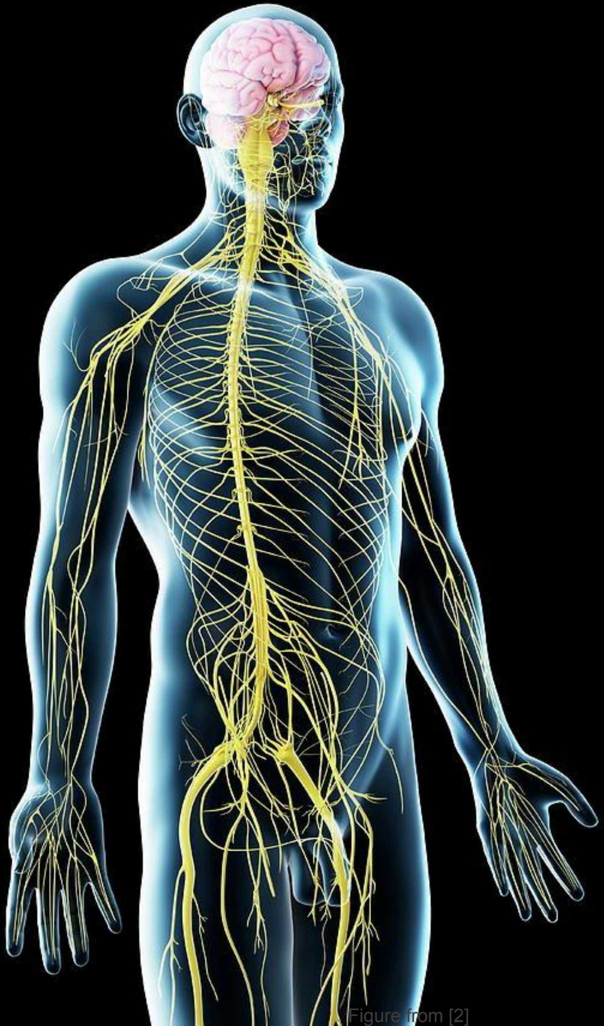
Figure from [2]

# SCI Digital Bridge: Hydrogel Approach

Rodrigo Anjos
Shiu-Cheng Wang

NX-436/Project

# Outline



- Background
  - Problems
  - Solutions and limitations
- Our solution
  - Recording
  - Stimulation
    - **Conductive hydrogel**
- Future
  - Roadmaps
  - Challenges


Generated with the assistance of ChatGPT and DALL·E by OpenAI.

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# Background

# Outline



- **Background**
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# Spinal Cord Injury

- C5 injury with ASIA-B severity

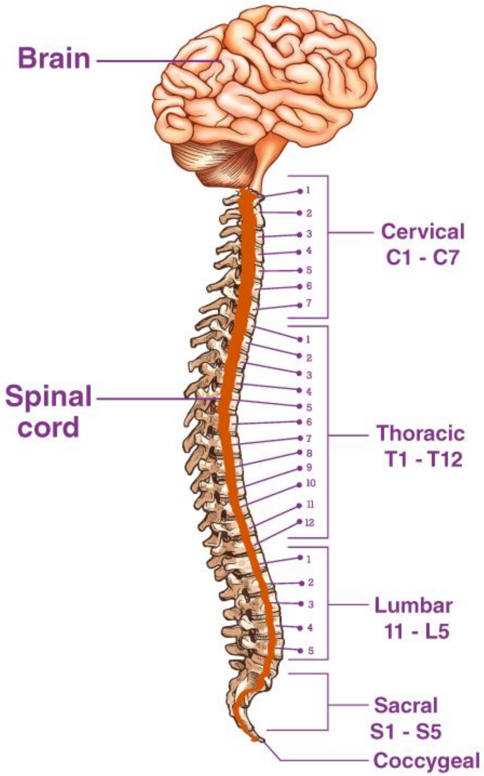


Fig. 1 - Spinal Cord [4]

# Outline

- **Background**
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# State of the art motor restoration

- Physical rehabilitation
- Regenerative Medicine
- BCIs

Fig. 2 - Physical rehabilitation [7]

# BCIs for motor restoration

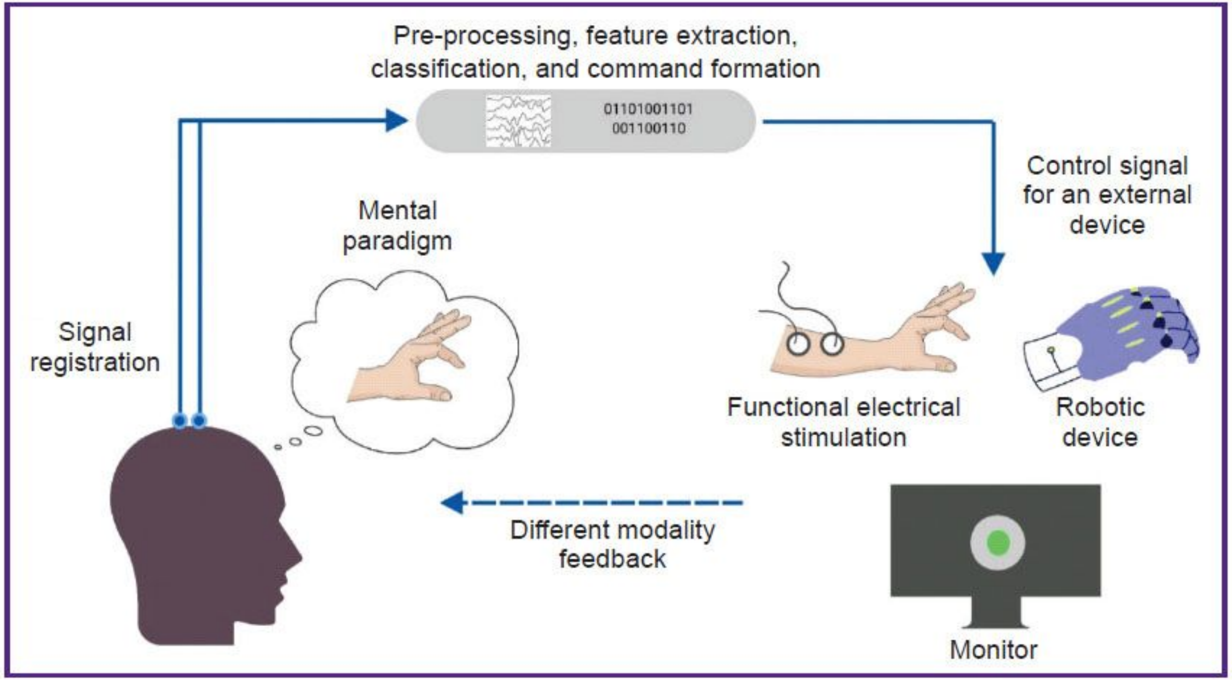



Fig. 3 - BCI for movement schematic [8]

# Sensors - State of the art

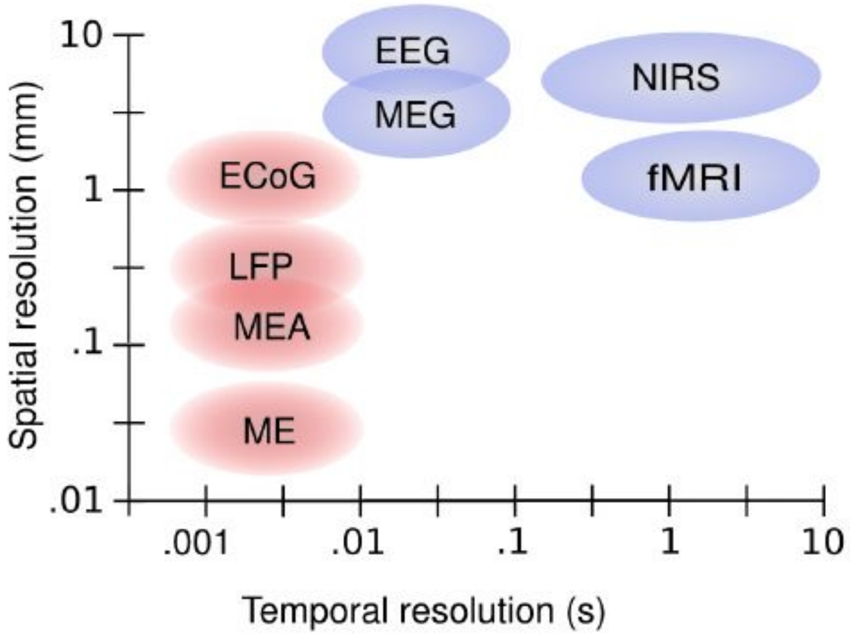



Fig. 4 - Types of sensors currently used [9]

# Decoders - State of the art

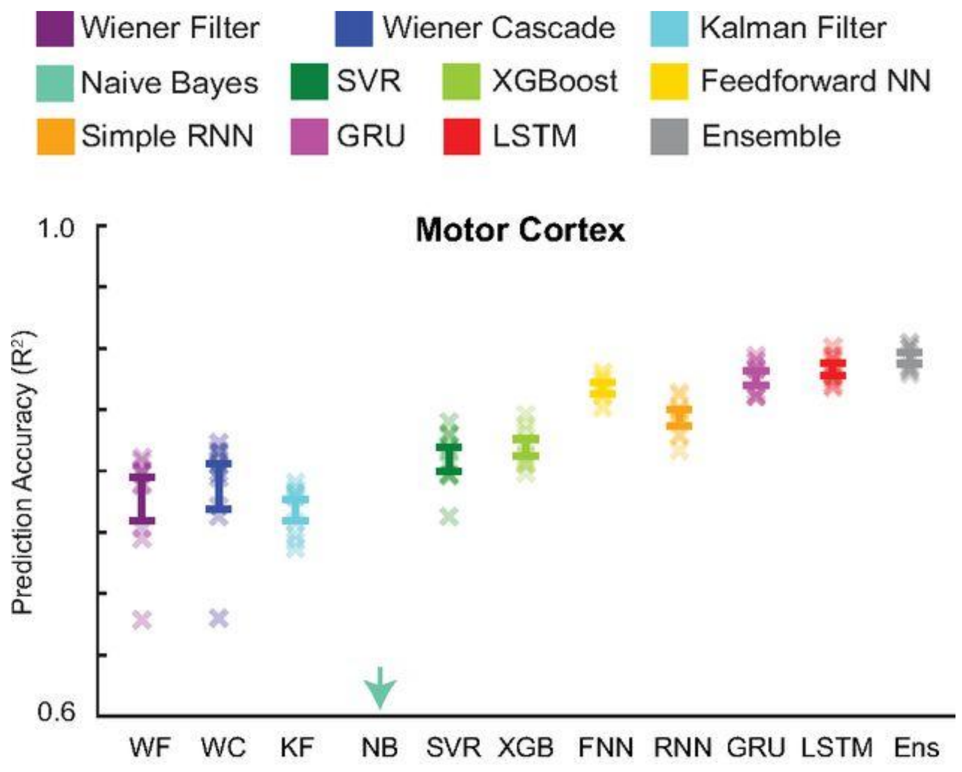
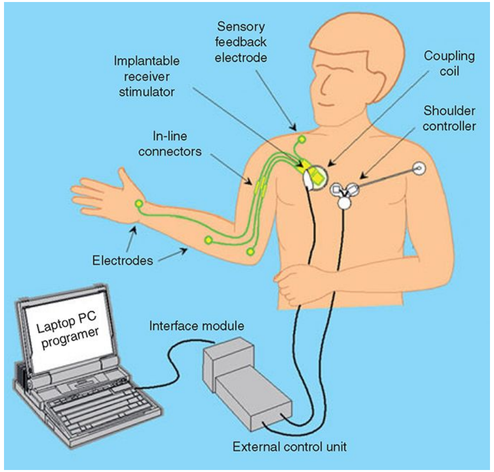



Fig. 5 - Comparison between different decoder algorithms [10]

# Effectors - State of the art

- Non-invasive stimulation
  - FES
- Robotic orthoses
- Exoskeletons
- Invasive Stimulation
  - EES
  - Peripheral Nerves and Muscles



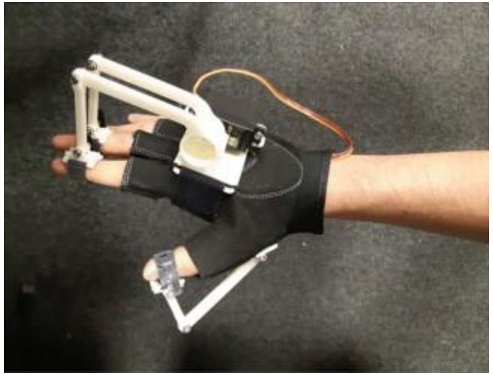



Fig. 6, 7 - Peripheral Nerve Stimulation [11] (Top), Robotic Hand Orthosis [12] (Bottom)

# Effectors - Current limitations

- mechanical incompatibility
- poor contact
- highly invasive

[13]

# Solution: Conductive Hydrogel

- Body like mechanical property
- Conform well to the stimulation sites
- Minimally invasive by injection

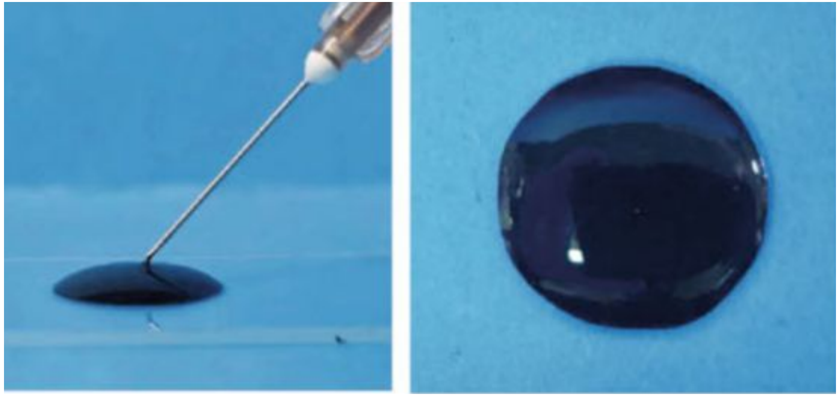


Fig. 8 - Injectable hydrogel [15]

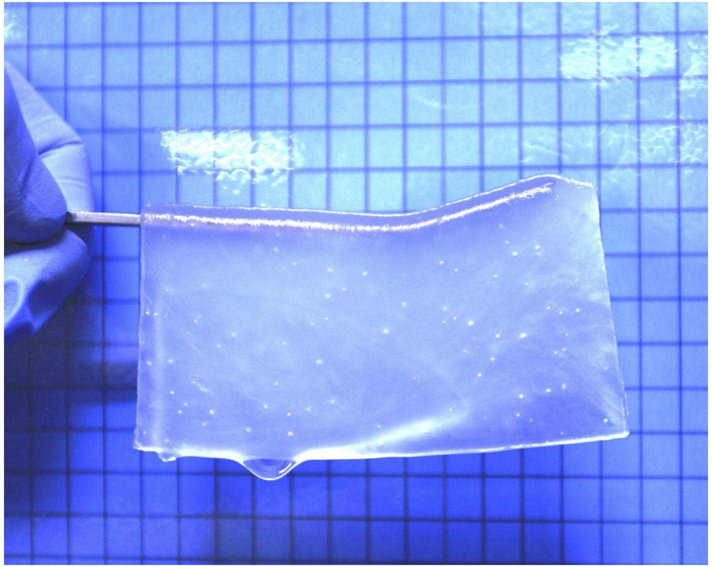


Fig. 9 - Hydrogel [16]

EPFL

# Our solution

# Outline

- Background
  - Problems
  - Solutions and limitations
- **Our solution**
  - **Recording**
  - Stimulation
    - **Conductive hydrogel**
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  - Challenges

# Our approach

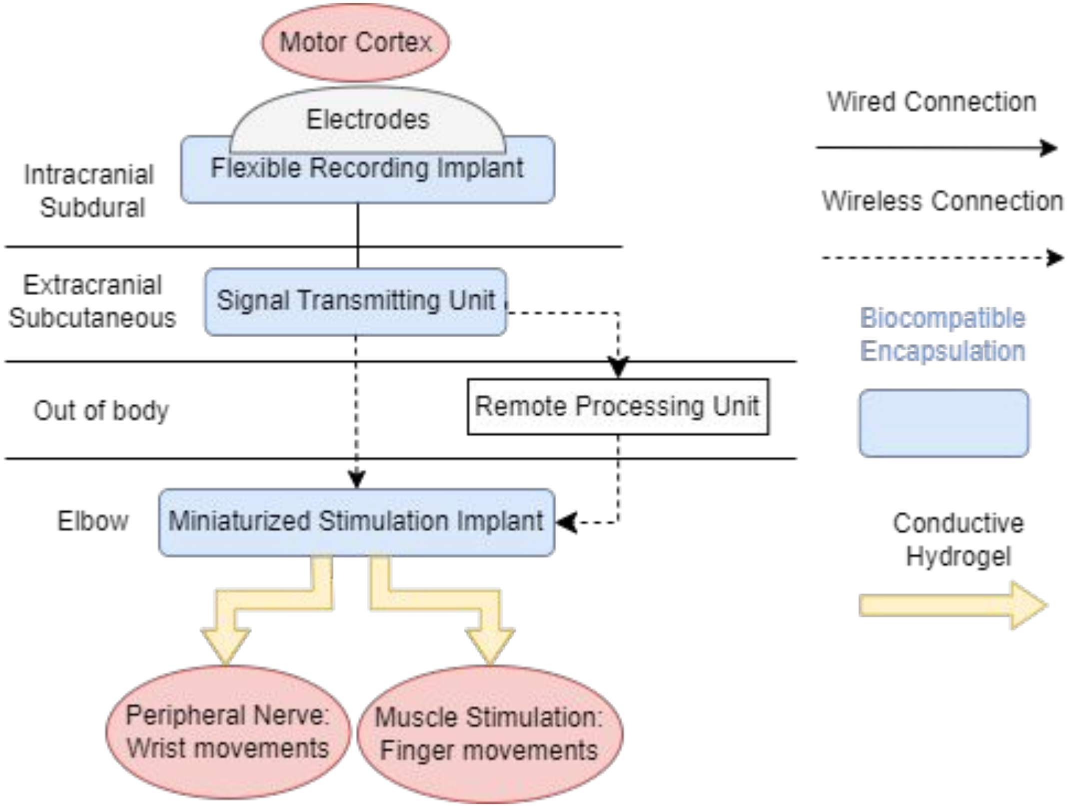


Fig. 10 - Schematic of our approach

# Sensors - Our approach

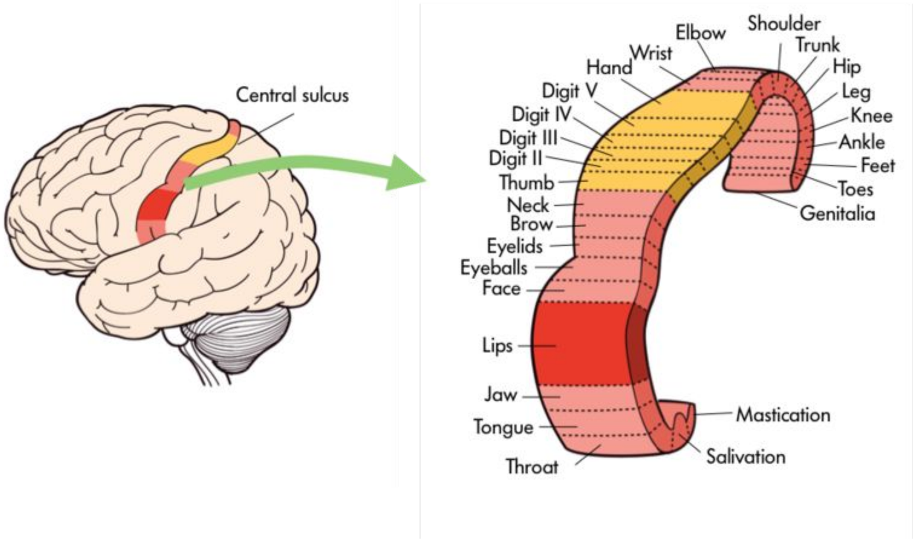


Fig. 11 - Location of recording electrodes [14]

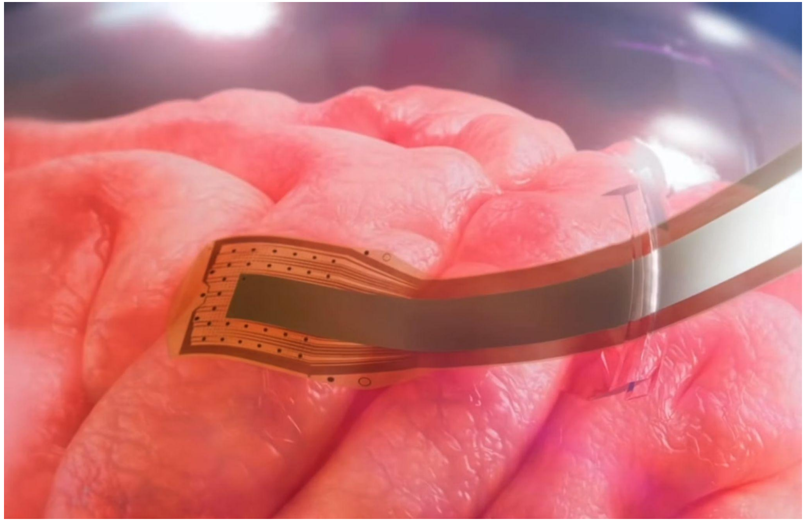

Fig. 12 - Precision Neuroscience MEA [15]

# Sensors - Our approach

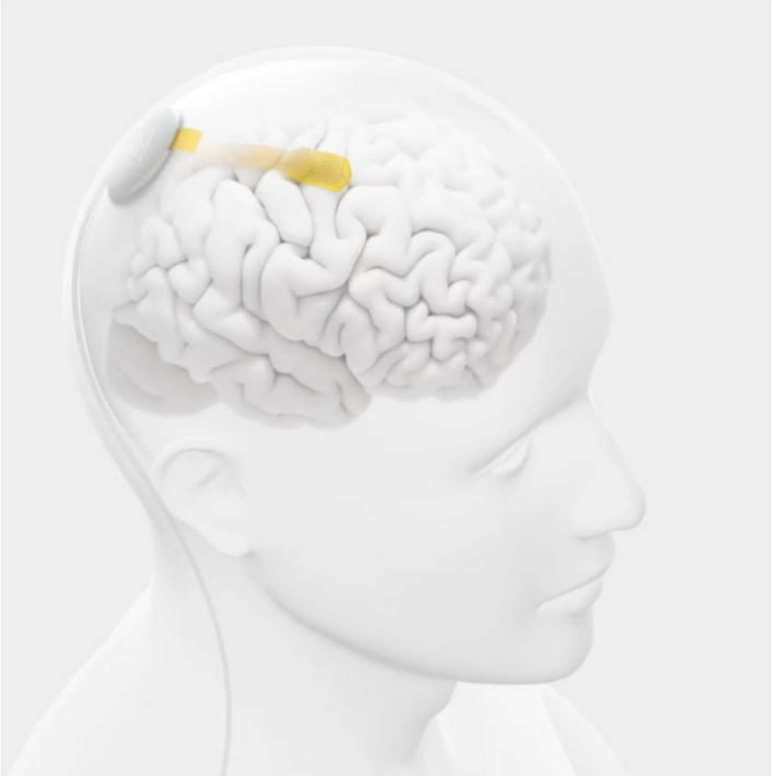

Fig. 13 - Chosen recording system [13]

# Decoder - Our approach

GAP9 microcontrollers (3.7x3.7 mm) [16] have been shown to be able to run sNNs for on-implant movement decoding [17]

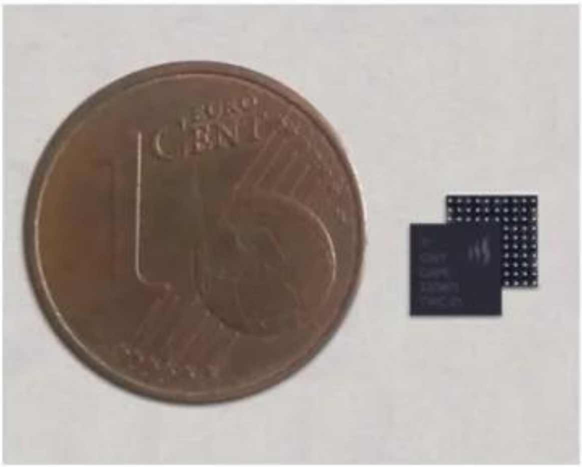



Fig. 14, 15 - GAP9 chip size comparison [18] (left), current use of these chips (right)

# Decoder - Our approach

A deep neural network is trained over 40 sessions

Use of an “updater” instead of constant retraining

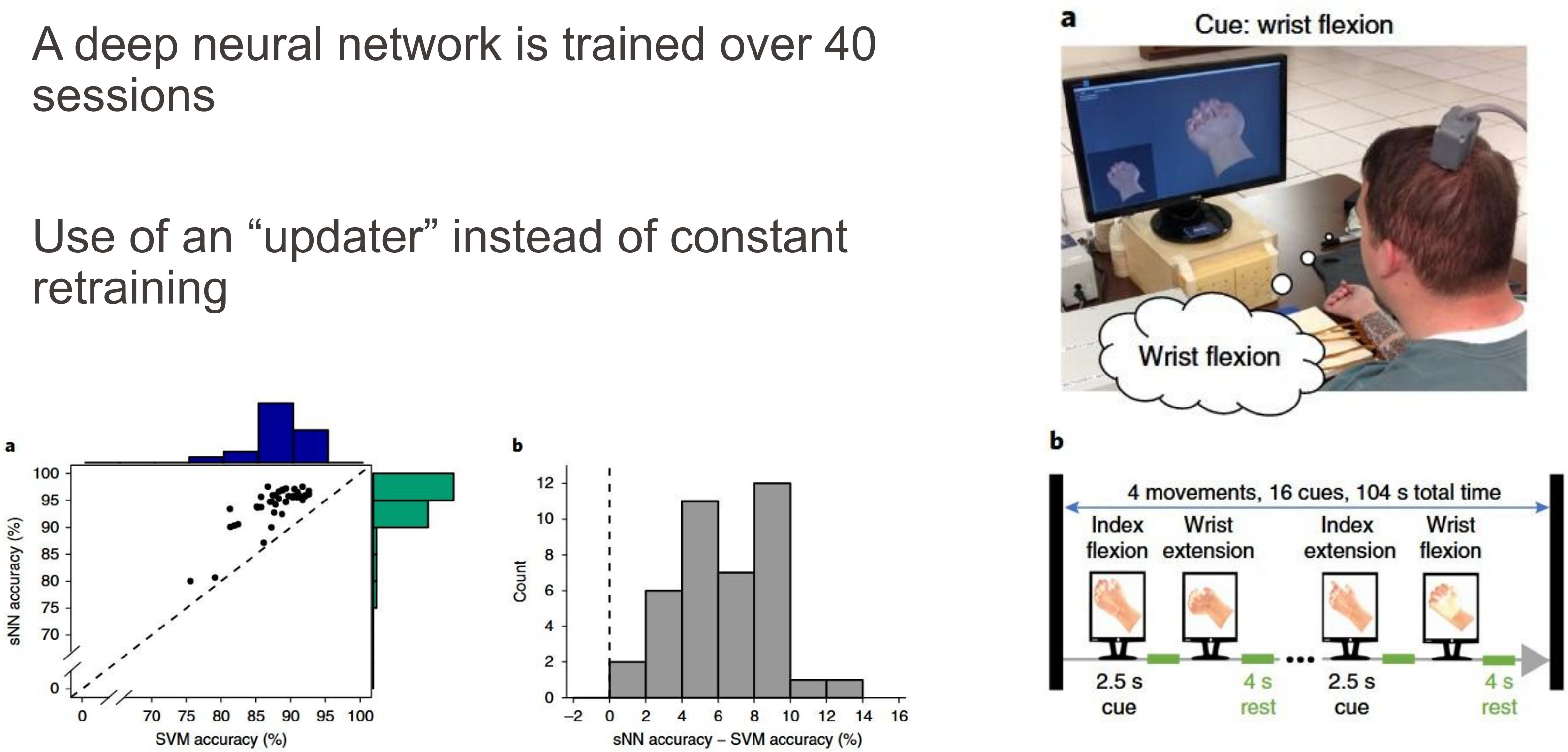


Fig. 16 - Training of sNN [19]

# Effector - Our approach

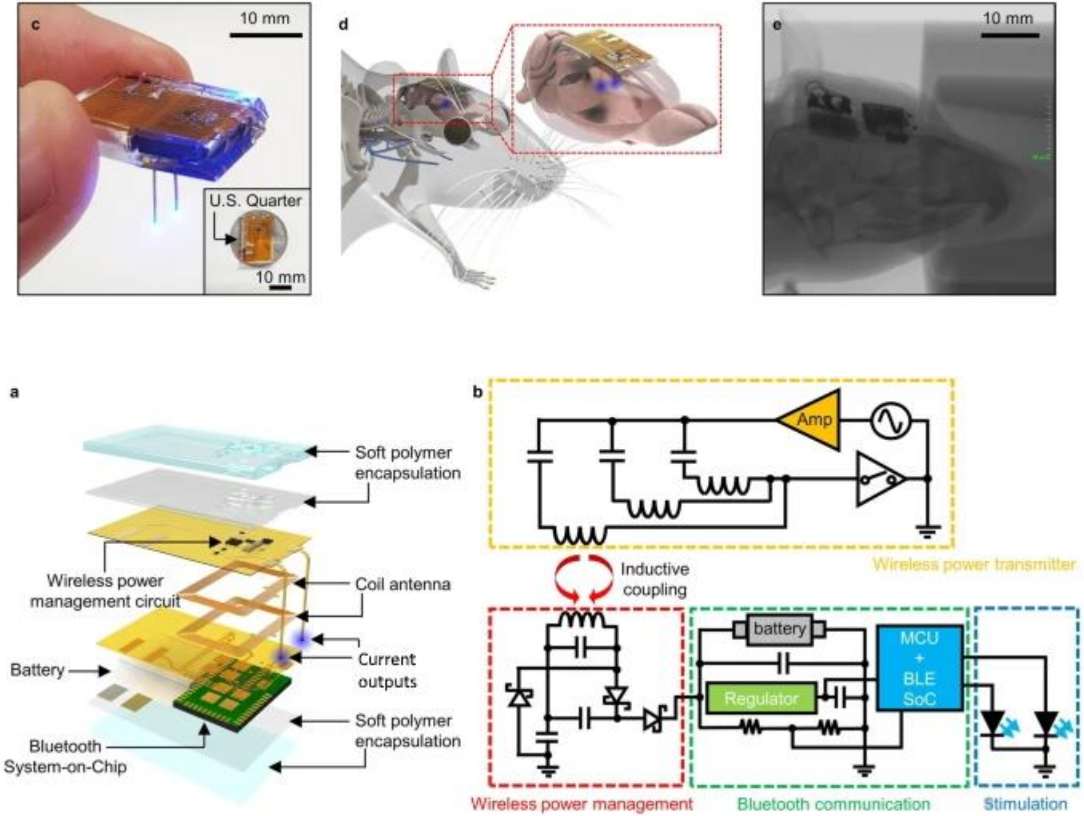


Fig. 17 - Effector with wireless data transmission [20]

# Our solution

# Outline

- Background
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# Effectors - Current limitations

- mechanical incompatibility
- poor contact
- highly invasive

[13]

# Solution: Conductive Hydrogel

- Body like mechanical property
- Conform well to the stimulation sites
- Minimally invasive by injection

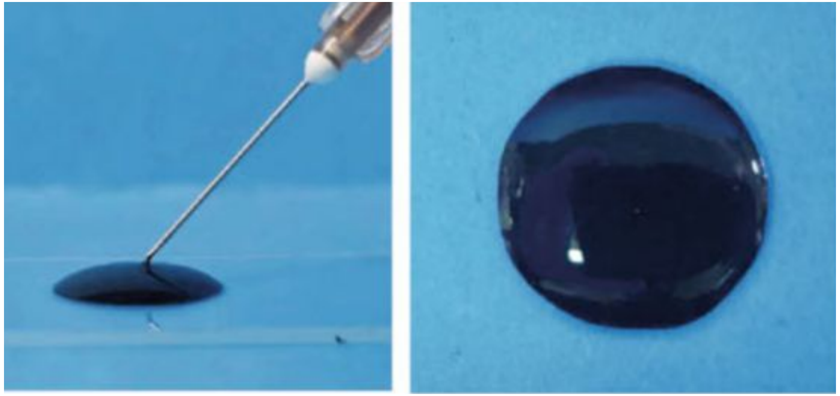


Fig. 8 - Injectable hydrogel [15]

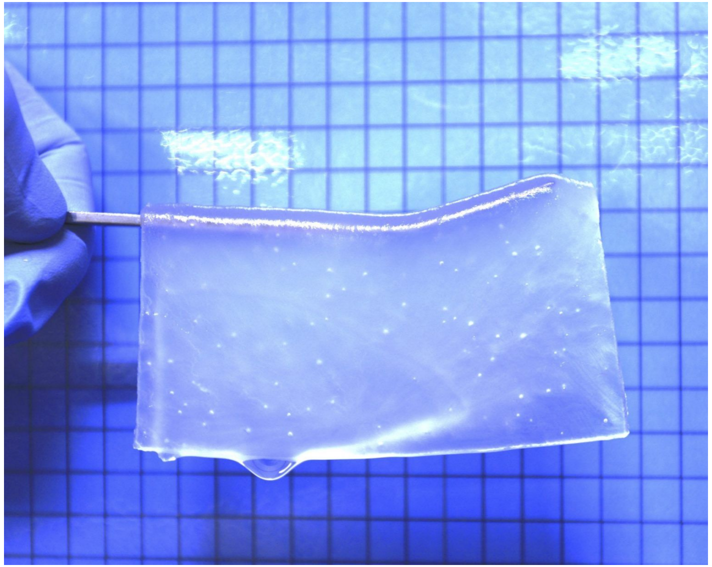


Fig. 9 - Hydrogel [16]

# Desired Properties

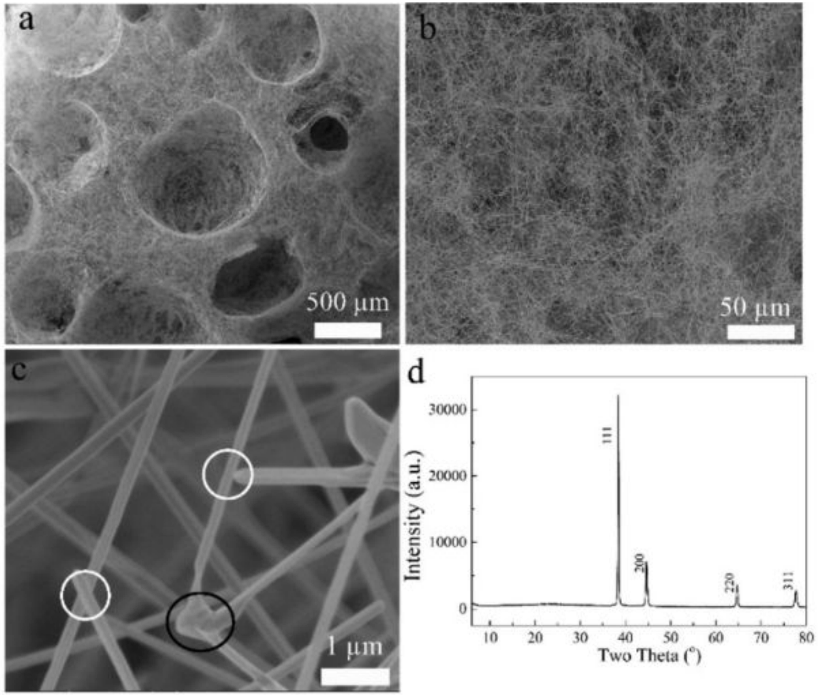
- High conductivity
- Good mechanical properties
- Injectability
- Biocompatibility

# Composition and Conductivity

Silver Nanowire Gel

| | |
|---|---|
| [17] | Huang et al. (2020) |
| **Composition** | **PDMS, 3D NW** |
| **Conductivity** | **$2.1 \times 10^5$ S/m** |
| Biocompatibility | Good, PDMS |
| Density | 24.3 mg/cm$^3$ |
| Compressive Yield Strength | 5.1 kPa |
| Compressive Modulus | 38.7 kPa |

Fig. 18 - (a–c) SEM images at different magnifications of AgNW aerogels.
(d) XRD pattern of the AgNW aerogels.

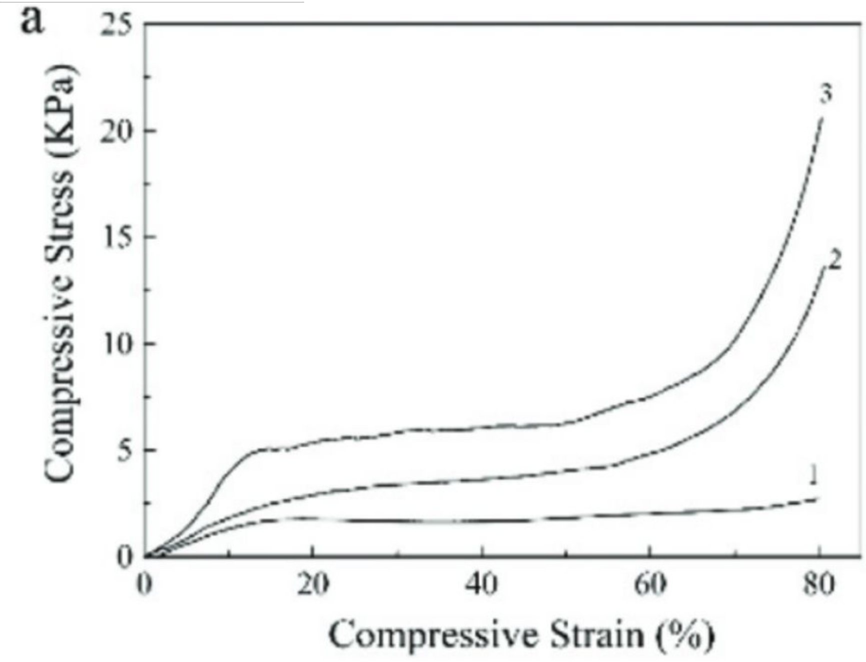


# Mechanical Property

Silver Nanowire Gel

| | |
|---|---|
| [17] | Huang et al. (2020) |
| Composition | PDMS, 3D NW |
| Conductivity | $2.1 \times 10^5$ S/m |
| Biocompatibility | Good, PDMS |
| Density | 24.3 mg/cm$^3$ |
| **Compressive Yield Strength** | **5.1 kPa** |
| **Compressive Modulus** | **38.7 kPa** |

Fig. 19 - Compressive stress–strain curves for AgNW aerogel of different densities: (1) 10.7 mg/cm3, (2) 15.2 mg/cm3, and (3) 24.3 mg/cm3

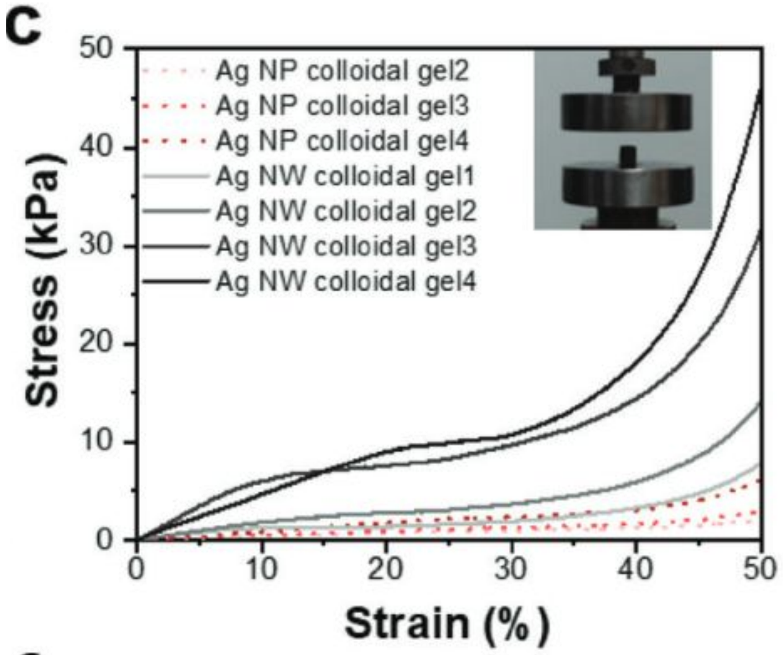


# Mechanical Property

Silver Nanowire Gel

| | |
|---|---|
| [18] | Du et al. (2024) |
| Composition | gelatin, 1D NW |
| Conductivity | 33 S/m |
| Biocompatibility | Good, gelatin |
| Density | not mentioned |
| **Compressive Yield Strength** | **9.2 kPa** |
| **Compressive Modulus** | **62.5 kPa** |

Fig. 20 - Compression curve of Ag NW colloidal gels and Ag NP colloidal gels



# Composition and Conductivity

Silver Nanowire Gel

| | |
|---|---|
| [18] | Du et al. (2024) |
| **Composition** | **gelatin, 1D NW** |
| **Conductivity** | **33 S/m** |
| Biocompatibility | Good, gelatin |
| Density | not mentioned |
| Compressive Yield Strength | 9.2 kPa |
| Compressive Modulus | 62.5 kPa |

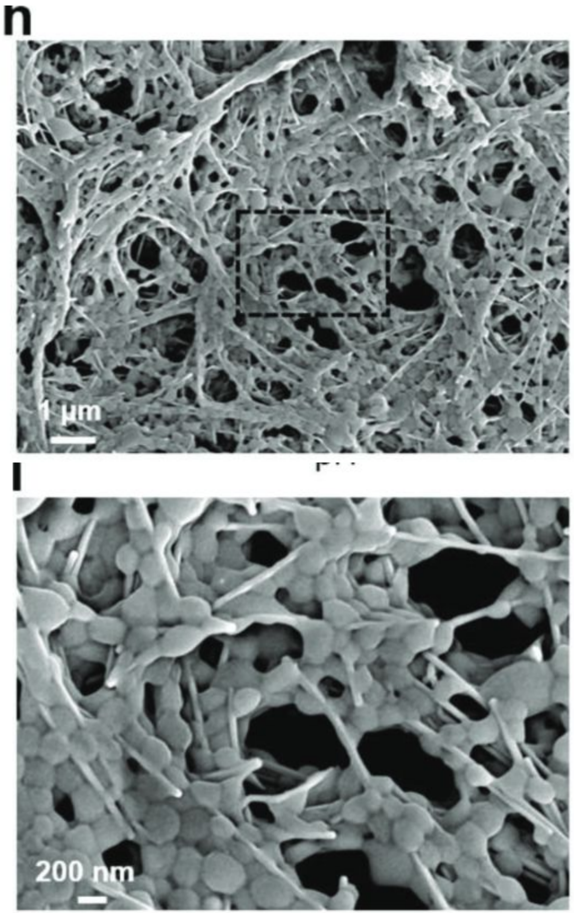



Fig. 21, 22 - SEM images of Ag NW colloidal gel

# Conductive Hydrogel

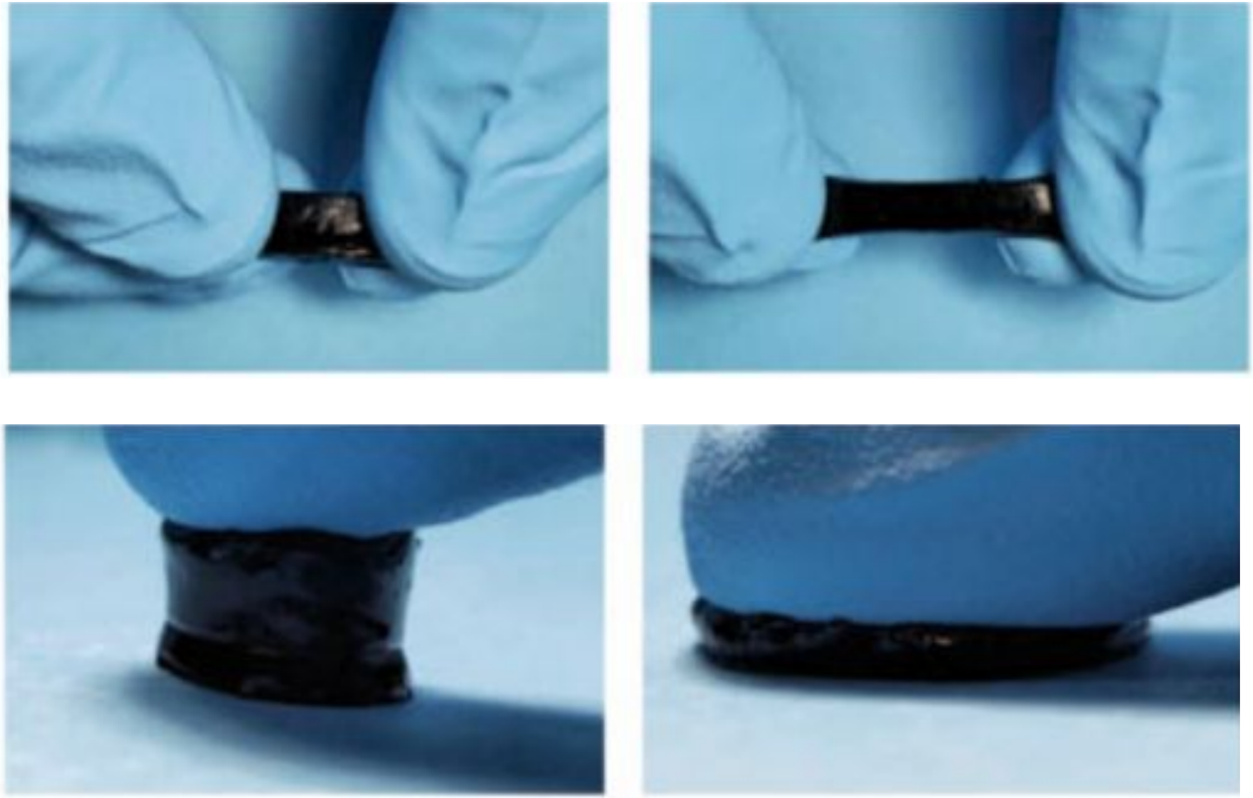


Fig. 23 - Hydrogel with desired properties [15]

# Conductive Hydrogel

Adhesion

- Tissue
- Device

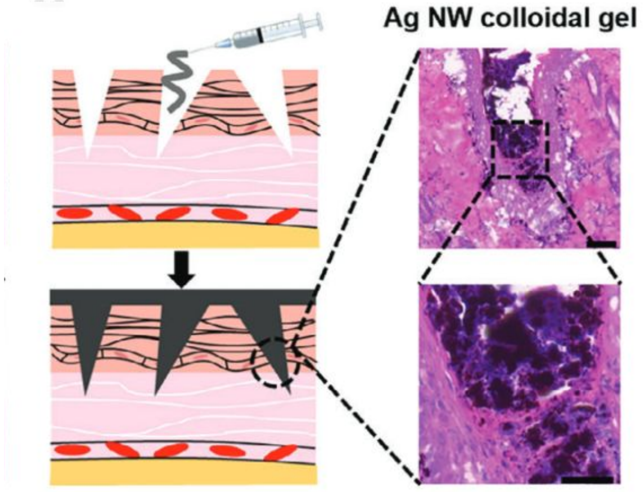



Fig. 24 - Ag NW colloidal gel applied in deep and irregular wounds [18]

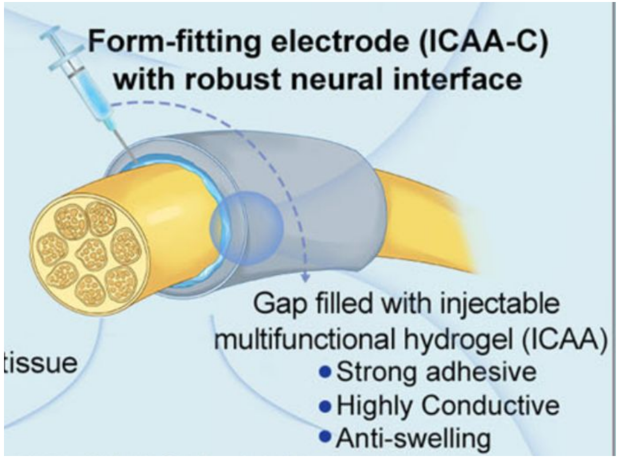



Fig. 25 - Cuff electrode with gap filled by injectable hydrogel [15]

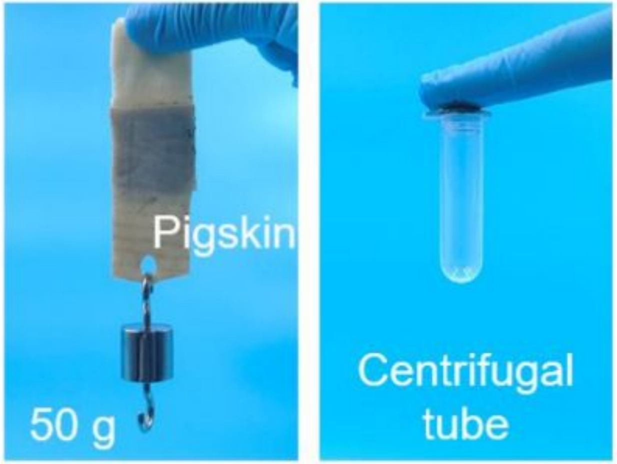



Fig. 26 - Ag NW colloidal gel adhered two pigskins together and pulled up a weight of 50 g and a centrifugal tube [18]

# Local Retention

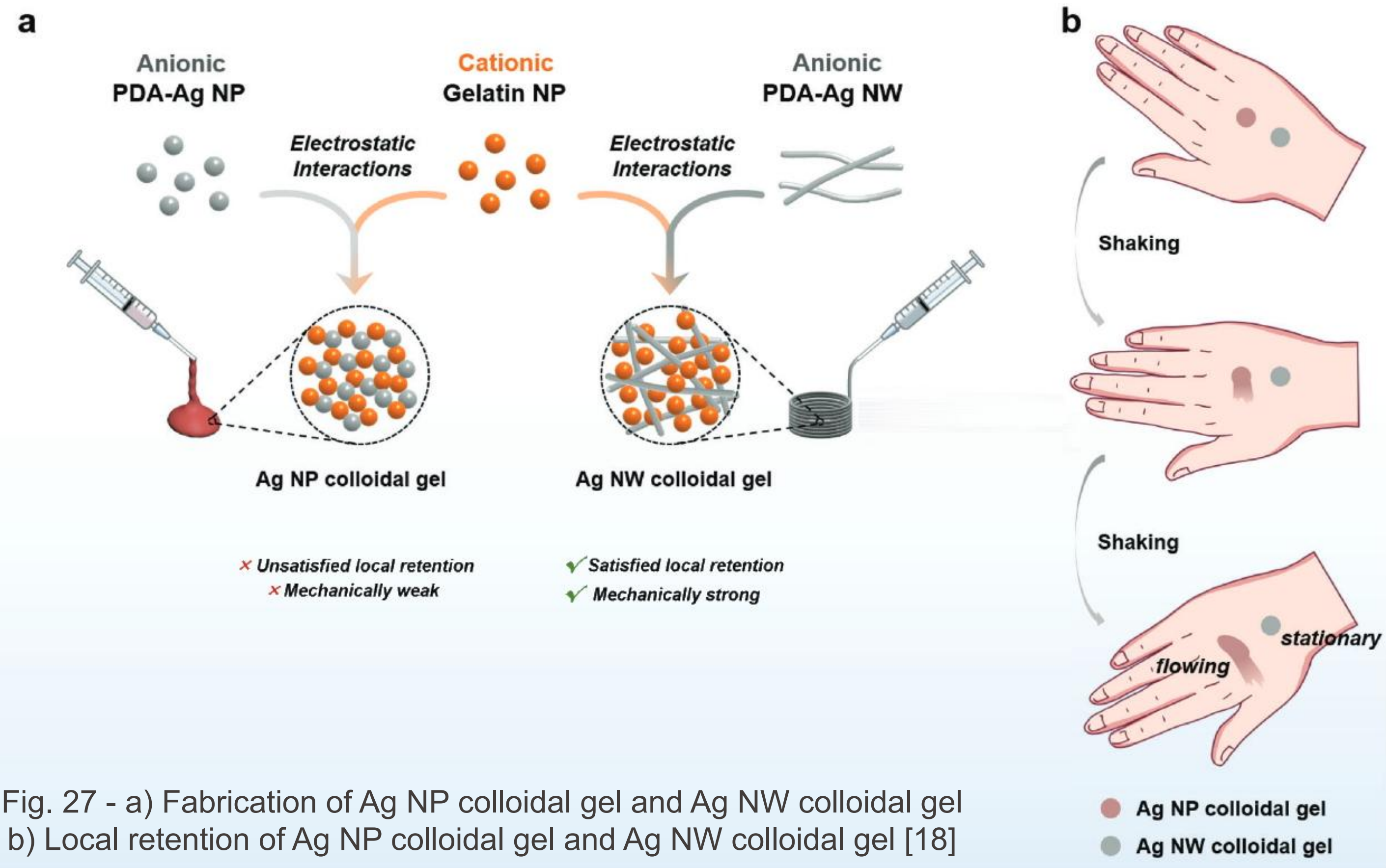
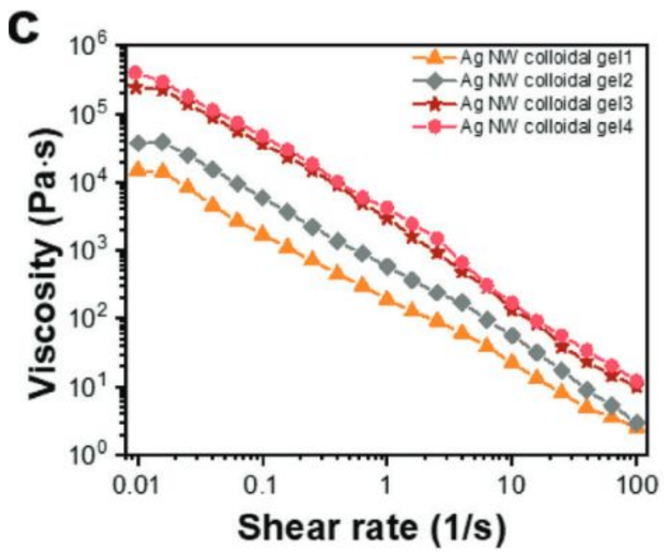


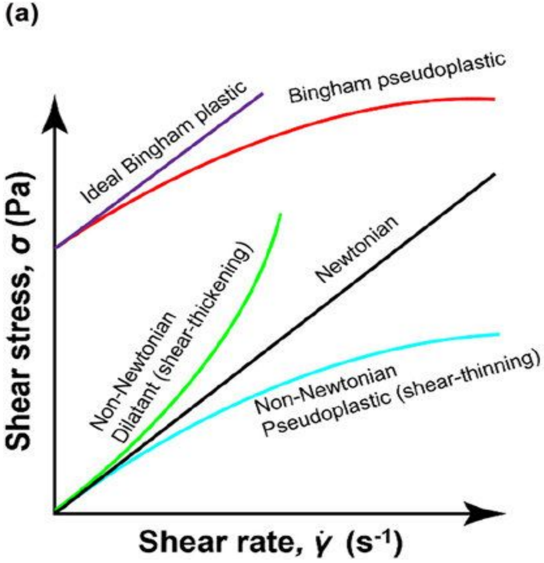

Fig. 27 - a) Fabrication of Ag NP colloidal gel and Ag NW colloidal gel
b) Local retention of Ag NP colloidal gel and Ag NW colloidal gel [18]

# Conductive Hydrogel

Injectability: Shear thinning

- Pros: easy for manipulation
- Cons: prone to mechanically instability



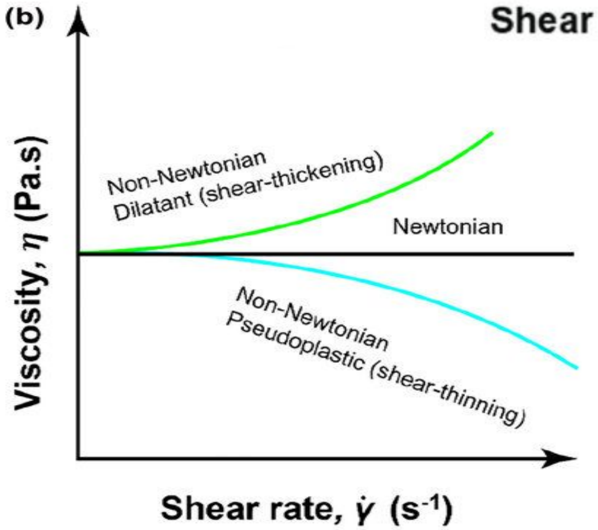




Fig. 28 - a) Shear stress as a function of shear rate [19]
b) Viscosity versus shear rate [19]
c) Viscosity and shear-thinning behavior of Ag NW colloidal gels [18]

# Conductive Hydrogel

Injectability: *In situ* gelation

- Pros
  - Perfect injectability
  - Good mechanical property after gelation
- Cons
  - Control and timing of the gelation
  - Intermediate chemicals

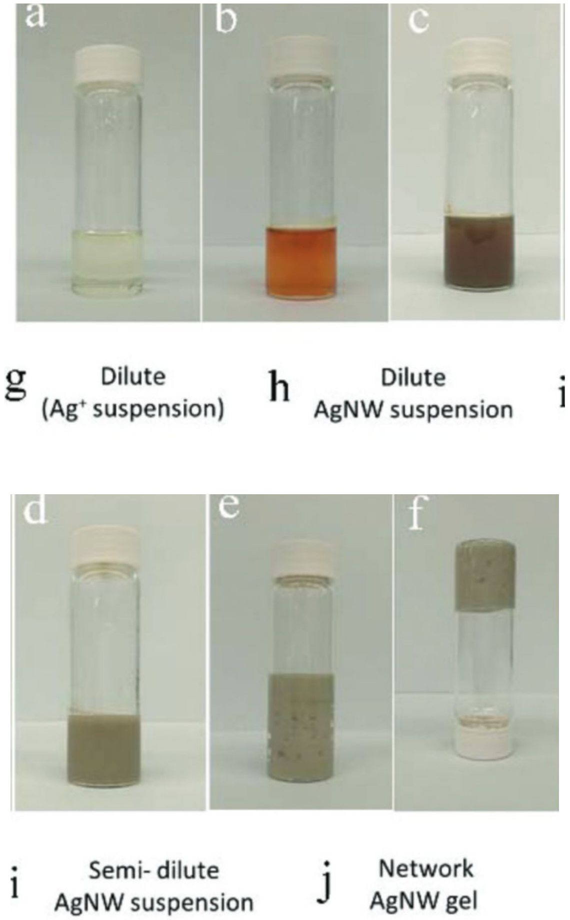



Fig. 29 - The process of forming AgNW wet gel [17]

# Ideal hydrogel

- Conductivity (Huang et al., 2020 & Du et al., 2024):
  - Dense silver nanowires (AgNWs)
- Local Retention (Du et al., 2024):
  - Polydopamine (PDA)-coated AgNWs
- Injectability:
  - In Situ Gelation (Yang et al., 2024) - Tannic acid modulation
  - Shear-Thinning (Jin et al., 2023) - Phenylborate-mediated crosslinking
- High Compressive Yield Strength (Du et al., 2024):
  - Dense 3D AgNWs

EPFL

# Stimulation

- Trade-off

peripheral nerve stimulation

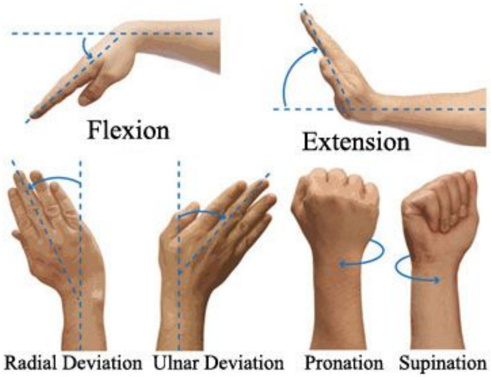
Natural

Less Fatigue

muscular stimulation

Higher selectivity

- Solution



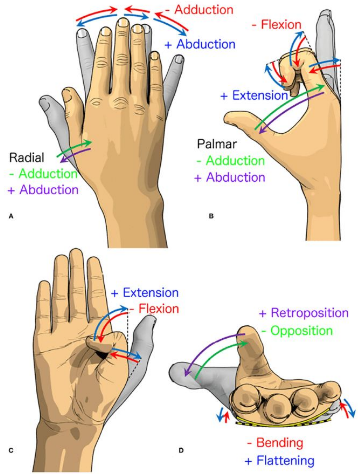




Fig. 30 - Wrist and hand movements [20]

# Location of Stimulation: wrist

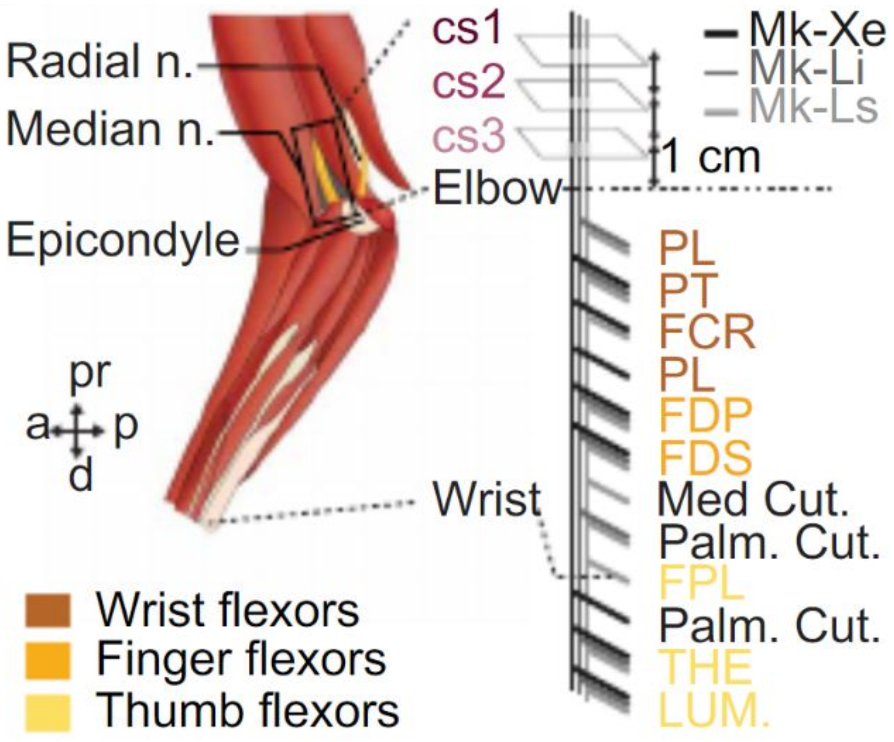
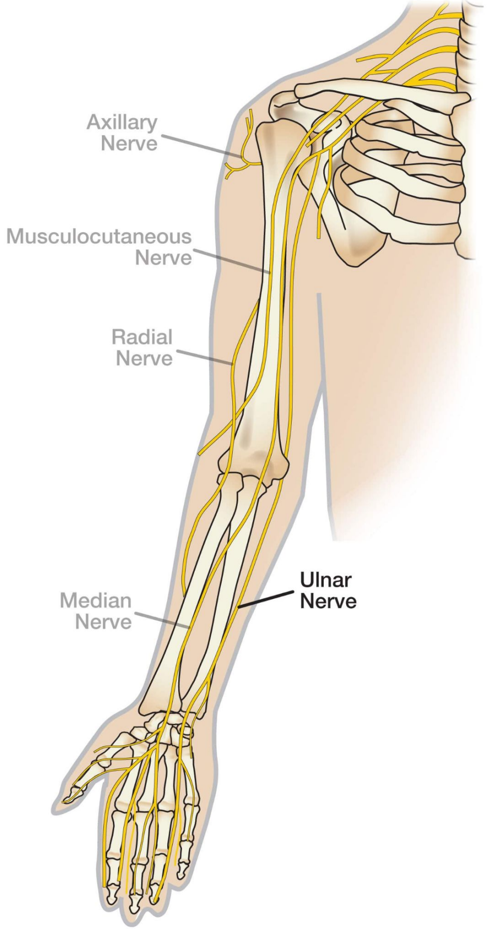
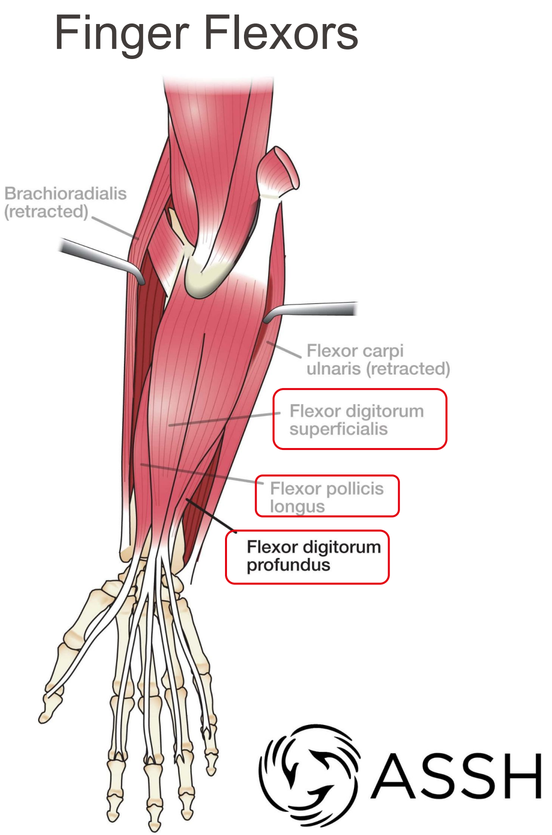



Fig. 31 - Nerves of the arm [21]



# Location of Stimulation: fingers



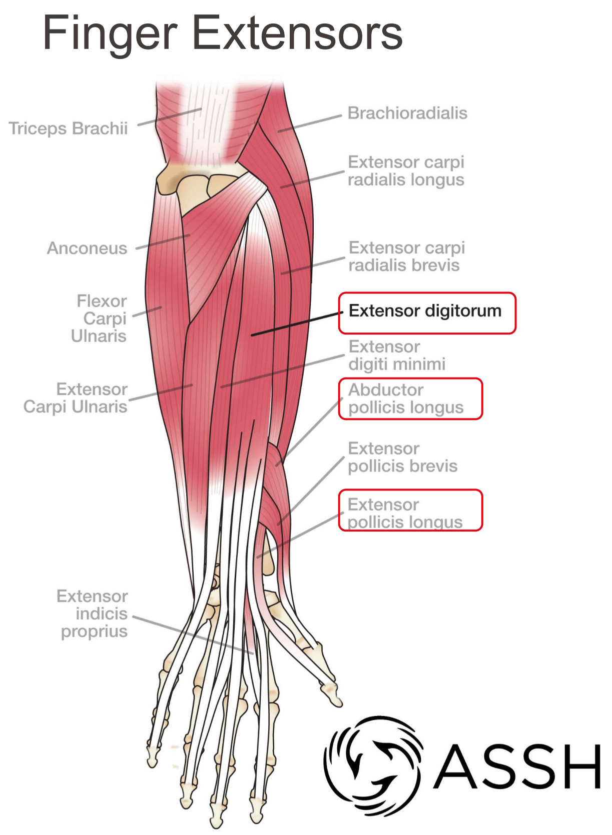




Fig. 32 - Finger flexor and extensor muscles [24]

# Location of Stimulation: fingers

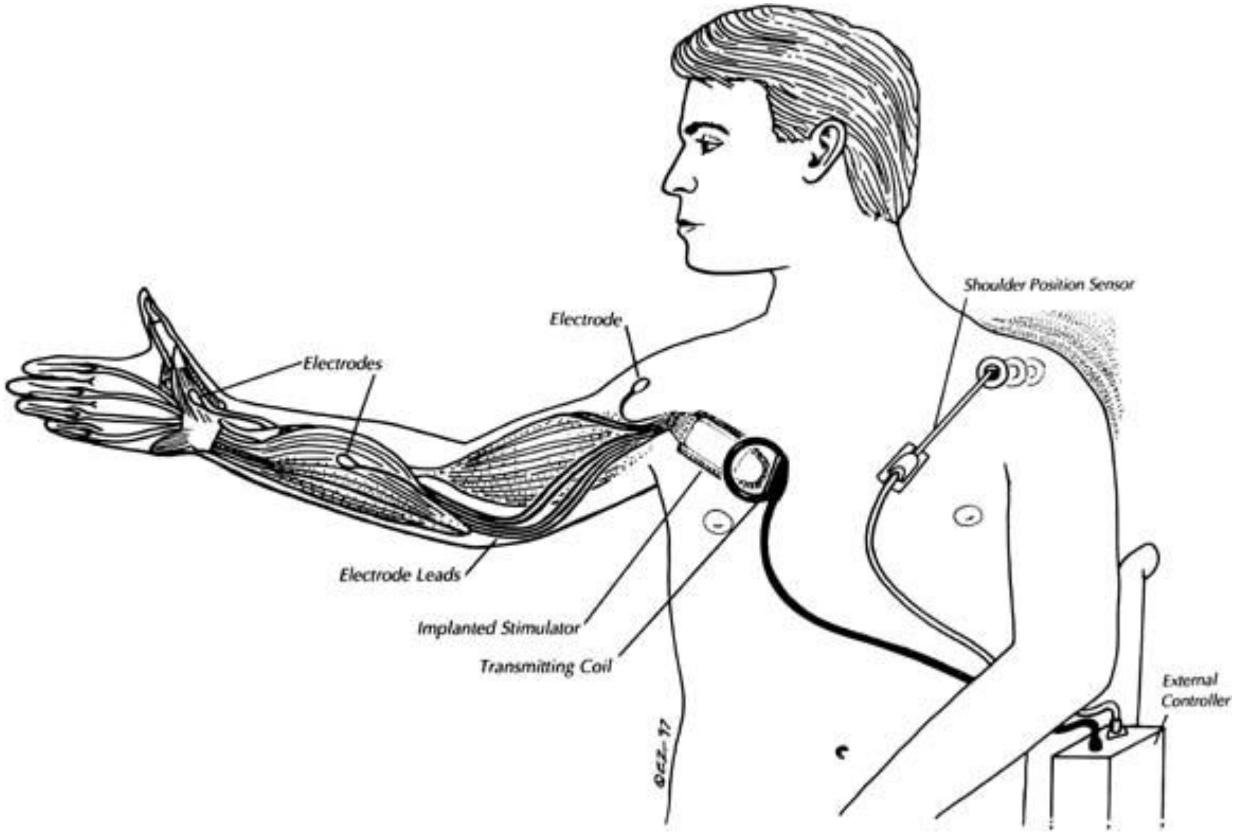



Fig. 33 - Example of implanted neuroprosthesis [34]

# Future

# Outline



- Background
  - Problems
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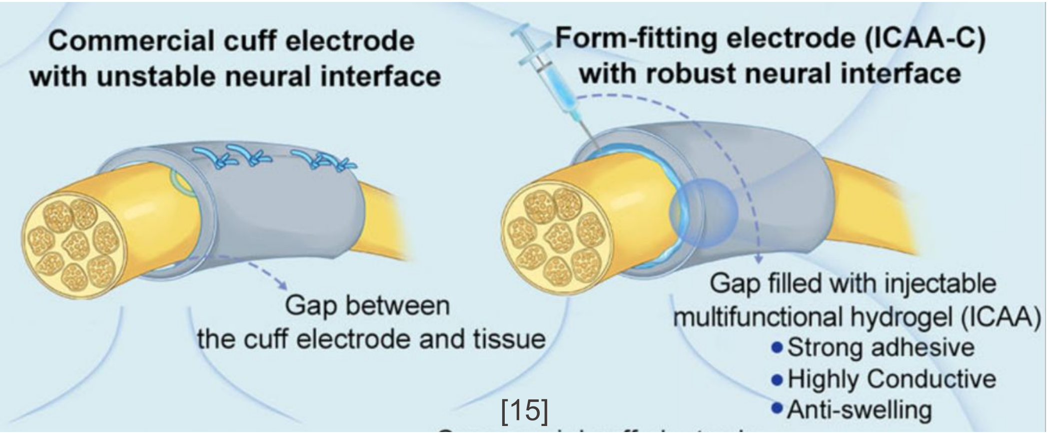
- Our solution
  - Recording
  - Stimulation
    - Conductive hydrogel
- **Future**
  - **Roadmaps**
  - Challenges

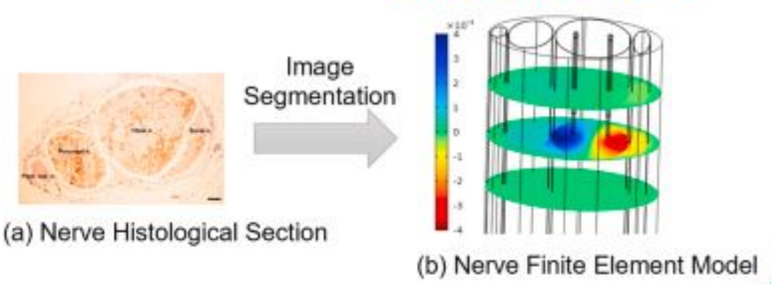
# Roadmap: Peripheral Nerve Stimulation

No wire cuff electrodes



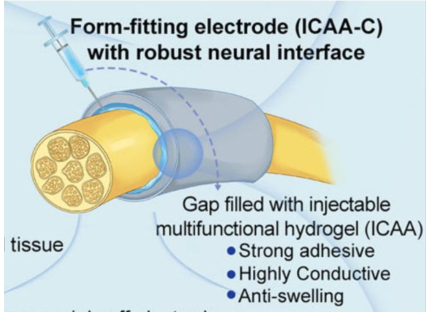

[15]

# Roadmap: Peripheral Nerve Stimulation



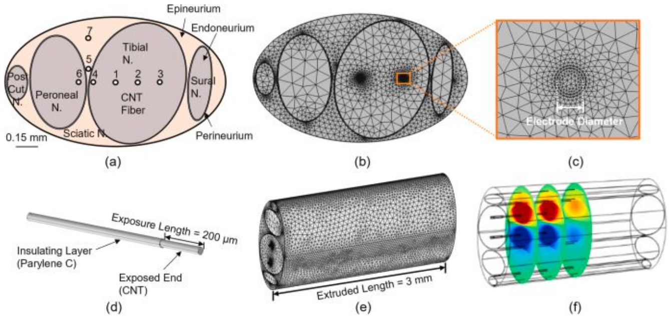

[26]

No wire cuff electrodes



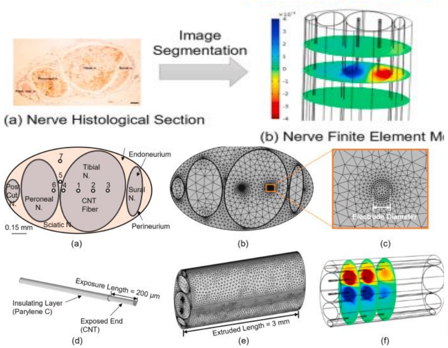

[15]

**Current steering FEM**



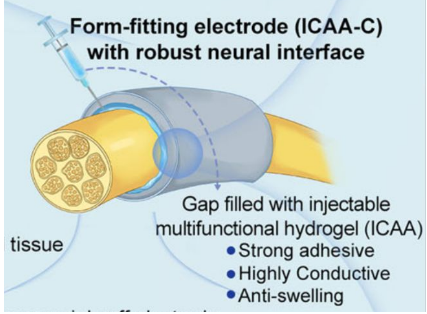
# Roadmap: Peripheral Nerve Stimulation

[26]

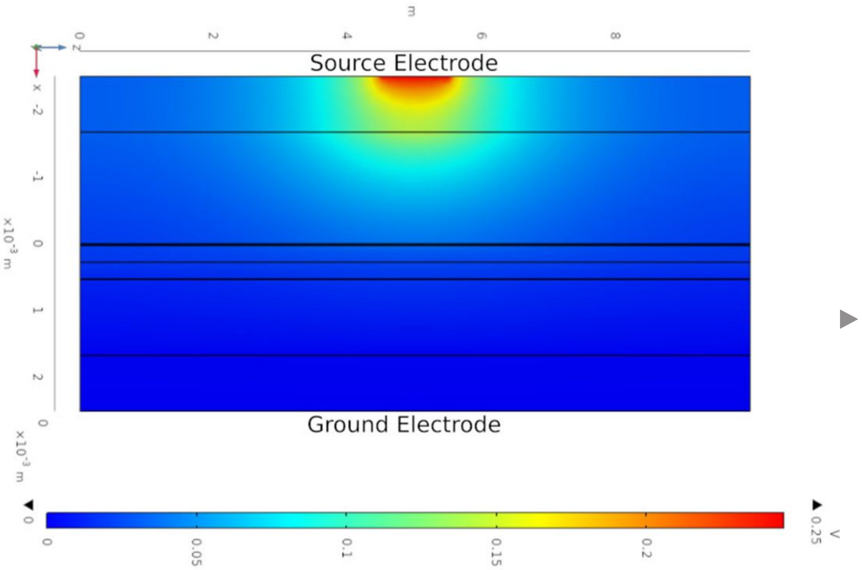



No wire cuff electrodes

Current steering FEM




[15]



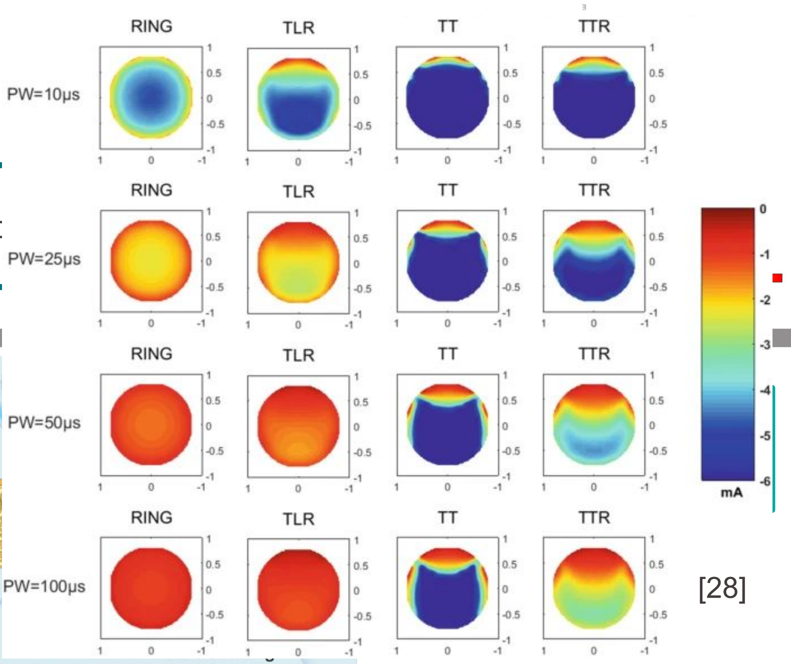

[27]

# Roadmap: Peripheral Nerve Stimulation

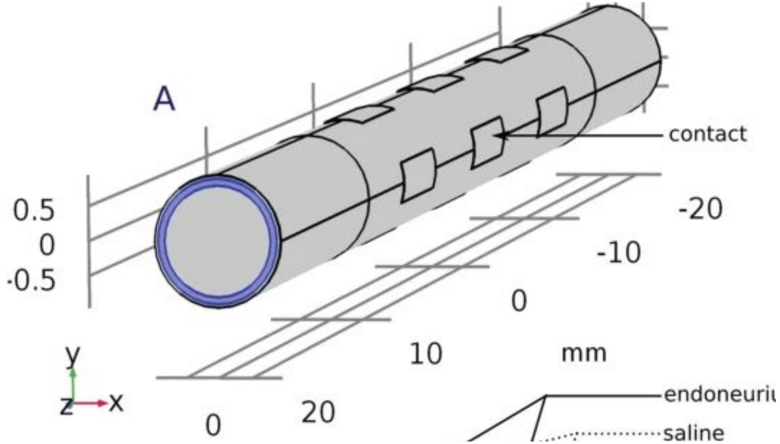
Nc

**Current Steering**

tissue

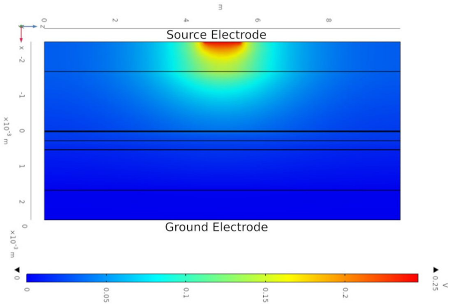



[28]

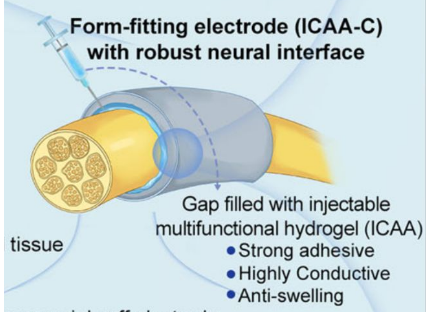



[15]

# Roadmap: Peripheral Stimulation

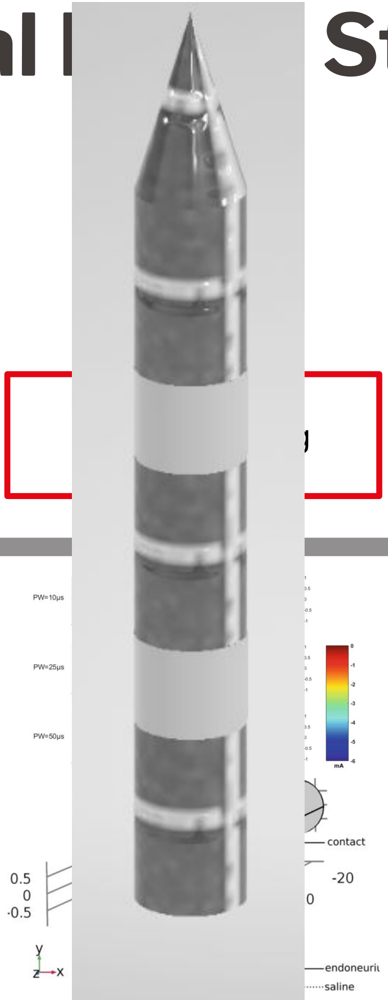



No wire cuff electrodes



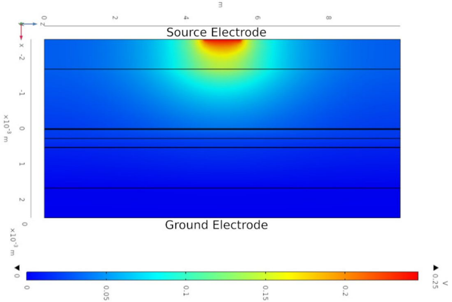

[15]

Current steering FEM



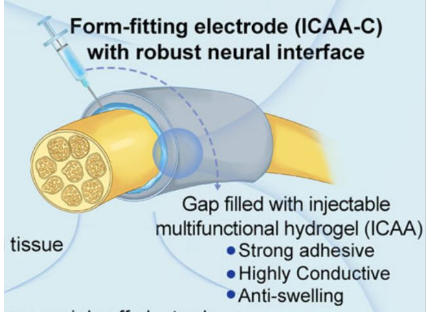

**3D patterned hydrogel**

# Roadmap: Peripheral Nerve Stimulation



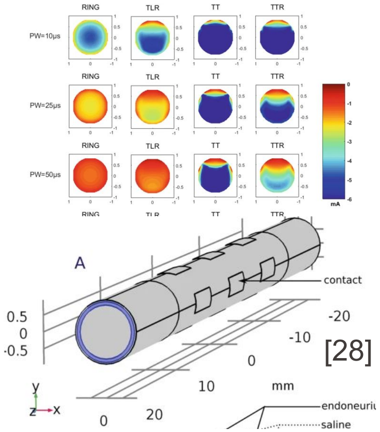

No wire cuff electrodes

Current Steering




[15]

Current steering FEM

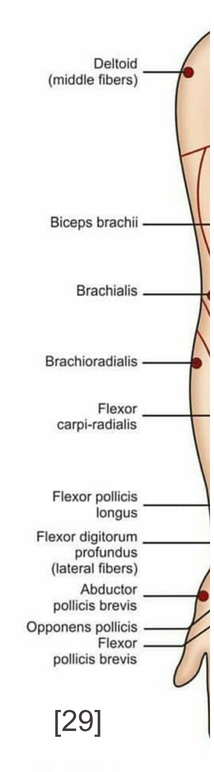



[28]

**3D patterned hydrogel**

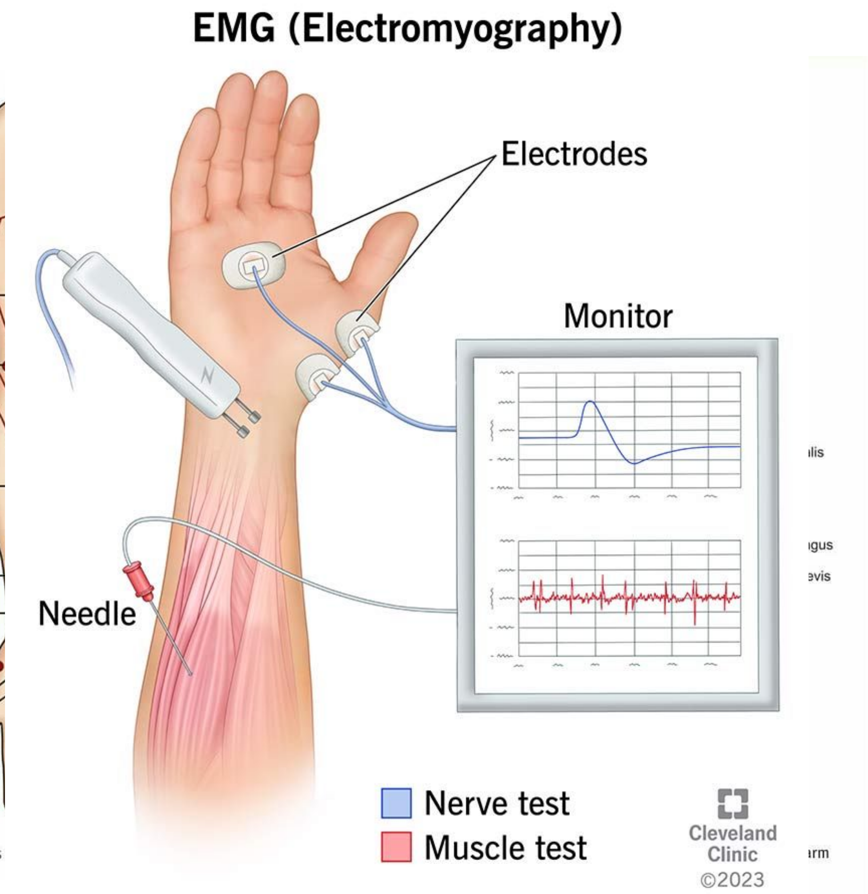
# Roadmap: Neuromuscular Stimulation

Motor point stimulation




[29]

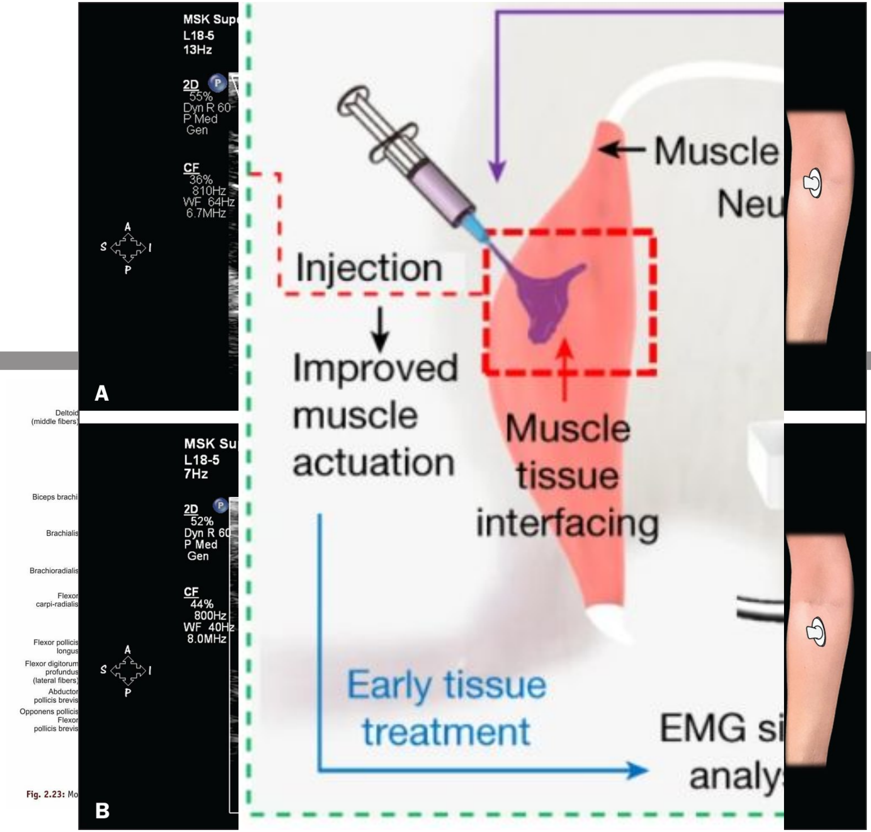
Fig. 2.23: Motor points




[30]

# Roadmap: Neuromuscular Stimulation

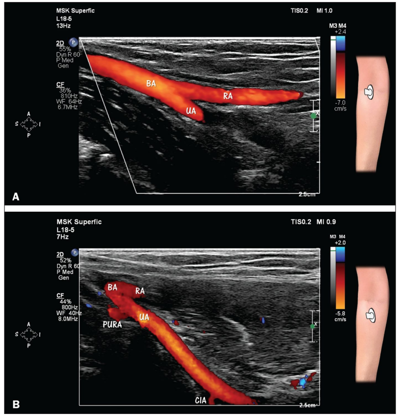
[31] [32]



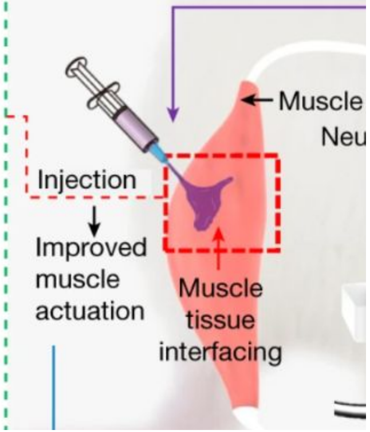

Intramuscular Stimulation

EPFL

# Roadmap: Neuromuscular Stimulation




[31]




[32]

Motor point stimulation

**Intramuscular Stimulation**

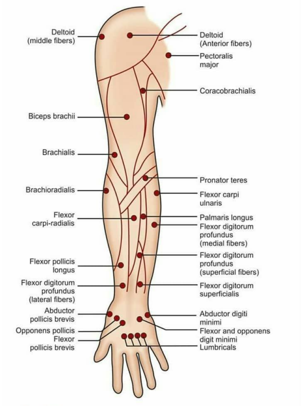
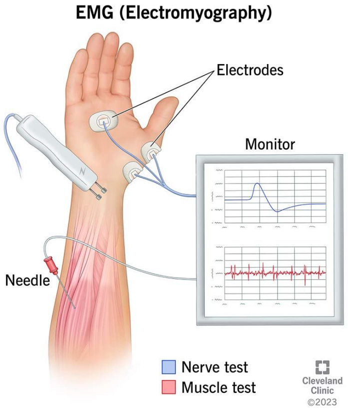



**Fig. 2.23:** Motor points of the anterior aspect of the right arm

[29]




[30]

# Tunnel Surgery

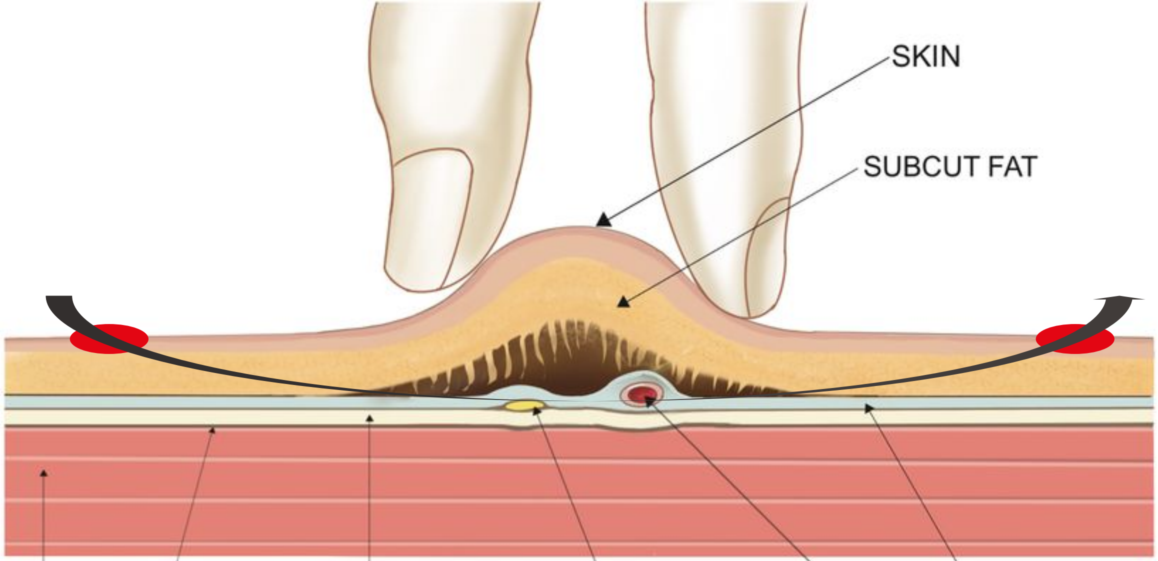



Fig. 16 - Schematic of the surgery [33]

# Outline

- Background
  - Problems
  - Solutions and limitations
- Our solution
  - Recording
  - Stimulation
    - Conductive hydrogel
- **Future**
  - Roadmaps
  - **Challenges**

# Challenges

- Long term use
- Temperature rise
- Peripheral nerve stimulation

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