



# Beyond the surface: Multichannel intramuscular EMG

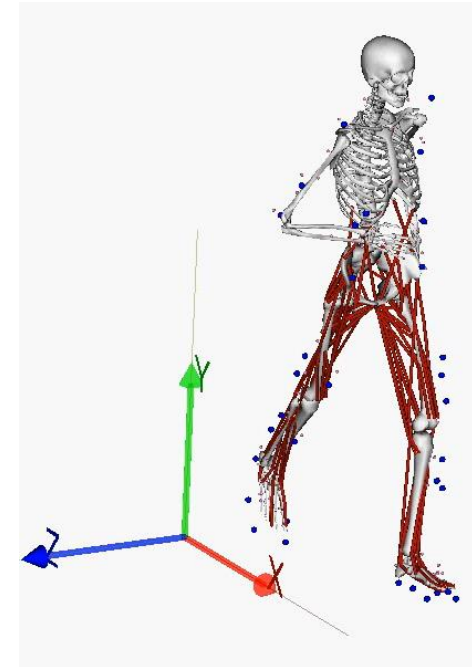
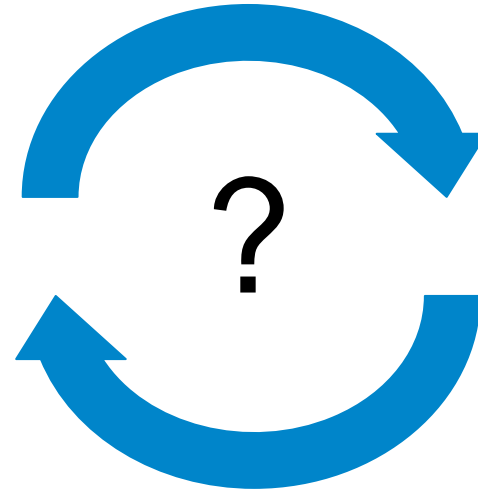
Silvia Muceli

Chalmers University of Technology

Gothenburg, Sweden

# Neuroscience and biomechanics

Main limitation in understanding human movements is the poor ability to record *in vivo* from large populations of neural cells to understand link between cellular mechanisms and functional meaning



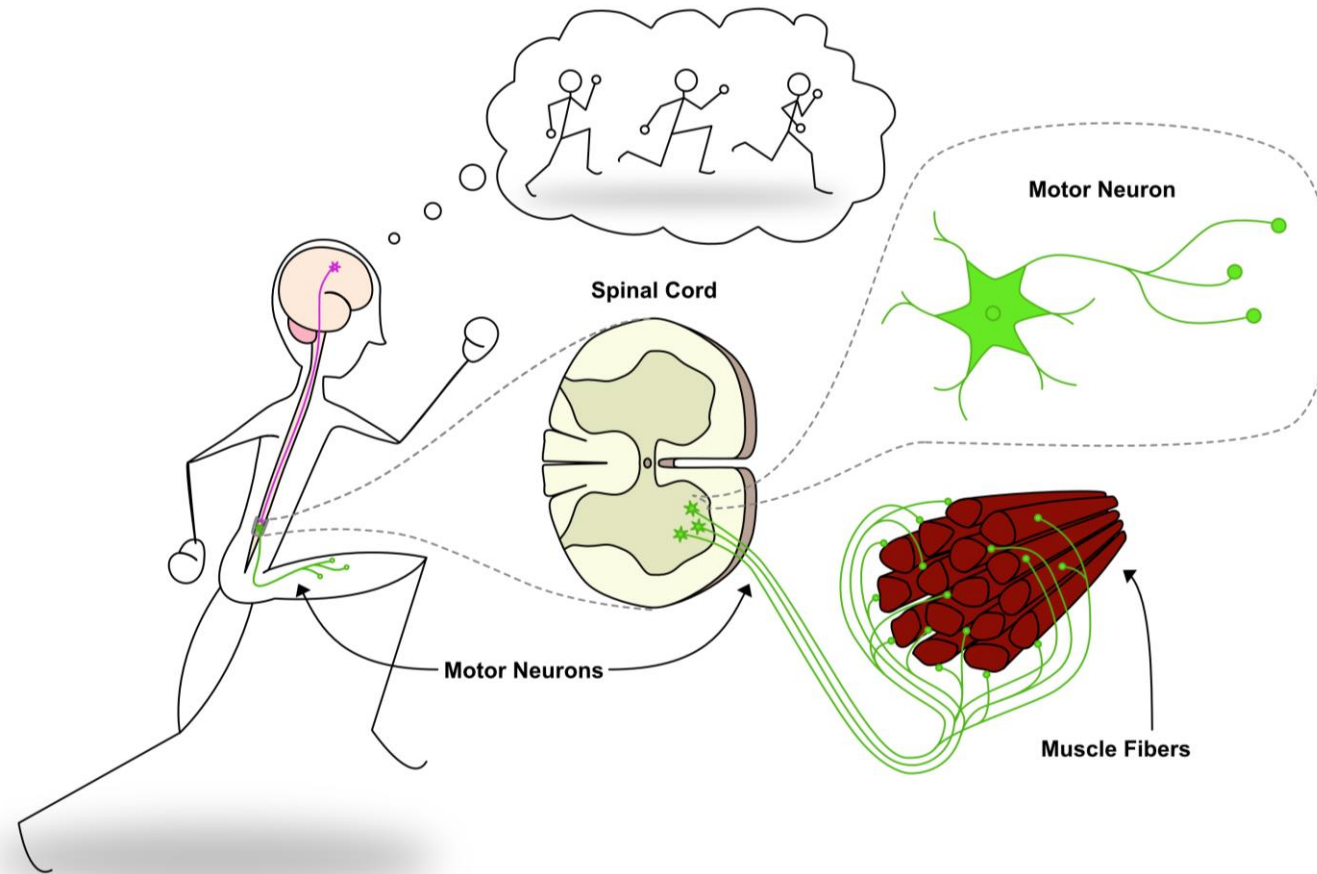
Biomechanics and Neurosciences: A failure to communicate, Enoka, Exerc Sport Sci Rev, 2004

# Outline

- Decoding spinal motor neurons
- Conventional technology
- Advances in technology
- Applications:
  - Movement physiology
  - Neural interfacing

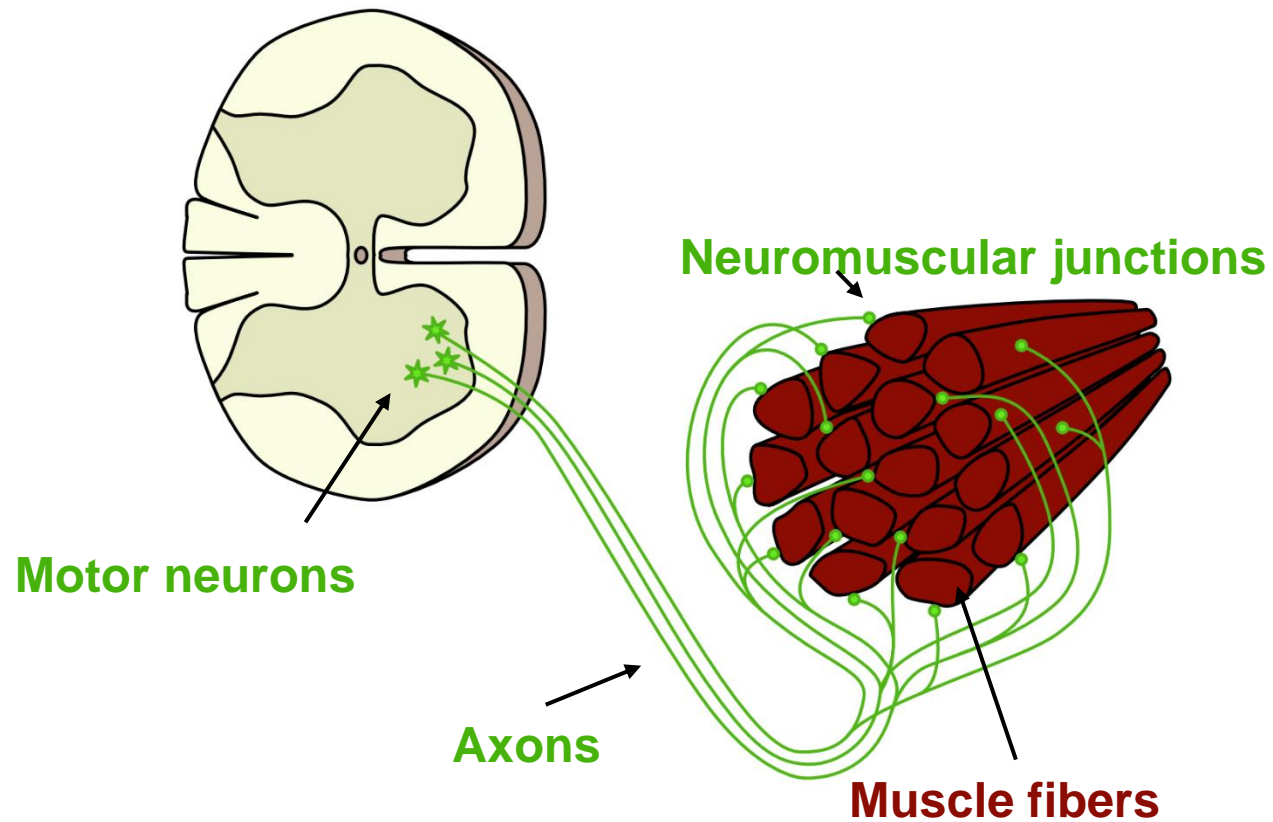
# DECODING SPINAL MOTOR NEURONS

# Movement generation

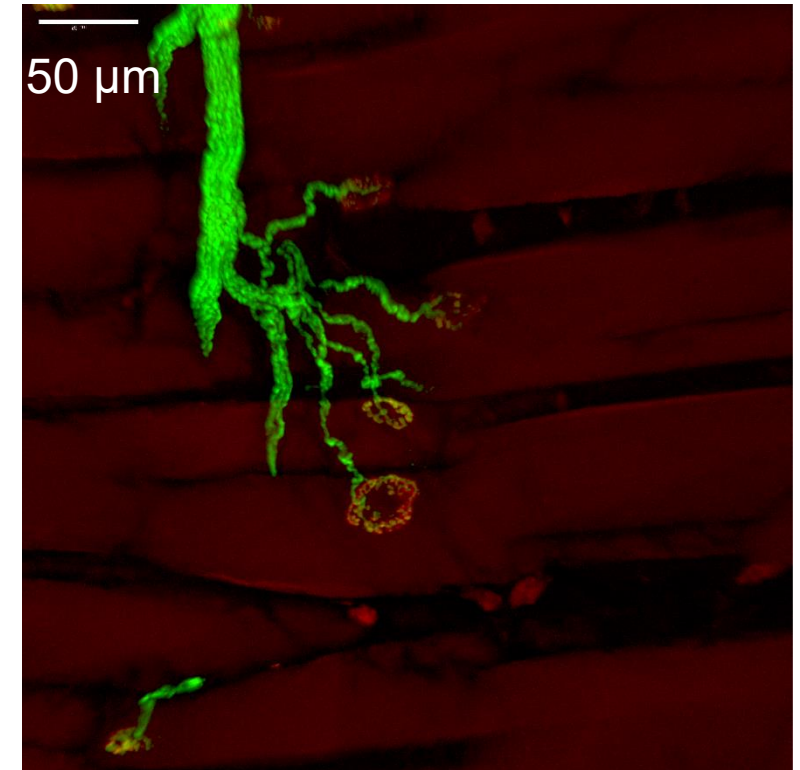


Hamstreet & Muceli, Frontiers Young Minds, 2022

# Motor unit



Neuromuscular junction (NMJ)

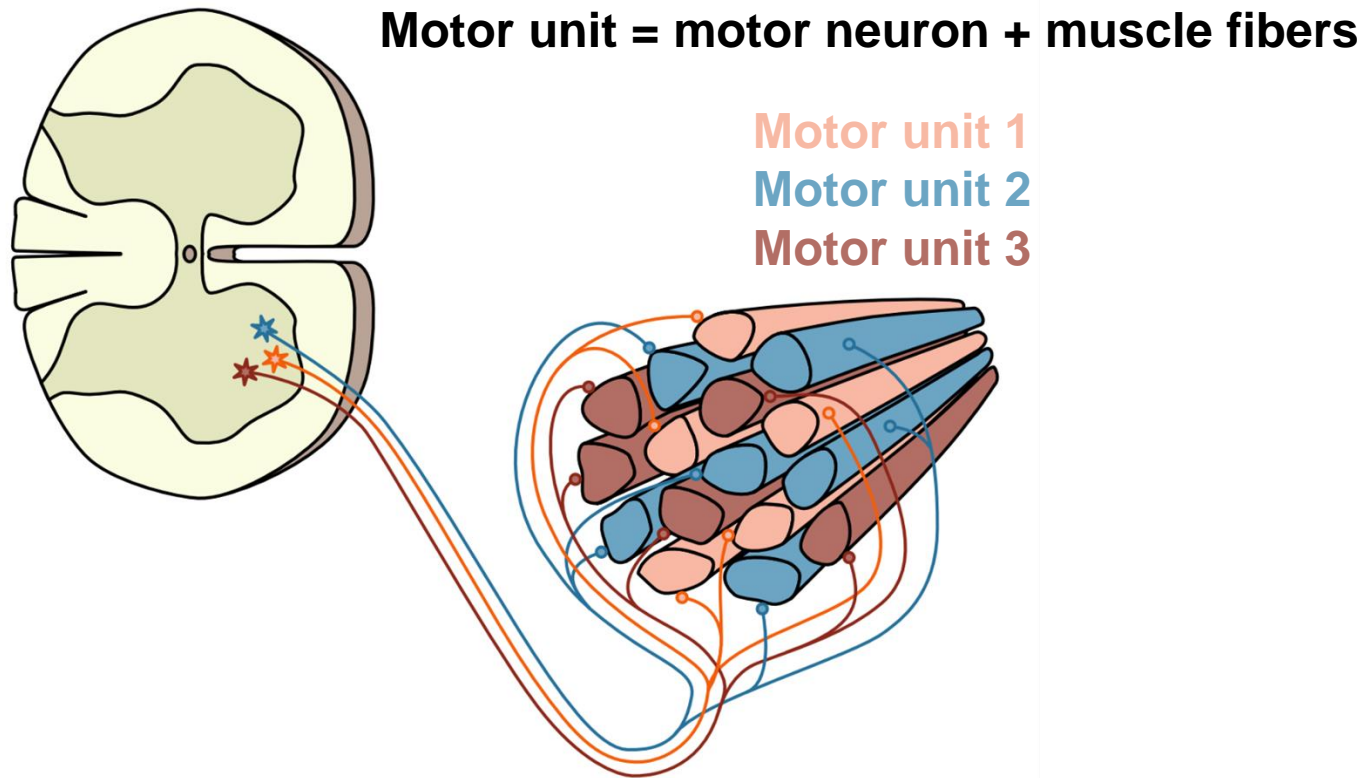


Hamstreet & Muceli, Frontiers Young Minds, 2022

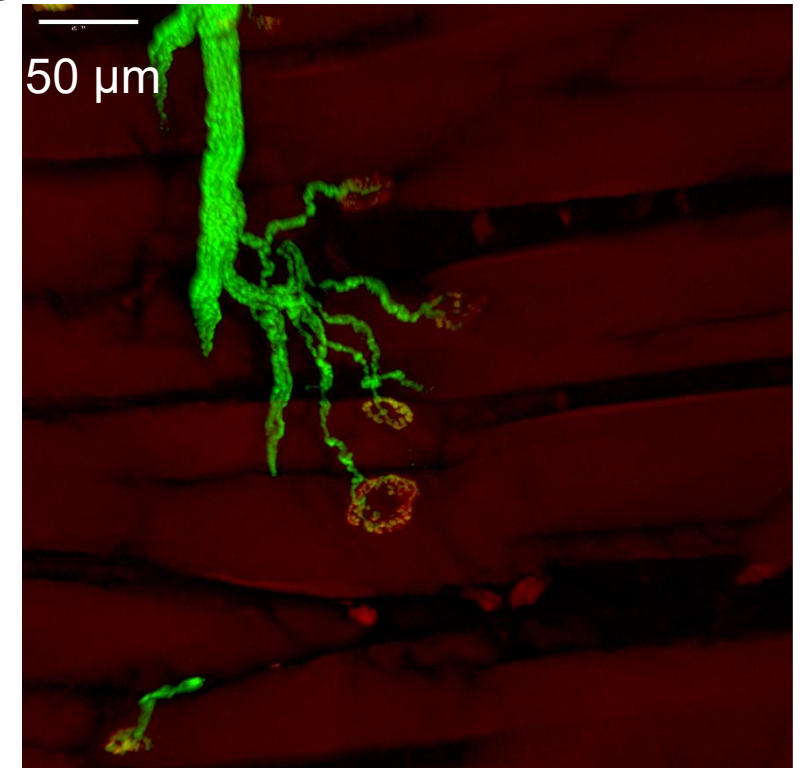
Muceli et al, J Neural Eng, 2019



# Motor unit



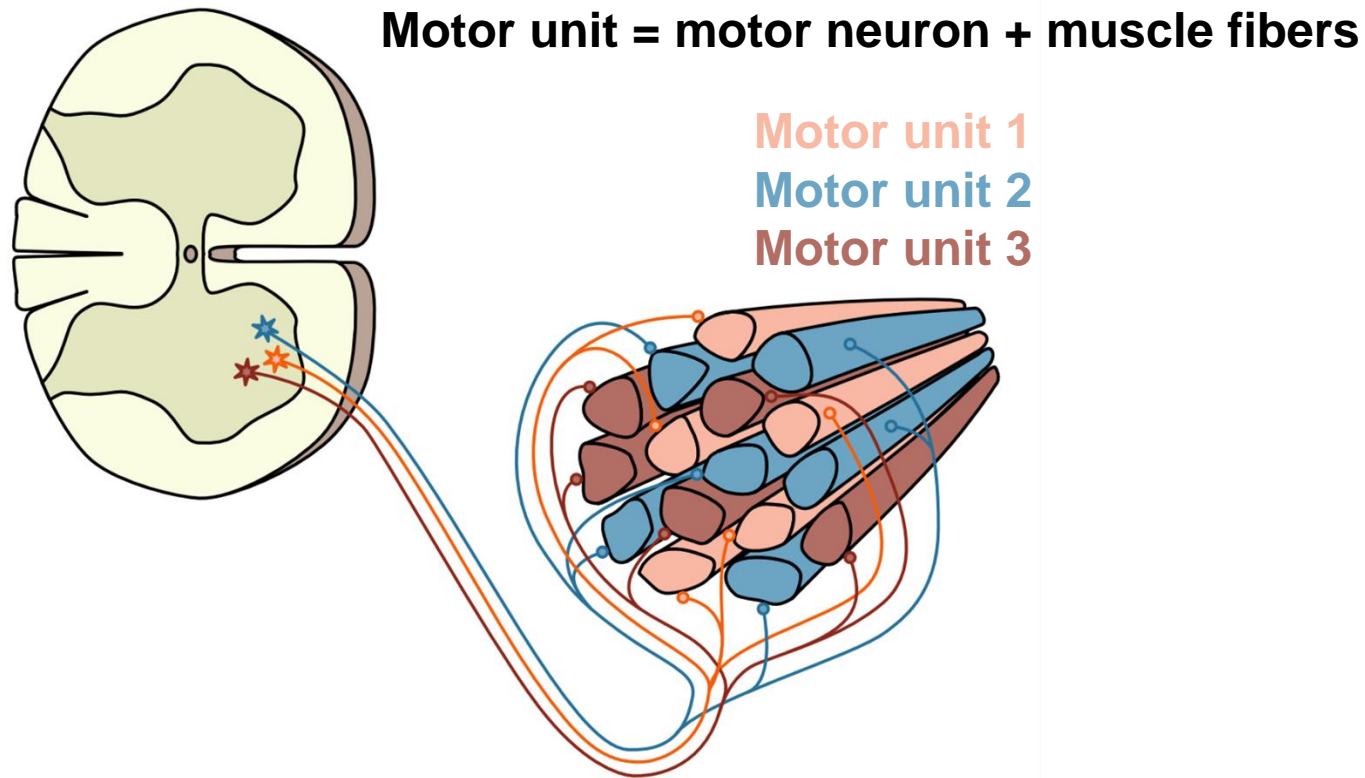
Neuromuscular junction (NMJ)



Hamstreet & Muceli, Frontiers Young Minds, 2022

Muceli et al, J Neural Eng, 2019

# Motor unit



Muscles are made of motor units controlled by spinal motor neurons

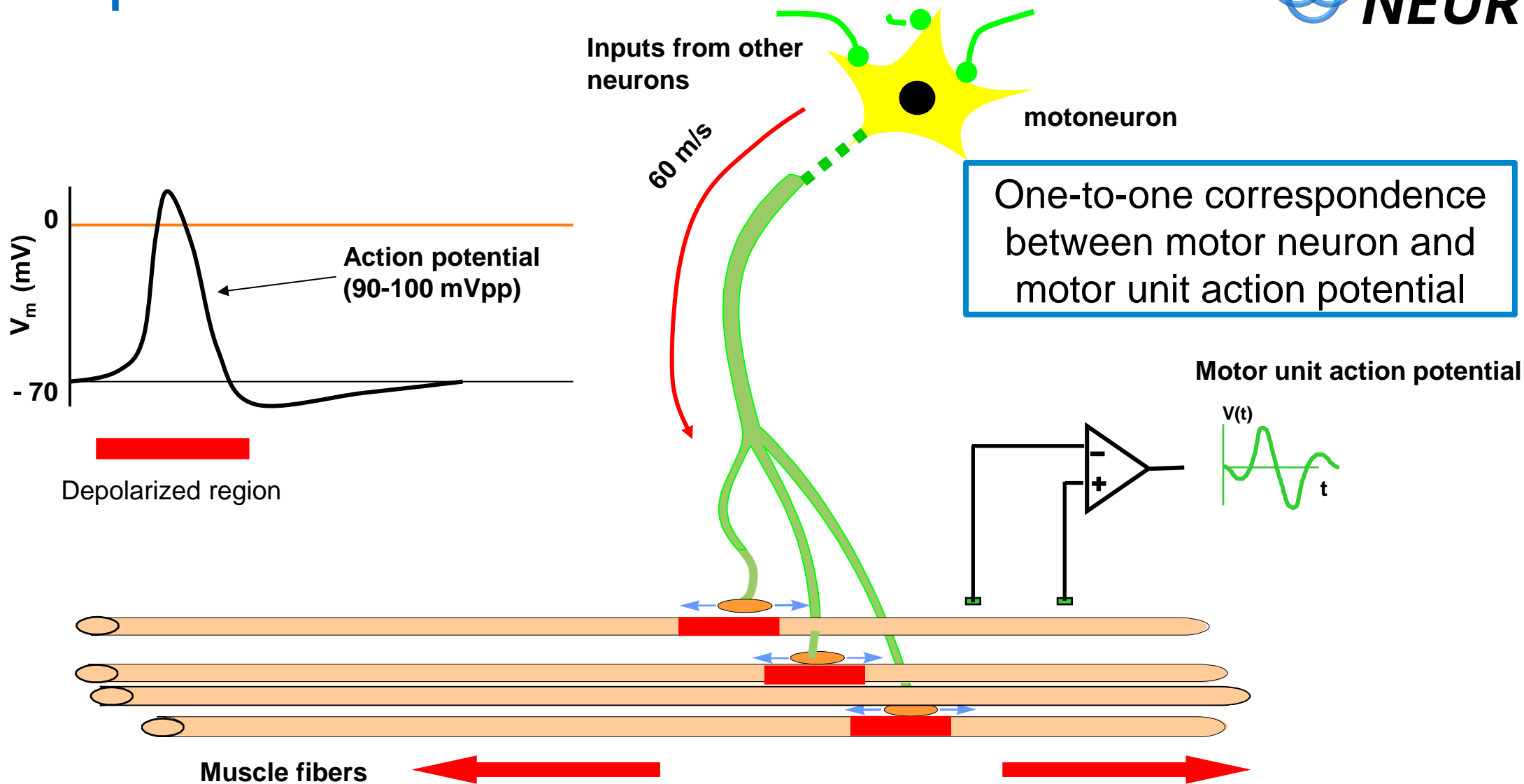
but ...

The spinal cord is encased within the vertebral canal of the vertebral spine

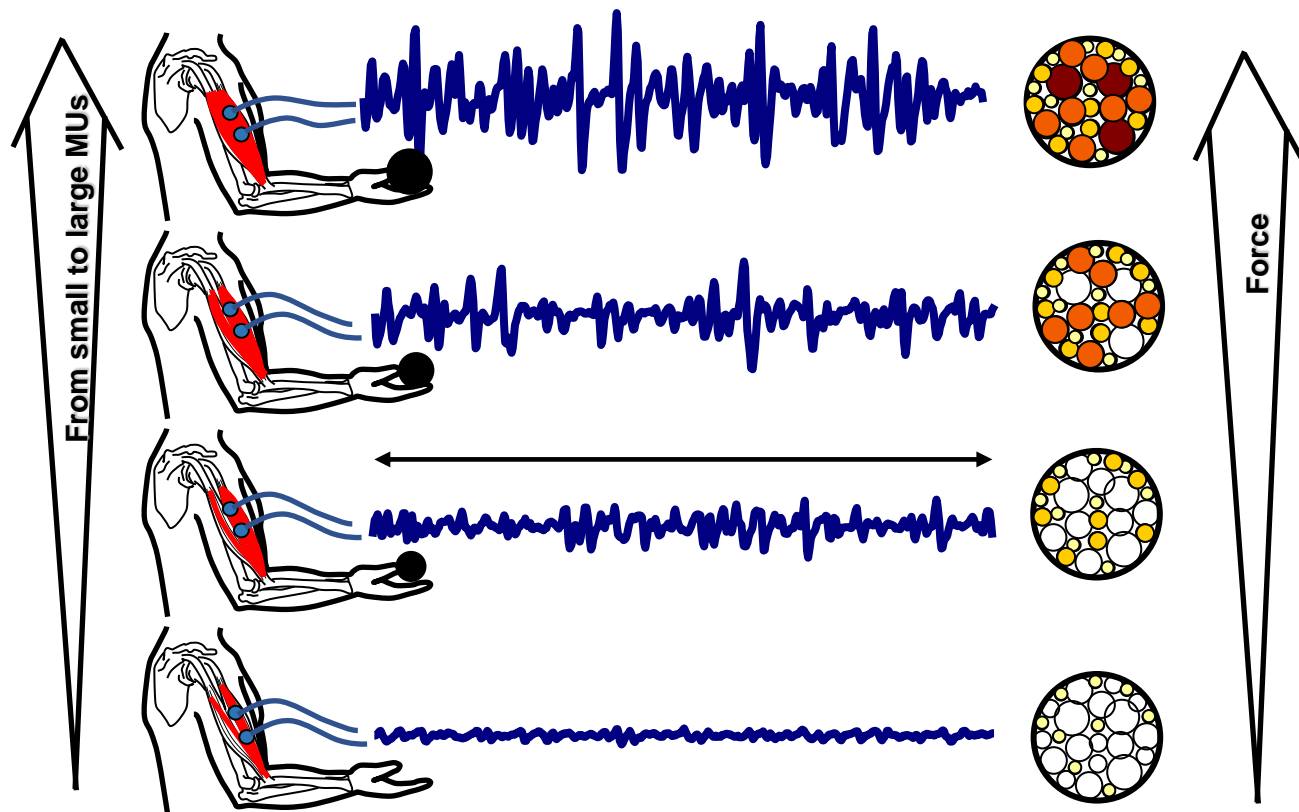
Hamstreet & Muceli, Frontiers Young Minds, 2022



# Action potential



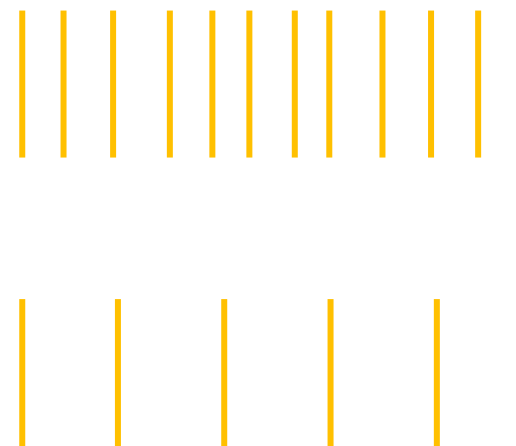
# Force modulation



Number of units (recruitment)

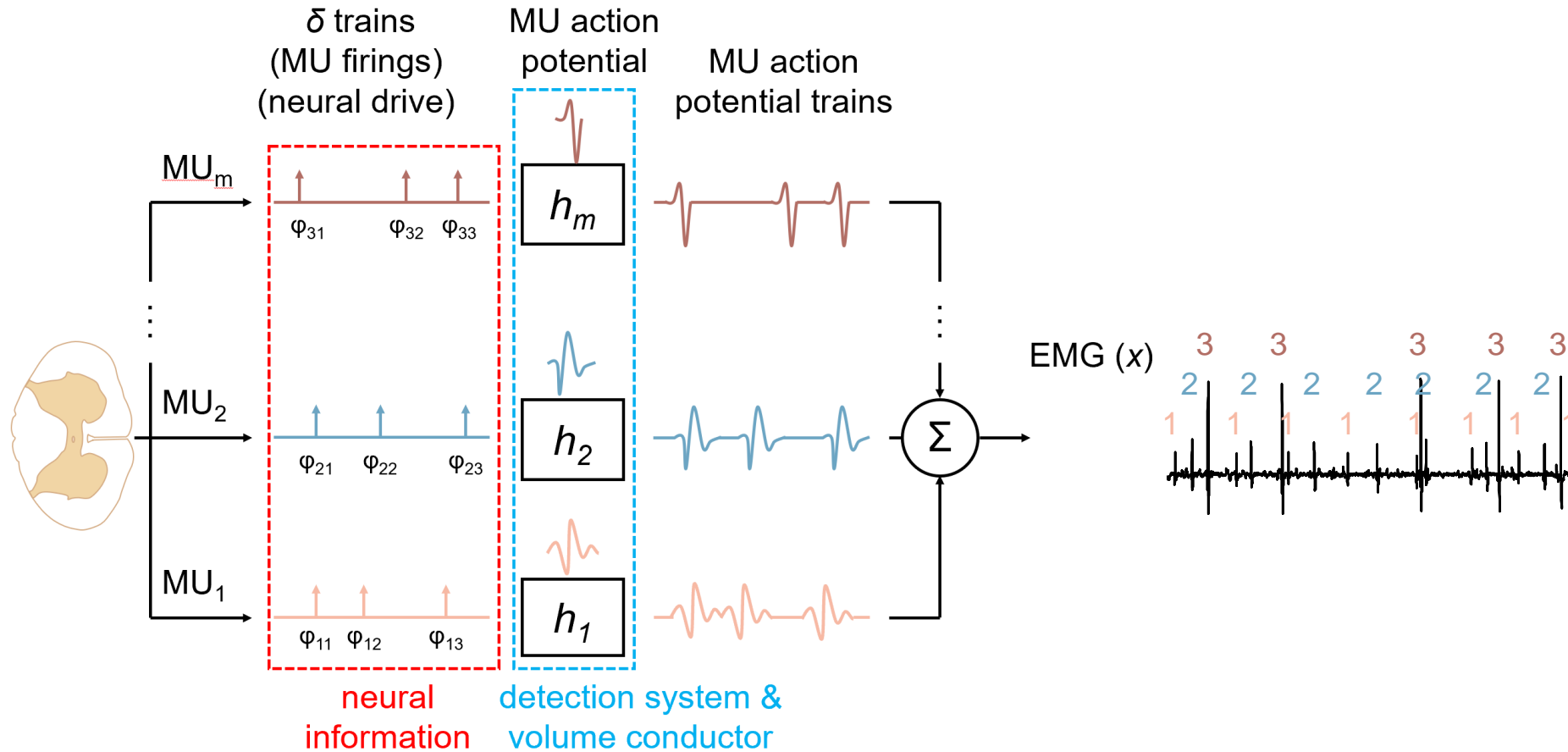
2 variables used by our nervous system to control force

- recruitment
- discharge rate



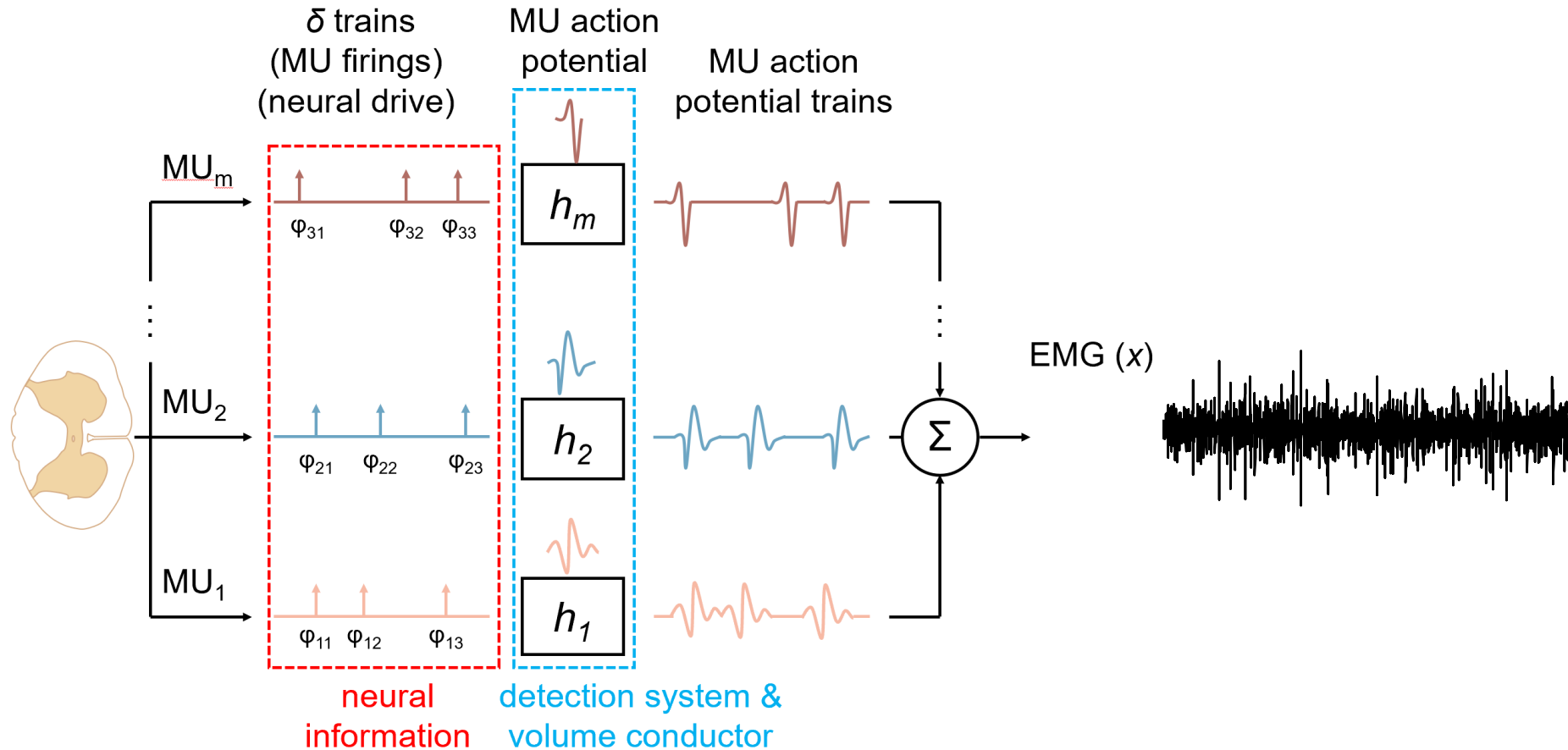
Discharge rate

# EMG generation



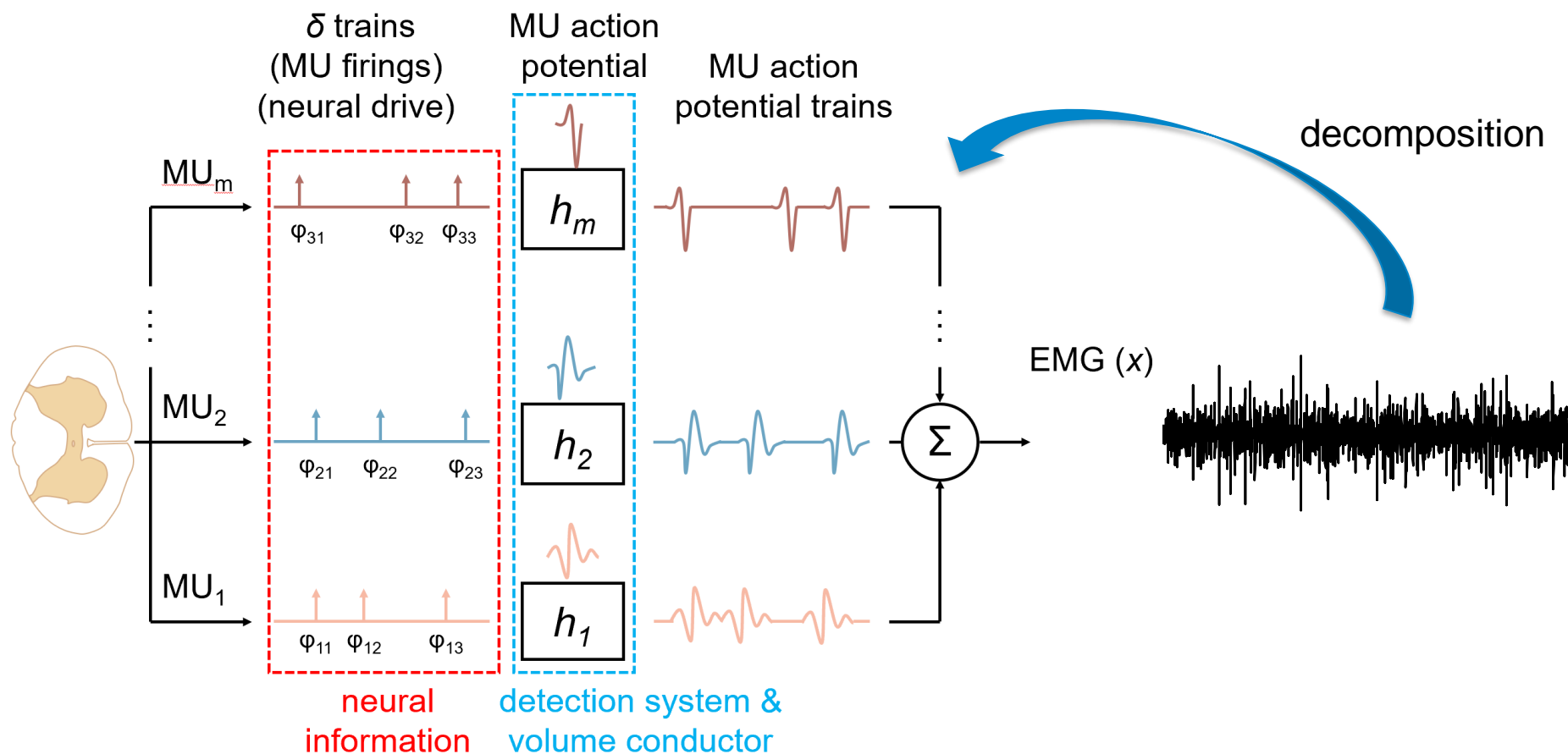
Muceli & Farina, Springer Handbook of Neuroengineering, 2023

# EMG generation



Muceli & Farina, Springer Handbook of Neuroengineering, 2023

# Reverse-engineering process

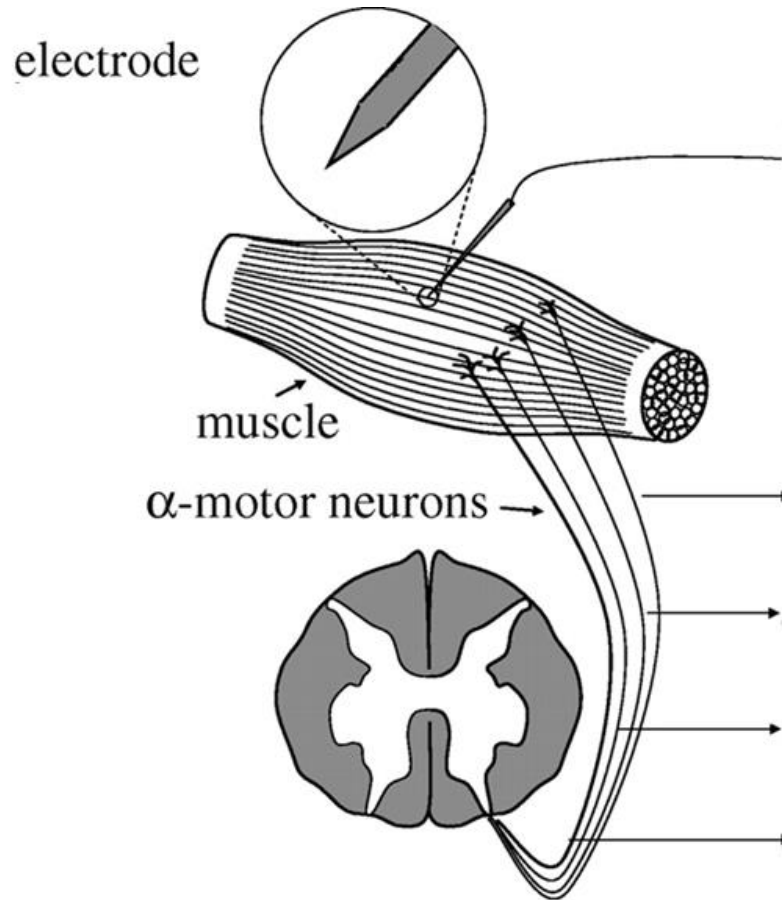


Muceli & Farina, Springer Handbook of Neuroengineering, 2023

# CONVENTIONAL TECHNOLOGY

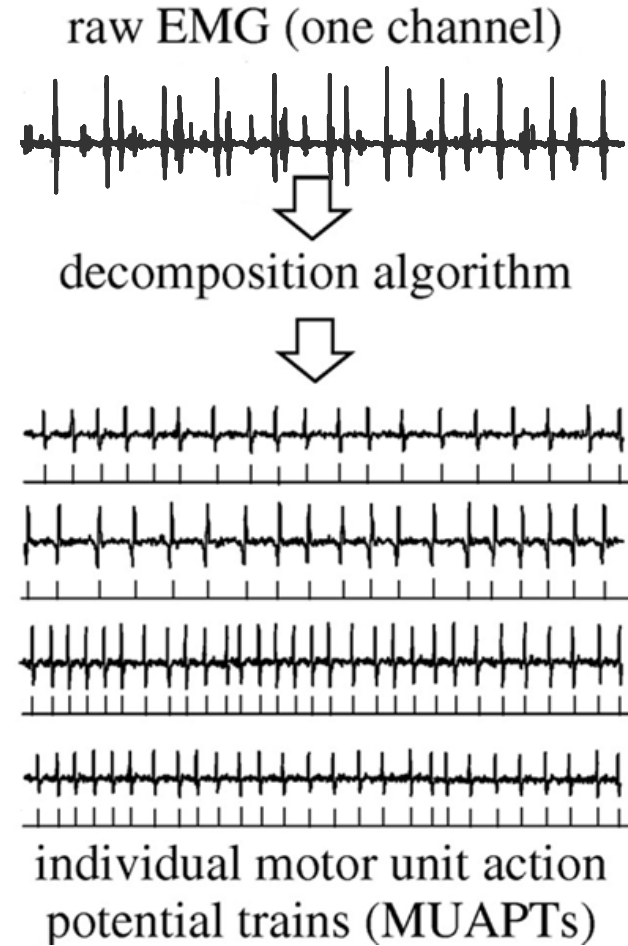


# Conventional technology

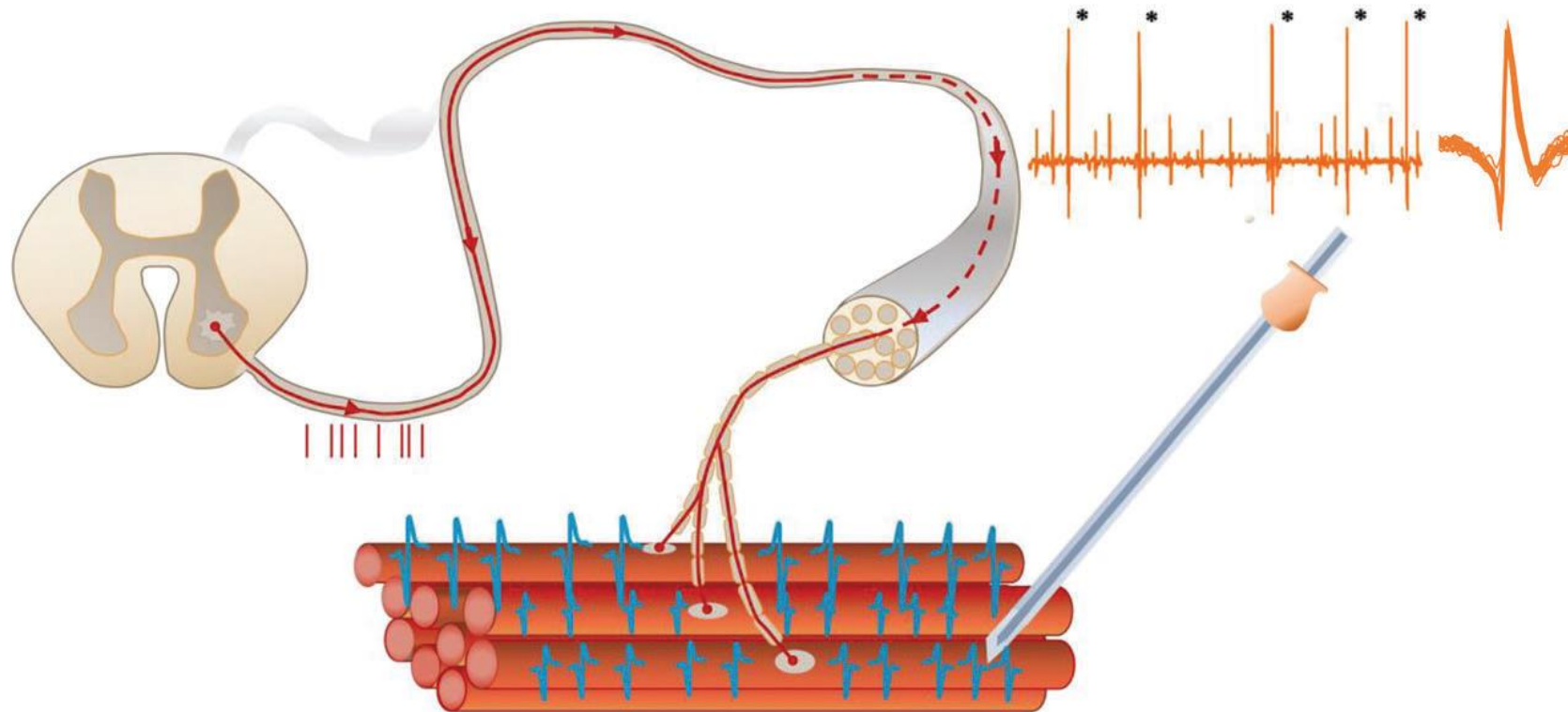


modified from  
Basmajian & De Luca, *Muscle alive*, 1985

## Decomposition



# Concentric needle



The Journal of  
**Physiology**

Adrian & Bronk, J Physiol, 1928, 1929  
Reviewed in Farina & Gandevia, J Physiol, 2024

# Fine wires

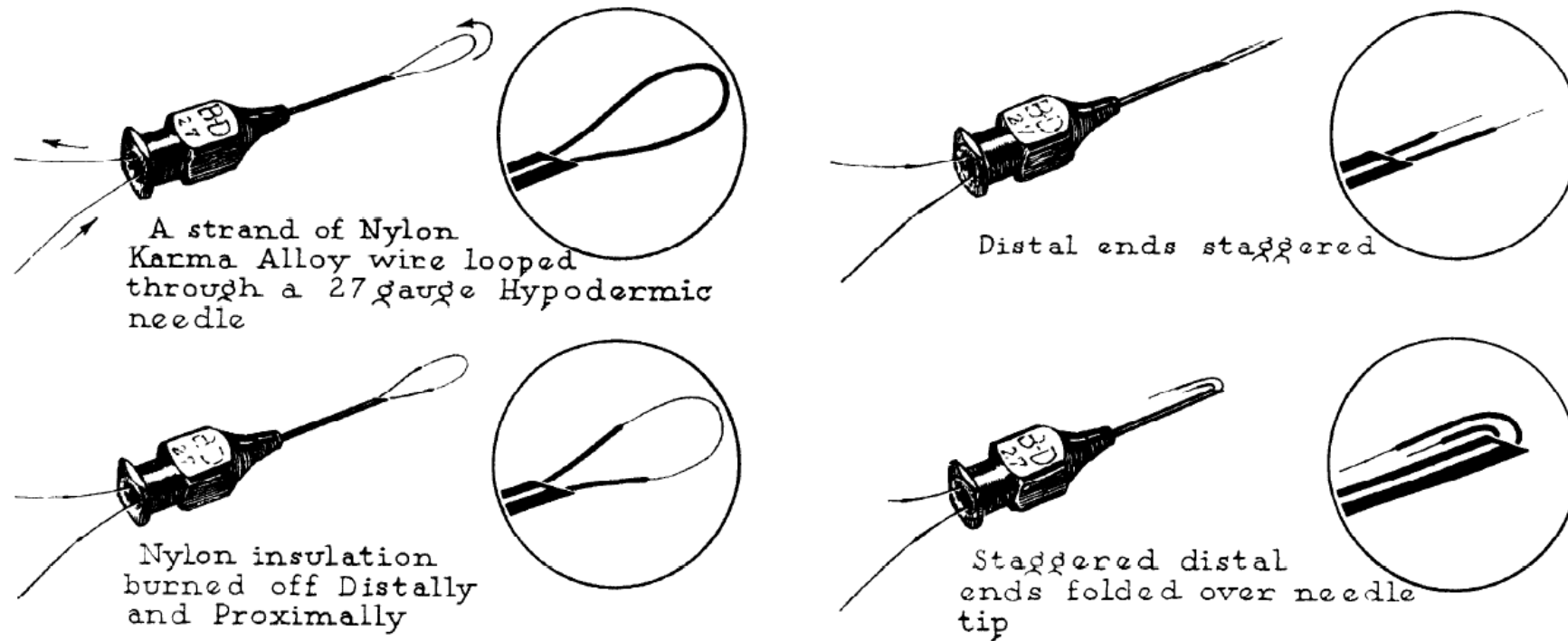
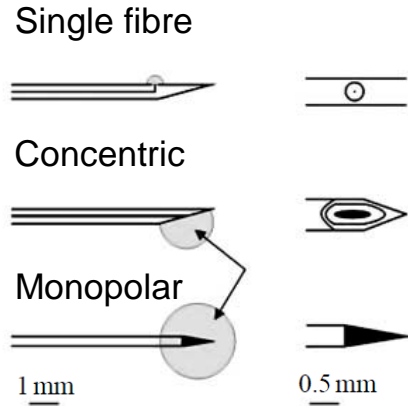


FIG. 1. Steps in making new bipolar electrode assembly before sterilization.

Basmajian & Stecko, J Appl Physiol, 1962

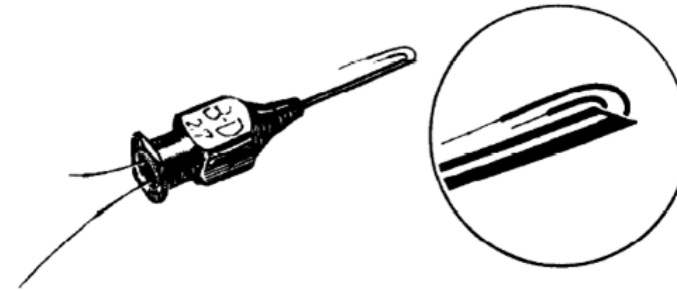
# Conventional technology

## Needles

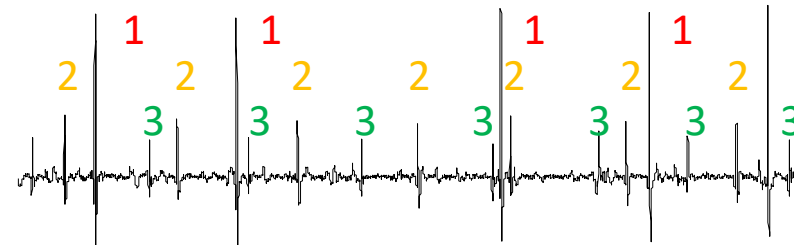
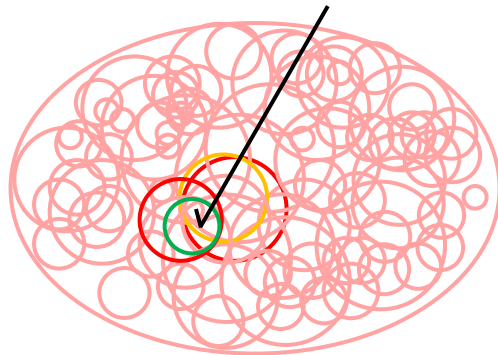


Merletti & Farina, Philos Trans A, Math Phys Eng Sci, 2009

## Fine wires



Basmajian & Stecko, J Appl Physiol, 1962

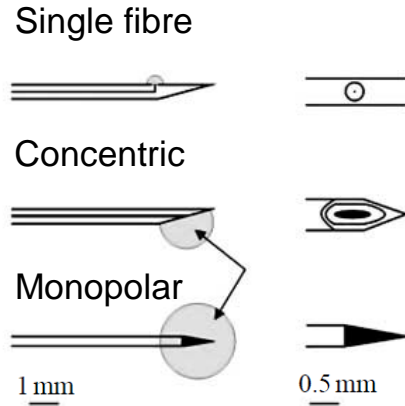


Spatial selectivity ↑

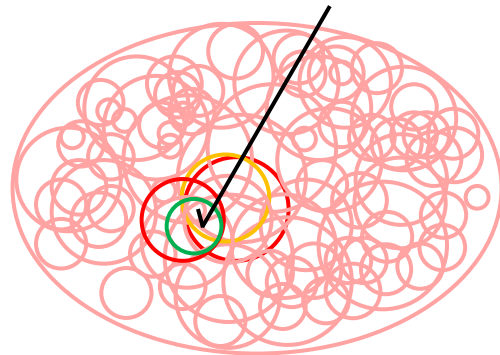
Number of extracted sources ↓

# Conventional technology

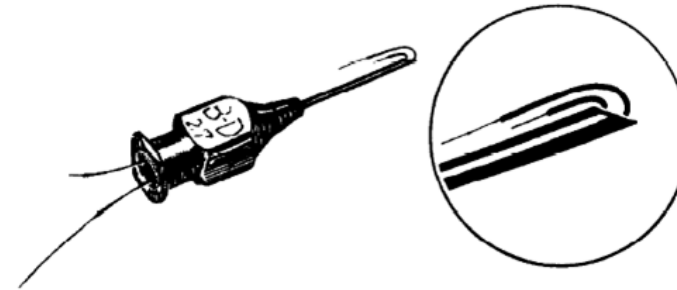
## Needles



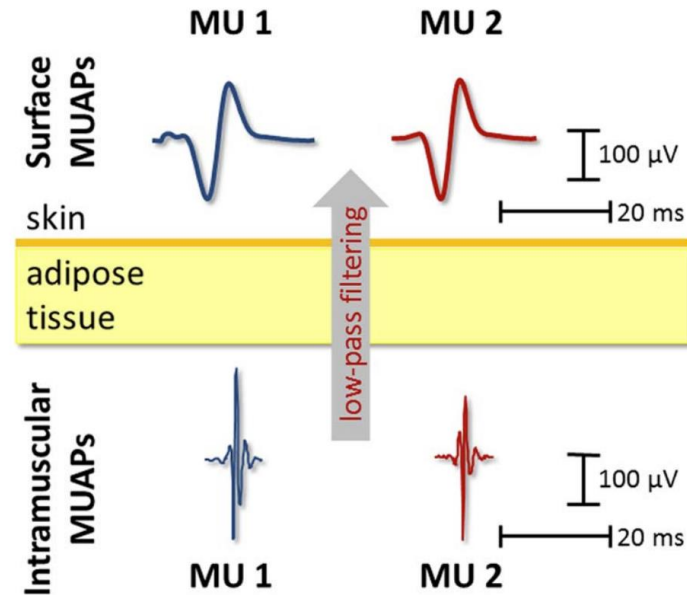
Merletti & Farina, Philos Trans A, Math Phys Eng Sci, 2009



## Fine wires



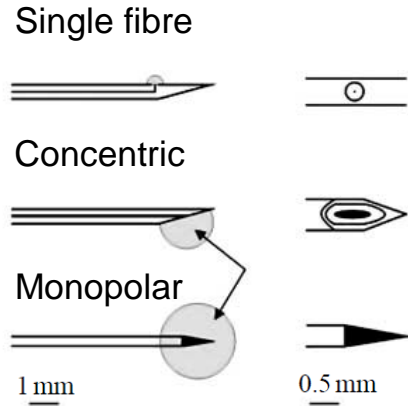
Basmajian & Stecko, J Appl Physiol, 1962



Farina & Holobar, Proc IEEE, 2016

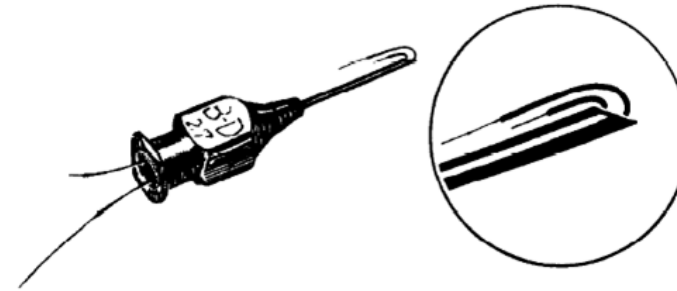
# Conventional technology

## Needles

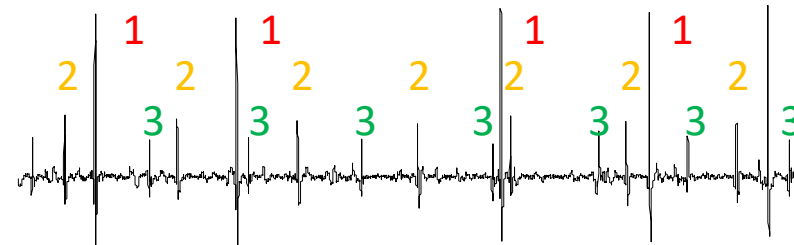
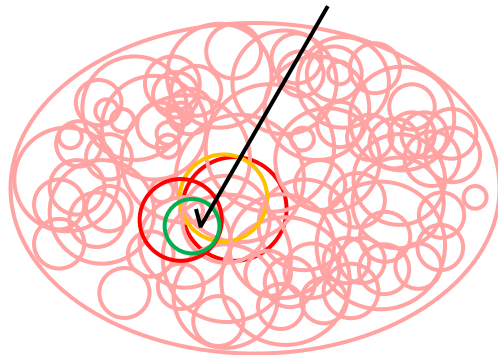


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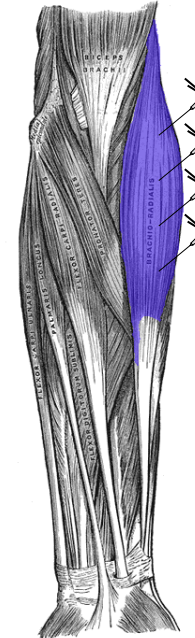
# Decomposition process

Pre-processing (high-pass filter)

Segmentation (detection of MUAPs)

Clustering of detected MUAPs

Resolving superpositions



Example: Multi-channel fine wire, isometric contraction.

<http://www.emglab.net/emglab/Signals/R008/R008.php?diagnosis=Normal&patient=1&muscle=Brachioradialis&links=direct>

# EMGLAB: a decomposition software



EMGLAB [Home](#) | [Software](#) | [Signals](#) | [Presentations](#) | [Publications](#)

## EMGLAB

A forum for sharing software, data, and information related to EMG decomposition.



EMG decomposition provides information about the coordinated activity of the motoneuron pool and the architectural organization of the muscle. This information is of interest in muscle physiology, motor control, kinesiology, and clinical neurophysiology.

- The goals of this project are to promote
- \* decomposition as a research tool
  - \* exchange and discussion of EMG data
  - \* attention to accuracy and precision
  - \* algorithm innovation

Projects	Software	News	Tutorials
<ul style="list-style-type: none"><li>* Standards for data files</li><li>* EMG signal database</li><li>* Assessing accuracy</li><li>* EMG analysis software</li></ul>	<ul style="list-style-type: none"><li>* EMGlab version 1.0 </li><li>New features include continuous scrolling, force display, exporting plots and data, printing.</li></ul>	<ul style="list-style-type: none"><li>* ISEK Decomposition Workshop 2008</li><li>* R010: 20-min contraction, cut-end fine wire.</li></ul>	<p><b>Please Contribute Discussion</b></p> <p><b>EMGLab RSS</b> </p> <p><b>FAQ</b></p>
sponsors: Veterans Affairs Palo Alto Rehabilitation Research and Development Center   National Institute of Neurological Disorders and Stroke			

McGill KC, Lateva ZC, Marateb HR. EMGLAB: an interactive EMG decomposition program. J Neurosci Methods 149(2):121-133, 2005.

[The software was available at <http://www.emglab.net>]

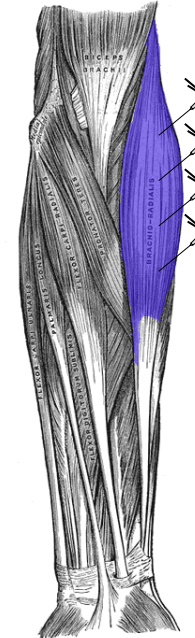
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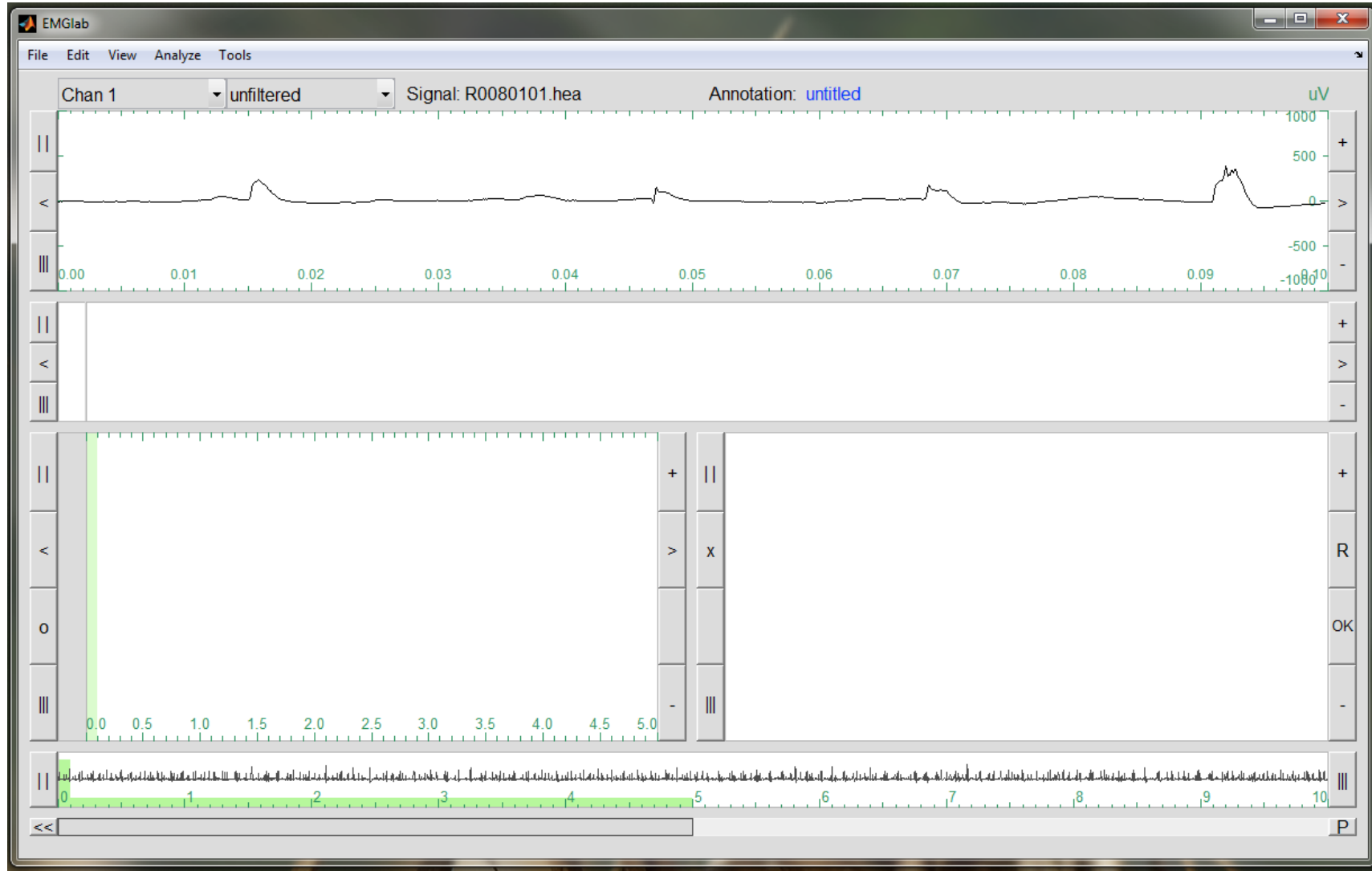
Resolving superpositions



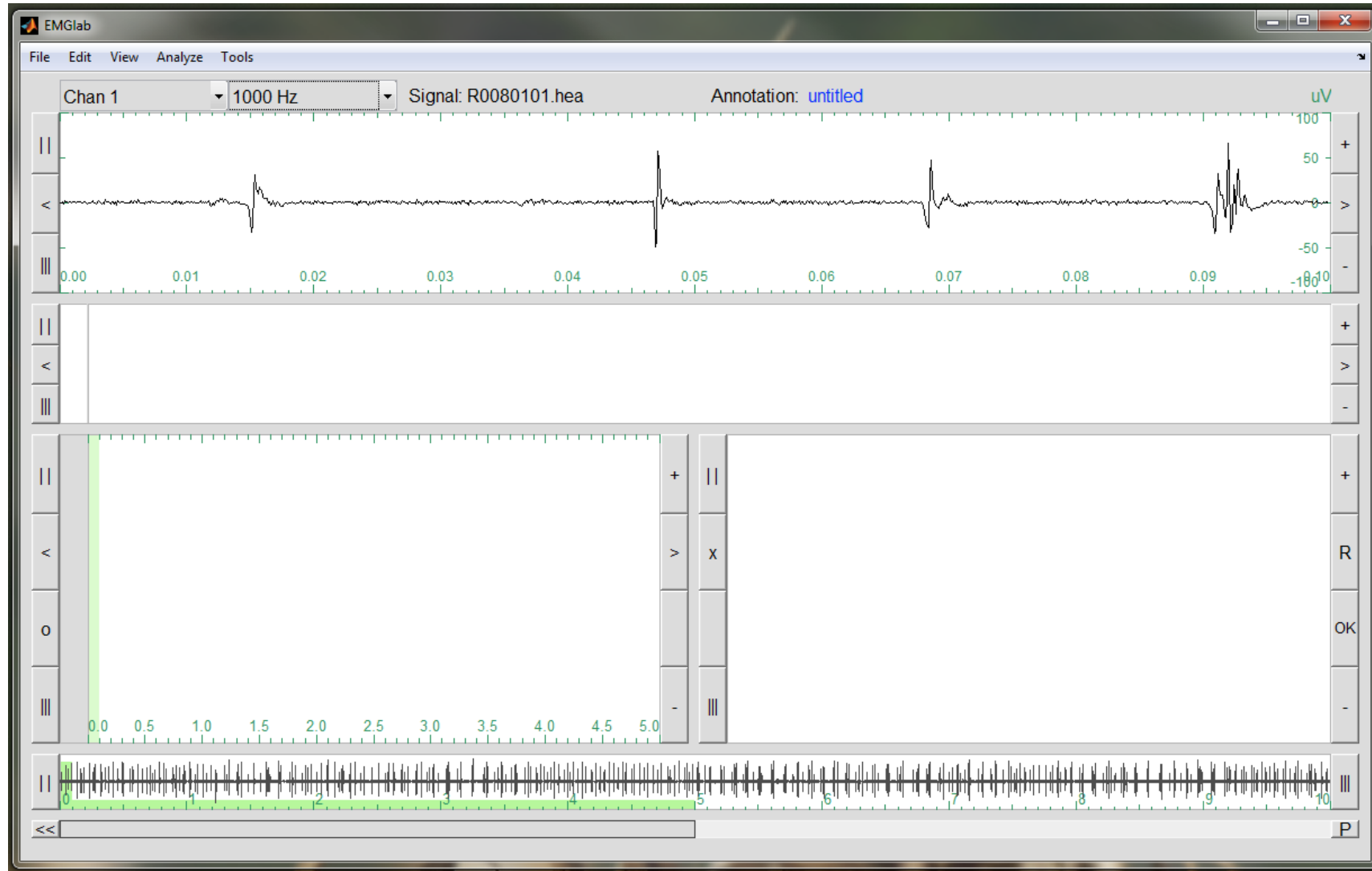
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<http://www.emglab.net/emglab/Signals/R008/R008.php?diagnosis=Normal&patient=1&muscle=Brachioradialis&links=direct>

# Preprocessing



# Preprocessing



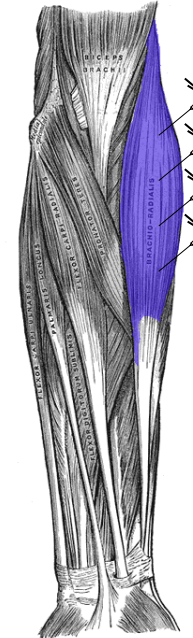
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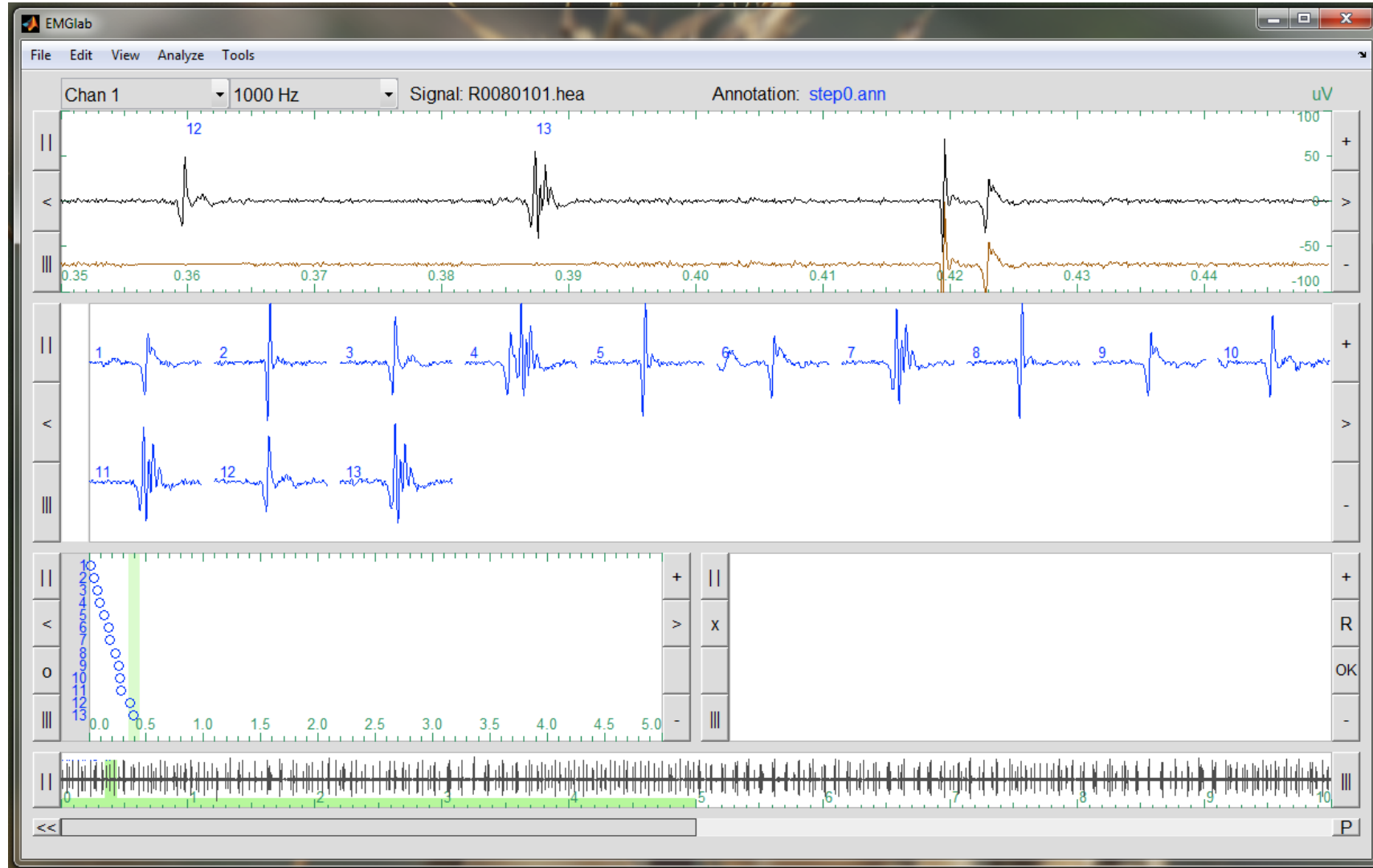


Example: Multi-channel fine wire, isometric contraction.

<http://www.emglab.net/emglab/Signals/R008/R008.php?diagnosis=Normal&patient=1&muscle=Brachioradialis&links=direct>



# Segmentation



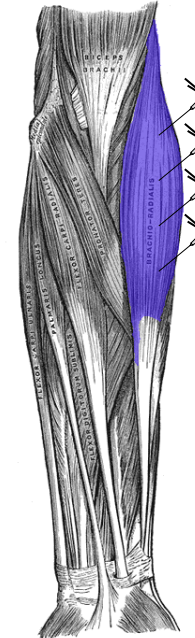
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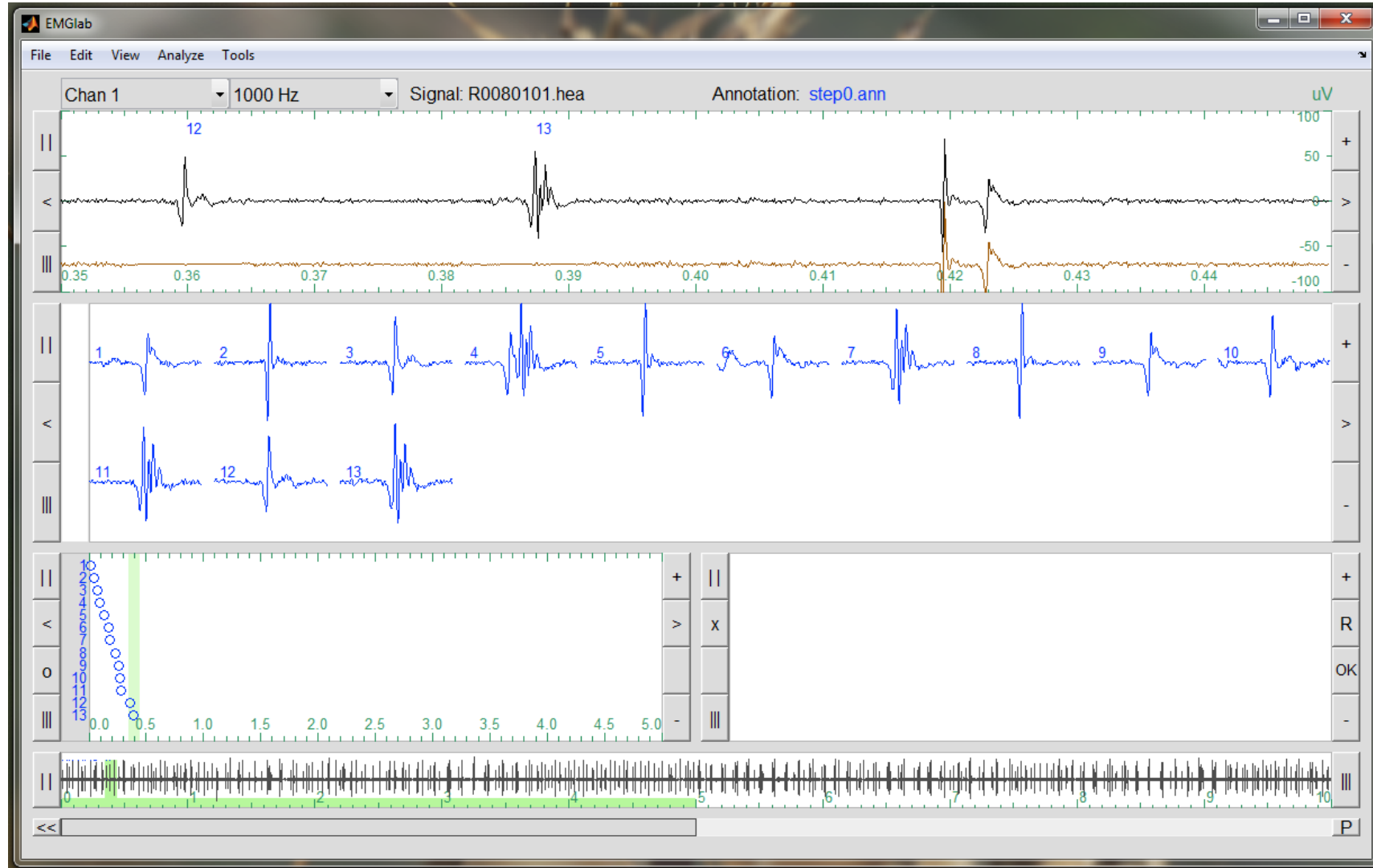
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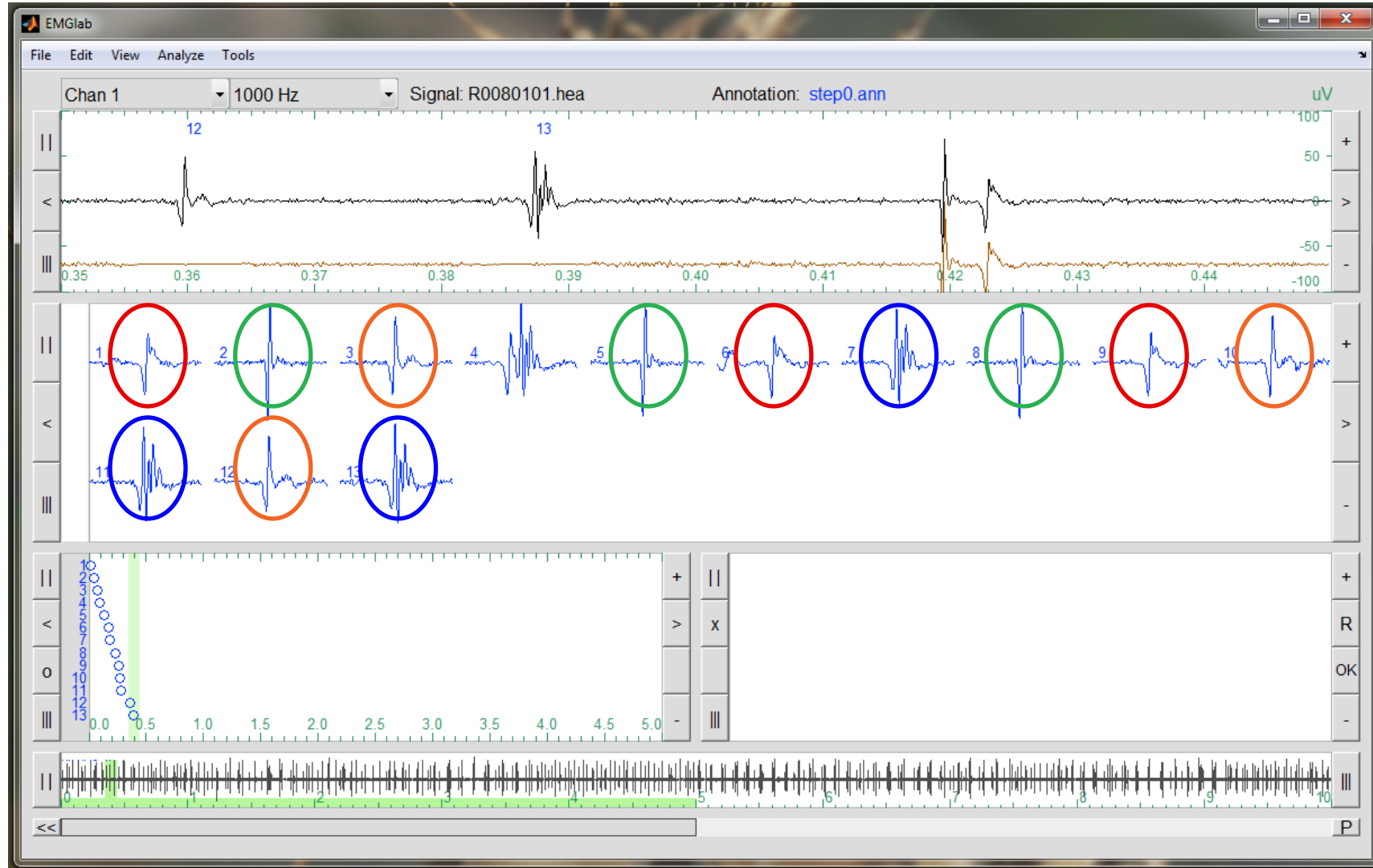
# Clustering



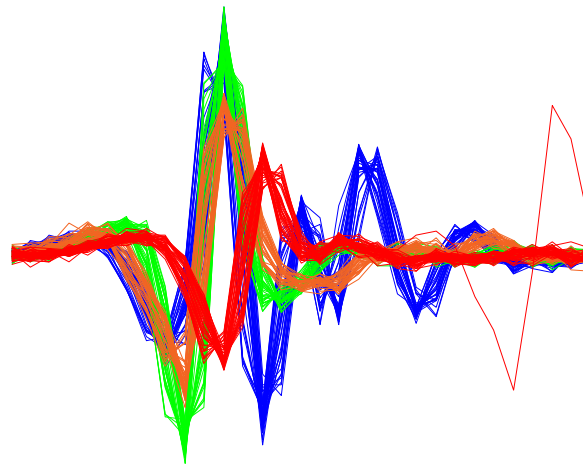
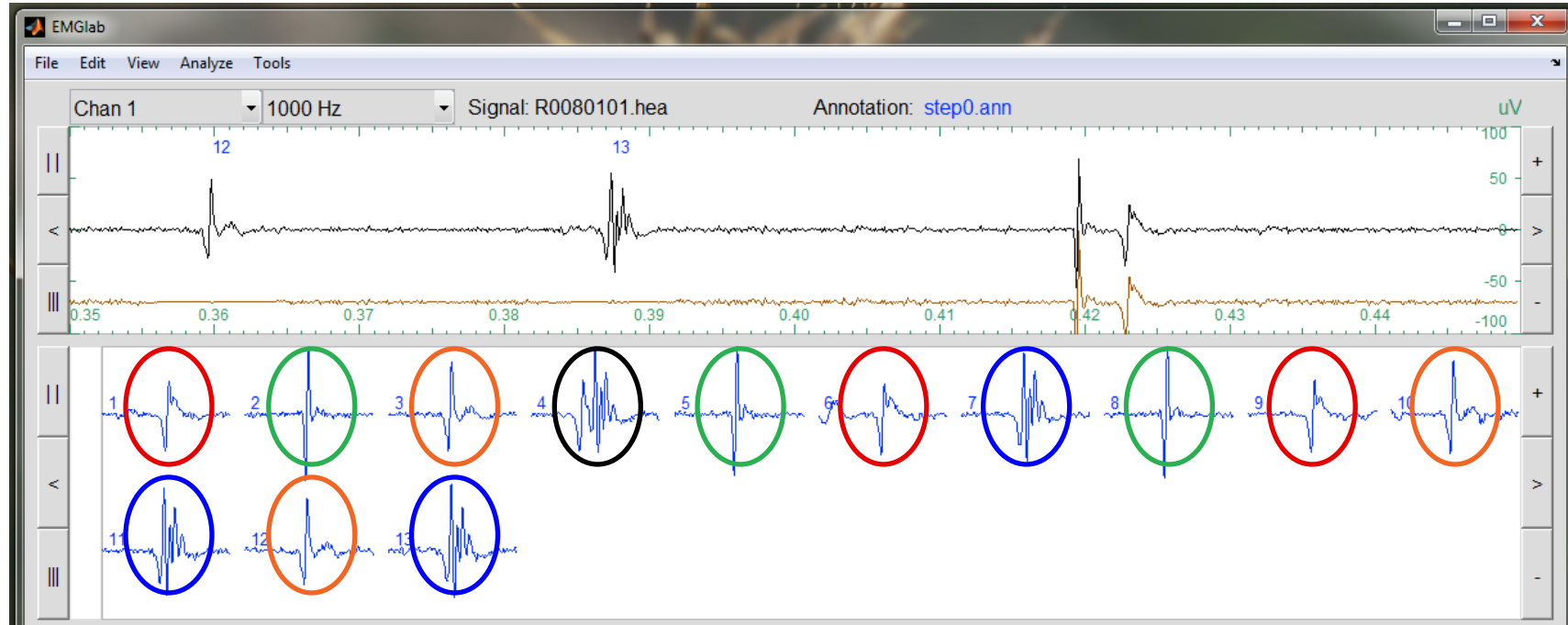
# Clustering



# Clustering

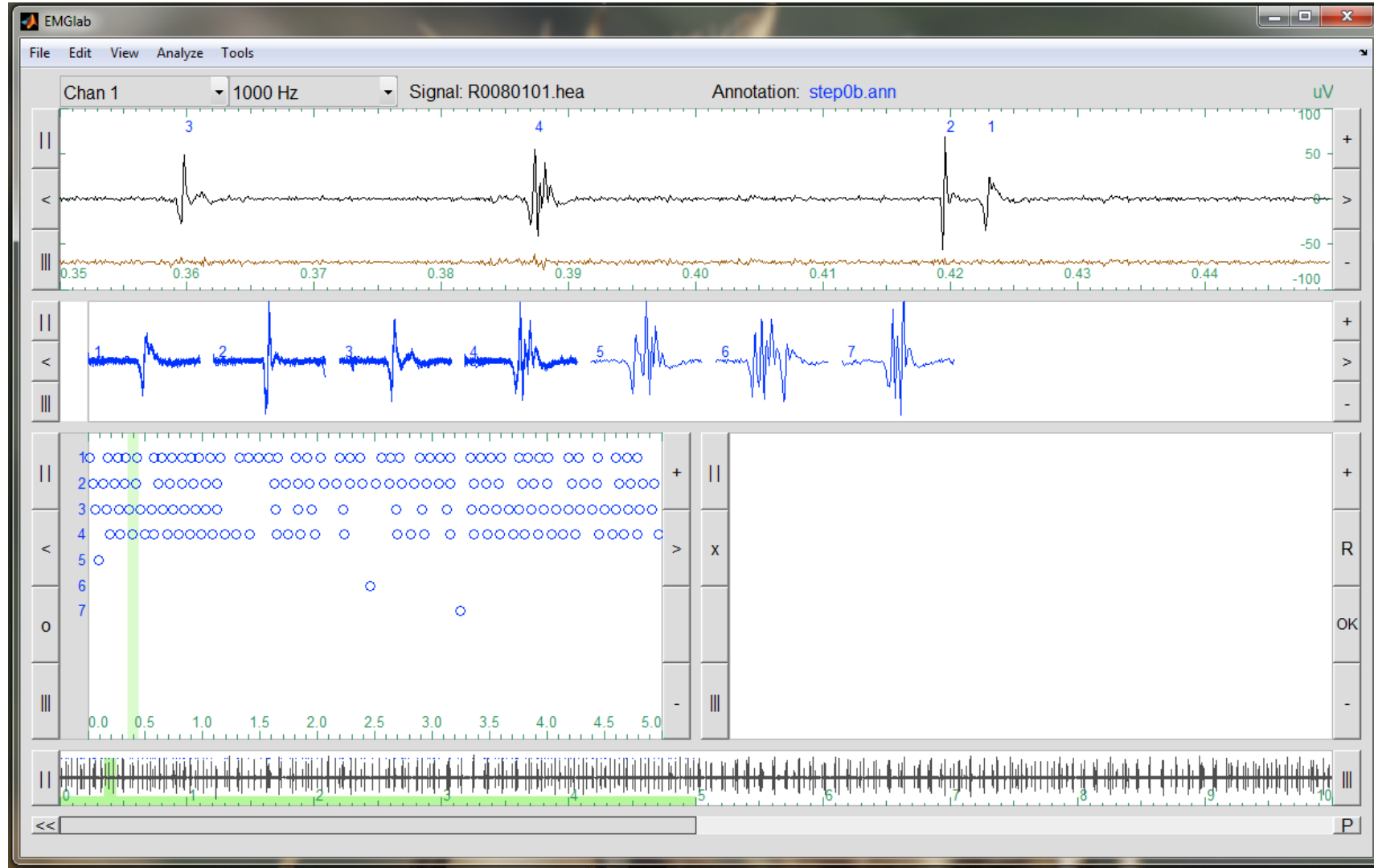


# Clustering

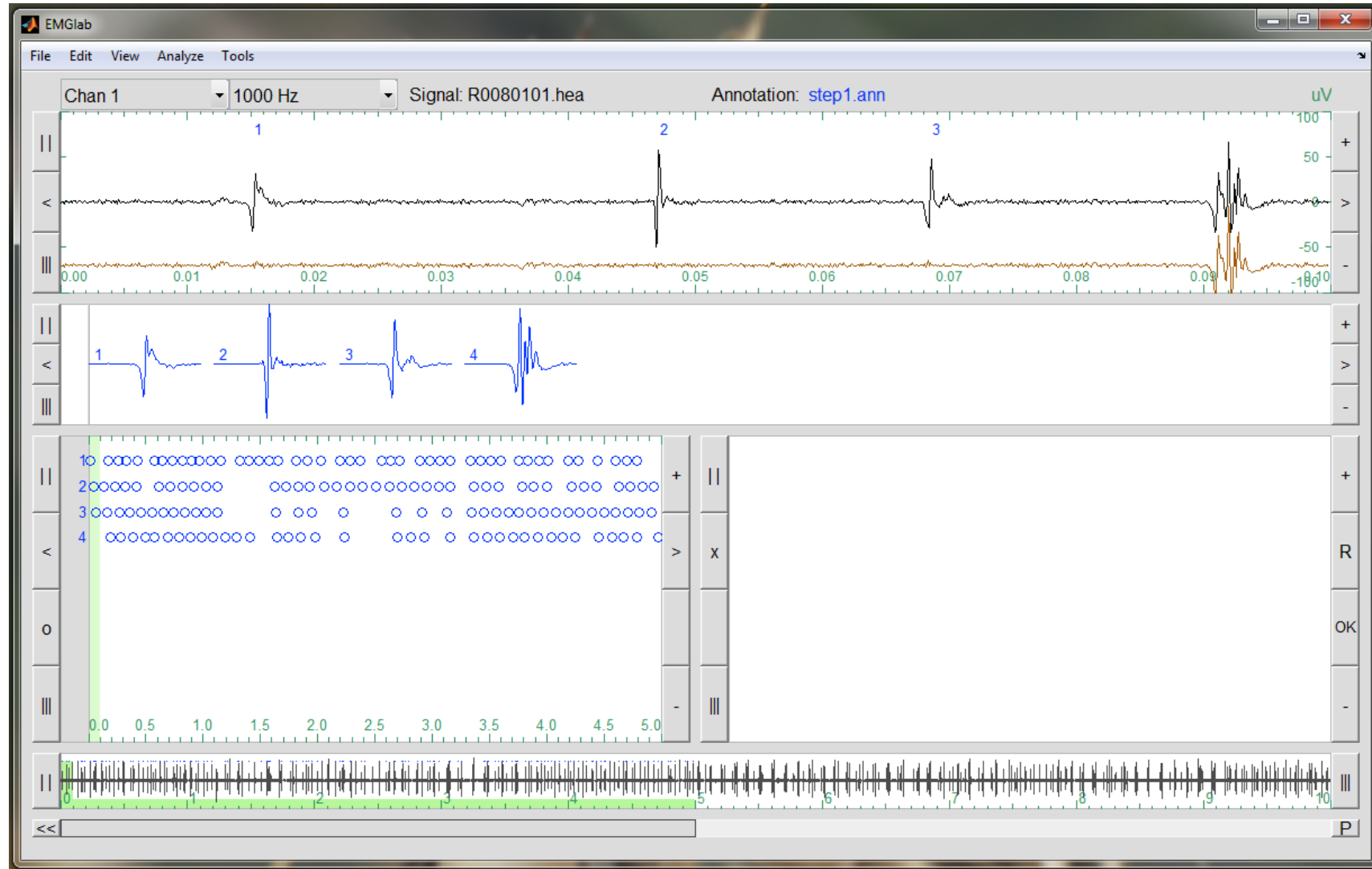




# Shimmer plot



# Clustering result



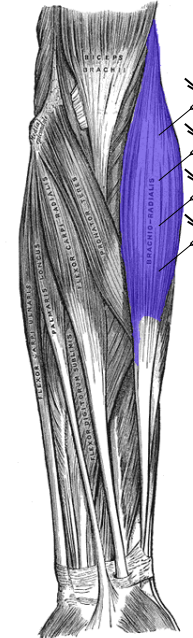
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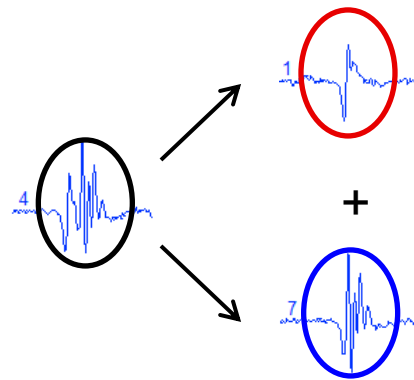
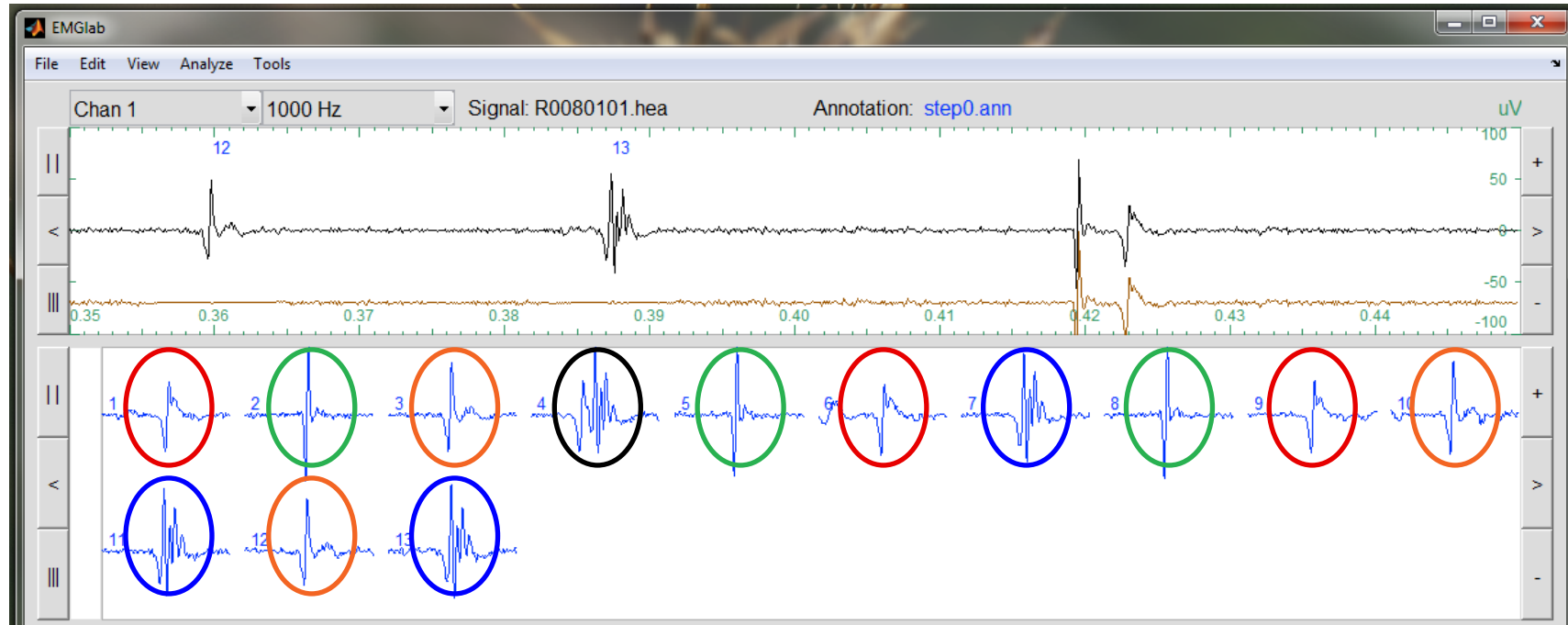
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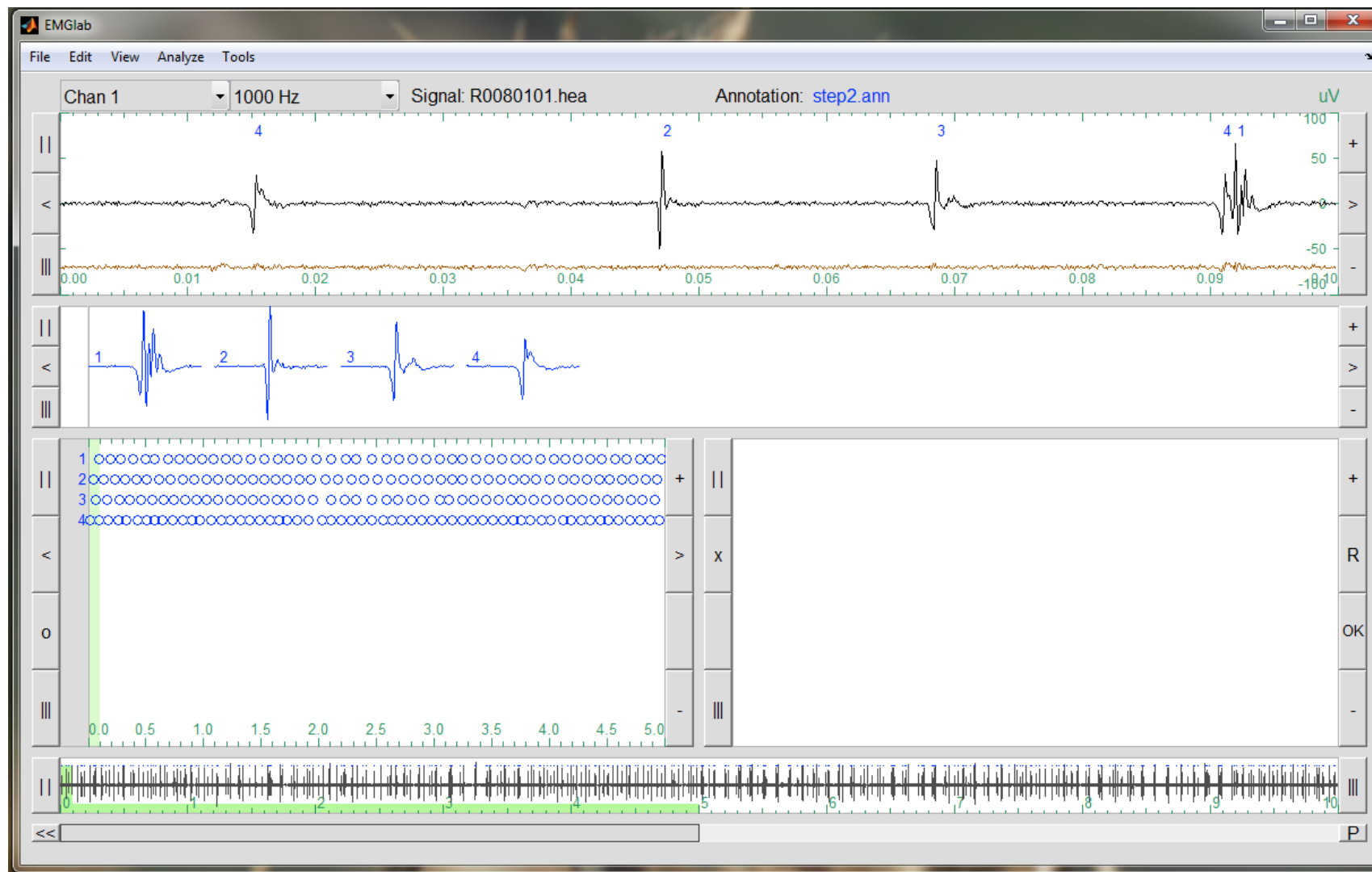
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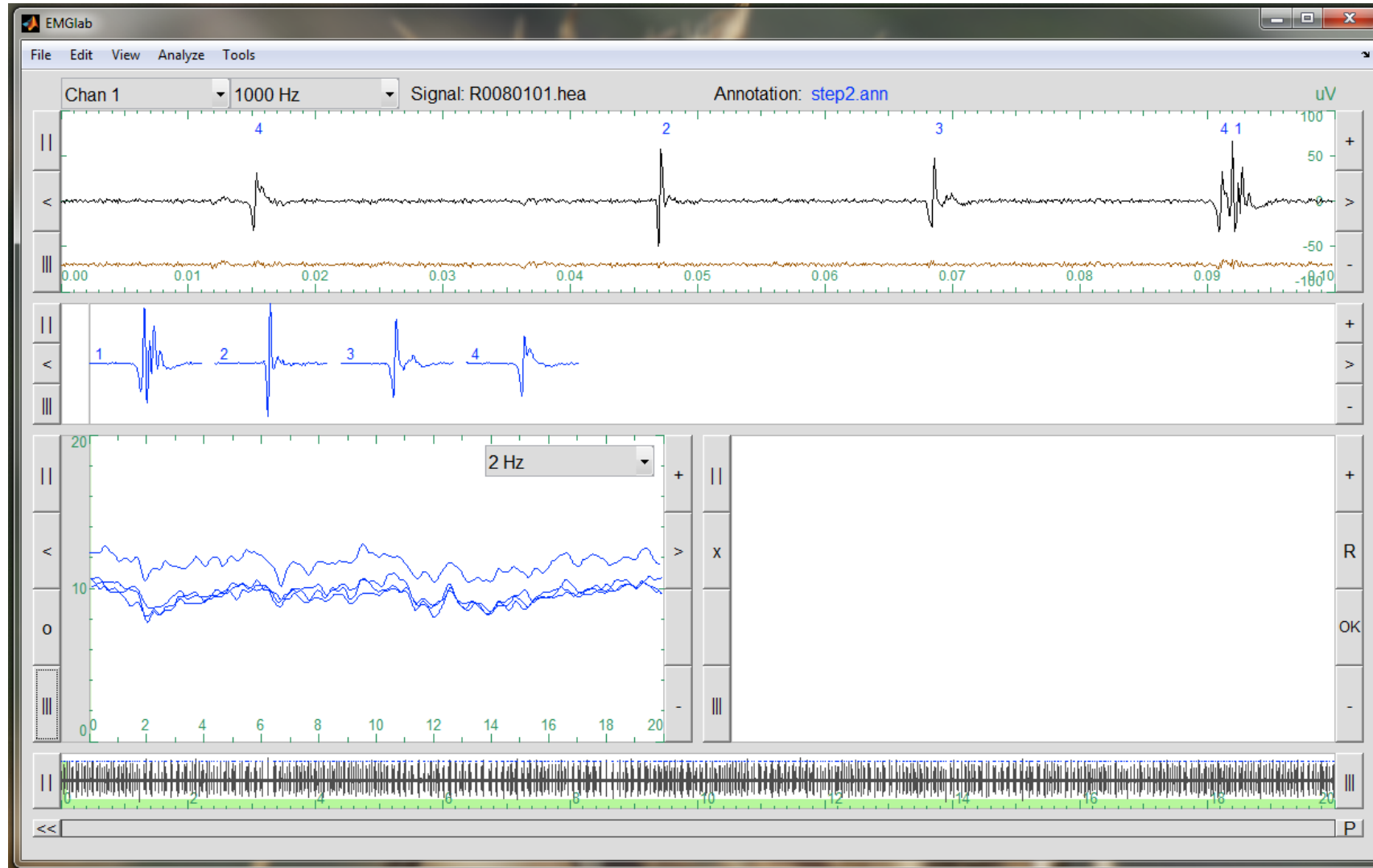
# Resolving superpositions

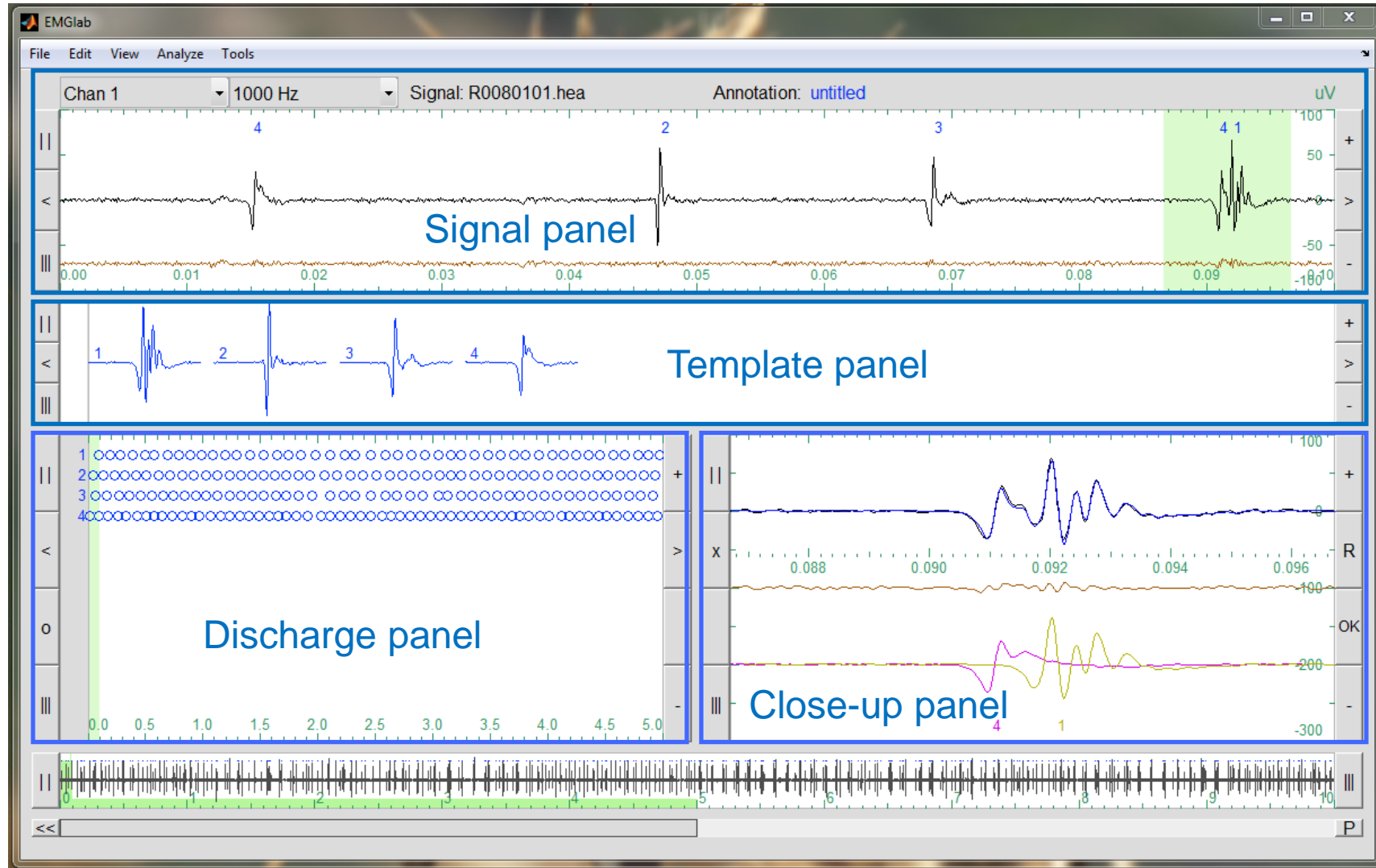


# Complete decomposition



# Accuracy check – common drive





# Pros and cons

- Pros

- In case of selective intramuscular EMG, we can decompose the signal into the constituent trains of action potentials
- By visual inspection of the signal and the patterns of the instantaneous discharge rate fluctuations, we can be confident about the decomposition results
- Intramuscular EMG is the **gold standard**

- Cons

- We can detect only **few units**



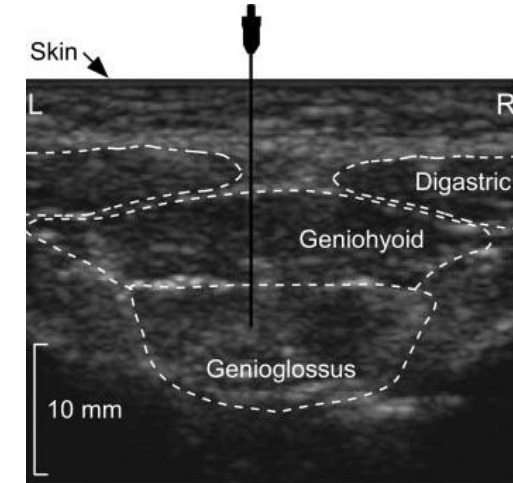
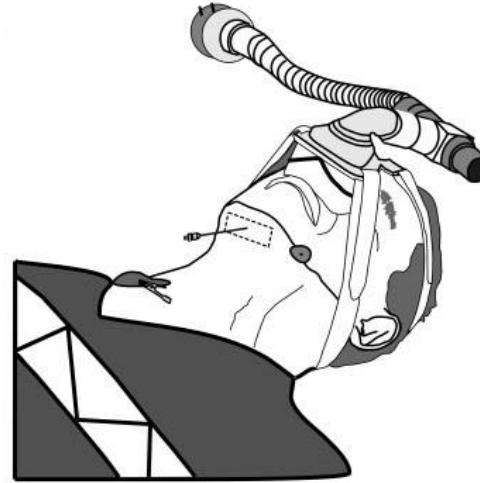
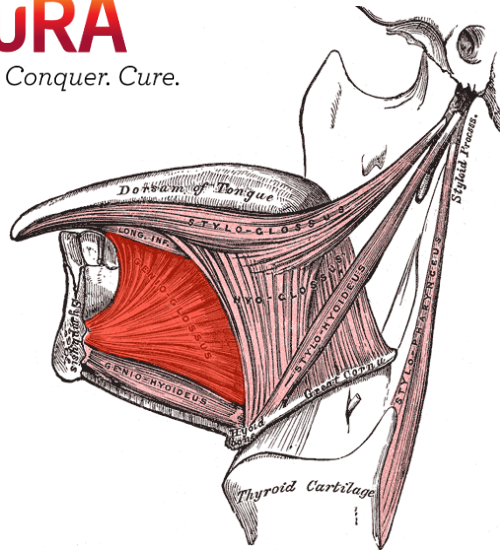
# How many motor neurons per muscle?

Muscle	$\alpha$ motor axons	Number of muscle fibers
Biceps brachii <sup>a,c</sup>	774	580,000
Brachioradialis <sup>e</sup>	315	>129,200
	350	
Cricothyroid <sup>a,d</sup>	112	18,550
First dorsal interosseus <sup>e</sup>	119	40,500
First lumbrical <sup>e</sup>	93	10,038
	98	10,500
Opponens pollicis <sup>a,c</sup>	133	79,000
Masseter <sup>b</sup>	1,452	929,000
Platysma <sup>e</sup>	1,096	27,100
Temporalis <sup>b</sup>	1,331	1,247,000
Medial gastrocnemius <sup>e</sup>	579	1,120,000
		964,000
Posterior cricoarytenoid <sup>a,d</sup>	140	16,200
Rectus lateralis <sup>f</sup>	4,150	22,000
Tensor tympani <sup>f</sup>	146	1,100
Tibialis anterior <sup>e</sup>	445	250,200
		292,500
Transverse arytenoid <sup>a,d</sup>	139	34,470

Are 3-4 units representative of the whole muscle?

Enoka, J Clin Neurophysiol, 1995

# Serial recordings



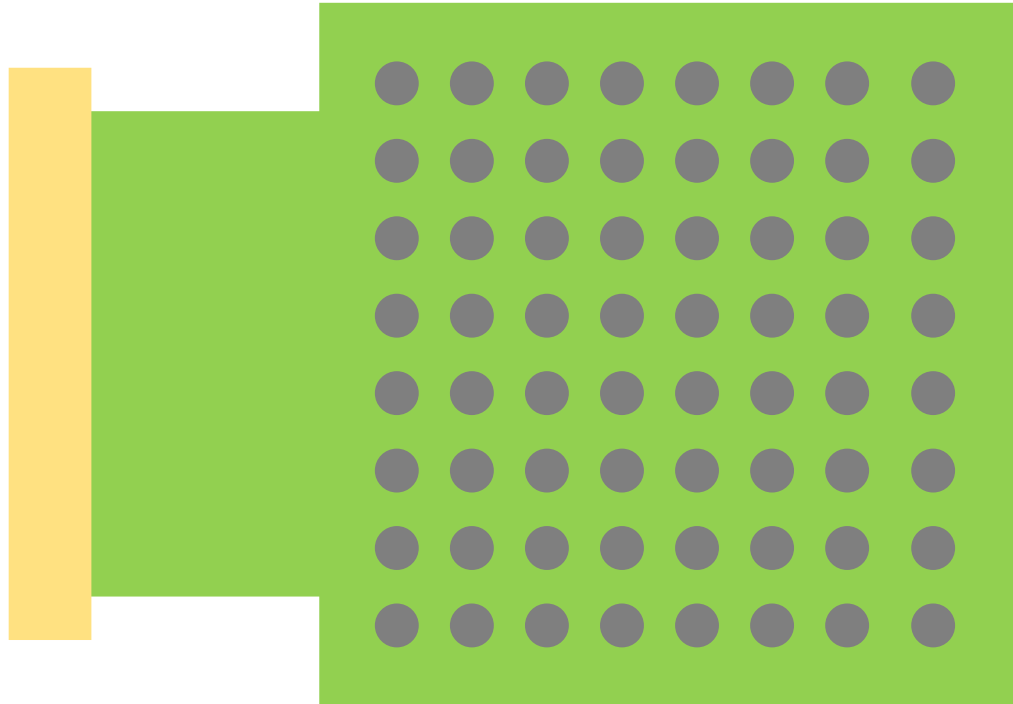
Saboisky et al, J Neurophysiol, 2005

Needles were inserted ... perpendicular to the skin surface to a depth of ~22–30 mm. GG EMG was recorded during stable quiet breathing for a minimum of 10 breaths at each recording site. **Ten different intramuscular sites** were studied in each subject via one to **three skin insertions** from the same side of the midline. The **needle was manipulated  $\pm 30^\circ$**  from horizontal in the sagittal plane to record from sites anterior and posterior to the insertion point (termed middle) within the GG. We estimate that the needle tip probably covered an arc of up to ~3 cm within the muscle.

# ADVANCES IN TECHNOLOGY

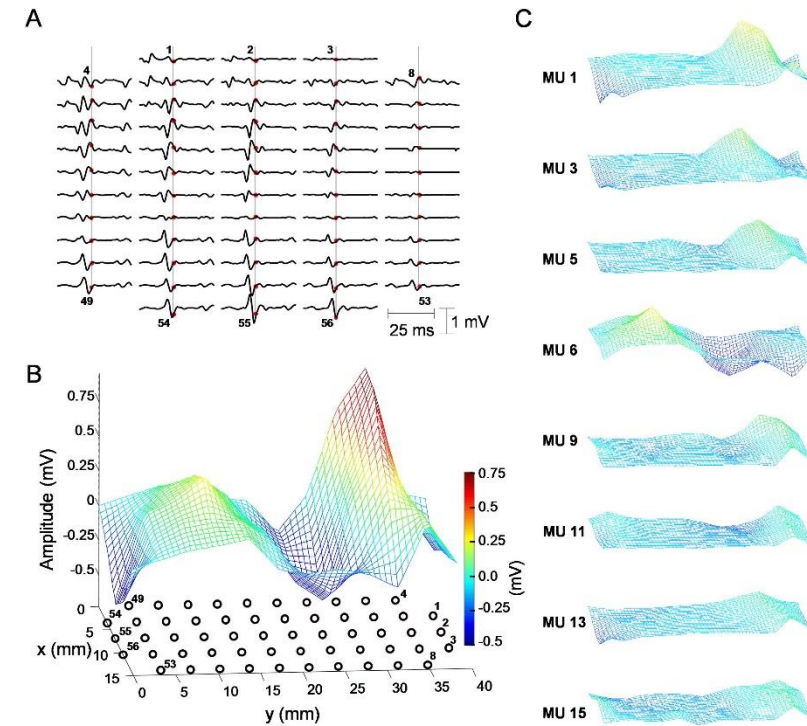
# High-density surface EMG technology

## Surface EMG Superficial muscles



Merletti & Muceli, J Electromyogr Kinesiol, 2019

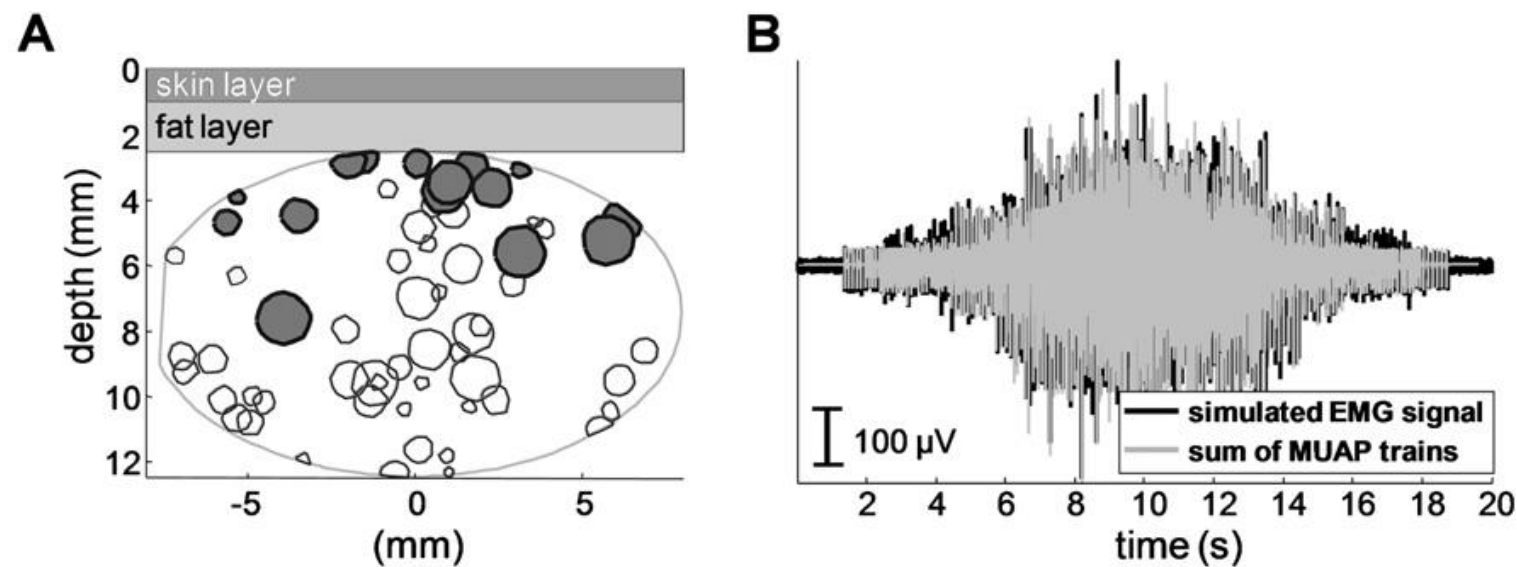
## Decomposition of high-density surface EMG



Holobar & Zazula, IEEE TSP, 2007  
Farina et al, Clin Neurophysiol, 2010

# Pros and cons

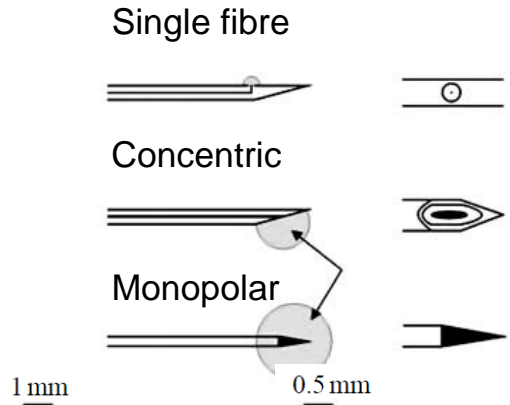
- Pros
- Non-invasive (children, patients)
- Number of detected motor units  $\uparrow$
- Cons
- Superficial muscles
- Biased sample



Farina et al, Clin Neurophysiol, 2010

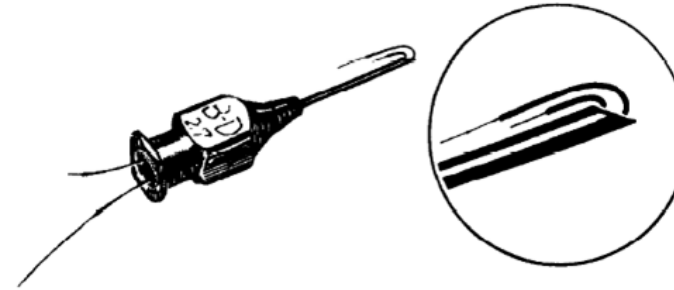
# Conventional technology

## Needles

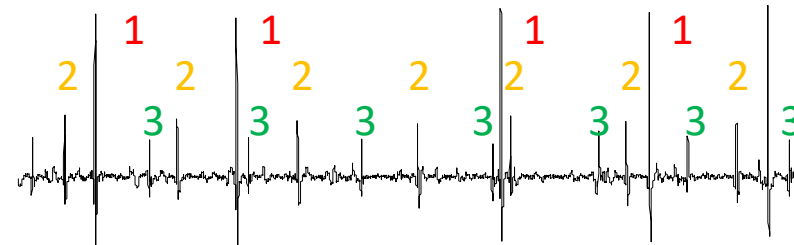
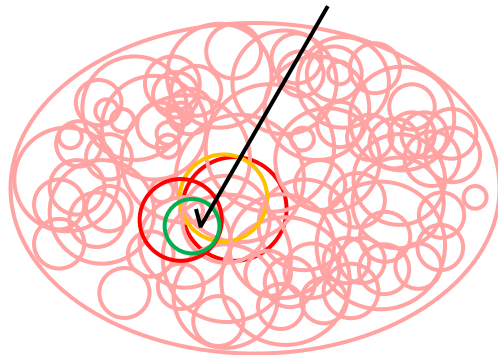


Merletti & Farina, Philos Trans A  
Math Phys Eng Sci, 2009

## Fine wires



Basmajian & Stecko  
J Appl Physiol, 1962

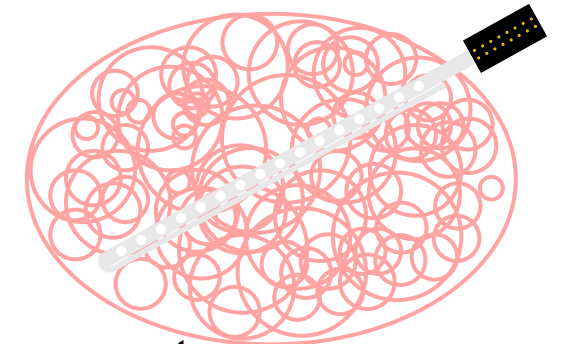


Spatial selectivity ↑

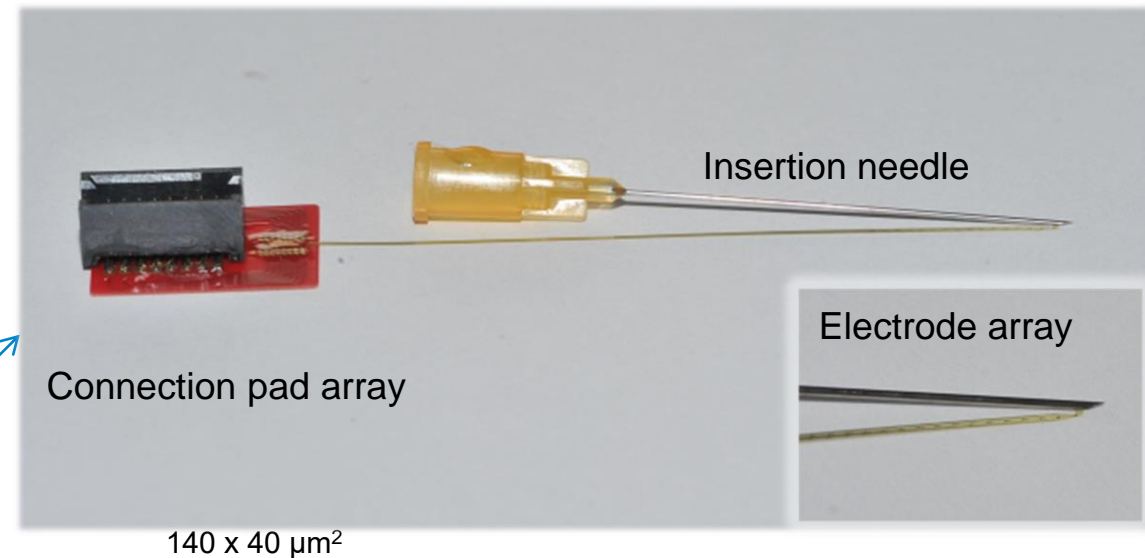
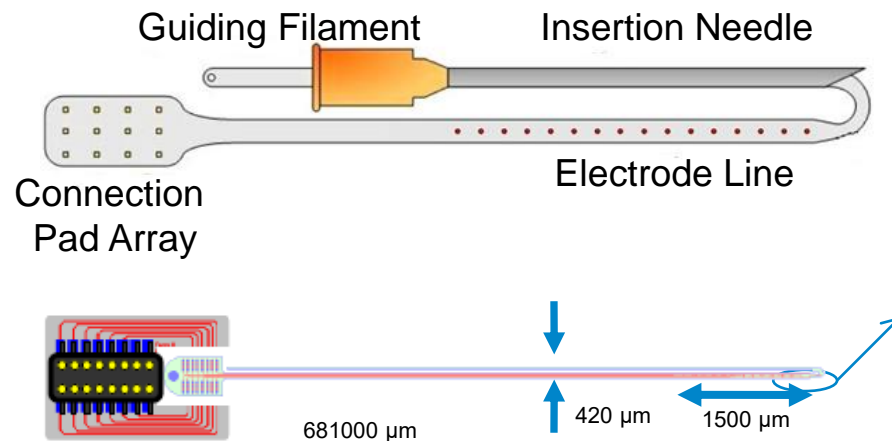
Number of extracted sources ↓

# Multichannel intramuscular EMG tech

Spatial selectivity ↑  
Number of detected sources ↓



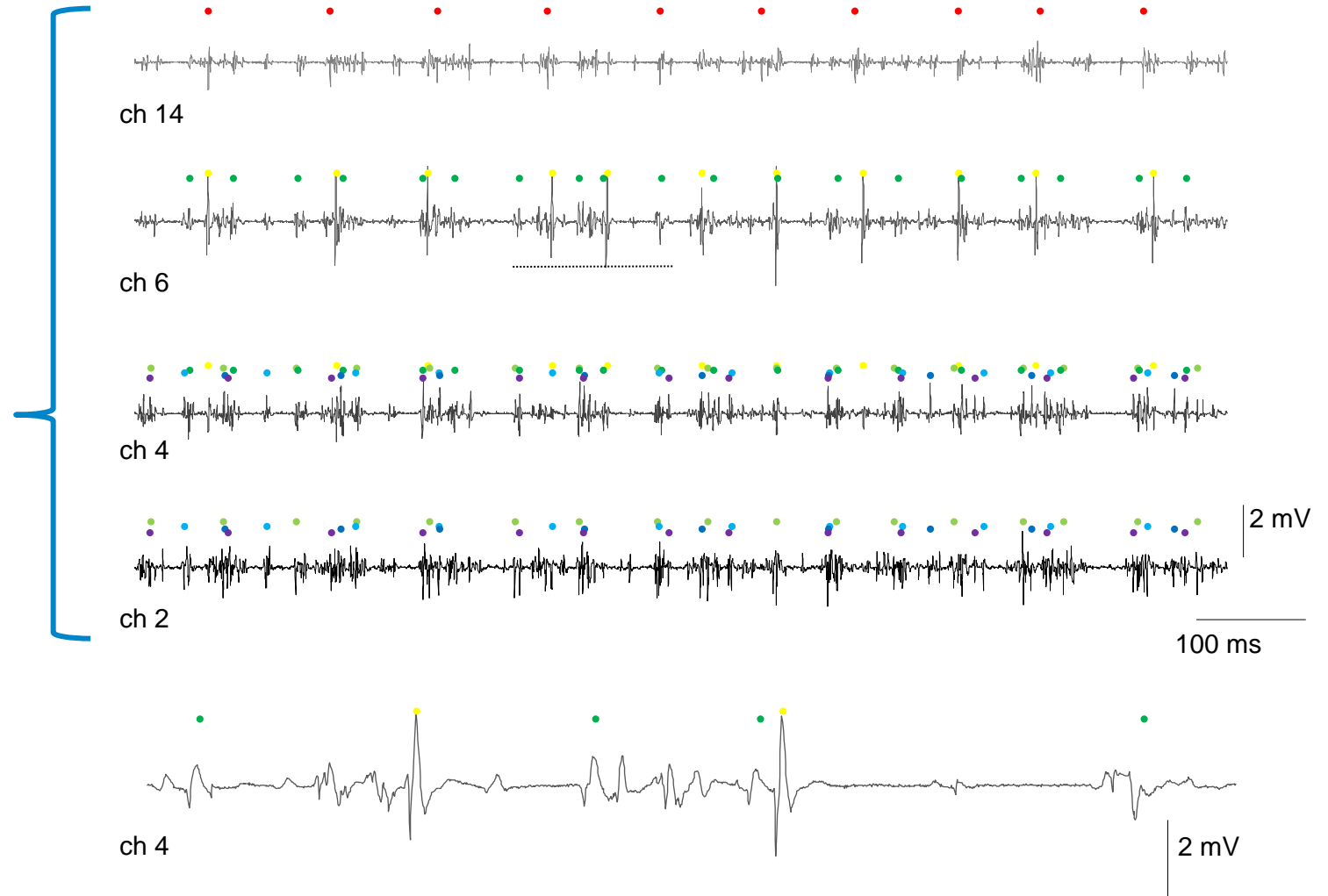
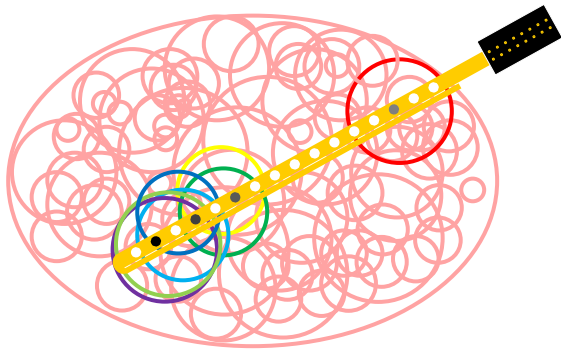
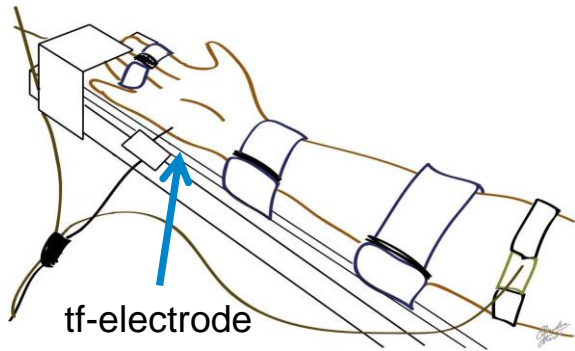
**SOLUTION:** selectivity + spatial sampling  
Thin-film wire system with several electrodes in specific geometry



Muceli et al, J Physiol, 2015



# Multichannel intramuscular EMG tech



Muceli et al, J Physiol, 2015



# Pros and cons

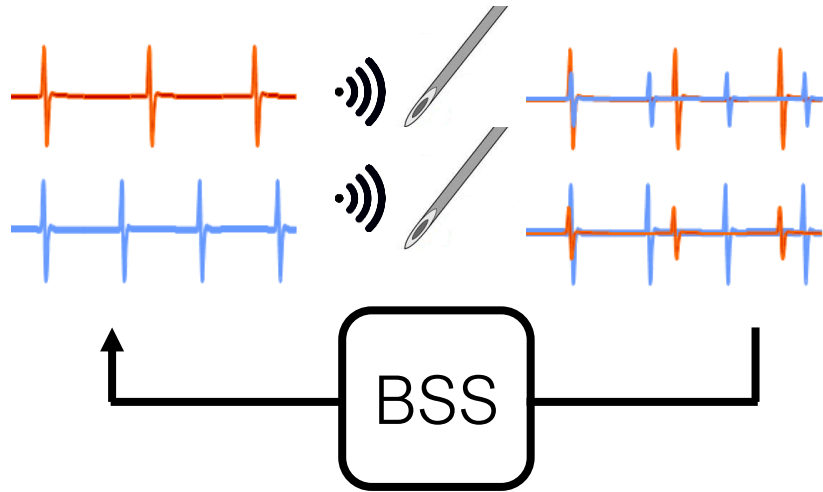
- Pros

- Number of detected motor units ↑
- No bias in motor unit detection

- Cons

- Minimally invasive
- Processing time ↑ (template-matching)

# How do we decode?



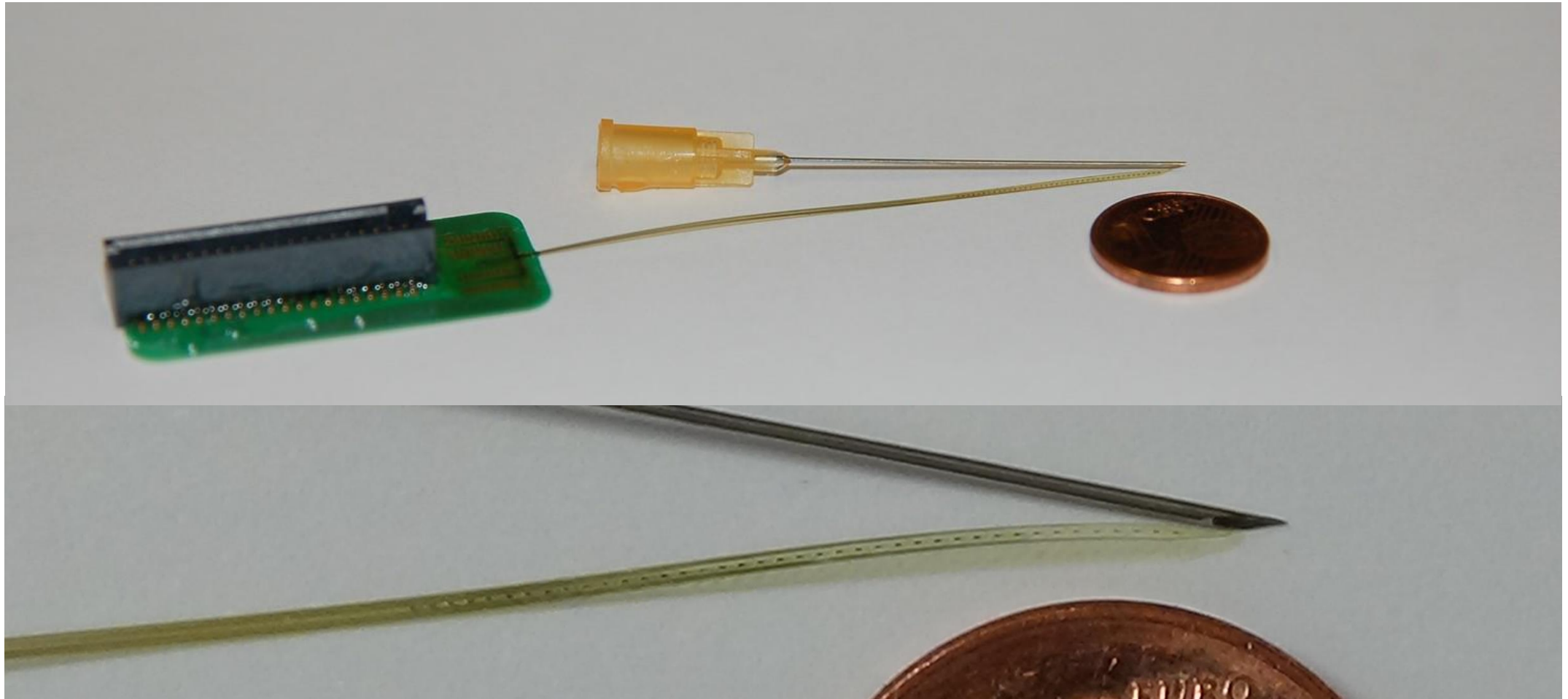
Holobar et al, IEEE TSP, 2007  
 Negro et al, J Neural Eng, 2016

Hp: more EMG channels than motoneurons

Contraction Level	No. MUs (manual)	No. MUs (automatic)	No. MUs common	RoA (%)
ADM 15 <i>ch</i>	23	14	14	91.8 ± 9.2 (60.6–98.7)
	31	14	14	91.5 ± 6.6 (75.7–99.2)
TA 2 × 16 <i>ch</i>	14	14	13	97.0 ± 7.0 (77.5–100.0)
	20	17	17	97.5 ± 4.5 (84.6–99.8)
	27	22	20	95.9 ± 3.4 (88.3–99.6)
TA 2 × 16 <i>ch</i>	53	22	22	95.6 ± 8.66 (58.9–99.1)
	57	24	24	93.9 ± 11.5 (45.0–99.3)
	60	21	21	93.4 ± 9.6 (55.7–100.0)

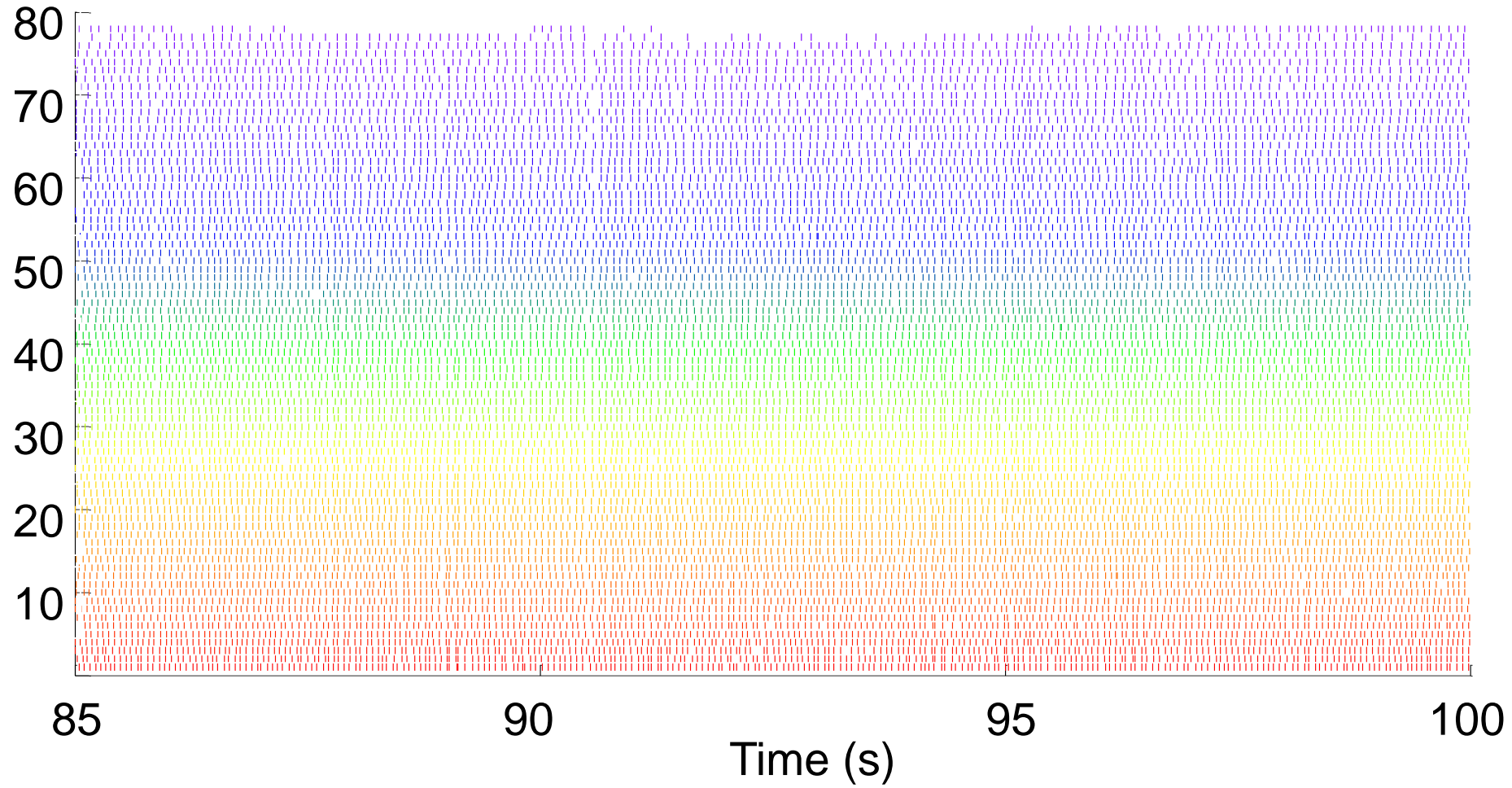
Let's increase the channel density!

# High-density intramuscular EMG tech



Muceli et al, Science Advances, 2022

# Neural decoding



Muceli at al, Science Advances, 2022

# Automatic decomposition

Subject	Force (%MVC)	Number of units (manual)	Number of units (automatic)	Rate of agreement
1, el1	20	50	40	<b>99</b>
1, el2	20	36	27	<b>98</b>
2	30	39	27	<b>100</b>
3	30	36	30	<b>99</b>

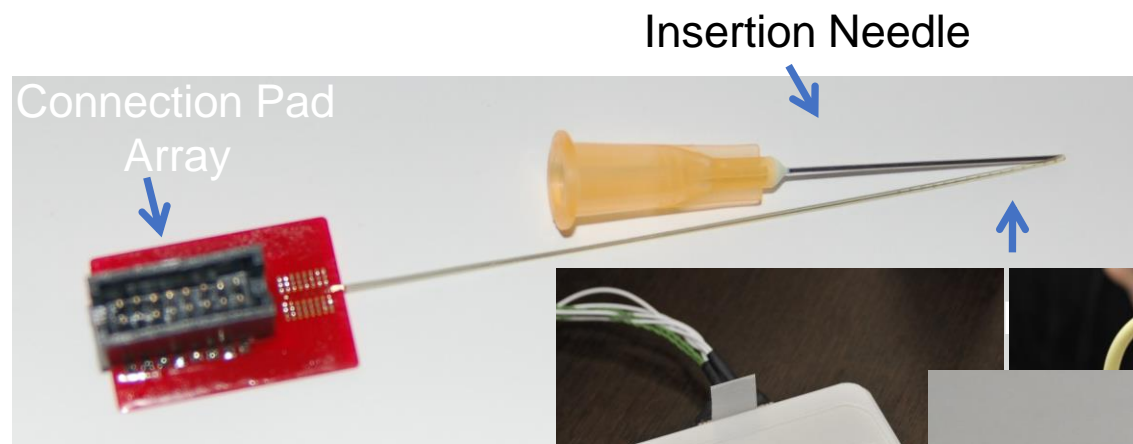
Muceli et al, Science Advances, 2022

# Summary

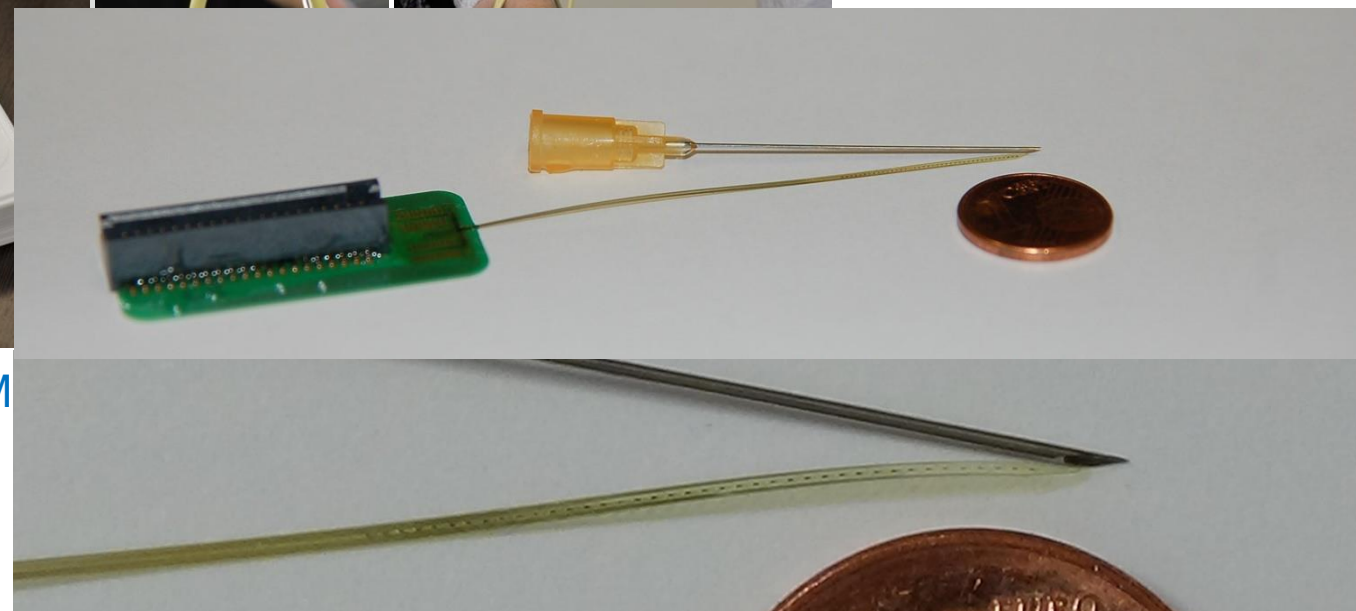


- High-density sensors
- EMG signals of good quality
- Accurate (automatic) decoding of large population of motor units
- Tailored design

# Tailored design



Muceli et al, J Ph



M

Muceli et al, Science Advances, 2022

# Which method is better?

- **Surface sensors**

- Superficial muscles
- Non-invasive
- Children

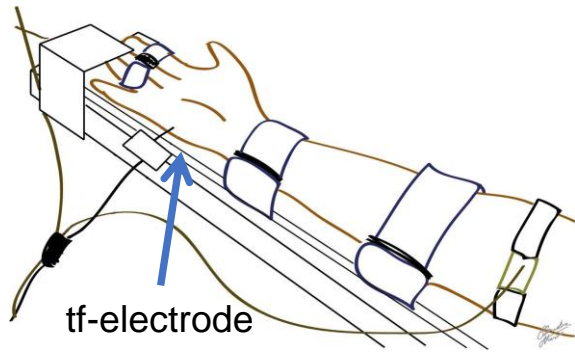
- **Intramuscular sensors**

- Both deep and superficial muscles
- Minimally invasive
- Not appropriated in case of coagulation diseases

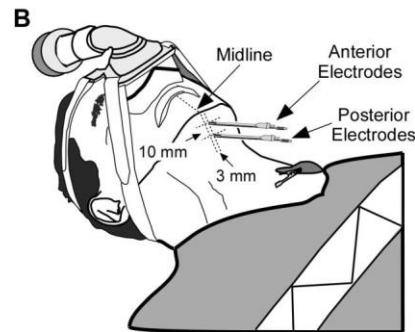
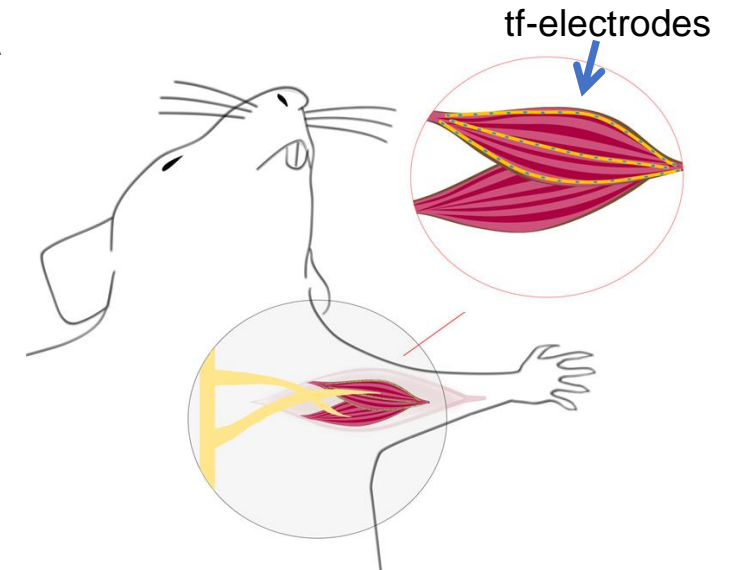
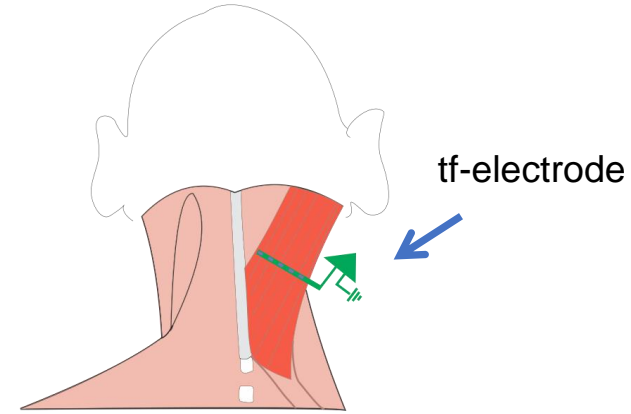
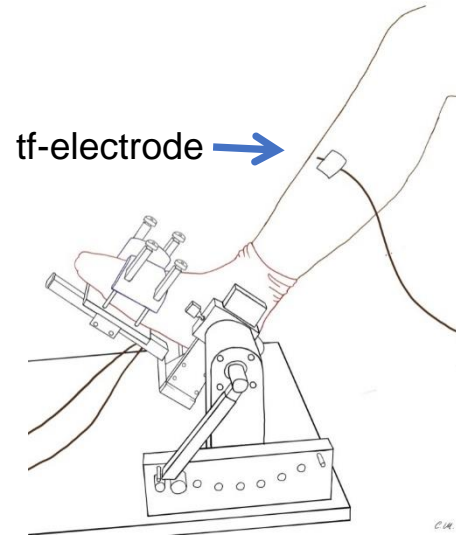
It depends on the application



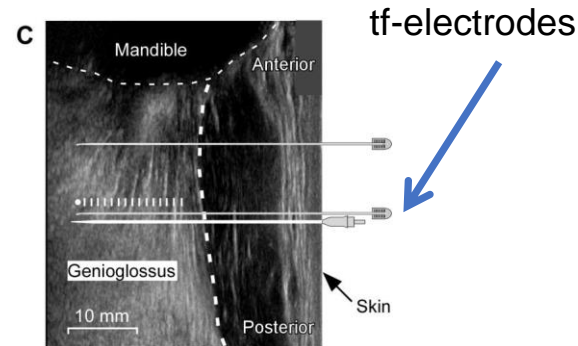
# Applications in humans and animals



Muceli et al, J Physiol, 2015



Luu et al, J Appl Physiol, 2018

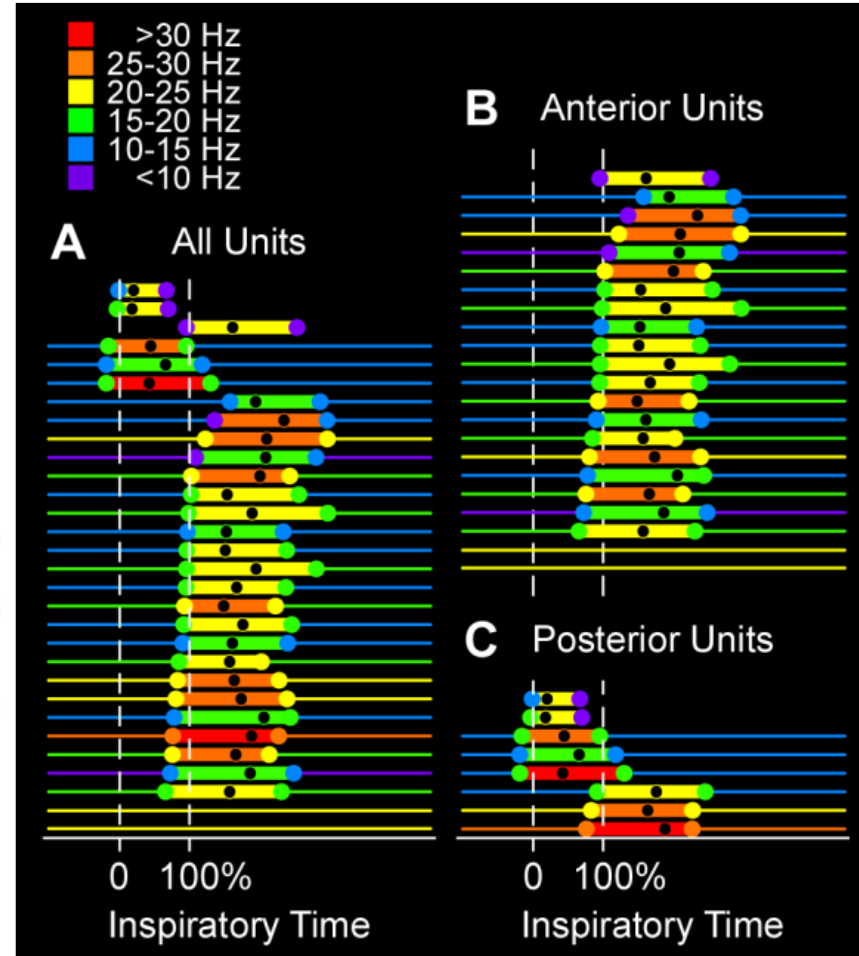
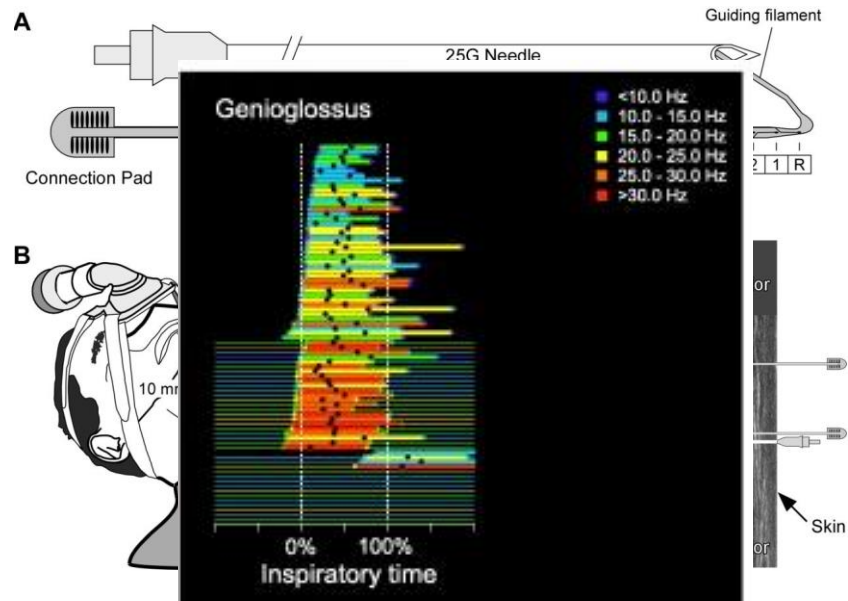


Muceli et al, J Neural Eng, 2019  
Bergmeister et al, Science Advances, 2019

# MOVEMENT PHYSIOLOGY

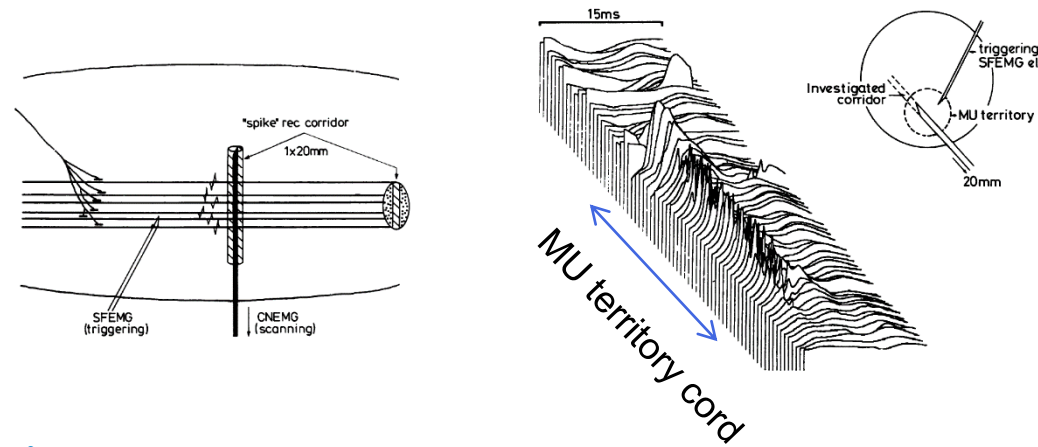
# Spatial sampling

Comprehensive information when we record from the whole muscle

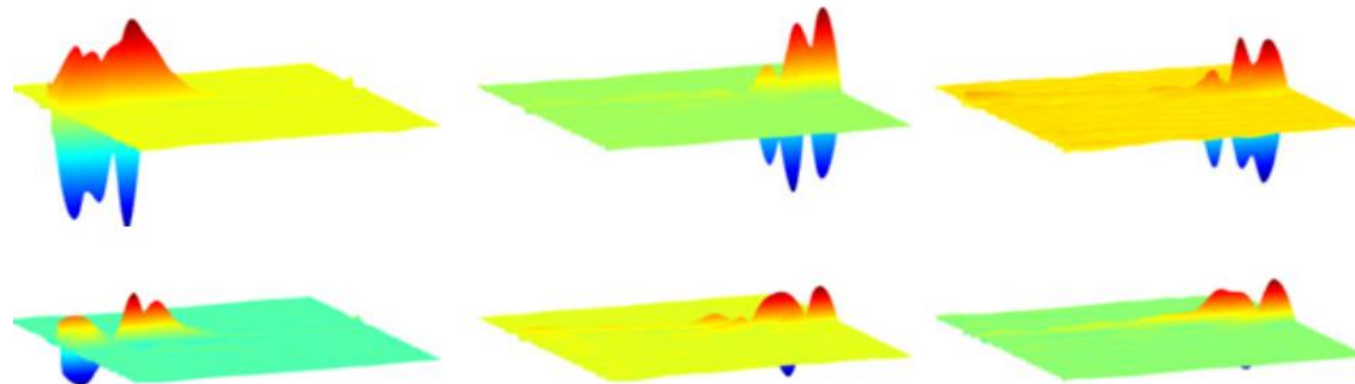


Lluch et al, *J Appl Physiol*, 2018  
*Neurobiol*, 2011

# Motor unit territories

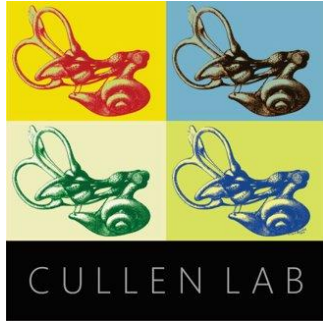


Stålberg & Antoni, J Neurol Neurosurg Psychiatry, 1980

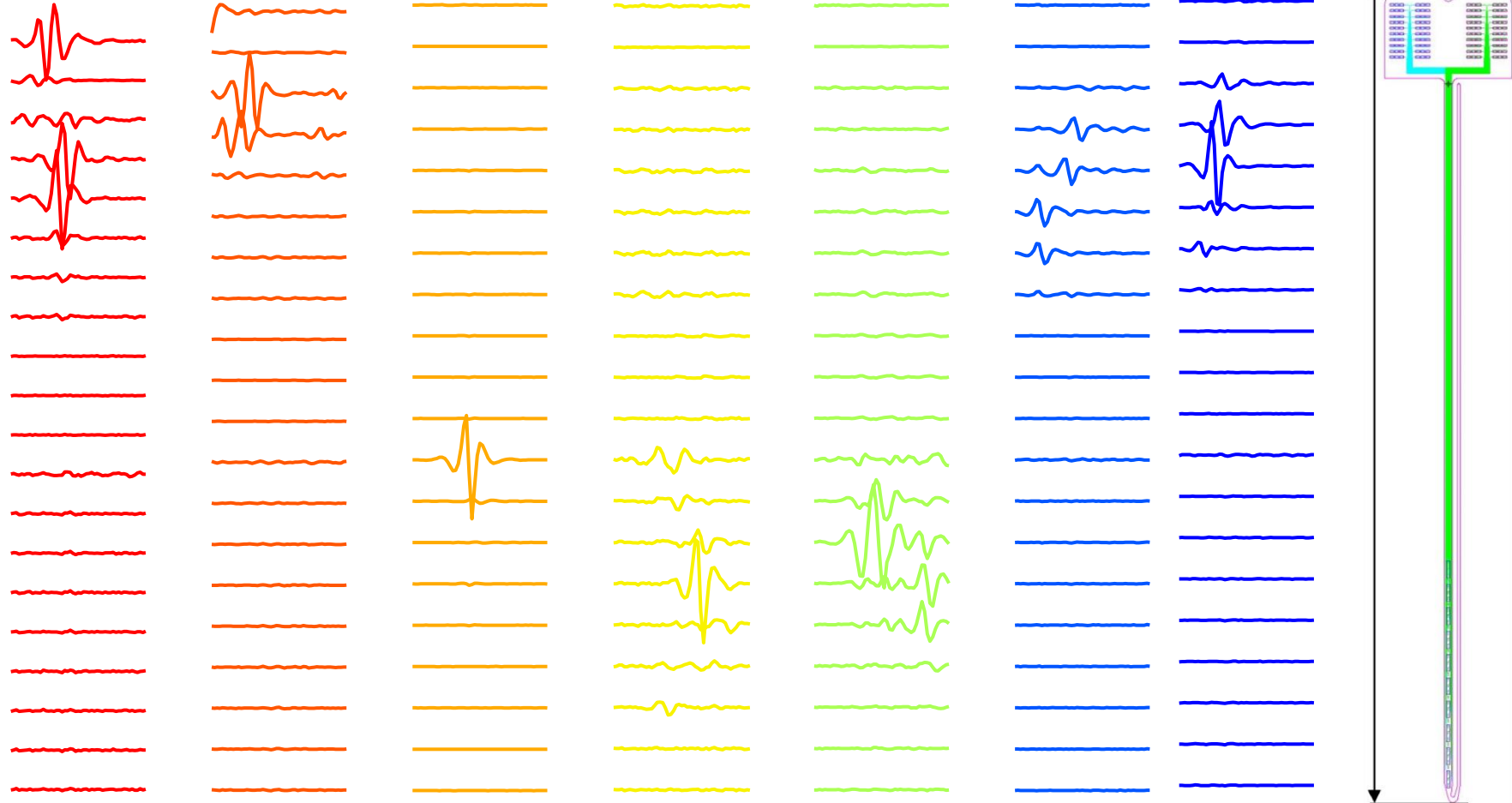
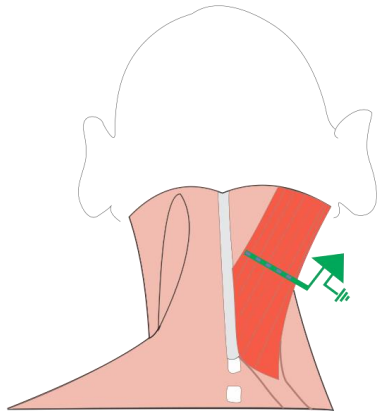


Muceli et al, J Physiol, 2015; Negro et al, J Neural Eng, 2016; Luu et al, J Appl Phys, 2018

# Spatial sampling



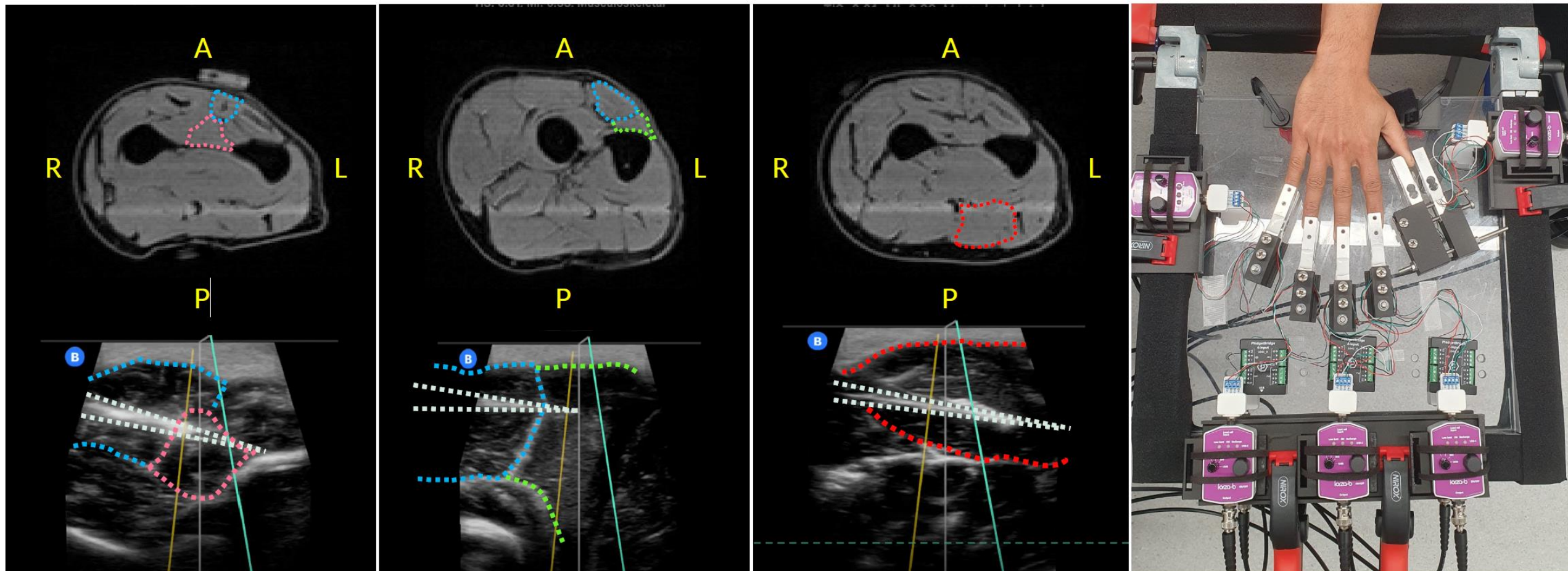
Robyn Mildren



# MYOELECRIC CONTROL

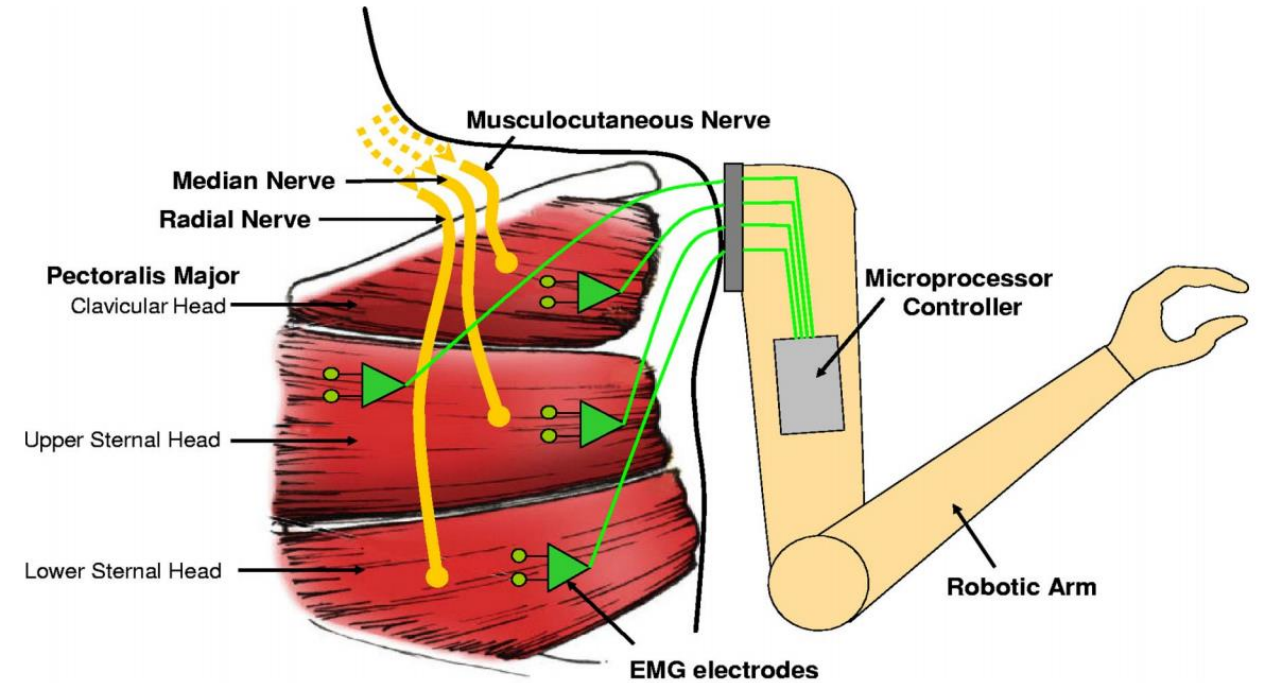
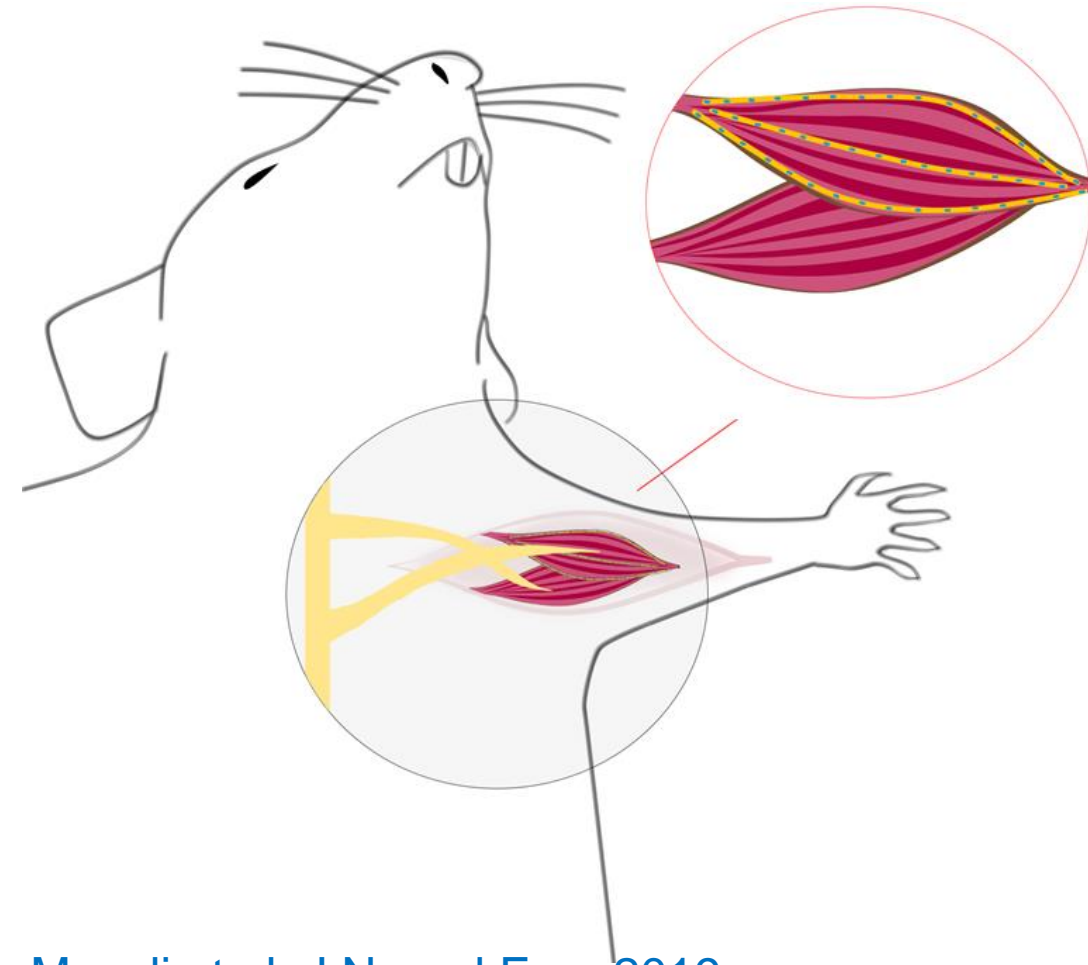


# Recording from deep muscles



Grison et al, under review

# Refine surgery models



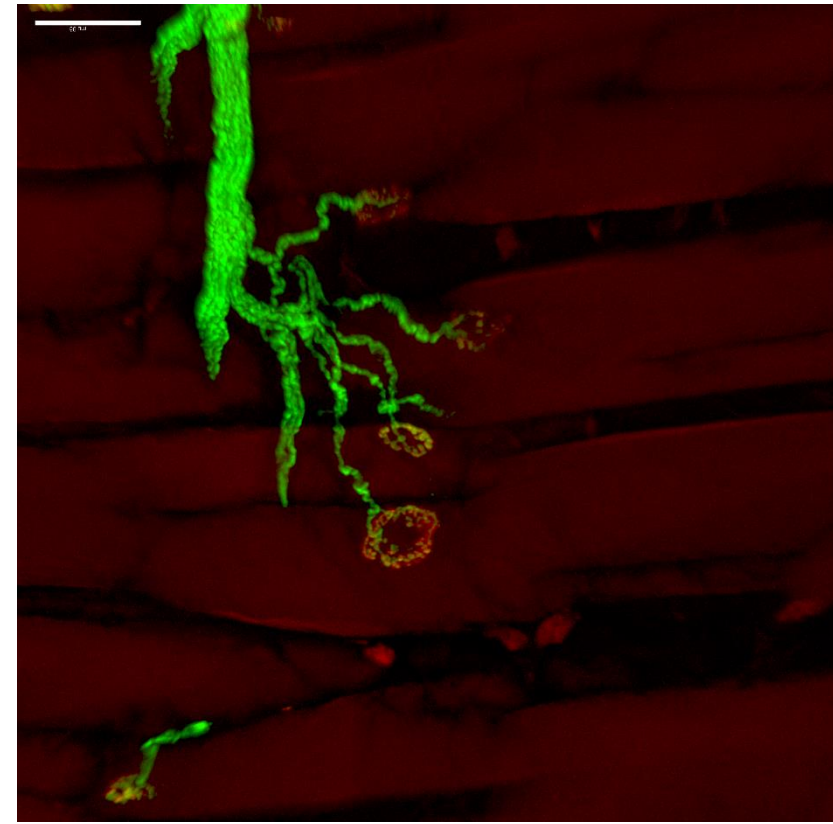
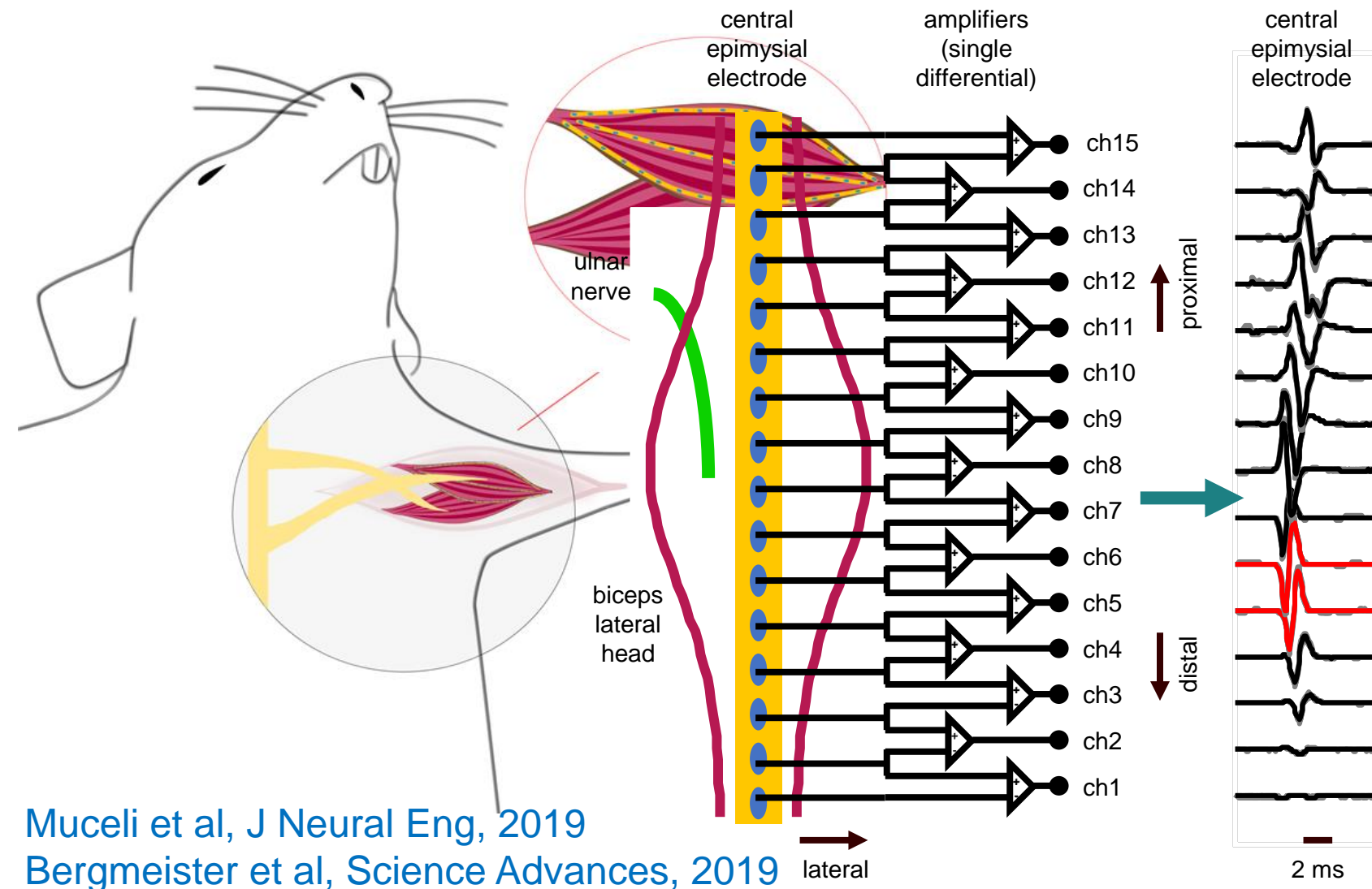
Zhou et al, J Neurophysiol, 2007

Muceli et al, J Neural Eng, 2019

Bergmeister et al, Science Advances, 2019



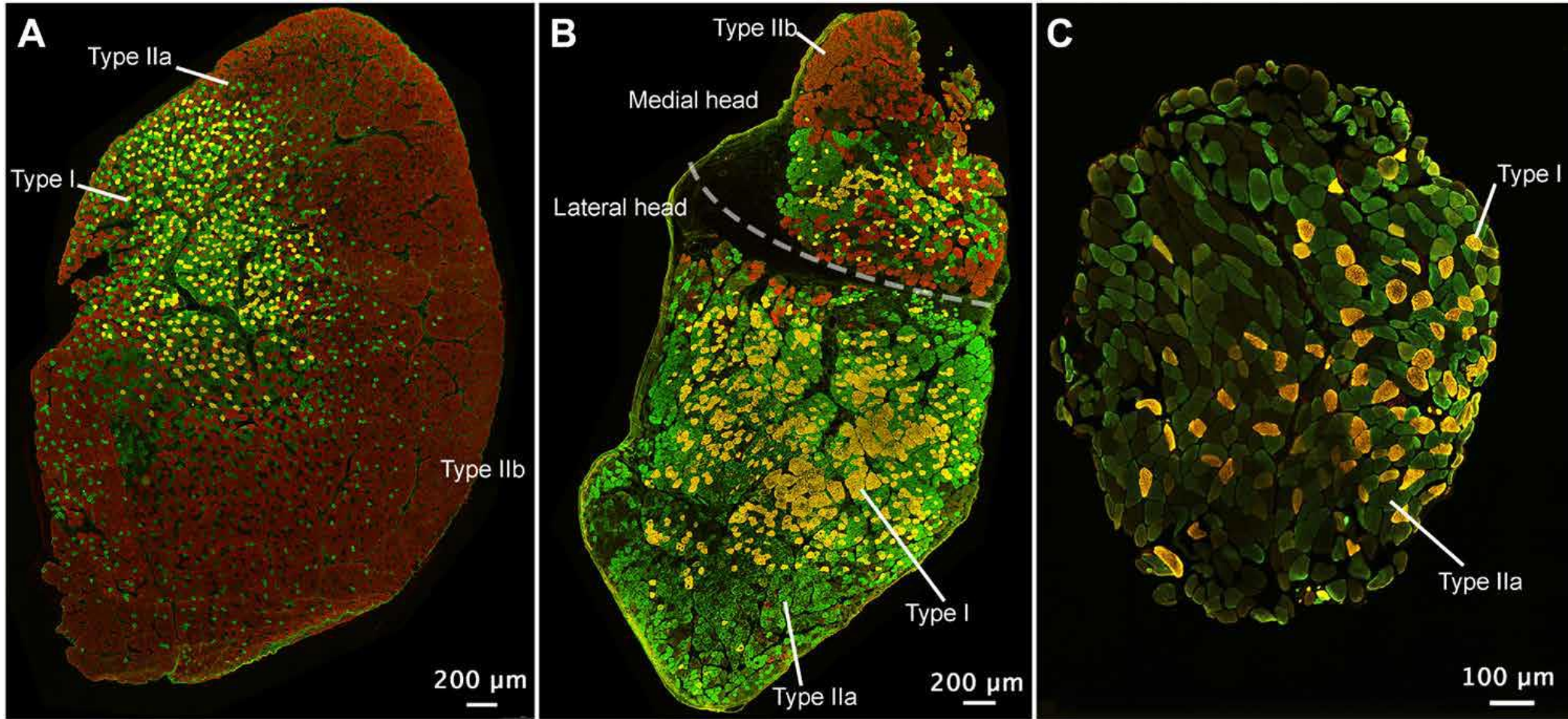
# Refine surgery models



Muceli et al, J Neural Eng, 2019

Bergmeister et al, Science Advances, 2019

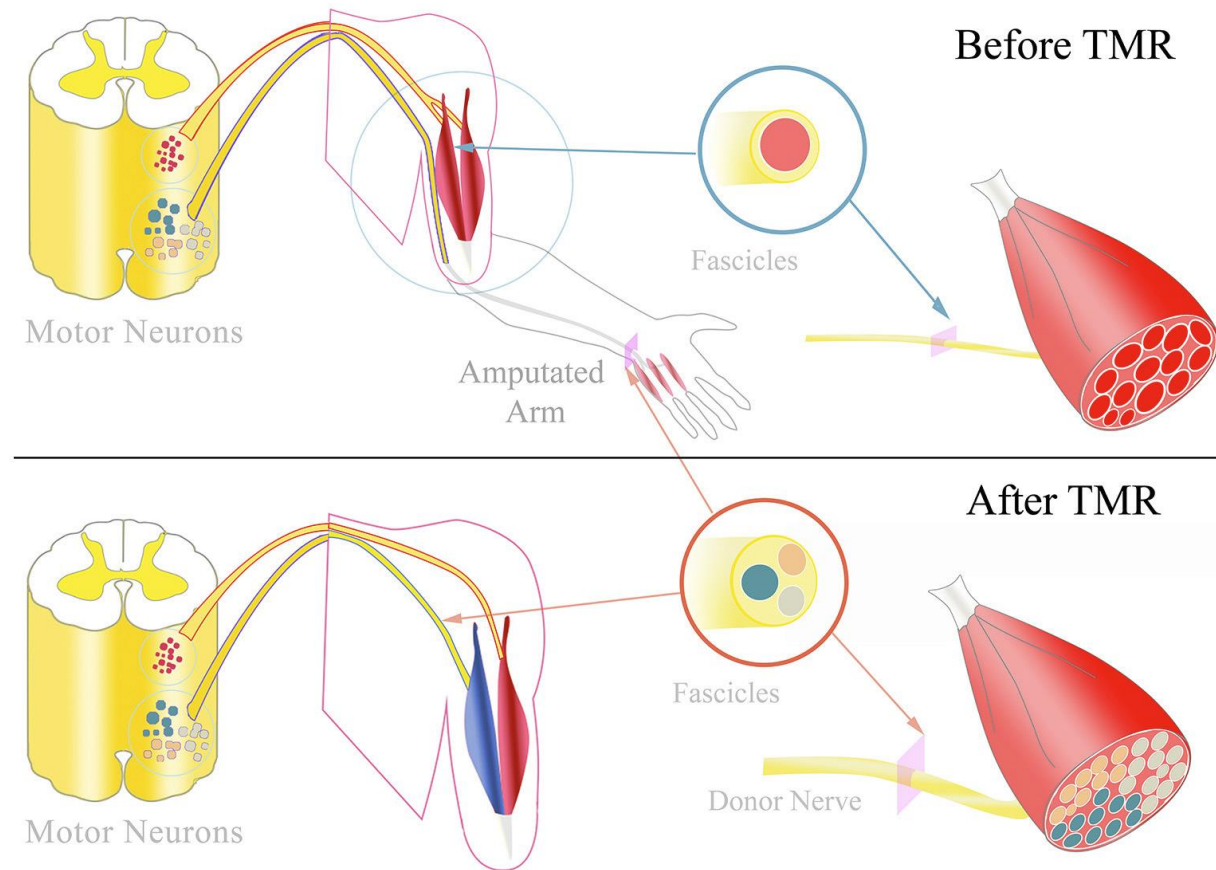
# Motor unit type change



Bergmeister et al, Science Advances, 2019

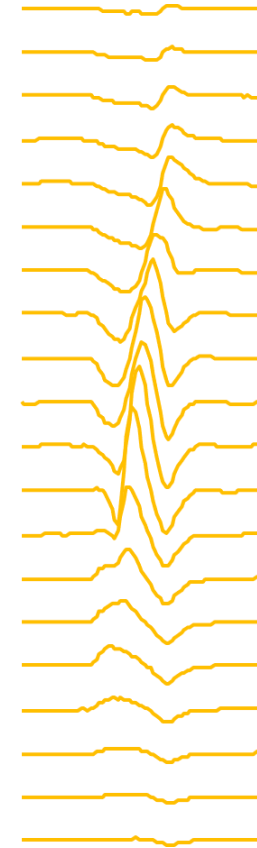
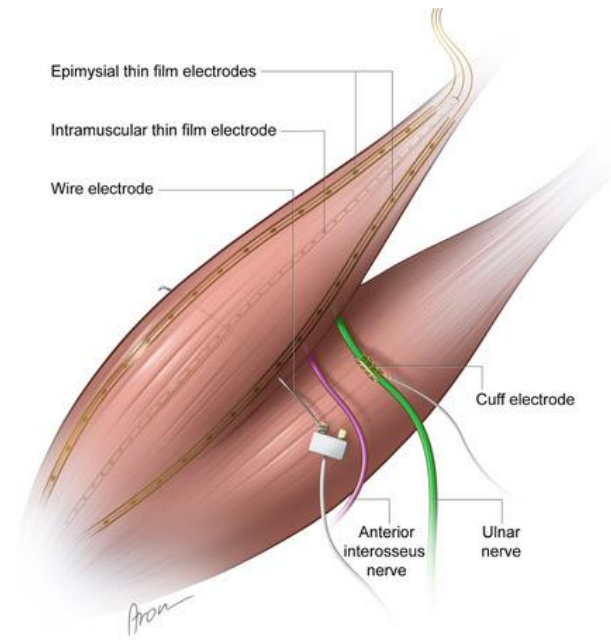
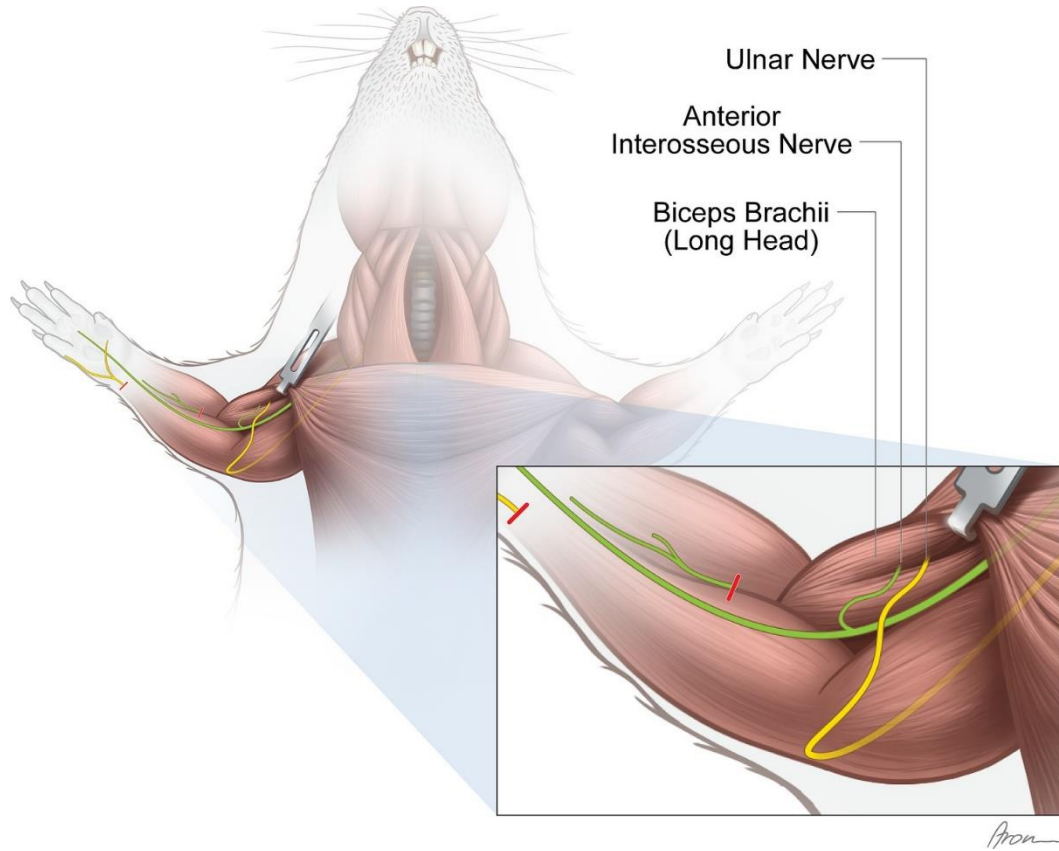


# Multiple reinnervation



Bergmeister et al, Front Neurosci, 2021

# Multiple reinnervation

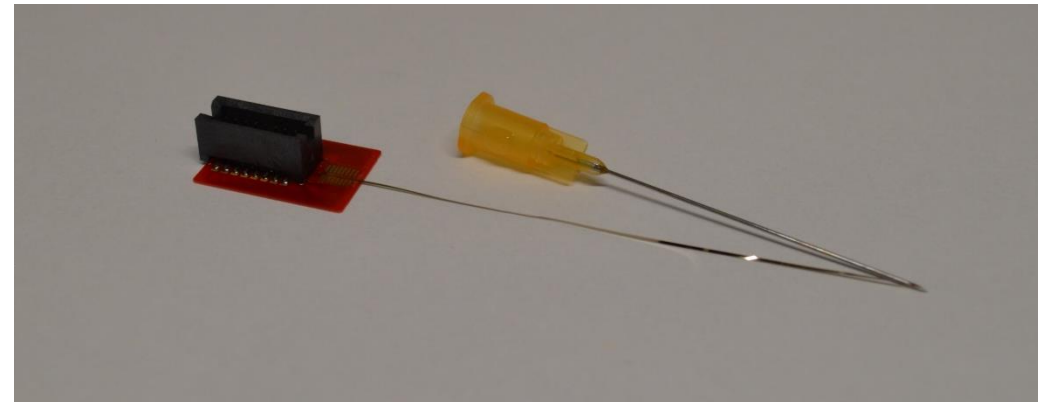
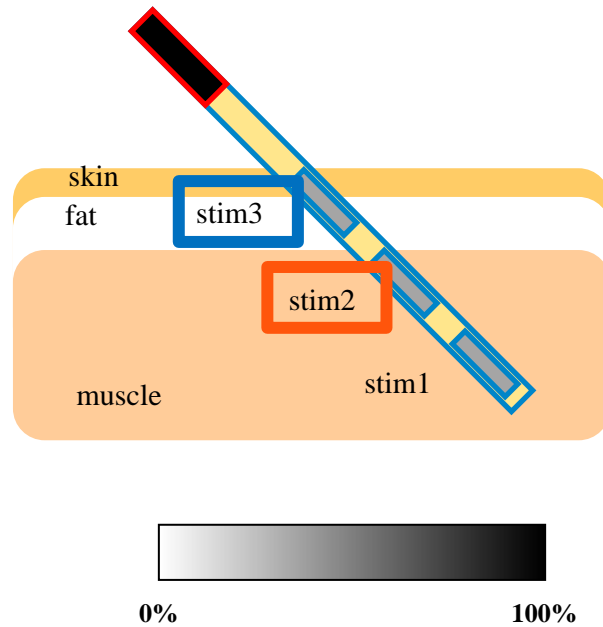


Luft et al, Elife, 2021

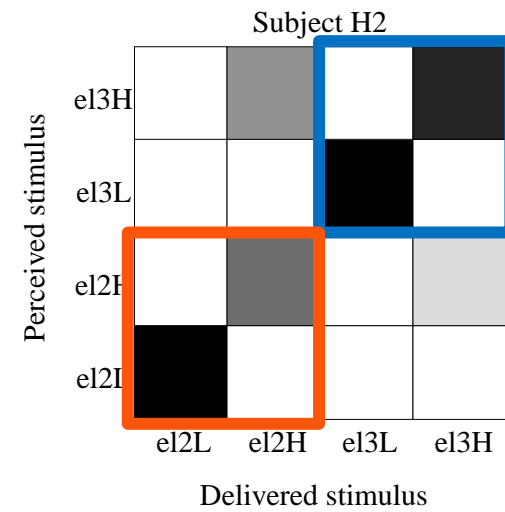
# Sensory feedback

## Acute tests

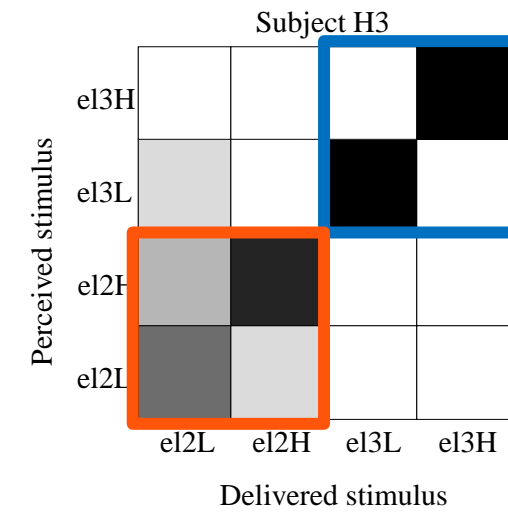
Electrode insertion



C



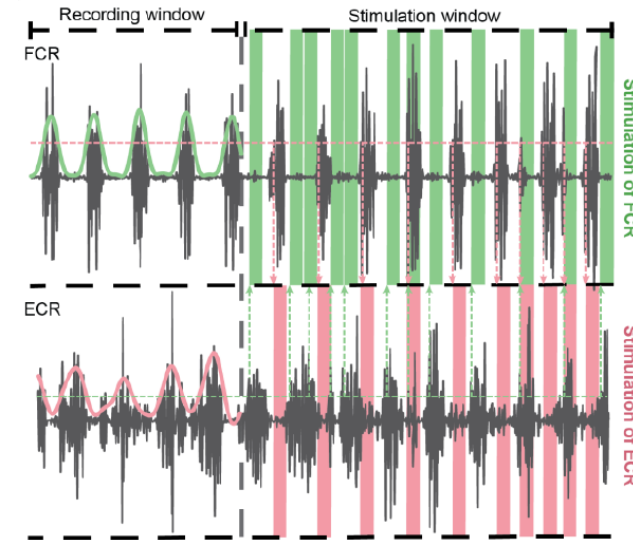
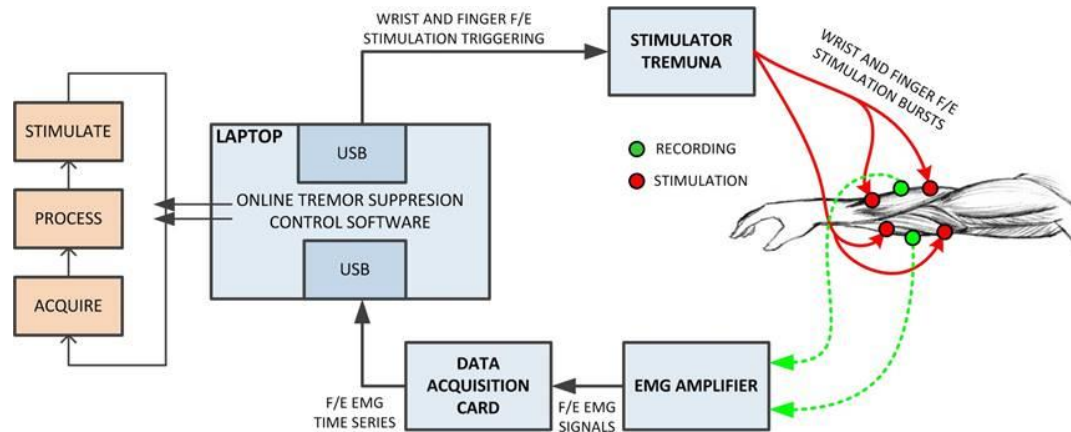
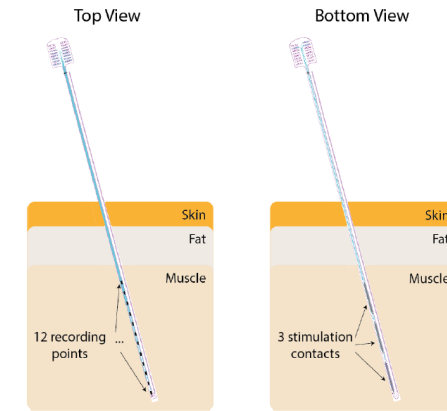
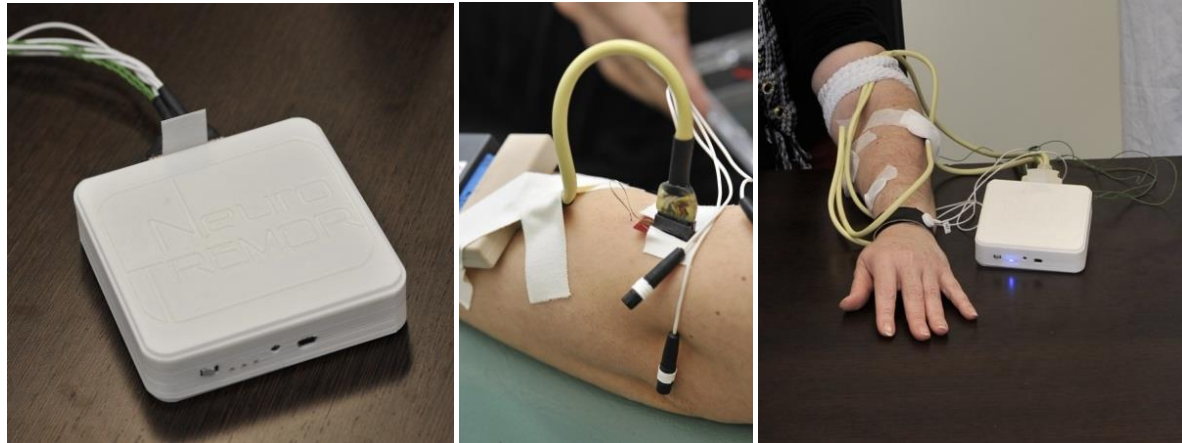
D



Muceli et al, J Neural Eng, 2019

# TREMOR SUPPRESSION

# Neuroprosthetics for tremor suppression



Dosen et al, IEEE TNSRE2015, Muceli et al, J Neural Eng, 2019, Pascual Valdunciel et al, IEEE TBME, 2021

# Tremor suppression



Pascual Valdunciel et al, IEEE TBME, 2021



# Summary



- Techniques for decoding of neural drive to muscles
- Novel electrodes with high spatial and time resolution
- Tailored design
- Fundamental research
- Refine surgery models
- Neuroprosthesis control
- Acute tests with invasive electrodes without surgery

# Collaborators



Dario Farina  
Agnese Grison

Jane Butler  
Simon Gandevia

Strahinja Došen  
Jakob Dideriksen

Wigand Poppendieck  
Klaus-Peter Hoffmann  
Andreas Schneider

Oskar Aszmann  
Konstantin Bergmeister  
Matthias Luft

José Pons  
Filipe Barroso  
A Pascual Valdunciel  
Francisco Grandas

Aleš Holobar  
Francesco Negro

Robyn Mildren  
Kathleen Cullen

Roger Enoka

Ken Yoshida

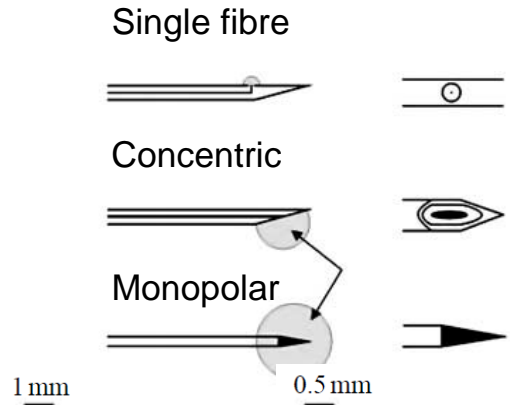
Roberto Merletti



THANK YOU FOR YOUR ATTENTION

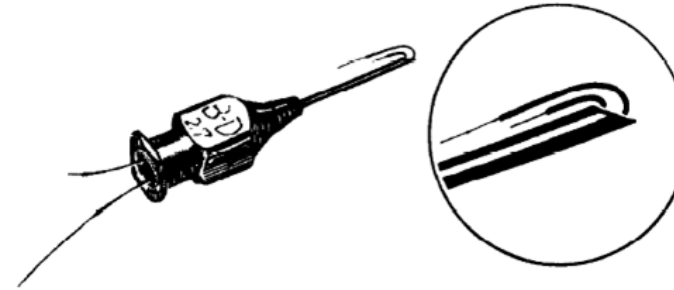
# Conventional technology

## Needles

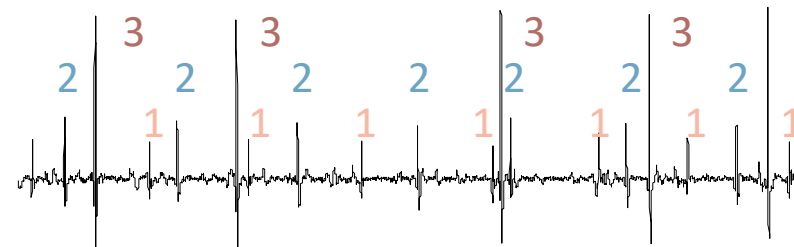
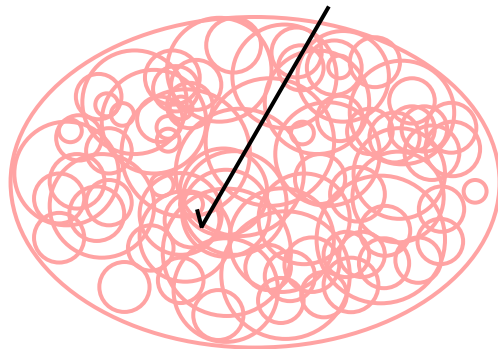


Merletti & Farina, Philos Trans A  
Math Phys Eng Sci, 2009

## Fine wires



Basmajian & Stecko  
J Appl Physiol, 1962



Spatial selectivity ↑

Number of extracted sources ↓

# Conventional technology

## Needles

Single fibre



Concentric



Monopolar

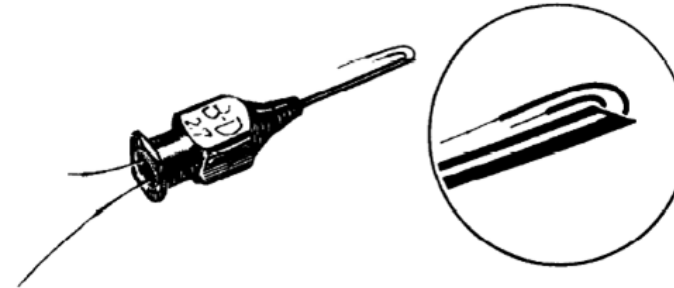


1 mm

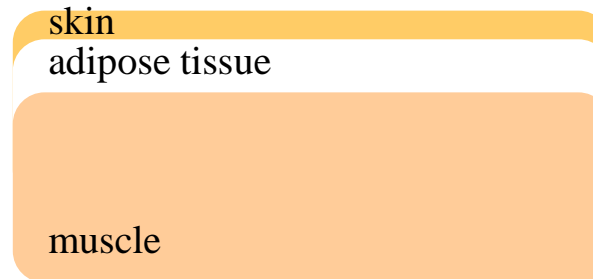
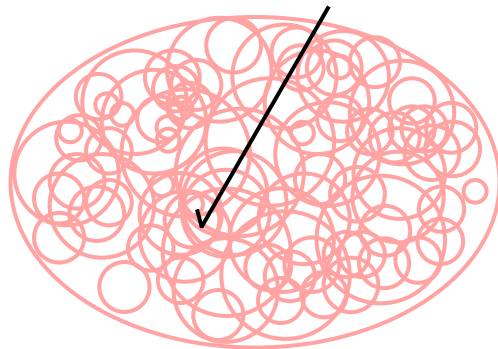
0.5 mm

Merletti & Farina, Philos Trans A  
Math Phys Eng Sci, 2009

## Fine wires



Basmajian & Stecko  
J Appl Physiol, 1962  
Electrode insertion



# Tremor suppression



Pascual Valdunciel et al, IEEE TBME, 2021