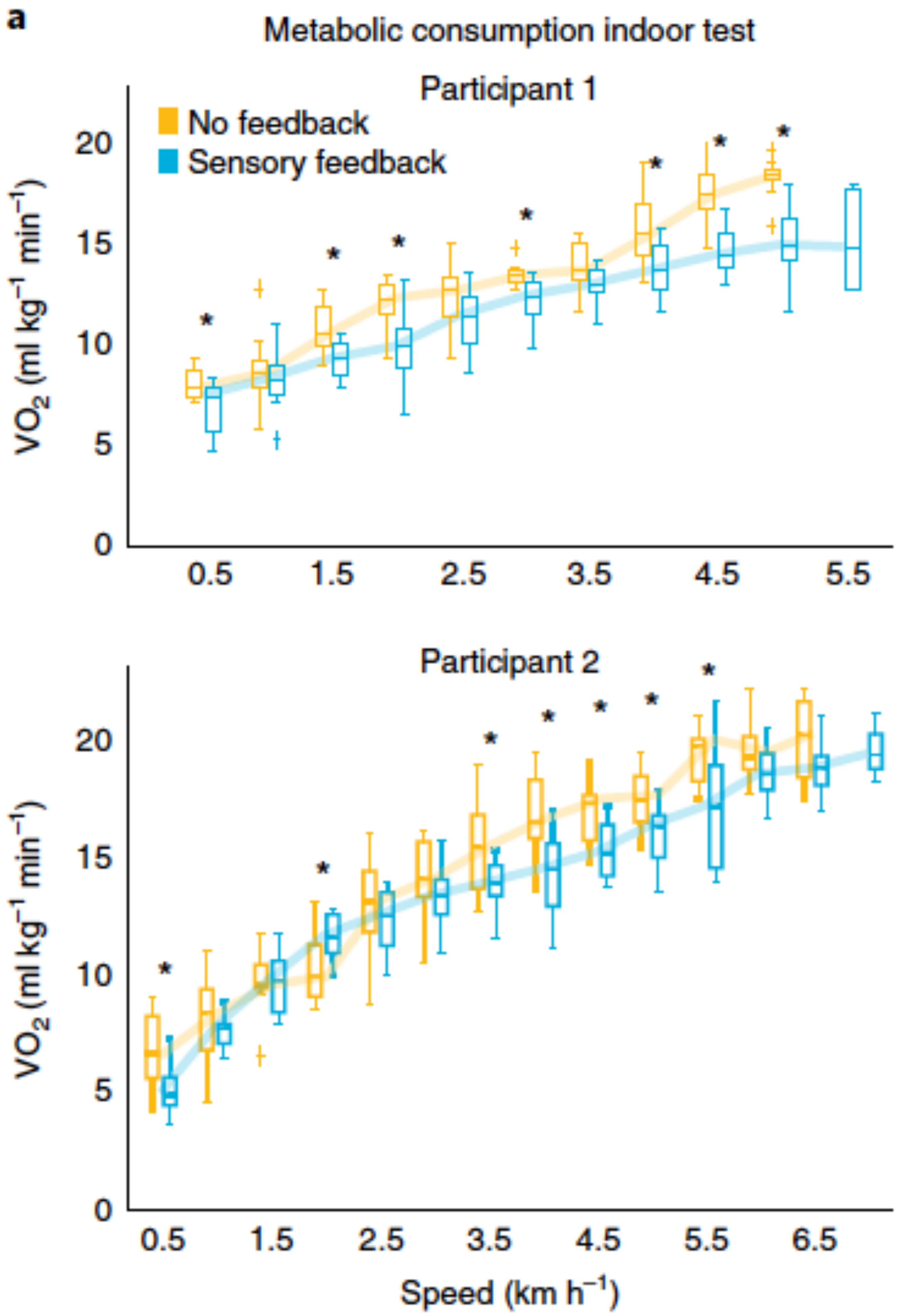
i4LIFE – Intraneural stimulation

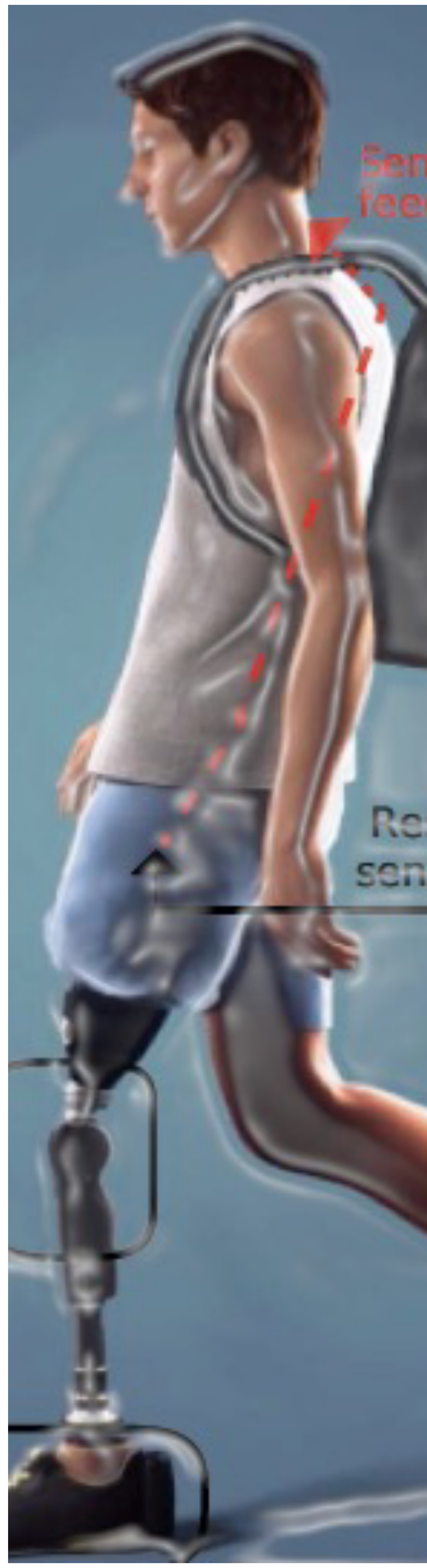
Petrini et al.,
Science Trans Med, 2019

Bidirectional neurocontrolled leg prostheses

Sensory feedback







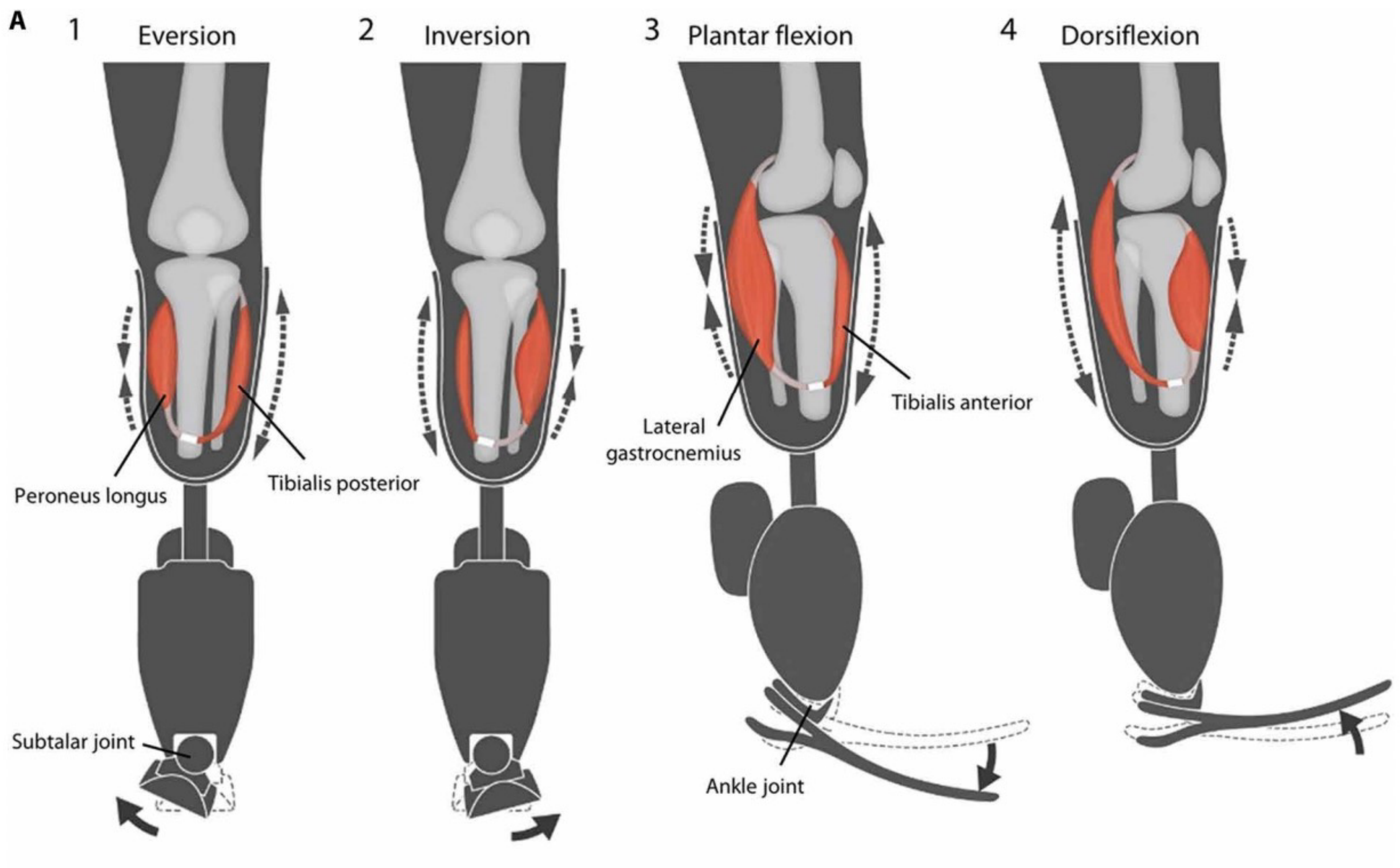
Walking speed and self-reported confidence increased while mental and physical fatigue decreased for both participants

Participants exhibited reduced phantom limb pain with neural sensory feedback.

Petrini et al., Nature Medicine, 2019

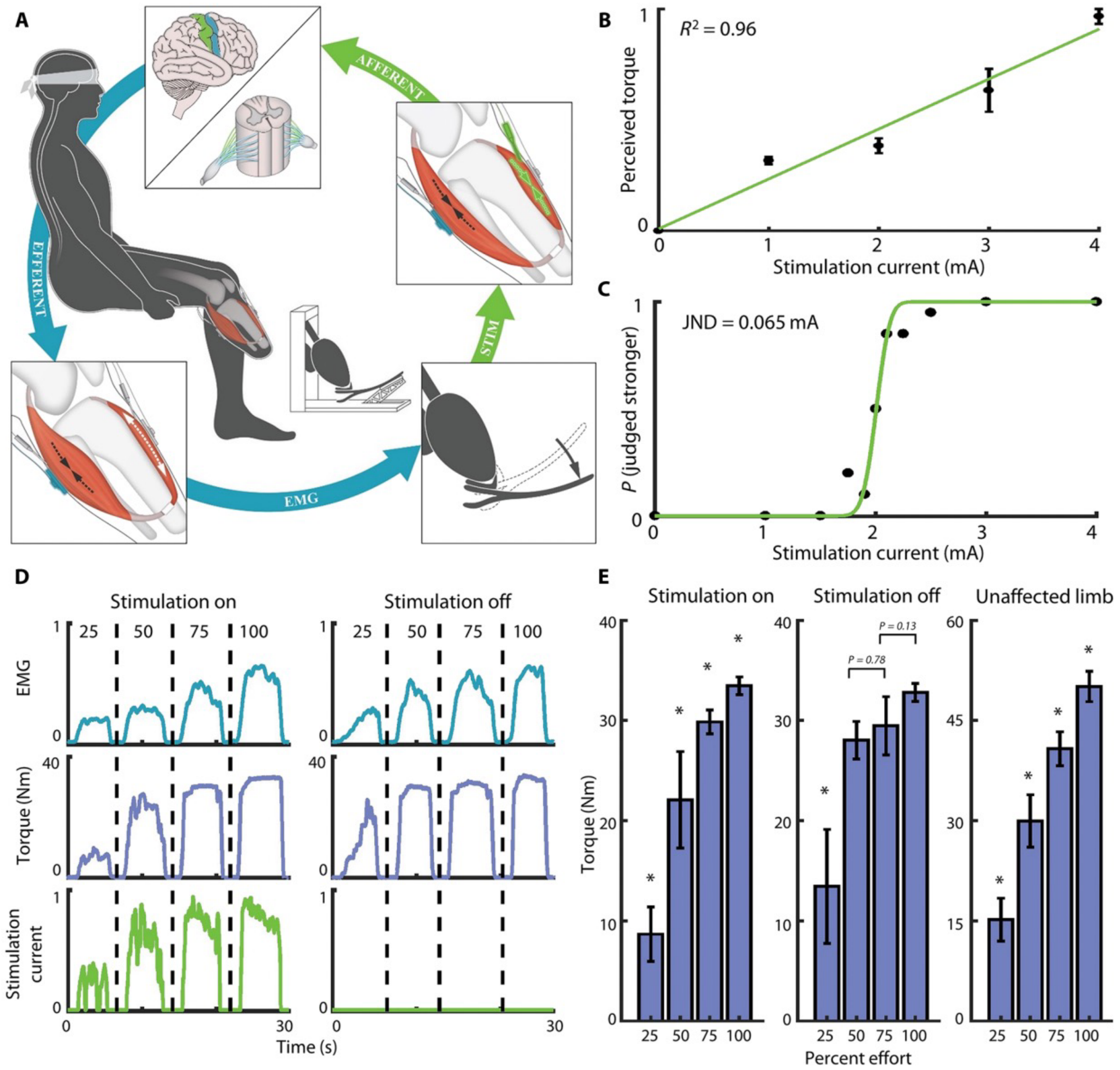
Agonist-antagonist myoneural interface

- 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

Agonist-antagonist myoneural interface – Closed-loop torque control

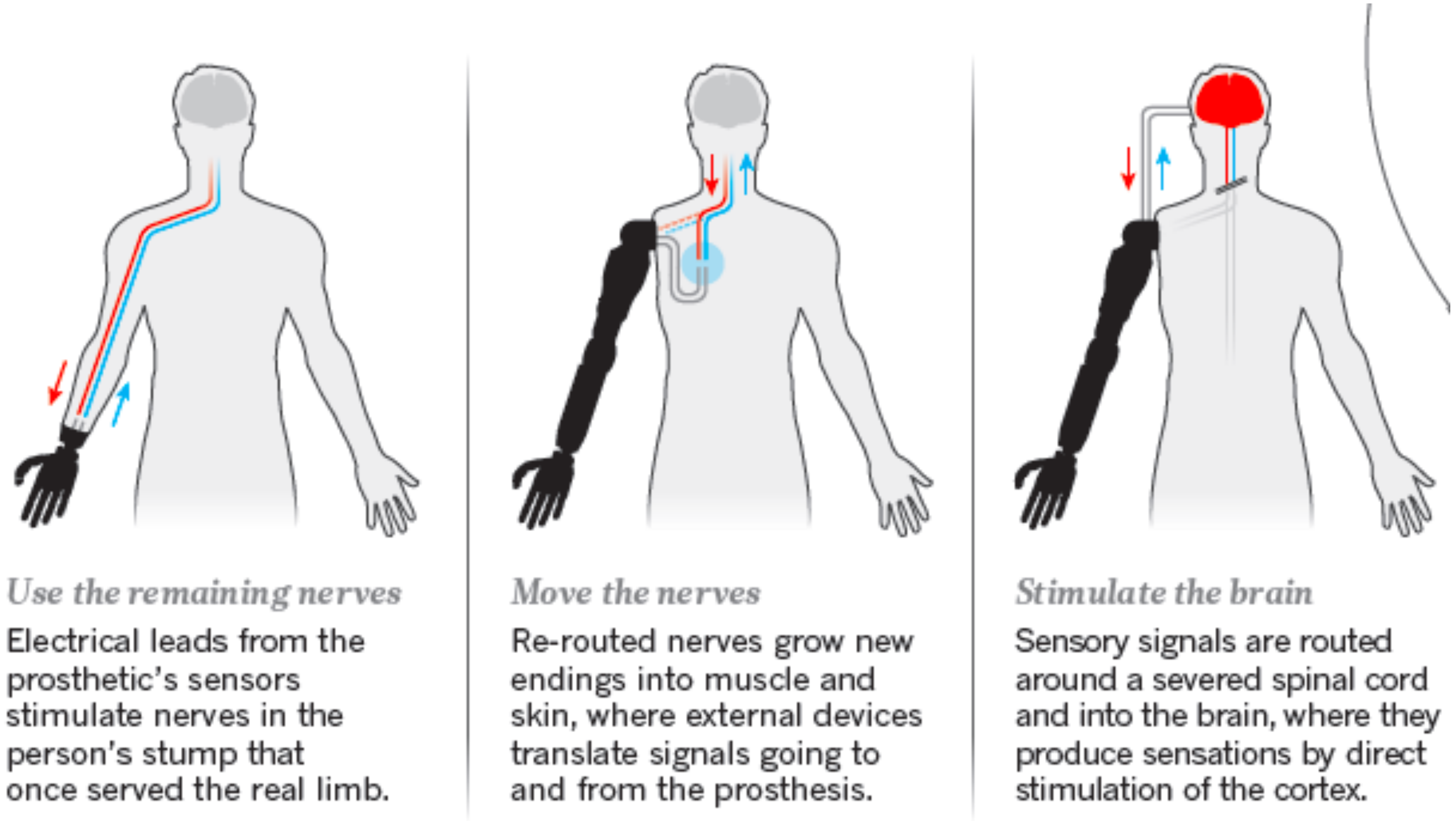


- (A) Schematic of the prosthesis-in-the-loop control architecture, in which afferent feedback of prosthetic joint torque is provided via FES of the antagonist muscle. The patient perceives this stimulation as a natural sensation of ankle torque
- (B) Magnitude estimation of perceived dorsiflexion torque as a function of stimulation current delivered to the tibialis anterior
- (C) Discrimination performance as a function of differences in stimulation current
- (D) Representative sample traces of lateral gastrocnemius EMG (blue), torque (purple), and stimulation current (green) during closed-loop torque control trials for the "stimulation on" (n = 79 total trials) and "stimulation off" (n = 79 total trials) cases
- (E) Summary data for closed-loop torque control trials in each of the stimulation on (n = 79 trials), stimulation off (n = 79 trials), and "unaffected limb" (n = 80 trials) cases

Clites et al., Science Trans Med, 2018

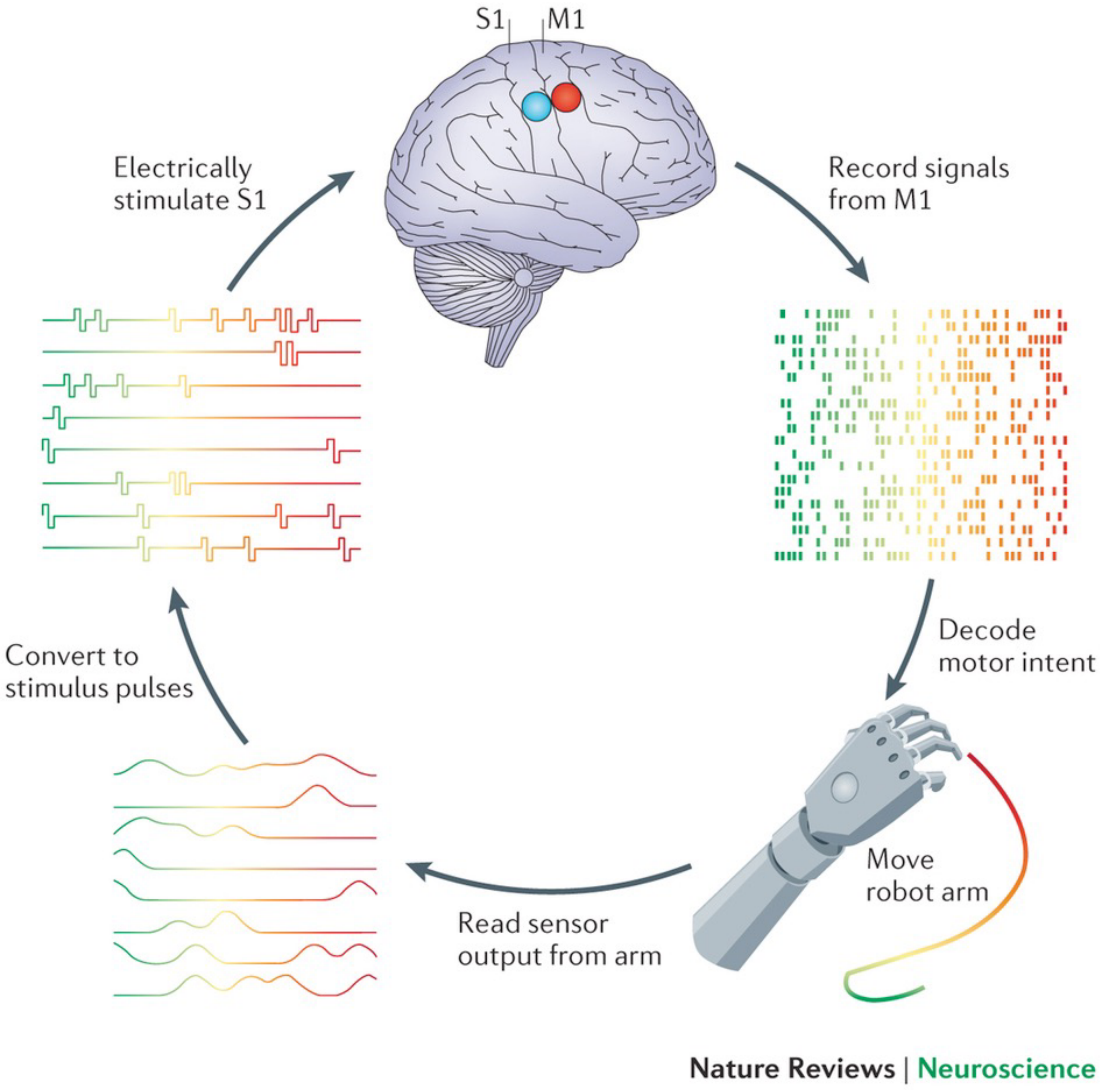
Sensory feedback

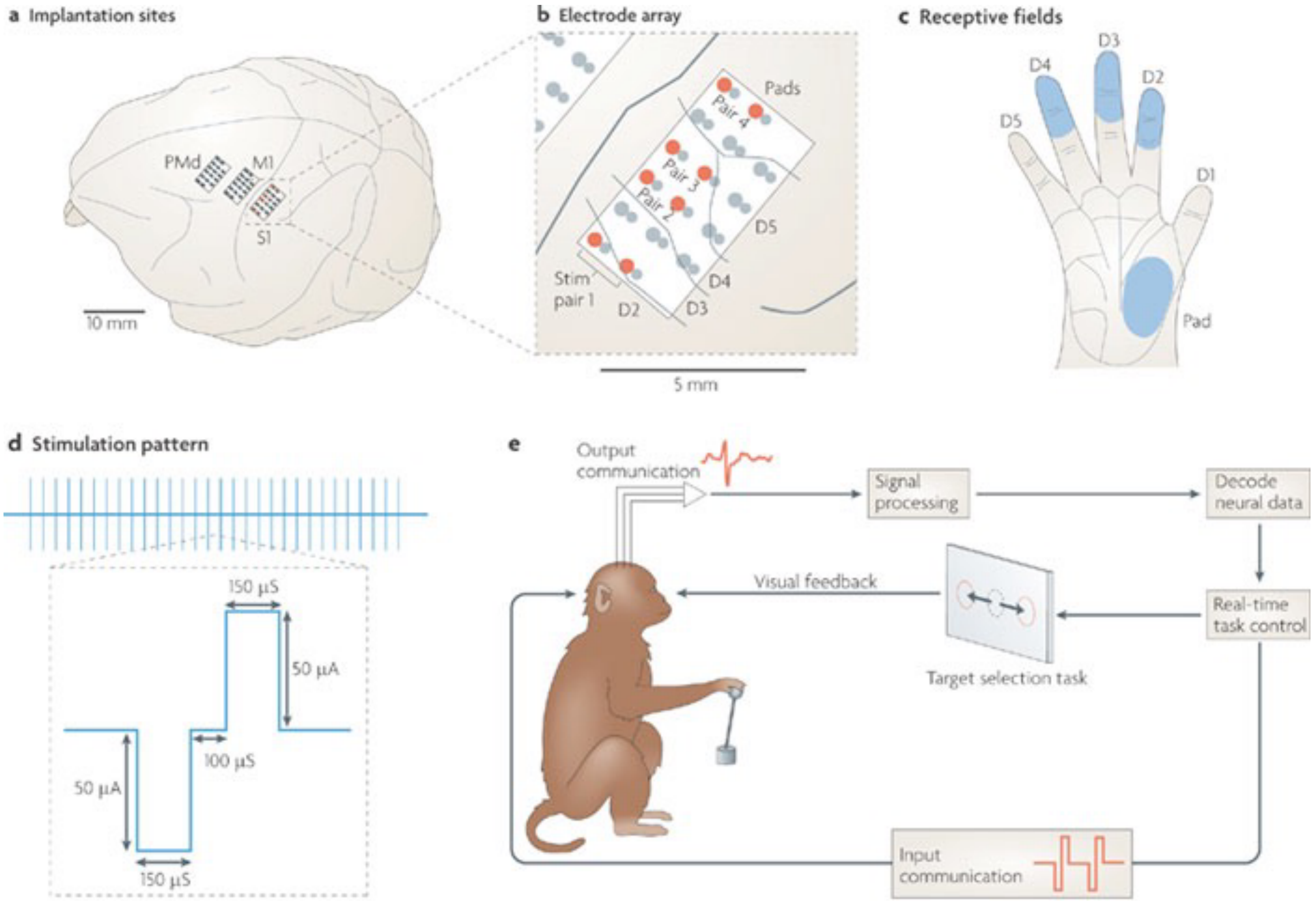
Real-time, and natural feedback from the hand prosthesis to the user is essential in order to enhance the control and functional impact of prosthetic hands in daily activities, prompting their full acceptance by the users



Kwok, Nature, 2013

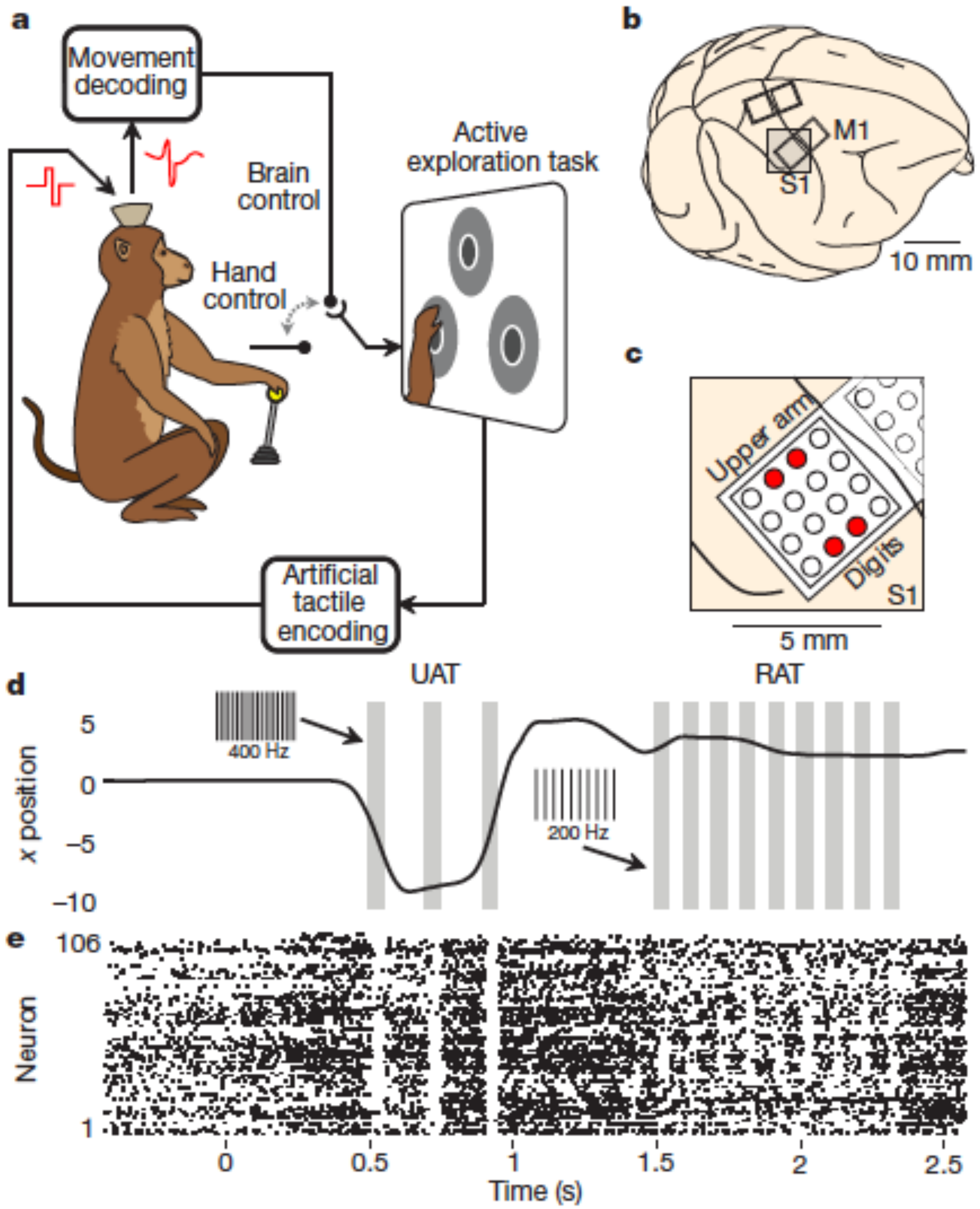
Brain-to-machine-to-brain interface





Nature Reviews | Neuroscience

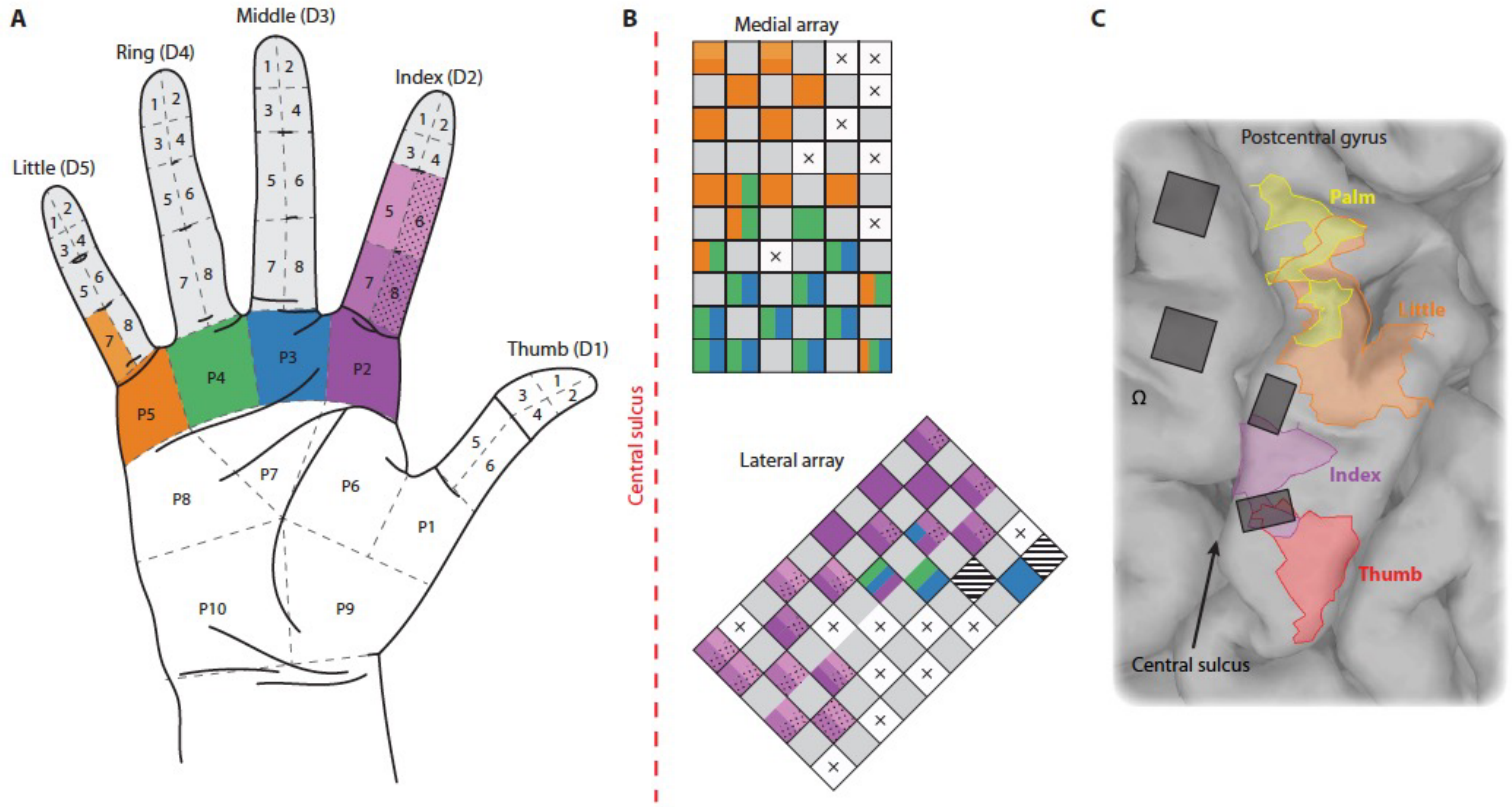
Intracortical sensory feedback



Intracortical sensory feedback is possible but the performance are still limited

O'Doherty et al., 2011

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



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

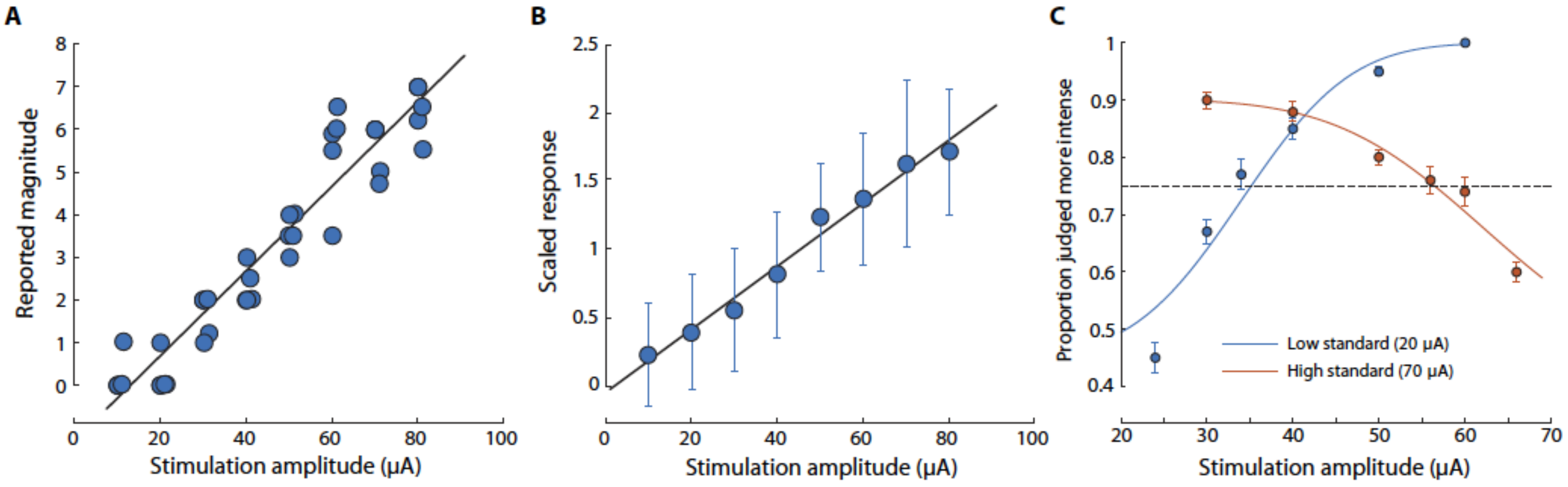
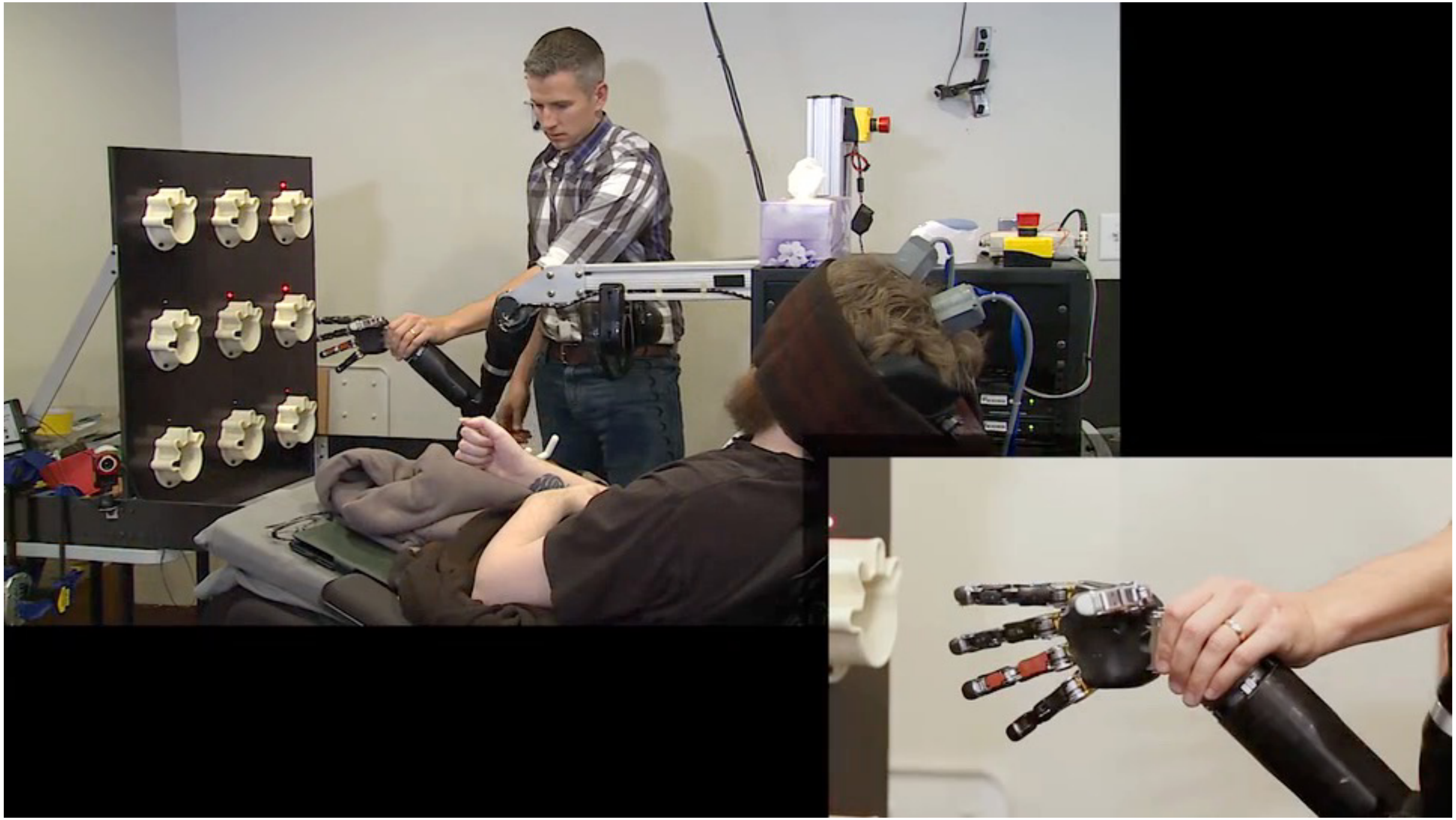


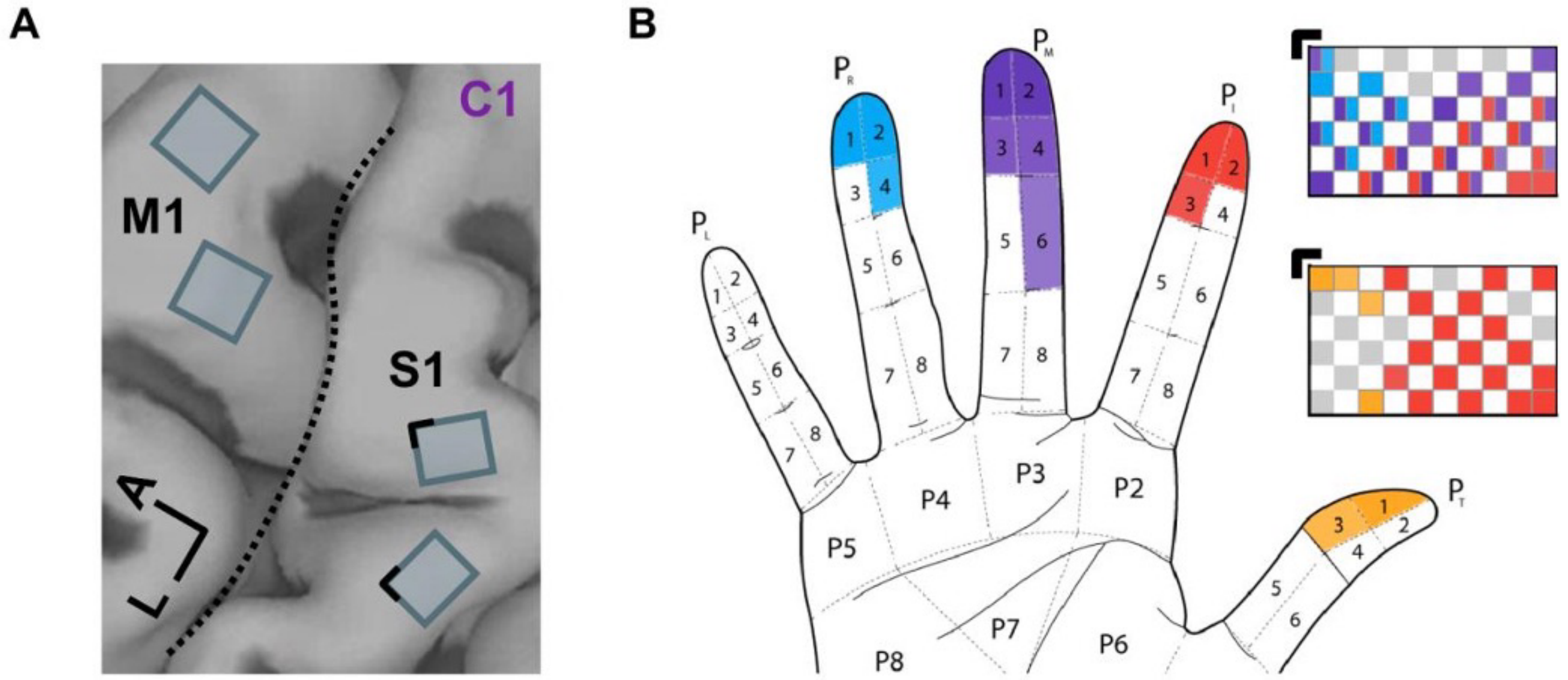
Table 2. Accuracy of prosthetic finger discrimination. The percentage of times that sensations were reported to originate from a specific finger (columns) when each prosthetic finger was touched (rows).

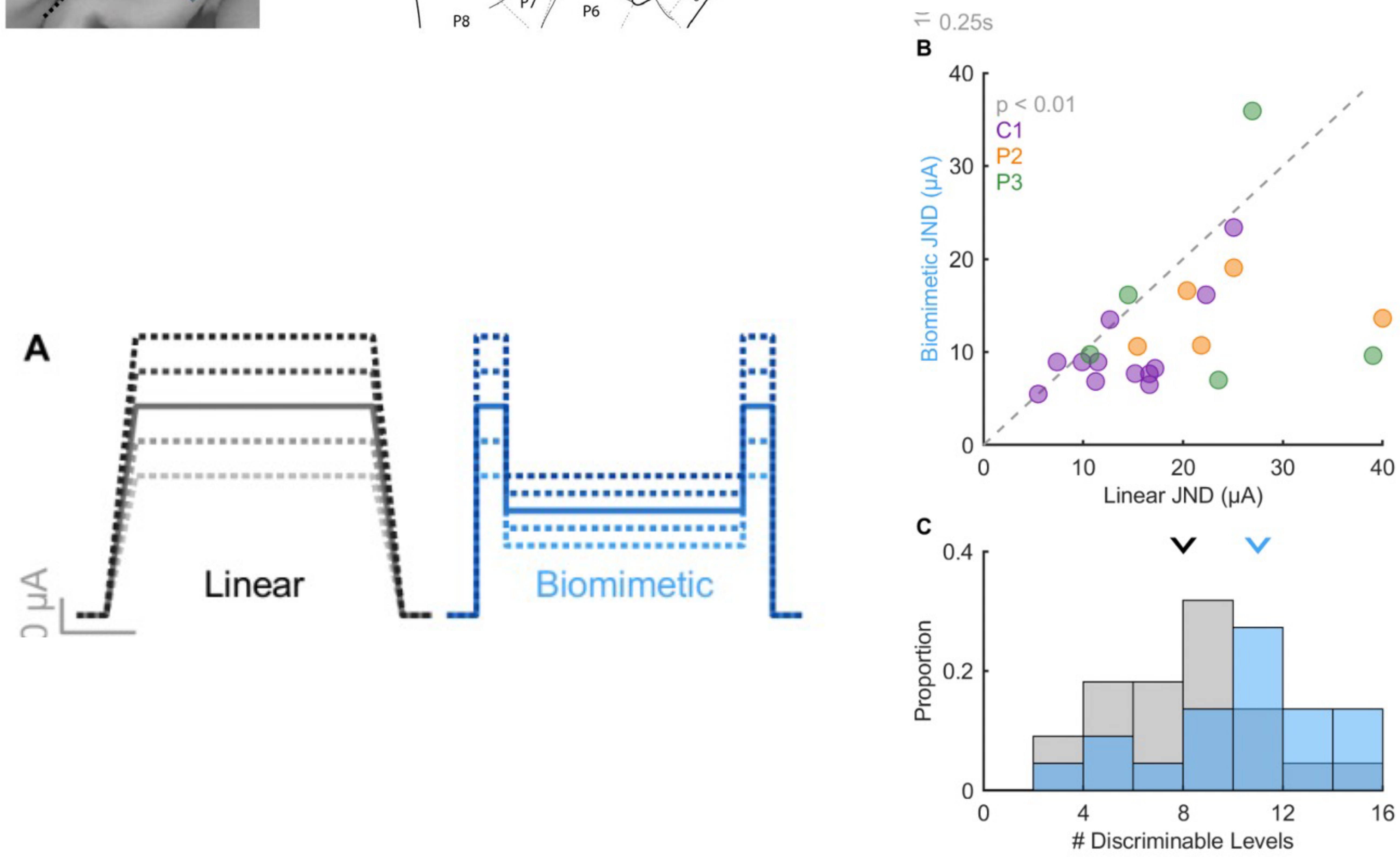
	Reported D2	Reported D3	Reported D4	Reported D5
Actual D2	96.9 ± 7.2%	1.5 ± 5.3%	1.5 ± 5.3%	0%
Actual D3	0%	73.5 ± 18.1%	21.9 ± 18.4%	0%
Actual D4	0%	18.5 ± 22.8%	73.1 ± 24.6%	6.5 ± 16.8%
Actual D5	0%	3.1 ± 7.2%	3.1 ± 10.7%	93.9 ± 12.1%

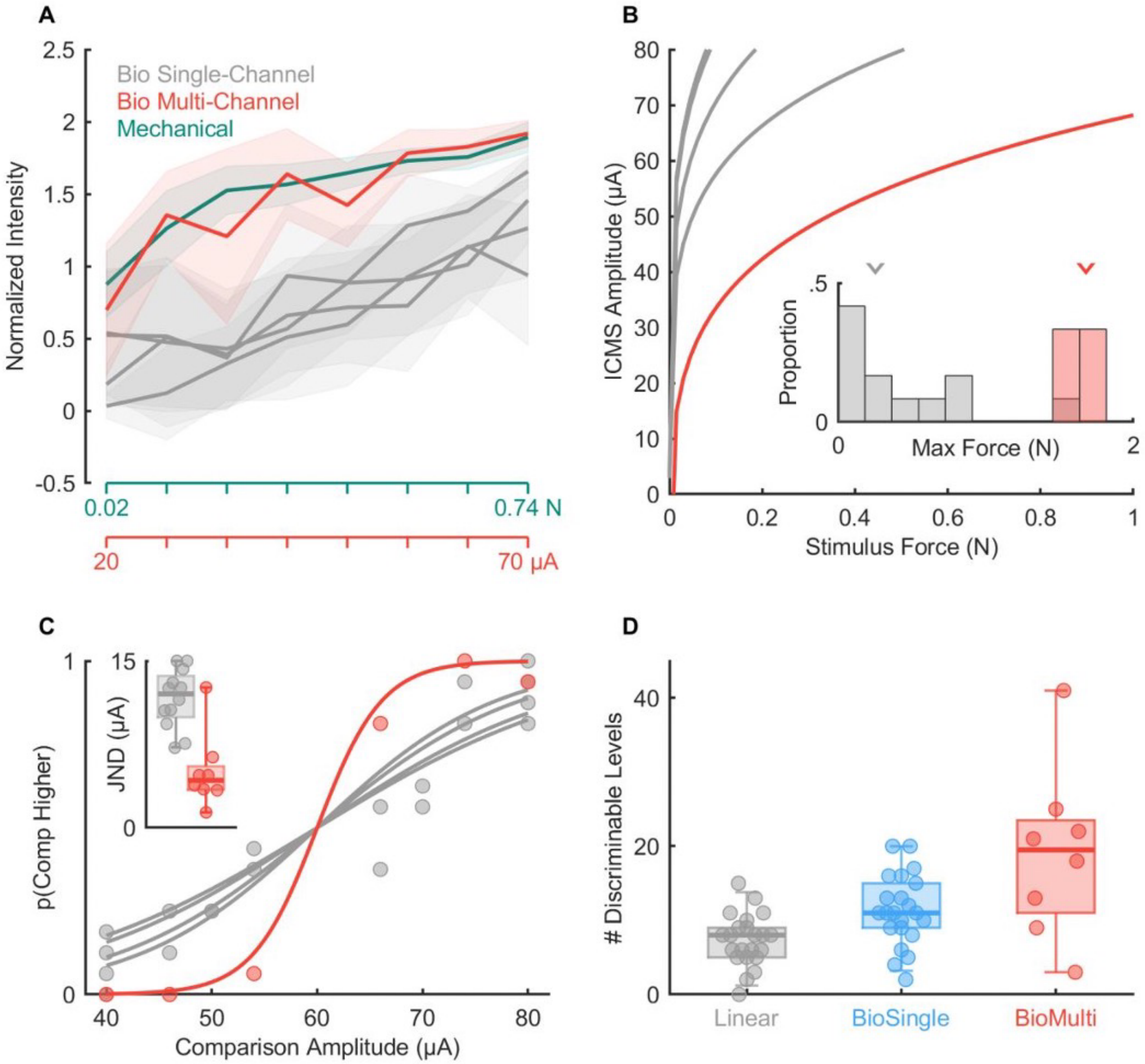
Brain-to-machine-to-brain interface in a quadriplegic subject



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







Greenspon et al., under review

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