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# Digital bridge restoring hand and arm functions after paralysis

## Advanced Methods for Human Neuromodulation Fall 2024


**Project Presentation**
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Guilherme Costa Ferreira
Raphaëlle Hartwig



École
polytechnique
fédérale de
Lausanne

# Outline

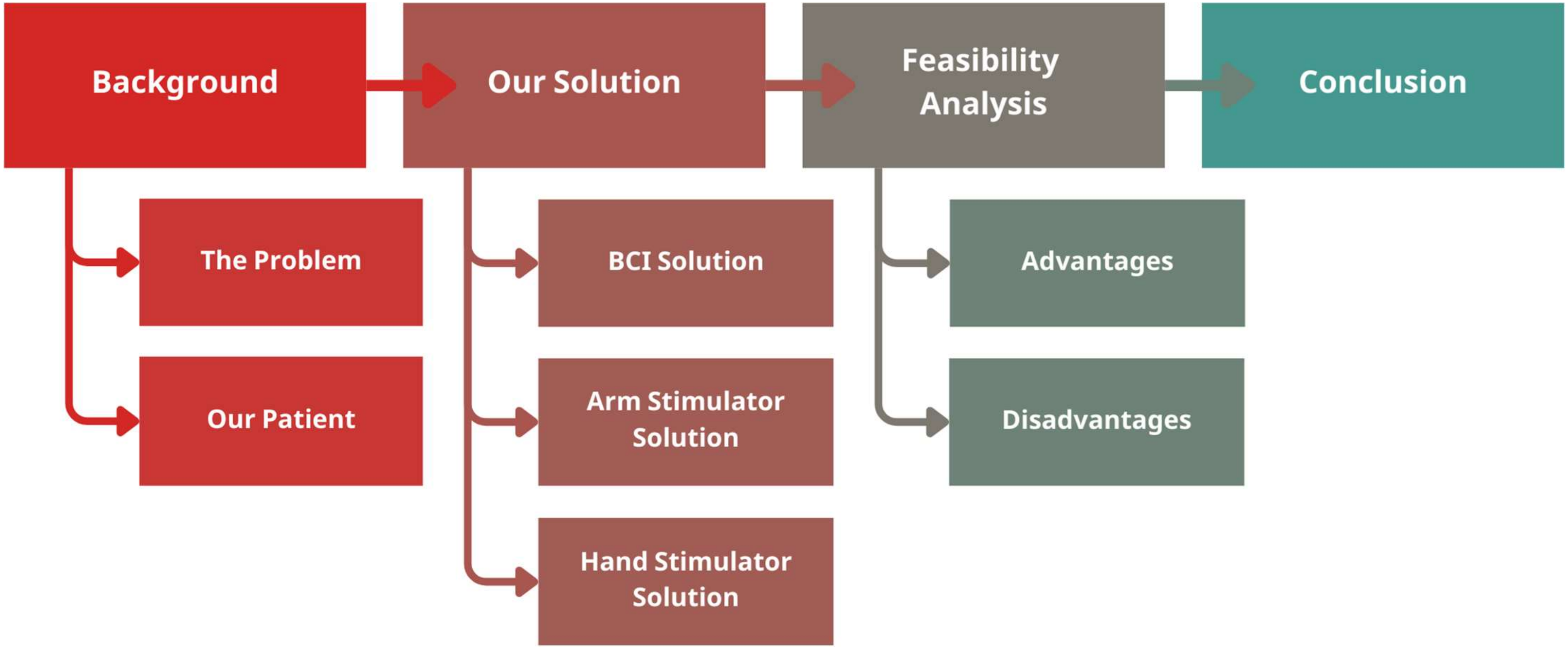


Fig 1 - Presentation Outline

# The Problem

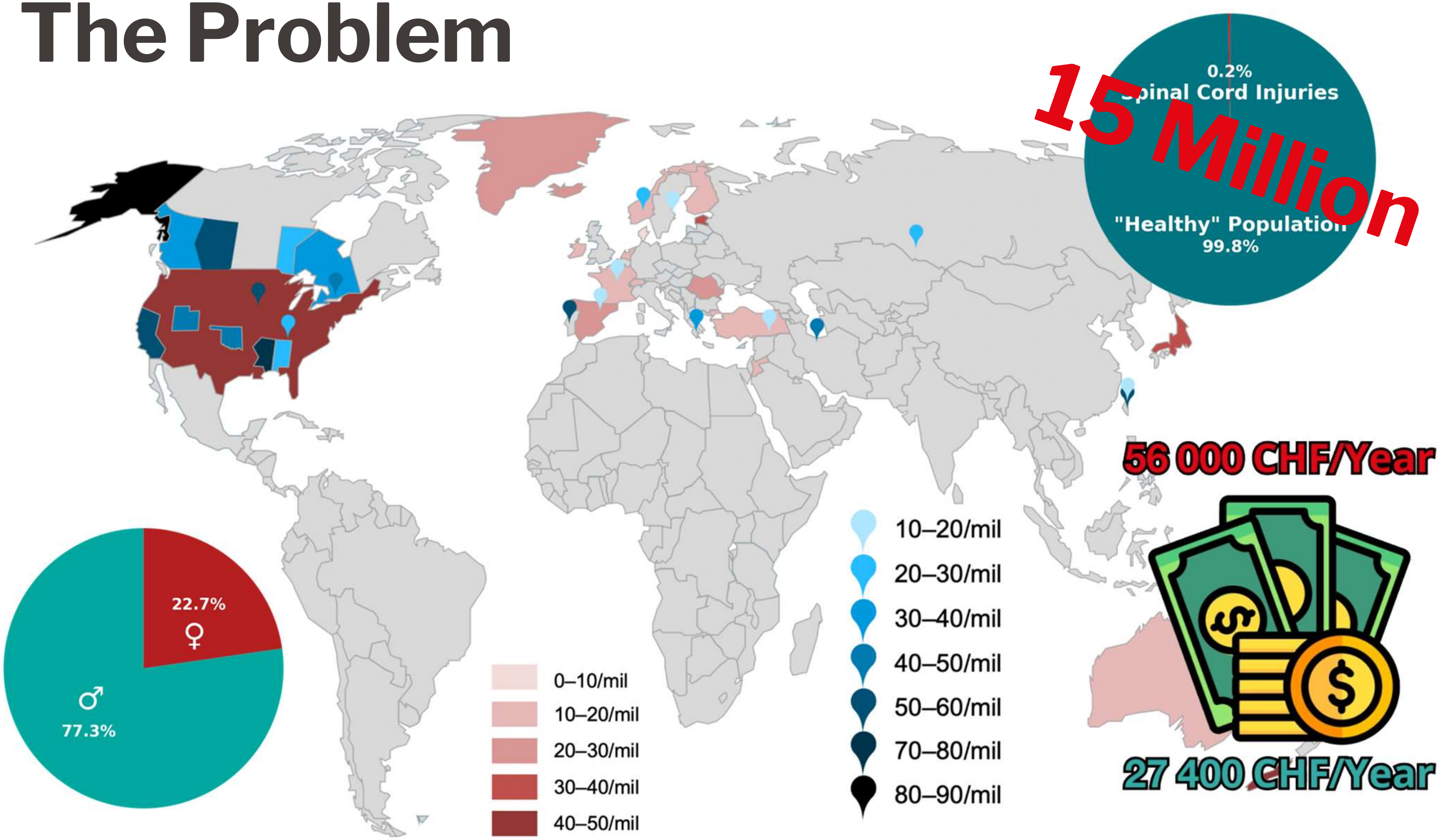


Fig 2 - World Distribution of Incidence obtained from Fehlings et al. (2014) and the yearly costs for a SCI patient Furlan et al. (2017)

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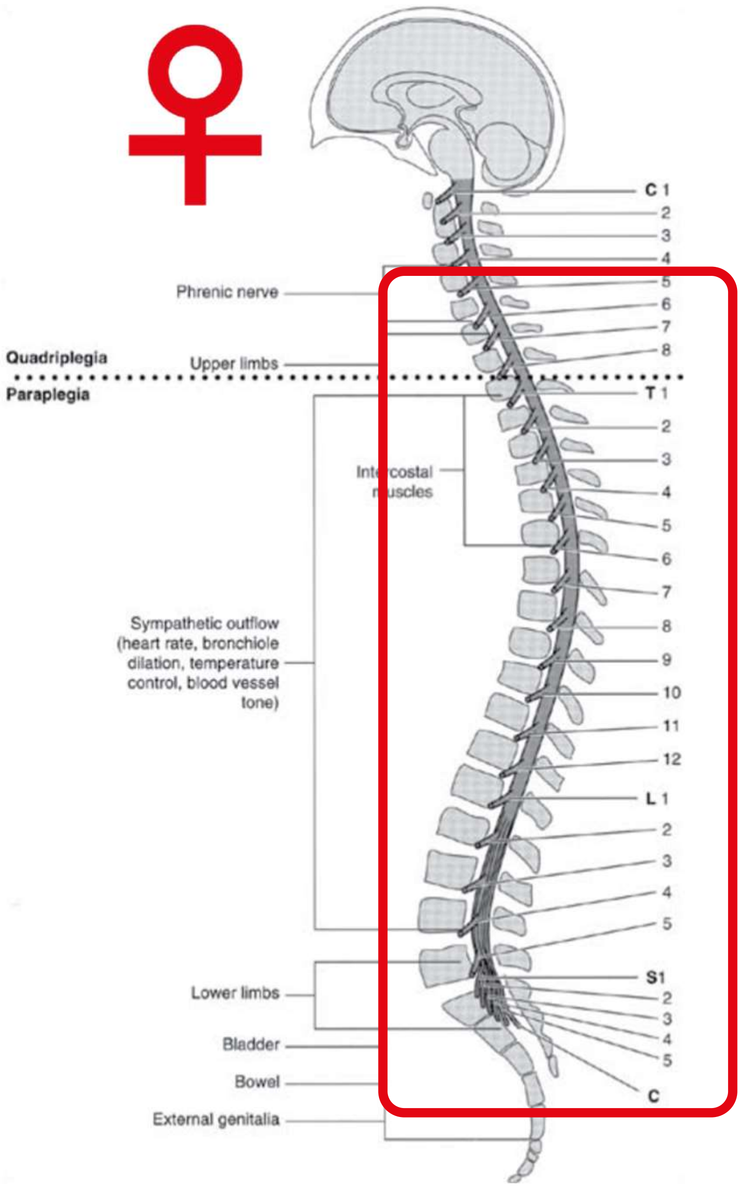
# Our Patient

| Description of clinical presentation | Grade |
|---|---|
| Complete: no preservation of function below level of injury, and no sacral sparing (S4-S5) | A |
| Incomplete: sensory but not motor function is preserved below the neurological level with sacral sparing | B |
| Incomplete: motor function is preserved below the neurological level, and more than half of key muscles below the neurological level have a muscle grade <3 | C |
| Incomplete: motor function is preserved below the neurological level, and at least half of key muscles below the neurological level have a muscle grade of 3 or more | D |
| Normal: motor and sensory function are normal | E |

Lesion at C5: only shoulder and biceps movements are preserved

Fig 3 - Spinal Cord Injury Scale from Wang et al. (2021)



# Our Solution

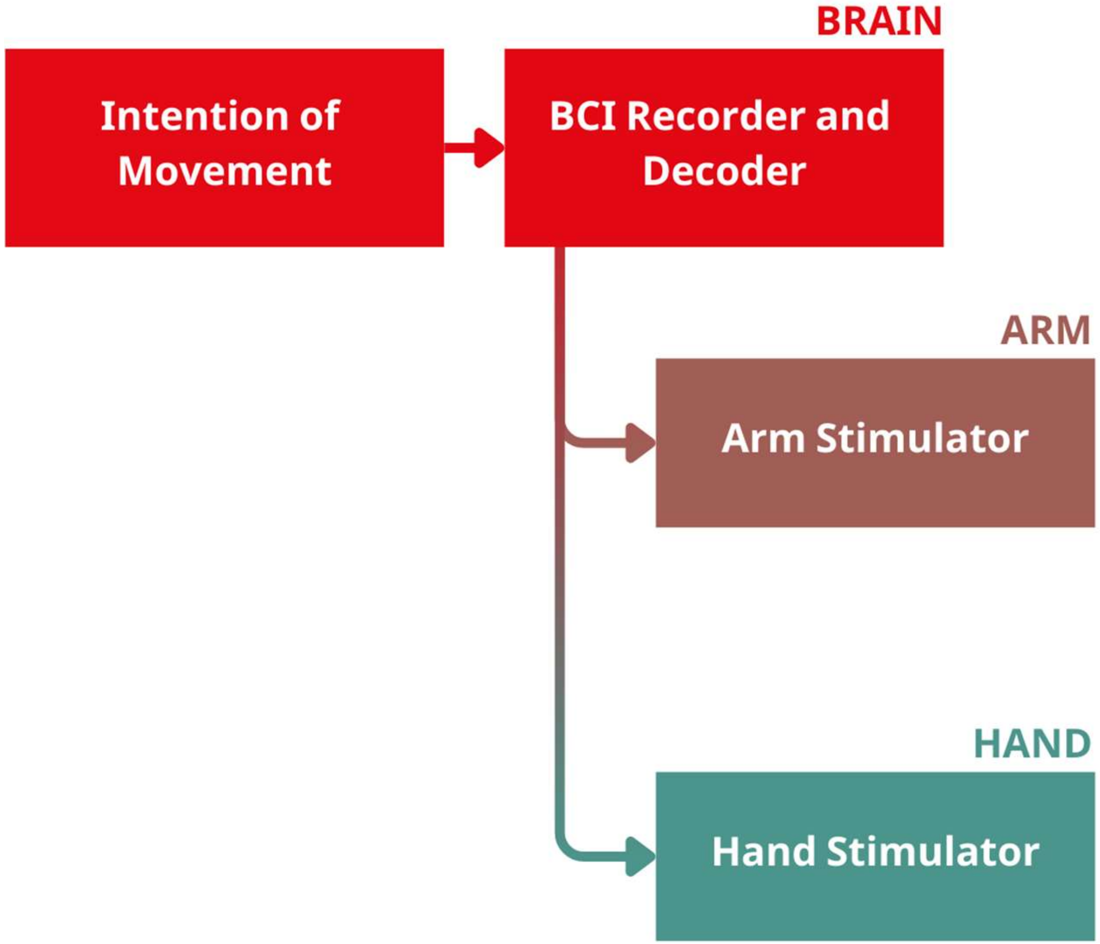
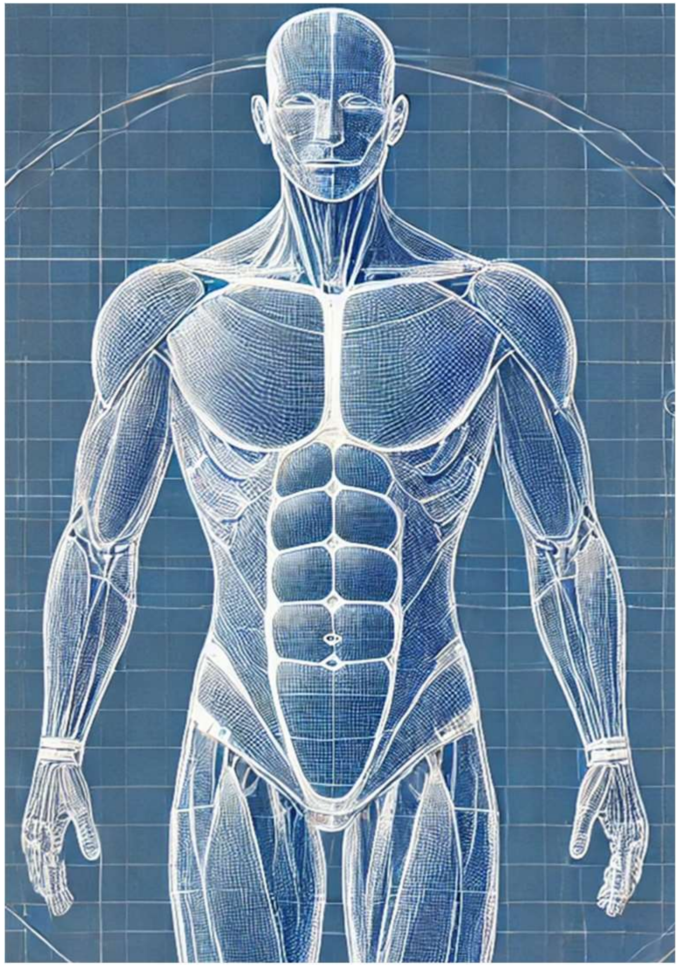



Fig 4 - Overview of our solution



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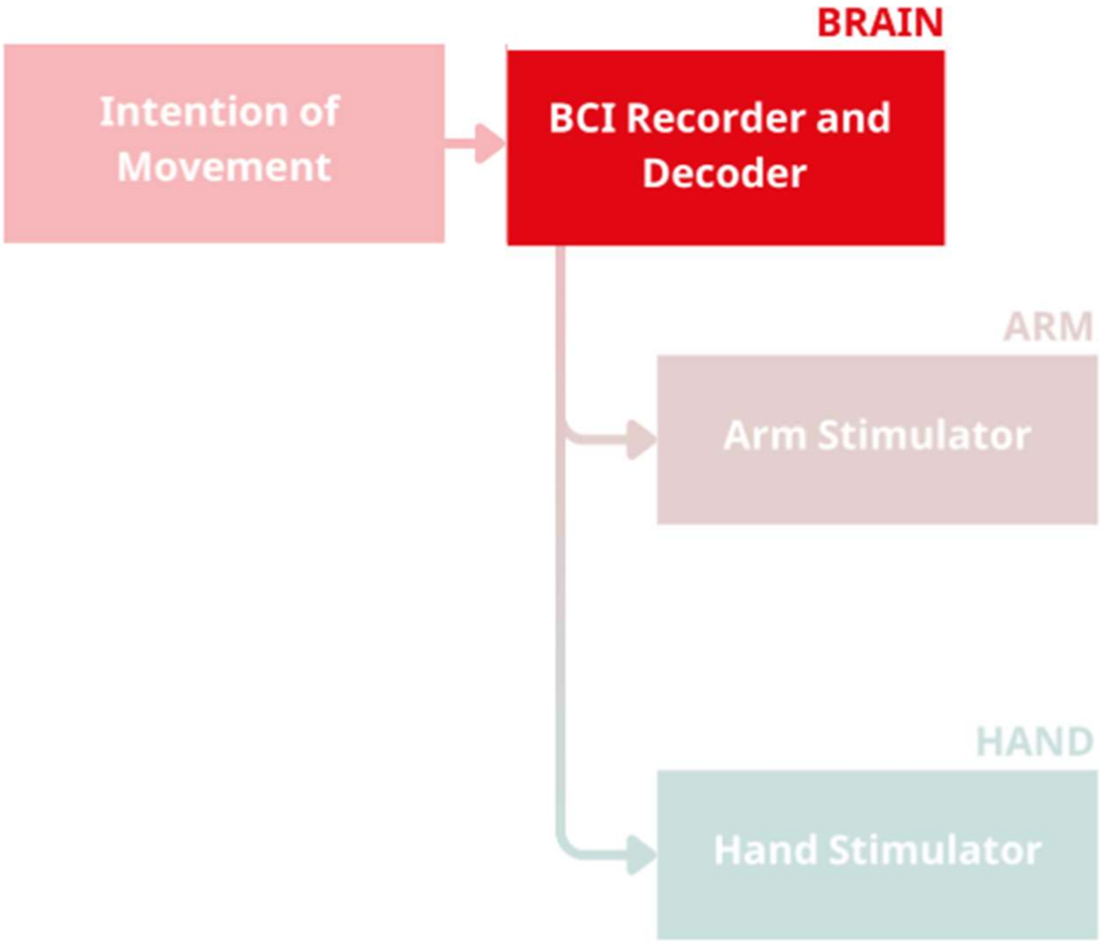


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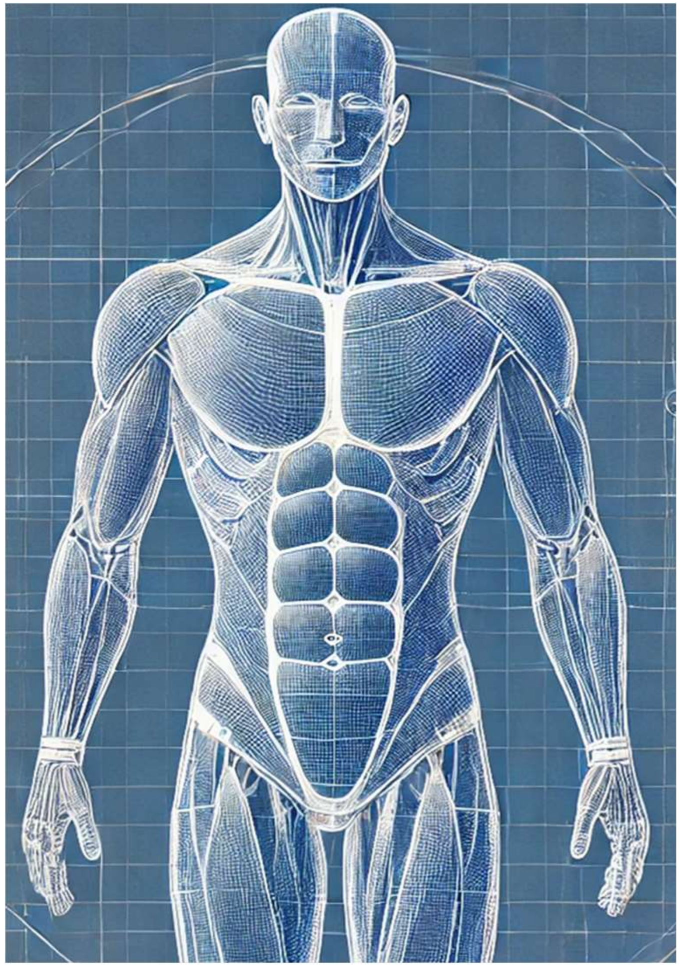


# BCI Recorder

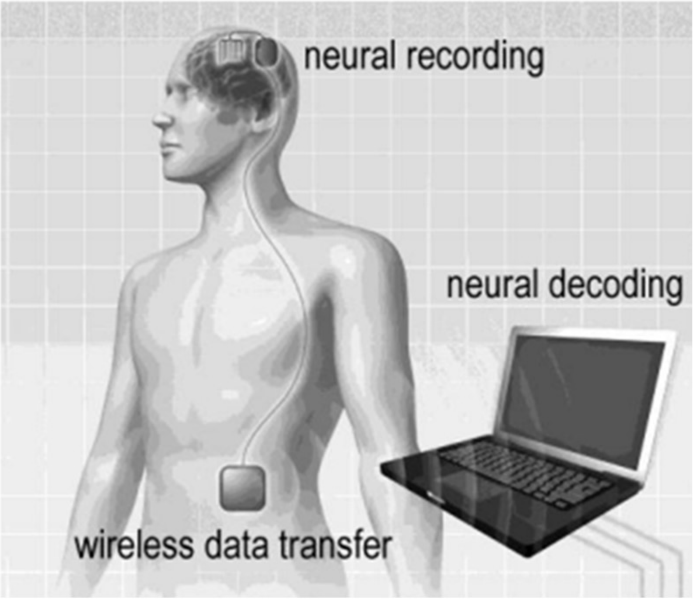


Fig 5 - Fully-Implantable Wireless System for Human BMI, Hirata et al. 2022

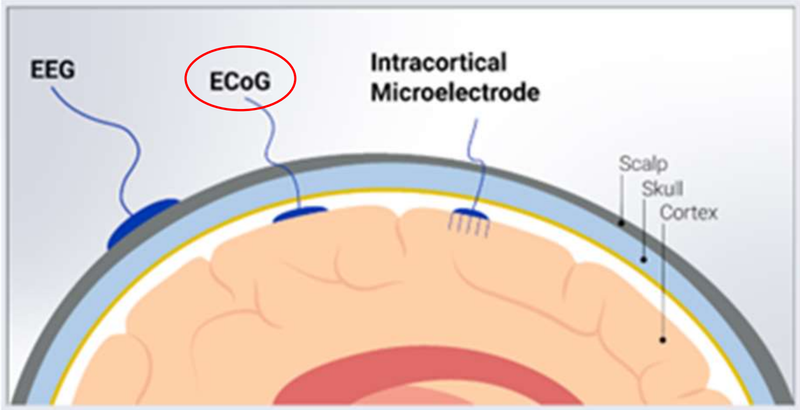


Fig 6 - EEG, ECoG and Intracortical electrodes, Paradromics 2022

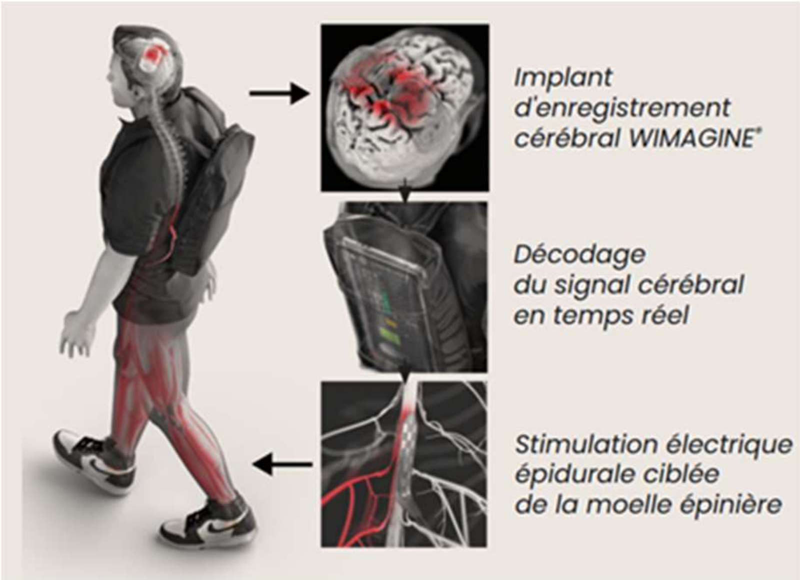


Fig 7 - WIMAGINE® by Clinatech, CEA-Leti 2023

# BCI Recorder

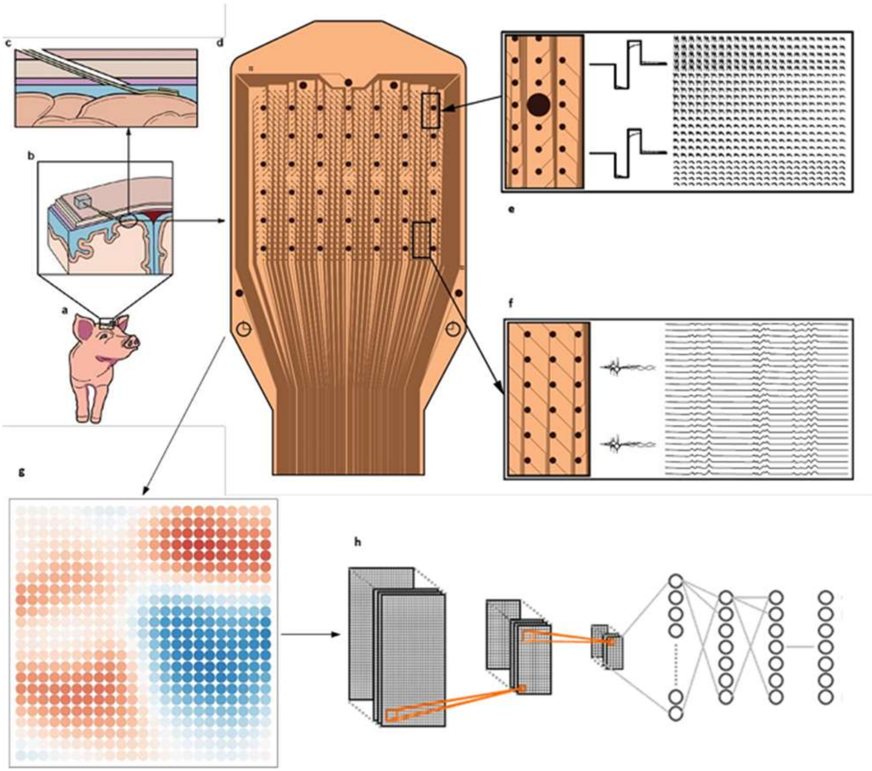


Fig 8 - Minimally invasive thin-film neural interface system, Rapoport et al. 2024

Fig 9 - The Layer 7 cortical interface, Precision Neuroscience 2024

# BCI Decoder

- ML algorithm detecting individual finger movements from ECoG signal
- Classification accuracy of 77.0%, improving the state-of-the-art by more than 11%
- Refined movement detection

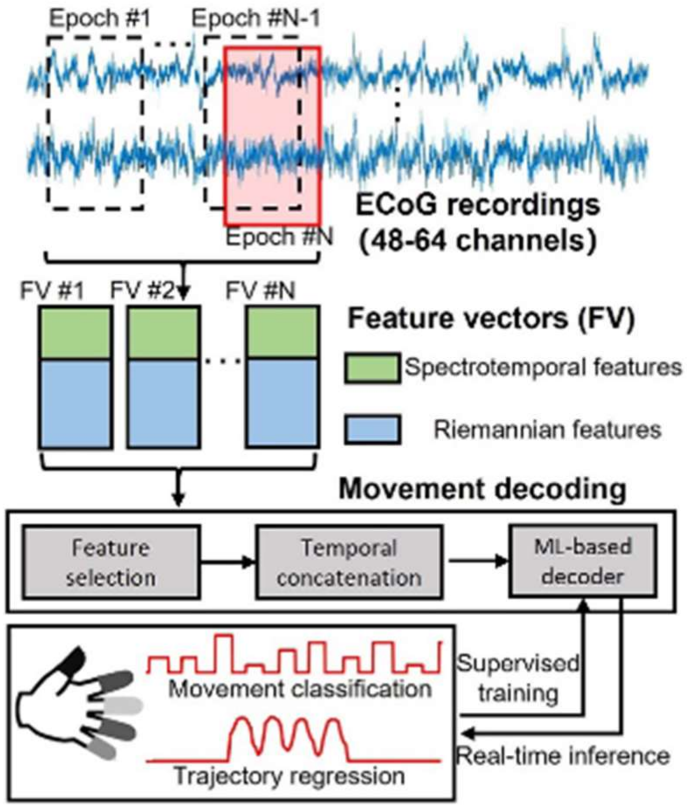
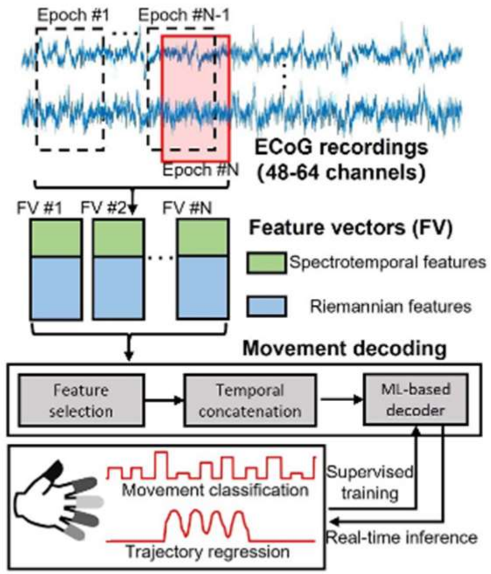



Fig 10 - ECoG-BMI framework, Lin Yao et al 2022

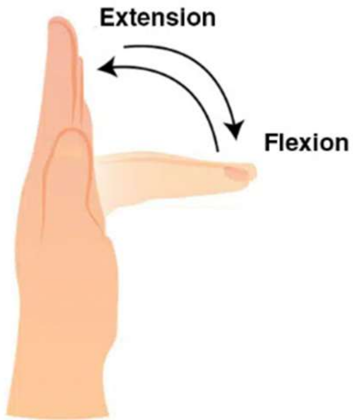
# BCI Summary

**Intended movement**

**µECoG recording**

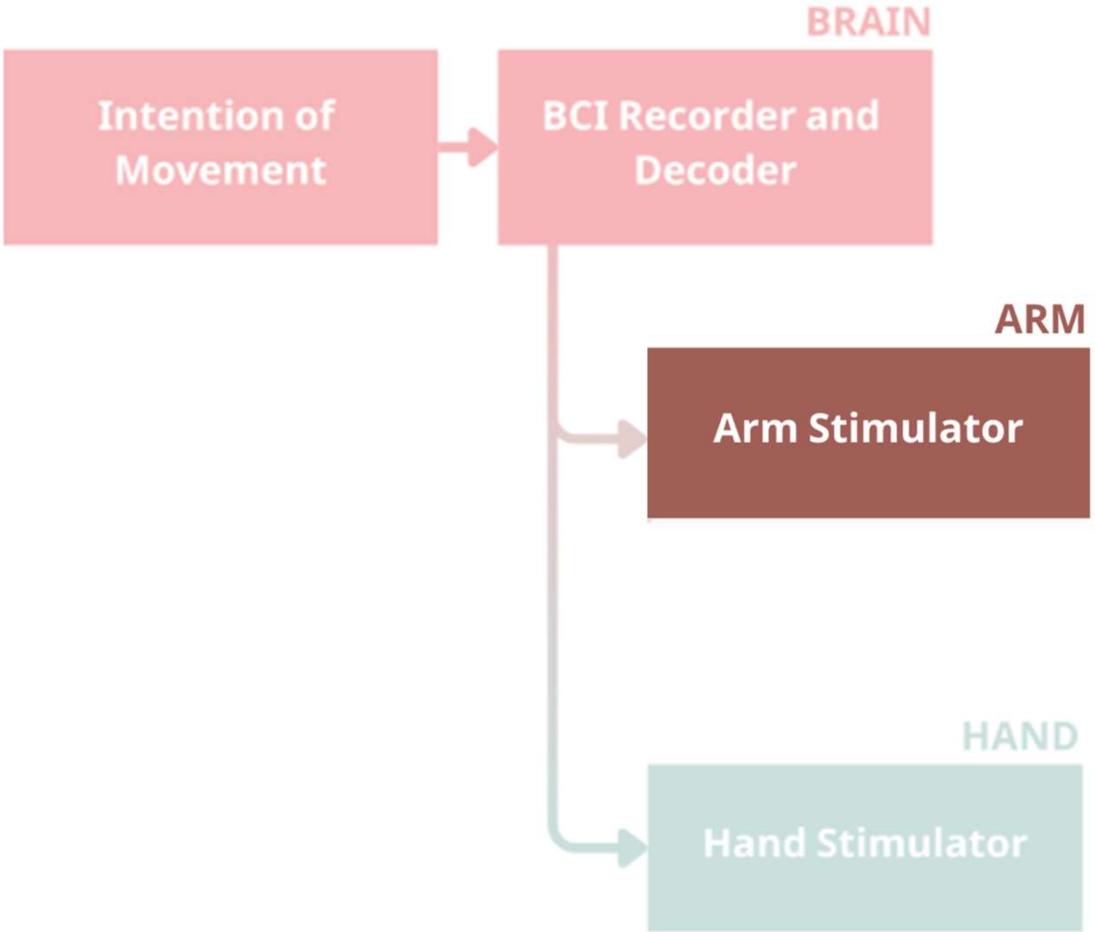



**ML decoding**




**Arm or finger stimulation**

# Our Solution

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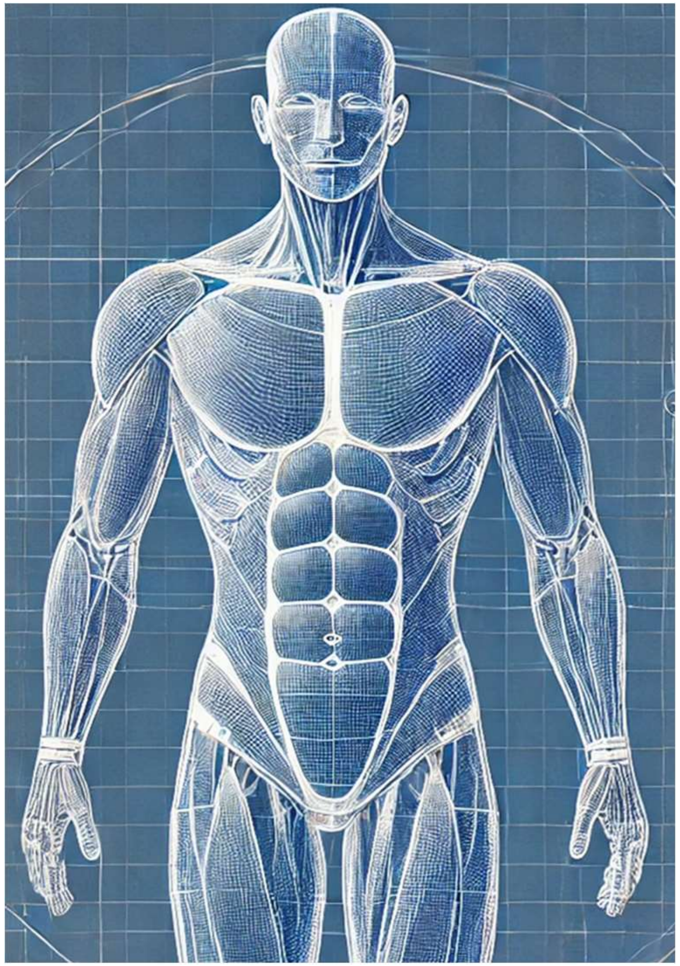

# Arm Anatomy

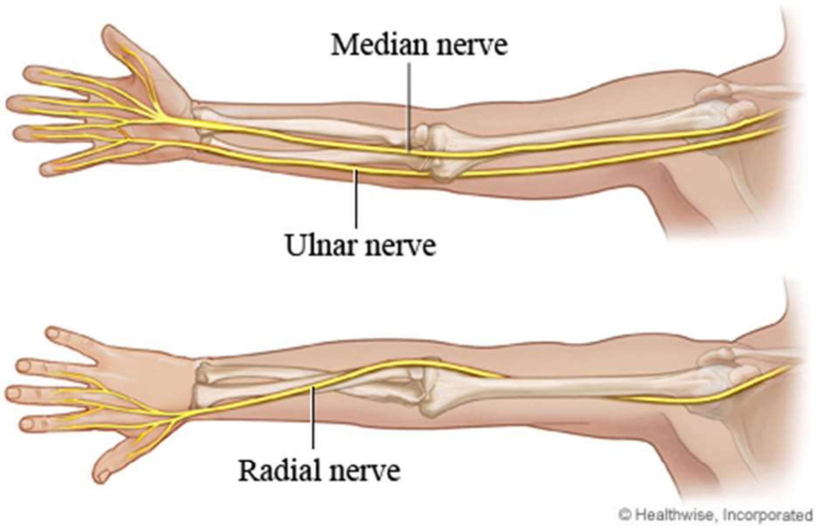


Fig 11 - Main Nerves that Innervate the arm and fingers according to Nerves of the Arm | Cigna (2022)

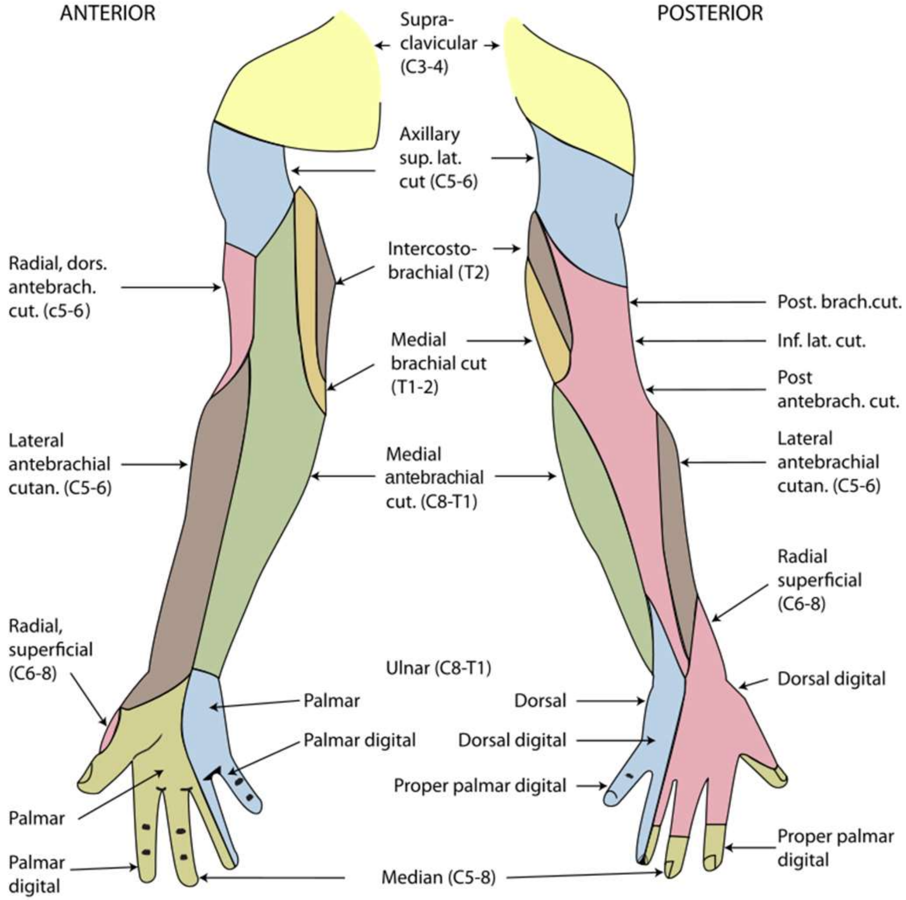


Fig 12 - Innervation map the arm and fingers according to Medial Cutaneous Nerve of Forearm (2023)

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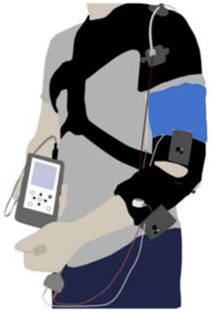
# **Arm Stimulator** Hybrid system concept

Combining Functional Electrical Stimulation (FES) arm sleeve with a light-weight exosuit



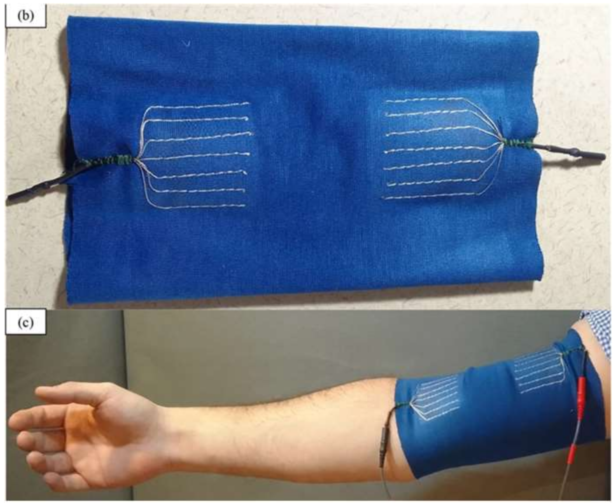
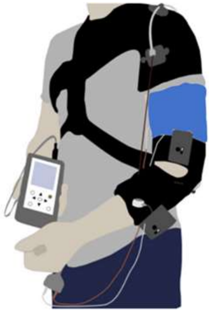



Fig 13 - FES sleeve
Garnier, B et al.(2024)


Fig 14 - FES-Exosuit hybrid system | Burchielli, D.(2020)



# **Arm Stimulator** Movement intention

The detection of the movement intention is done by the BCI and EMG signals from the biceps

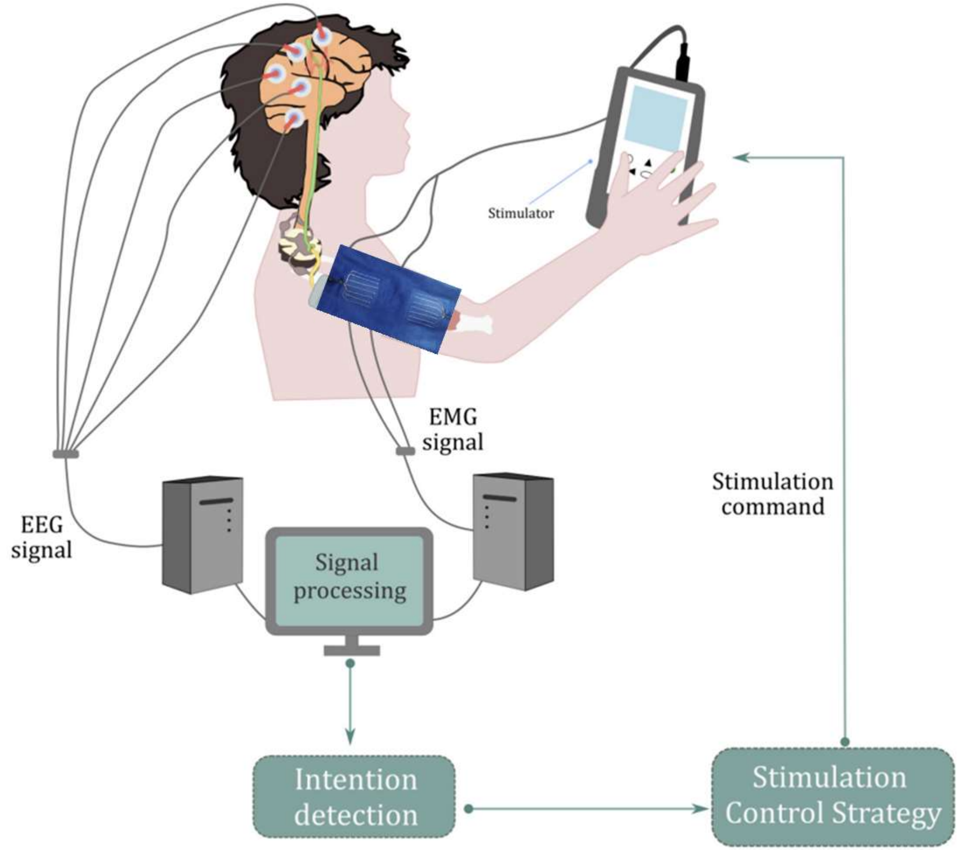
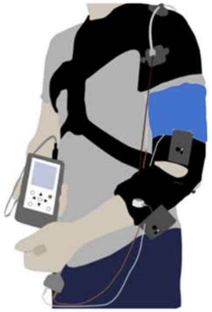



Fig 15 - Movement intention detection | Burchielli, D.(2020)



# **Arm Stimulator**
# Real time control

**Movement initiation**
FES to the triceps muscles

Exosuit assists

**Feedback**
Assistance is proportional to the BCI detection & EMG activity recorded from each muscles

Allows continuous movement adjustment in time

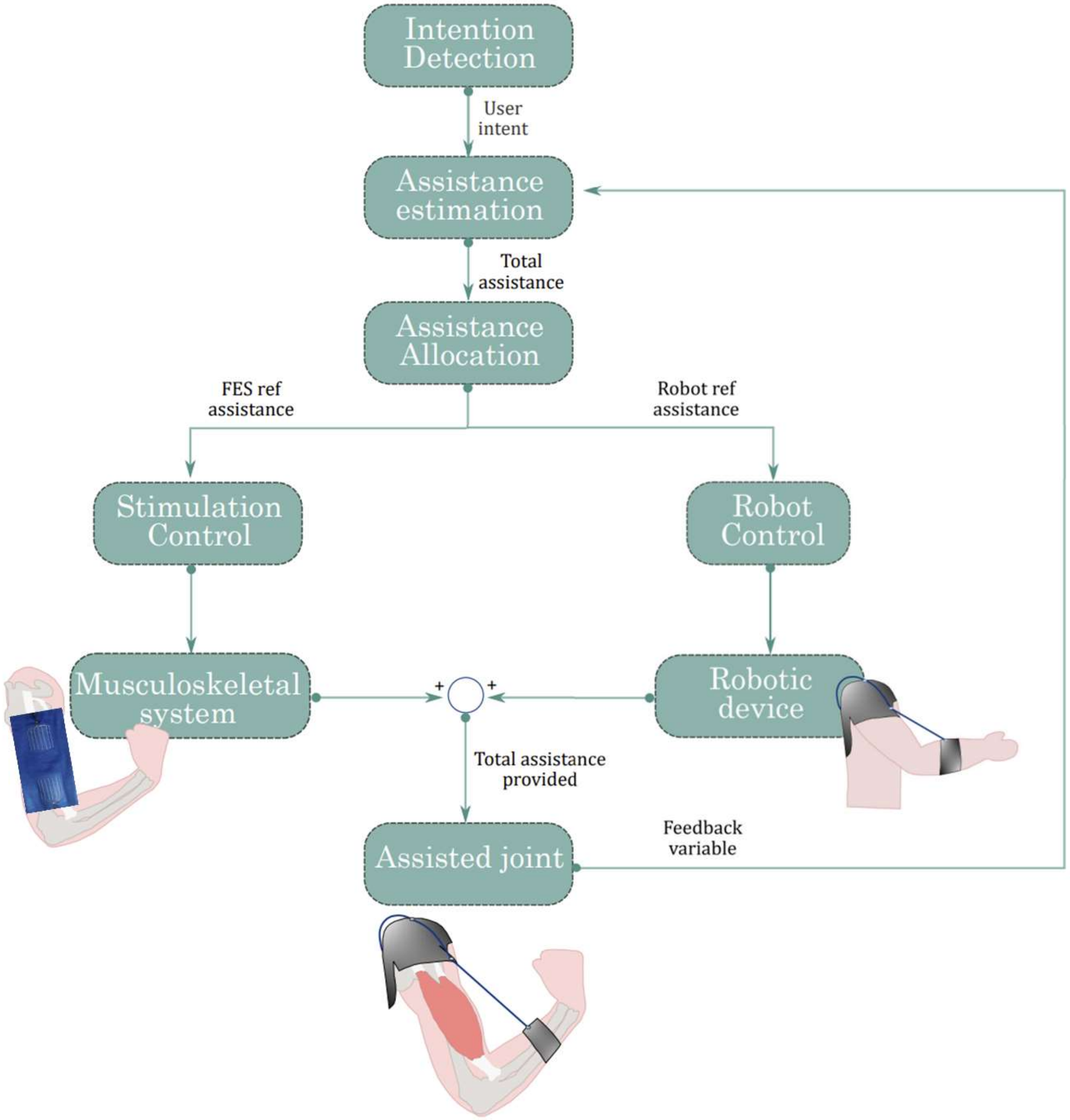
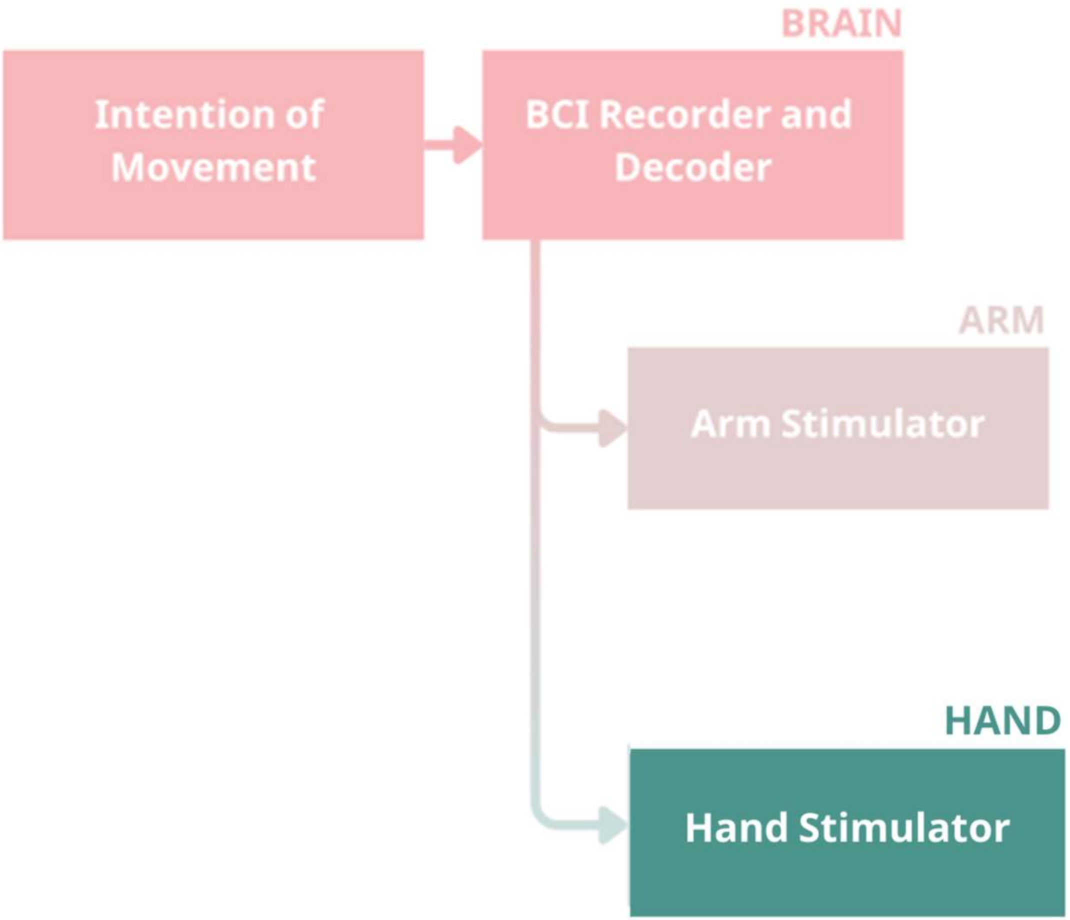



Fig 16 - Possible architecture for a hybrid control strategy | Burchielli, D.(2020)

# Our Solution

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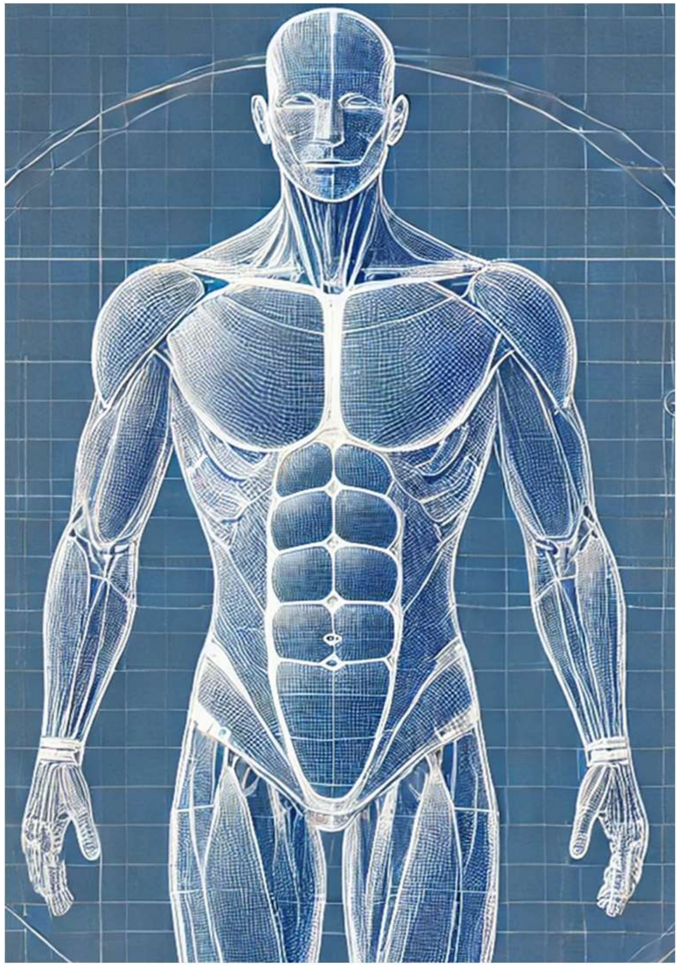

# The State of the Art

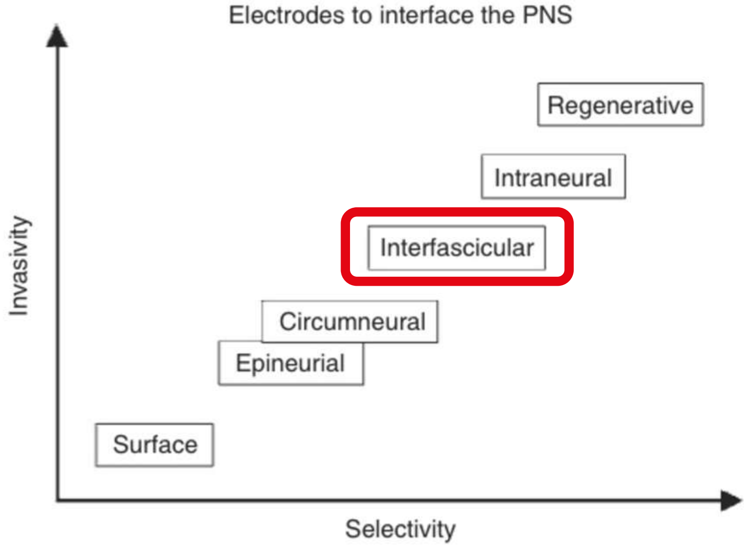


Fig 17 - Different PNS Interfaces Approaches from Leprince (2012)

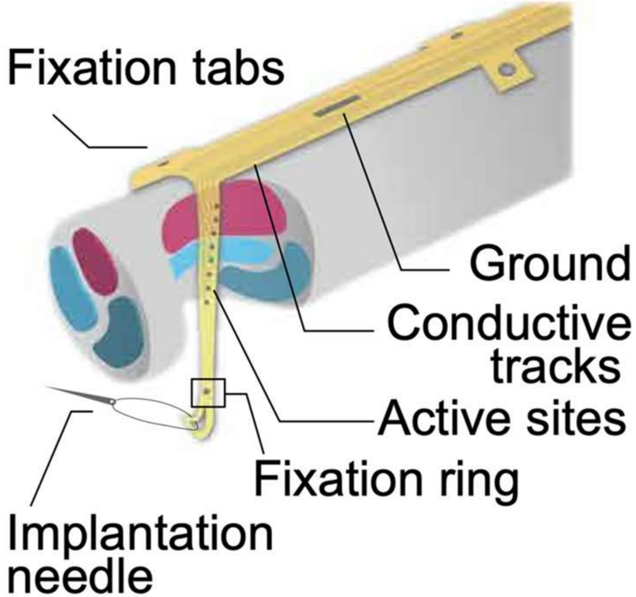


Fig 18 - Intrafascicular PNS Interface used in Badi et al. (2021)

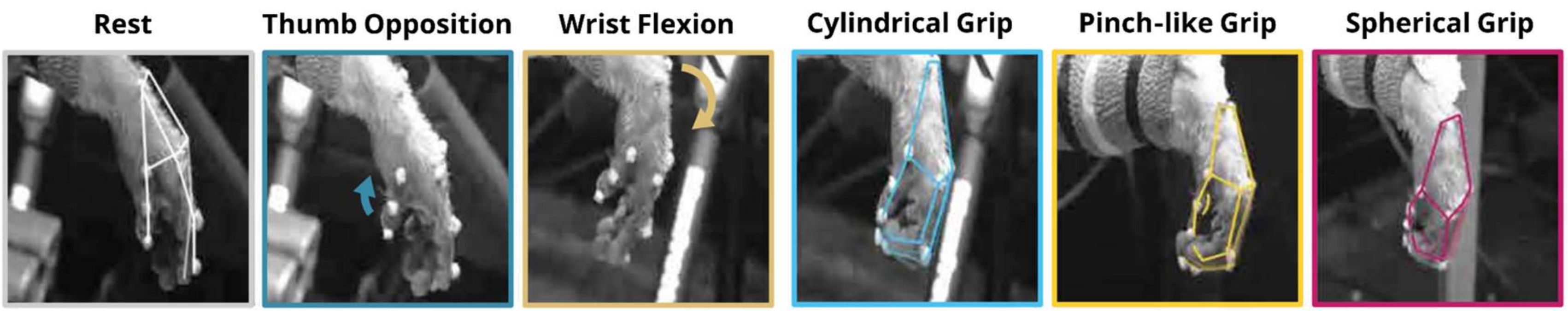


Fig 19 - Different recovered movements by the approach in Badi et al. (2021)

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# The Hand Roadmap

1 Adapt Badi et al. (2021) for StimDust

2 Test the approach in Humans

3 Migrate Electrodes Lower

4 Increase Selectivity and Dexterity

# The StimDust

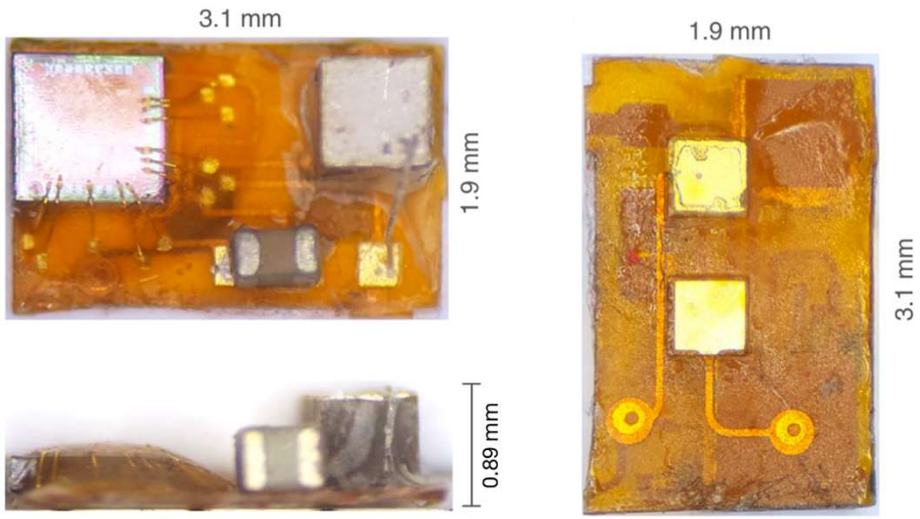



Fig 20 - StimDust Size from Piech et al. (2020)

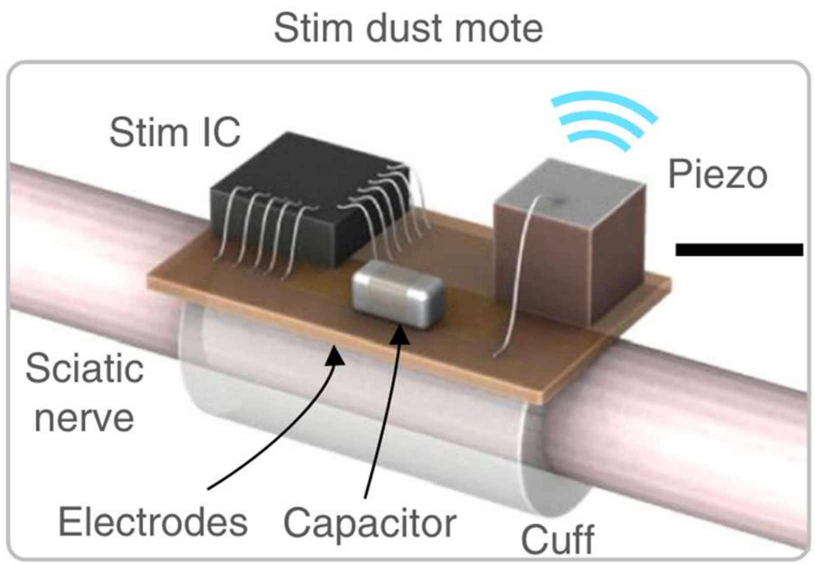



Fig 21 - StimDust Approach from Piech et al. (2020)

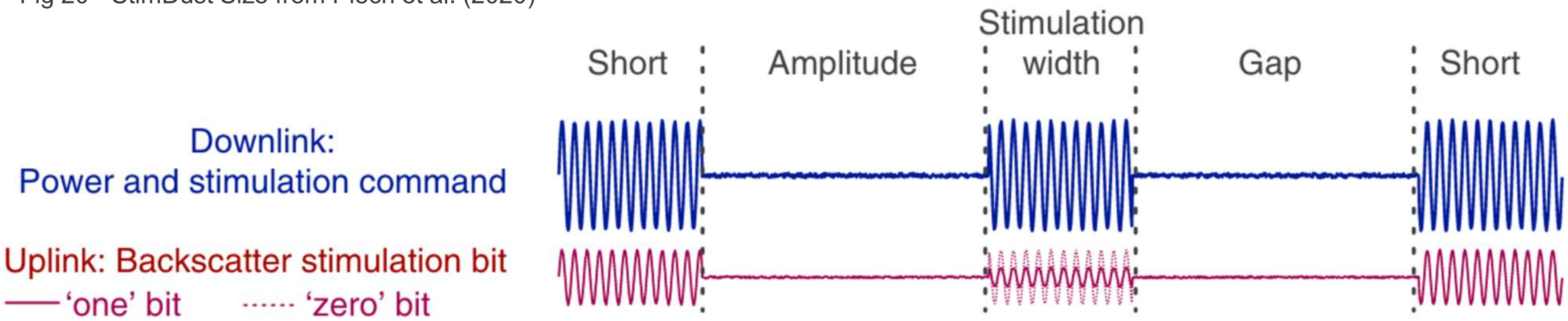



Fig 22 - StimDust Signal Encoding from Piech et al. (2020)

# The StimDust

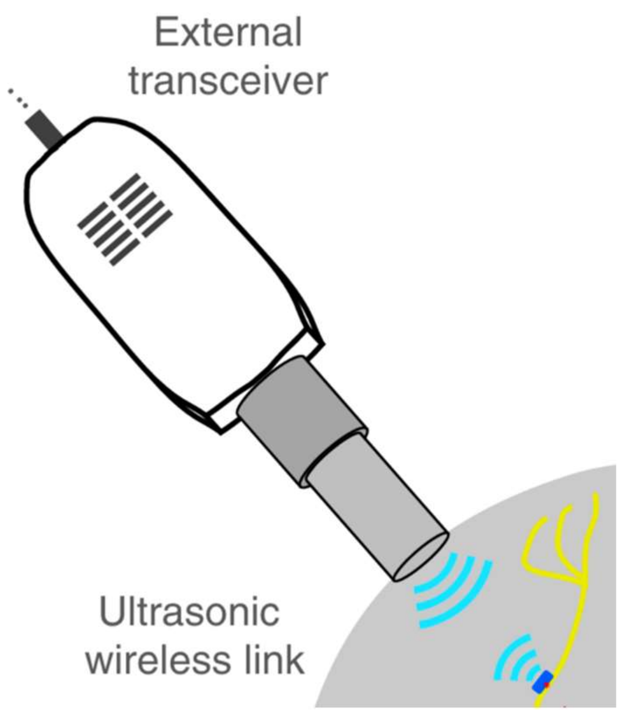



Fig 23 - StimDust US Generator from Piech et al. (2020)

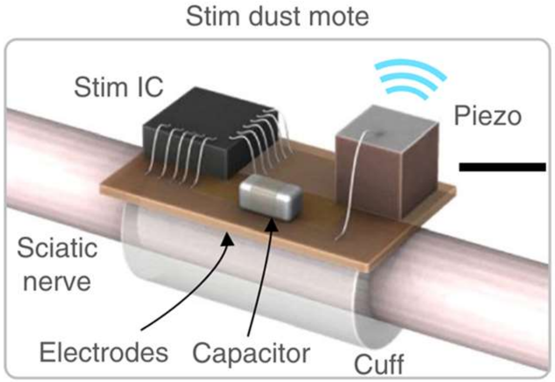



Fig 21 - StimDust Approach from Piech et al. (2020)

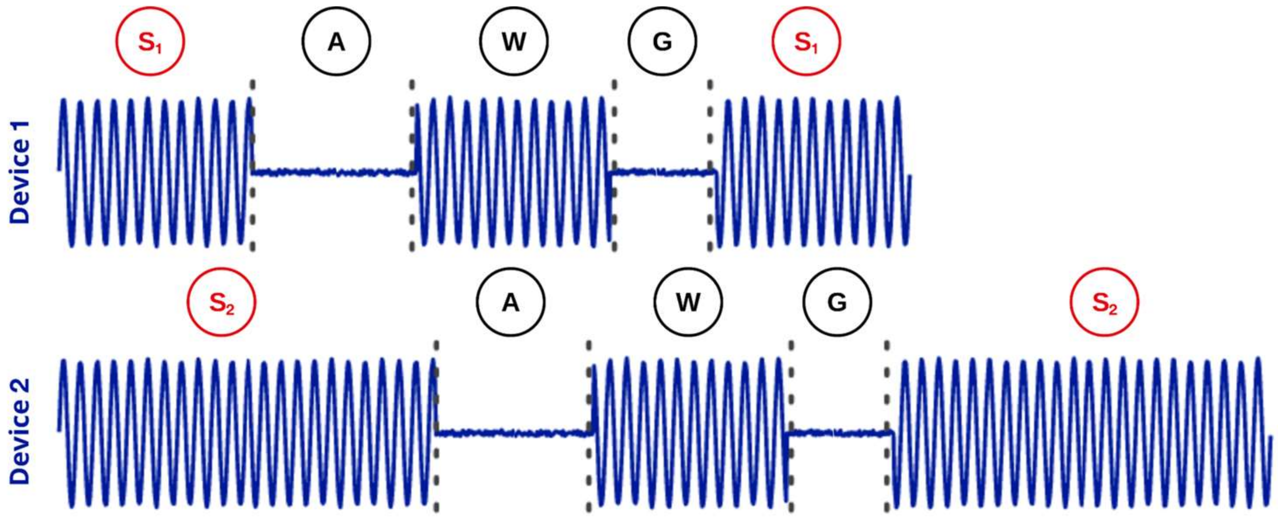



Fig 24 - StimDust Signal for different implantable motes

# The StimDust

| SPECS | STIMDUST | BADI ET AL. (2021) |
|---|---|---|
| Pulse Duration (μs) | 0.45 - 392 | 40 - 80 |
| Stimulation Frequency (Hz) | 0 - 5000 | 40 - 100 |
| Stimulation Current Amplitude (μA) | 50 - 400 | 20 - 2000 |
| Stimulation Waveform | Monophasic with gap | Charge-balanced, cathodic-first Biphasic |

Fig 26 - StimDust stimulation parameters versus requirements from Badi et al. (2021)

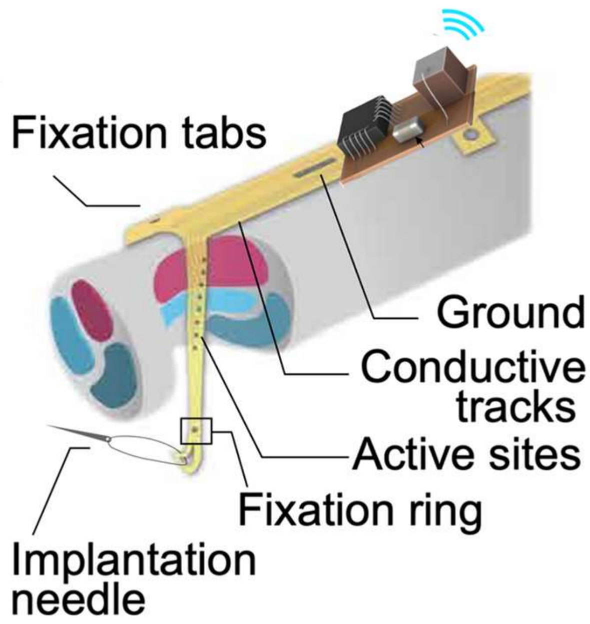



Fig 18 - StimDust stimulation parameters versus requirements from Badi et al. (2021)

# The Hand Roadmap

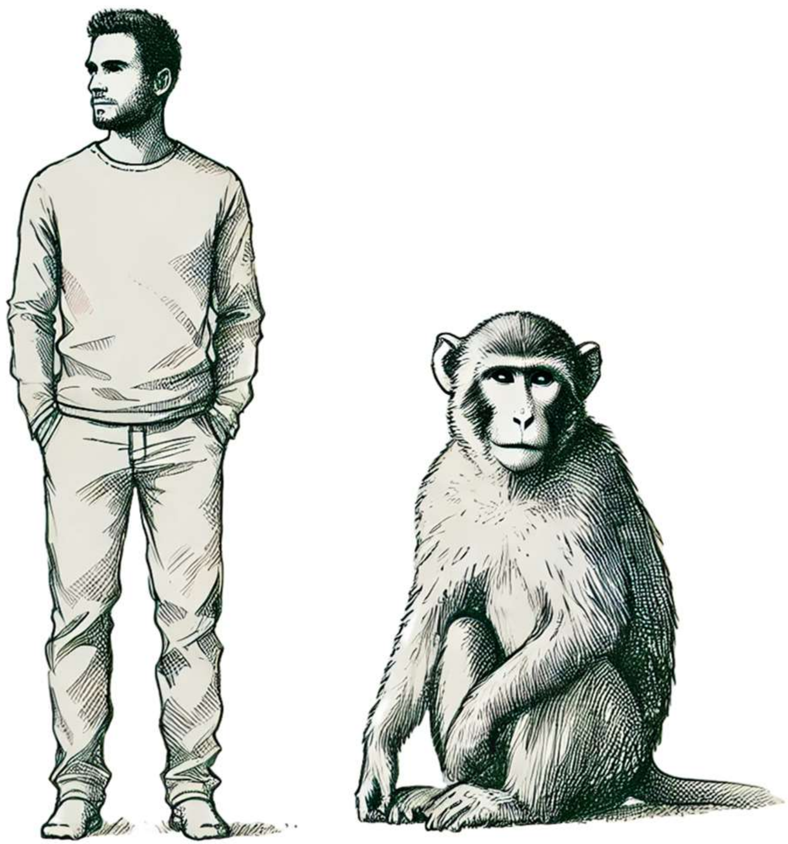
1 Adapt Badi et al. (2021) for StimDust

2 Test the approach in Humans

3 Migrate Electrodes Lower

4 Increase Selectivity and Dexterity

# From Monkeys to Humans



## How to Get the Positioning?

**Cadaveric Studies**
- Chambers et al. (2021)
- Delgado-Martínez et al. (2016)

**Optical Coherence Tomography**
- Carolus et al. (2019)
- Monroy et al. (2023)

# Optical Coherence Tomography

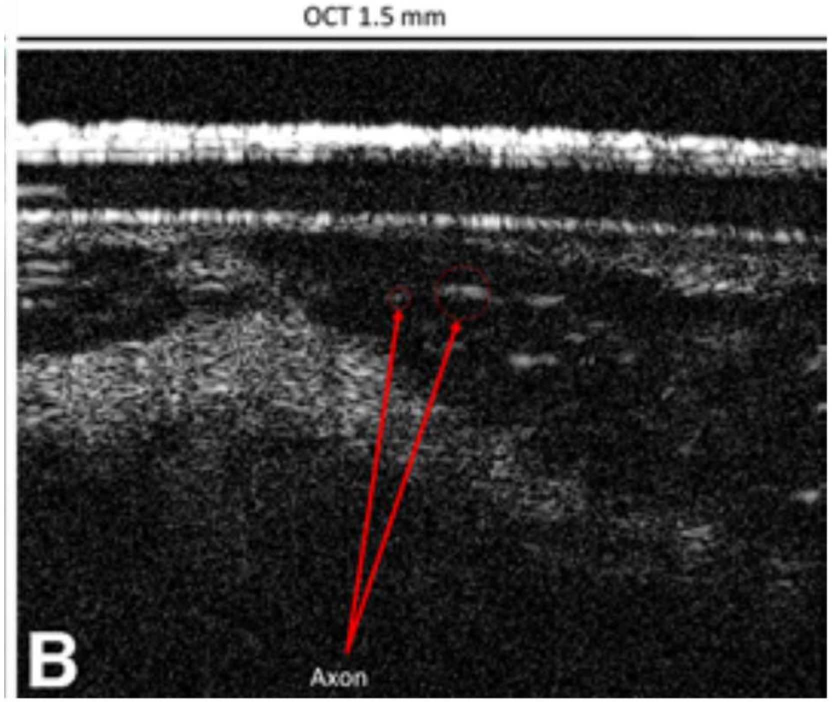



Fig XX - OCT Image example from Carolus et al. (2019) where individual axons are visible

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# Leveraging the StimDust

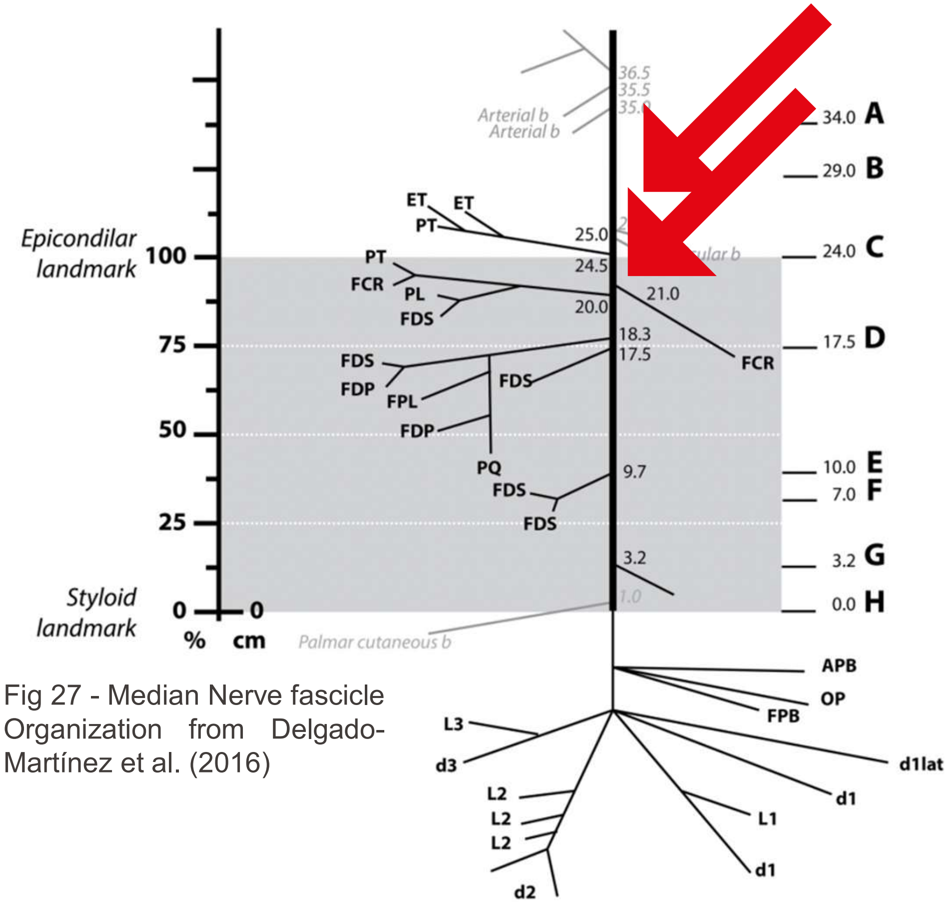



Fig 27 - Median Nerve fascicle Organization from Delgado-Martínez et al. (2016)

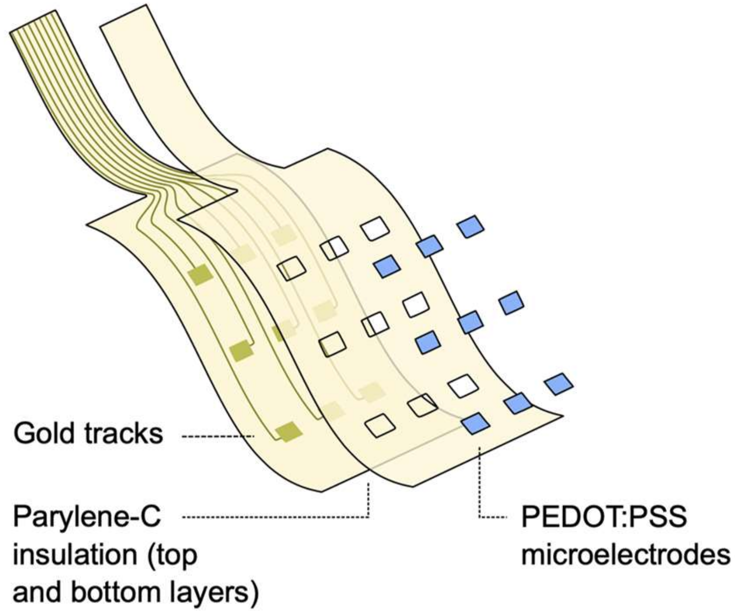



Fig 28 - Ultraconformable cuff implants for long- term bidirectional interfacing of peripheral nerves at sub-nerve resolutions (Carnicer-Lombarte et al. (2024))

# Leveraging the StimDust

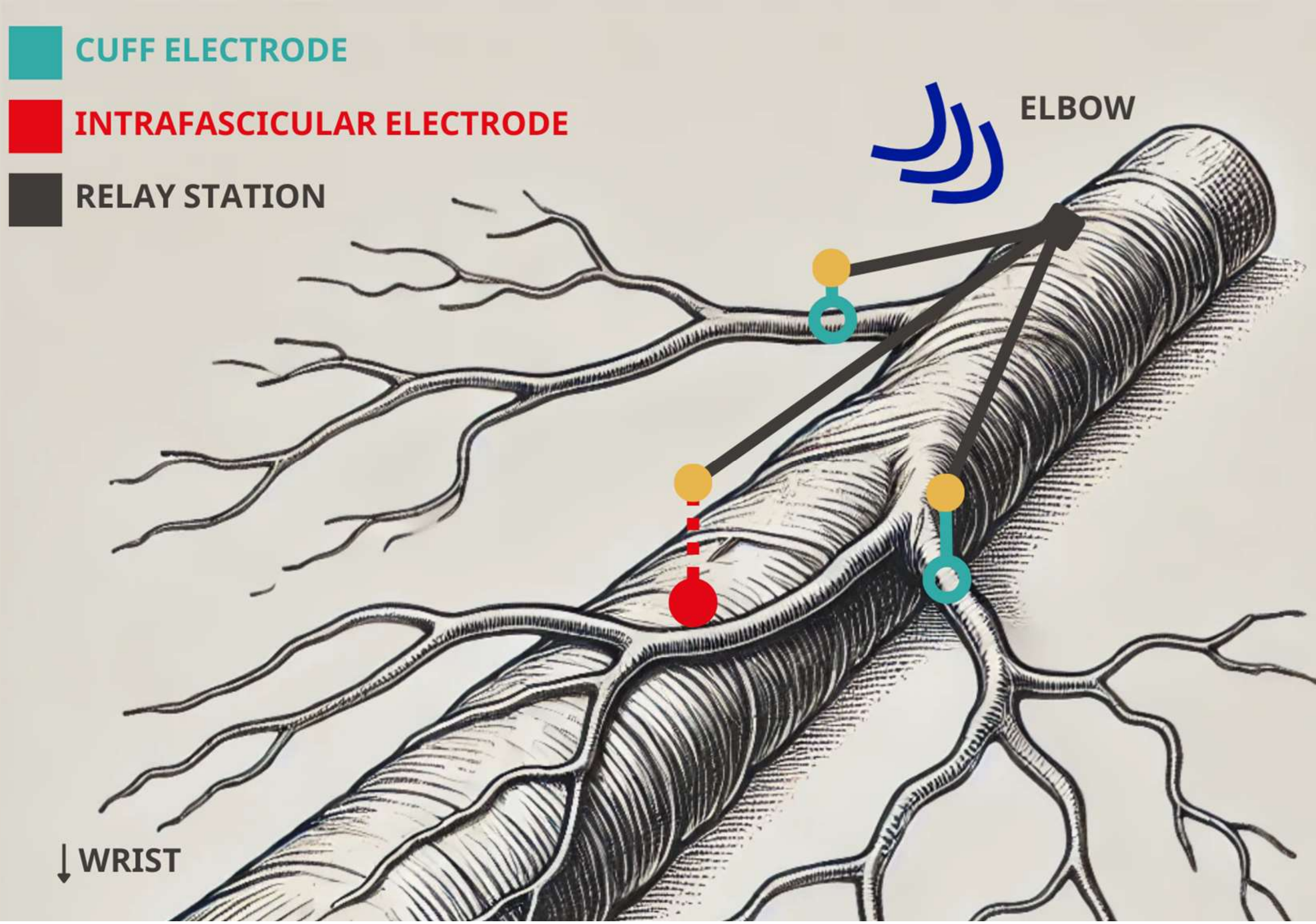



Fig 29 - Wiring based on LCP Film with Gold interconnects from Gwang Seong Choi et al. (2022)

# The Hand Roadmap

1. Adapt Badi et al. (2021) for StimDust
2. Test the approach in Humans
3. Migrate Electrodes Lower
4. Increase Selectivity and Dexterity

# Feasibility Analysis

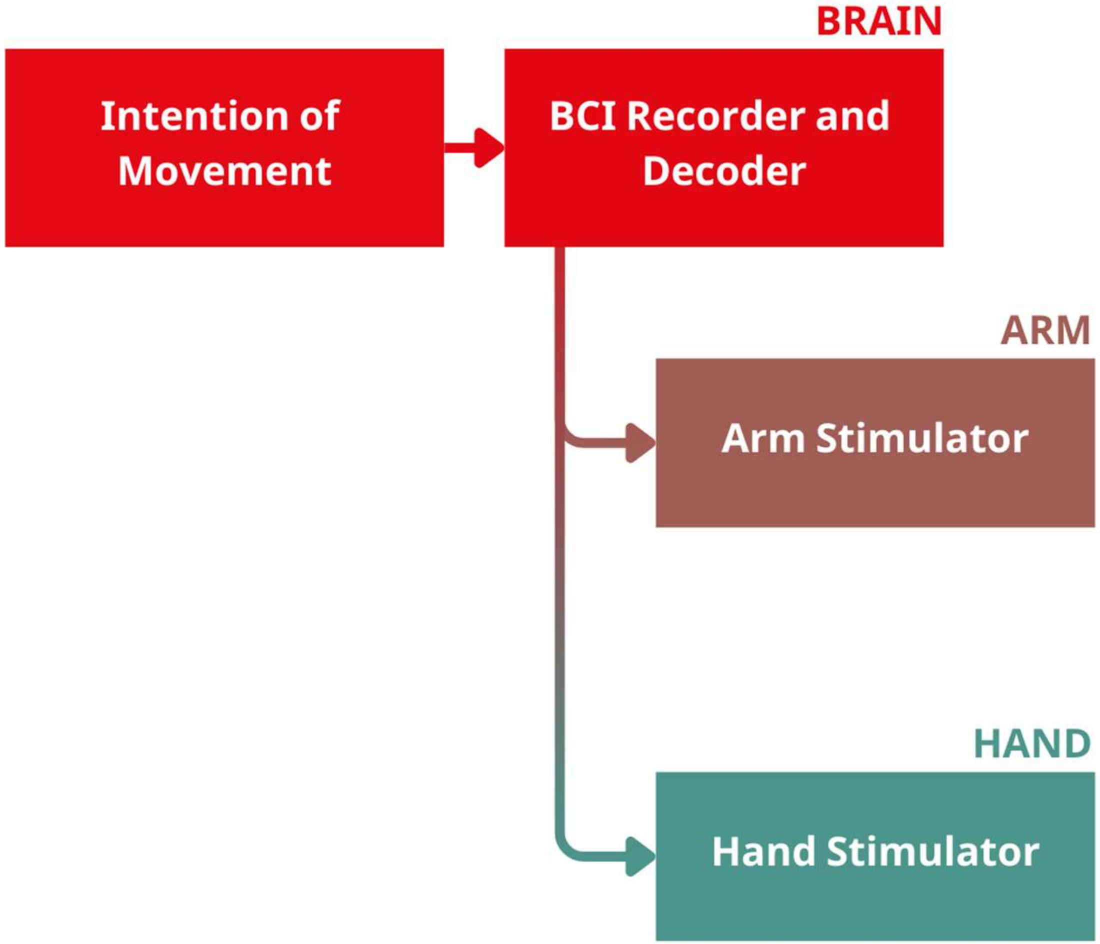
## General
- Two brain surgeries and two hand surgeries

## BCI Recorder and Decoder
- Decoding resolution for individual finger movement
- Bulky wiring

## Arm Stimulator
- Arm sleeve placement
- Limited space for electrodes

## Hand Stimulator
- US generator's focal plane, size, power source
- Variable invasiveness with relay stations
- Closed-loop possibility

# Conclusion

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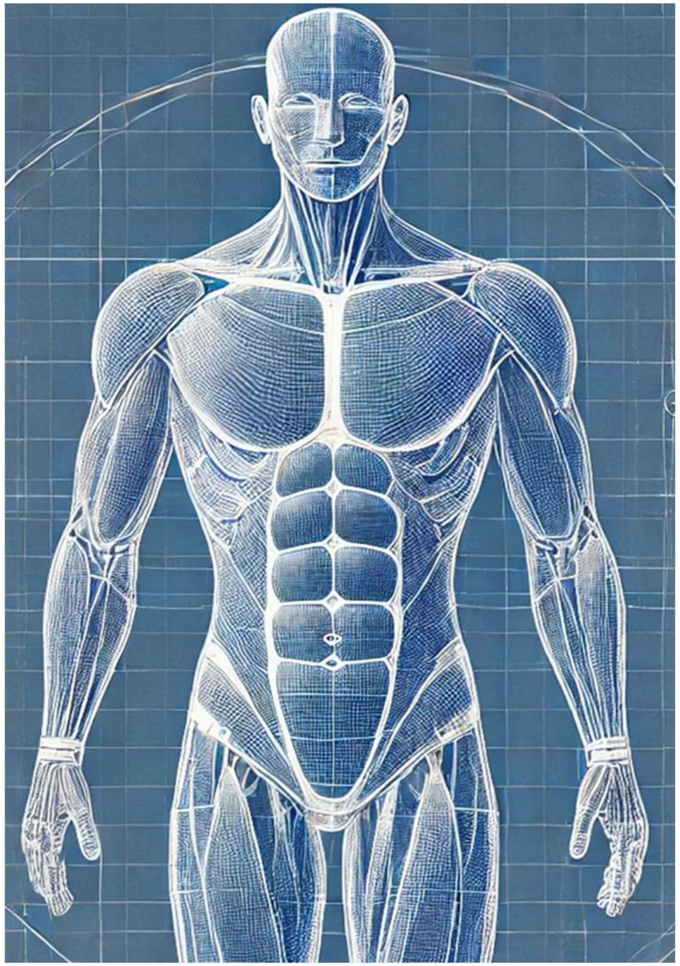

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# Thank You for the Attention

## Advanced Methods for Human Neuromodulation Fall 2024

**Feel free to ask Questions!**

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ESTEBAN SOURCES

# Extra slides

List of what we should put in extra slides to answer potential questions

Make a limitations slide

Esteban: Slide about stim and emg electrodes on the same spot issue
Esteban: Slide with more details regarding the functionning

# Arm Anatomy Recap

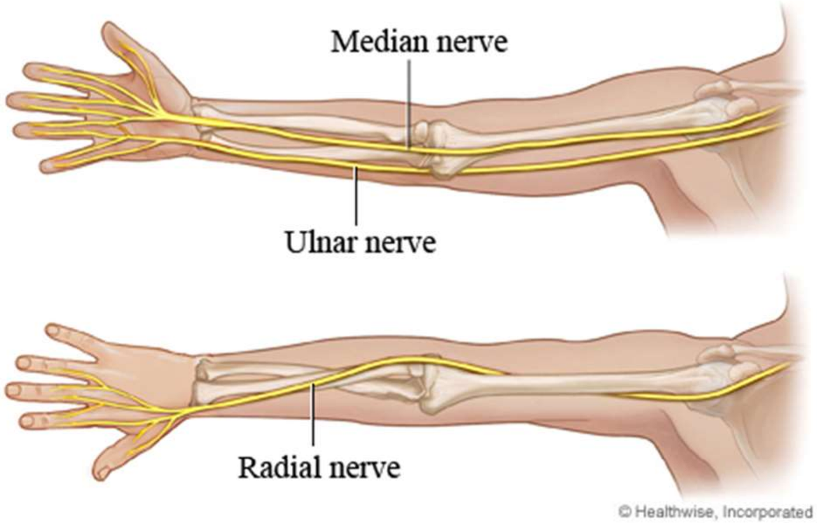



Fig 11 - Main Nerves that Innervate the arm and fingers according to Nerves of the Arm | Cigna (2022)

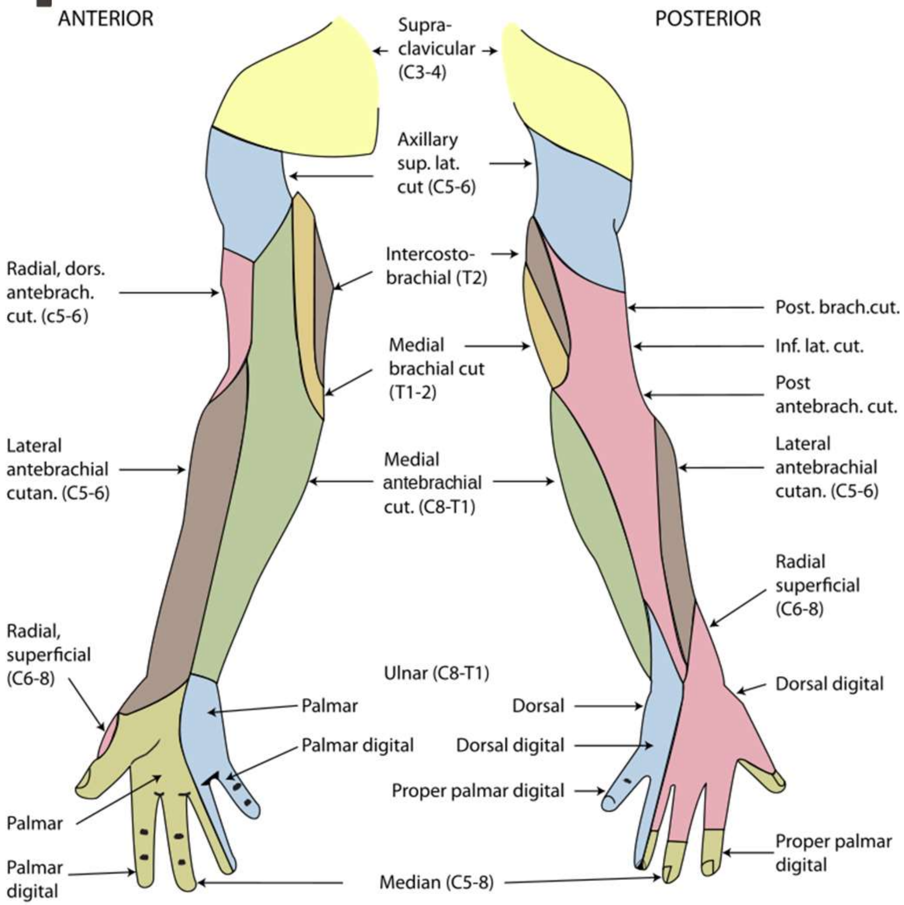



Fig 12 - Innervation map the arm and fingers according to Medial Cutaneous Nerve of Forearm (2023)

# How to train your Patient

# The 7 layer cortical interface

- Thin-film electrode arrays with minimally invasive surgical procedure
- Bidirectional communication (both recording and stimulation)
- Demonstrate the feasibility and safety of delivering reversible implants containing over 2,000 microelectrodes to multiple functional regions in both hemispheres of the brain simultaneously
- Demonstrate in vivo performance in minipigs in anesthetized states and during awake locomotor behavior

Fig 9 - The Layer 7 cortical interface, Precision Neuroscience 2024

# The 7 layer cortical interface

- Minimally invasive subdural implantation using a novel “cranial micro-slit” technique
- Interconnecting cable of each microelectrode array module passes through a dural incision and a cranial micro-slit incision, tunneled under the scalp and connected to an individual head stage
- The Layer 7 device contains 1,024 electrodes in ~1.5 cm2 of surface array, with an inter-electrode spacing of 400 µm
- High-density intraoperative cortical surface recordings have so far been performed in 17 patients as proof-of-concept studies

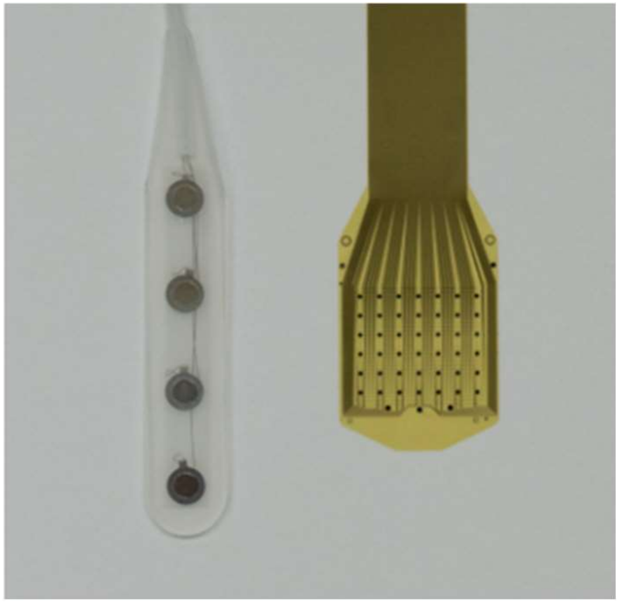


Fig 9 - The Layer 7 cortical interface, Precision Neuroscience 2024

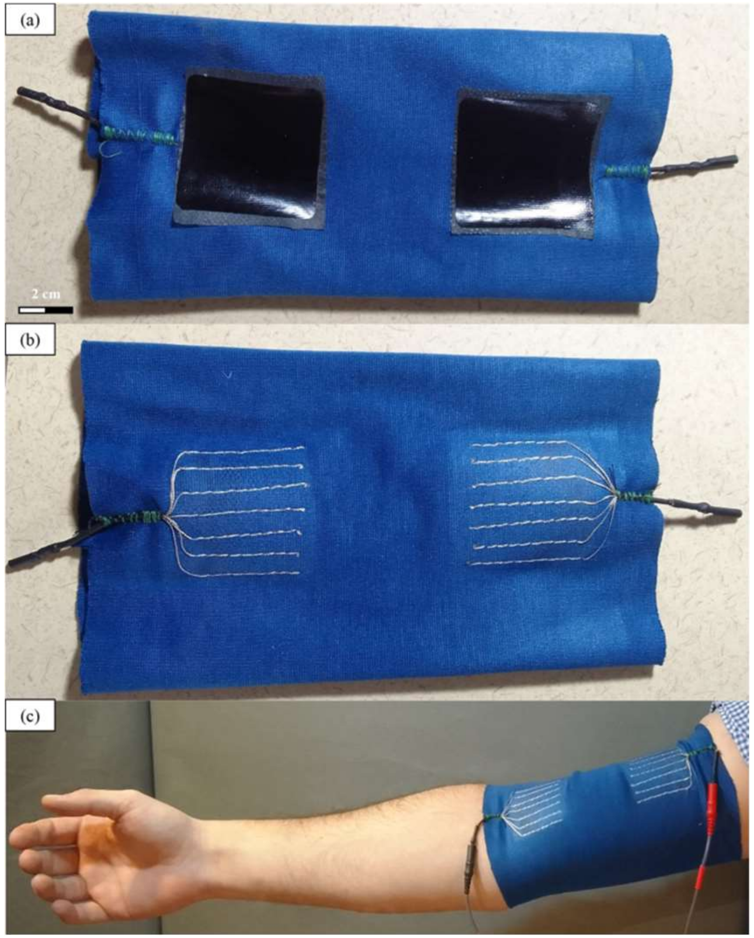
# **Arm stimulator** FES arm sleeve

Advantages:

The **tests** conducted with stimulation, showed that the smart FES sleeve performance, in terms of stimulation intensities, perceived comfort and muscle torque, **are at least as good as the hydrogel electrodes.**

Materials:

The prototype is composed of a knitted sleeve made of polyester, viscose and elastane that integrates carbon-based dry electrodes and electrical tracks connected to the stimulator. The carbon-based dry electrodes are fixed on the textile substrate by thermal compression onto a nonwoven thermoadhesive and sewn conductive matrix made of textile silver-plated conductive yarns.



# **Arm Stimulator** Mechanism details

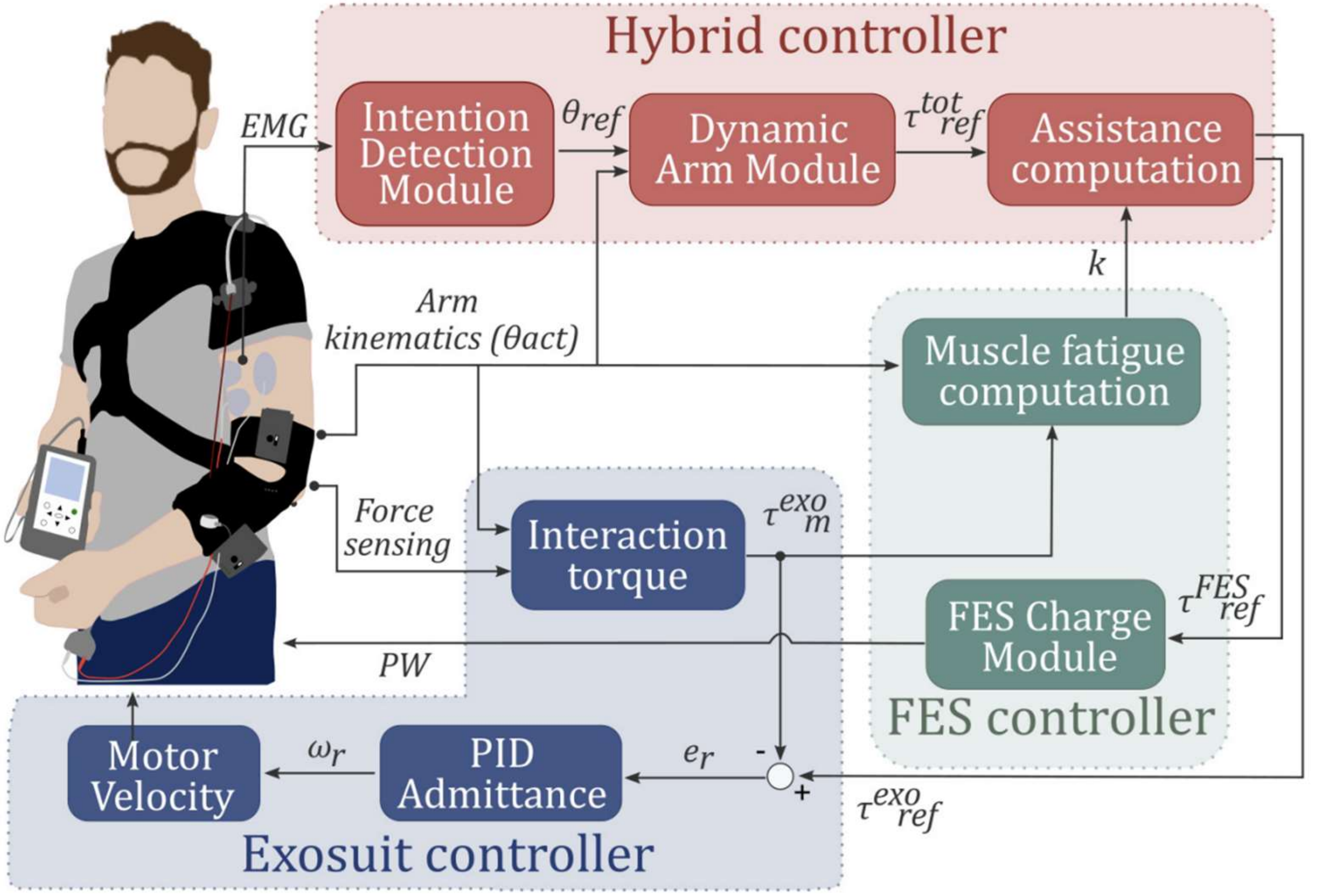



Figure 2: Real time control framework.

The implemented real-time control consists in a hybrid approach that coordinates the assistance from the exosuit and from FES.

Three main layers are interconnected in a close loop system:

(i) Hybrid Controller that detects the subject's intention and computes the assistance for both the devices

(ii) Exosuit Controller which modulates the motor actuation

(iii) FES Controller that manages the stimulation.

# **Arm stimulator** Exosuit for fatigue

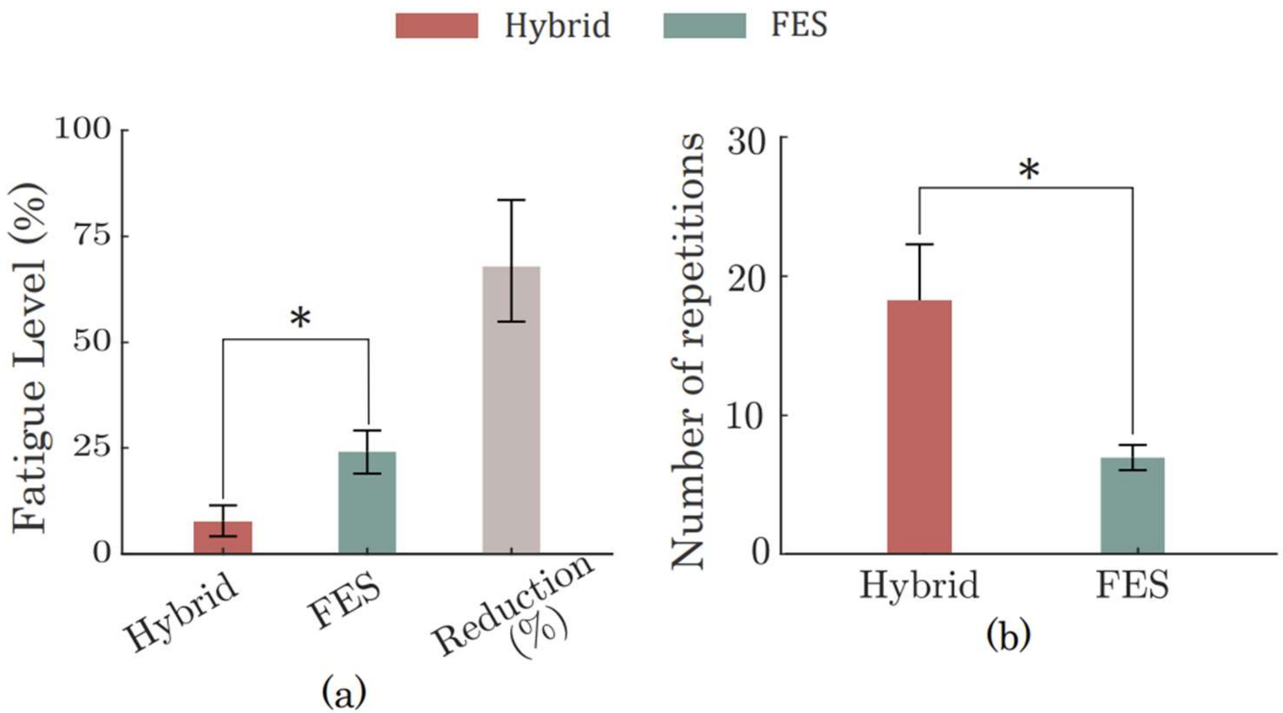



Figure 4.2: *Fatigue results.* (a)Fatigue level post trial for the *FES* and *Hybrid* conditions. The percentage reduction of the *Hybrid* fatigue with respect to *FES* is shown. (b)Fatigue onset results, indicated as the first repetition during which the state machine entered inside the *Compensation* phase.

# Arm stimulator Exosuit specificities

## Active elbow exosuit

The soft exosuit used in this work is a fully-embedded system built by ARIES Lab (ZITI, Heidelberg, Germany) [3], able to assist elbow movements (Fig.1). It comprises a textile harness that connects arm and forearm, made starting from a passive orthosis. The actuation stage aids elbow flexion/extension through a brushless motor (T-Motor, AK60-6, 24V, 6:1 planetary gear-head reduction, Cube Mars actuator, TMOTOR, China) which drives the pulley (35mm) around which the artificial tendon is wound (Black Braided Kevlar Fiber, KT5703-06, 2:2 kN max load). On the textile harness two anchor points are suited both on the distal and proximal side of the elbow and they are linked to the motor pulley via a Bowden cable (Shimano SLR, 5mm, Sakai, Japan). A force sensor (ZNLBM-1, 20 kg max load, China) is placed in between the connection of the cable with the distal anchor point and it measures the cable tension. Two Inertial Measurement Units (IMU, Bosch, BNO055, Germany) detect the arm kinematics and orientation. The actuation unit and the power supply (Tattu, 14.8V, 3700mAh, 45C) are screwed on the back protector. The control unit is driven by a microprocessor (Arduino MKR 1010 WiFi,Arduino, Ivrea, Italy) that receives sensors measuraments via wireless protocol and sends the signals to the actuation stage via CAN-bus [3]. Moreover, a Bluetooth Low-Energy interface was developed to allow the Arduino to control the electrical stimulator.

## Electrical stimulator

The electrical stimulator (KT motion, Medel, Hamburg, Germany) was used to stimulate the biceps inducing elbow flexion by means of two electrodes (Krauth+Timmermann, 4x6 cm area) placed over the muscle belly. When the stimulation is off, the EMG activity of the same muscle is measured. Biphasic electrial pulses at a frequency of 40 Hz were delivered to induce muscle contraction. The current amplitude was tuned for each subject as described in Section *Calibration Procedure* and kept constant, whereas the pulse width (PW) was modulated during the movement.

(PW) was modulated during the movement.

# **Arm stimulator** Exosuit for both arms


# THE END