HYBRID NEURO

Ultrasound as a Neural Interface

Summer School: Hybrid Neural Interfaces, 10th - July 2024

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Neuromechanics and Rehabilitation Technology, Bioengineering Department

Imperial College London, UK

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Imperial College London

Topics

1. Motivation
2. What is Ultrasound?
3. Application 1. Motor Unit Decomposition via Ultrafast Ultrasound
4. Break Time
5. Translational challenges: Laboratory → Real-World
6. Application 2. Interfacing with Wearable A-mode Ultrasound
7. Questions and Answers

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Motivation

- Interfacing with the Brain is **Very Challenging**

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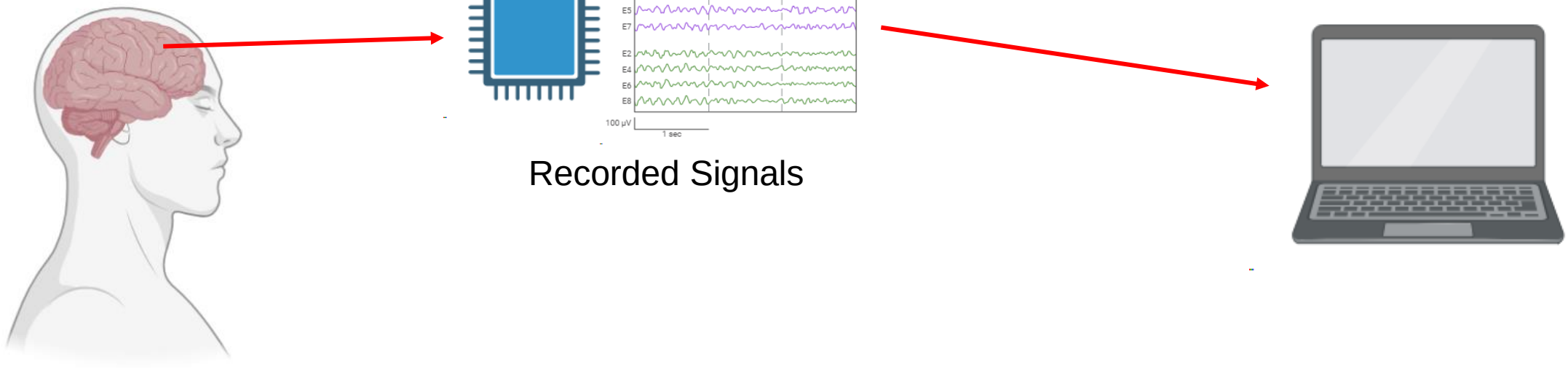
Motivation

- Interfacing with the Brain is **Very Challenging**



Recorded Signals

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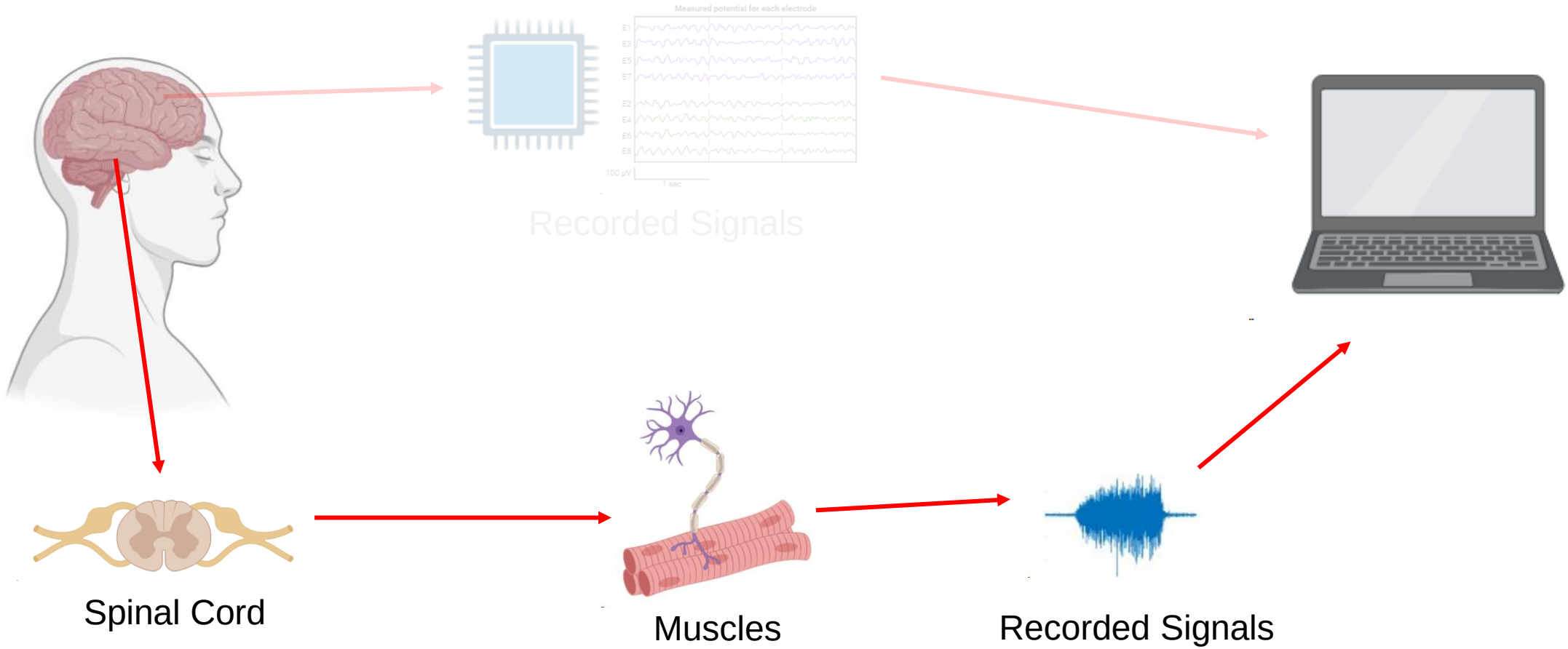
Motivation

- Interfacing with the Brain is **Via Muscles** may be **Less Challenging**



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How to do it them?

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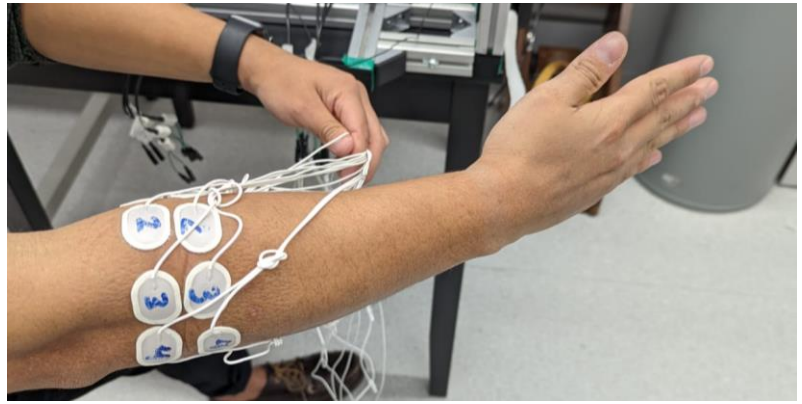
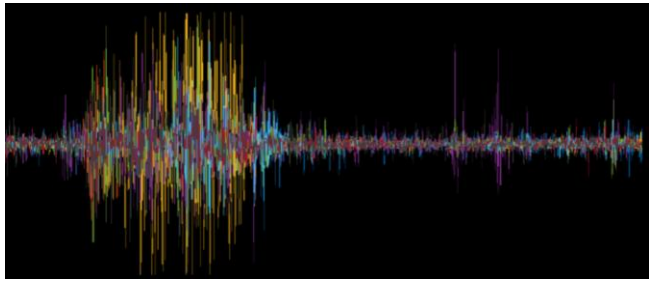
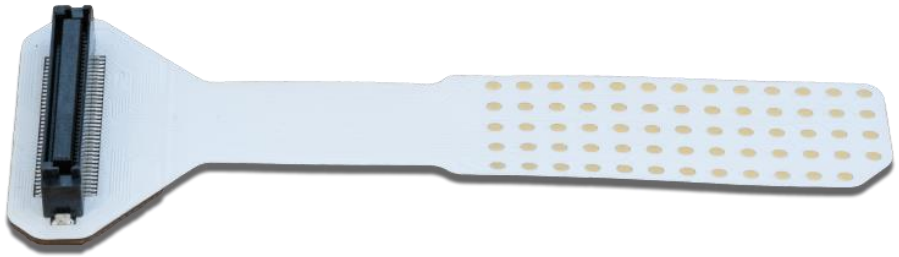
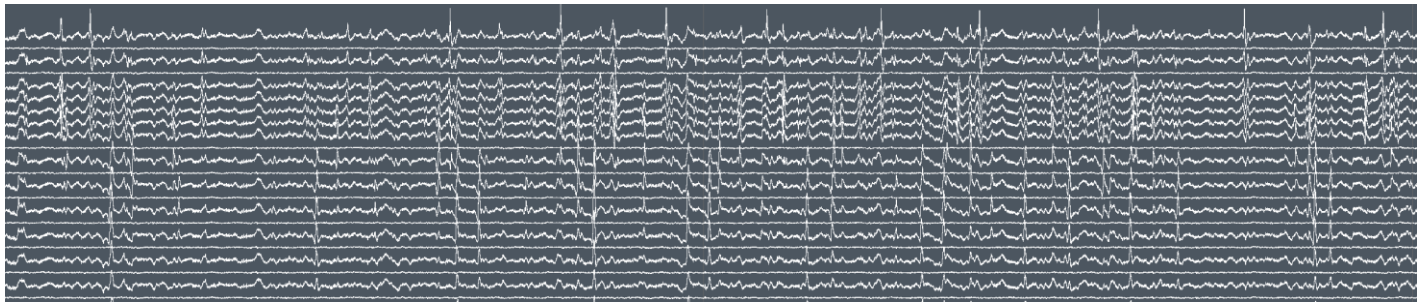
Surface Electromyography (sEMG)





High Density Surface Electromyography (HDsEMG)





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You would not be the first one to think of that

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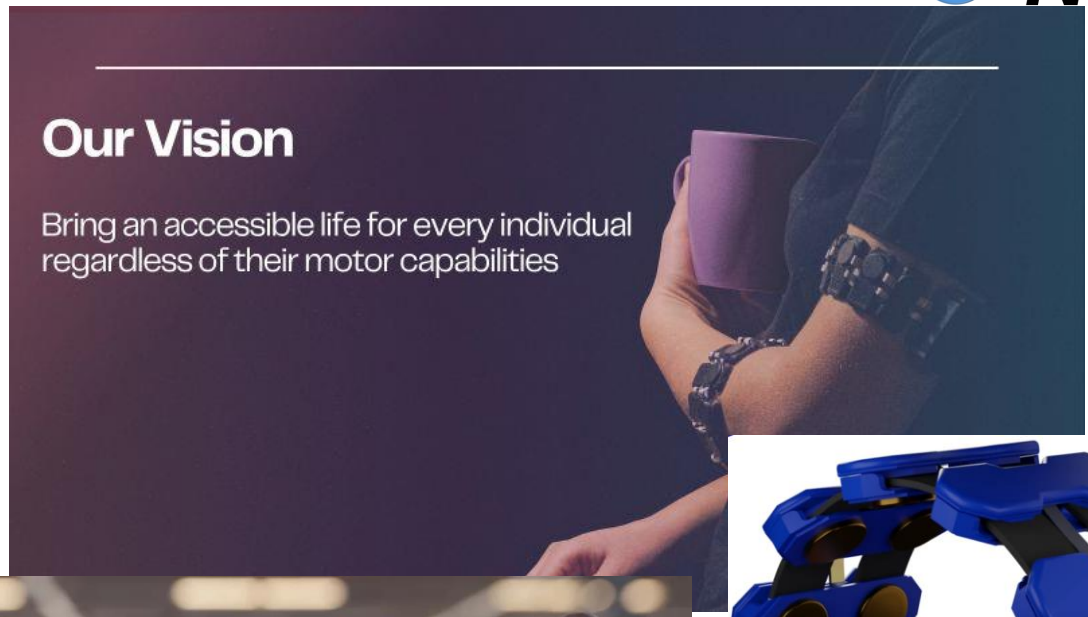
[2]



[4]

[5]

[6]

[3]

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[1] Myo Armband, Thalmic Labs
[2] Neubond
[3] AXON, Mindfeed
[4] MindRove
[5] gForcePro, OYMotion
[6] Meta Reality Labs

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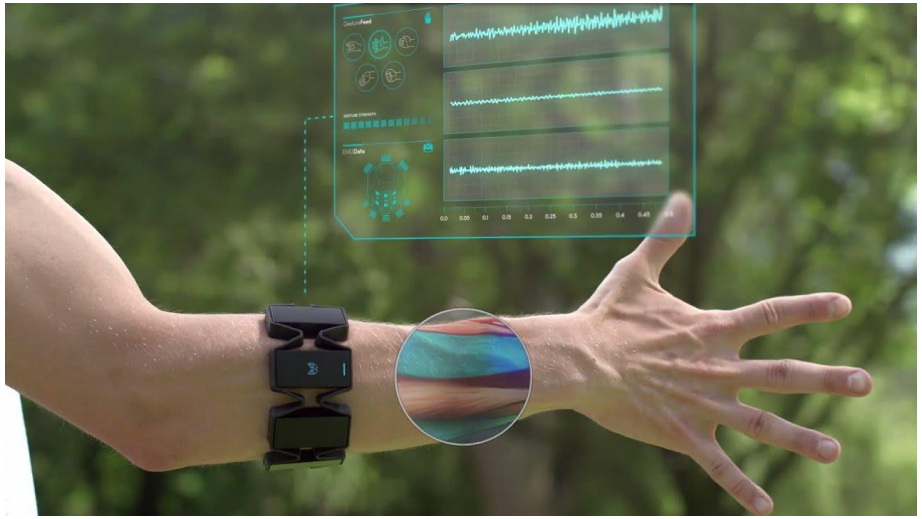
[1]



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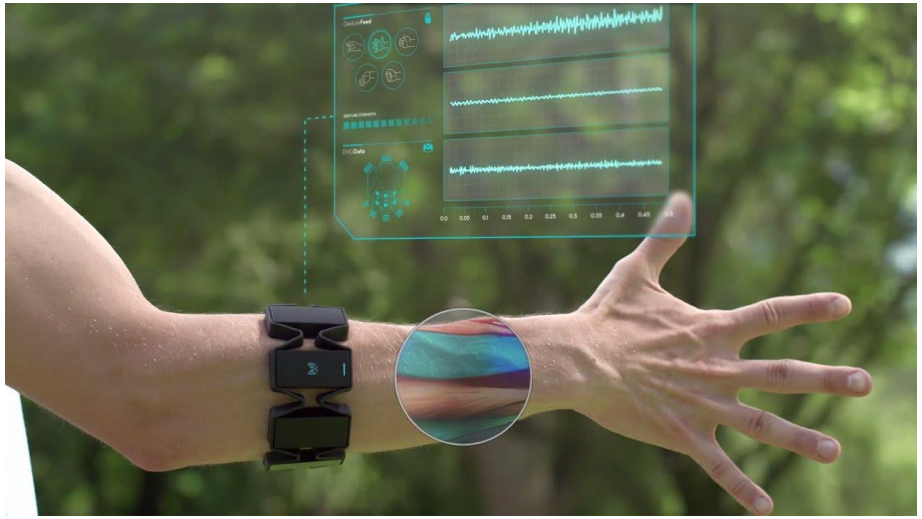

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The Gadget That Will Make You Feel Like Being A Jedi Is Just Months Away

Dave Smith Jun 24, 2014, 2:51 PM BST

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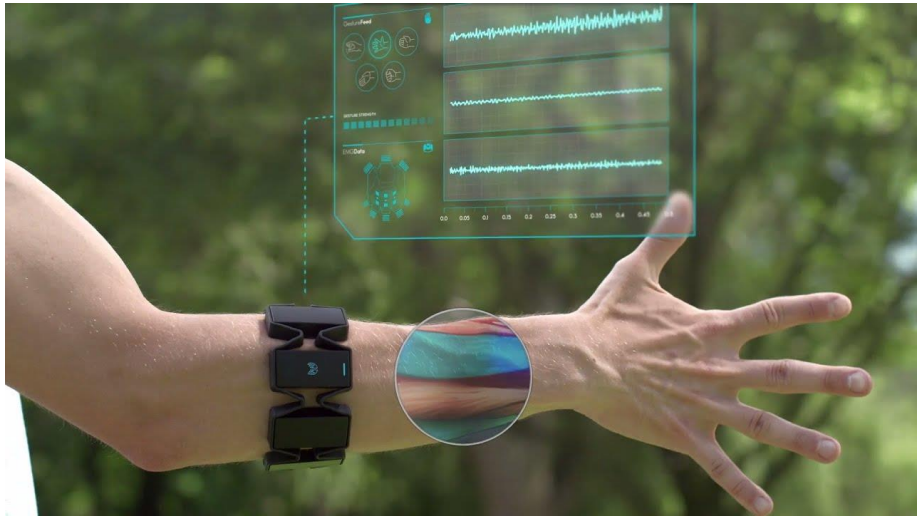

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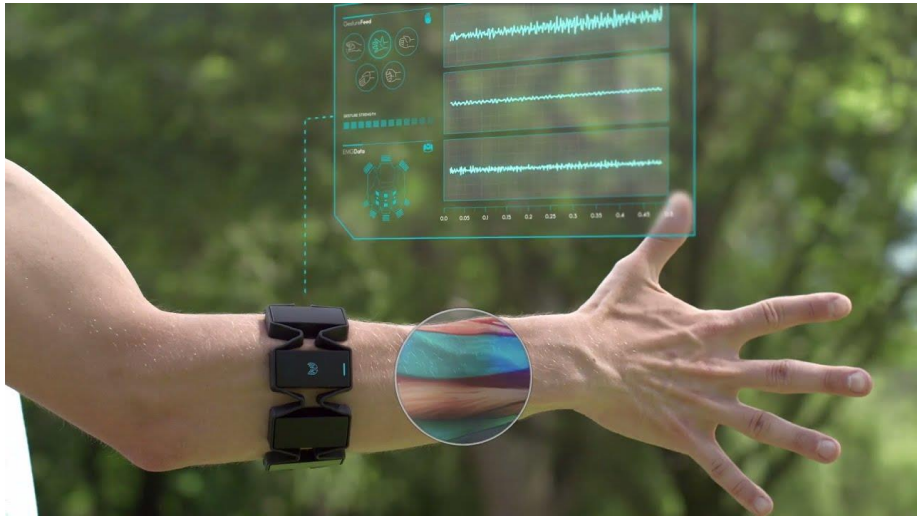

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Interfacing with the Brain is **Via Muscles** may be **Less Challenging**

But it is still **Very Challenging**

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[1] Myo Armband, Thalmic Labs

Could we try something else?

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sEMG is an **amazing** technology but is has
inherent limitations

”EMG cross talk, muscle coactivation, and limited sampling depth compromise the ability to estimate dexterous motor intent.”
- E. Scheme et al.

“While sEMG is the standard approach in commercial active prostheses, it presents inherent limitations, such as high sensitivity, to electrode location and electrode skin contact, as well as a relatively small detection depth”
– **X. Yang. et al.**

“The recorded EMG signals always contaminated by several types of background noises due to the type of electronic equipment, movement of electrodes and cables, movement of the subject during signal recording and other physiological factors which make it very difficult for classifying.”
- A. Sultana et al.

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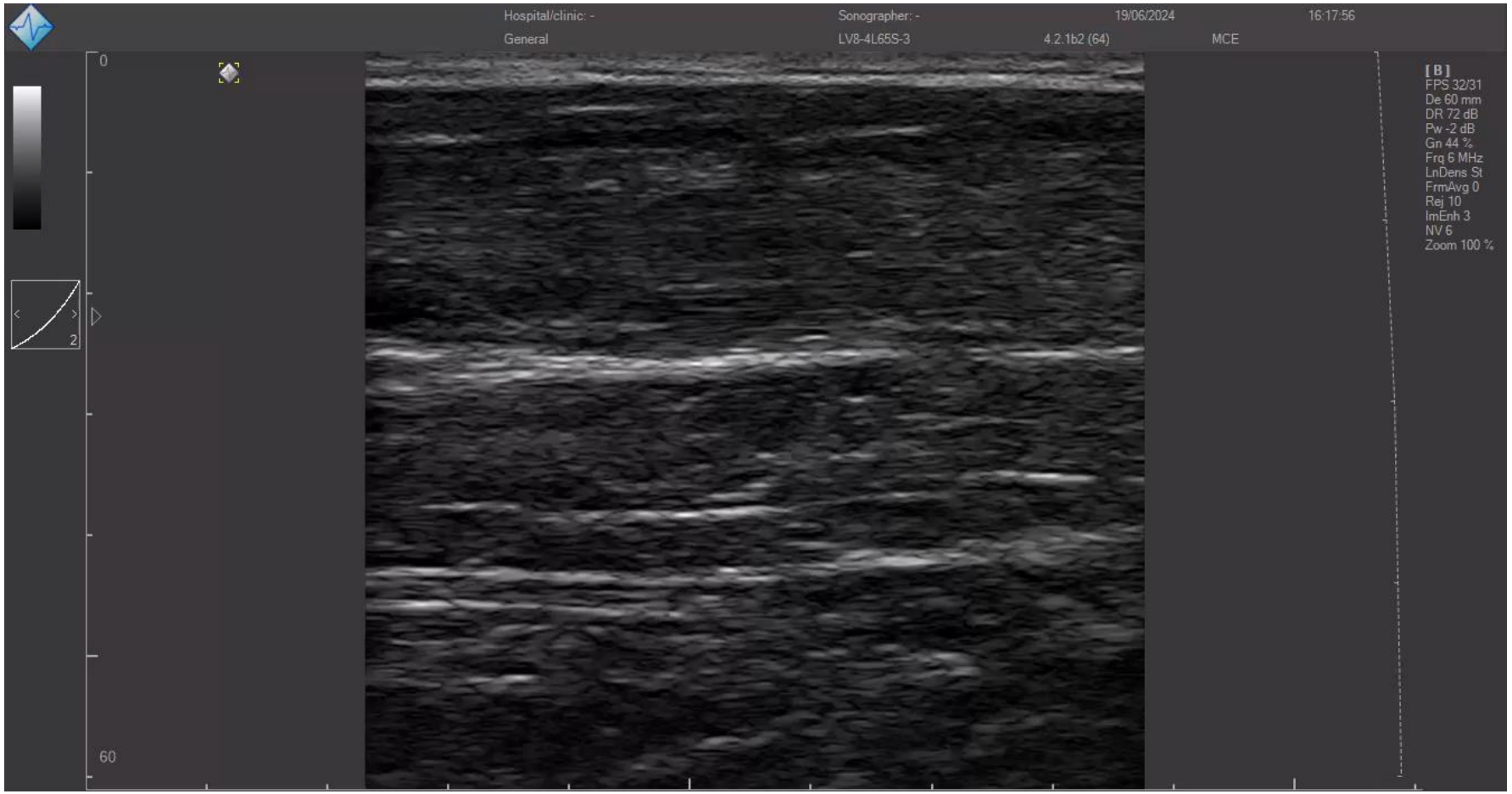
Could we use other signal modalities?

- **Ultrasound** can be used to image the Musculoskeletal system



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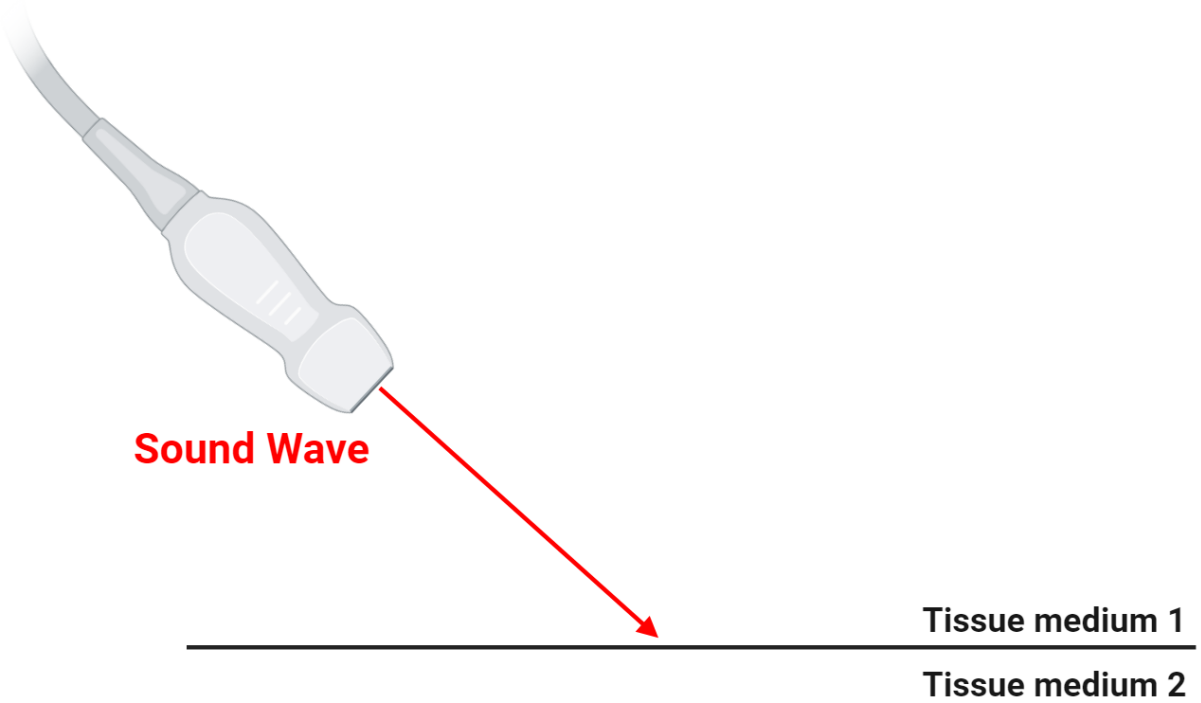
Basic Principles



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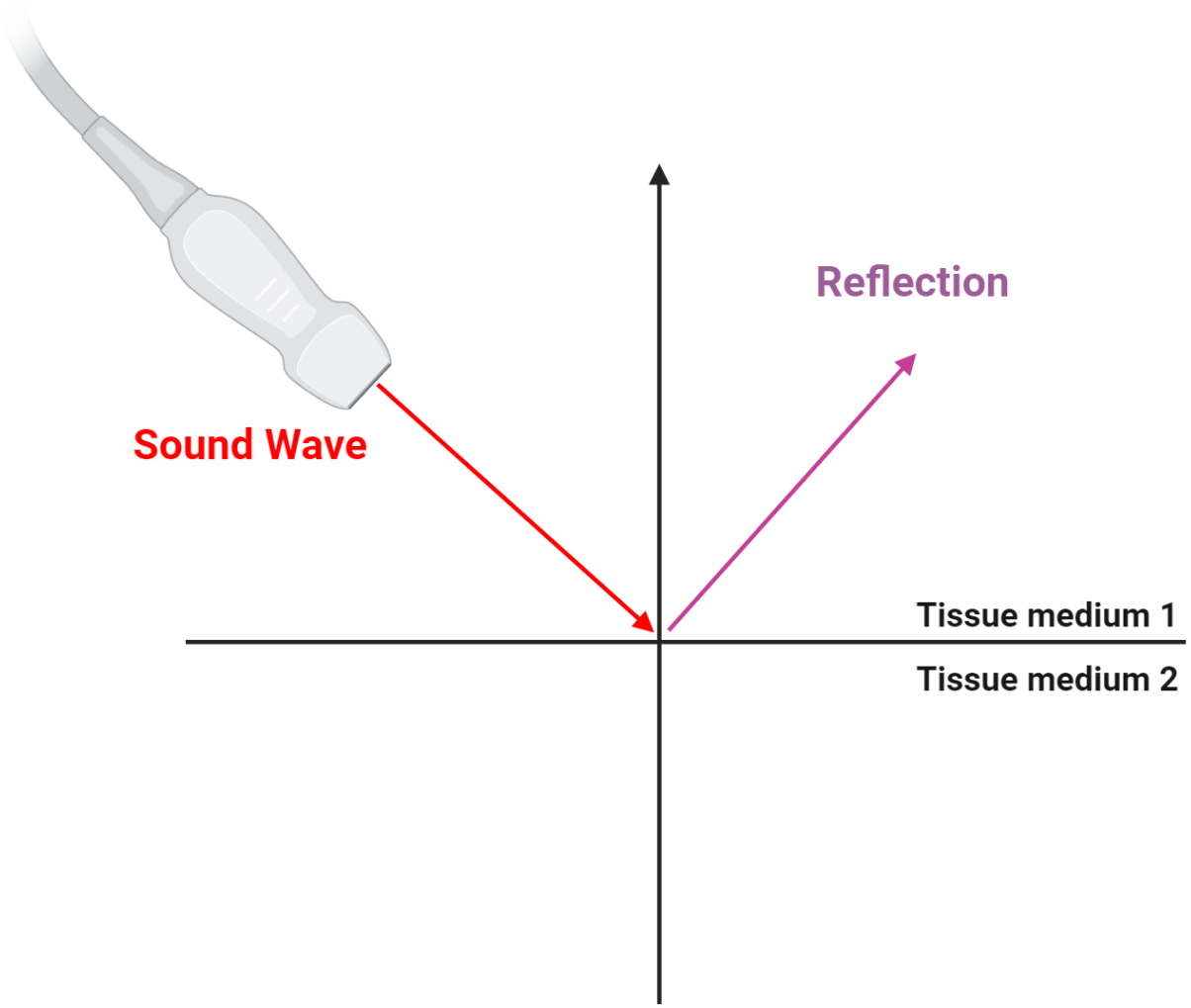

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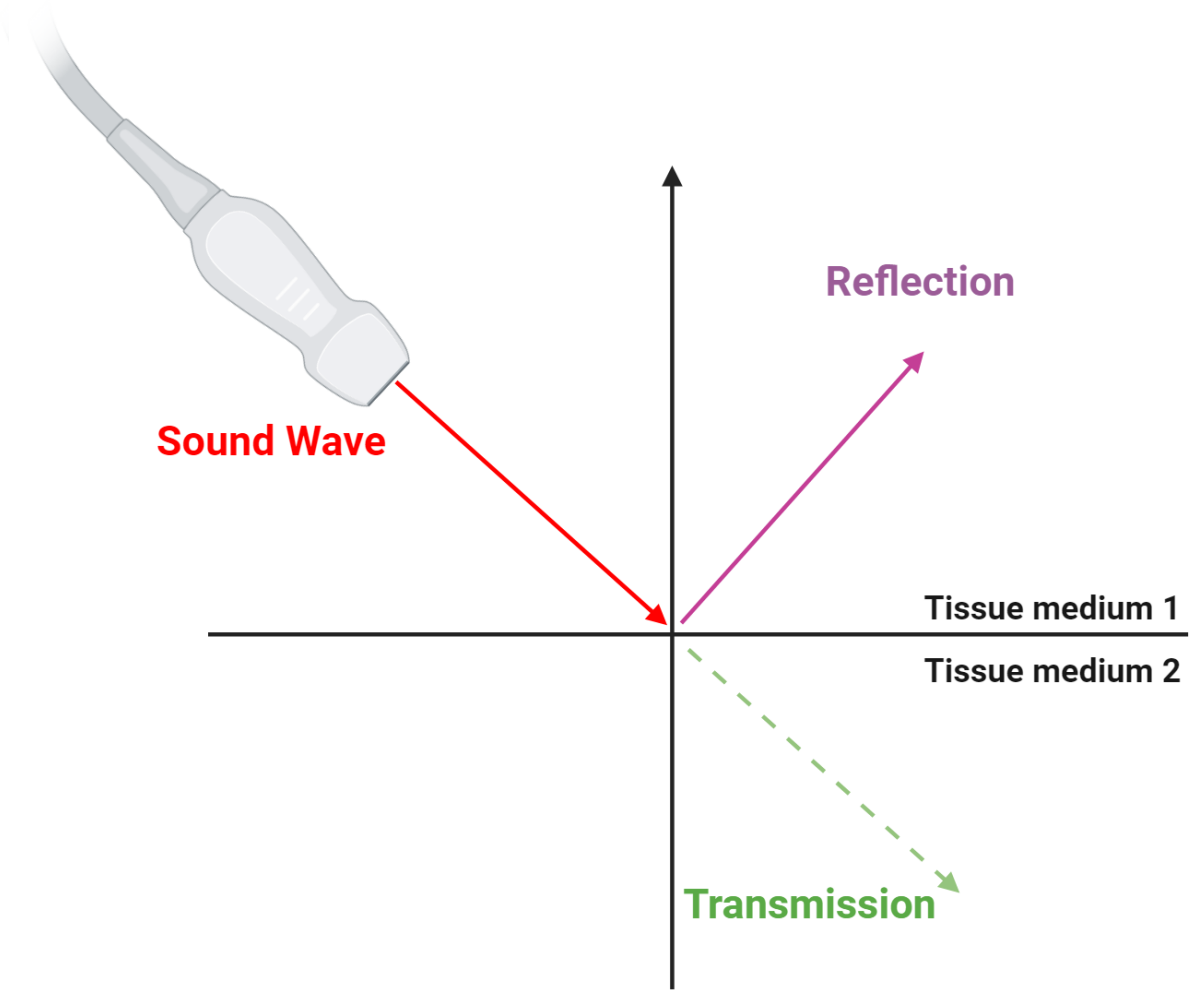

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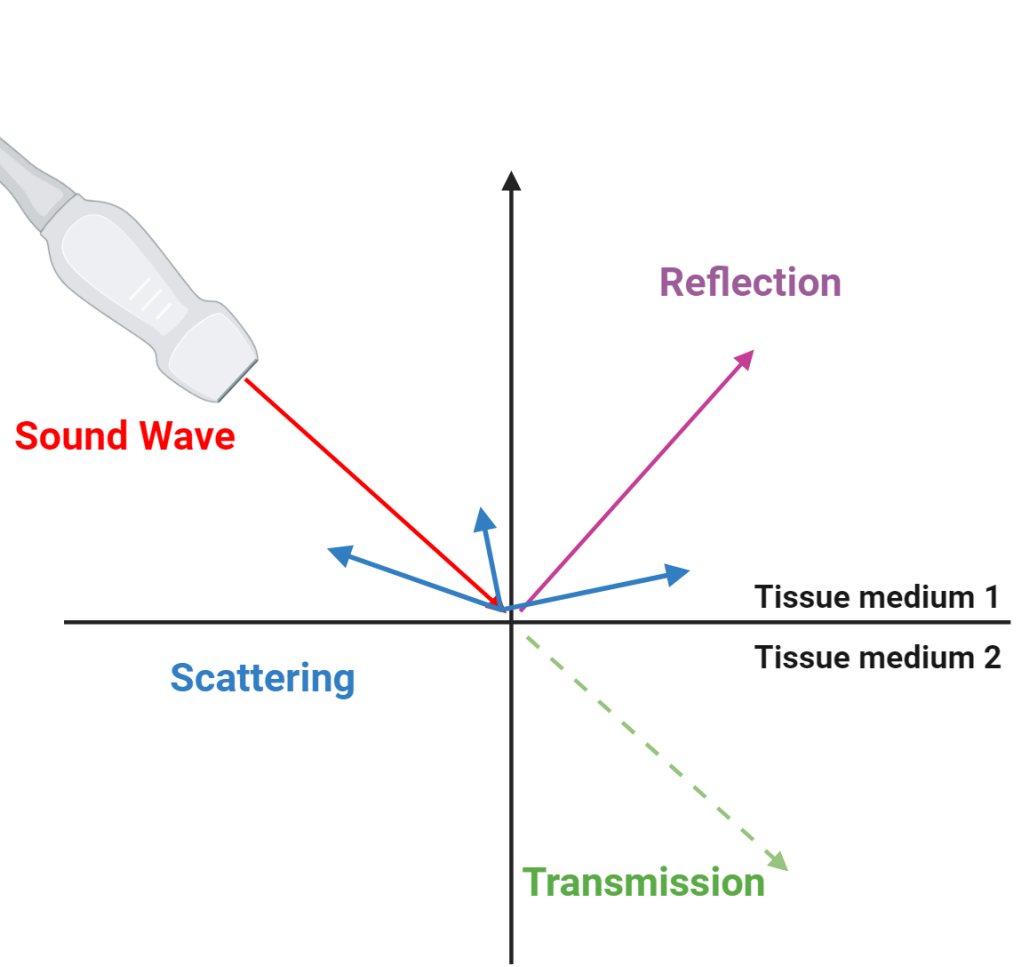

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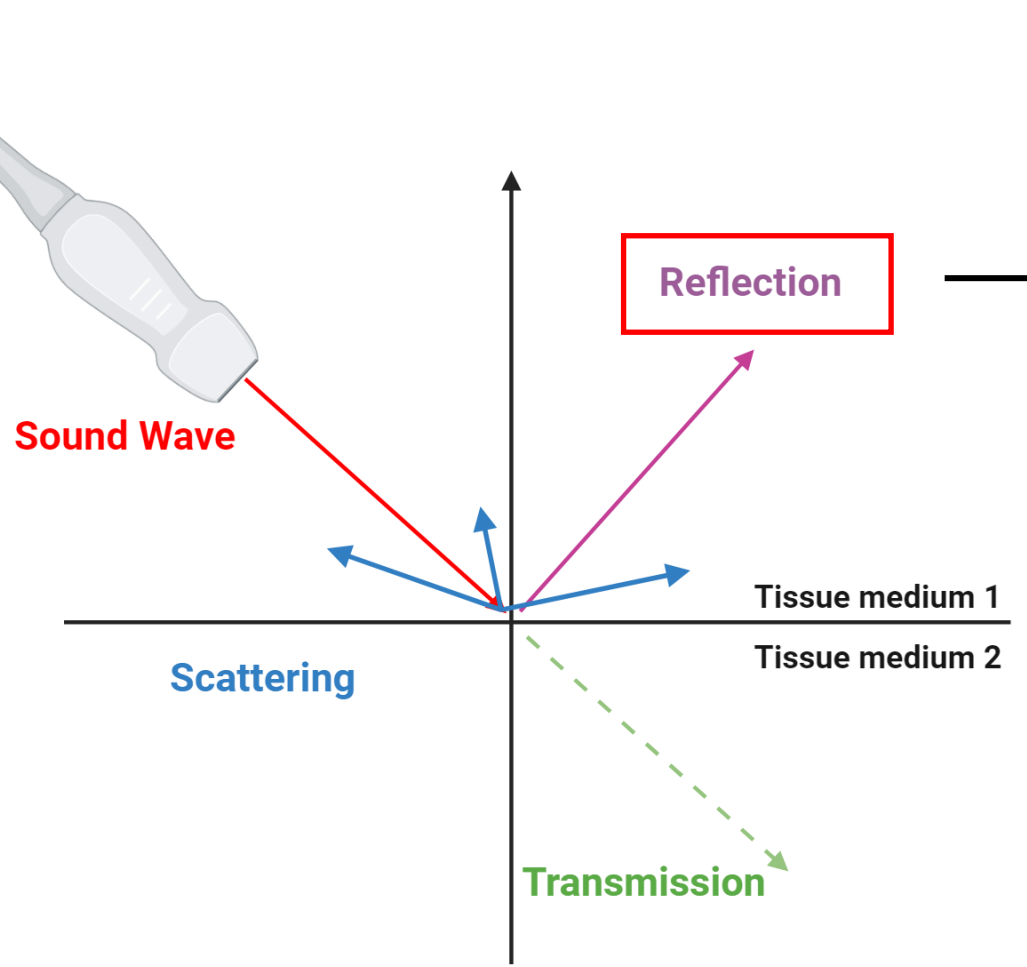

Medical Ultrasound is mostly interested in reflections

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Basic Principles

- Unlike EMG, Ultrasound is not biologically generated

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- Unlike EMG, Ultrasound is not biologically generated

Ultrasound acquisition has 2 Phases

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↓

Ultrasound acquisition has 2 Phases

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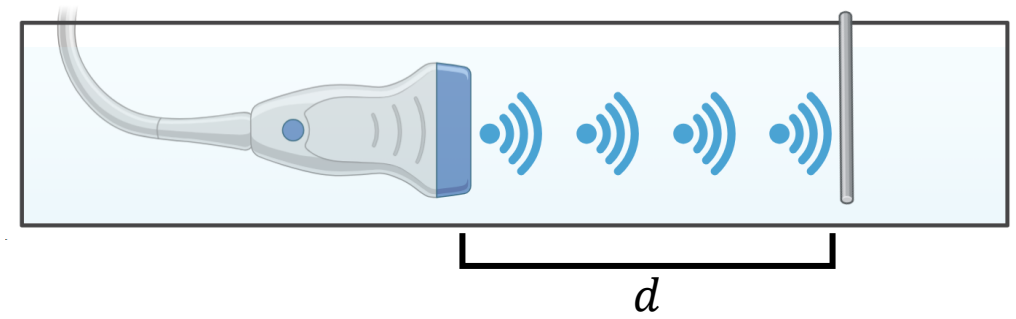

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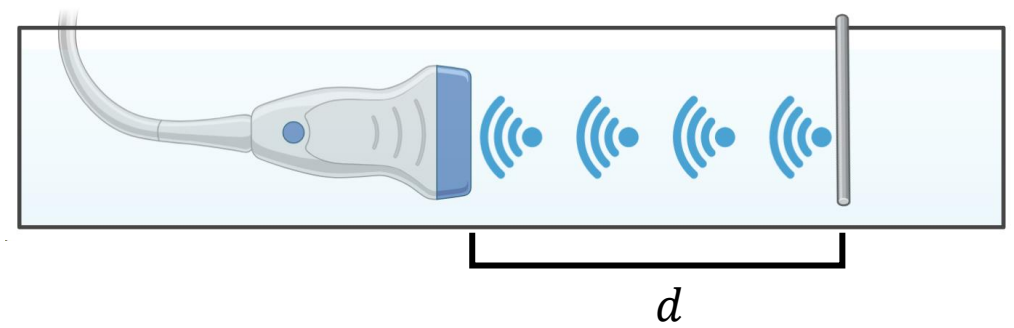

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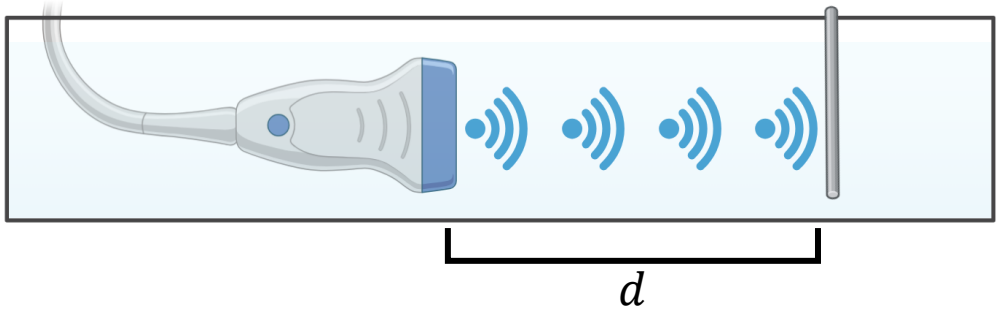

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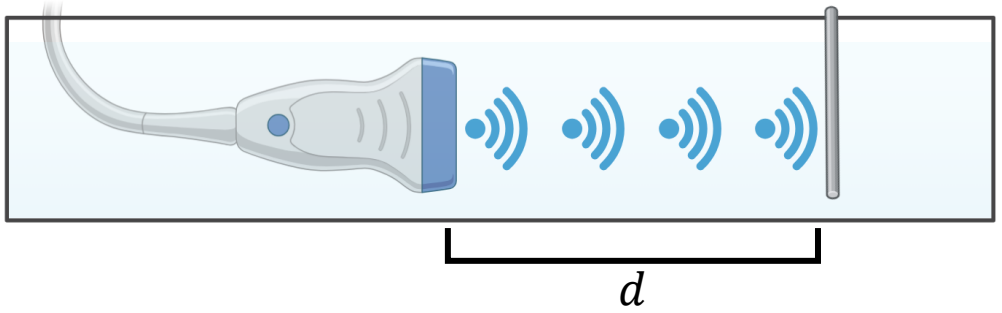

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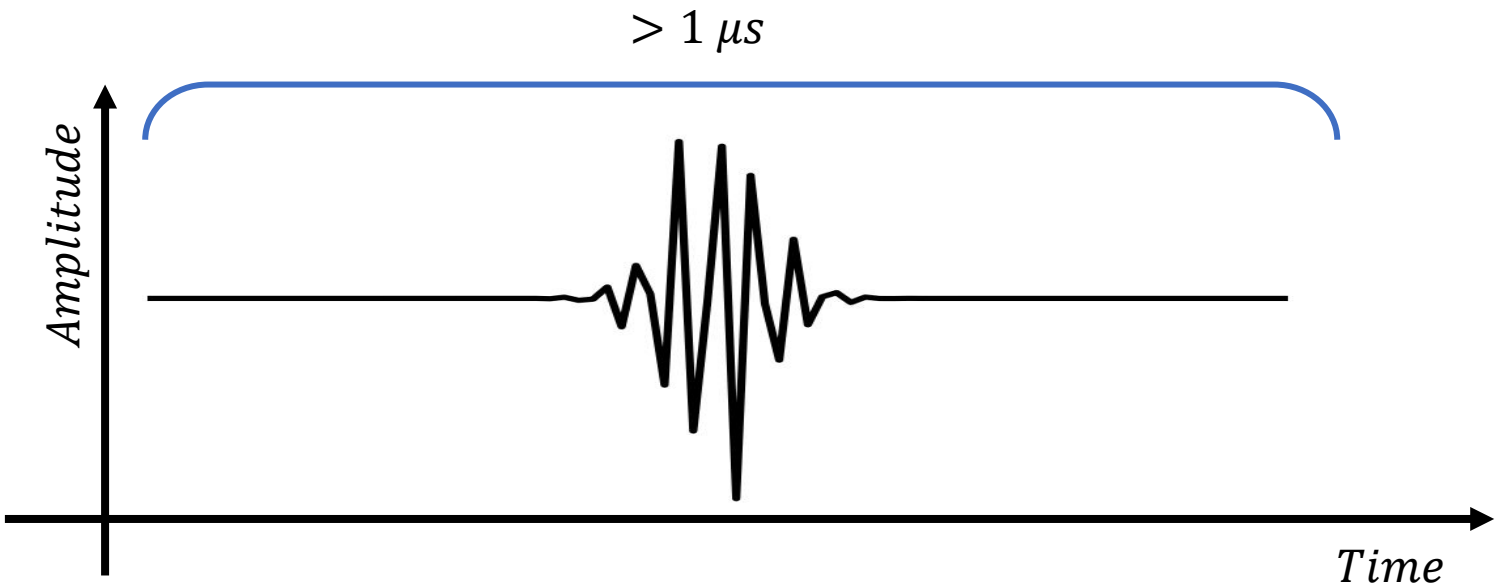

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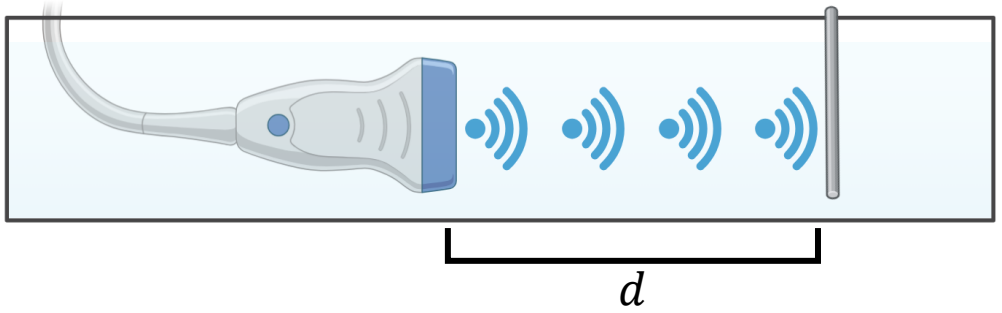

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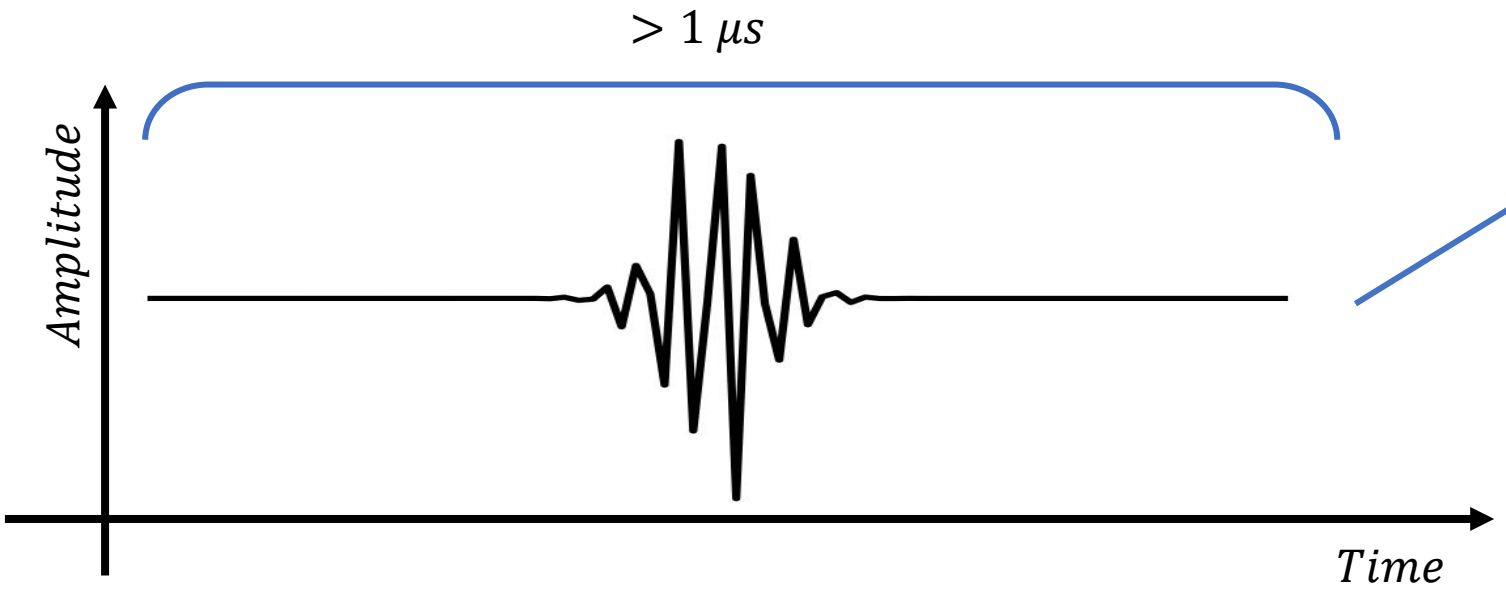

Various parameters can be defined:

- Centre Frequency
- Bandwidth
- Voltage
- …..

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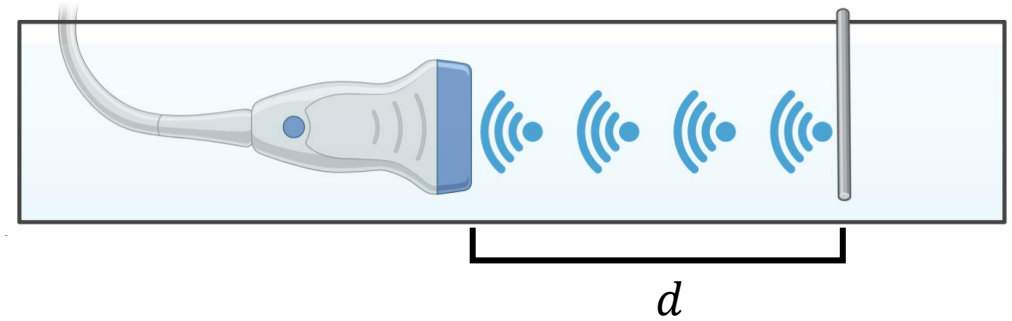

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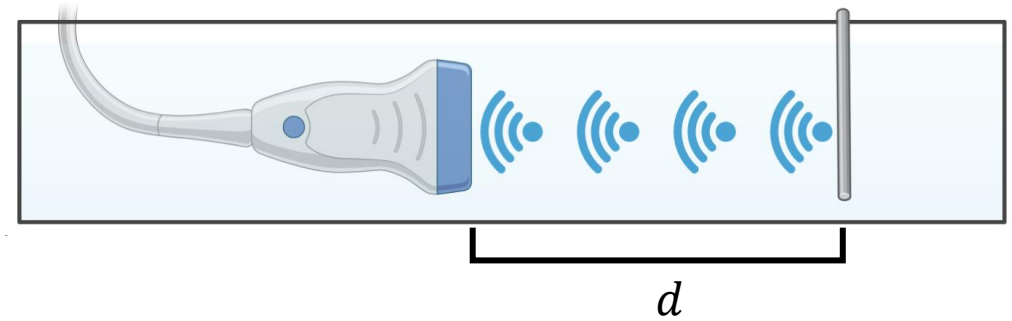

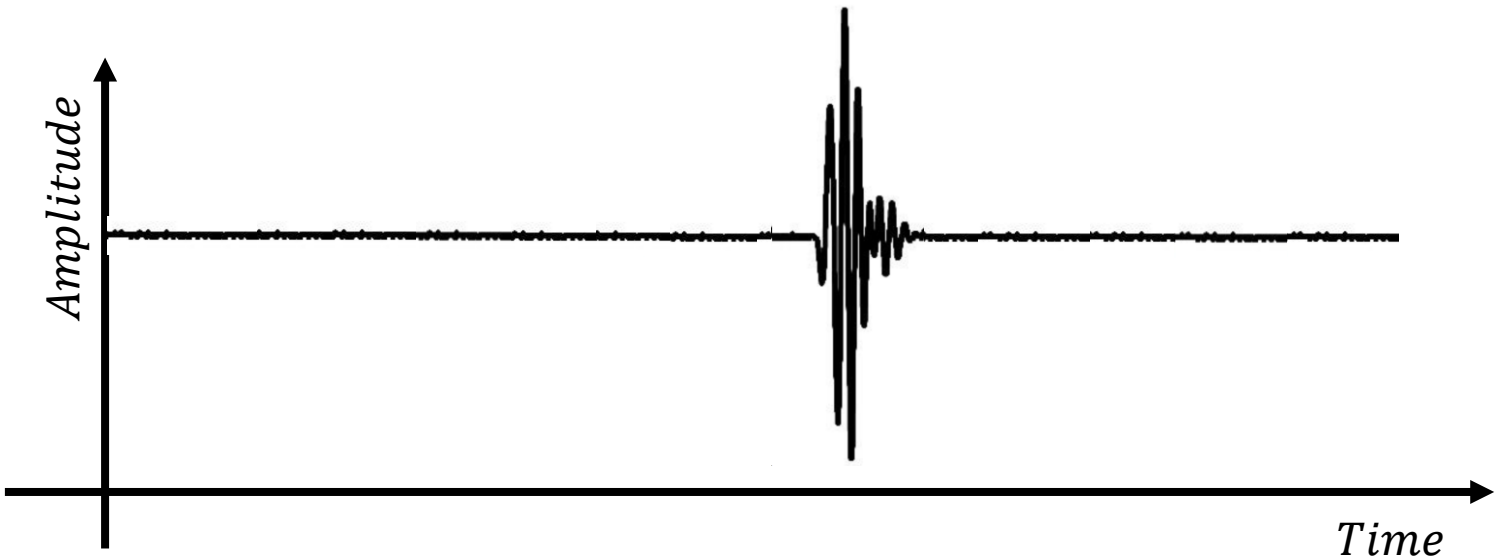

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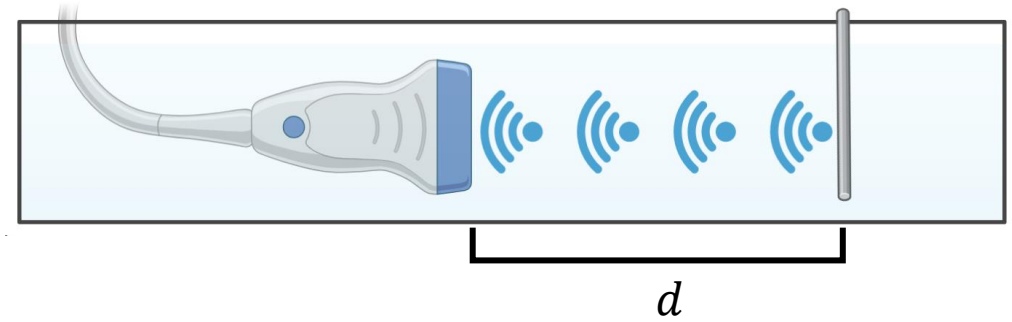

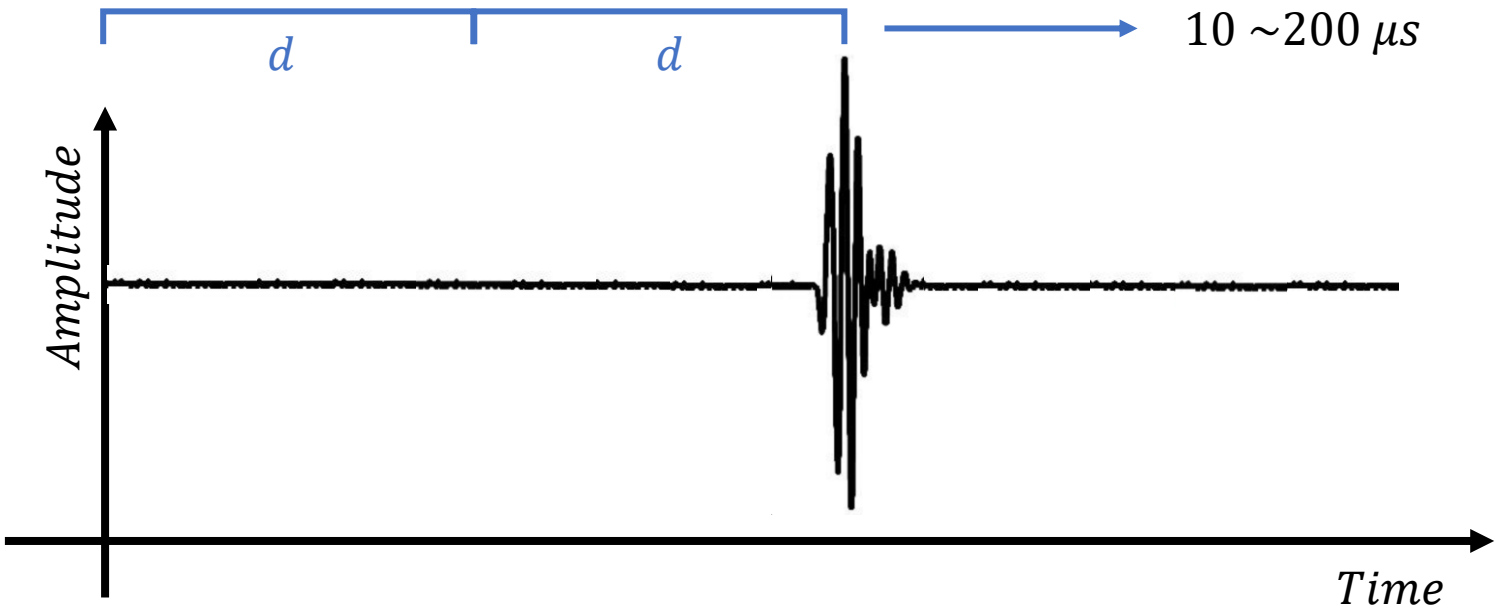

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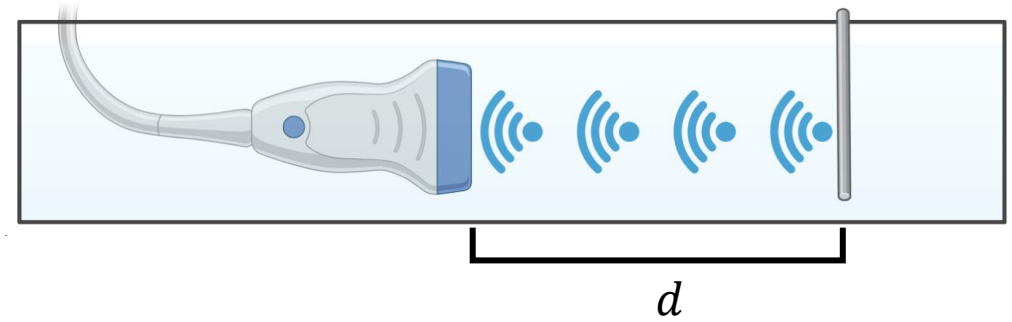

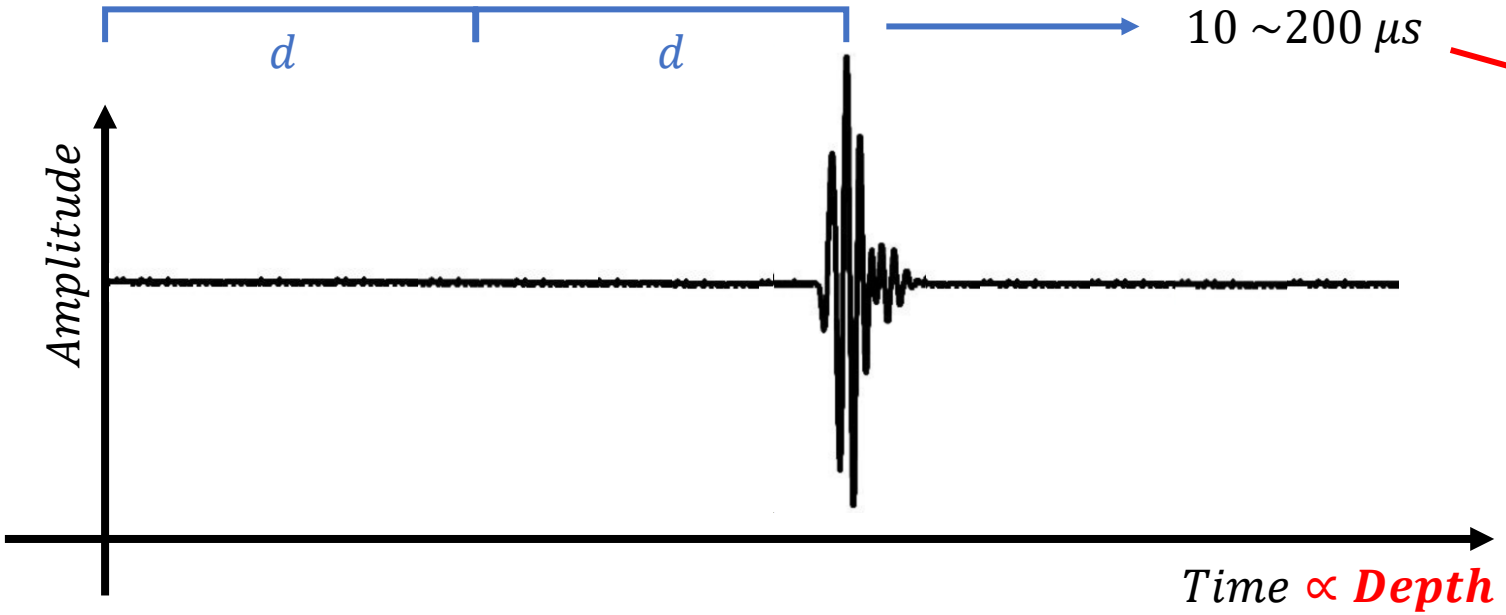

$10 \sim 200\ \mu s$

Time (t) can be converted to penetration depth

$$Depth = \frac{t\ * c_{soft\ tissue}}{2}$$

$$c_{soft\ tissue} = 1450\ m/s$$

Therefore,

$$Depth \approx\ 2cm \sim 15cm$$

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Ultrasound Modalities

- Ultrasound principles can be used to in a number of different imaging modalities:
  - A-mode
  - M-mode
  - B-mode
  - Colour Doppler, Power Doppler, Spectral Doppler
  - Transient elastography
  - Shear-wave elastography
  - Strain Imaging
  - Microbubble Ultrasound Super-resolution
  - Ultrasound Tomography
  - ……

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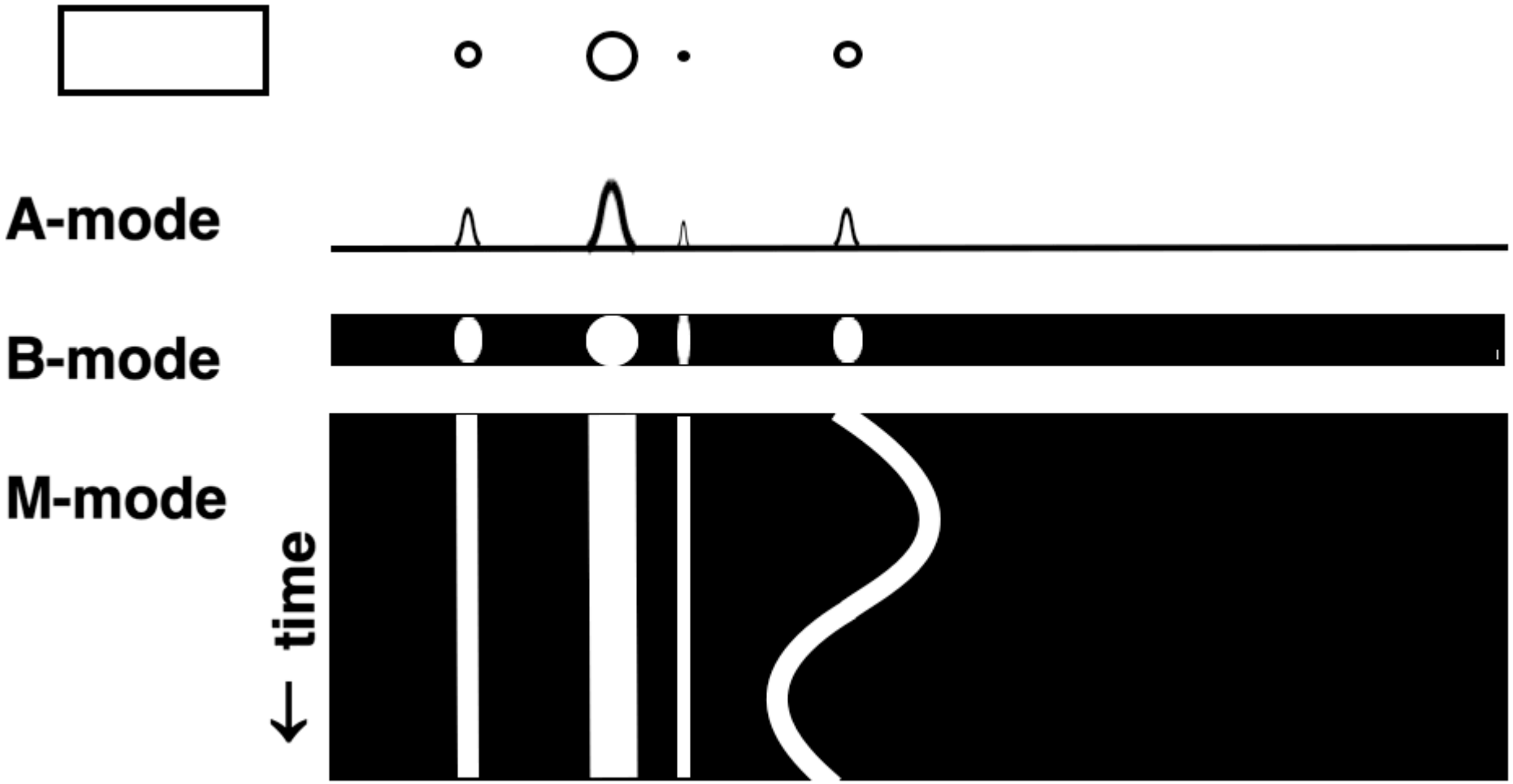

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[1] https://folk.ntnu.no/stoylen/strainrate/Basic_ultrasound.html

Ultrasound Modalities

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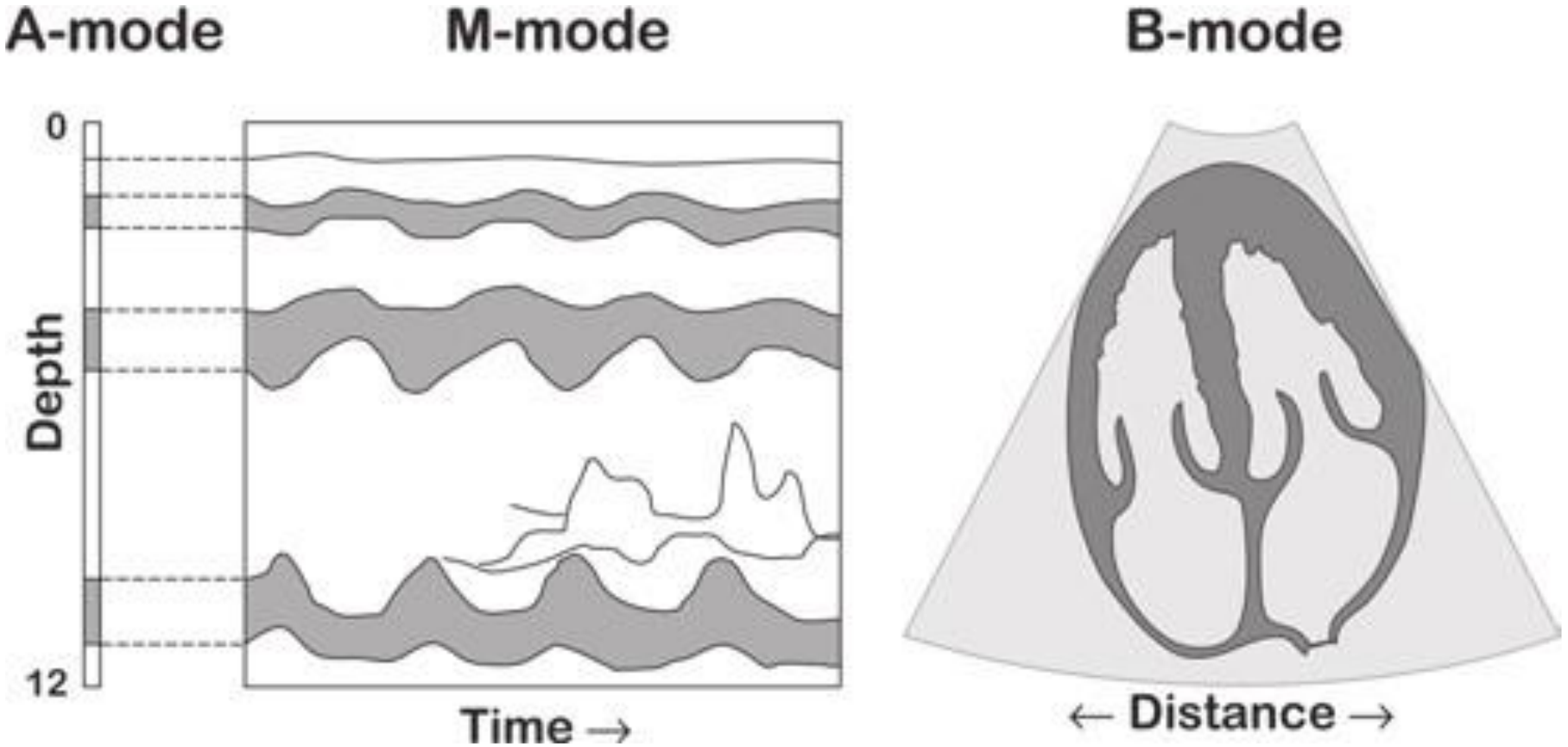

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[1] S. Conrad, "Focused Echocardiography in the ICU," 2010, pp. 139-181.

Ultrasound Modalities

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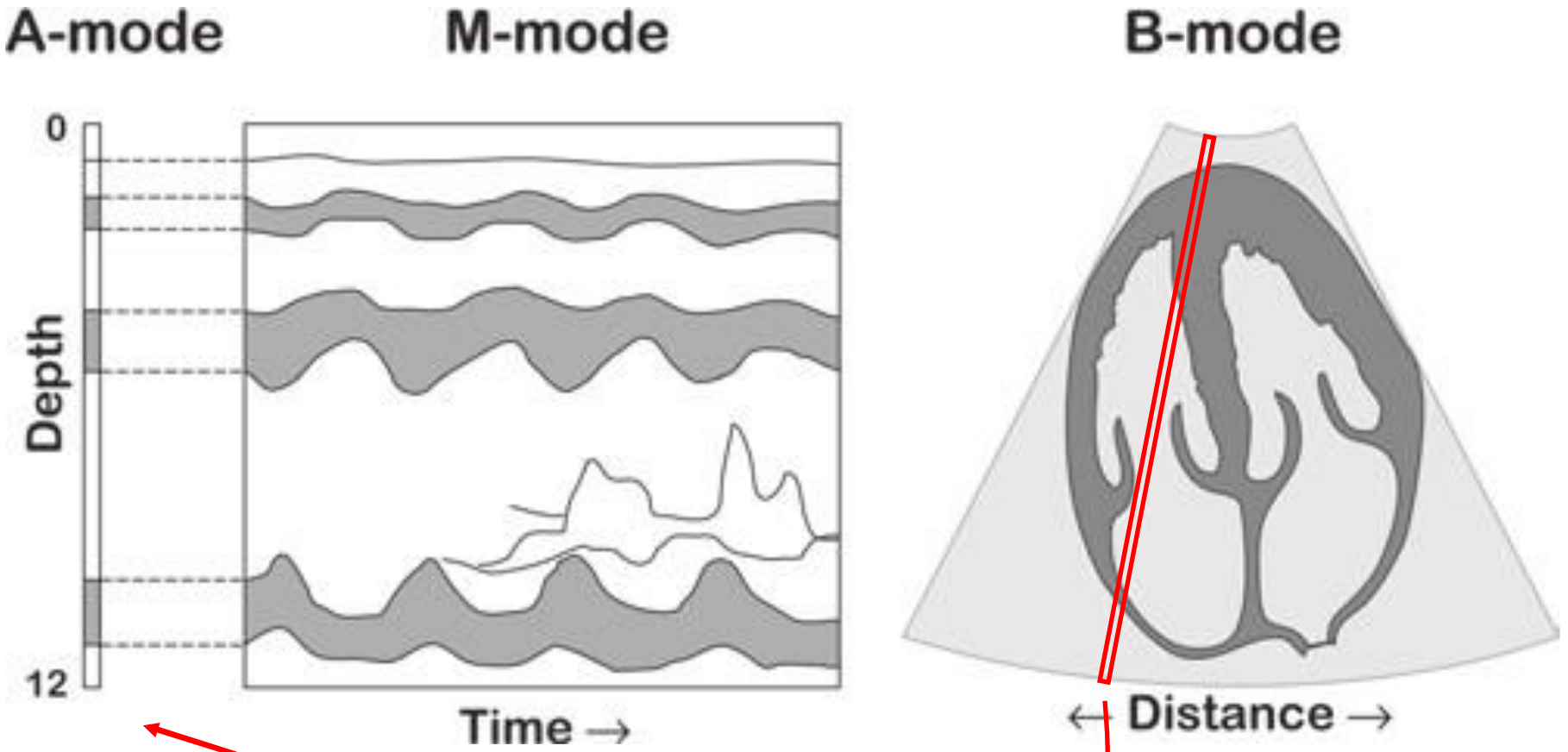

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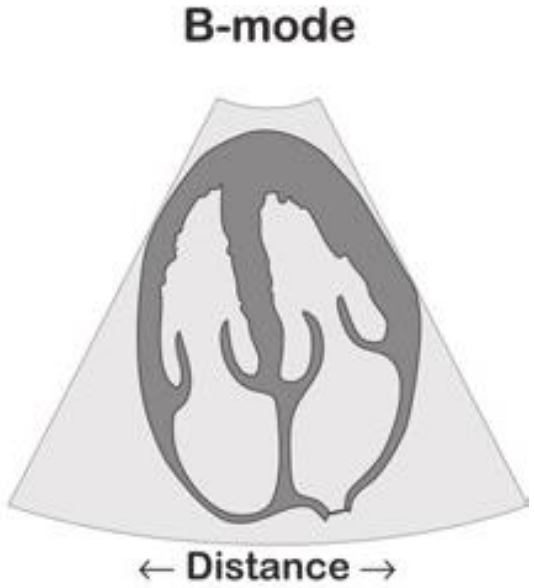

Conventional
“line-by-line”

Ultrafast B-mode
“Plane Wave”

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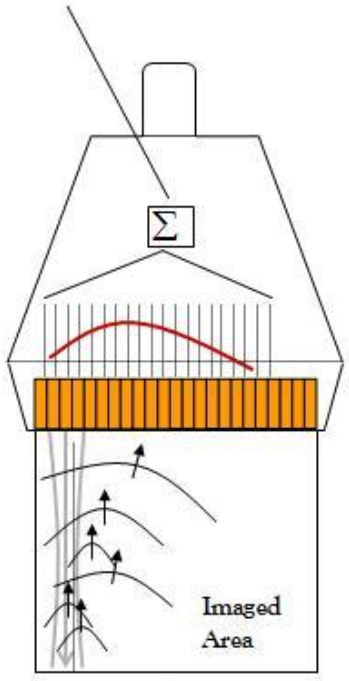
Conventional vs Ultrafast US



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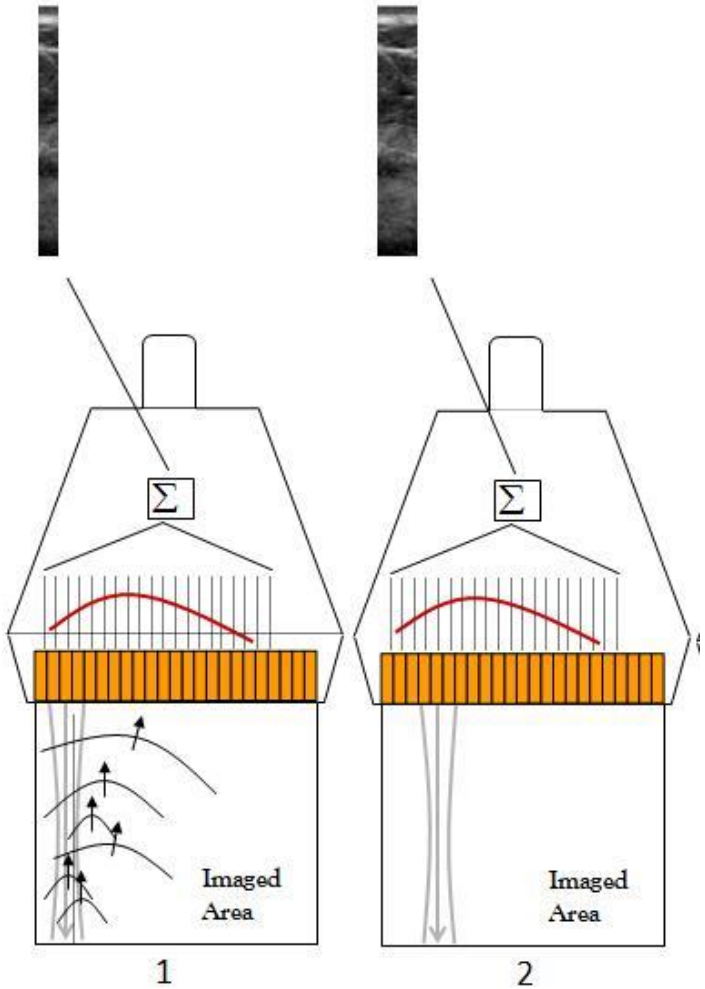
[1] Ultrafast Ultrasound Imaging, Ultrasound Imaging - Medical Applications

Conventional vs Ultrafast US



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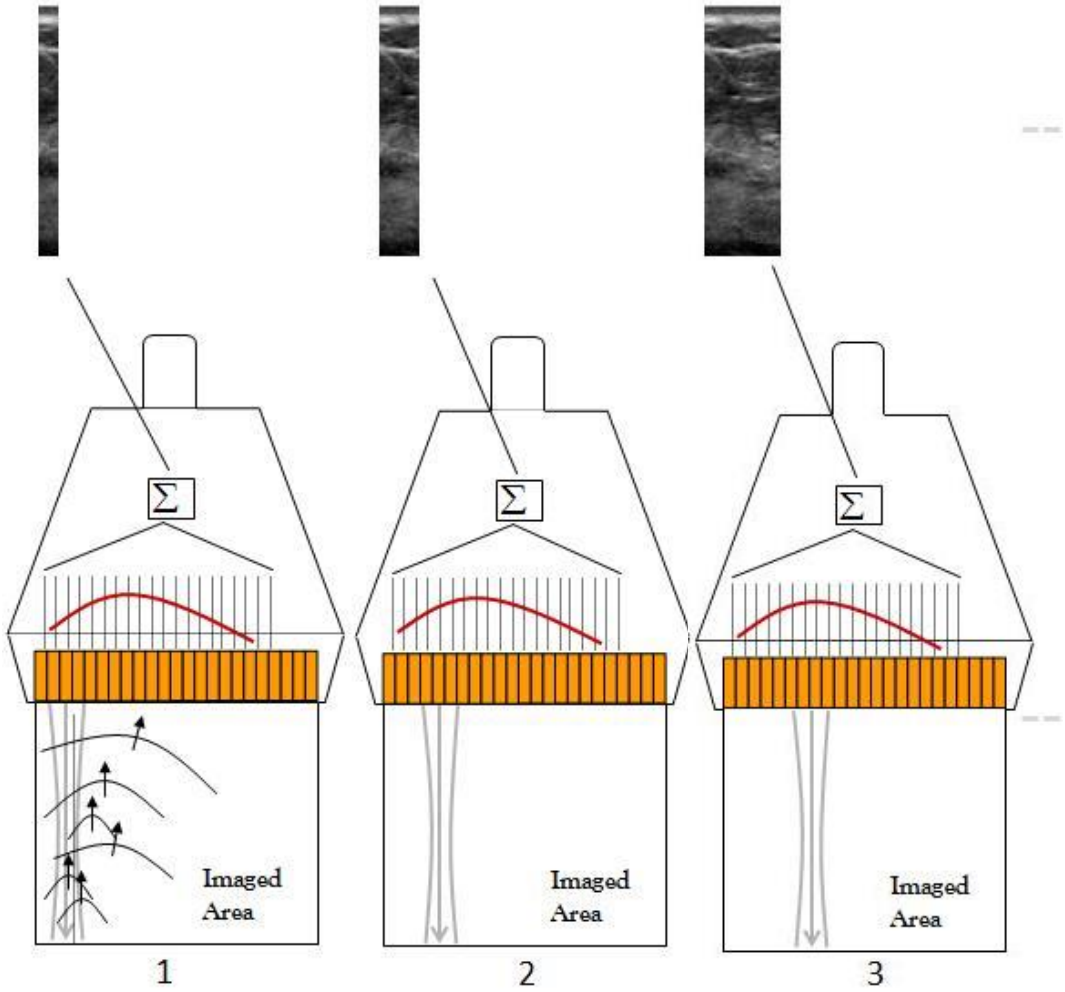

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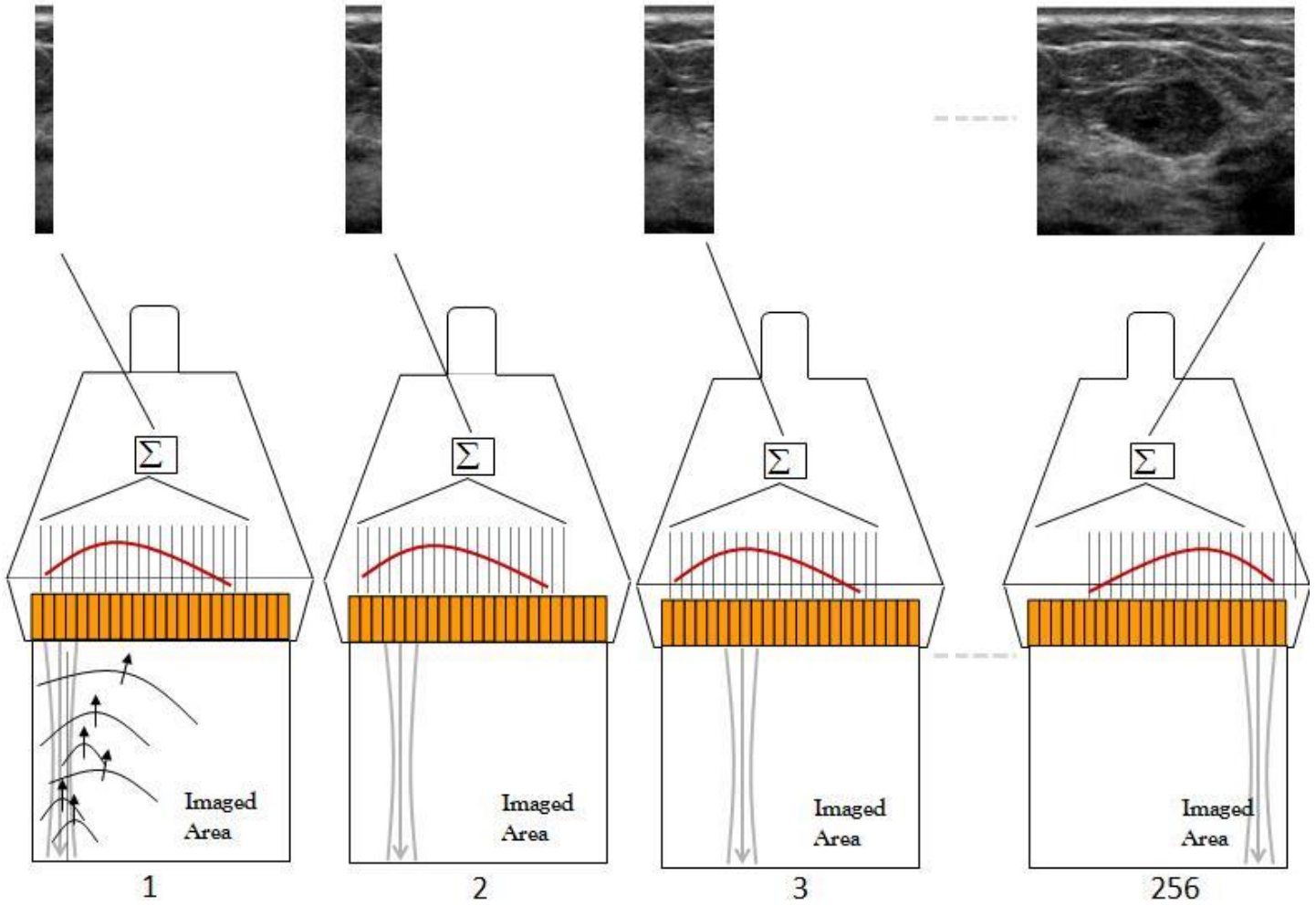

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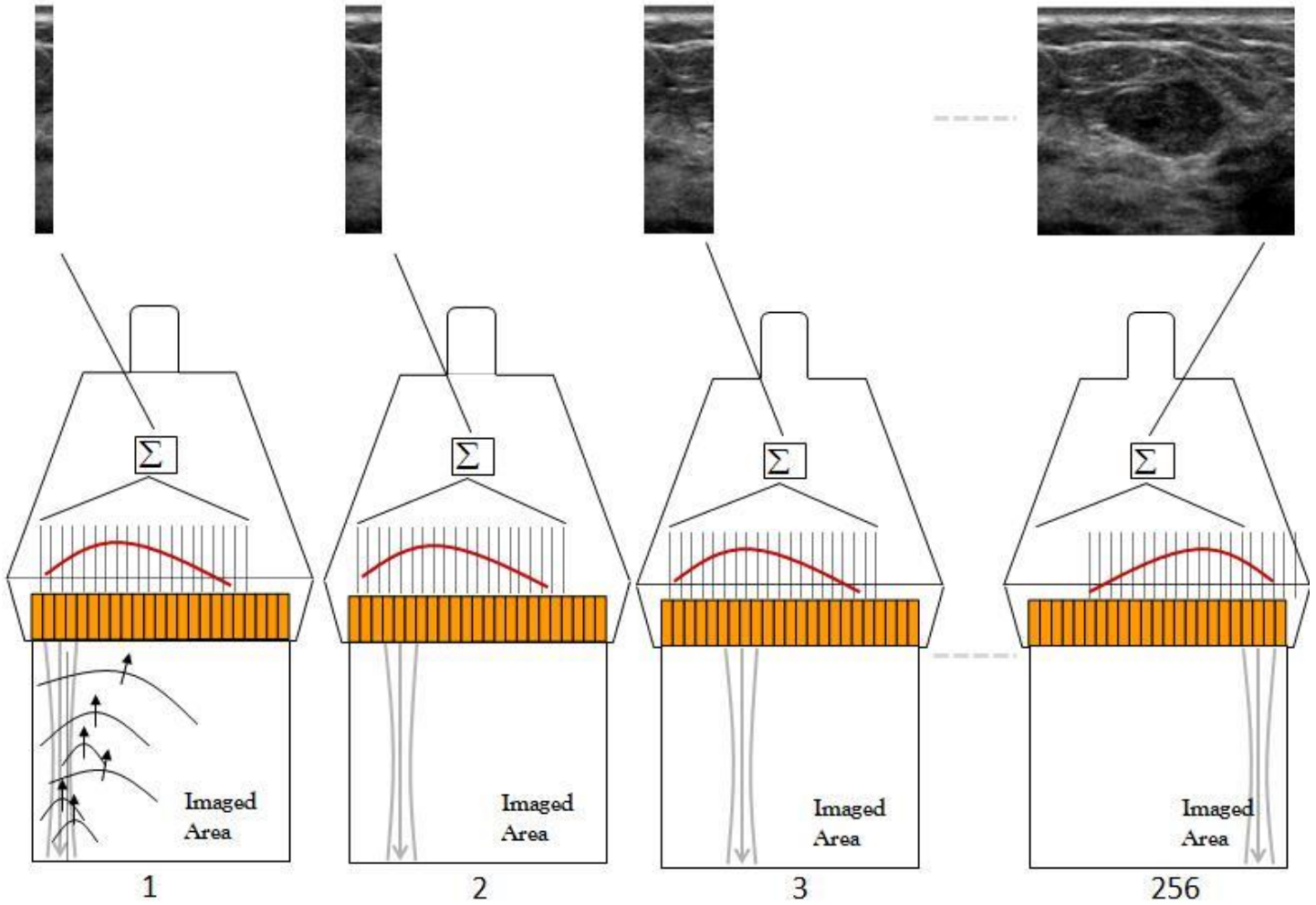

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Time to build and image can be expressed as:

$$T_i = \frac{N_{lines} * 2 * depth}{c}$$

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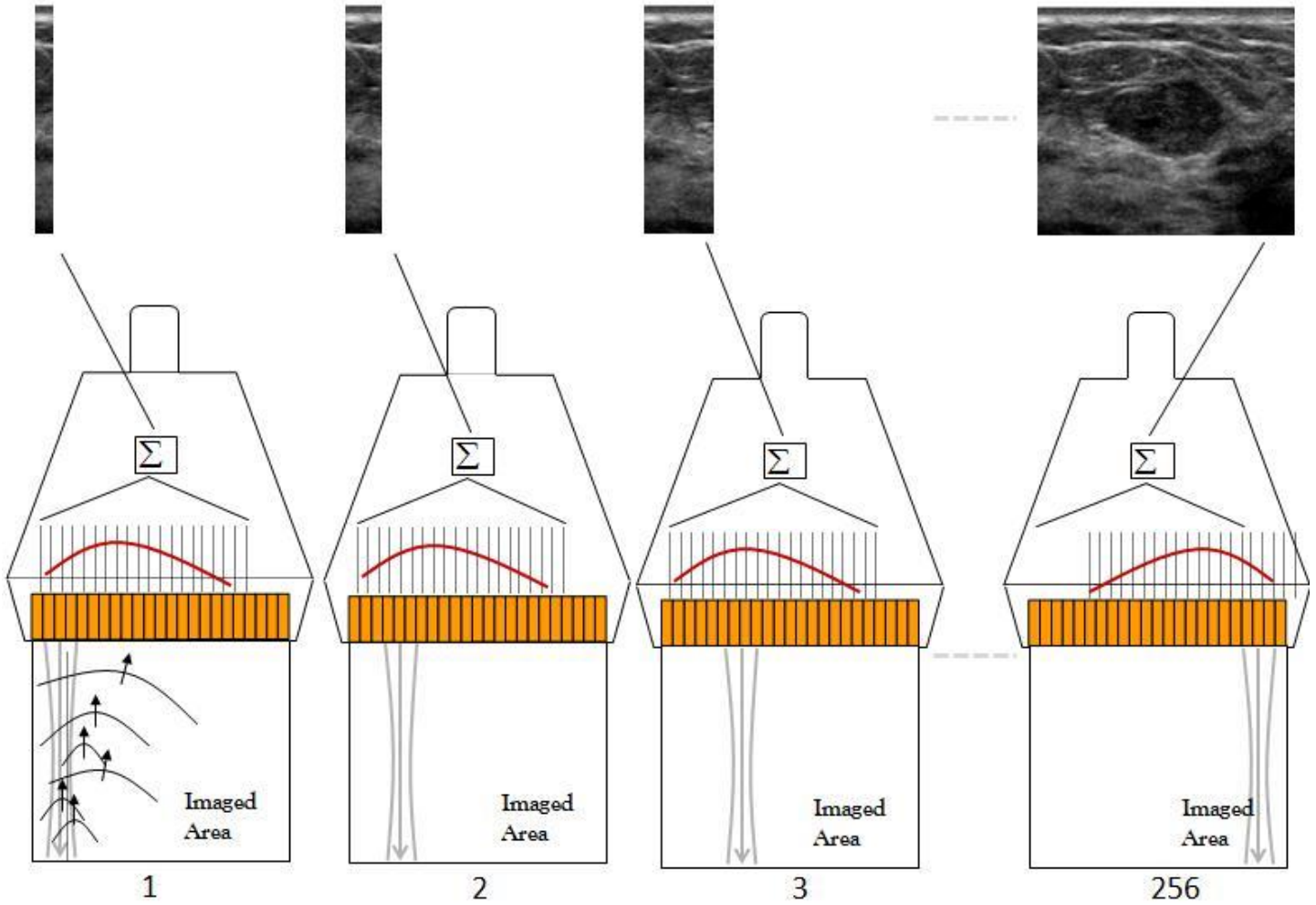

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$$c = 1540\ m/s$$
$$N_{lines} = 256$$
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Therefore:

$$T_i \approx 60\ Hz$$

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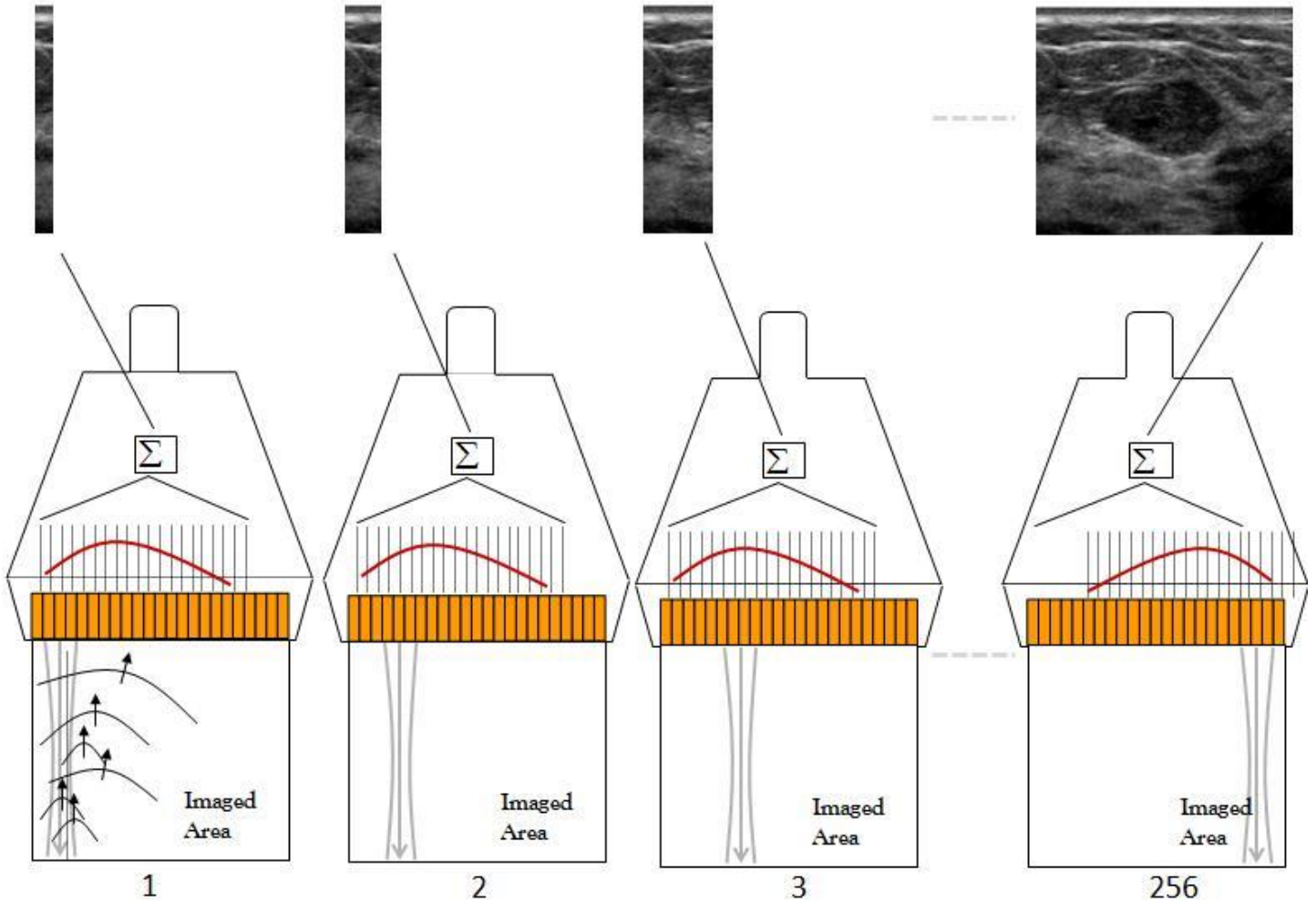

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Conventional US applications have theoretical frame rate limits from $20{\sim}150Hz$

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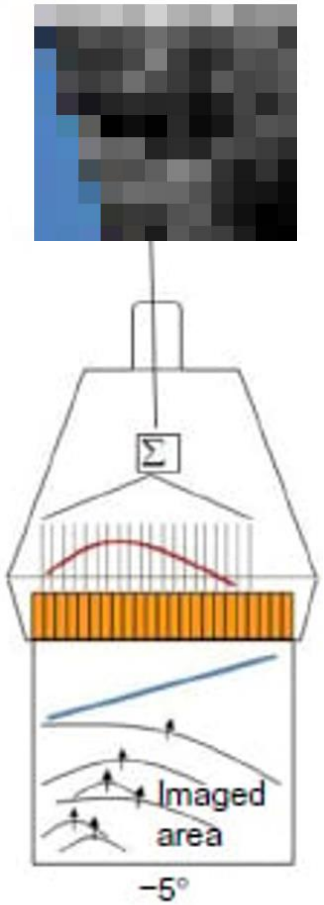

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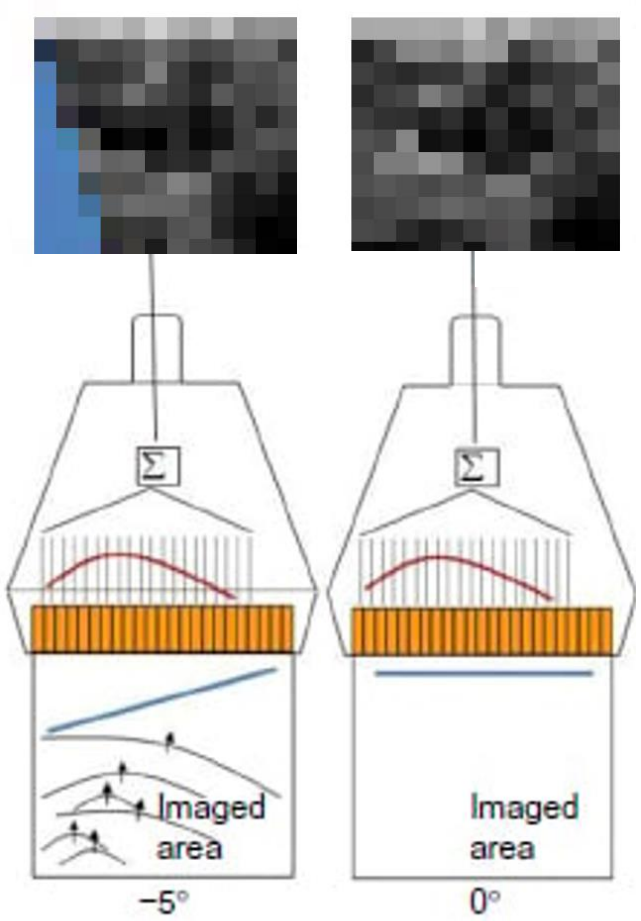

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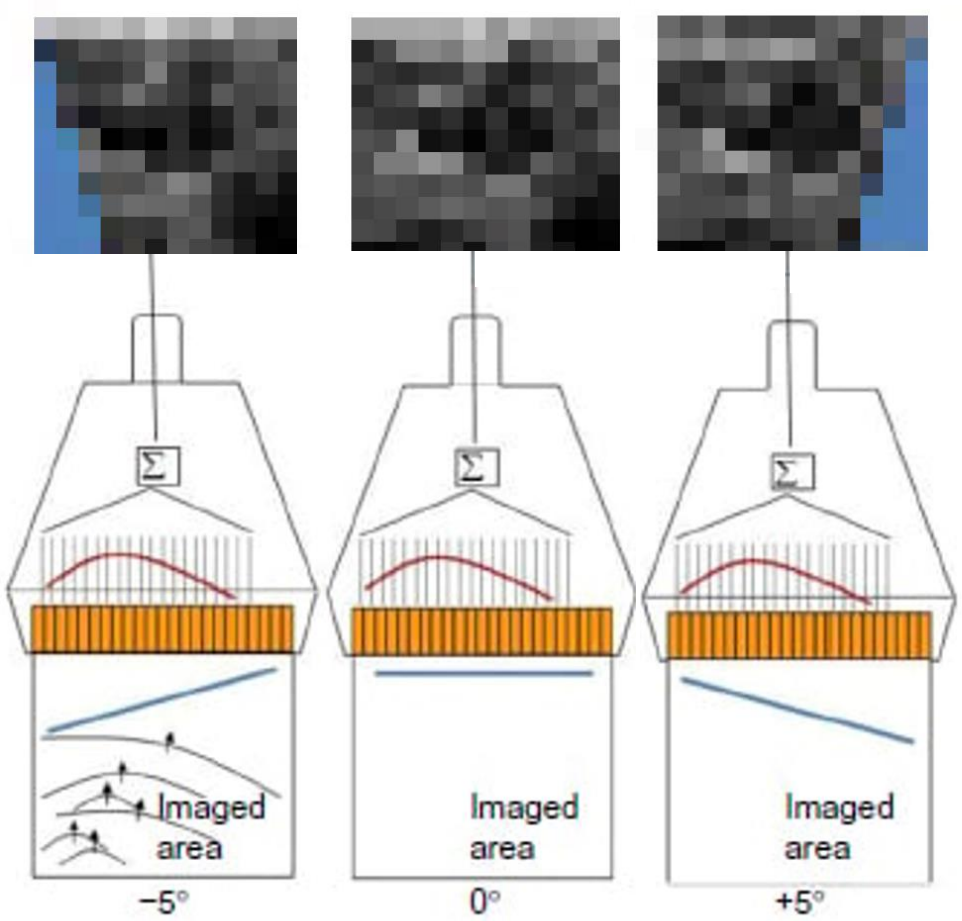

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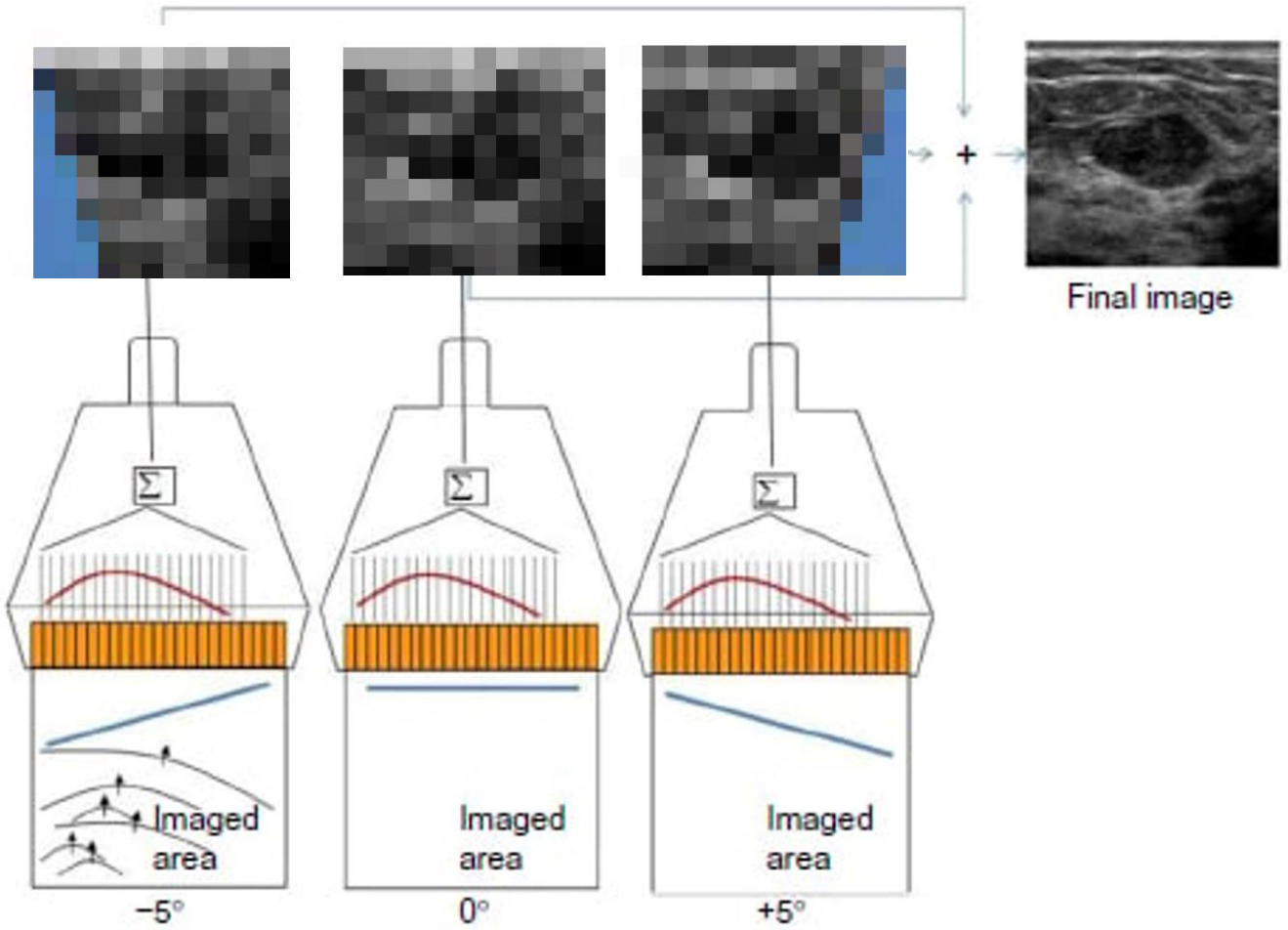

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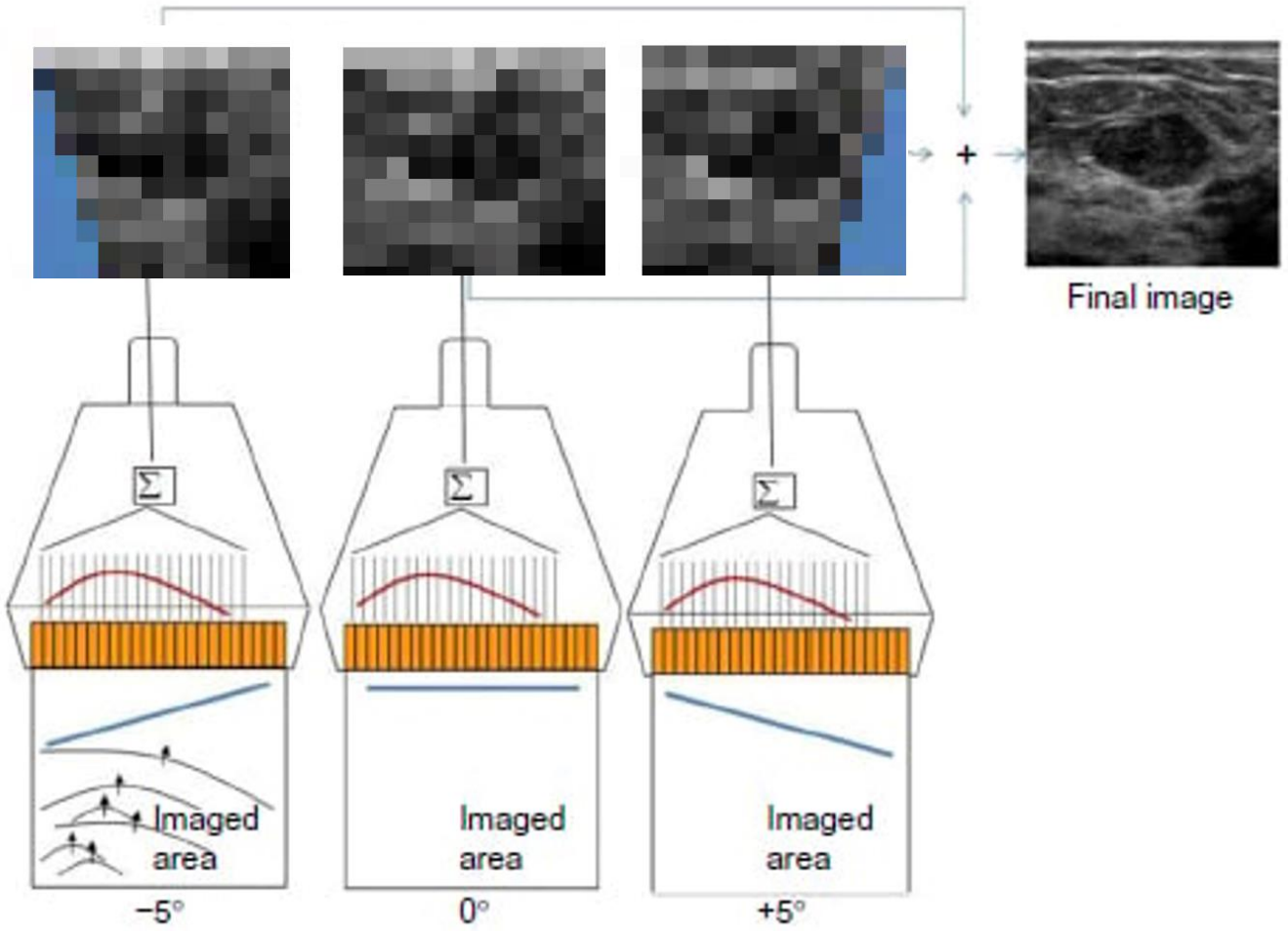

[1]

Going back to our previous equation:

$$T_i = \frac{N_{angles} * 2 * depth}{c}$$

Given:

$$c = 1540\ m/s$$
$$N_{angles} = 11$$
$$depth = 5\ cm$$

Therefore:

$$T_i \approx 1400\ Hz$$

Ultrafast US unlocks theoretical frame rates up to $\sim 5000\ Hz$

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What Unlocked Ultrafast US?

[1] The concept of ultrafast ultrasound imaging was first introduced by Bruneel et al almost **40 years ago**

[2]

Ultrafast echotomographic system using optical processing of ultrasonic signals*

C. Bruneel, R. Torguet, K. M. Rouvaen, E. Bridoux, and B. Nongaillard

Laboratoire d'Opto-Acousto-Electronique—Equipe de Recherche Associée au C.N.R.S. No 593, Centre Universitaire de Valenciennes, 59326 Valenciennes, France

(Received 15 November 1976; accepted for publication 16 February 1977)

An ultrafast ultrasonic tomograph has been developed in our laboratory for direct observation of the living tissues inside the human body. Acousto-optic interaction is the basic principle of our system. The information carried by the acoustic wave is impressed on a light beam diffracted during the acousto-optic interaction and an optical system is used for displaying a real image of an isonified object. A first and simple realization has been used to check the principle of operation. Directions for future improvements are discussed.

PACS numbers: 87.70.Es, 43.85.+f, 87.50.Ce

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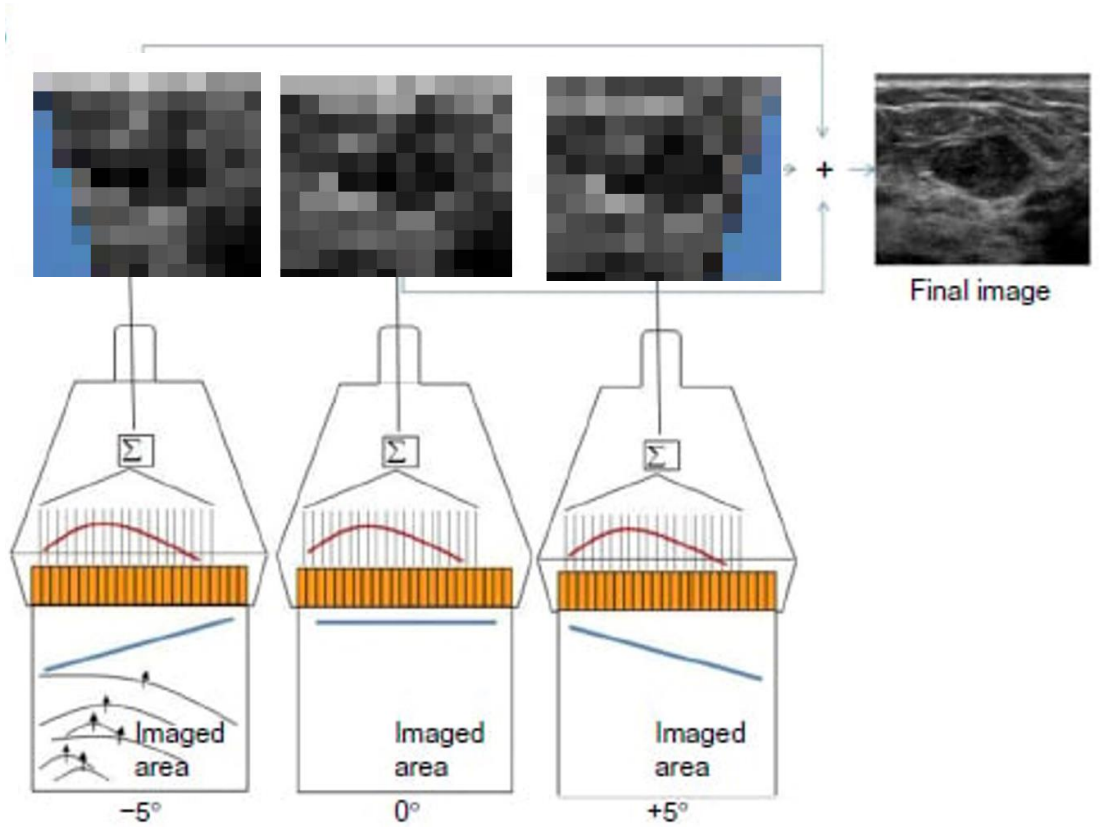

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Beamforming

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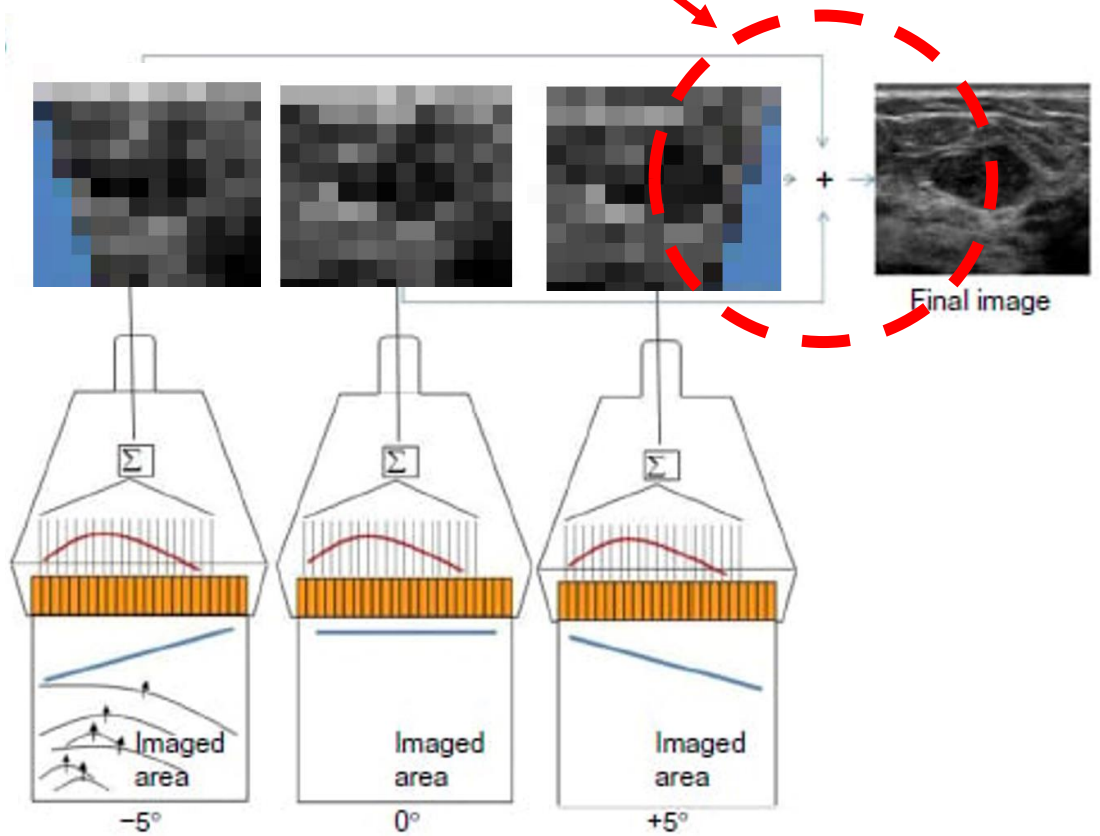

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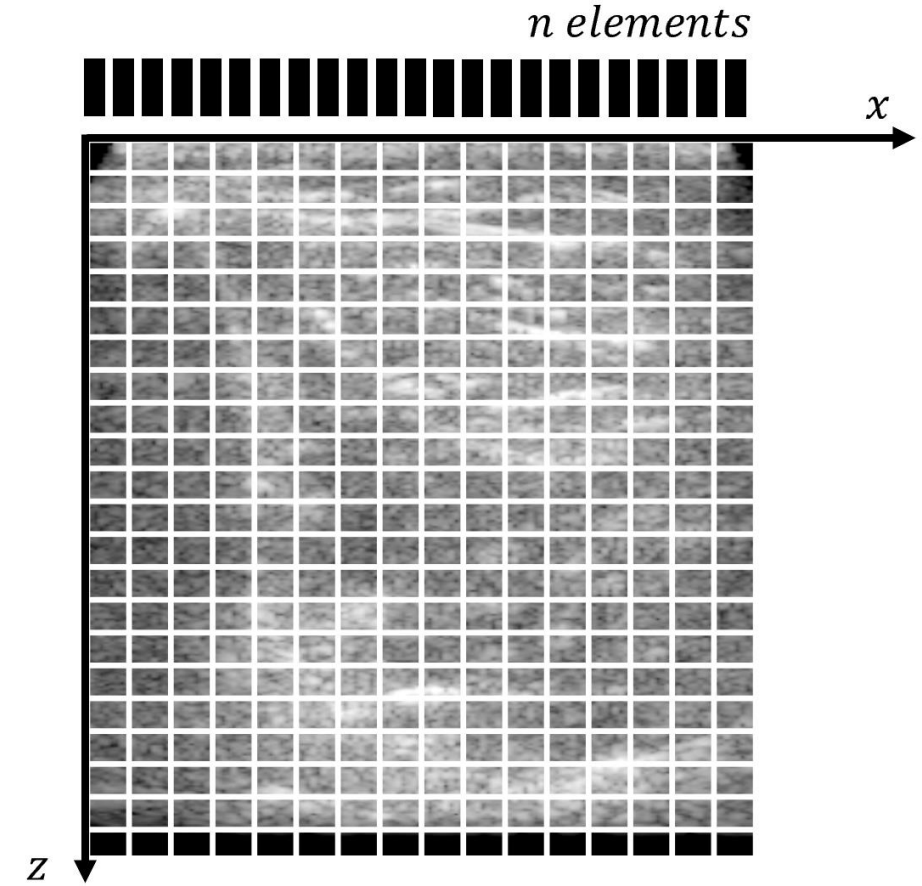

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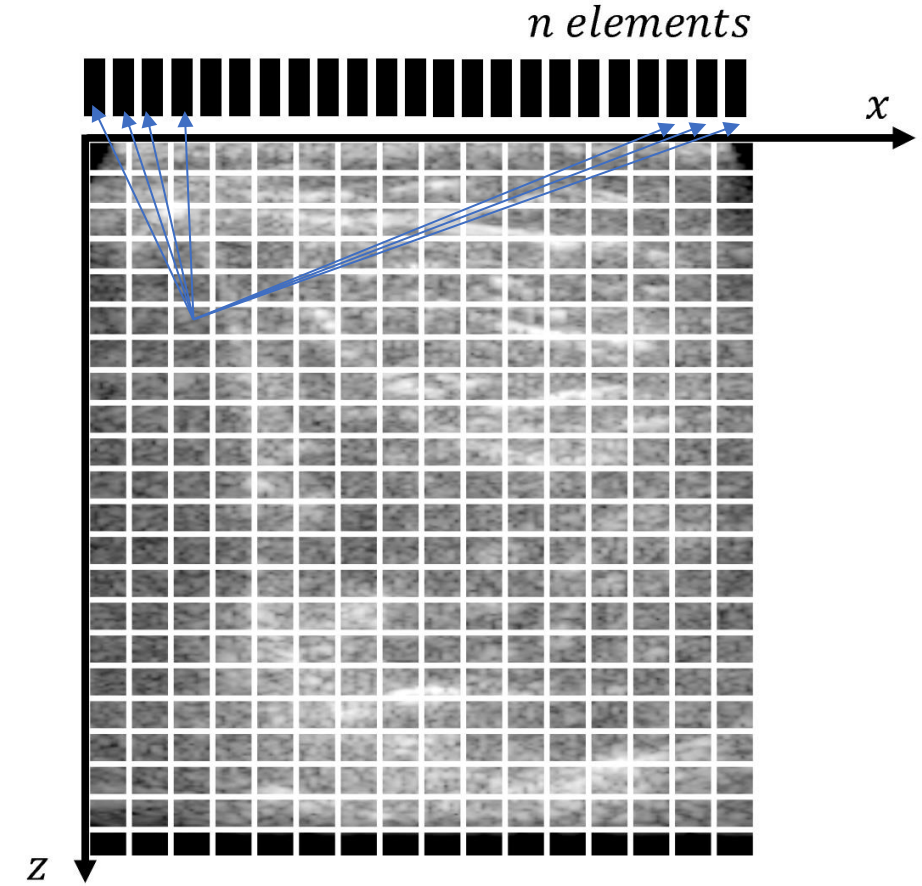

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Topics

1. Motivation
2. What is Ultrasound?
3. **Application 1. Motor Unit Decomposition via Ultrafast Ultrasound**
4. Break Time
5. Translational challenges: Laboratory → Real-World
6. Application 2. Interfacing with Wearable A-mode Ultrasound
7. Questions and Answers

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What all of this has to do with Neural Interfaces?

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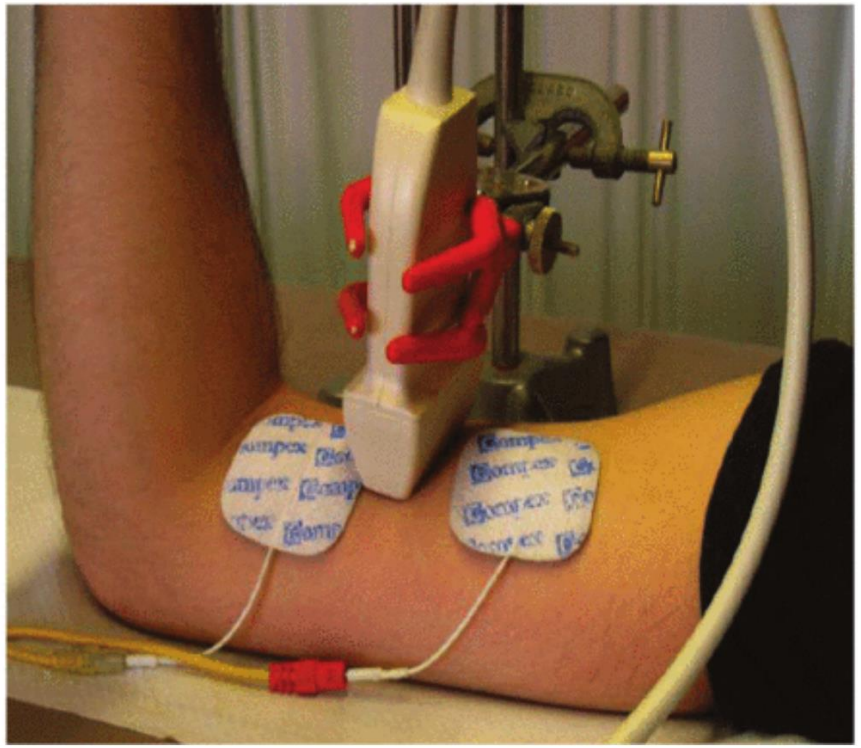
IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, VOL. 55, NO. 10, OCTOBER 2008 2177

Assessment of the Mechanical Properties of the Musculoskeletal System Using 2-D and 3-D Very High Frame Rate Ultrasound

Thomas Deffieux, Jean-Luc Gennisson, Mickaël Tanter, and Mathias Fink



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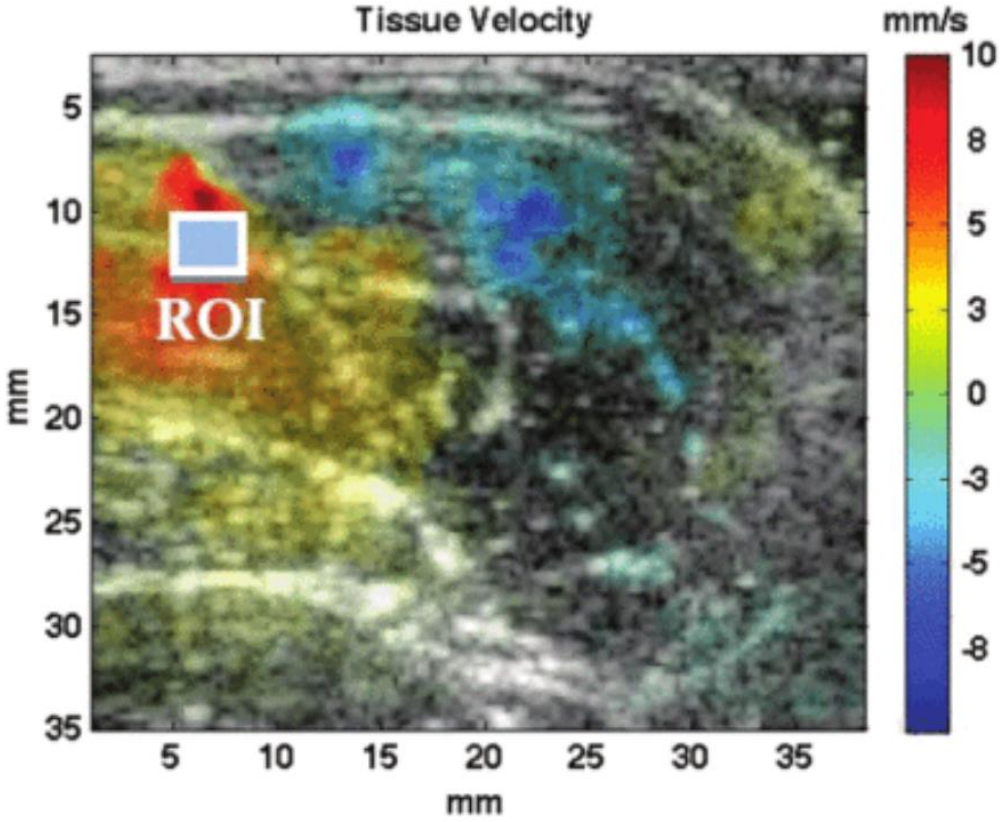

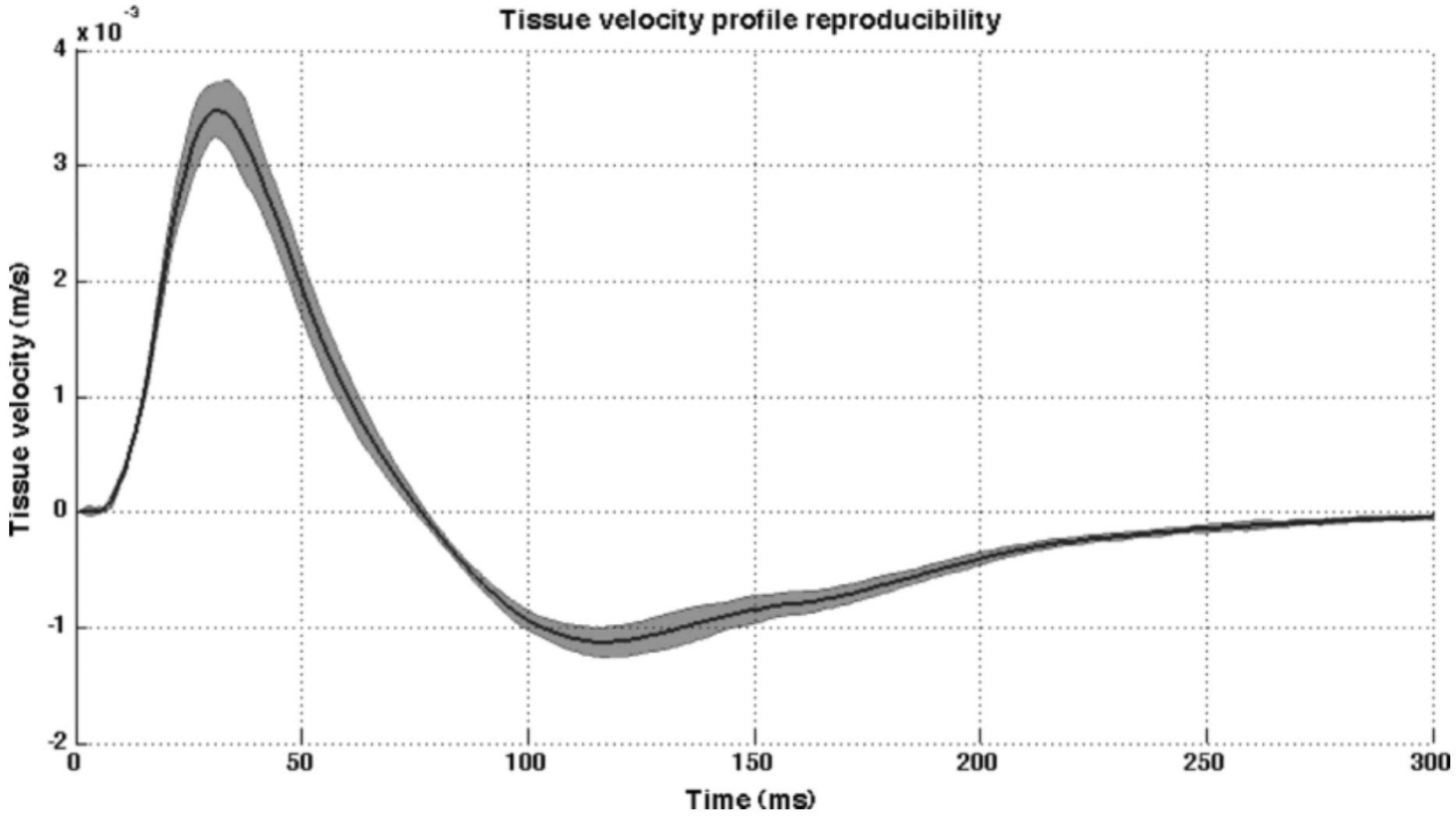

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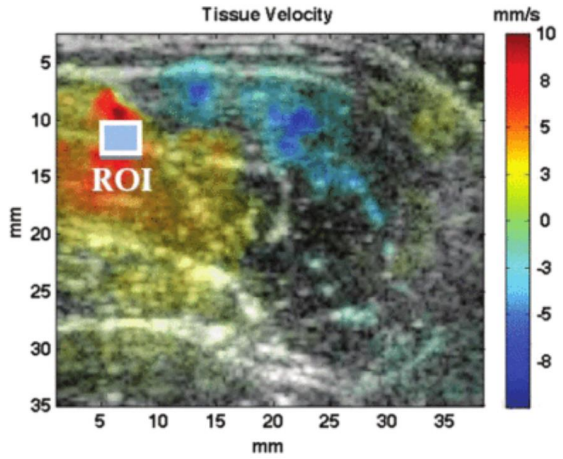

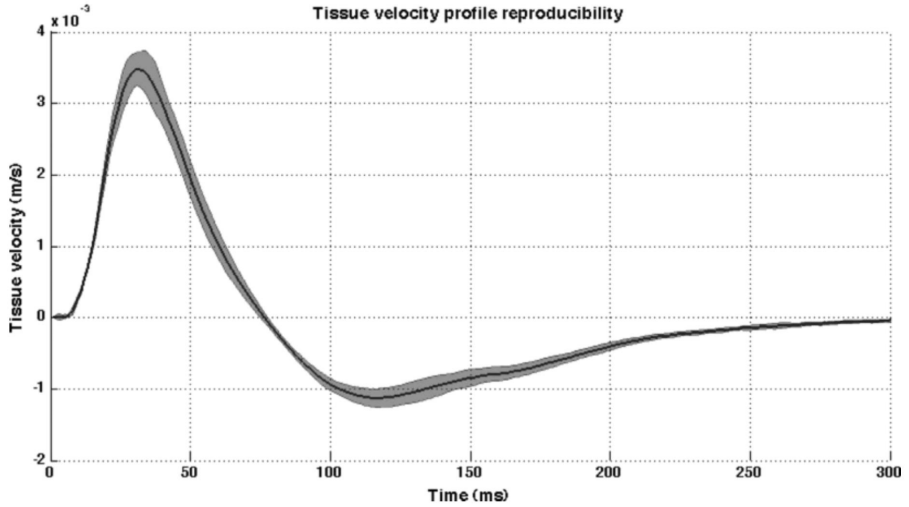

What this study shows us.

- Ultrafast ultrasound can image localized transient motion inside muscles
- When electrically stimulated we can record distinct reproducible twitch like motions

What we don't know.

- Can we image fibre movement during voluntary contractions?
- Can we image and decompose individual motor unit spiking activity?

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The start of our Investigation

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Proposal

1) Simultaneous HDsEMG and Ultrafast Ultrasound recording

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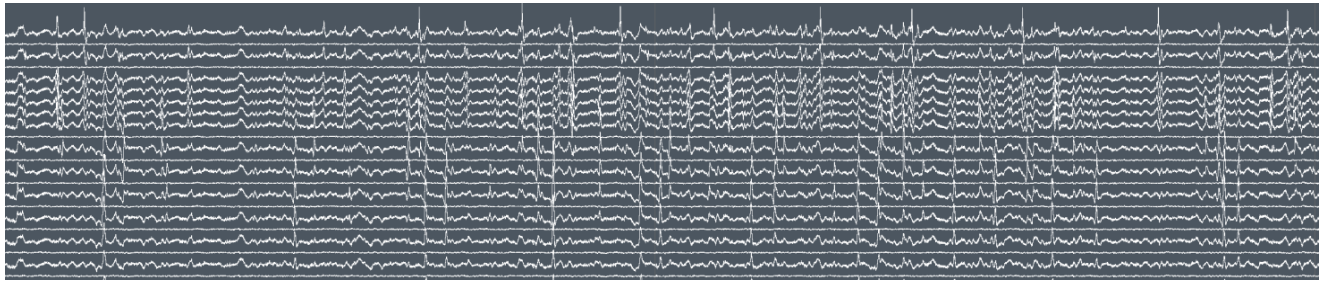
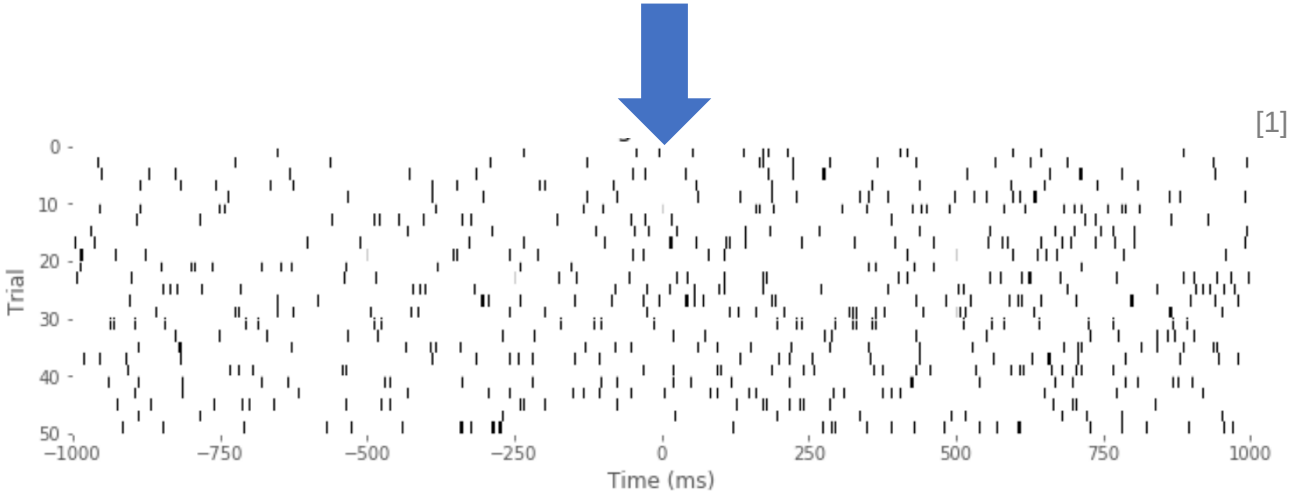
2) Decompose MUs via HDsEMG





[1]

[1] https://mark-kramer.github.io/Case-Studies-Python/10.html

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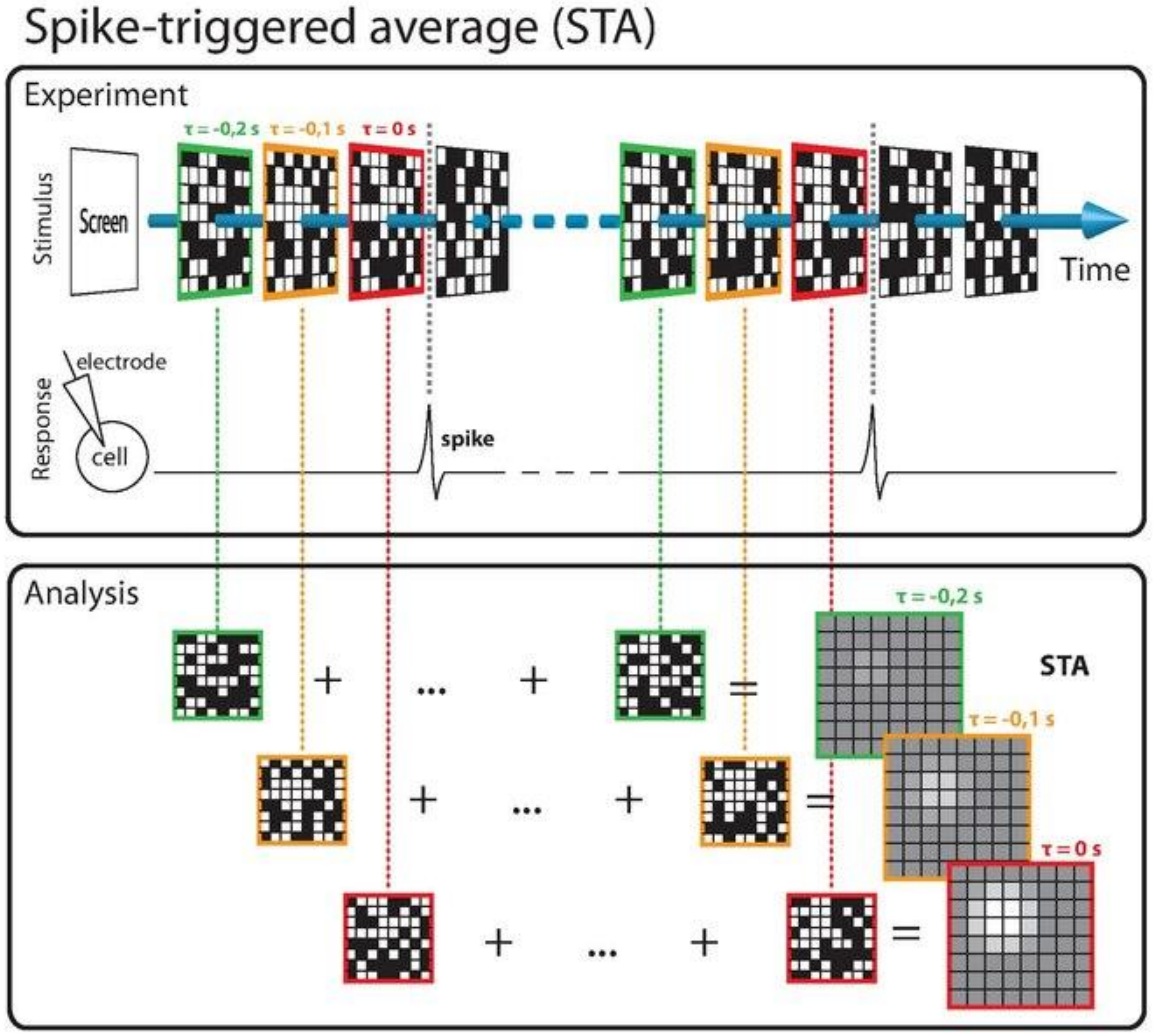
Proposal

1) Simultaneous HDsEMG and Ultrafast Ultrasound recording

2) Decompose MUs via HDsEMG

3) Use the MUs spiking times to perform a Spike trigger average (STA) on the US velocity maps

4) **Profit?**



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[1] https://en.wikipedia.org/wiki/File:Illustration_diagram_for_the_Spike-triggered_average.pdf

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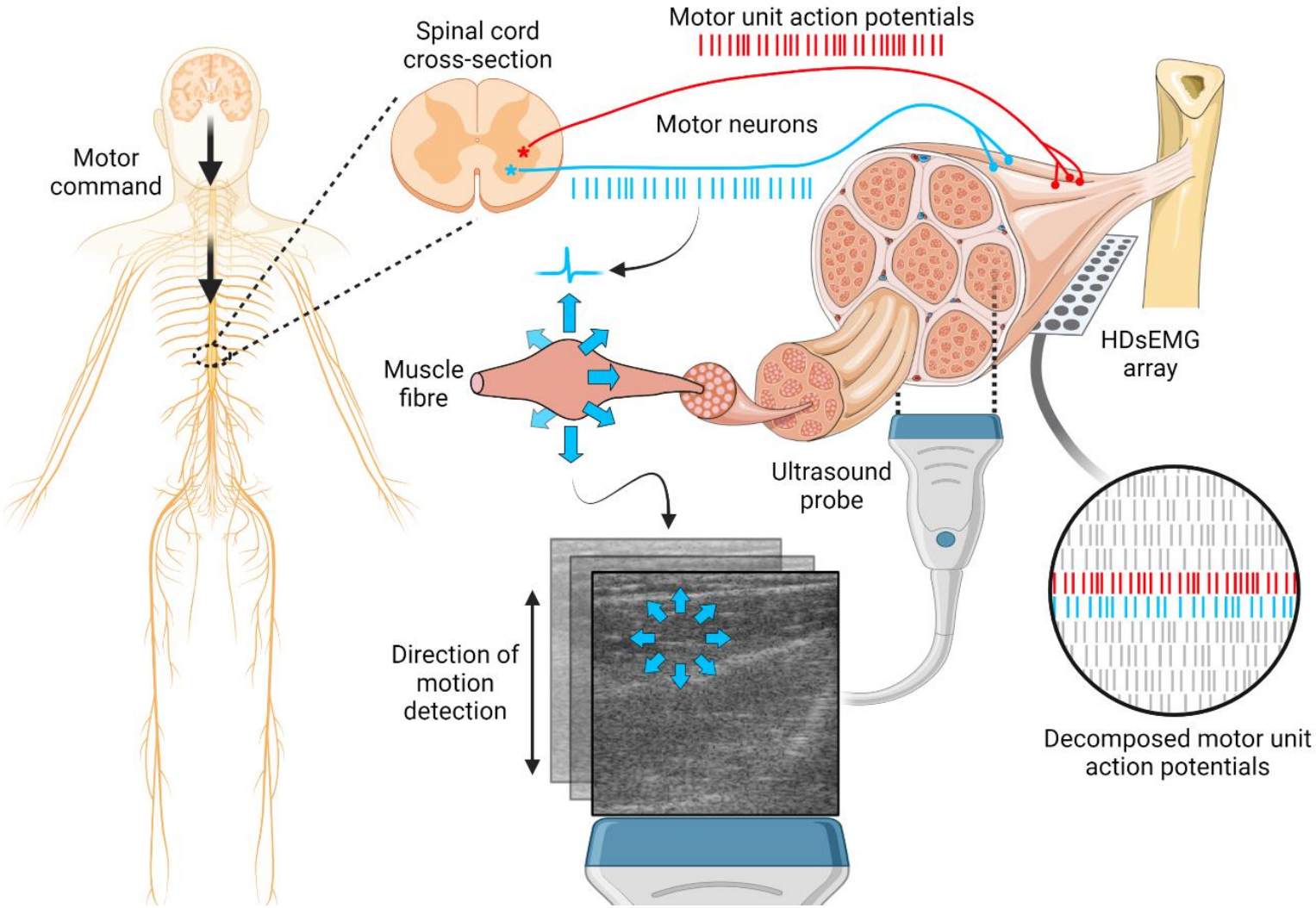

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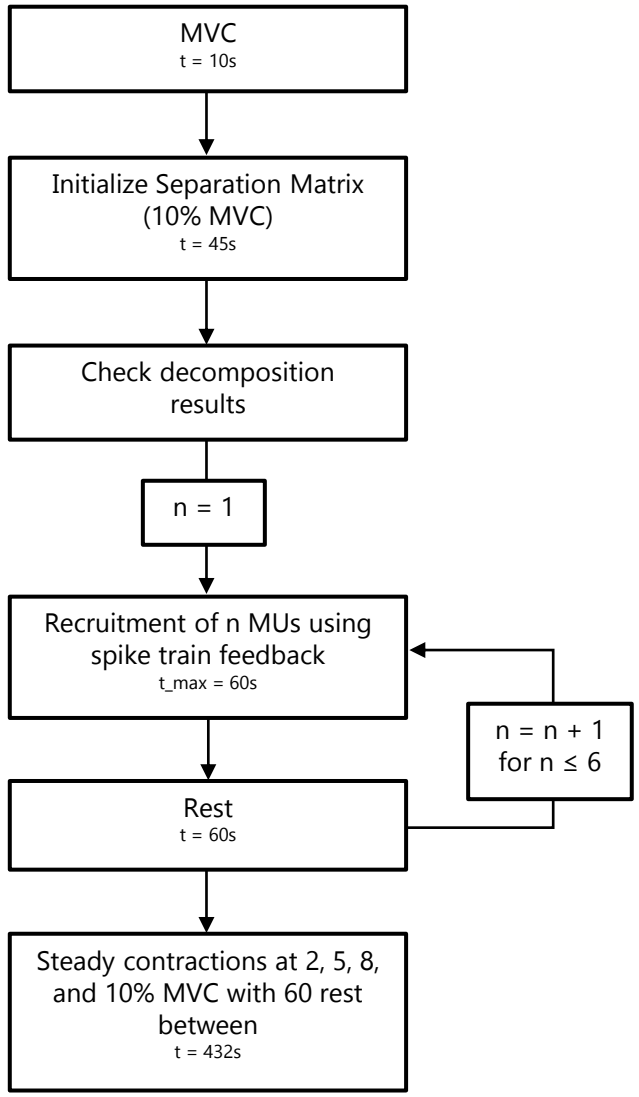
(A) (B)



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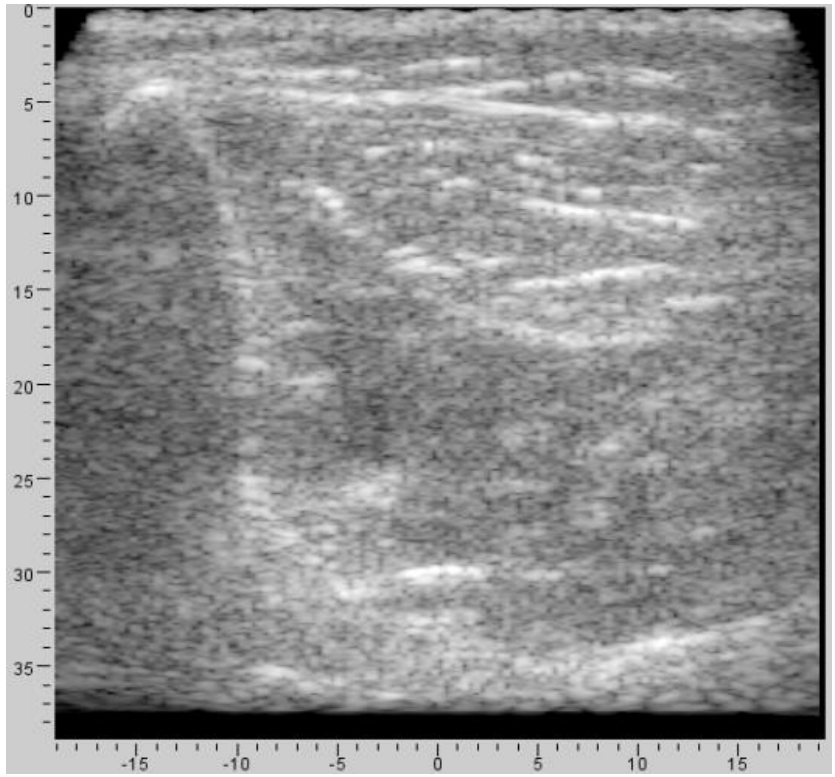

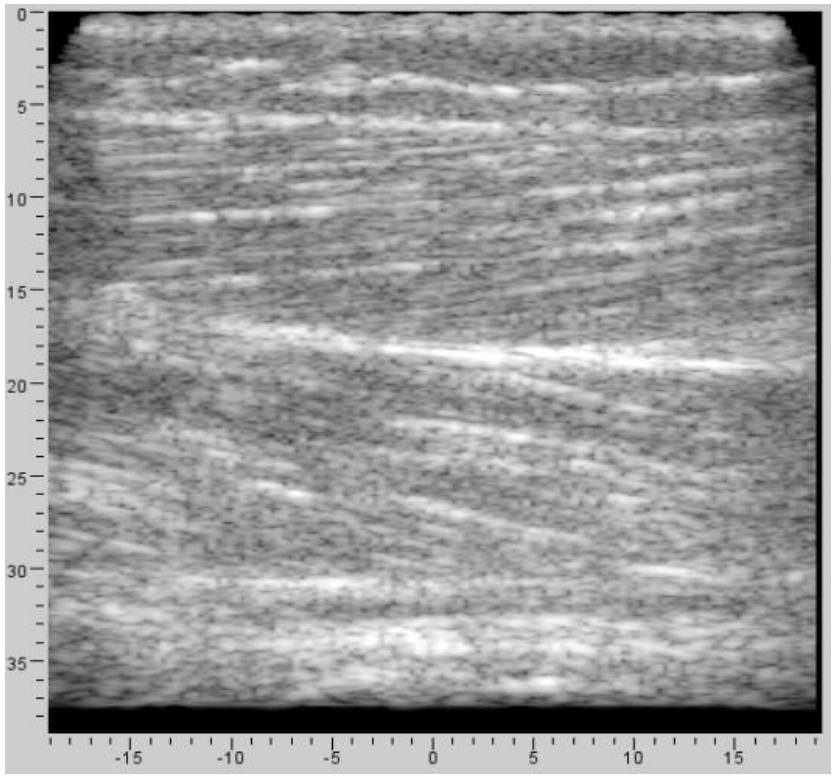

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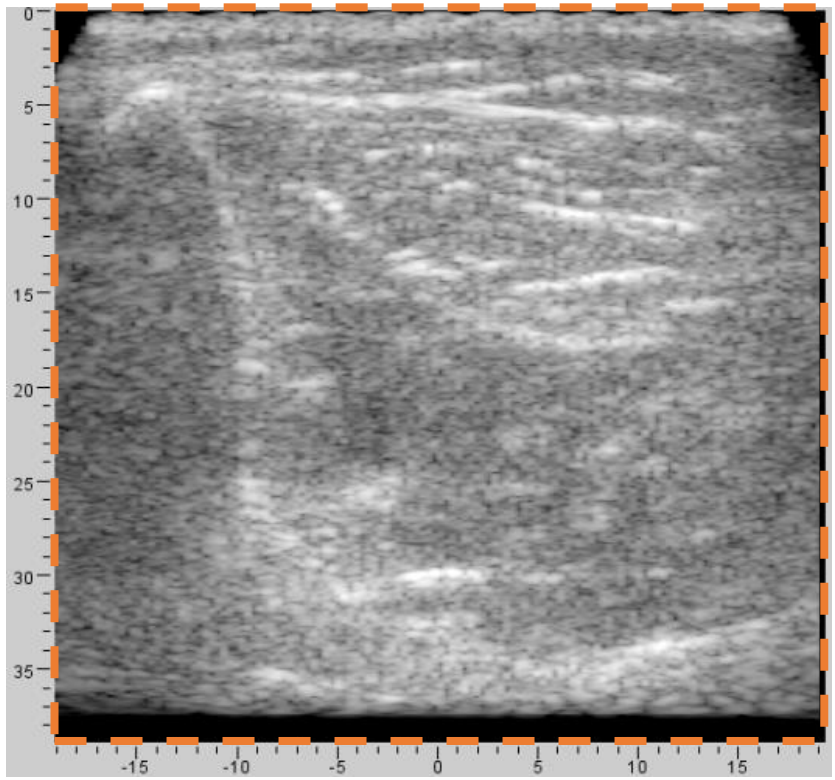

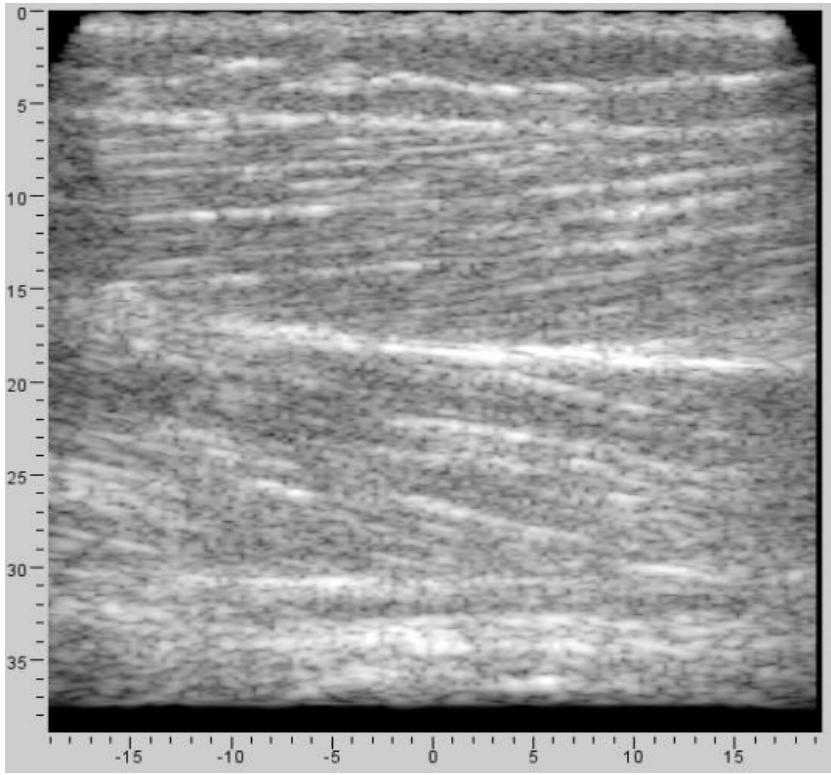

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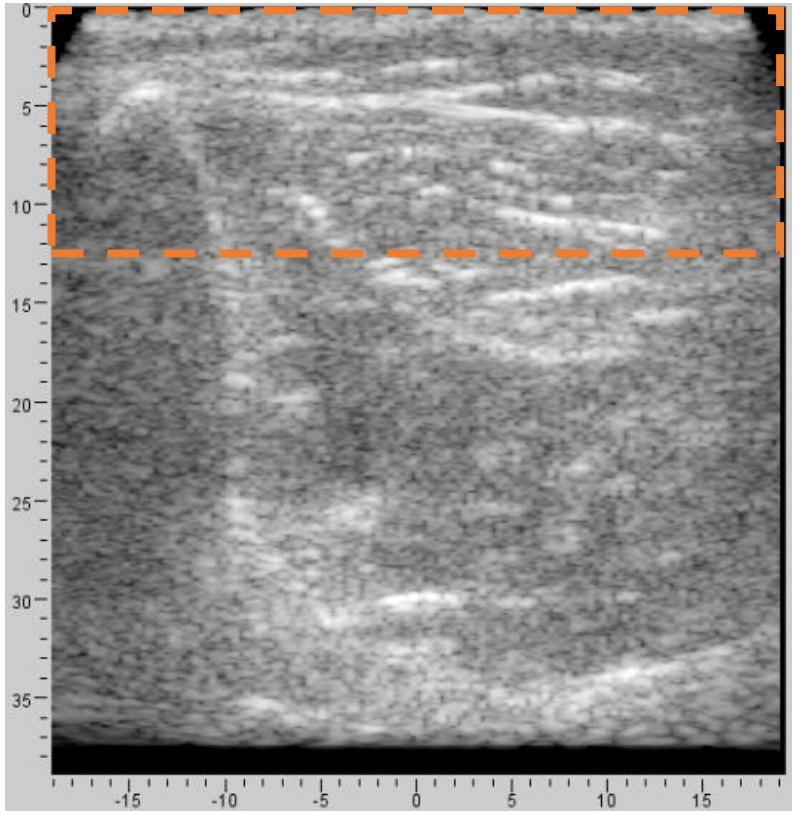

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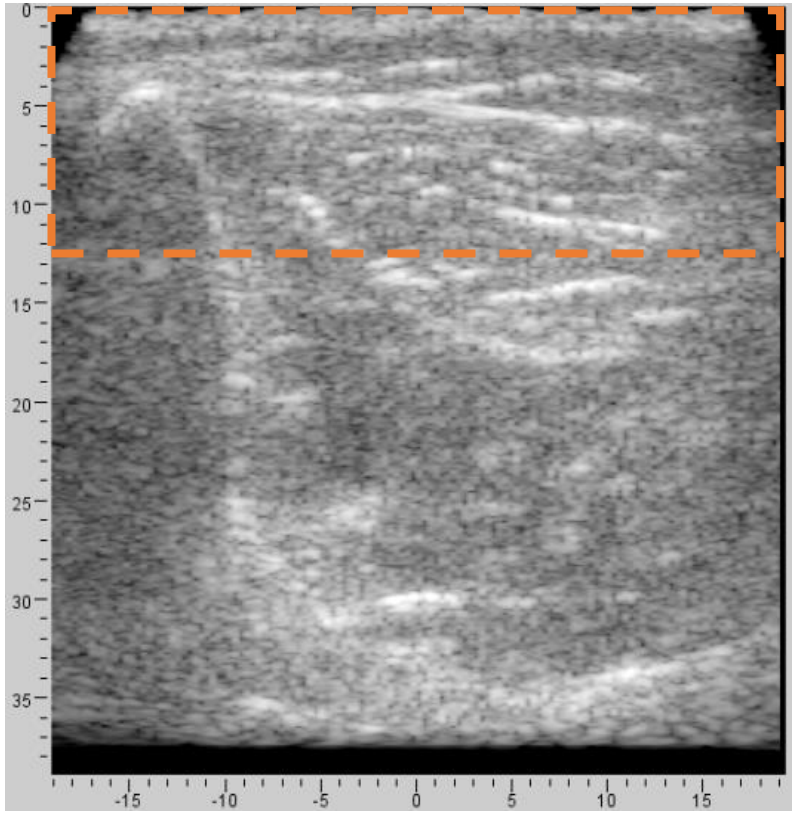

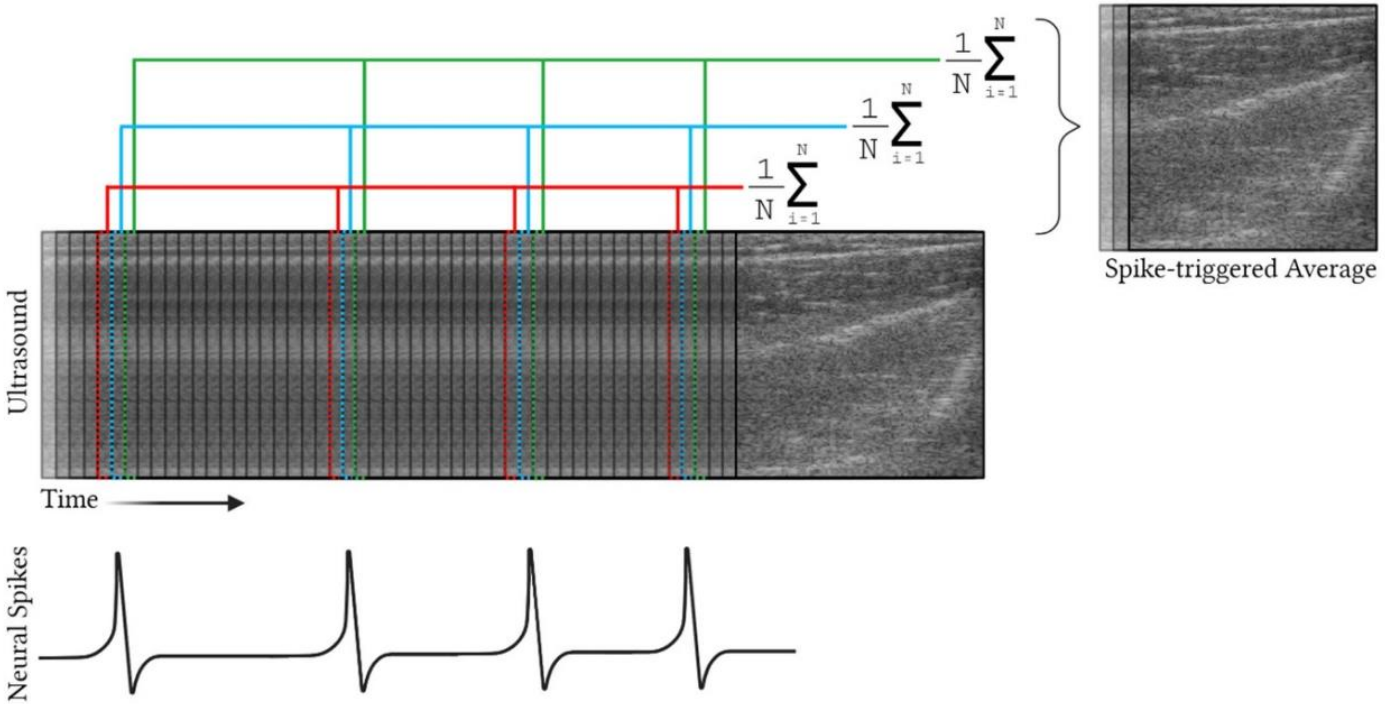

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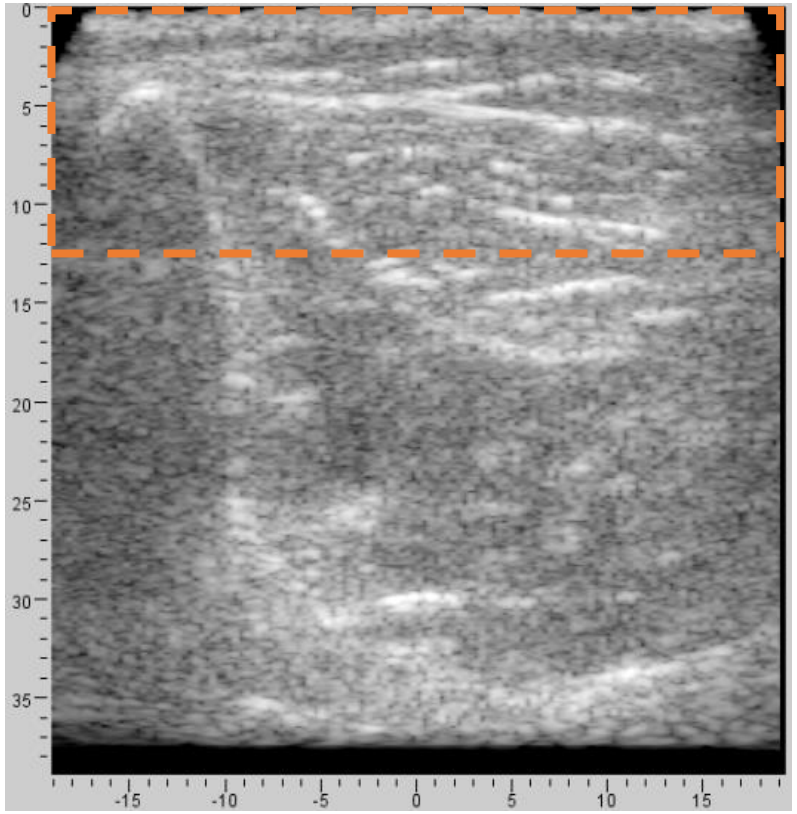

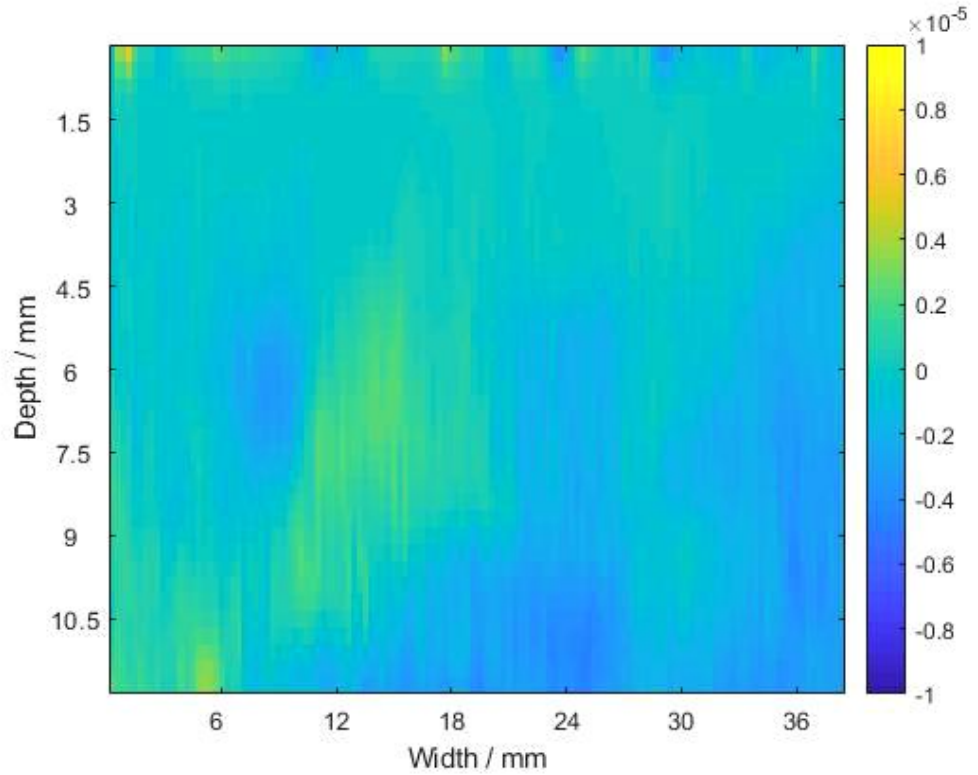

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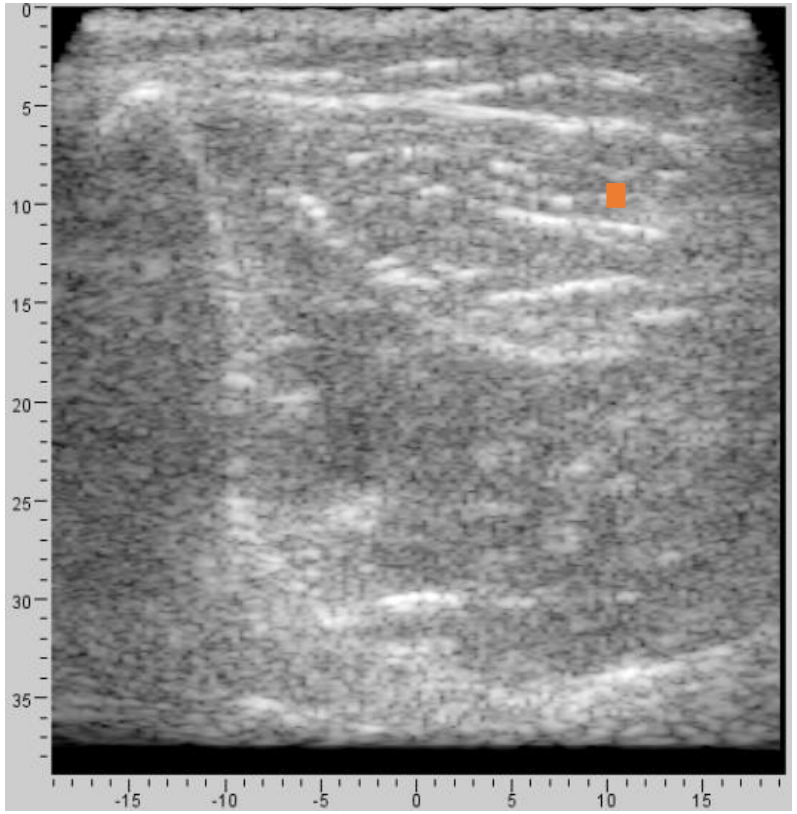

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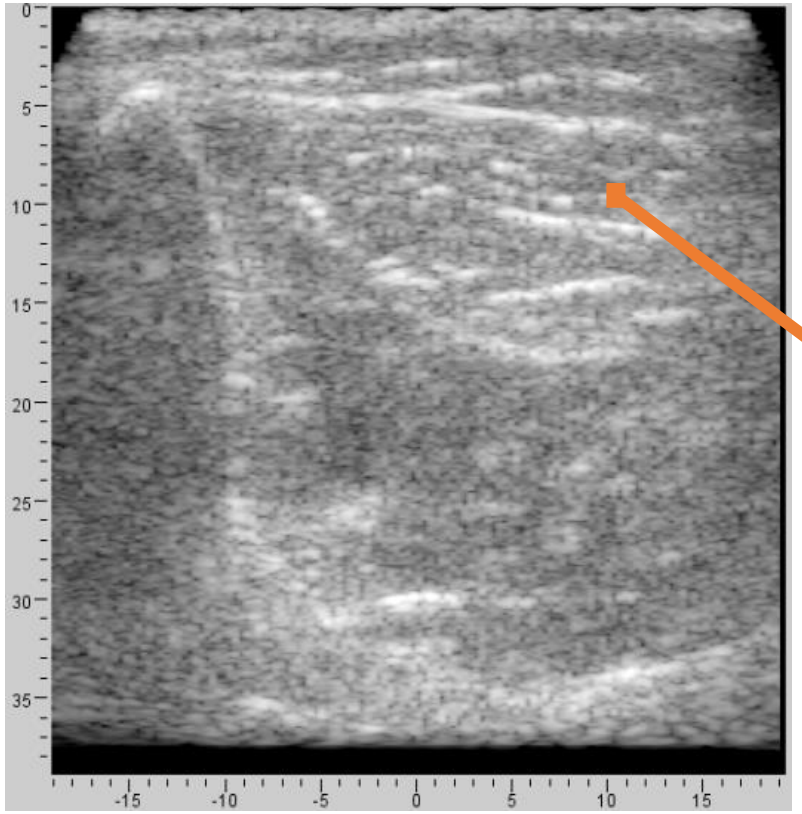

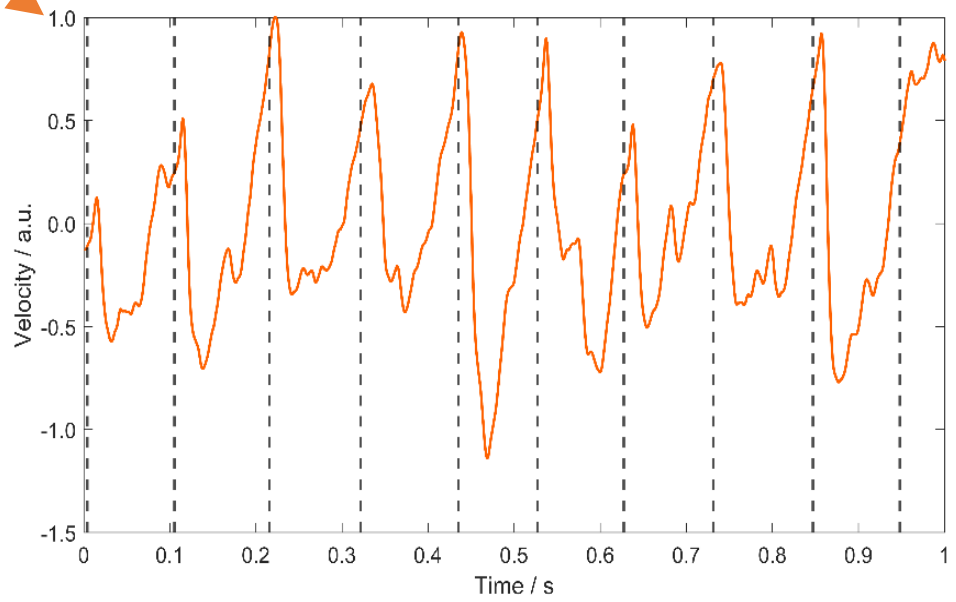

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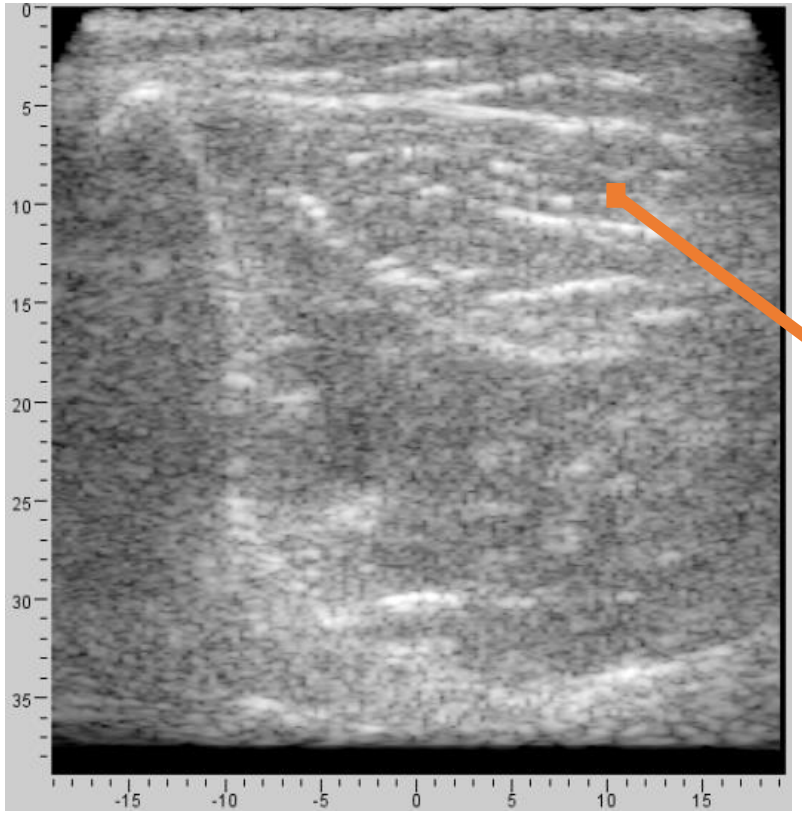

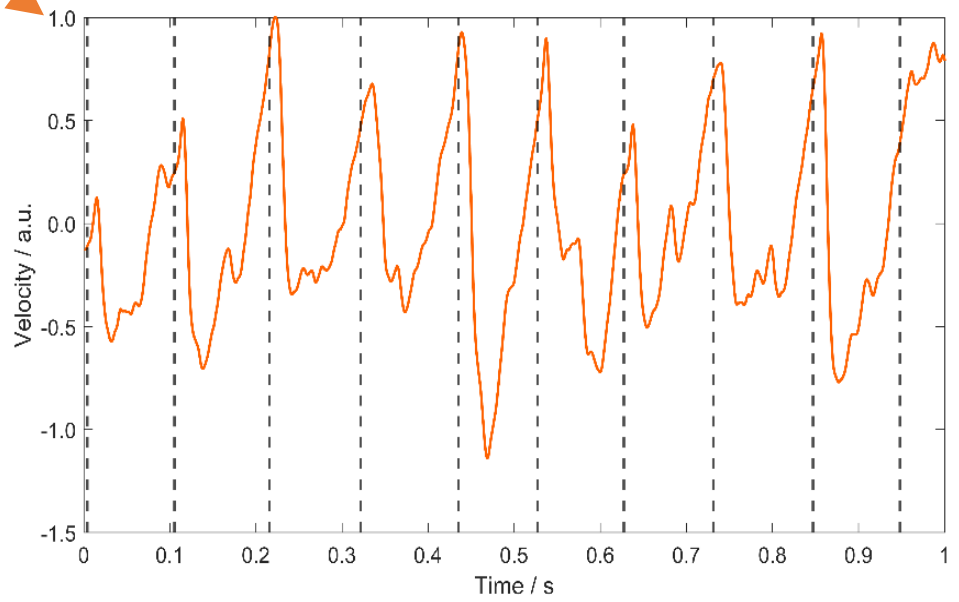

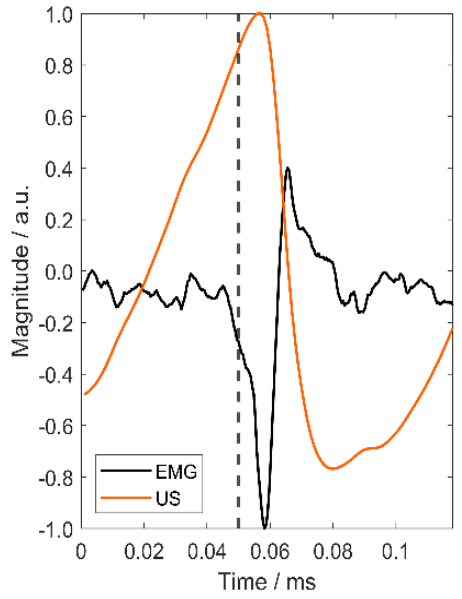

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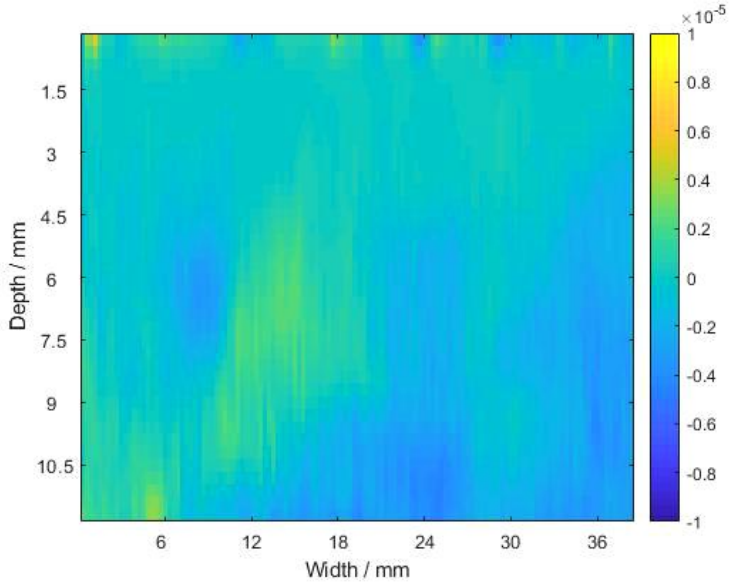
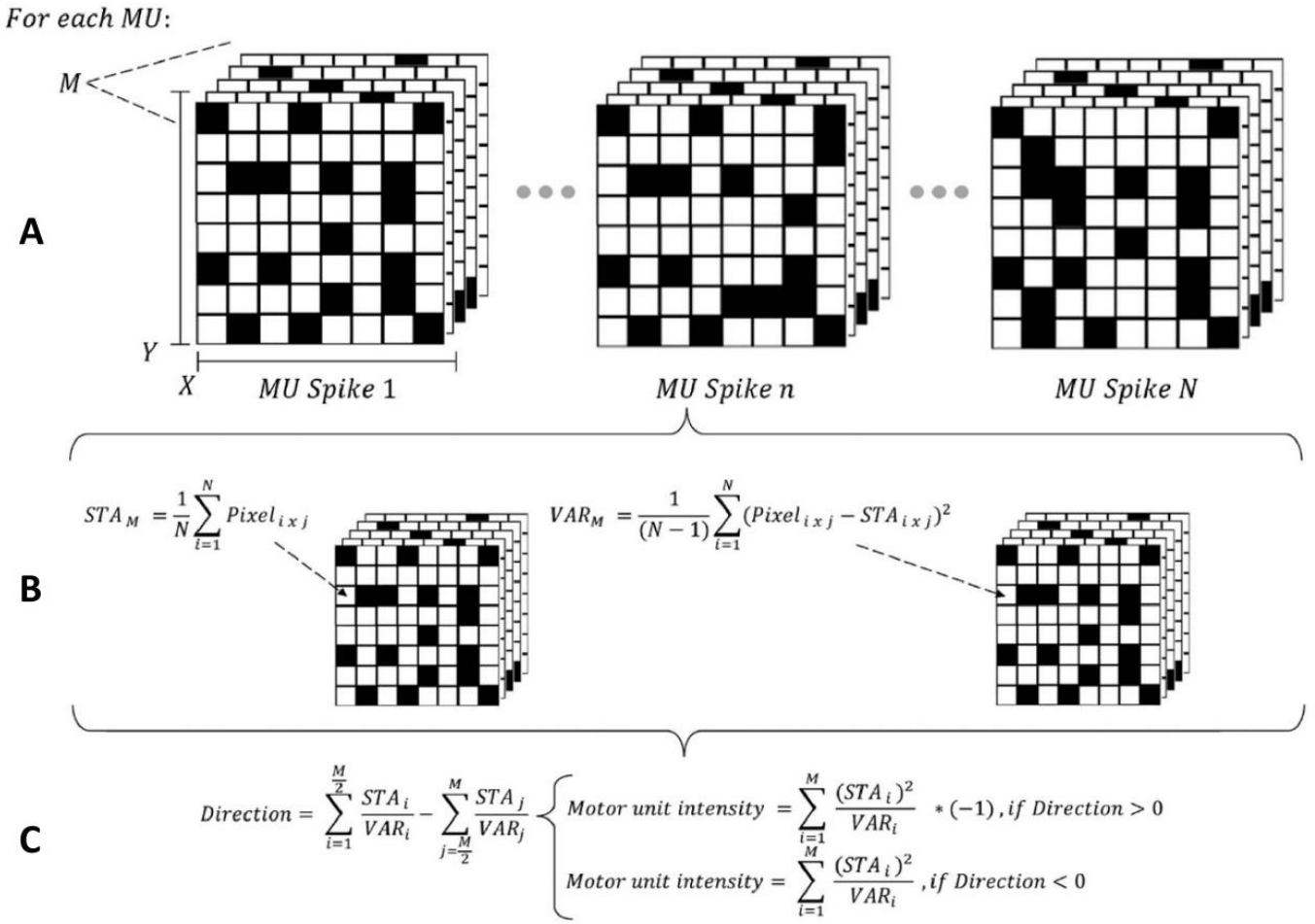
The start of our Investigation





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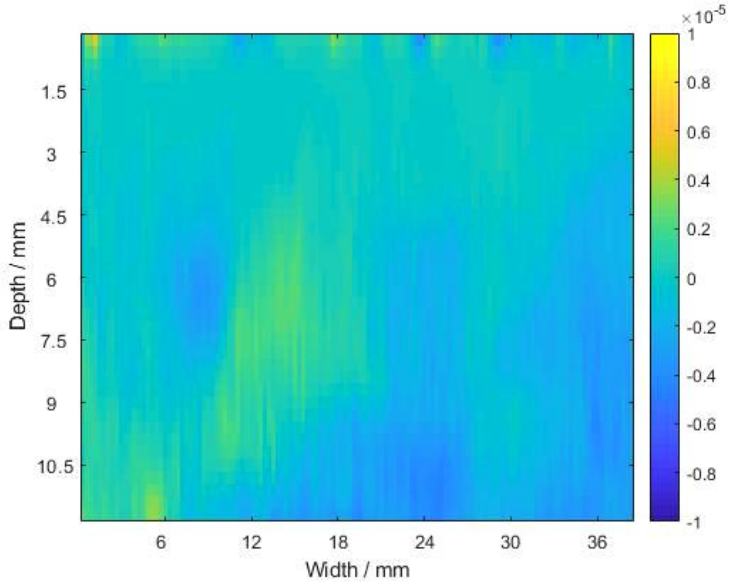

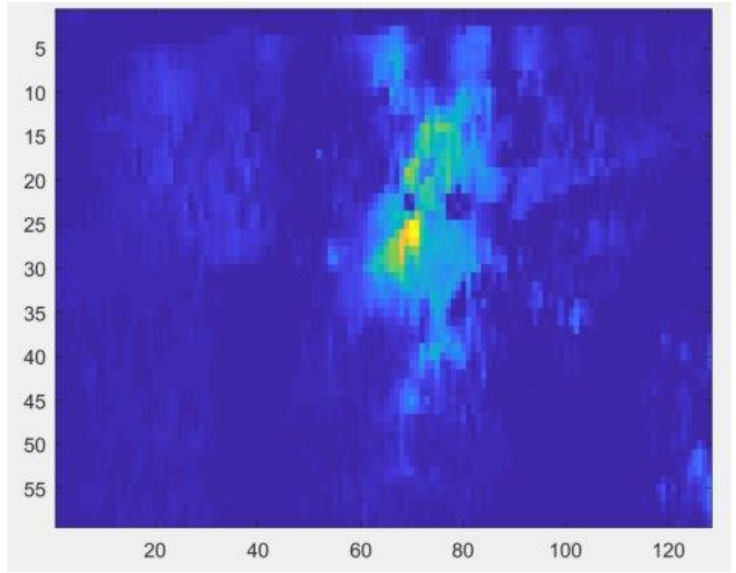

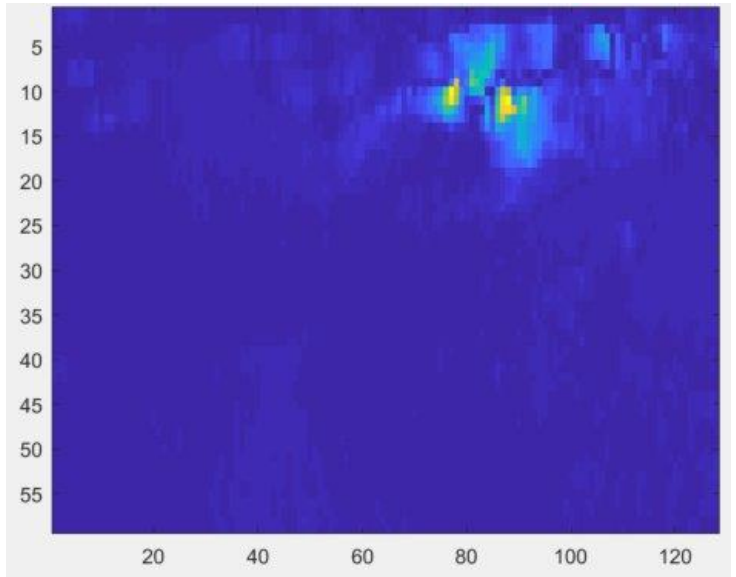

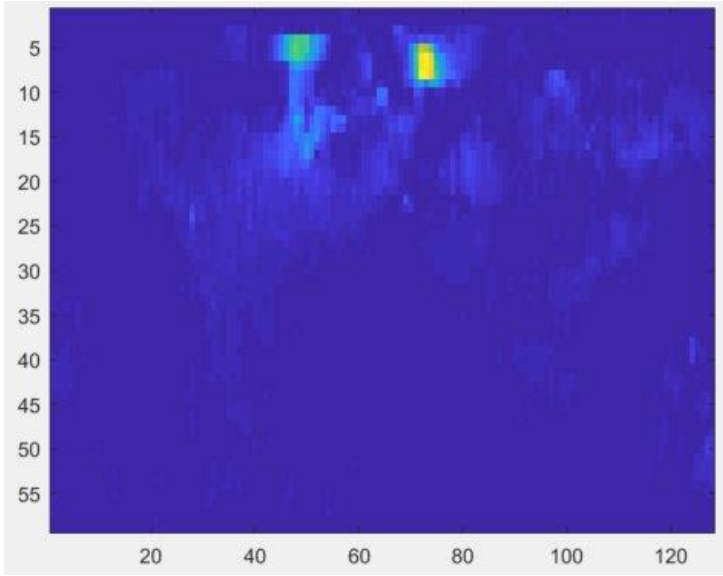

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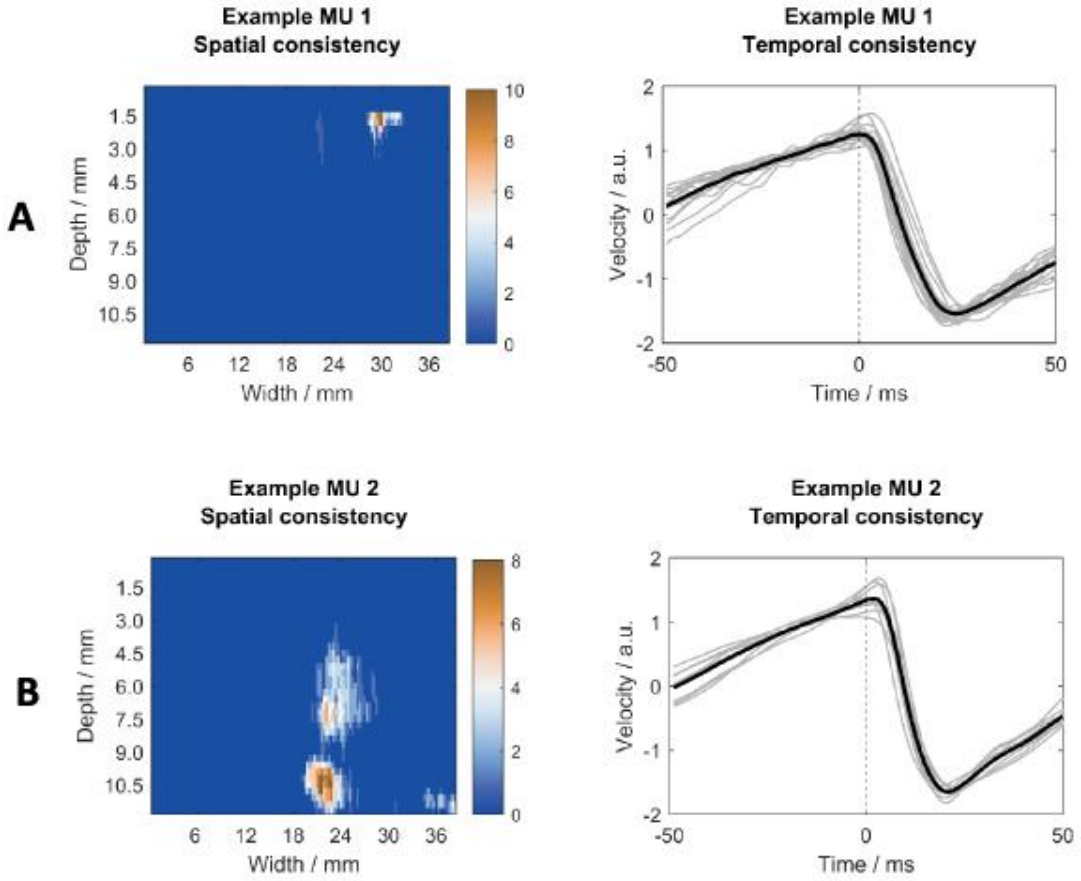

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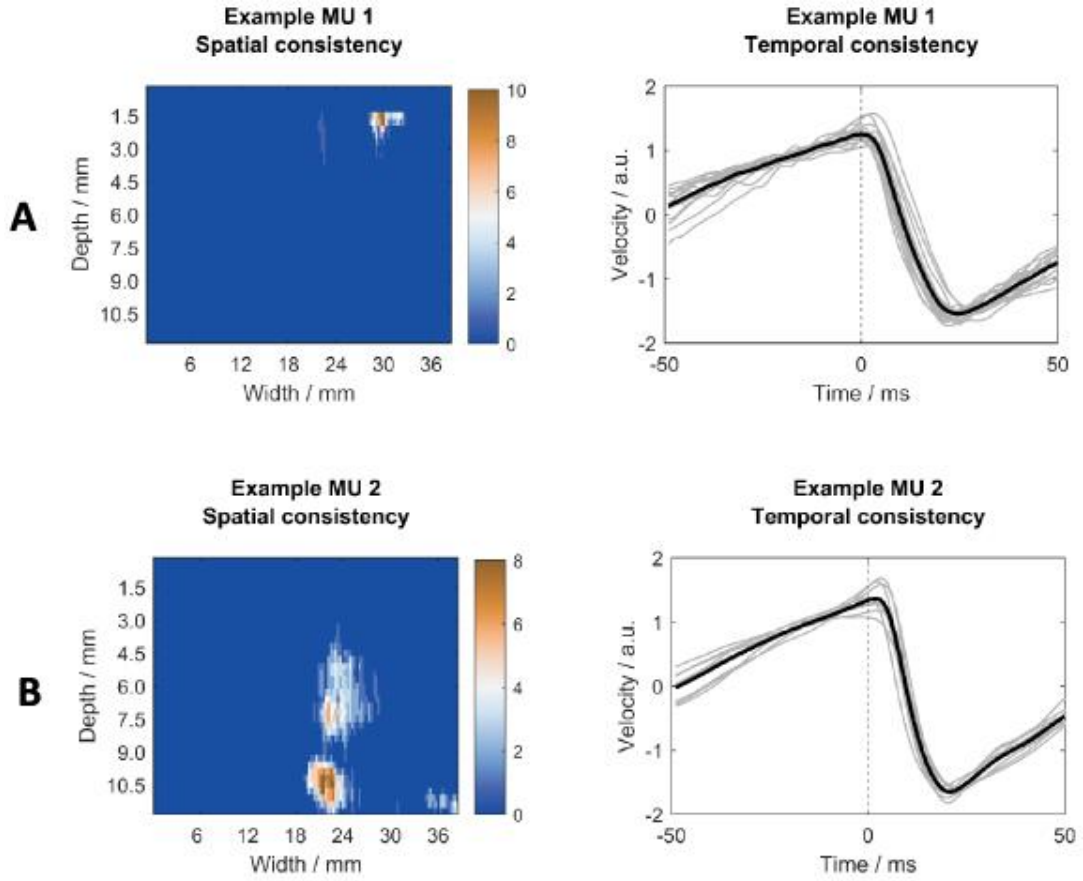

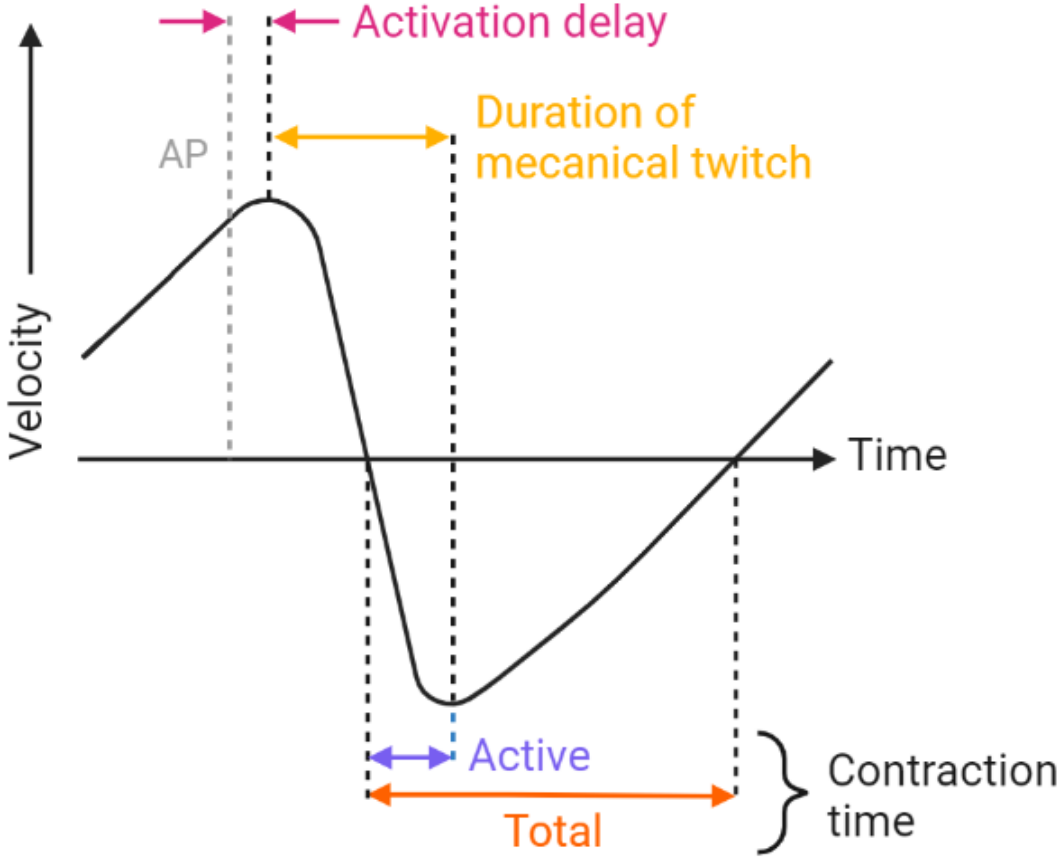

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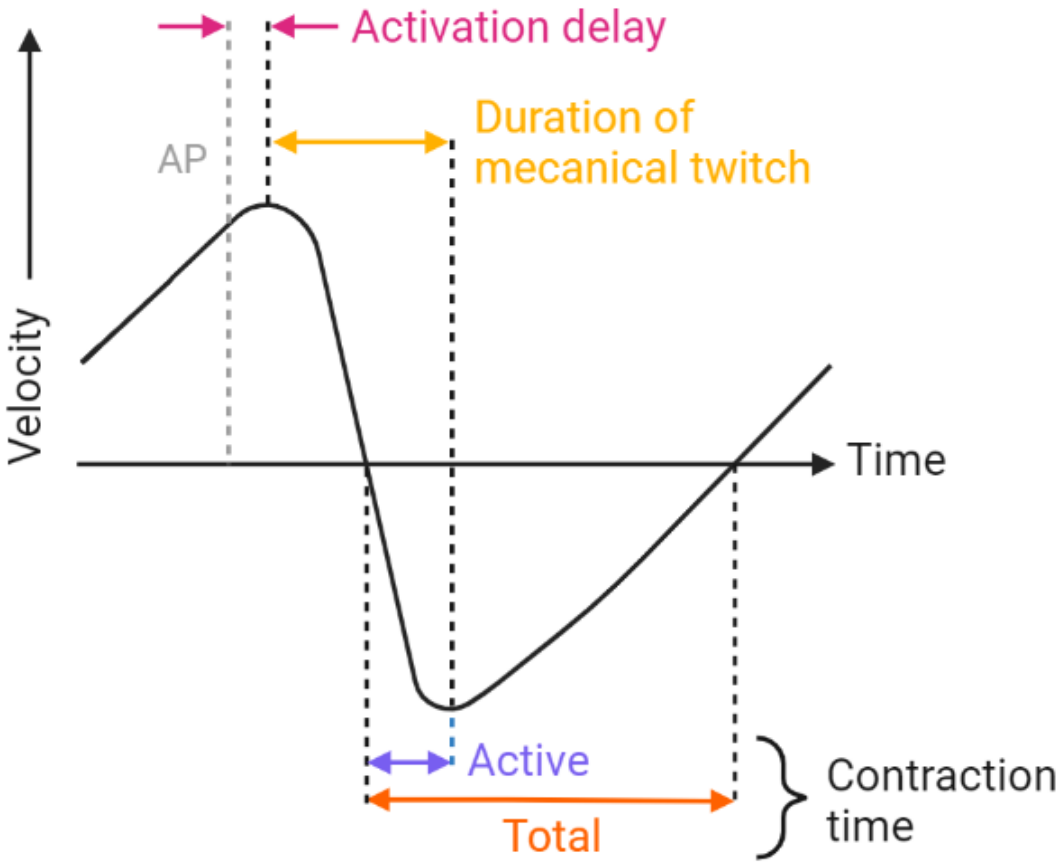

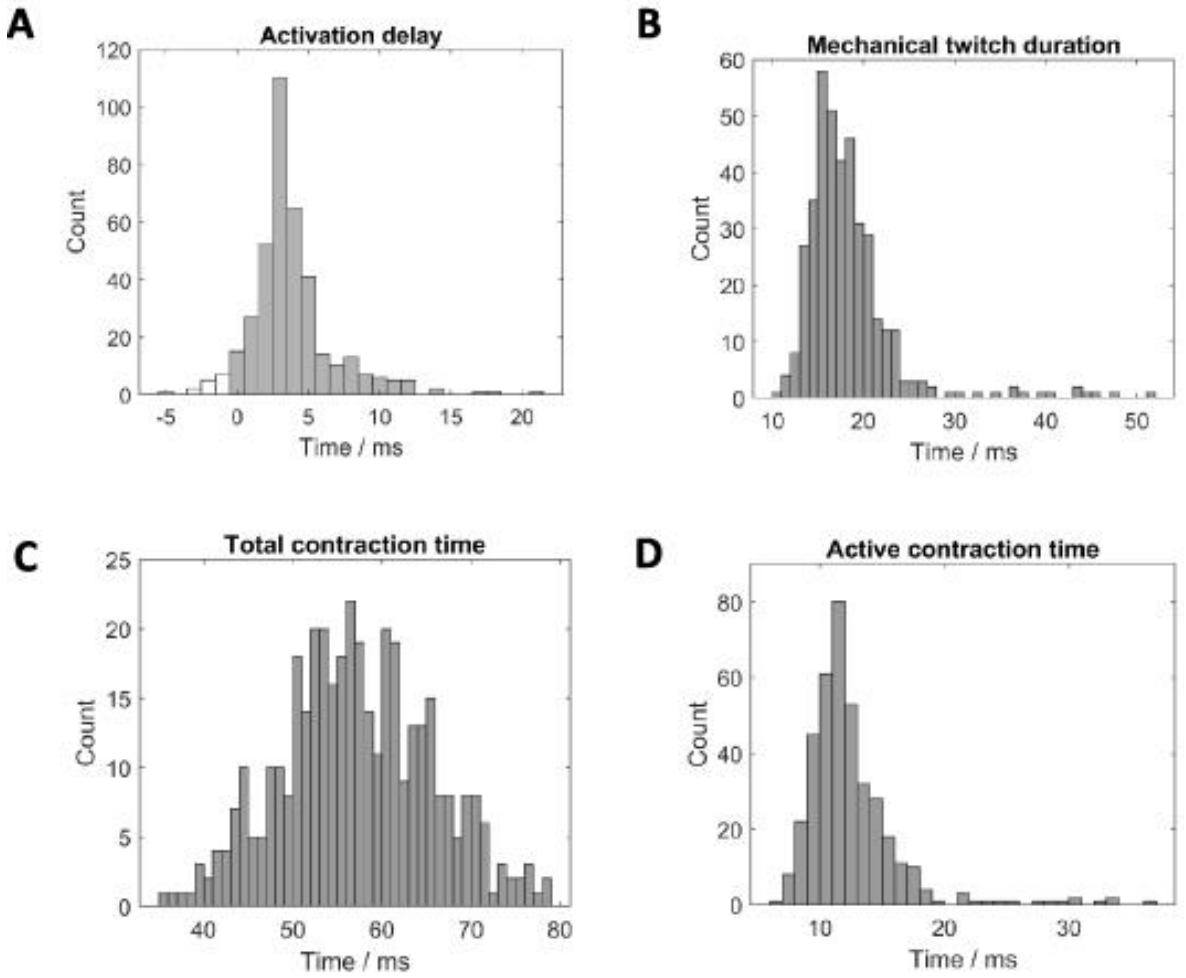

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Initial Conclusions

What worked

1) US is able to track individual twitch profiles during voluntary tetanic contractions.

2) Twitches are present (above noise level) both after STA and individually

3) US can track MUs in space along the plane as well as indicate some “motion territory”

Future Challenges

1) MU Twitches are not simple. They have varied and unique shapes

2) There is a lot of overlap between units. We don’t really know how they interact

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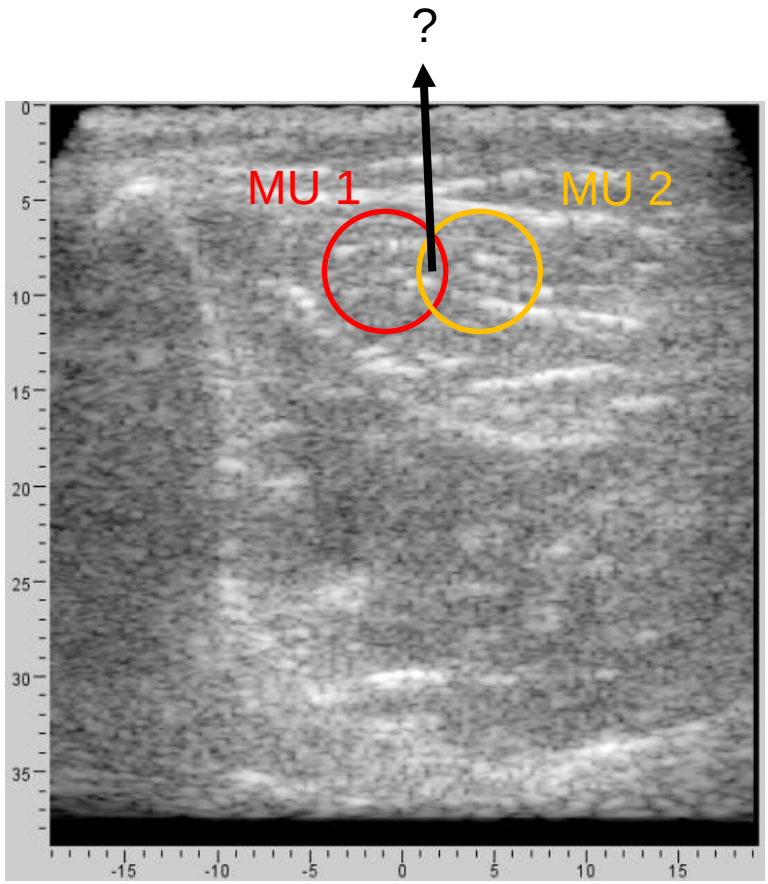
Follow-up investigation - Linearity

Questions

- How linear, if at all, is the mechanical twitch summation?
- Do MU twitch profiles change at different force levels?
- Do MU twitch profiles change with recruitment order?



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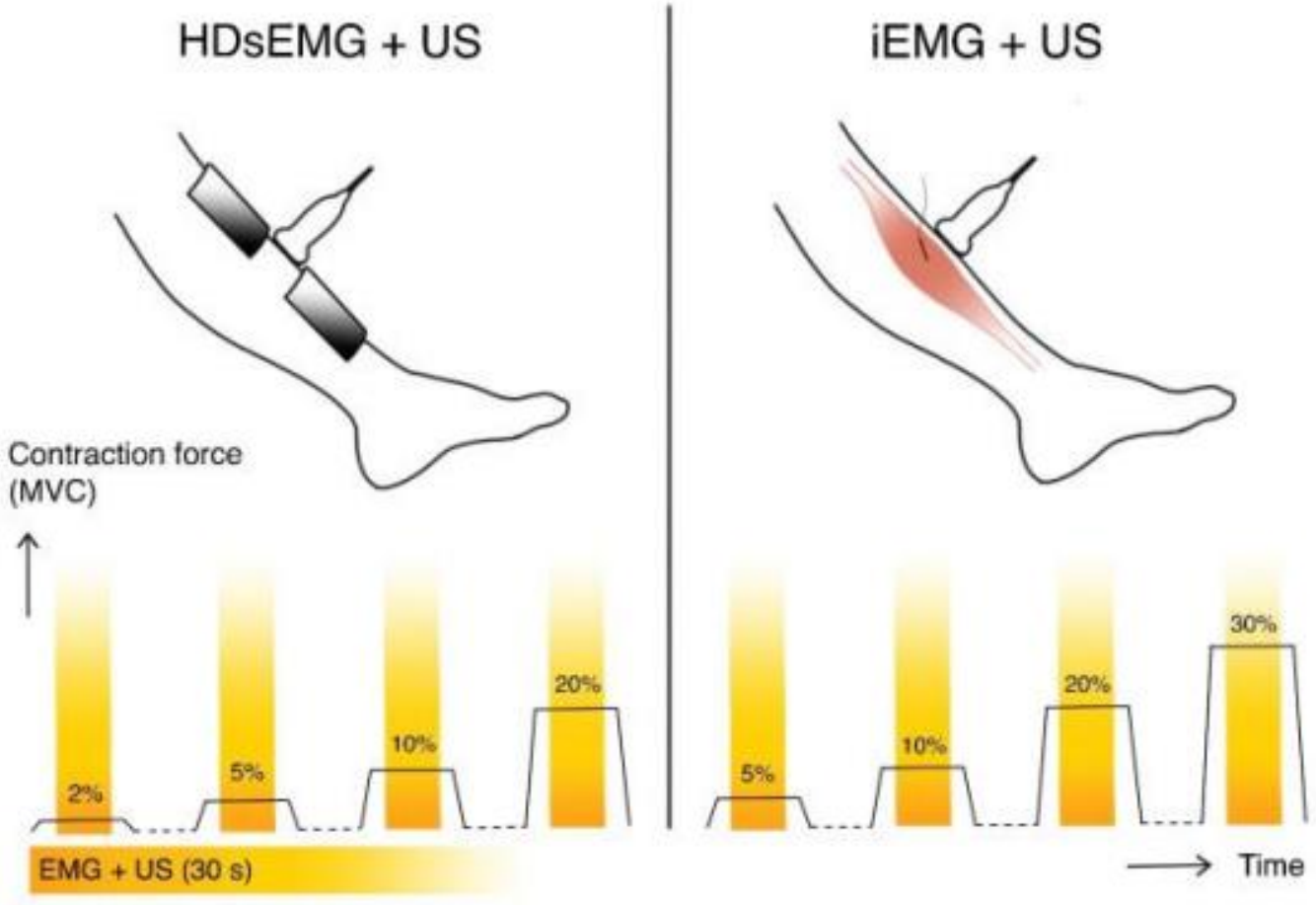
Twitches Changes at increasing force levels



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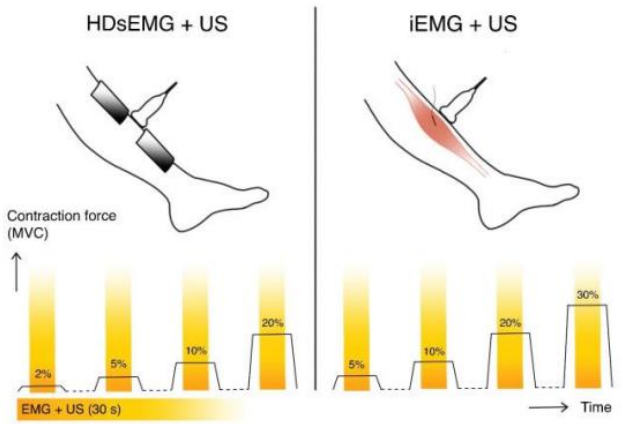

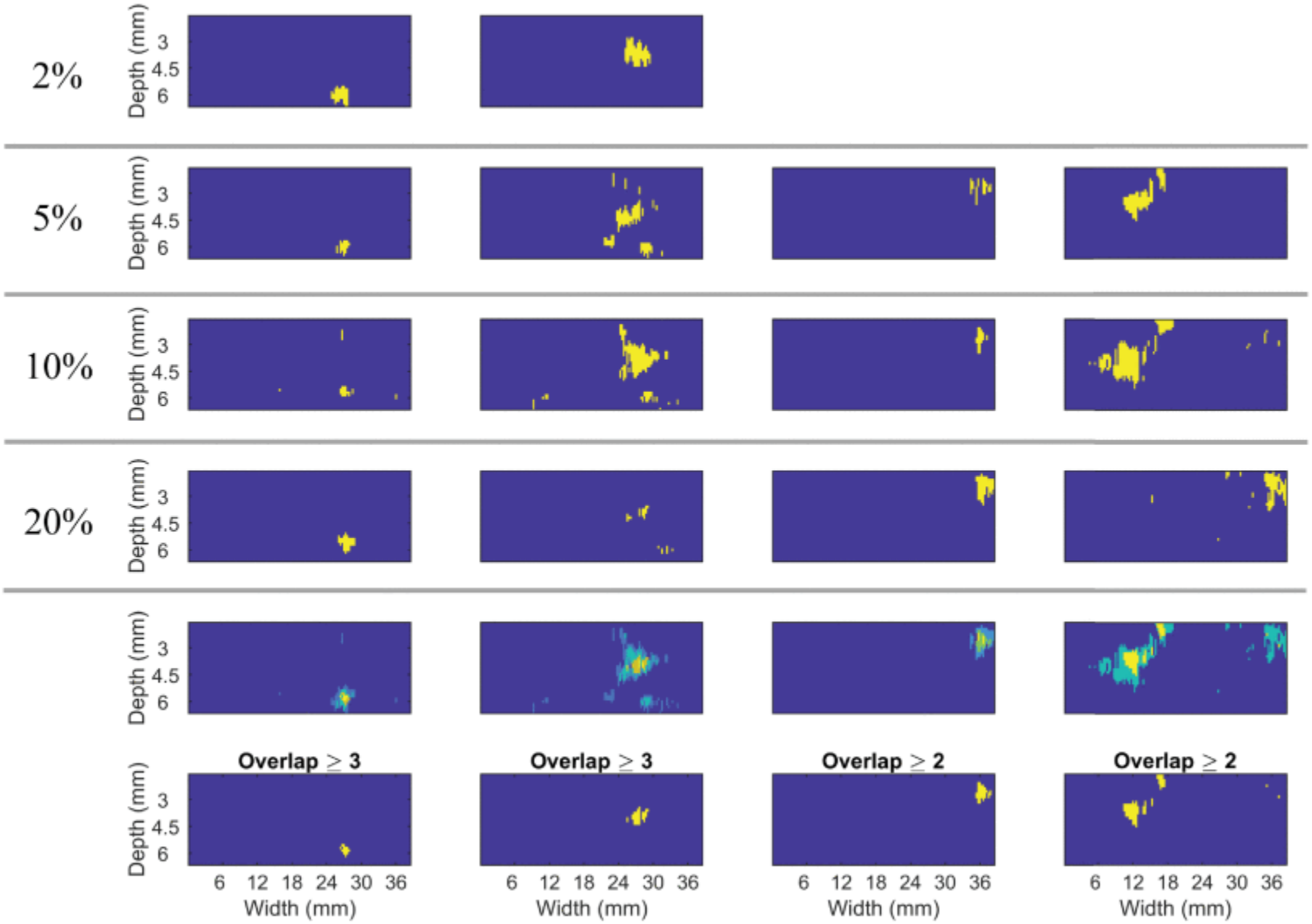

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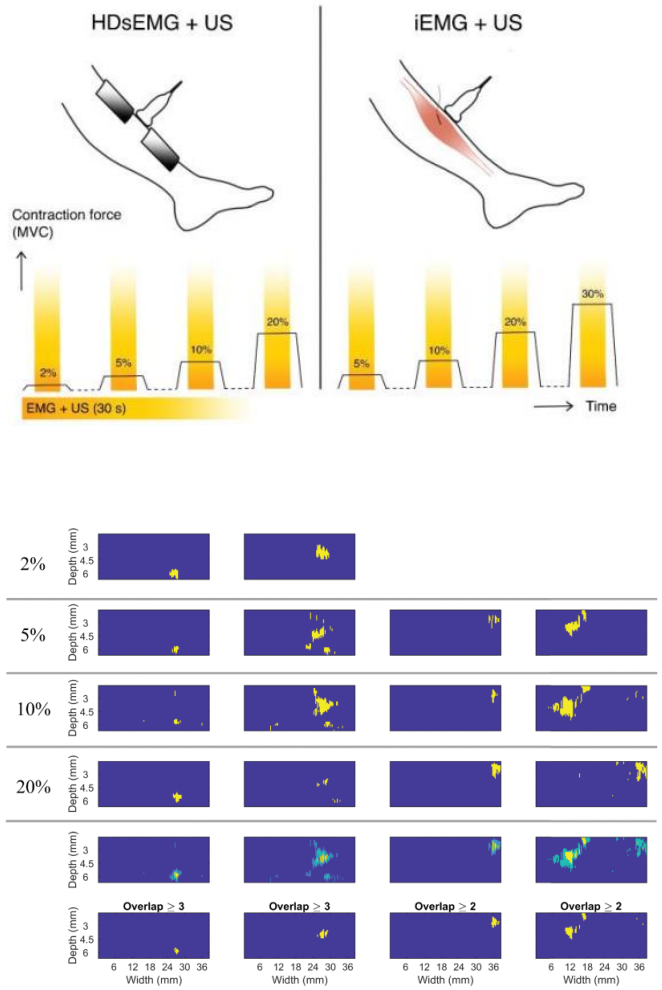

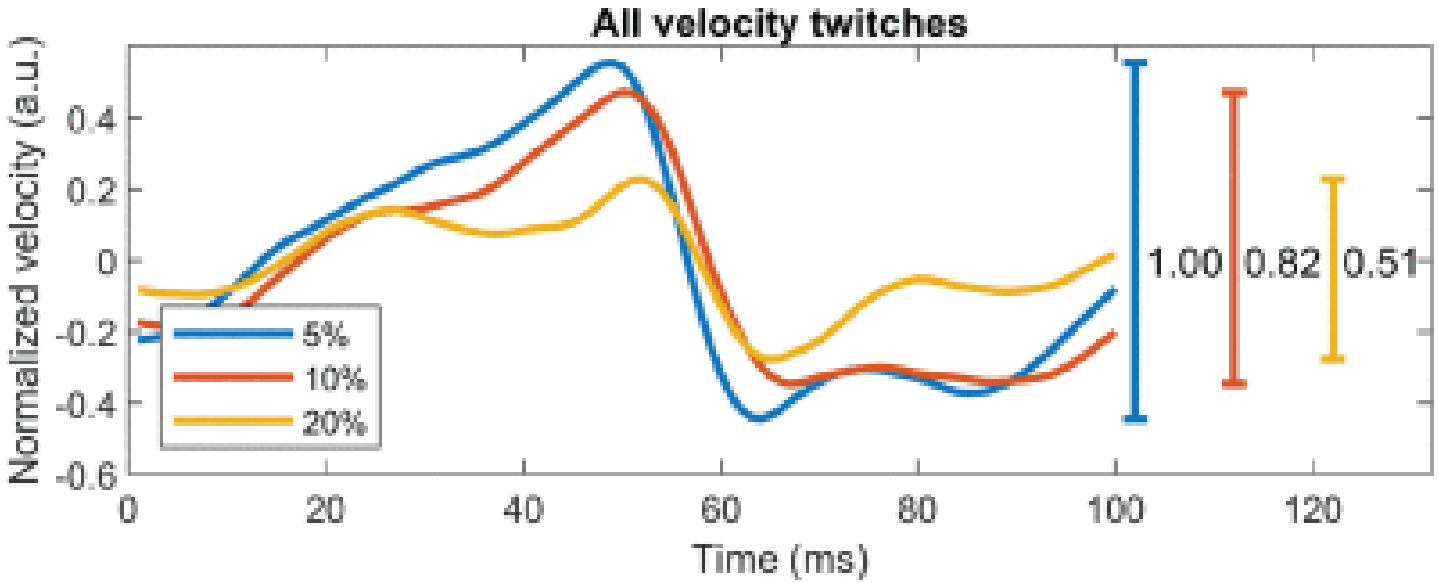

The Average amplitude of all twitches seem to decrease with higher force levels?

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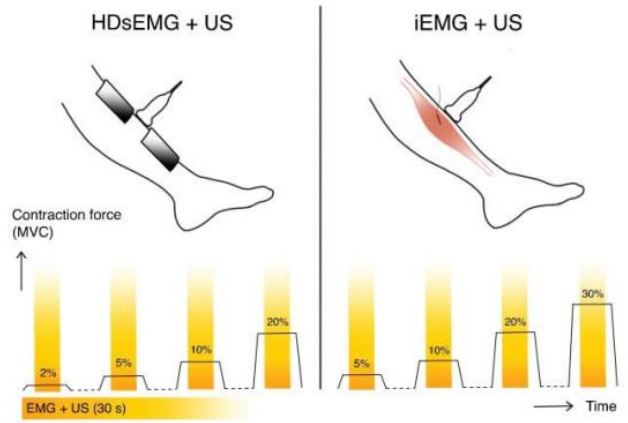

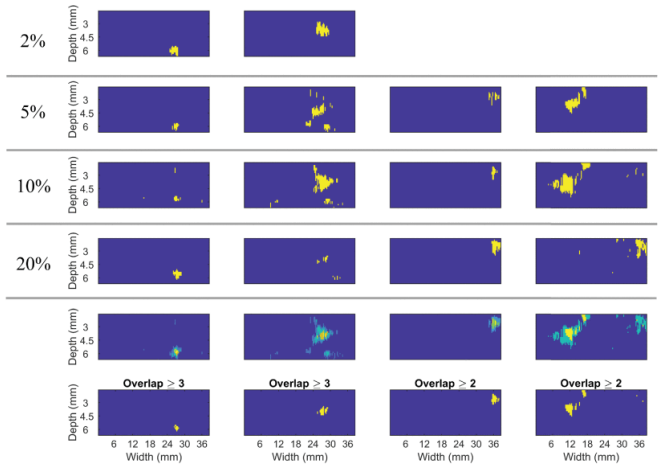

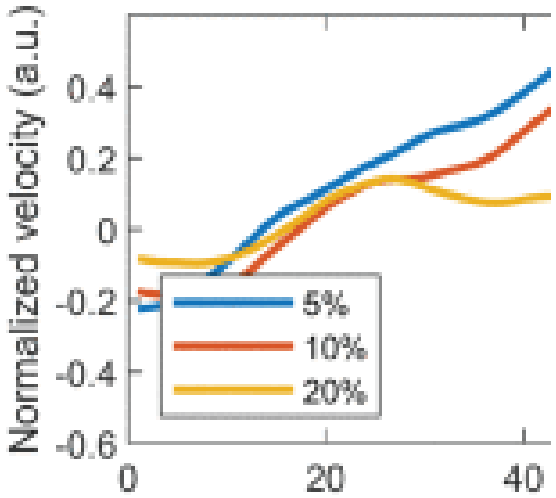

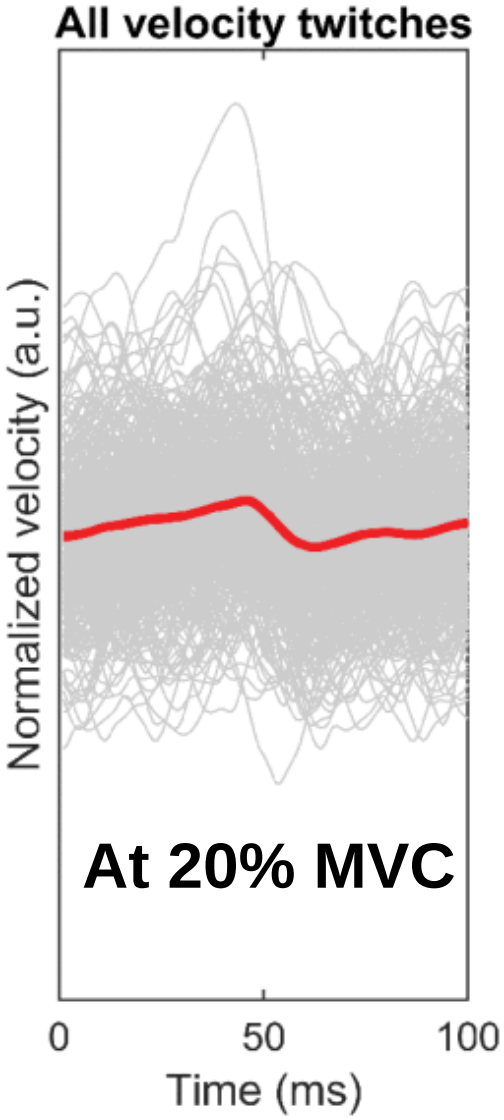

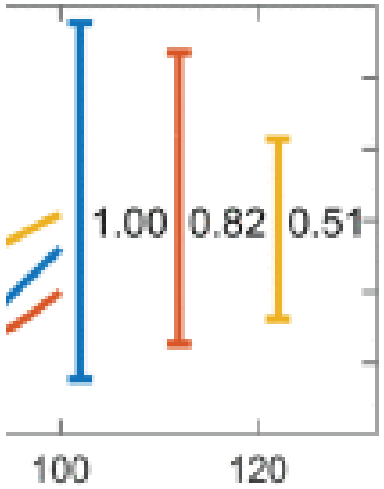

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Twitches Changes at increasing force levels

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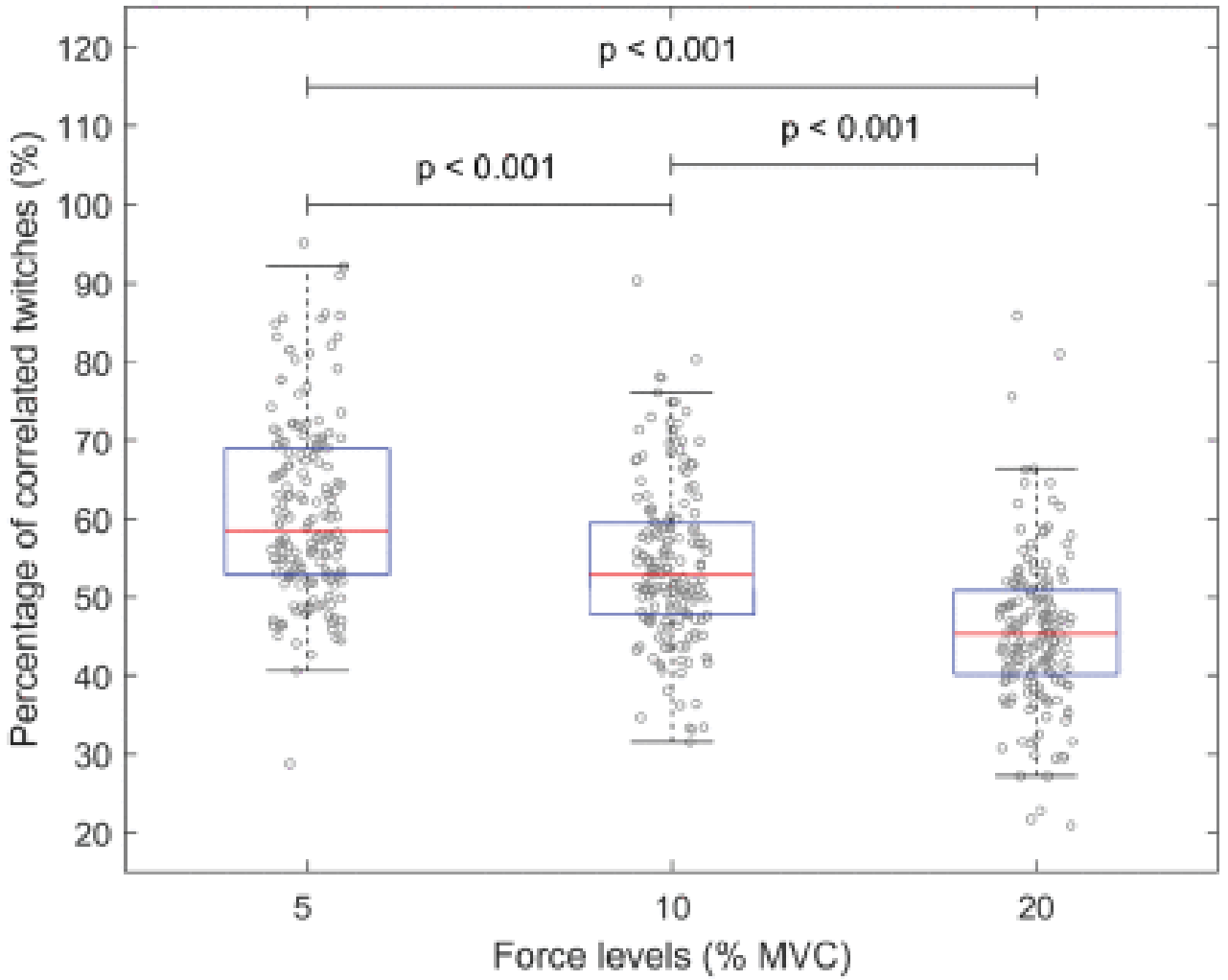
Correlation between individual spikes of a MU



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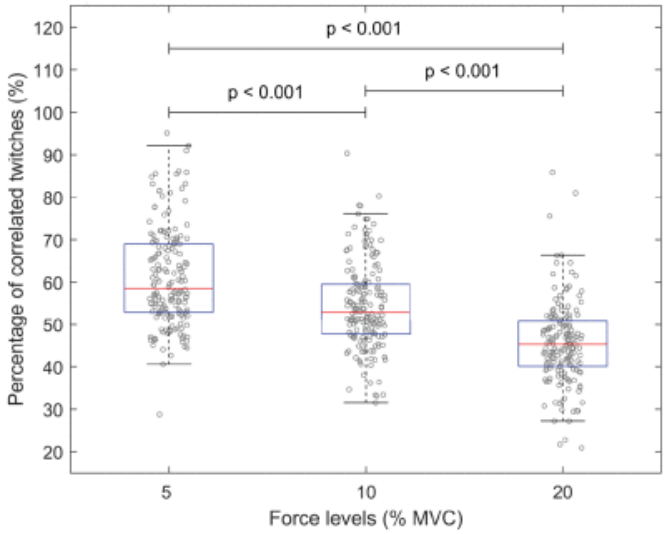

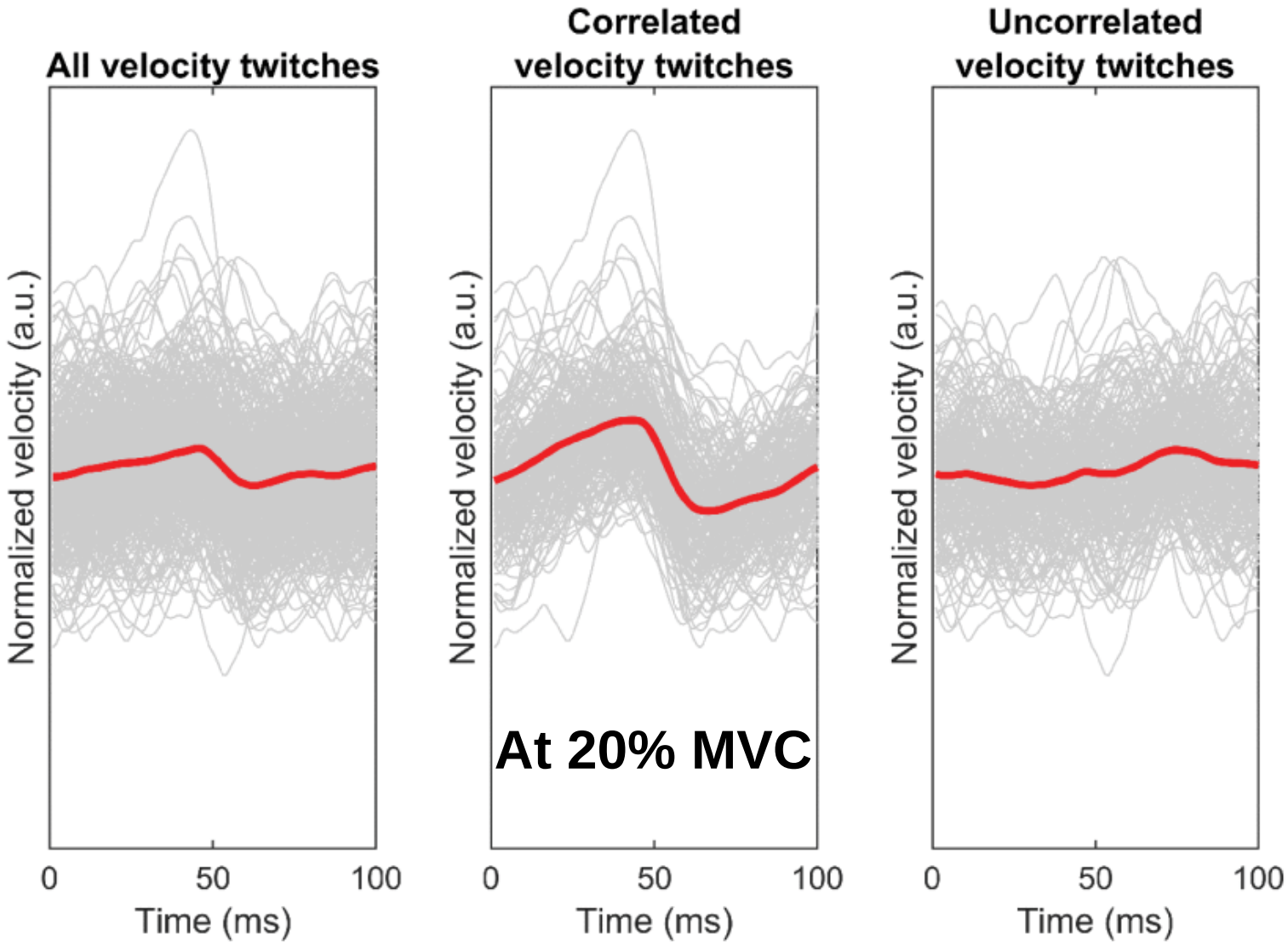

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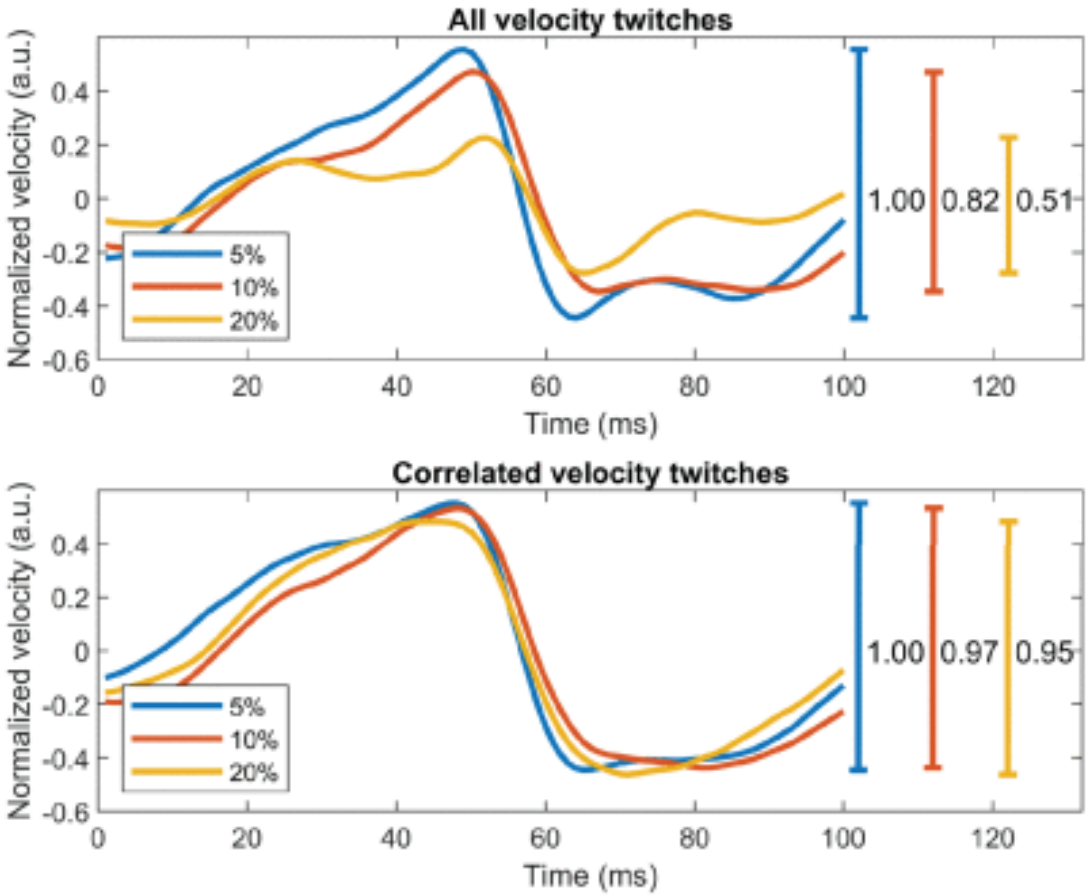

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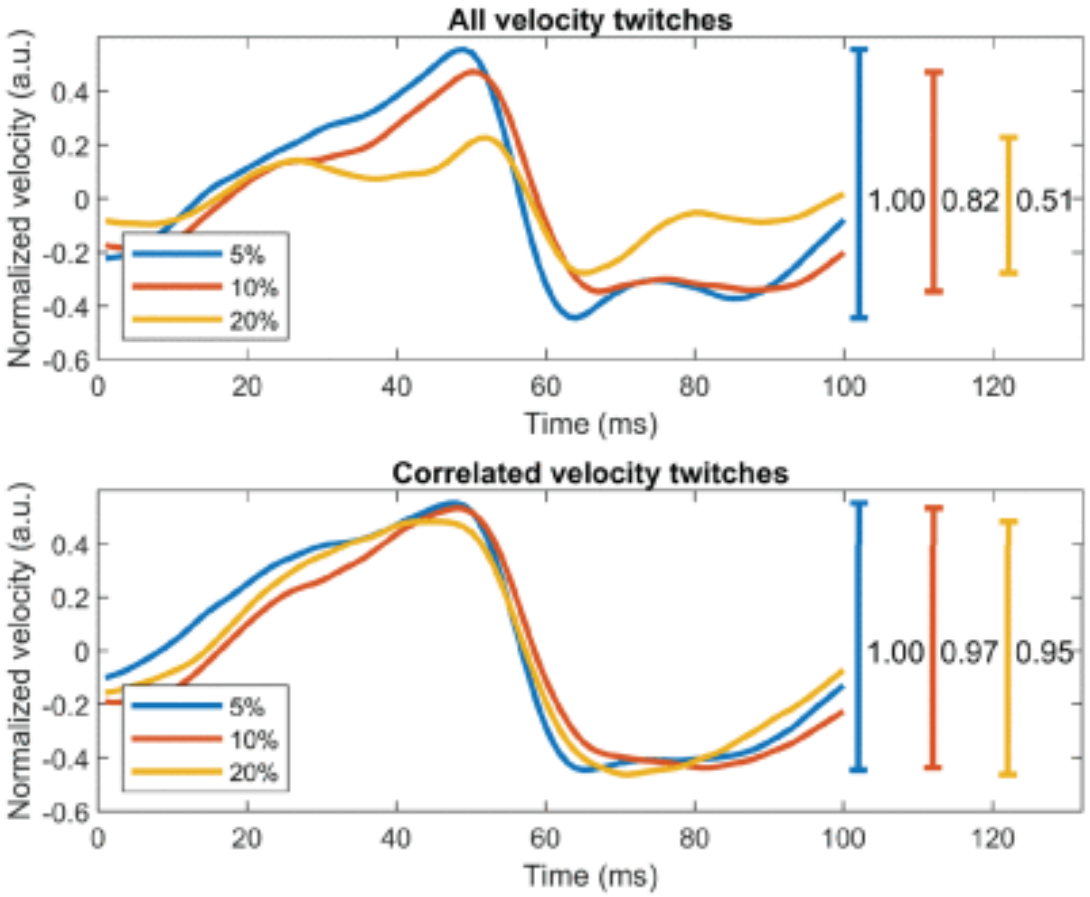

Questions.
Do MU twitch profiles change at different force levels?

Do not seem to cause significant changes in the average “standard” twitch amplitude/shape

Do introduce more uncorrelated twitches to a spike train

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Twitches Changes due to Recruitment order

Given US gives MU spatial location can we analyse units close to each other.

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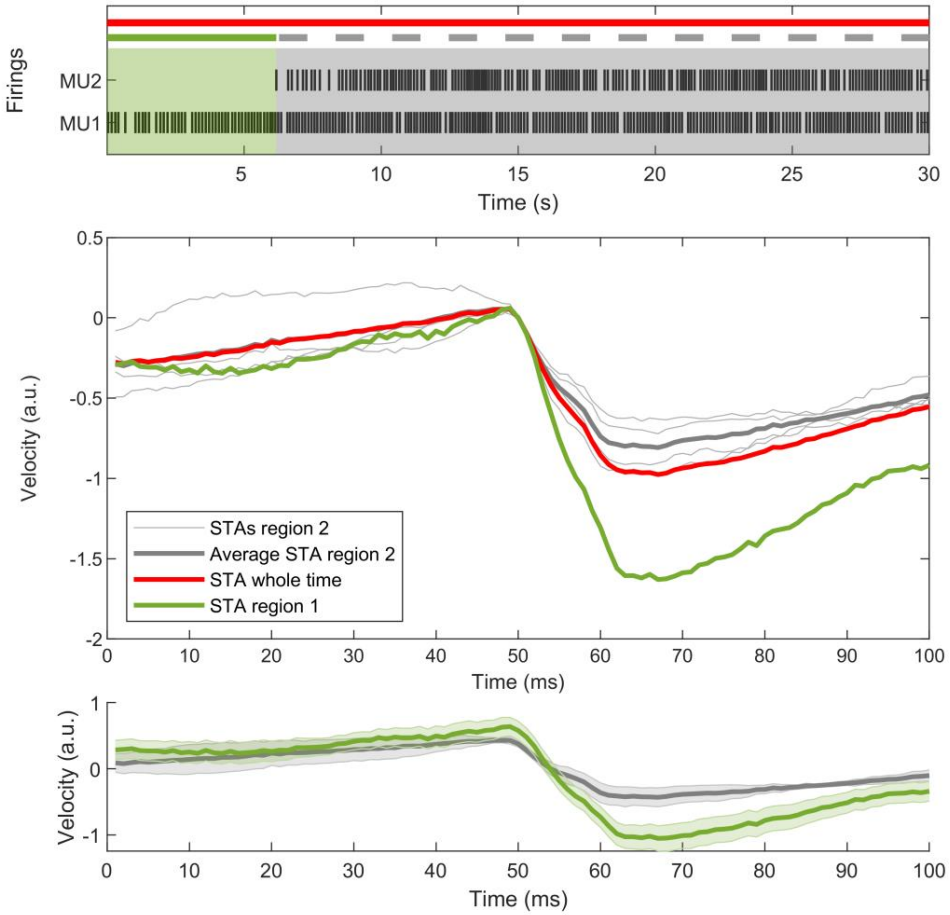

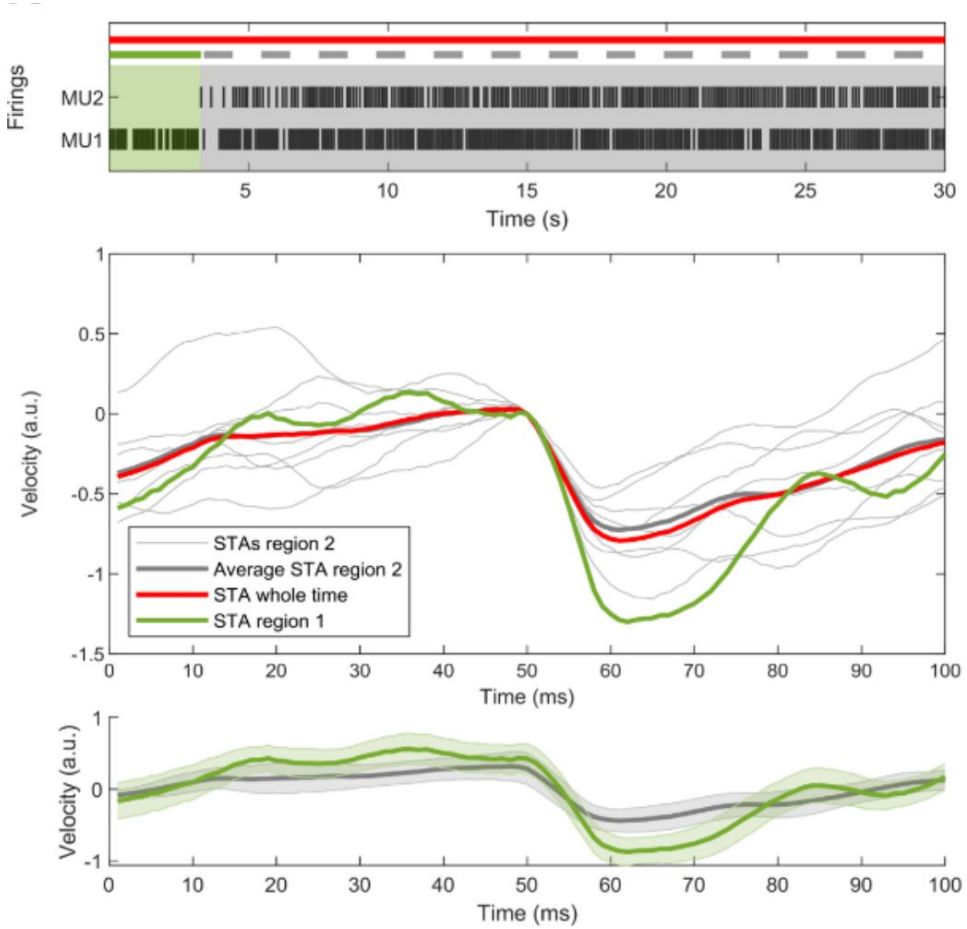

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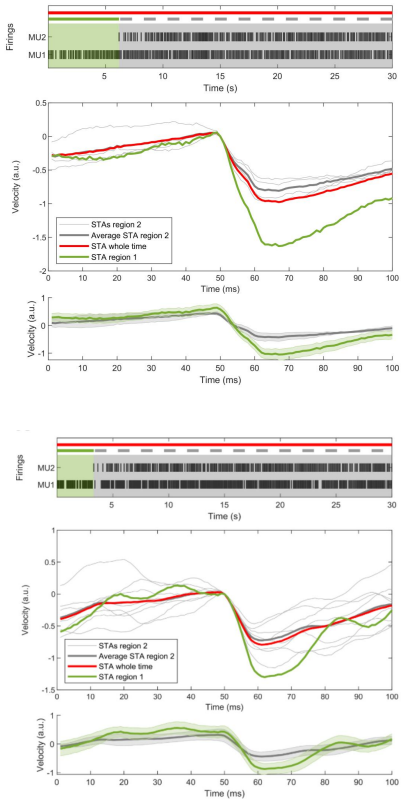

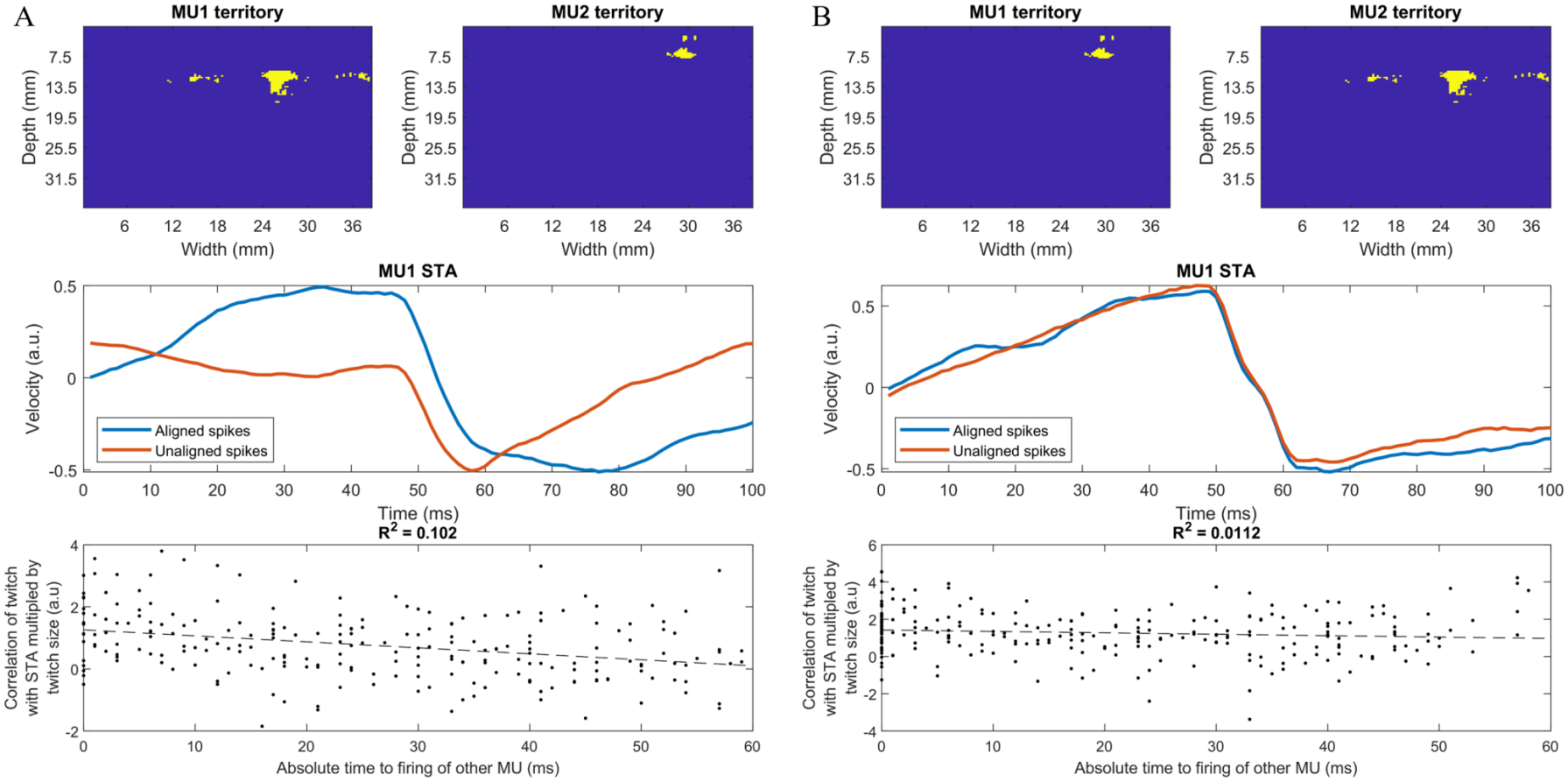

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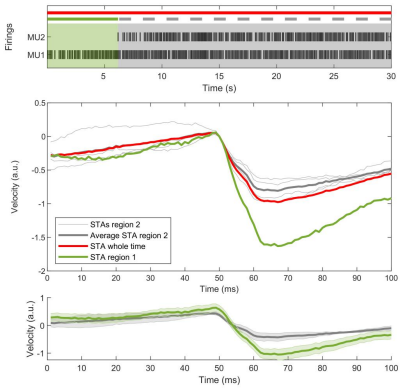

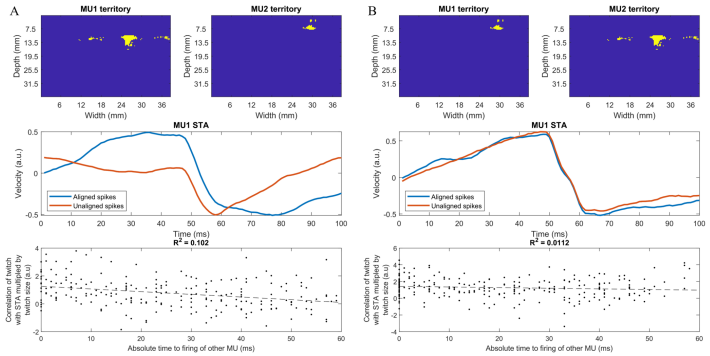

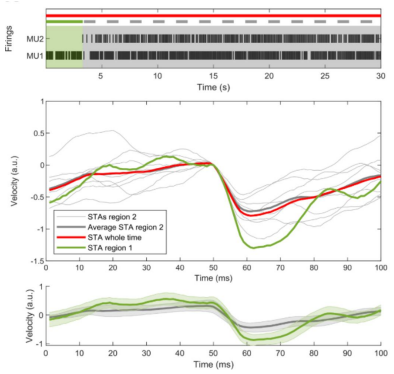

Question.

1. How linear, if at all, is the mechanical twitch summation?

2. Do MU twitch profiles change with recruitment order?

Twitches from spatially close MUs **do affect each other**

Influence from spatially close MUs is **not symmetrical**, and **may be modulated by recruitment order**

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MU decomposition with only US

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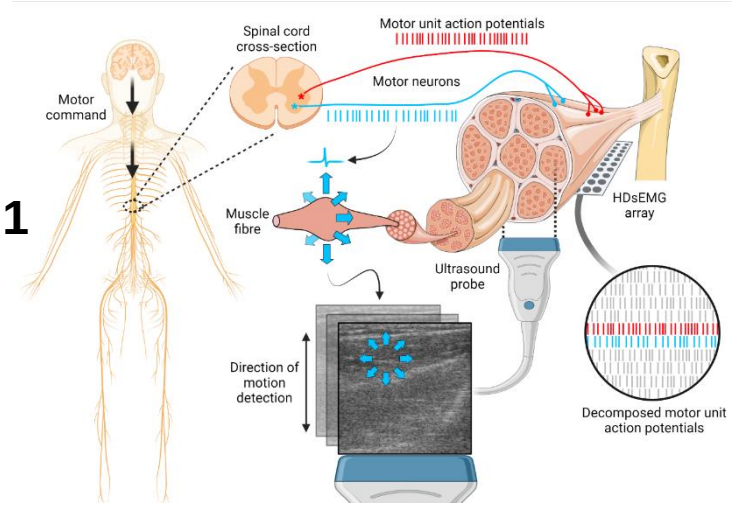
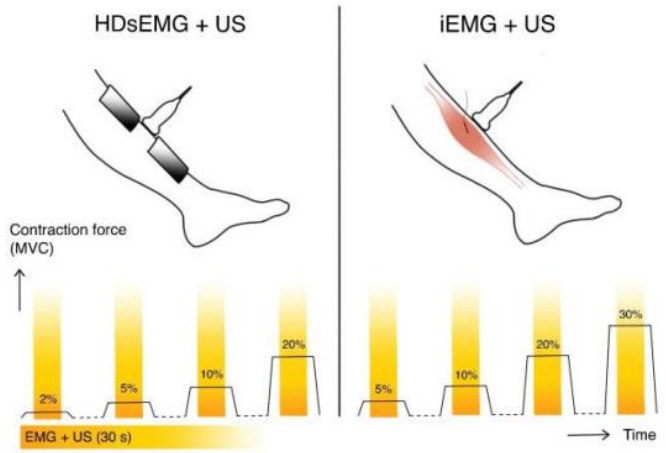
Study 1



Study 2



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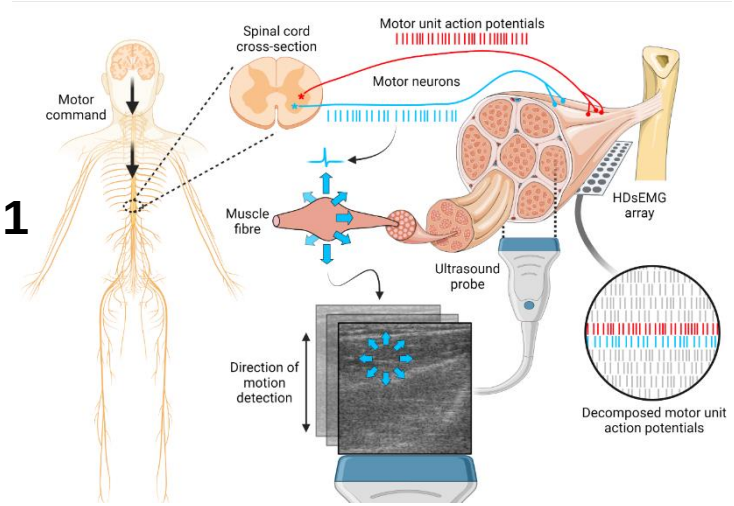

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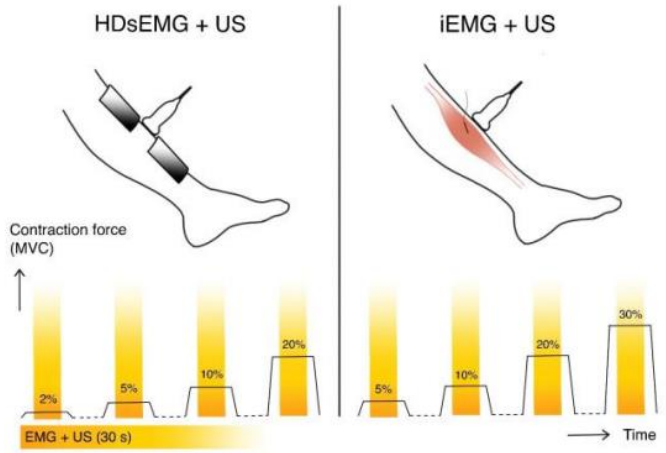
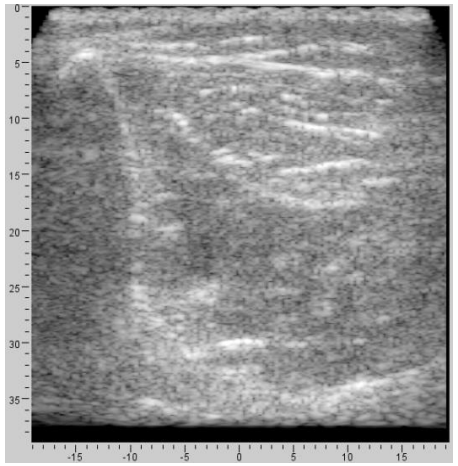
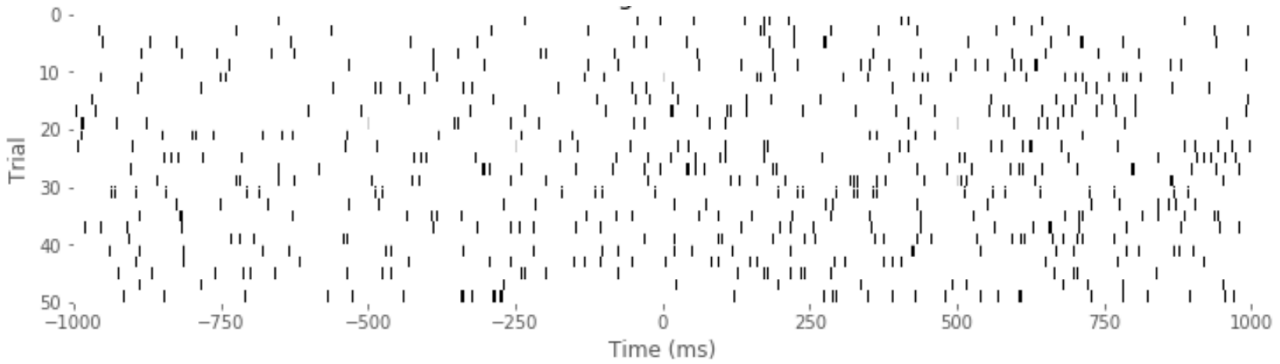




Magic?



[1]

[1] https://mark-kramer.github.io/Case-Studies-Python/10.html

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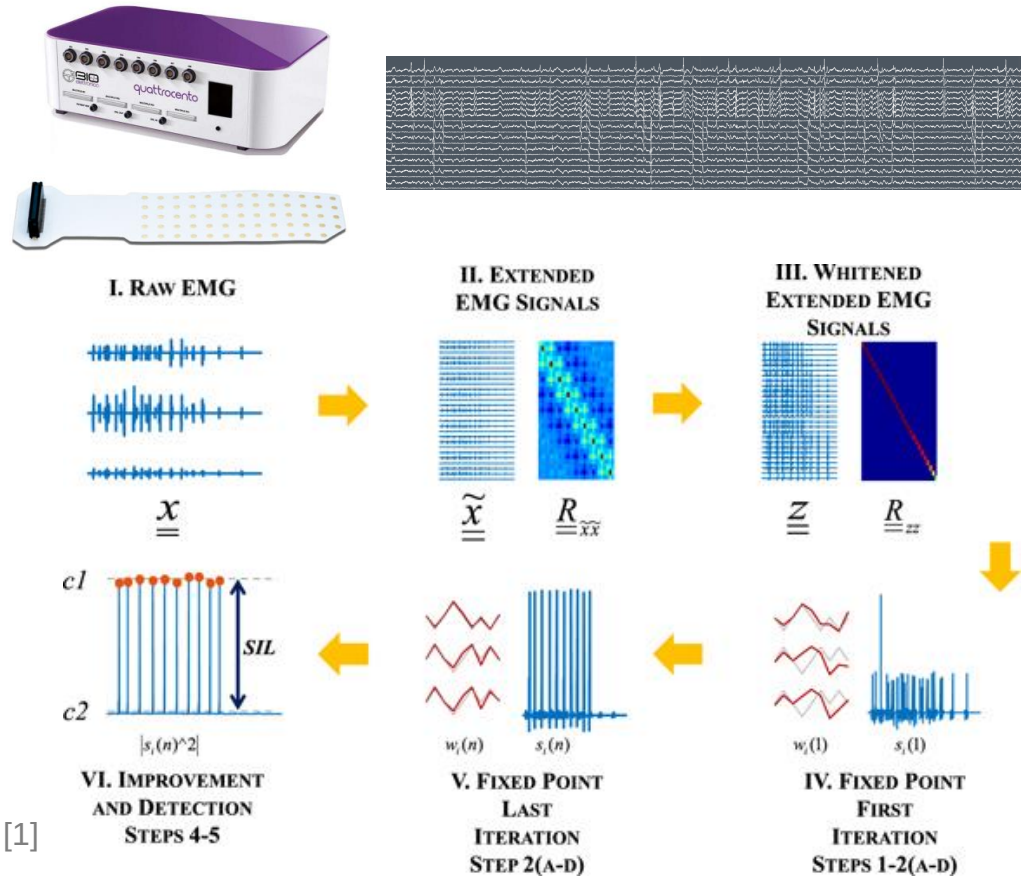
MU decomposition with only US

Given our Experience with EMG.



[1]

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[1] Francesco Negro et al. Multi-channel intramuscular and surface EMG decomposition by convolutive blind source separation, 2016

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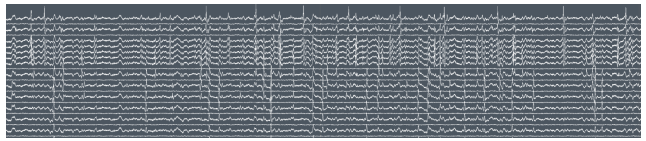

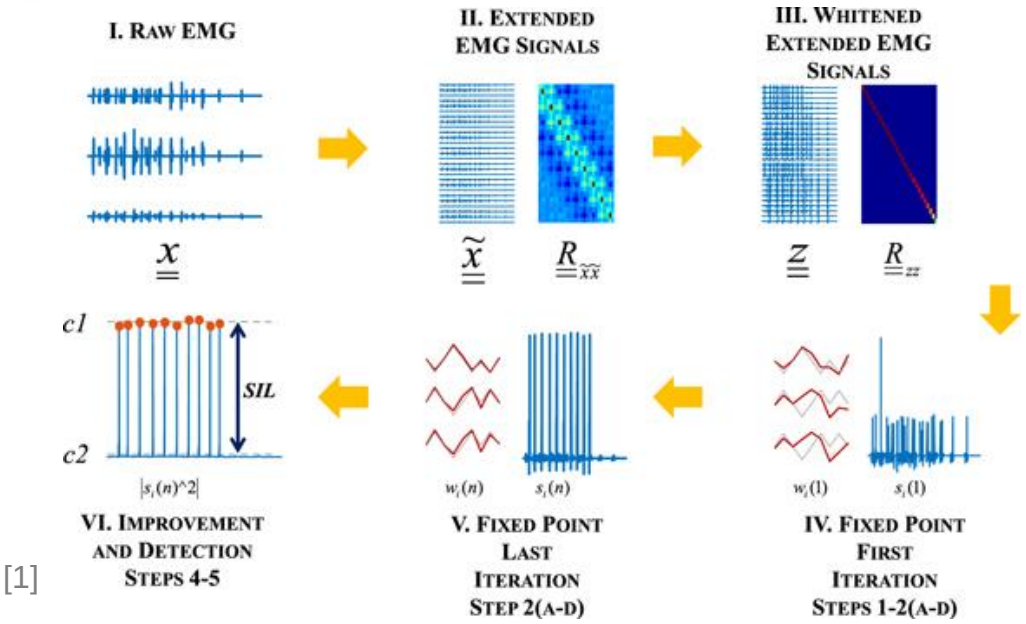

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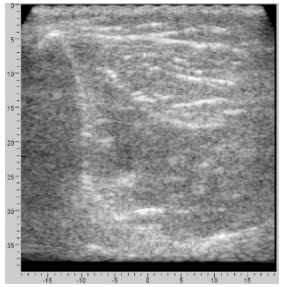

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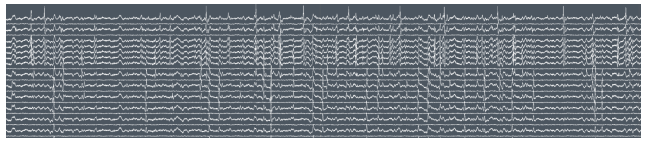
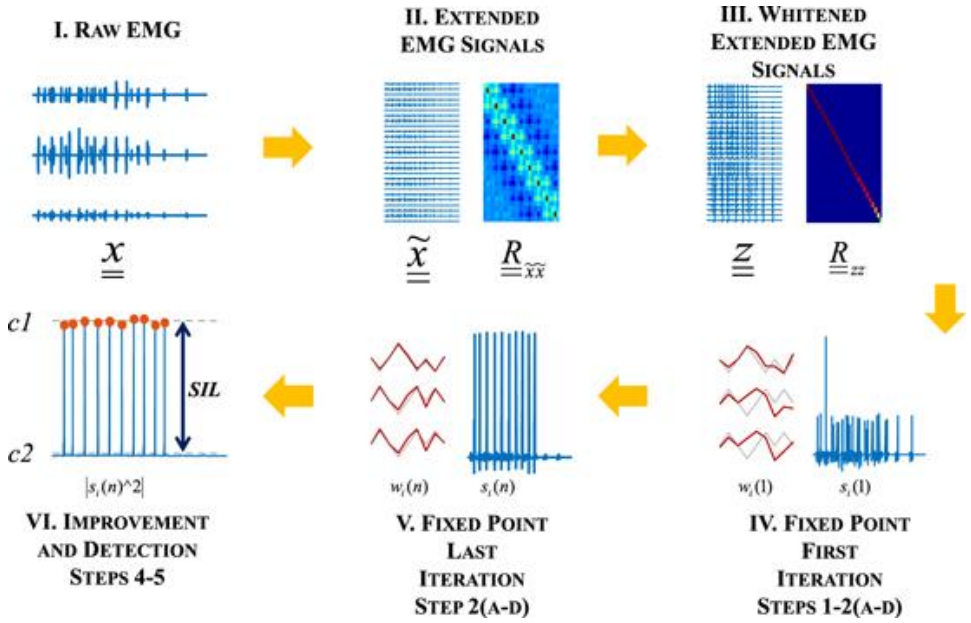
[1] Francesco Negro et al. Multi-channel intramuscular and surface EMG decomposition by convolutive blind source separation, 2016

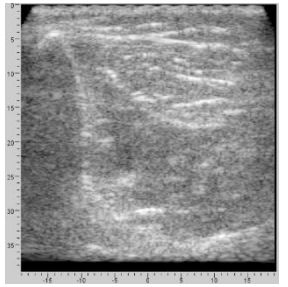
MU decomposition with only US

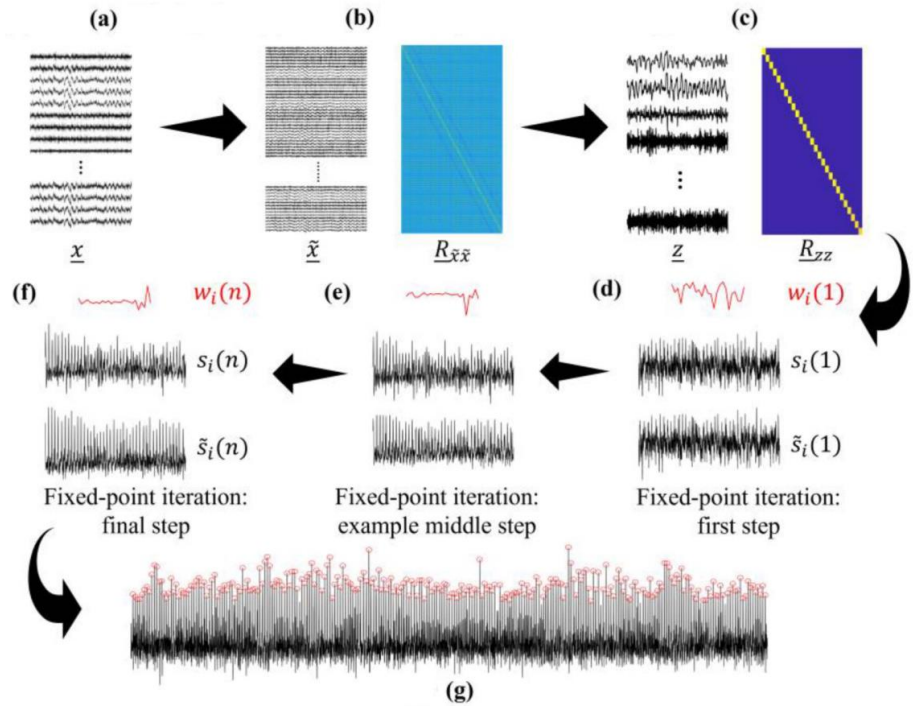
Given our Experience with EMG.





[1]





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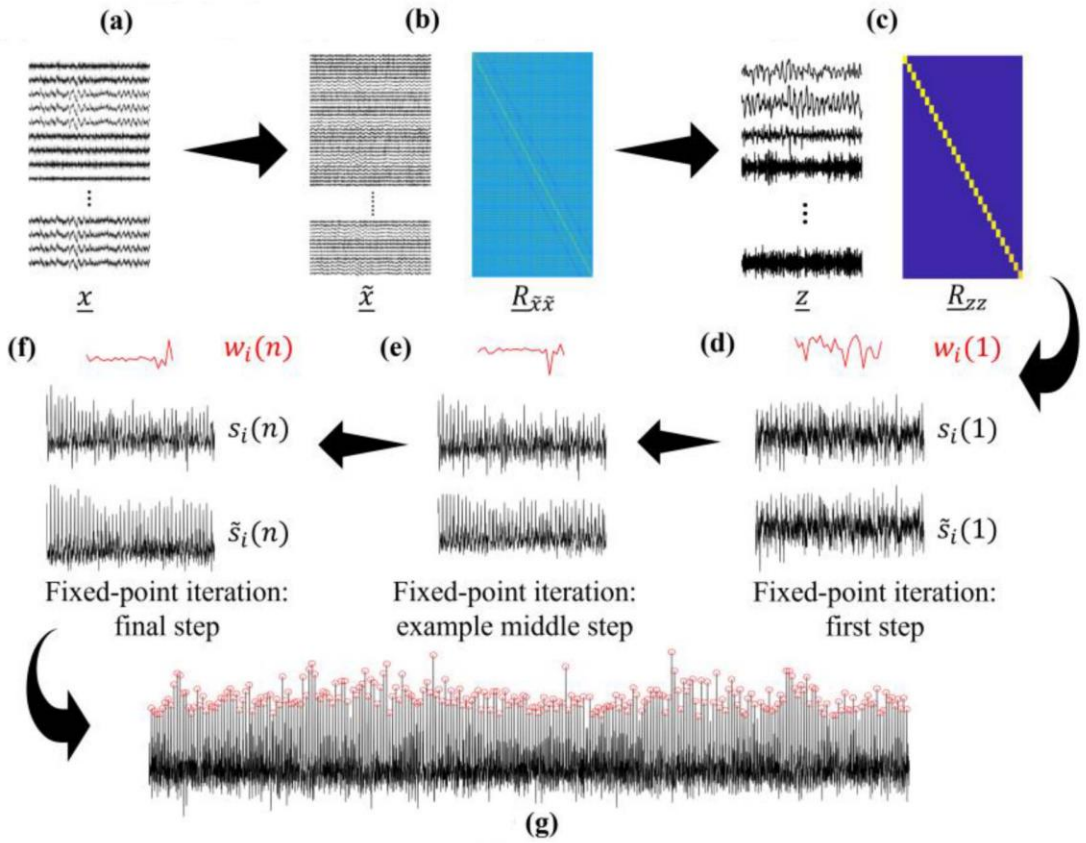
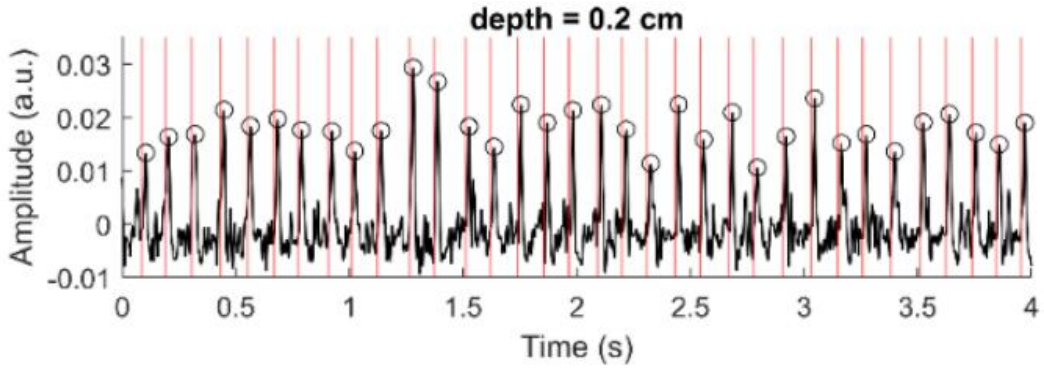


Using our Dataset of Simultaneous HDsEMG and US



Black – US decomposed
Red – HDsEMG decomposed

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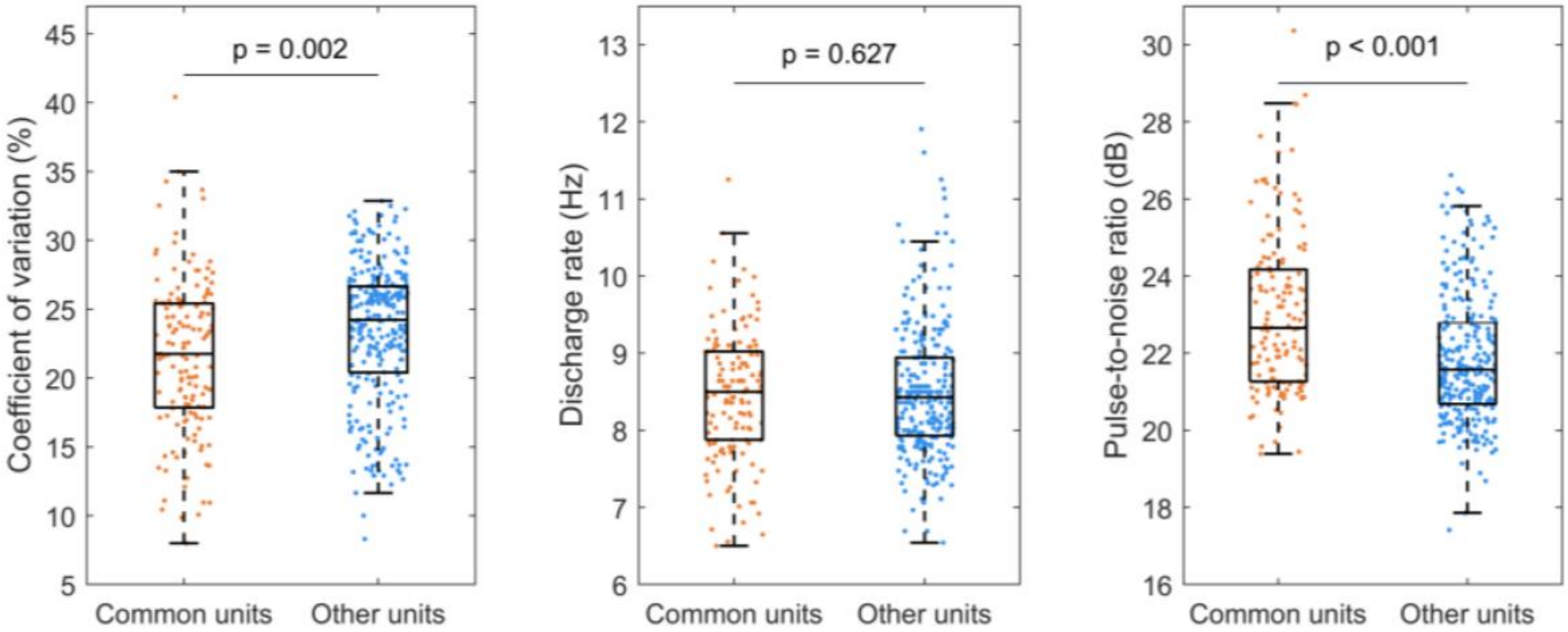
Emma Lubel et al. Accurate Identification of Motoneuron Discharges from Ultrasound Images Across the Full Muscle Cross-Section, 2023

MU decomposition with only US

Two source validation.



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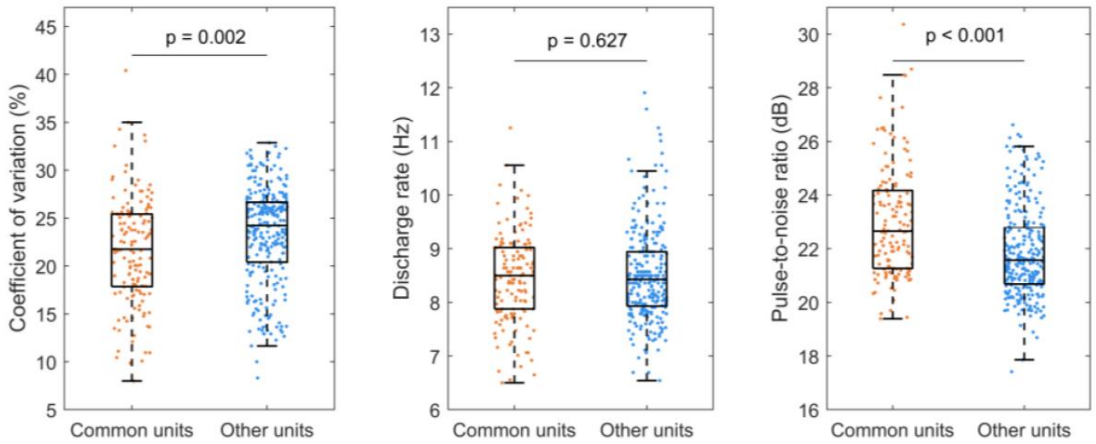

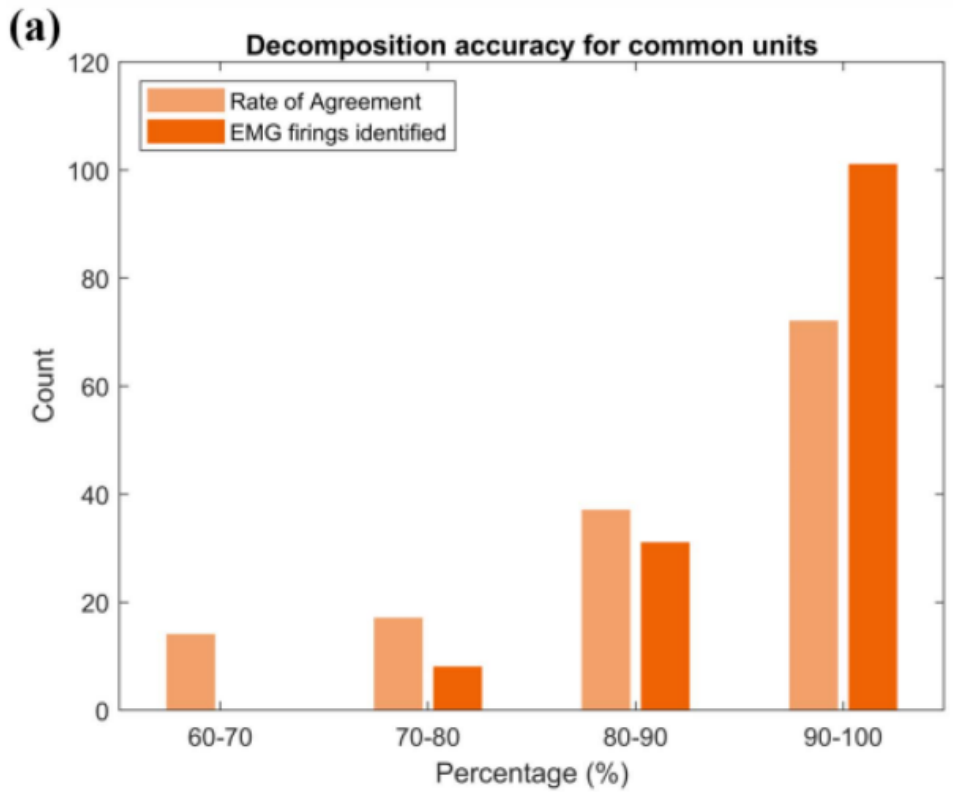

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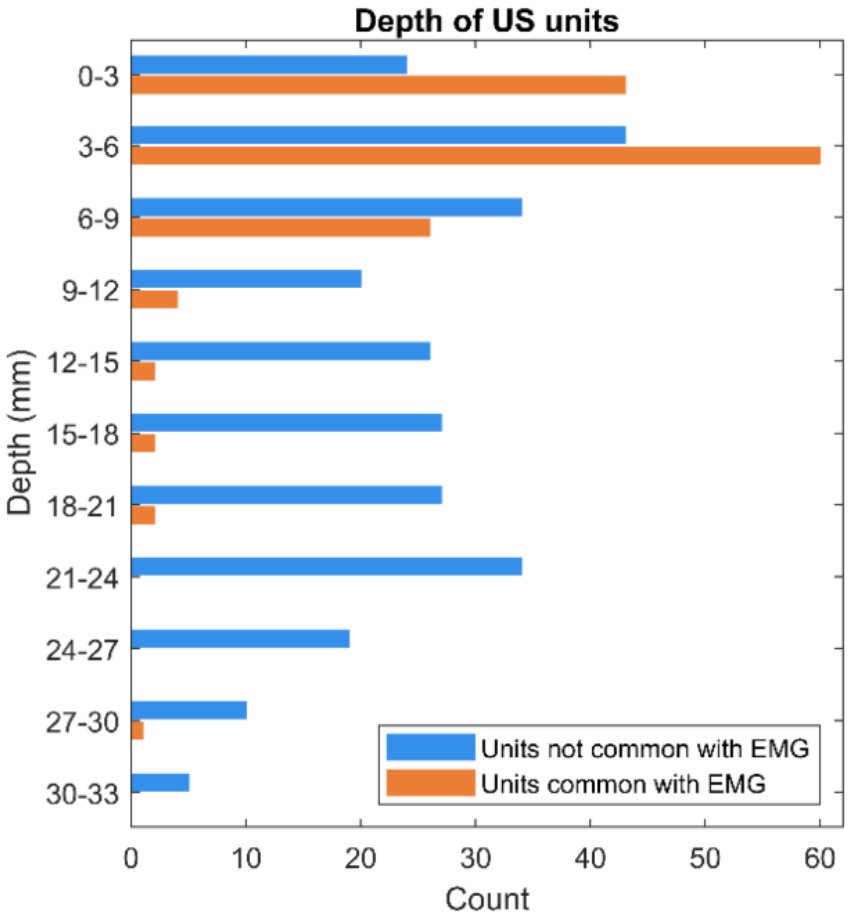
MU decomposition with only US

The Ultrasound Differential.



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MU decomposition with only US

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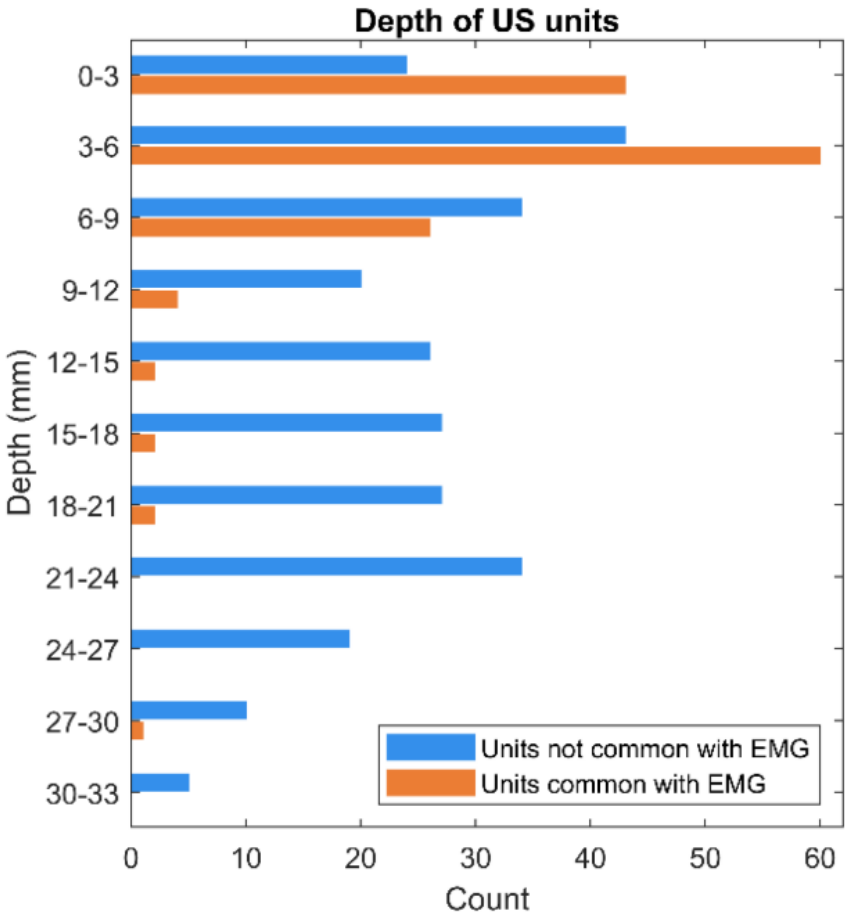

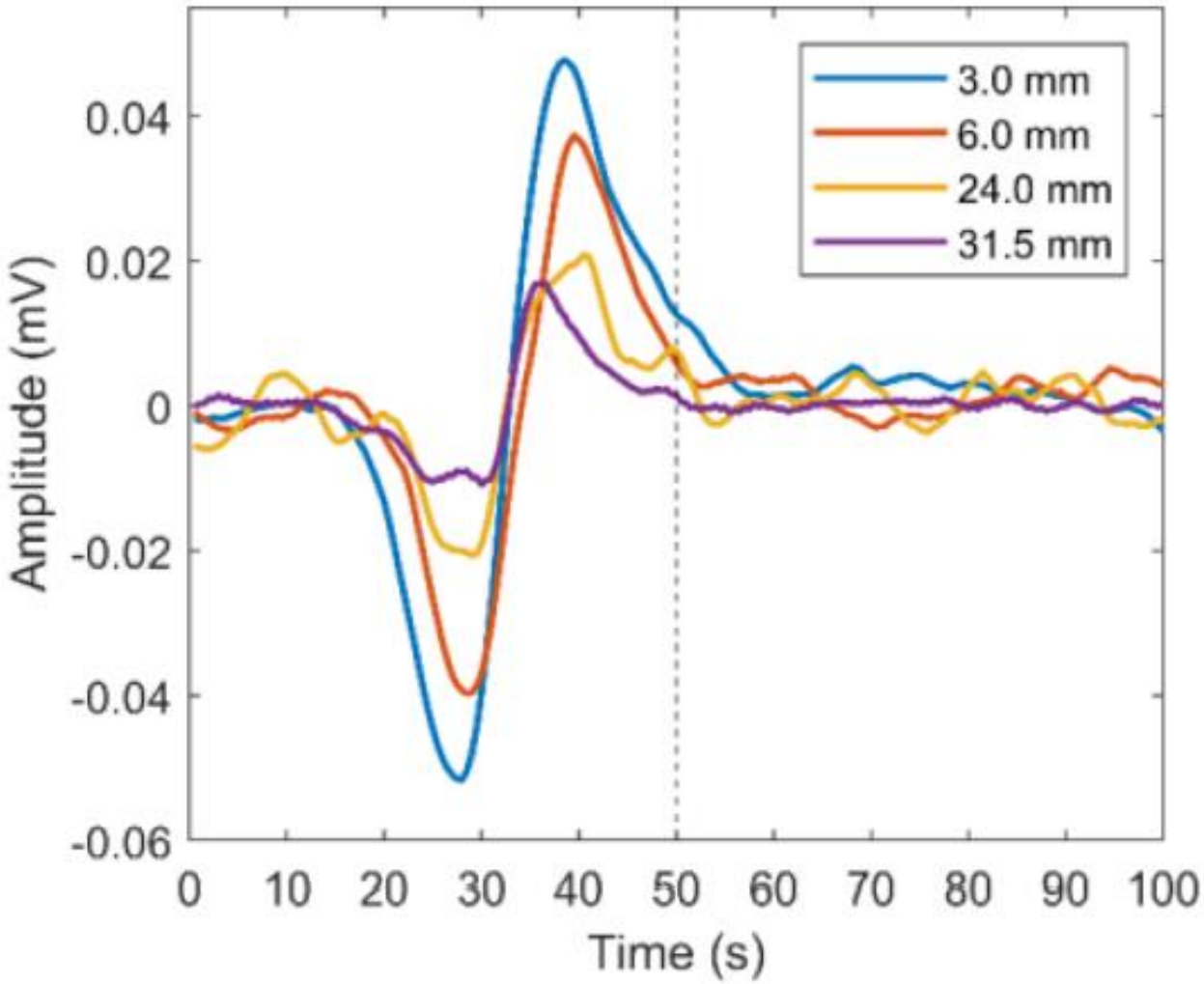

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Break Time!

HYBRID NEURO

Happy to answer questions during the Break

All this work so far was done offline

Each 44 Kg

Long processing

After the break

What can ultrasound do when you are restricted to:

Portable Electronics

Real-time Processing

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Topics

1. Motivation
2. What is Ultrasound?
3. Application 1. Motor Unit Decomposition via Ultrafast Ultrasound
4. Break Time
5. **Translational challenges: Laboratory → Real-World**
6. Application 2. Interfacing with Wearable A-mode Ultrasound
7. Questions and Answers

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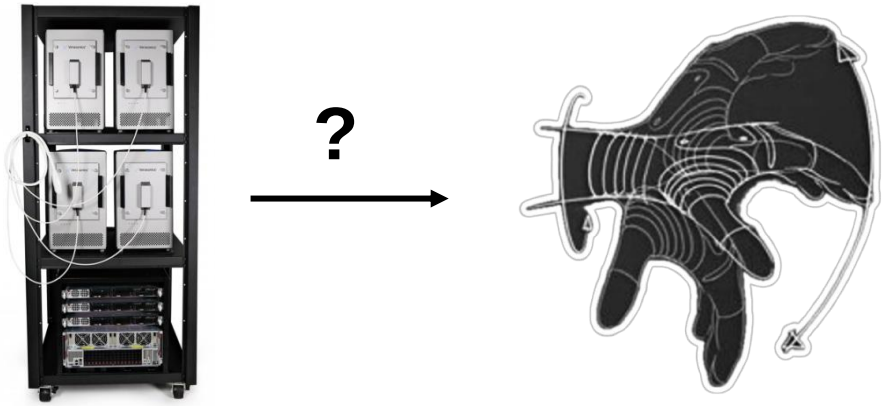
Why do we not use the MU decomposition method?

- US decomposition is **potentially great** for Human Machine Interface control



But it currently still faces a number of **practical limitations**

1. Likely limited performance on higher forces
2. Validation only conducted on Isometric conditions
3. Probes are large, bulky and not stable during movement
4. Acquisition system required is not portable
5. Beamforming + Processing + Decomposition is fairly slow

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Are there other ways of using ultrasound to interface with muscles?

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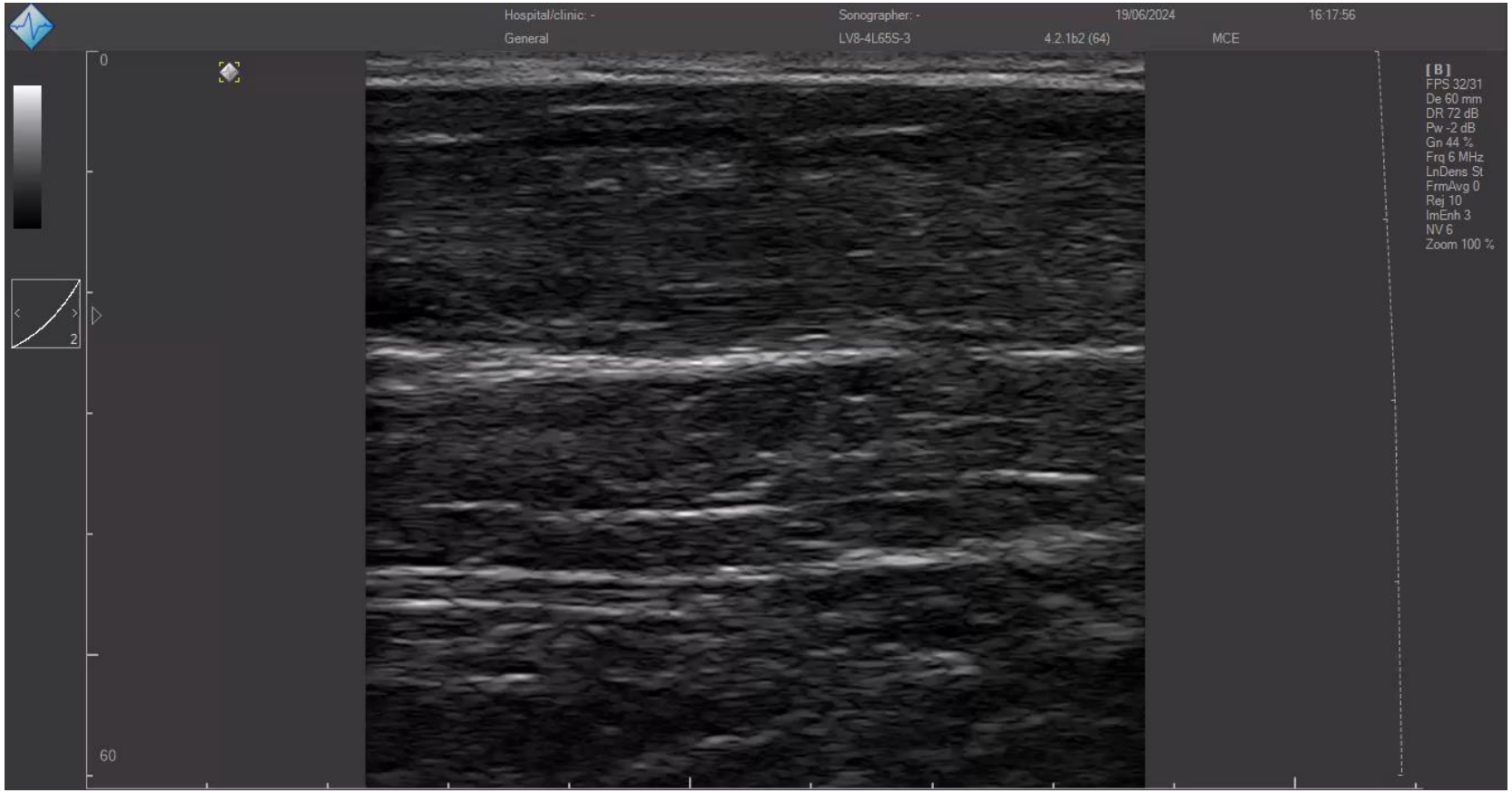
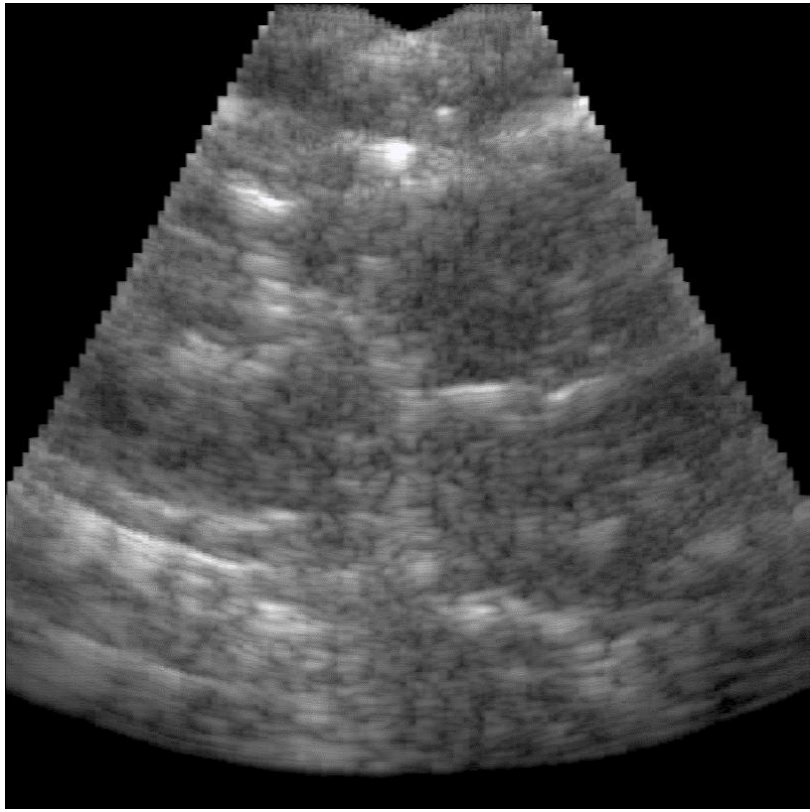
- Ultrasound can also image **gross muscular movement**





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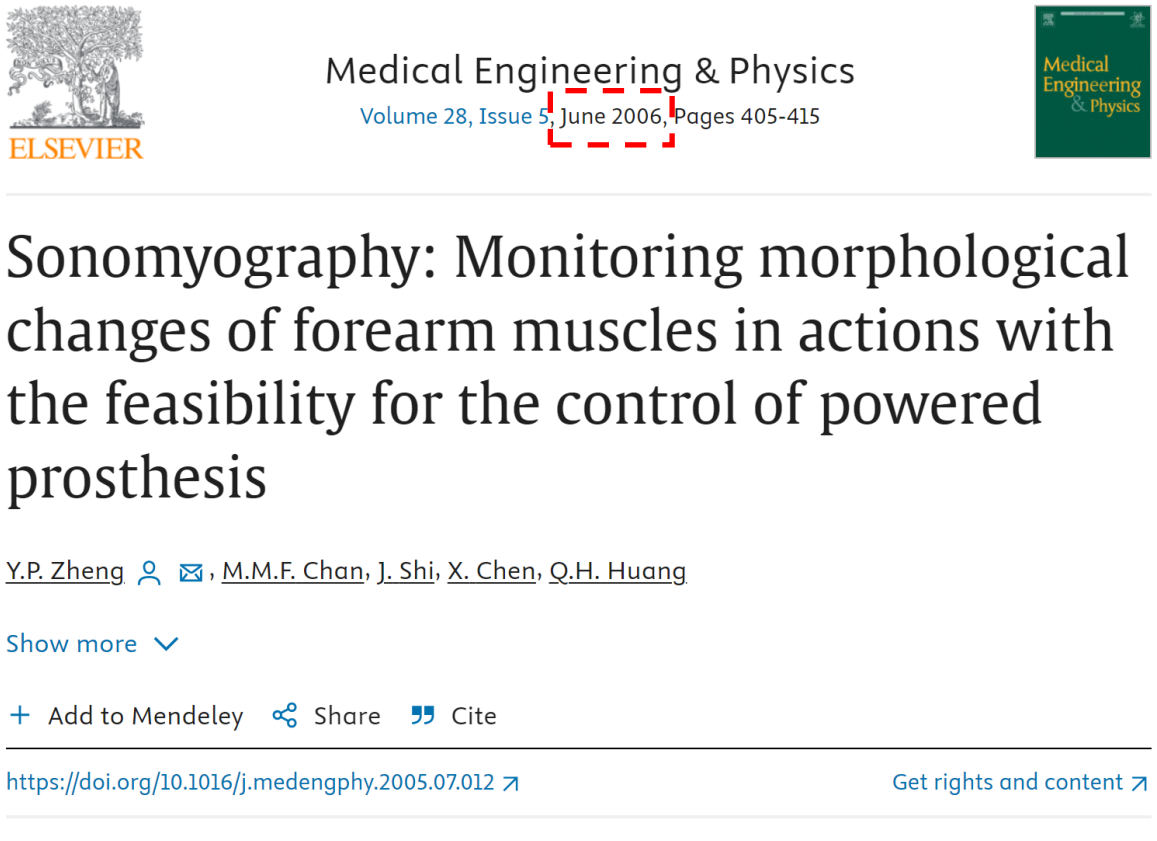
First work investigating it in a control perspective



ELSEVIER

Medical Engineering & Physics

Volume 28, Issue 5, June 2006, Pages 405-415

Medical Engineering & Physics

Sonomyography: Monitoring morphological changes of forearm muscles in actions with the feasibility for the control of powered prosthesis

Y.P. Zheng, M.M.F. Chan, J. Shi, X. Chen, Q.H. Huang

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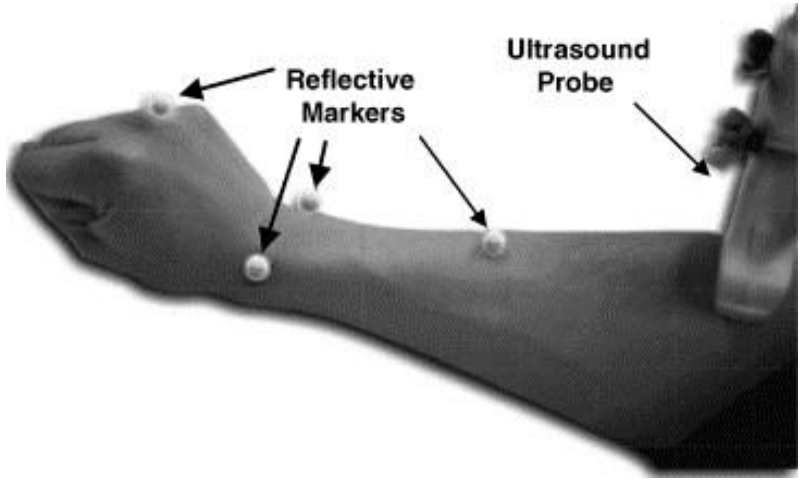

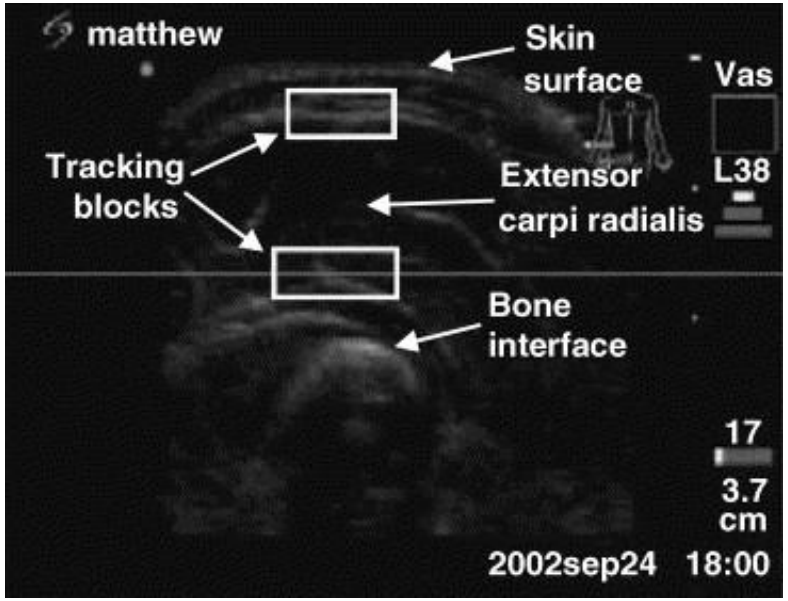

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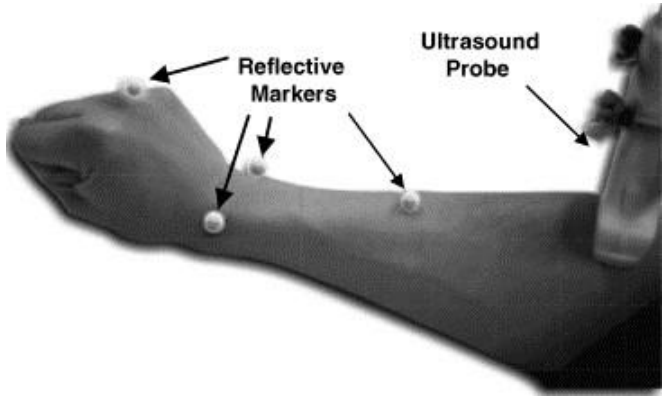

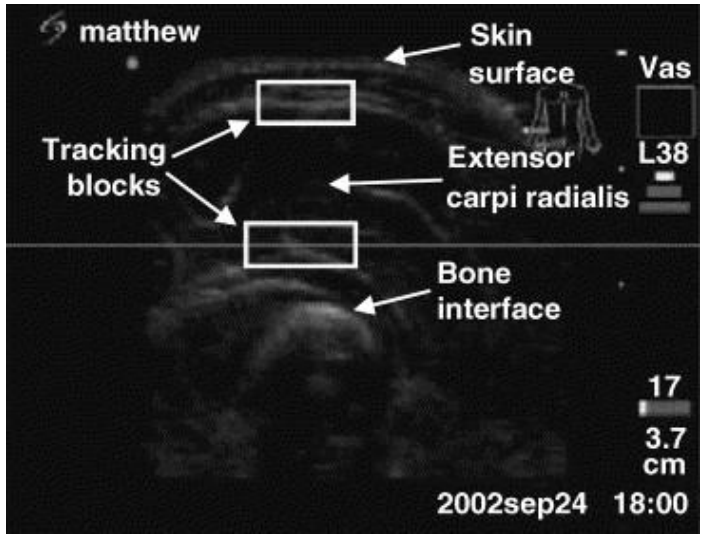

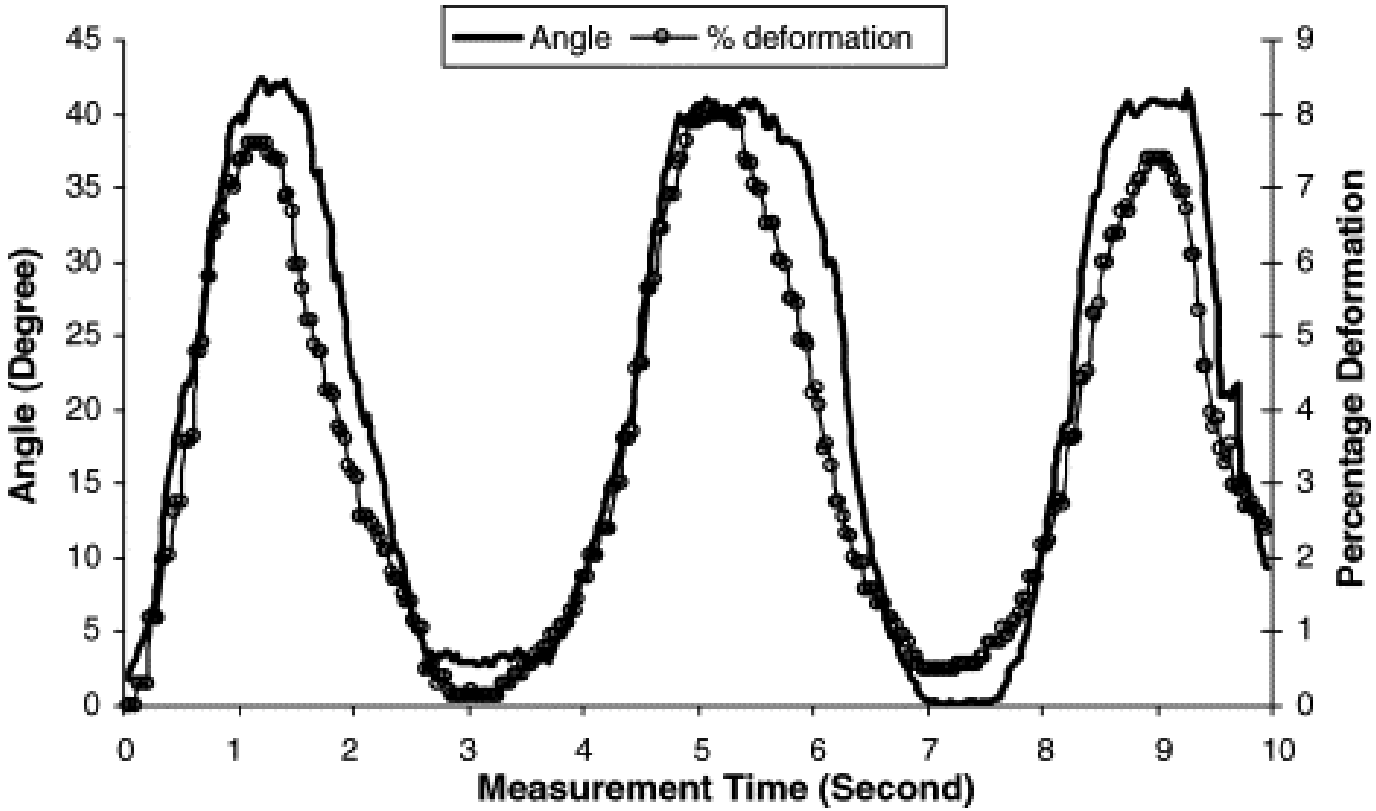

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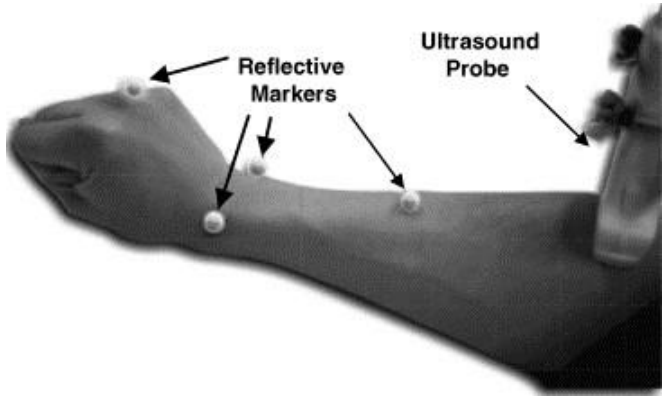

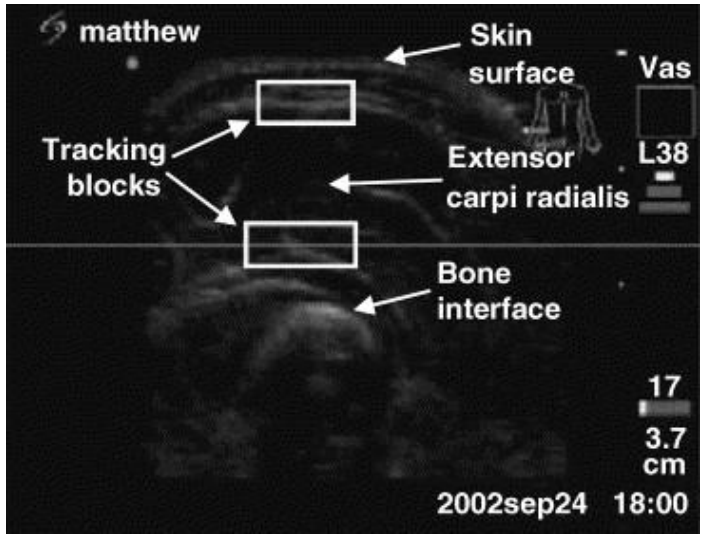

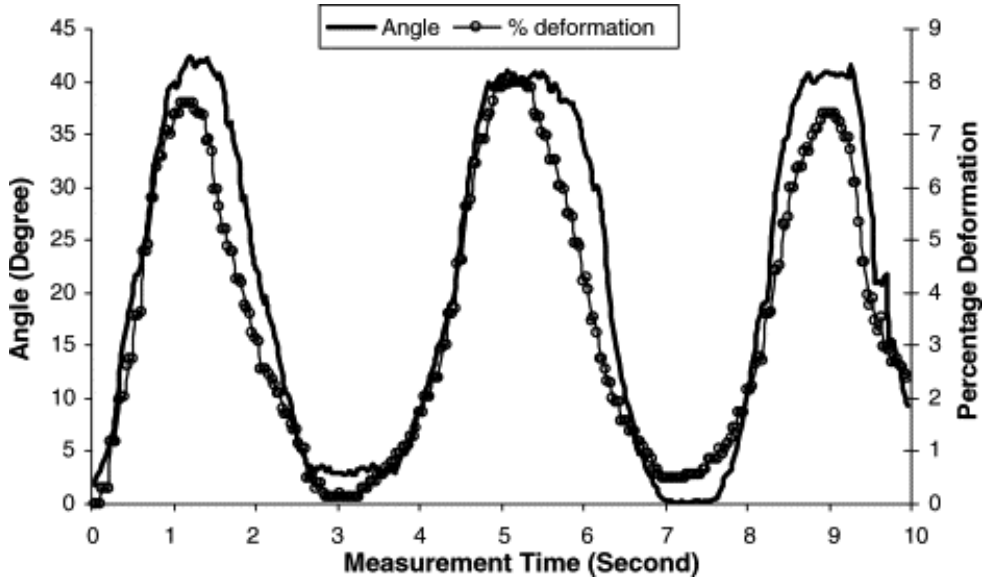

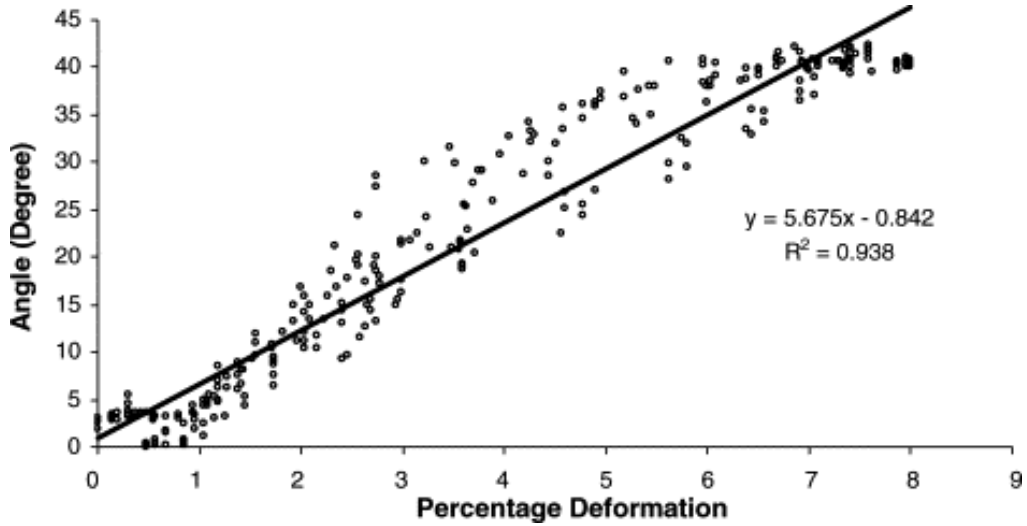

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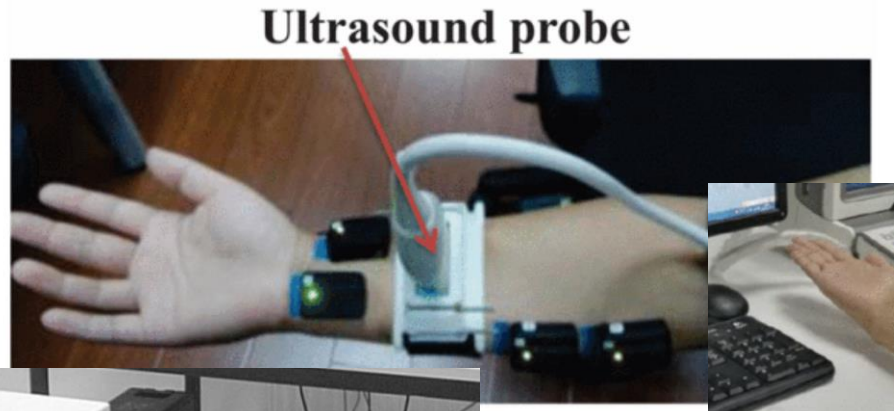
Follow-up B-mode HMI literature

2017	Huang and Yang et al.
2012	Castellini et al.
2019	Yang and Huang et al.
2012	Shi et al.
2014	Sikdar et al.
2016	Huang et al.
2005	Zheng et al.
2016	Akhlaghi et al.
2013	Castellini et al.
2014	Ravindra and Castellini et al.
2017	Jess McIntosh et al.
2017	Khan and Akhlaghi et al.
2019	Akhlaghi et al.
2019	Dhawan and Skidar et al.
2020	Engdahl and Skidar et al.
2021	Engdahl and Skidar et al.
2022	Engdahl and Skidar et al.
2022	Jianmin Li et al.
2021	Alexander et al.
2021	Yang Zheng and Xiaogang Hu et al.



[1]

[4]

[2]

[5]

[3]

[6]

[1] Huang et al.
[2,3] Castellini et al.
[4] Yang et al.
[5] Ravindra et al.
[6] Engdahl et al.

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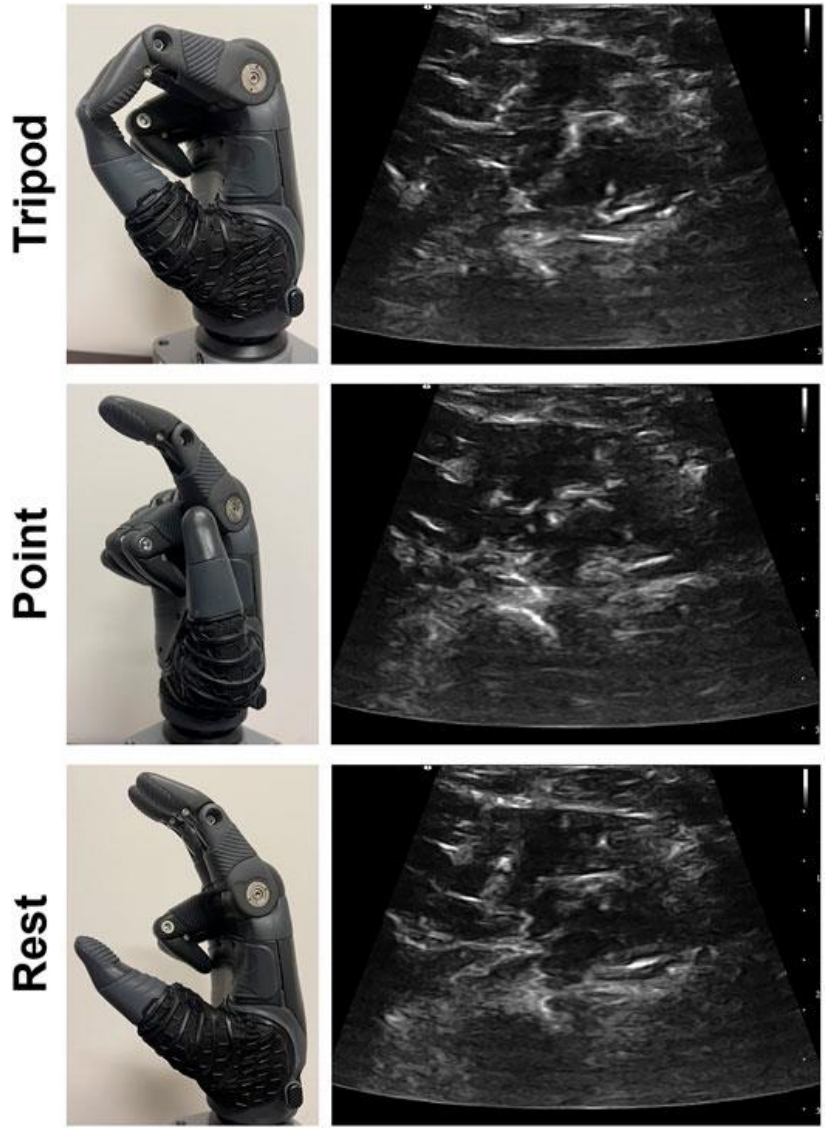

Engfahl et al. First Demonstration of Functional Task Performance Using a Sonomyographic Prosthesis: A Case Study

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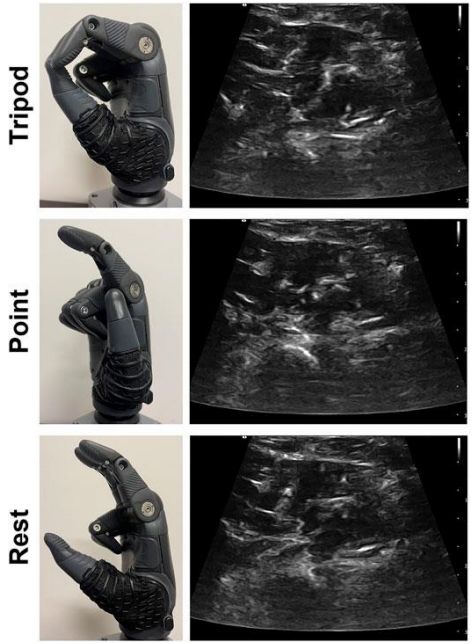

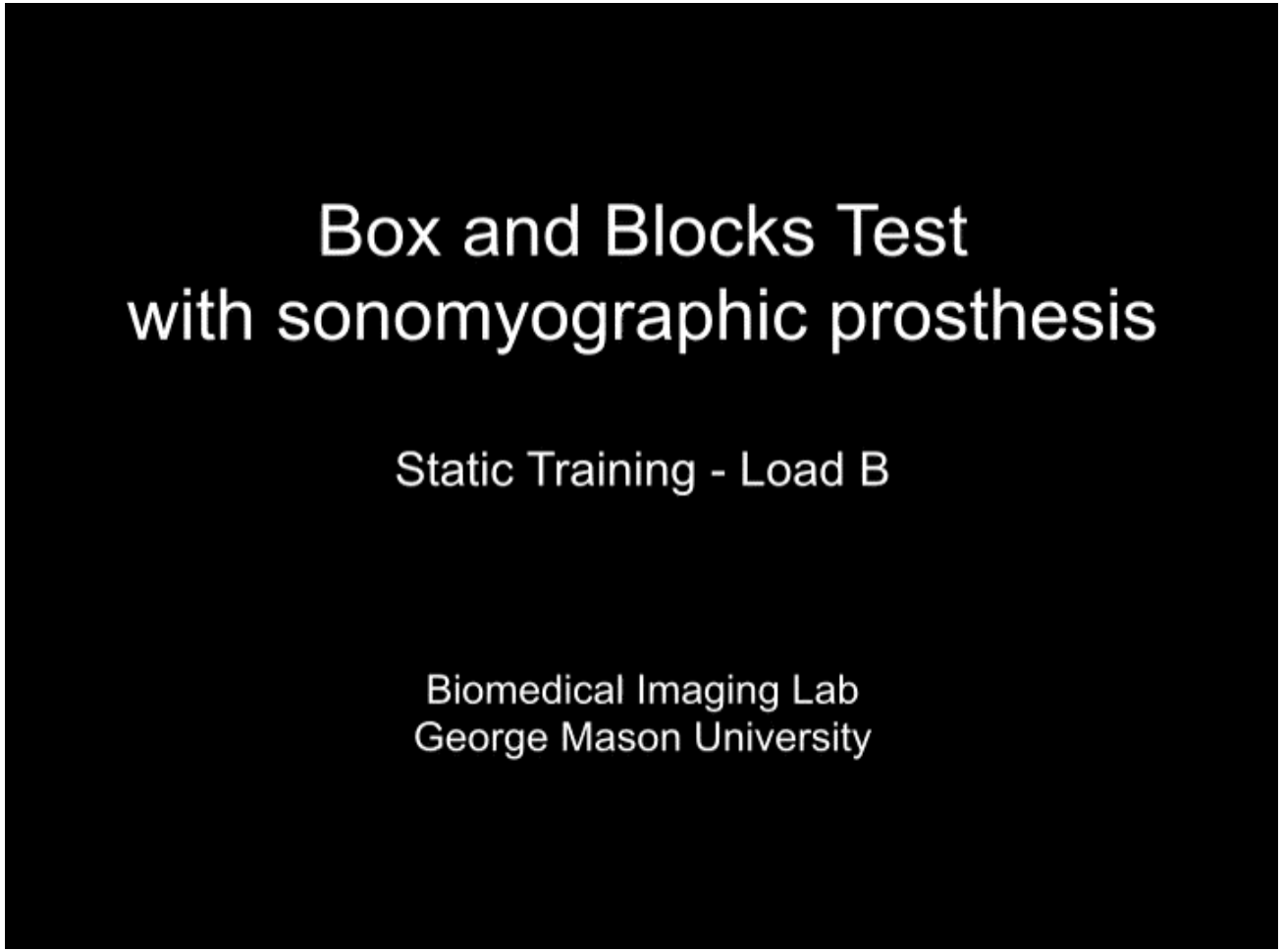

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Practical Limitations of B-mode Ultrasound

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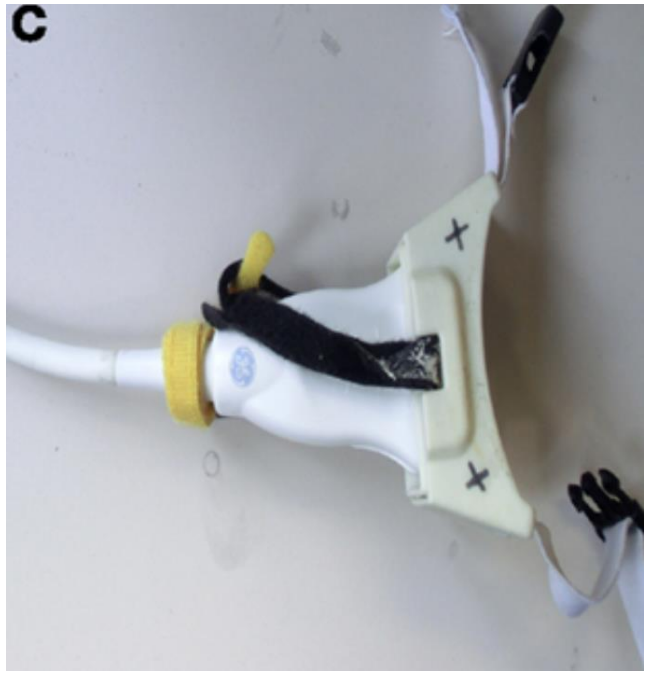
Issue n° 1 – Probe Size and Weight

[1]



[2]

Traditional Clinical Probes and systems are far too large and bulky for be used as Human Machine Interface Products

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[1] Ravindra et al
[2] Cannon

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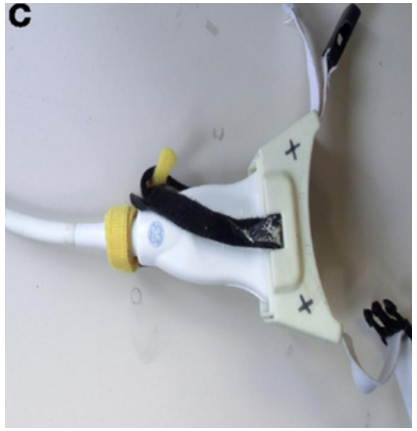
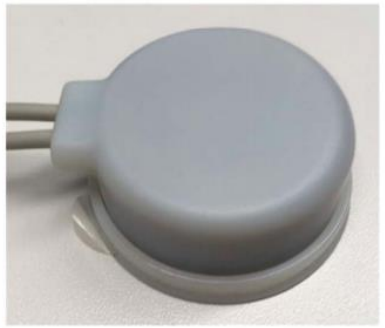


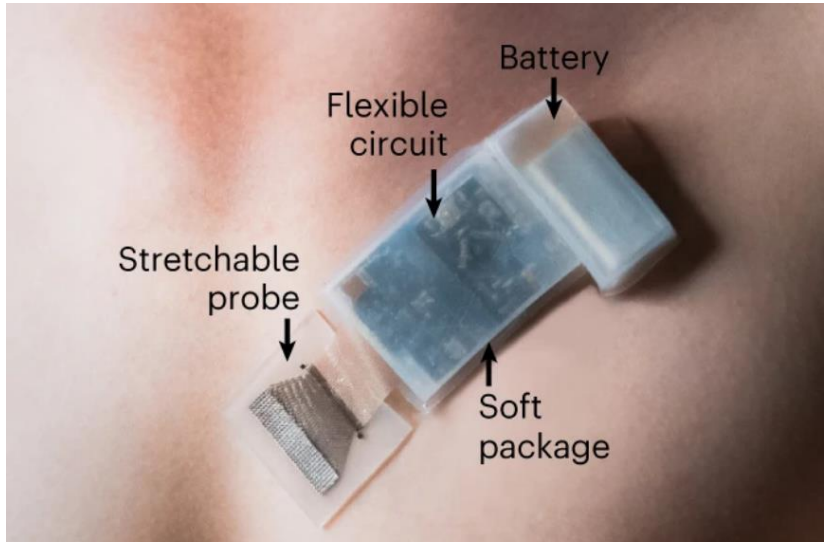
[1]

[2]

[3]



Portable Systems



[4]

Fully Wearable Systems

Very Recent Solutions

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[1] Ravindra et al
[2] Cannon
[3] Fournelle et al.
[4] Lin et al.

Practical Limitations of B-mode Ultrasound

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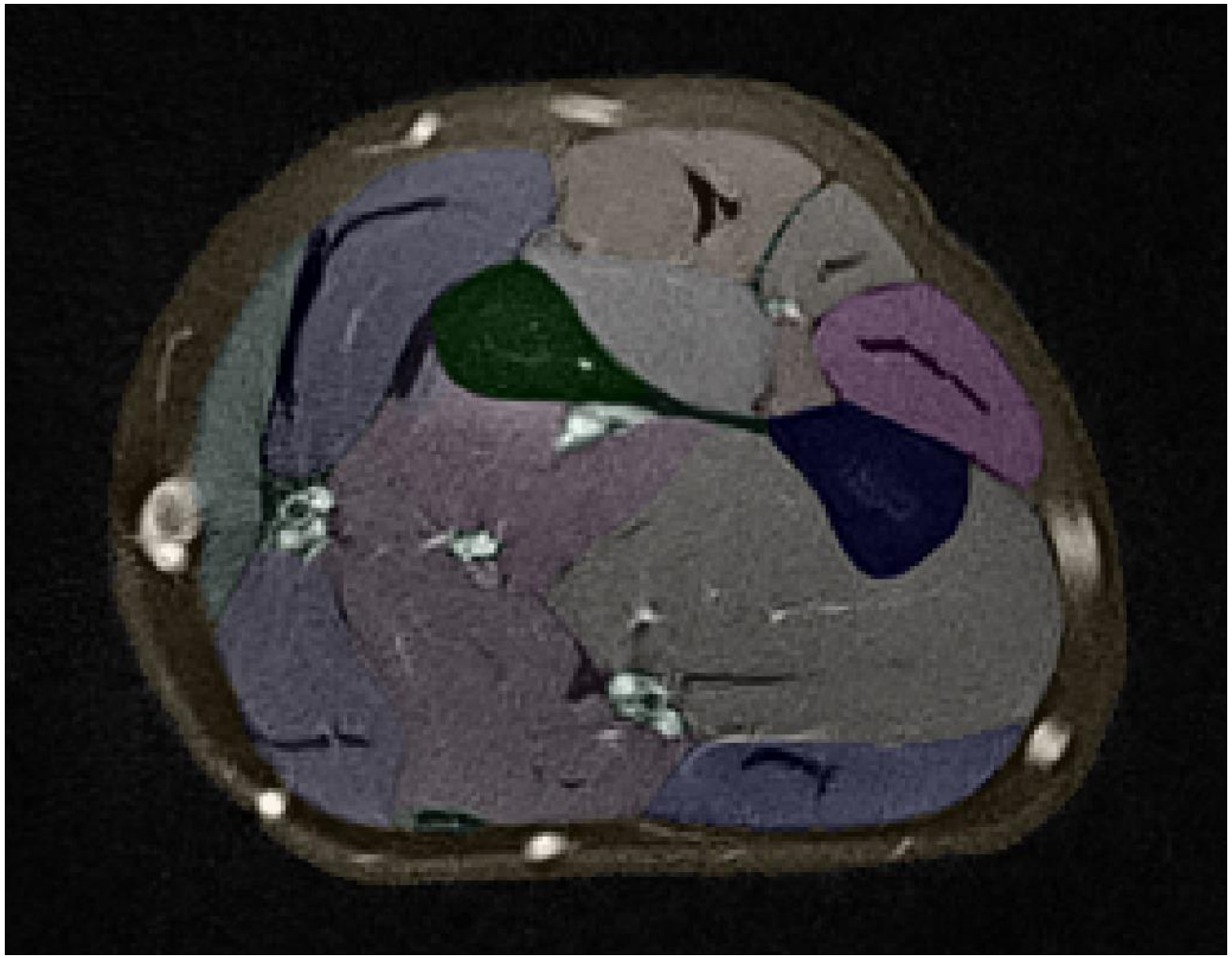
Issue n° 2 – Limited Field of View



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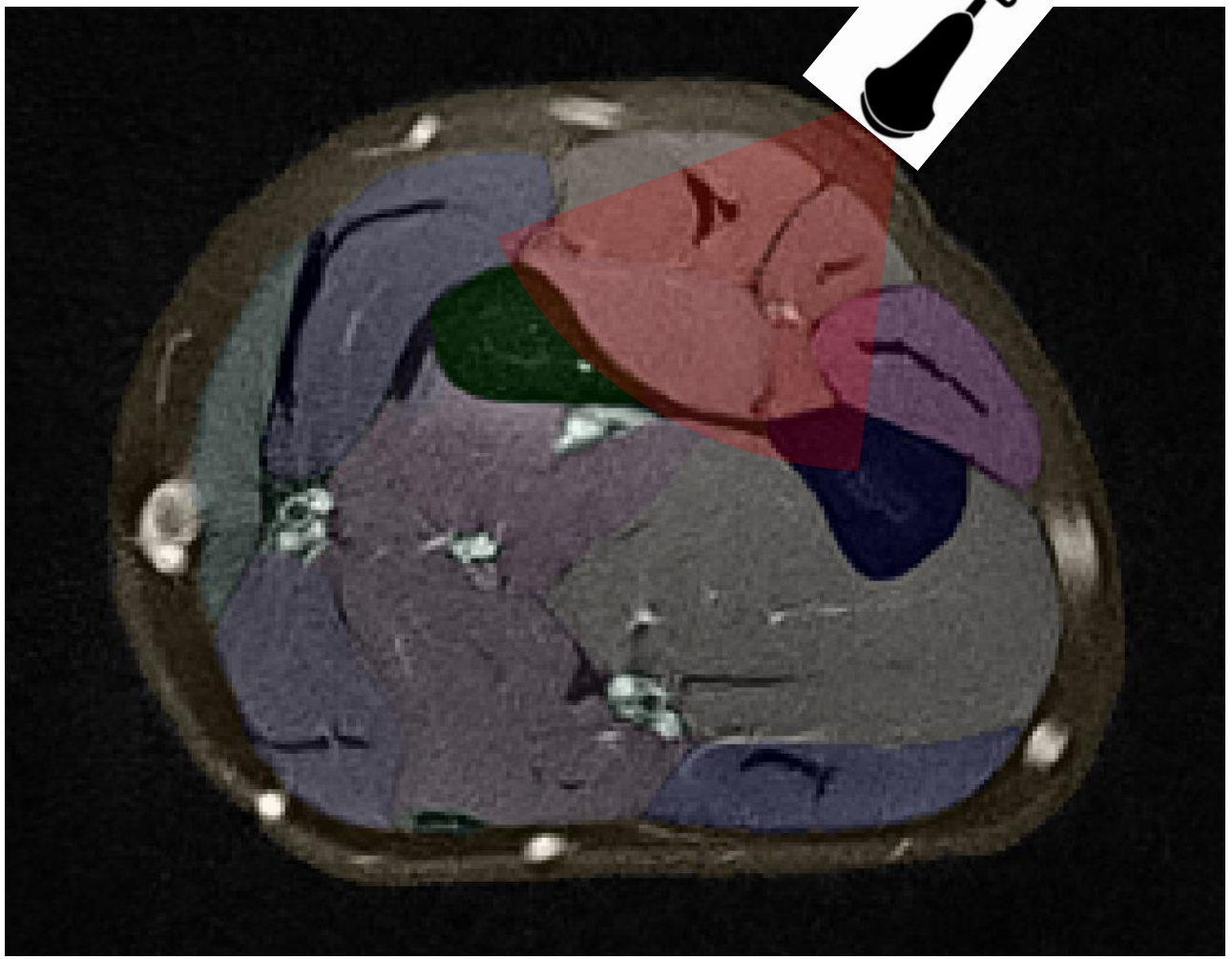

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A potential new avenue to wearability

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Original Research Report

Towards the application of one-dimensional sonomyography for powered upper-limb prosthetic control using machine learning models

Jing-Yi Guo[1], Yong-Ping Zheng[2], Hong-Bo Xie[3] and Terry K Koo[1]

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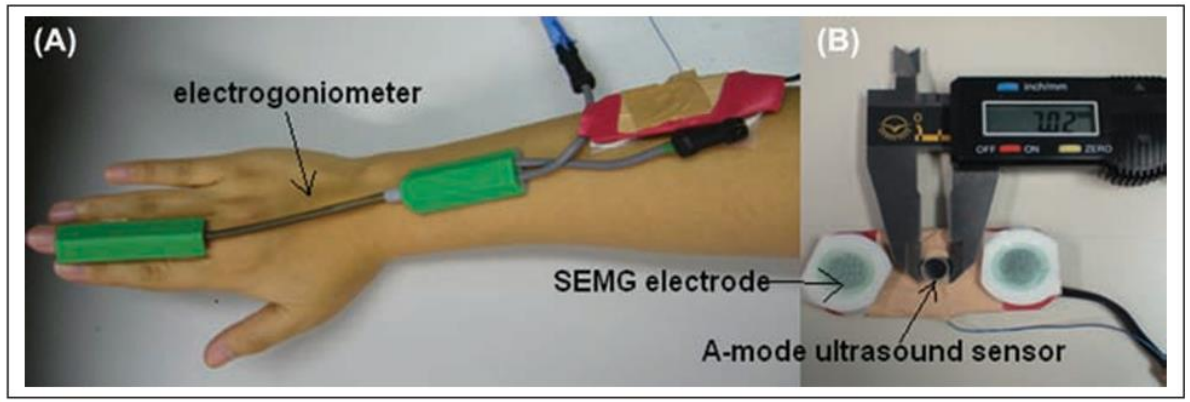

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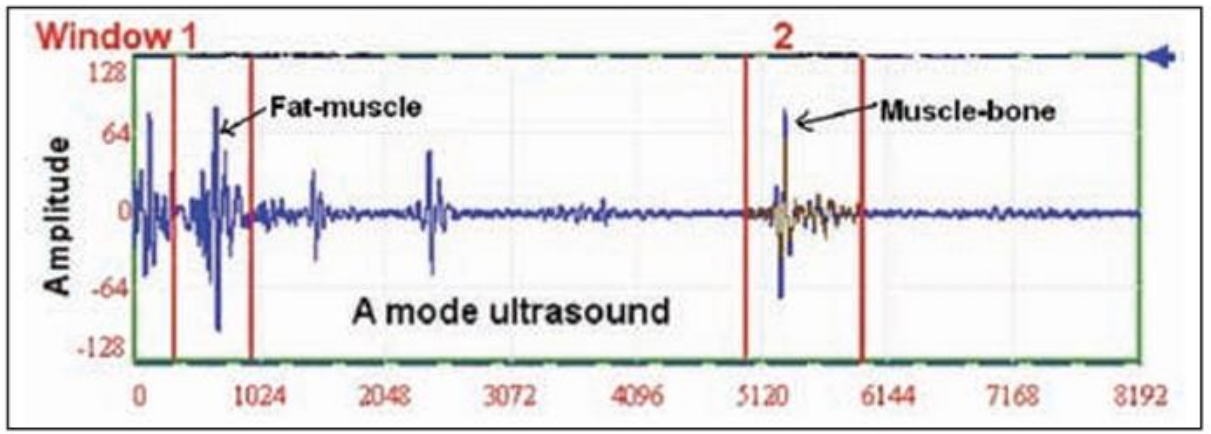

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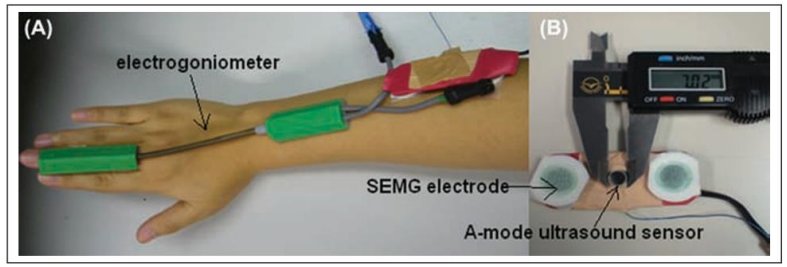

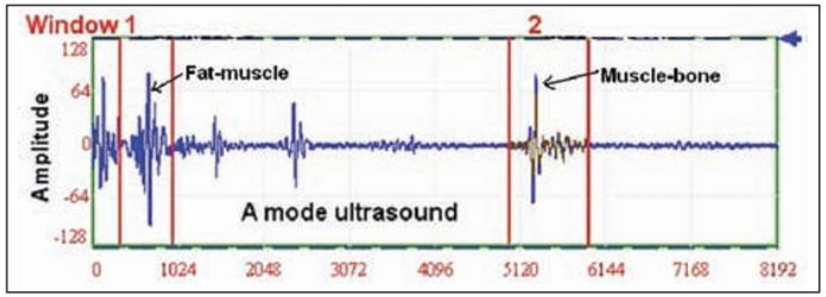

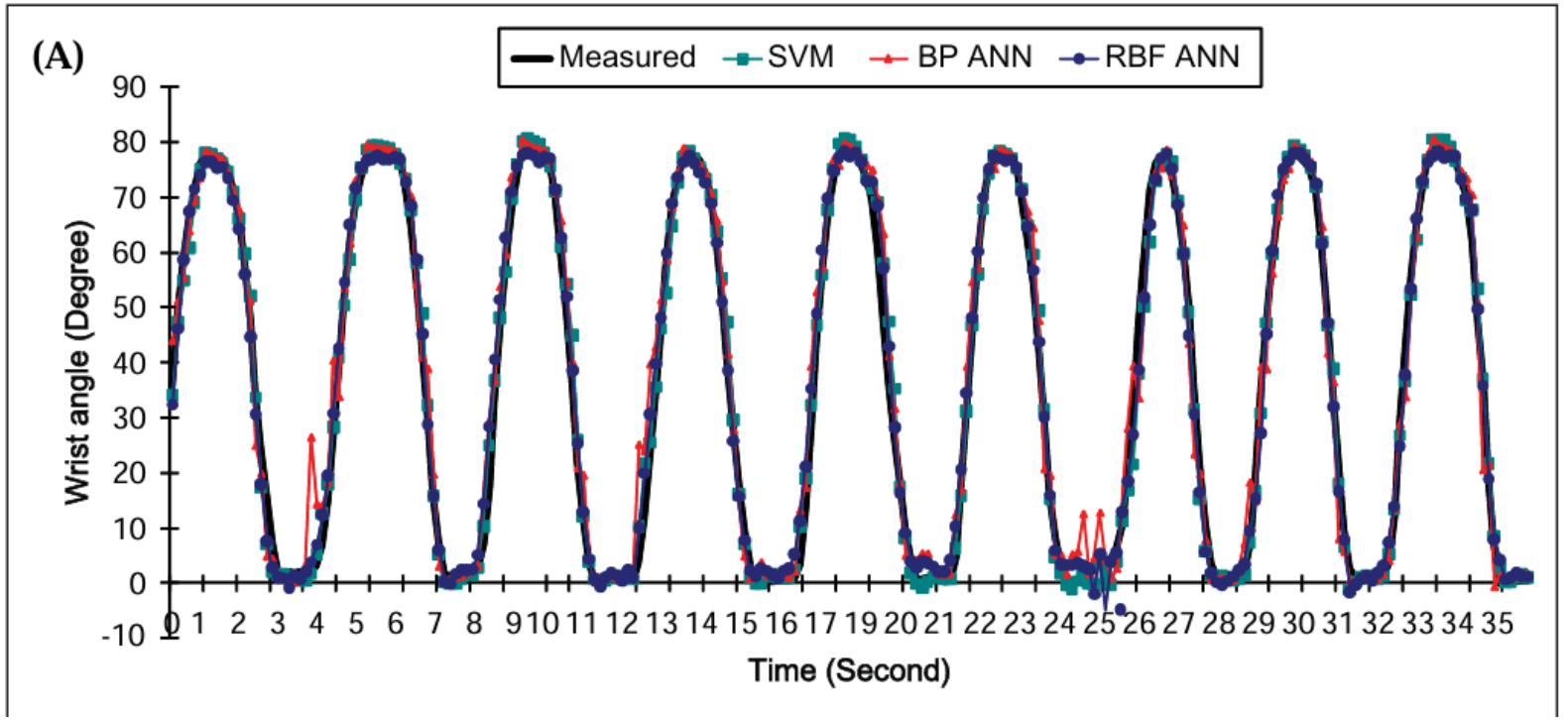

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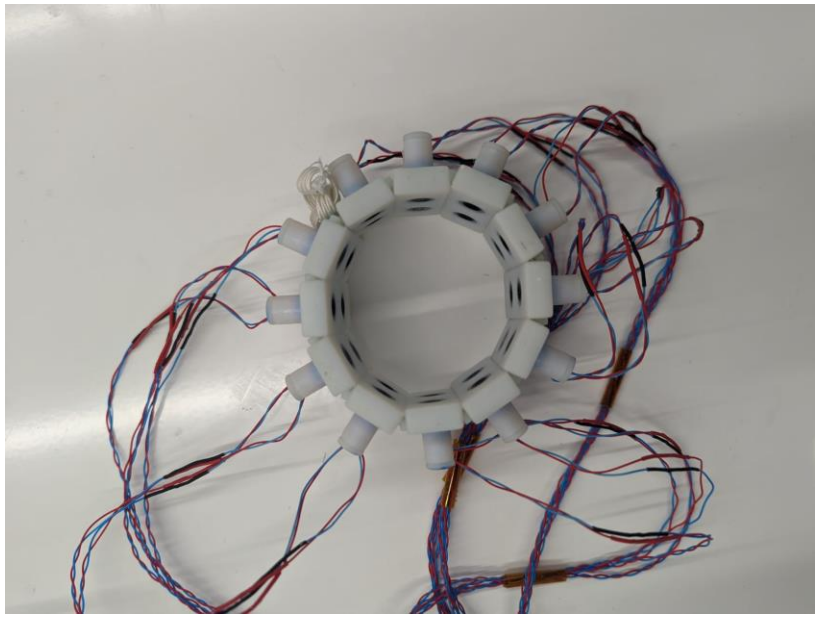
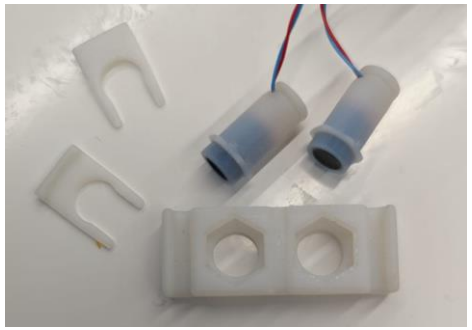
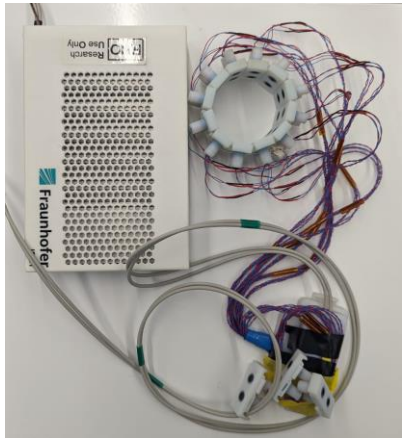
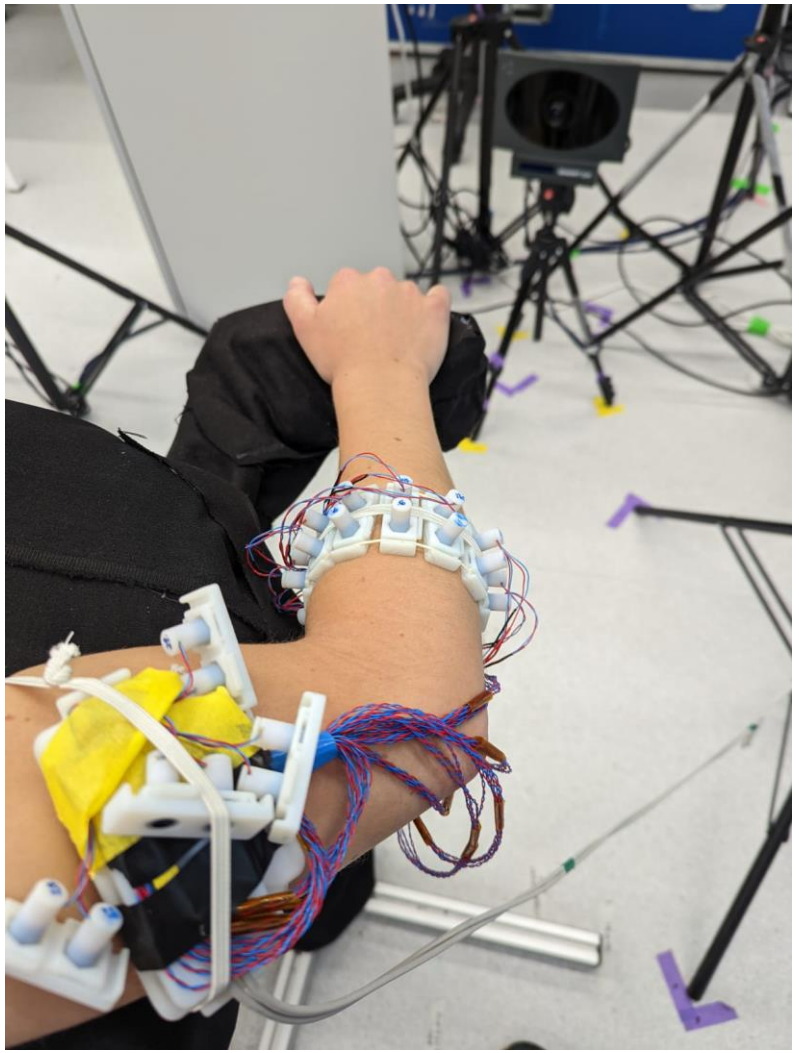
Our Prototype Approach









A-Mode Ultrasound bracelet

- 24 channels divided in two circles
- 1 MHz Centre Frequency
- Unfocused, 15° opening angle

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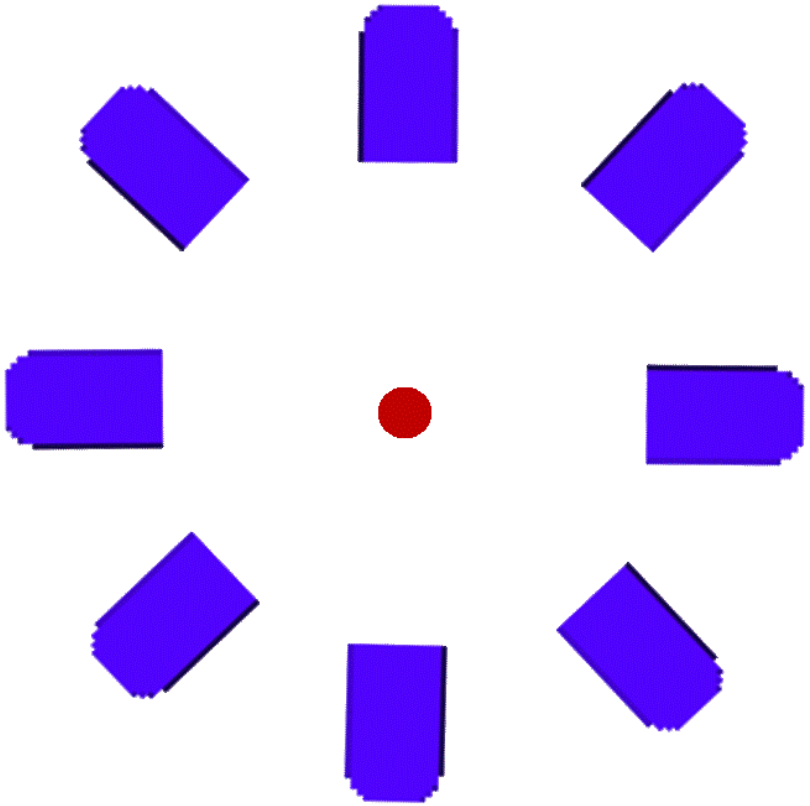
Proposing a different recording method

HYBRID NEURO

Single Transmit Single Receive A-mode



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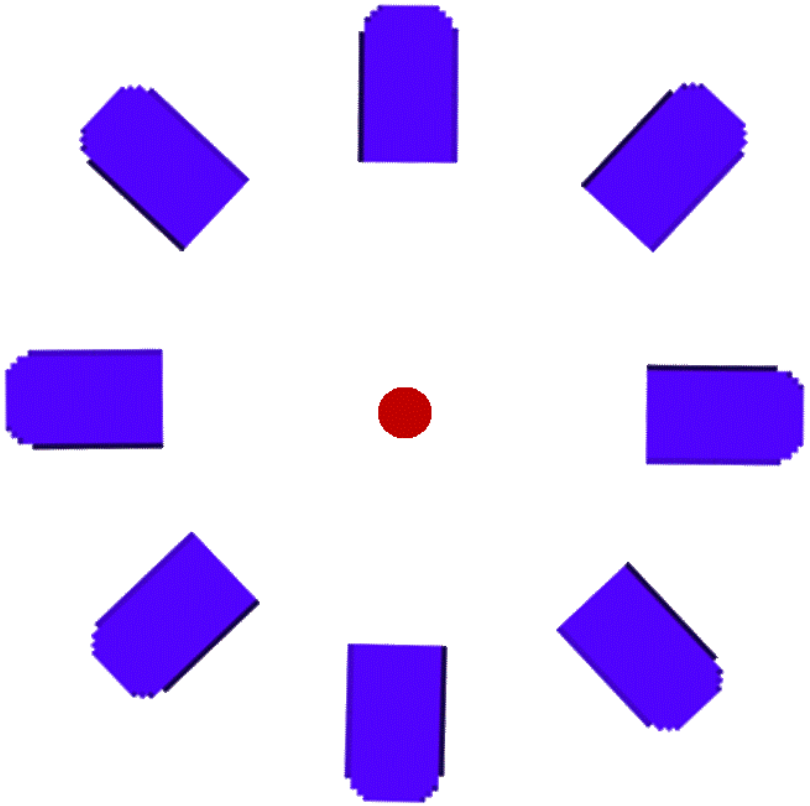
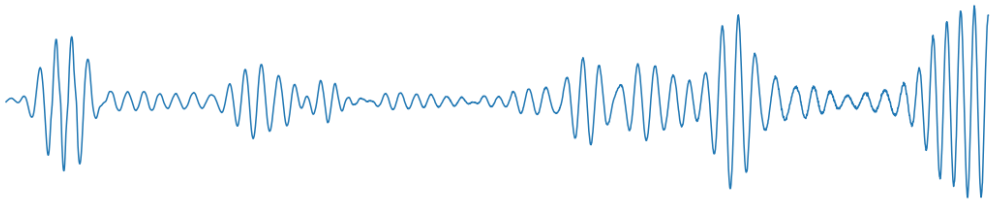
Single Transmit Single Receive A-mode





$1^{st}\ Transmission$

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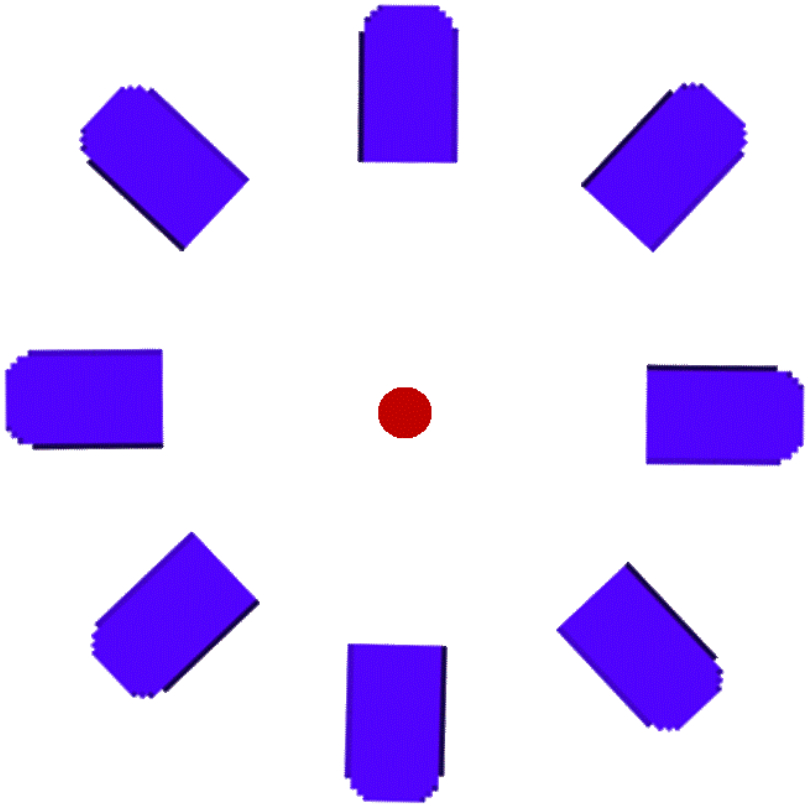
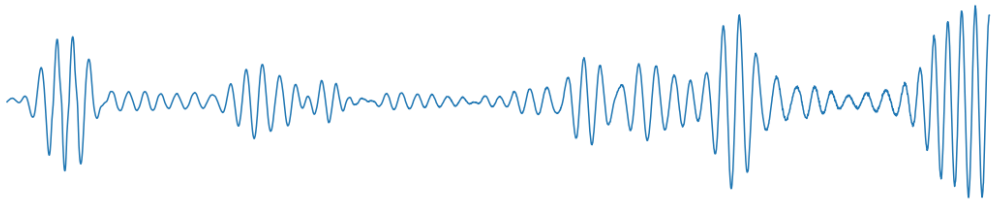
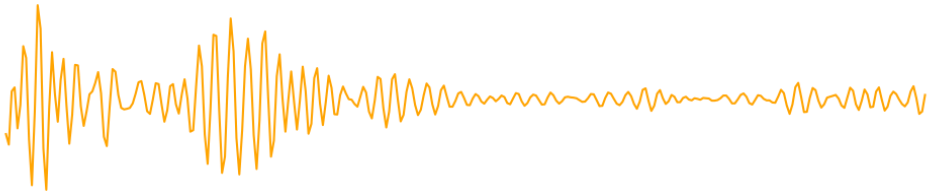
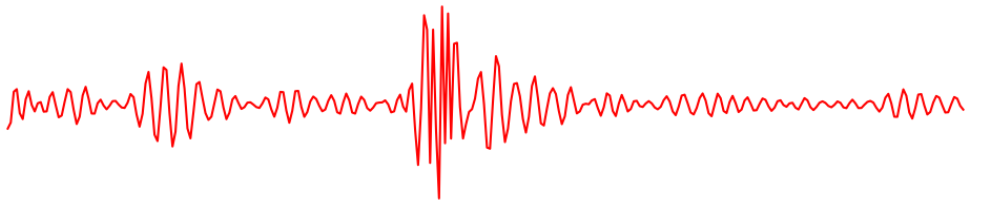




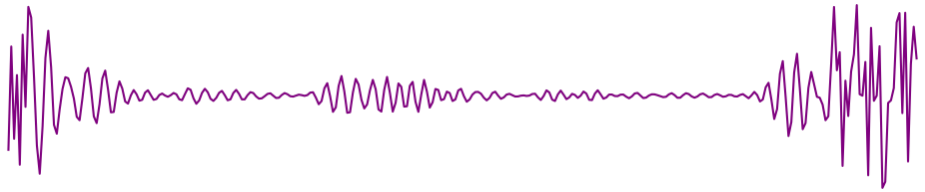
$1^{st}\ Transmission$



$2^{nd}\ Transmission$



$N-1^{th}\ Transmission$



$N^{th}\ Transmission$

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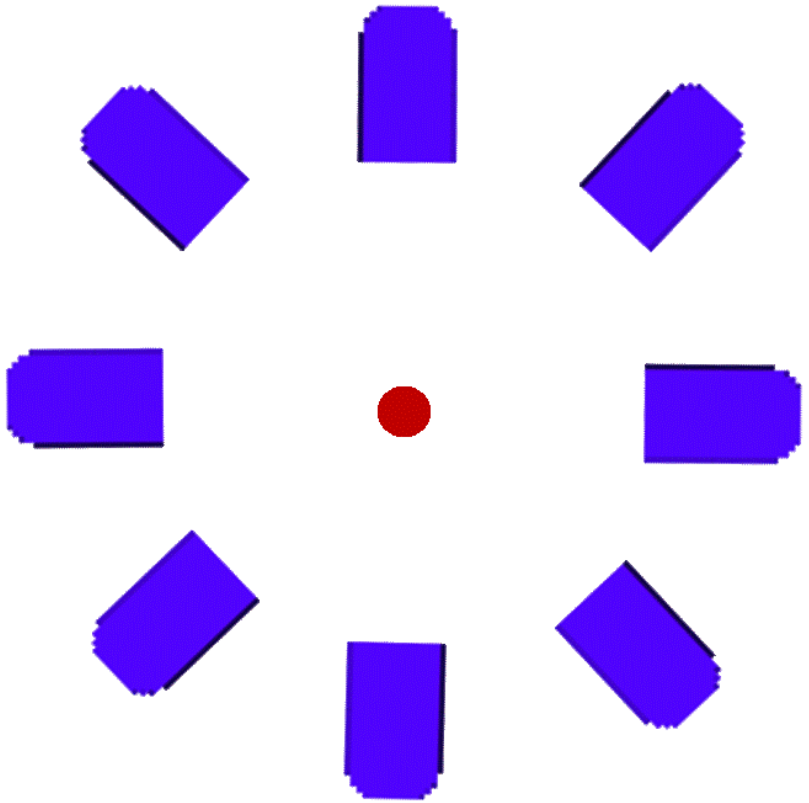
Proposing a different recording method

HYBRID NEURO

Single Transmit Multiple Receive A-mode



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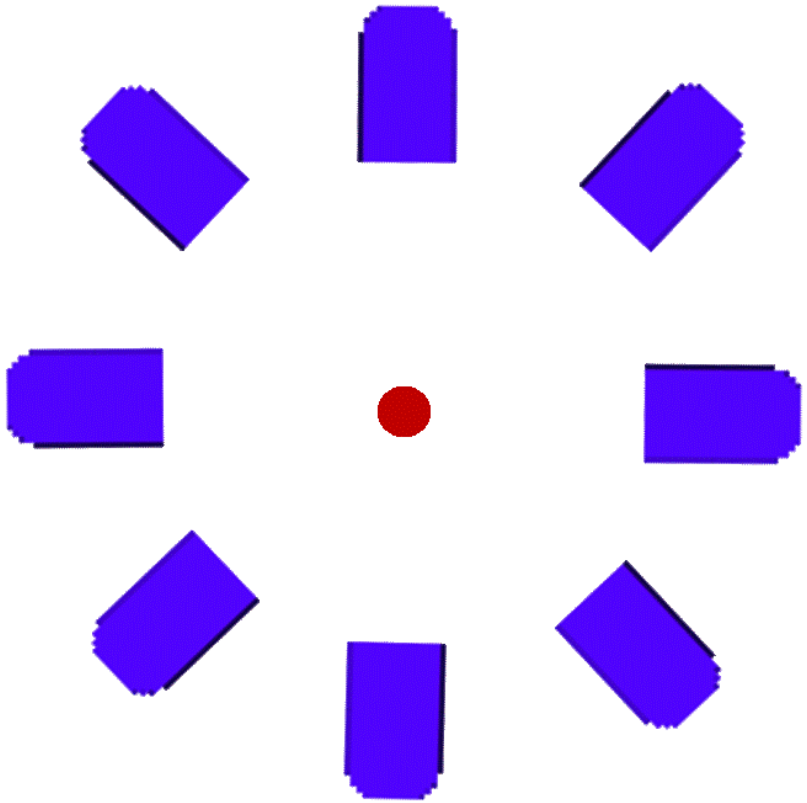
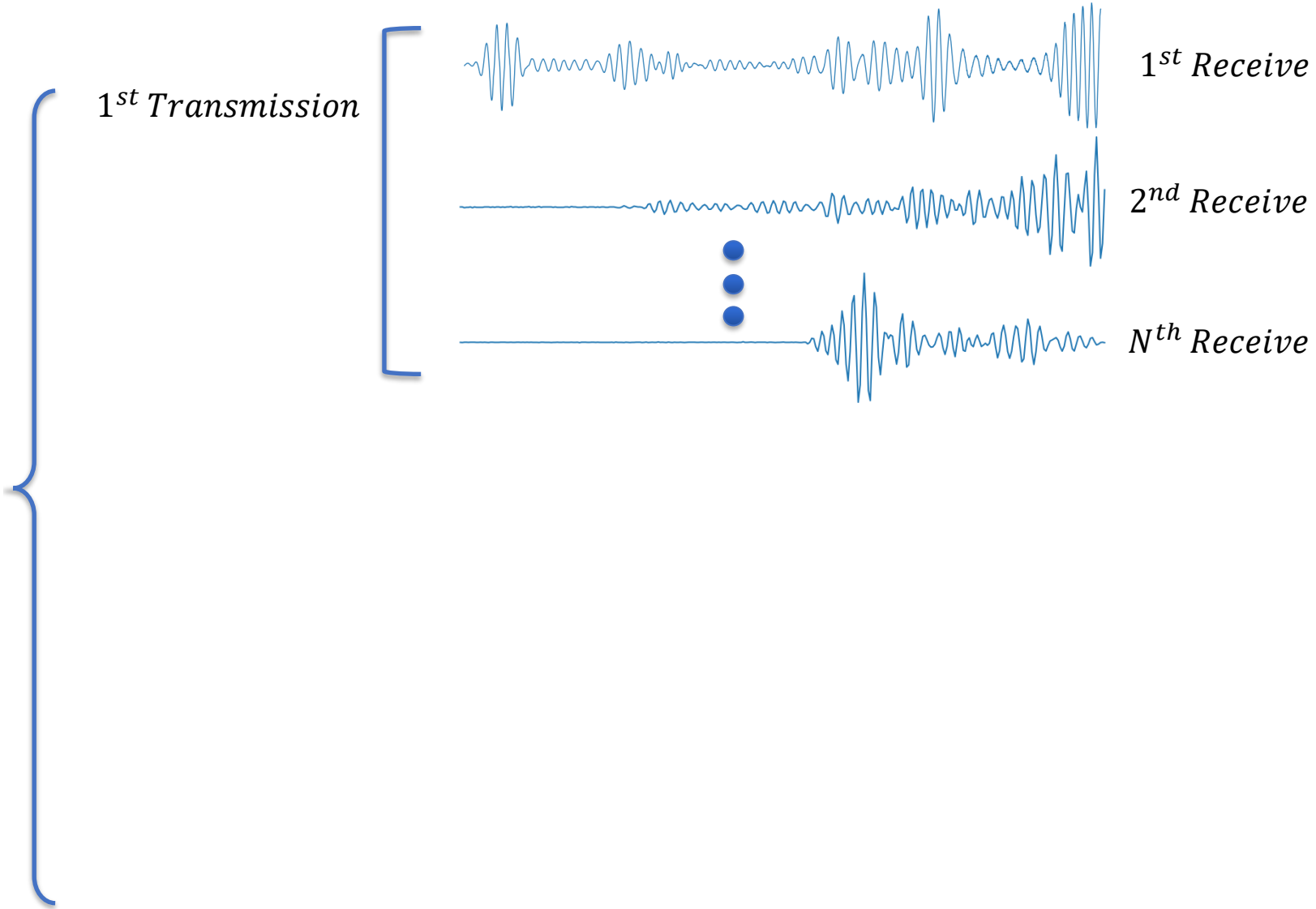
Proposing a different recording method

Single Transmit Multiple Receive A-mode





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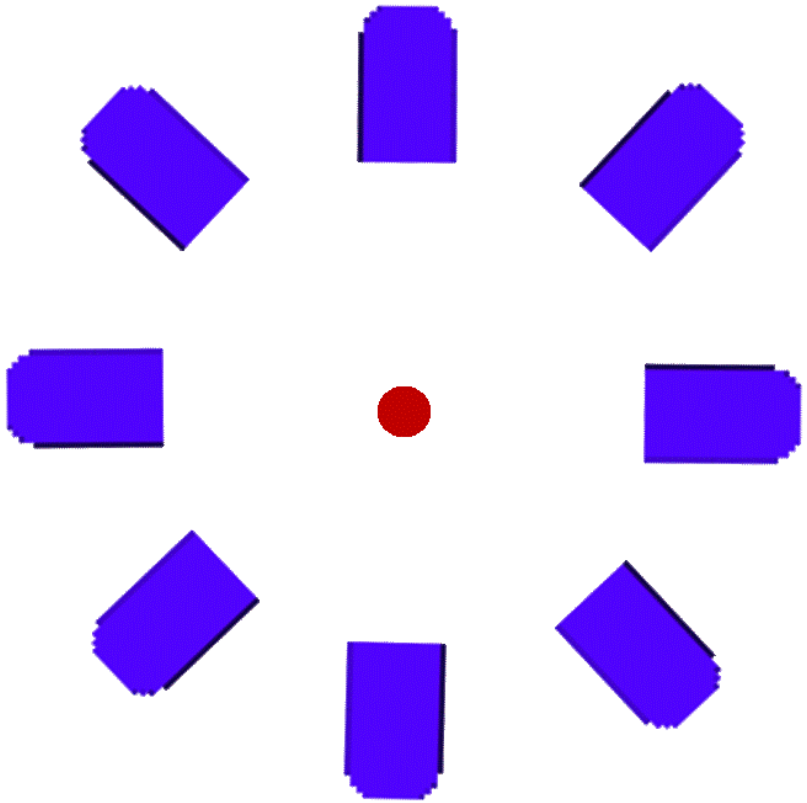
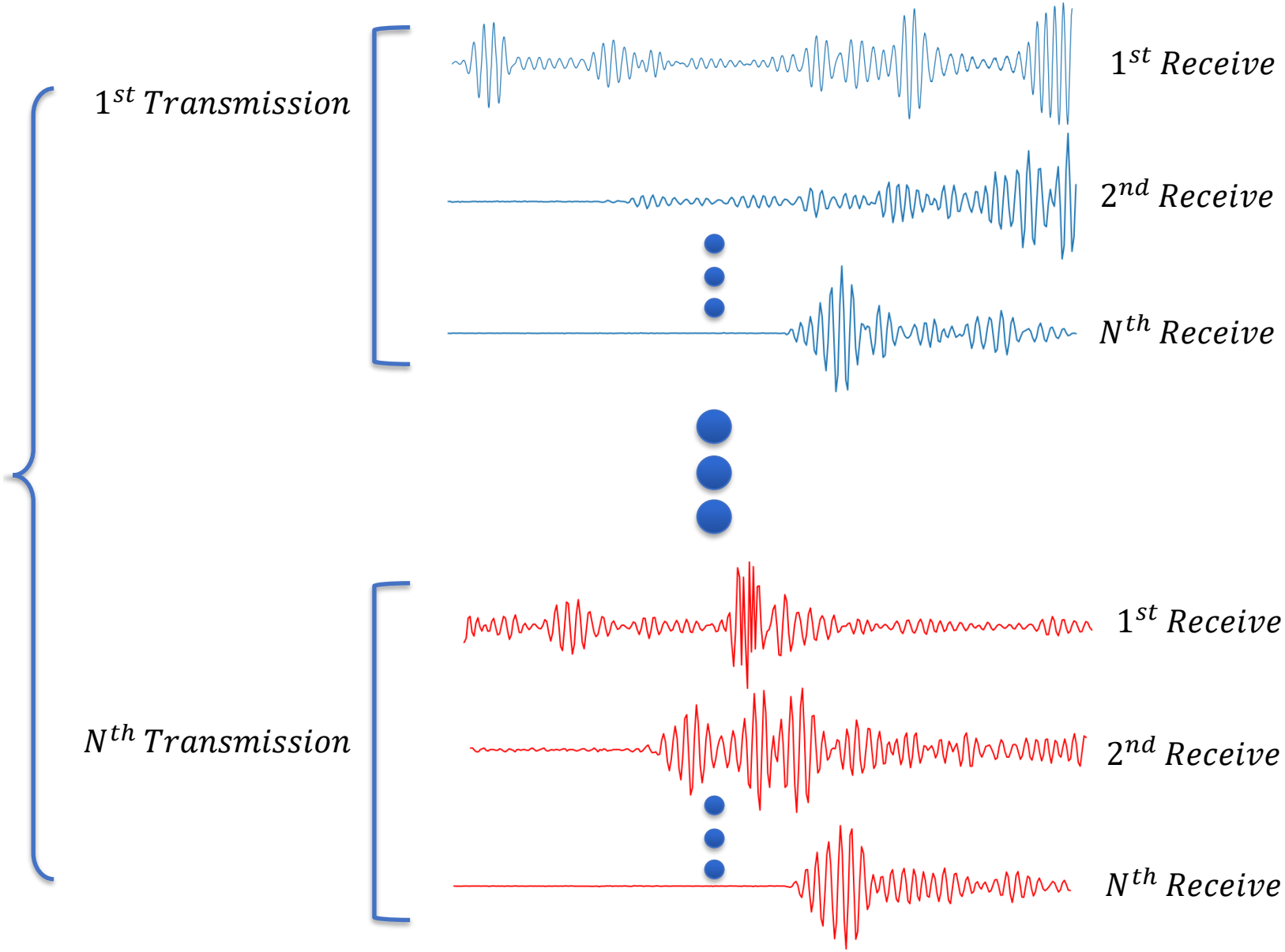
Proposing a different recording method

HYBRID NEURO

Single Transmit Multiple Receive A-mode





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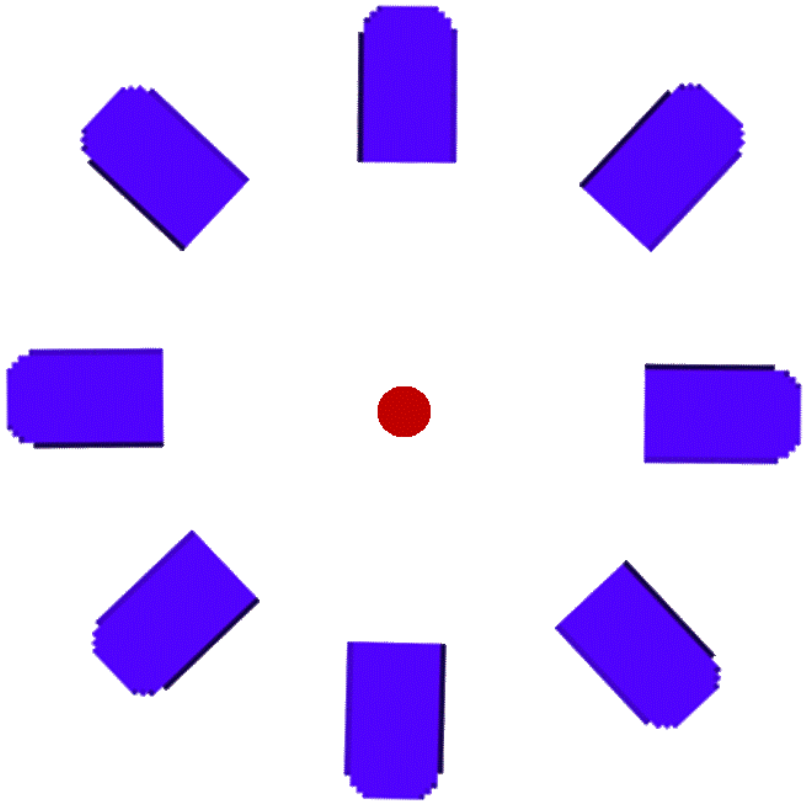

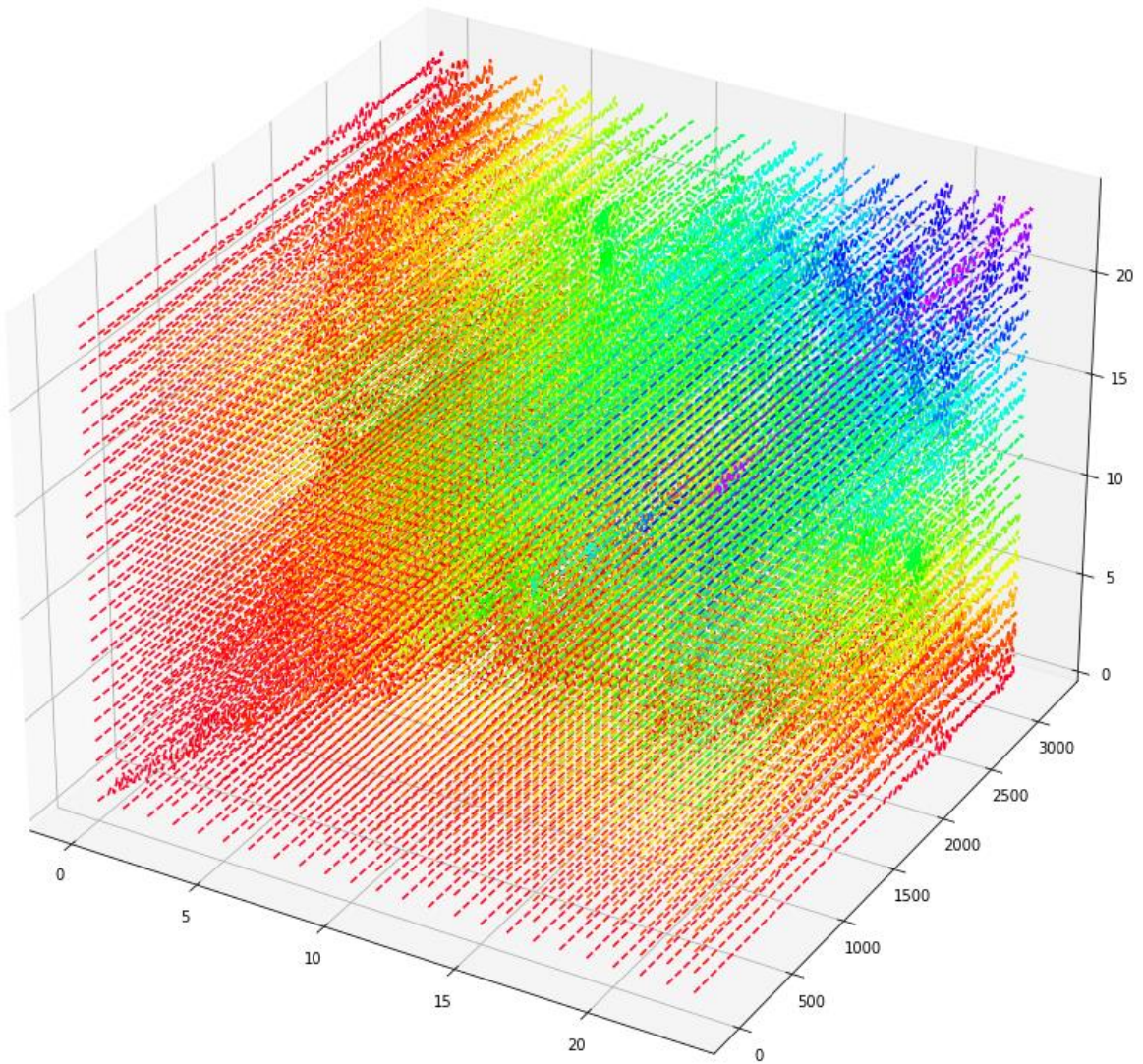

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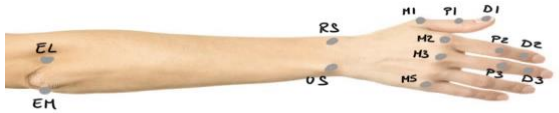
Experiment 1 – Offline



Motion Capture

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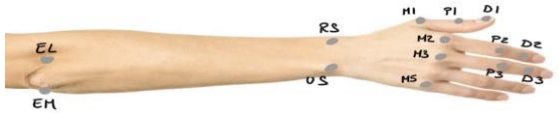
Experiment 1 – Offline

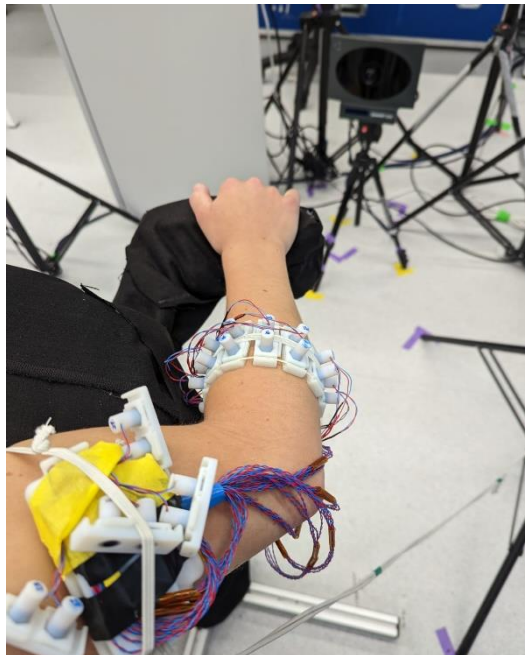


Motion Capture

High Density surface EMG

OR

A-mode Ultrasound



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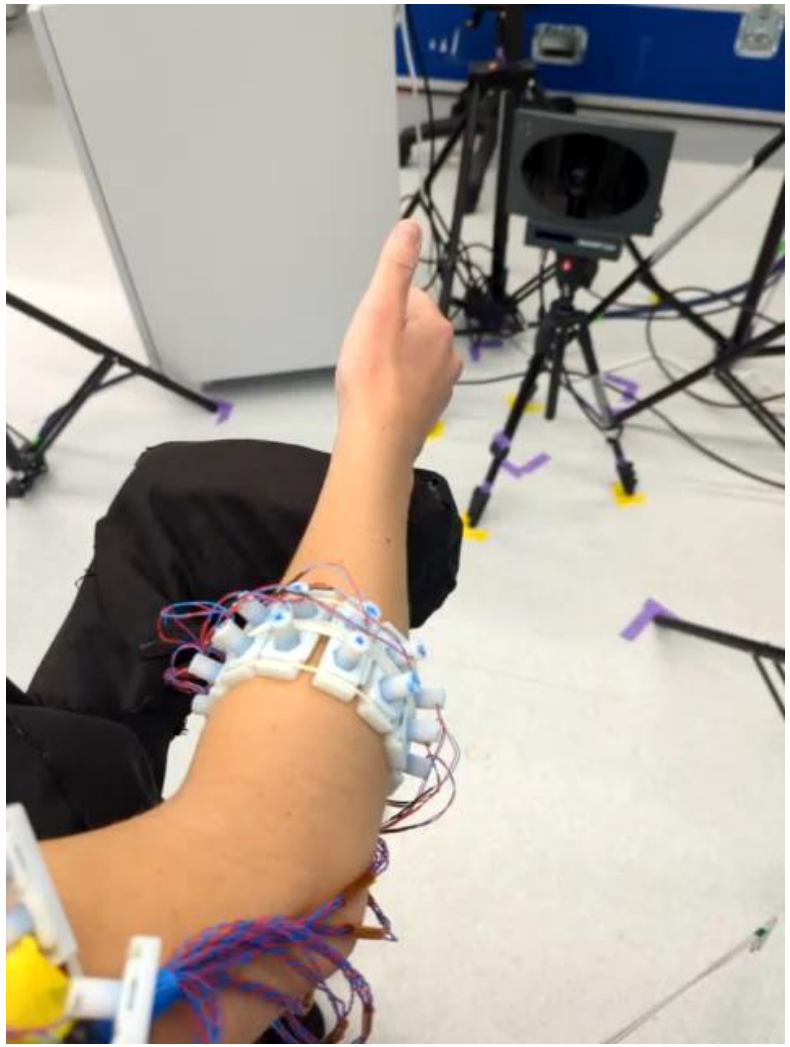
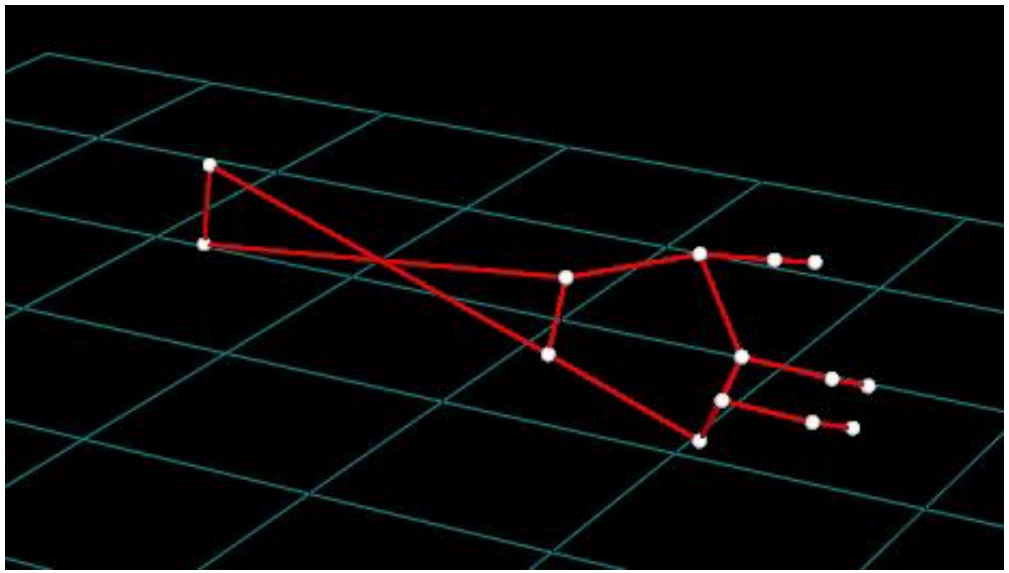


Participant moving

Video for Guidance



MOCAP regressed 3D XYZ locations

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Experiment 1 – Offline

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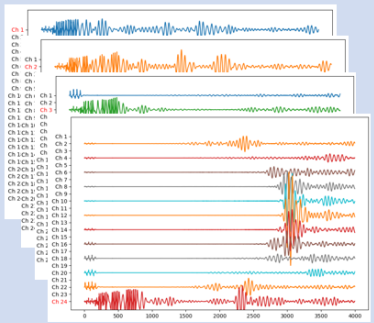
Raw A-mode Ultrasound

24 shots x 24 channels
4000 samples per line

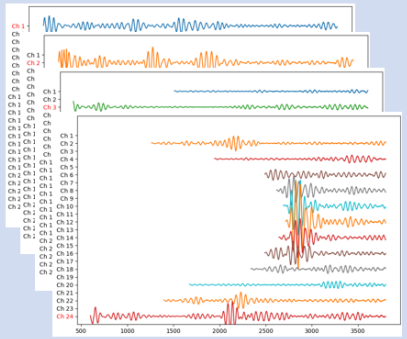
Pre-processing

Channel Selection and TGC



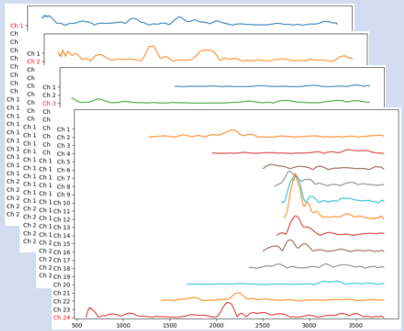
24 shots x 12 channels

Noise and Delay Correction

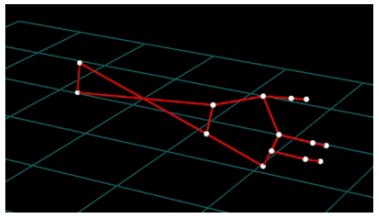


900 - 3200 samples per line

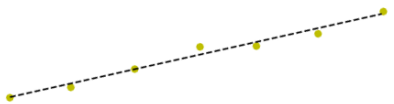
Smoothing and Enveloping



Motion Capture angles

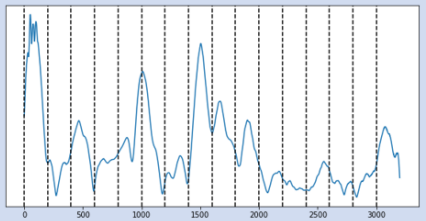


Linear Regression



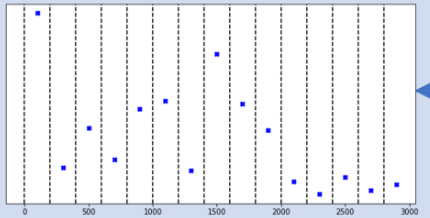
Feature Extraction

Windowing



Windows of 200 samples

Root Mean Square



> 3000 features

Principal Component Analysis

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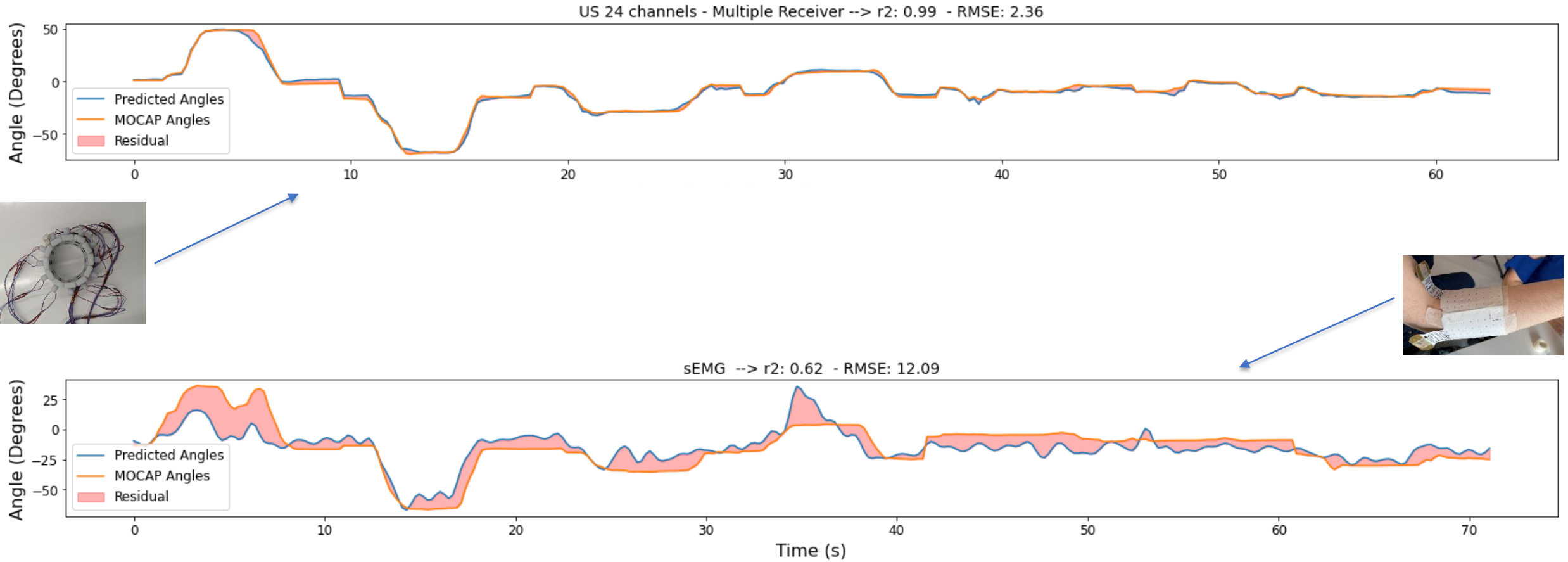
Experiment 1 – Offline



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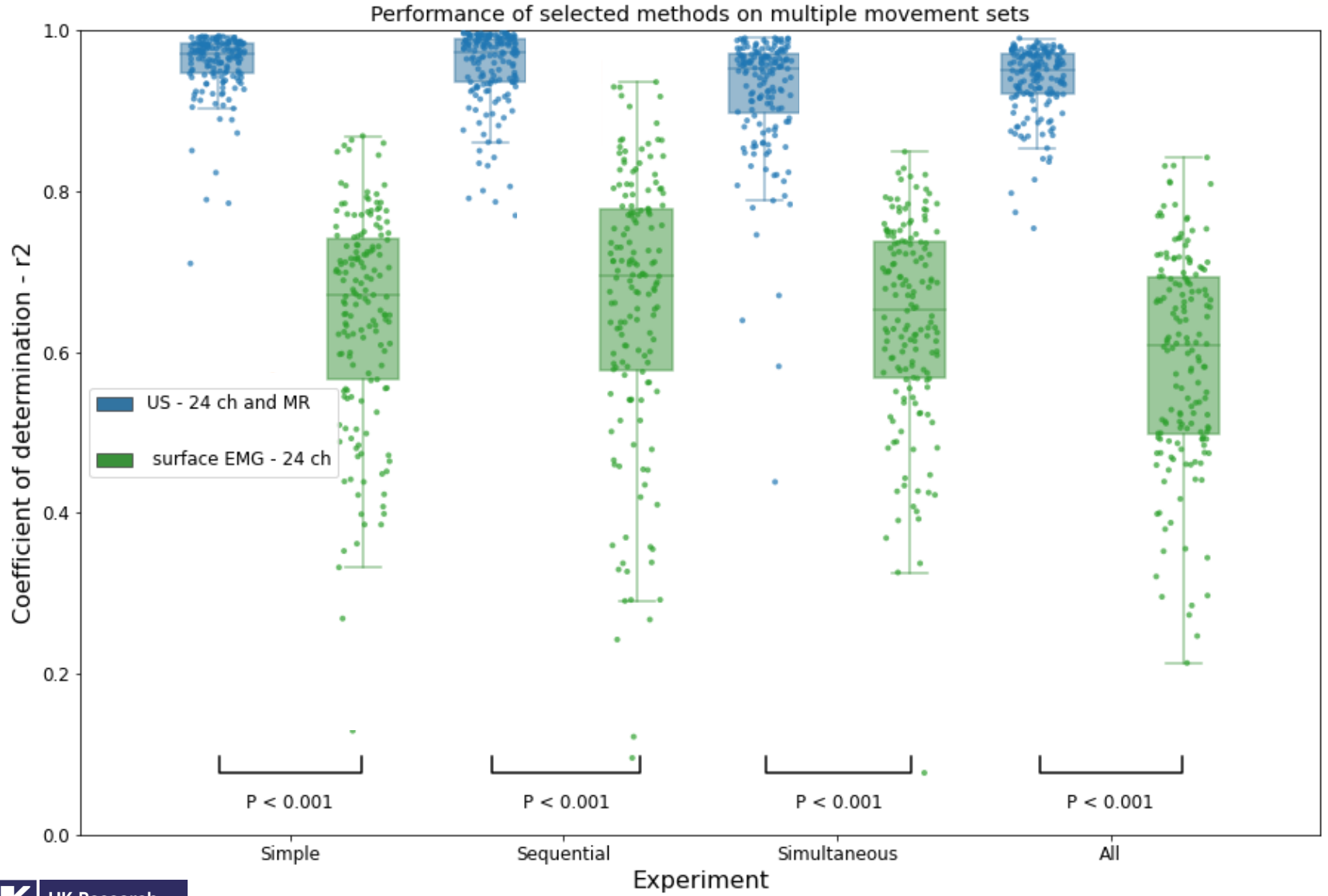

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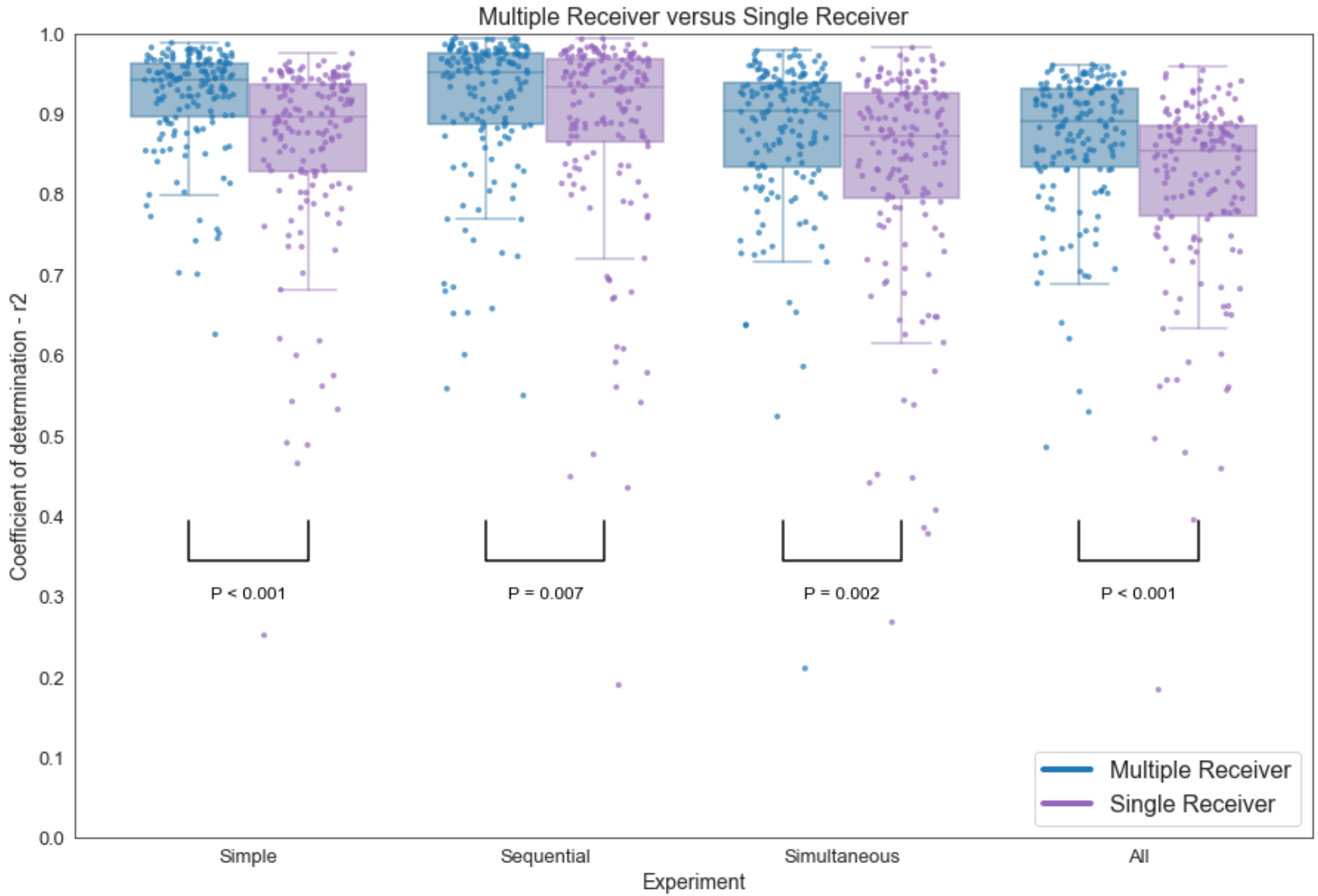

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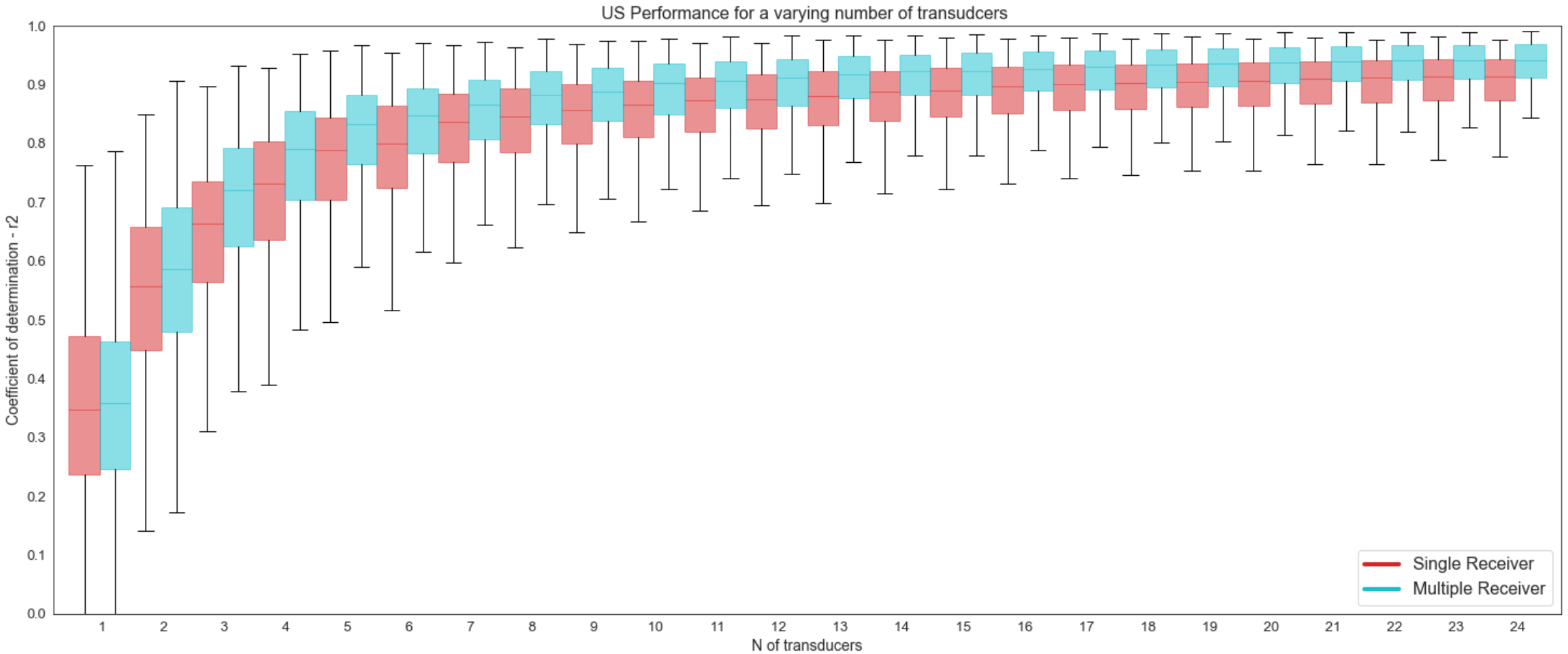

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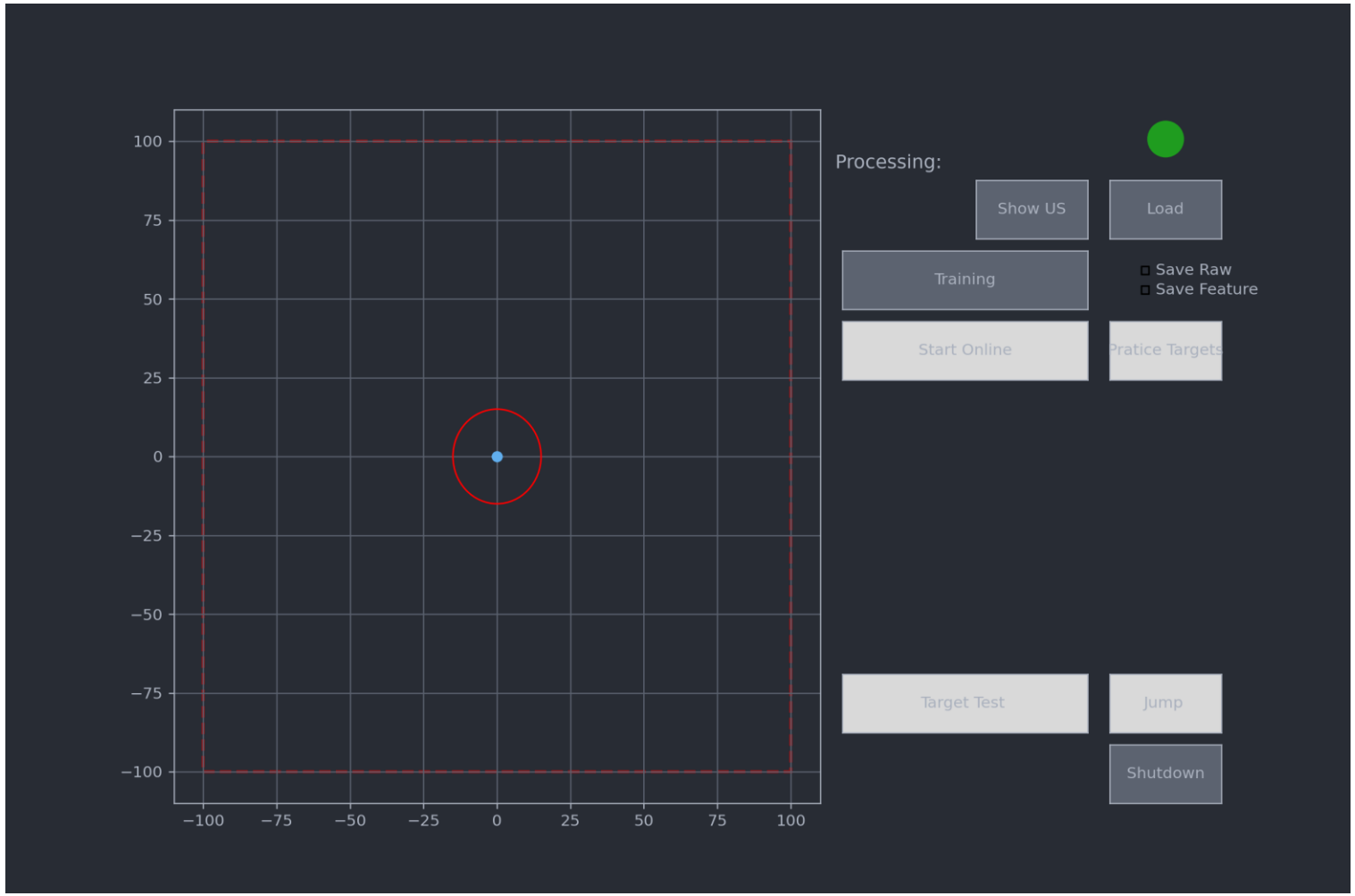
Sgambato et al. High Performance Wearable Ultrasound as a Human-Machine Interface for wrist and hand kinematic tracking

Experiment 2 - Online

- Simultaneous 3 DoF control
  - Flex-Ext
  - Pro-Sup
  - Hand Open-Close
- 8 Participants
- Target Achievement Test
  - 26 targets
  - 30s to reach – stay for 0.5s
- Requiring simultaneous activation of 1 DoF, 2 DoF and 3 DoF



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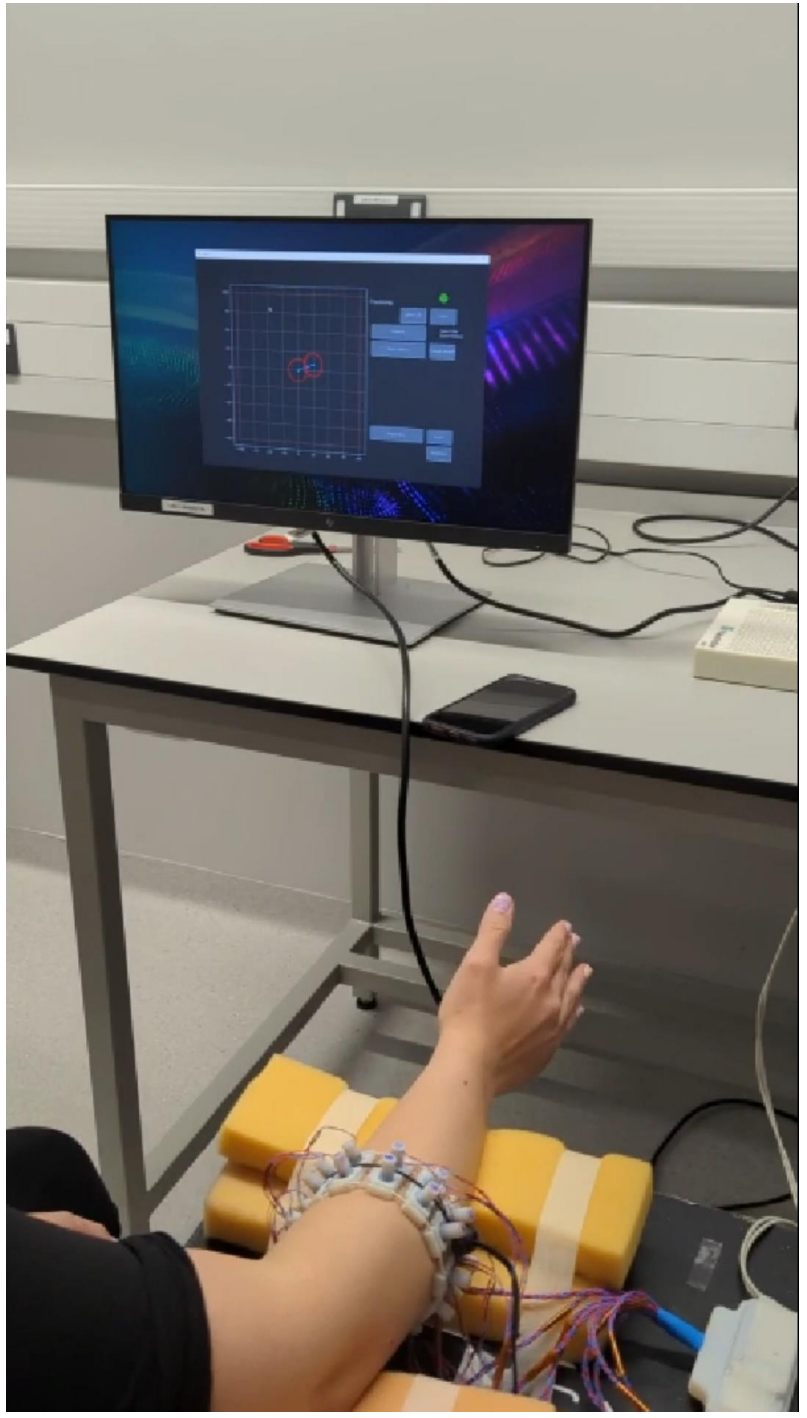

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Experiment 2 - Online

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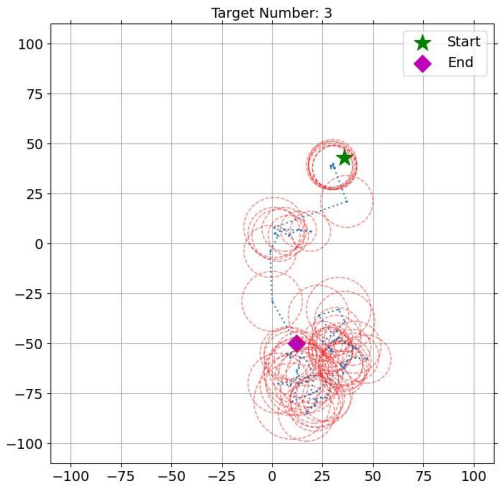
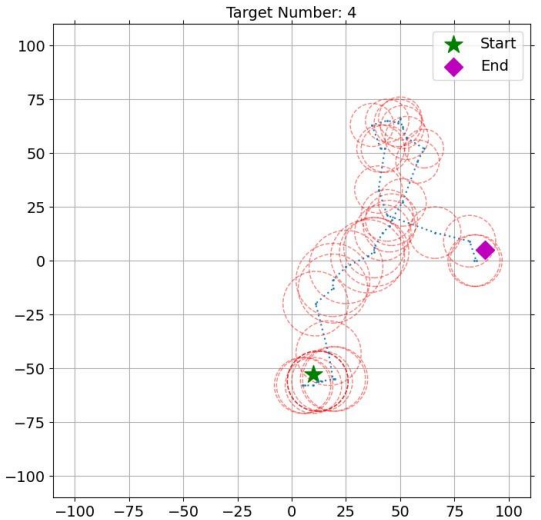
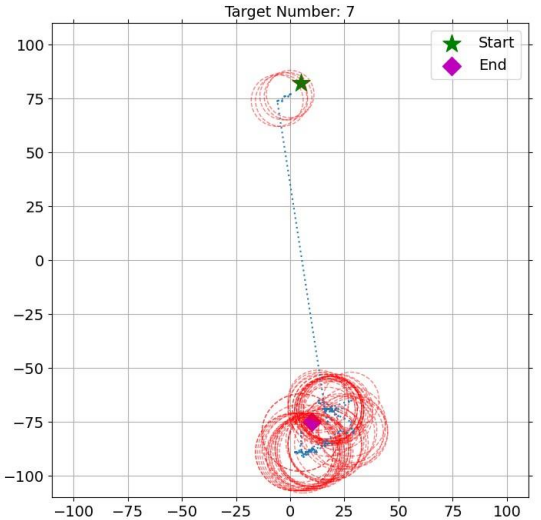
(A)



(B)



(C)



(D)

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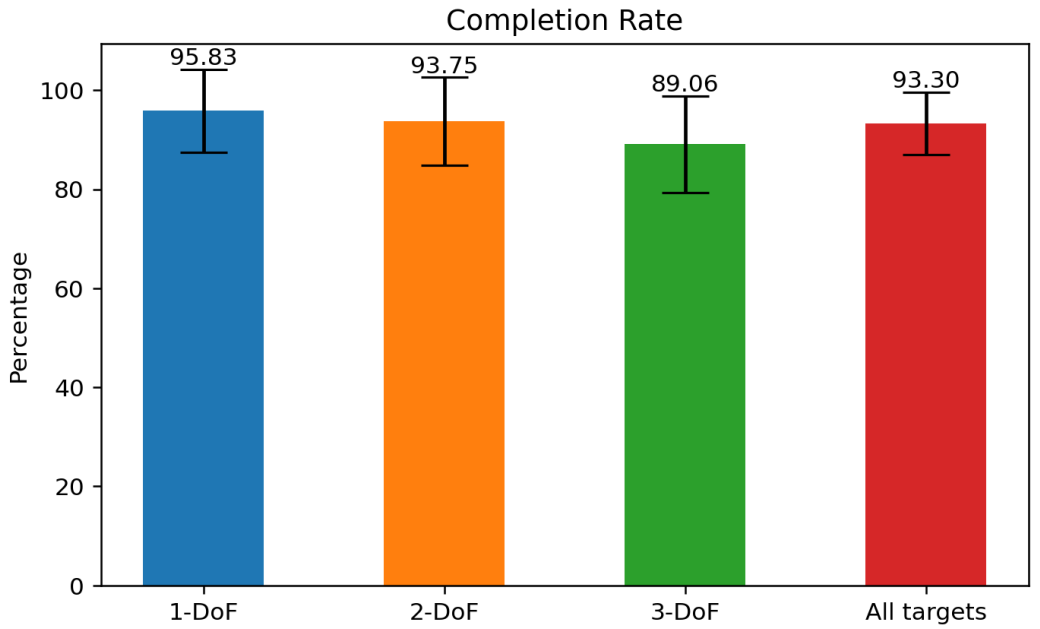

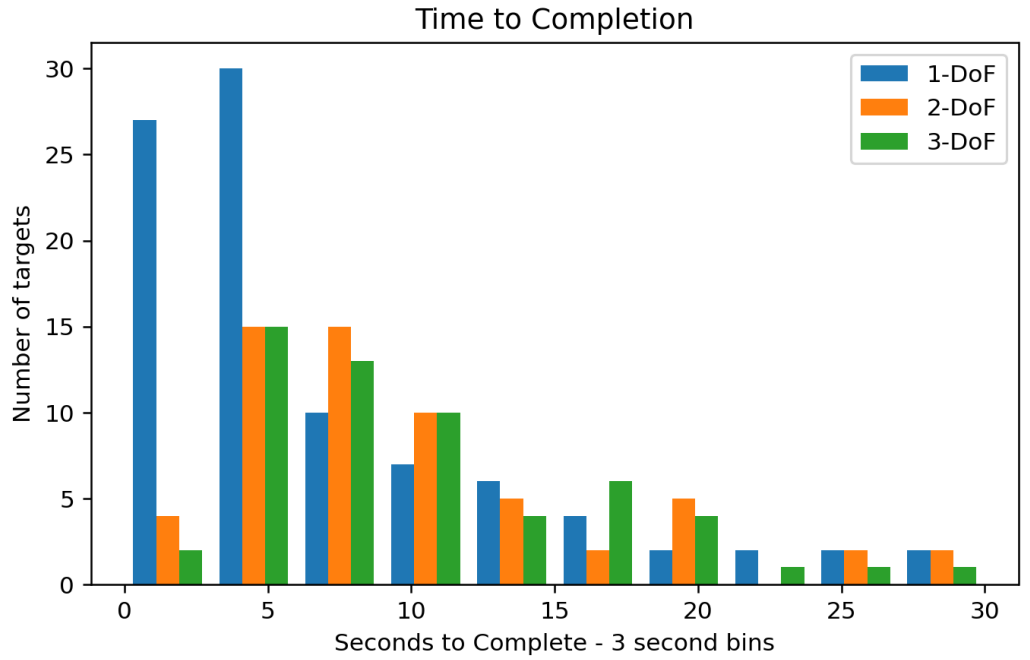

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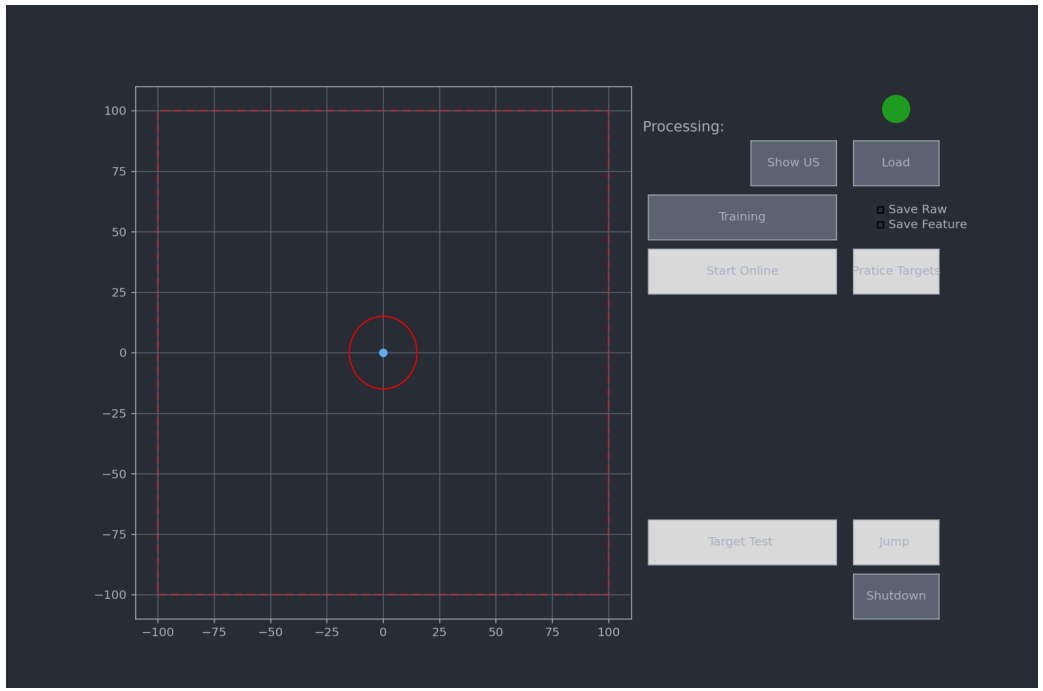
Towards validation on Prosthesis



[1]

[2]

[3]

[4]

[1] Ossur i-Limb
[2] TASKA Hand
[3] Otobock Michelangelo
[4] Prensilia IH2 Azzurra

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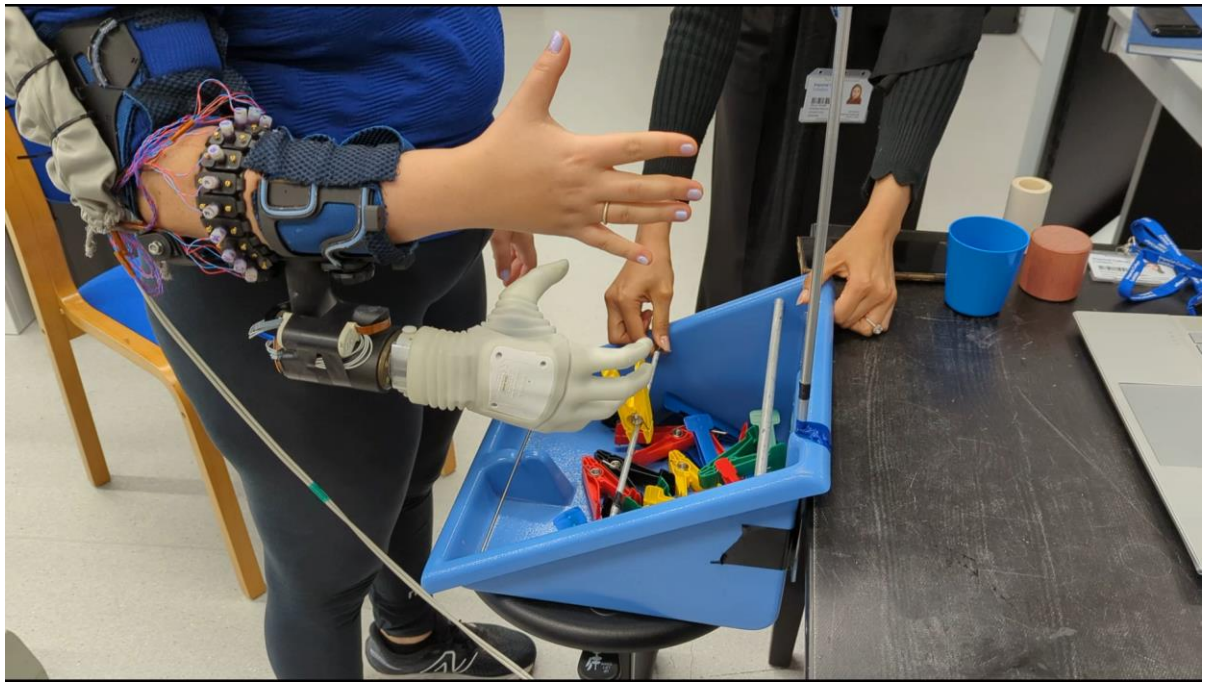
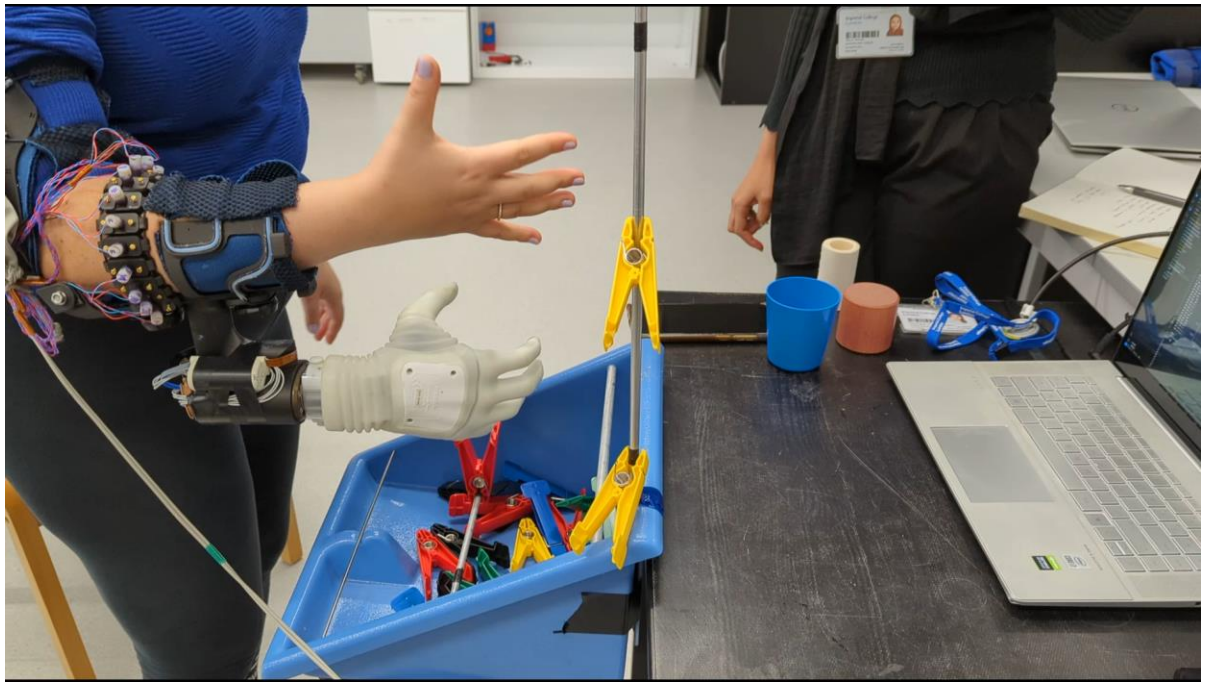
Towards validation on Prosthesis

HYBRID NEURO





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Towards validation on Prosthesis

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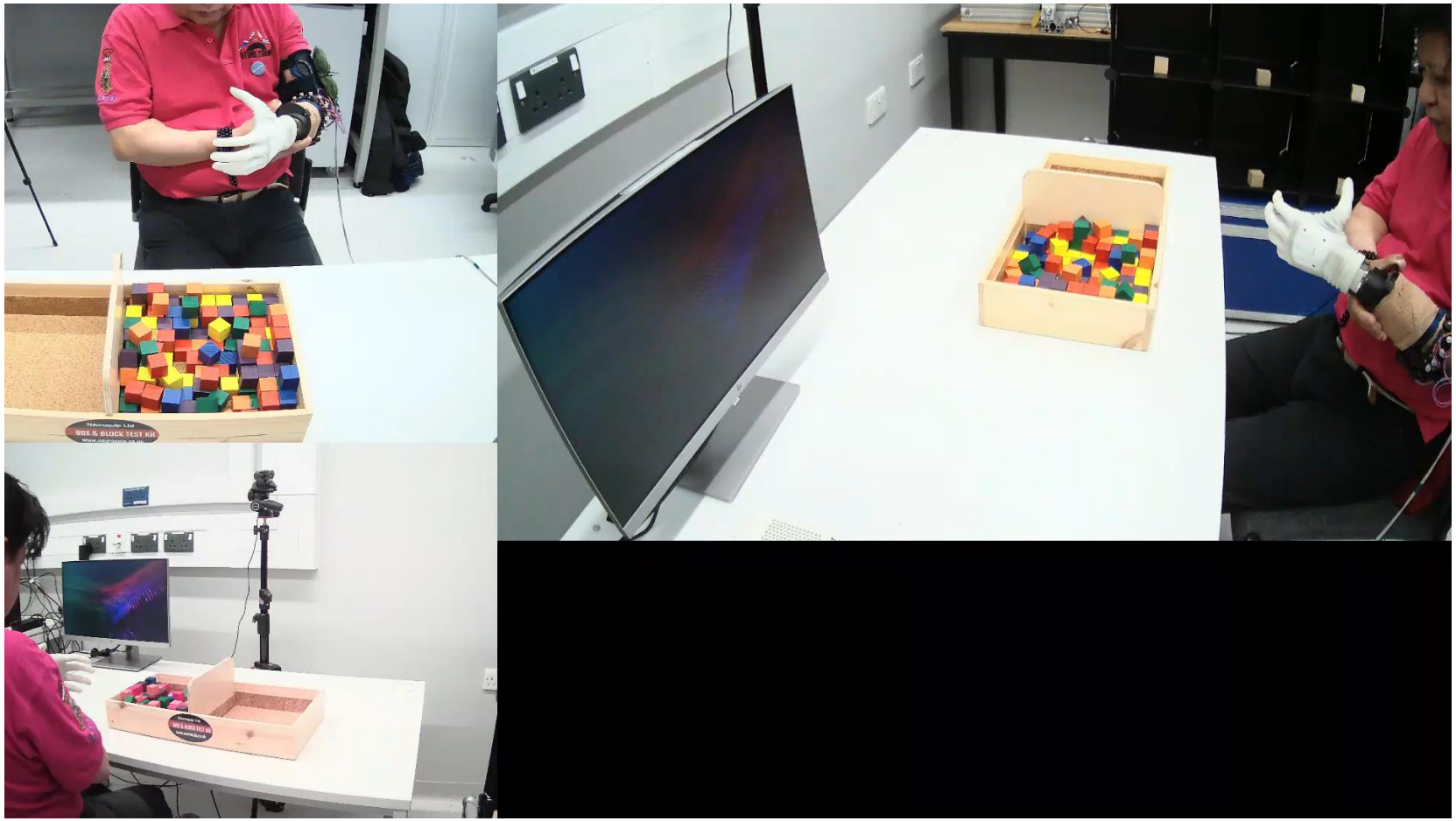

Issues:

- Unsatisfactory socket fit
- Limited space for sensors
- Poor coverage of stump
- Sensor slippage

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Towards validation on Prosthesis

Traditional Thermoplastic Socket Fabrication

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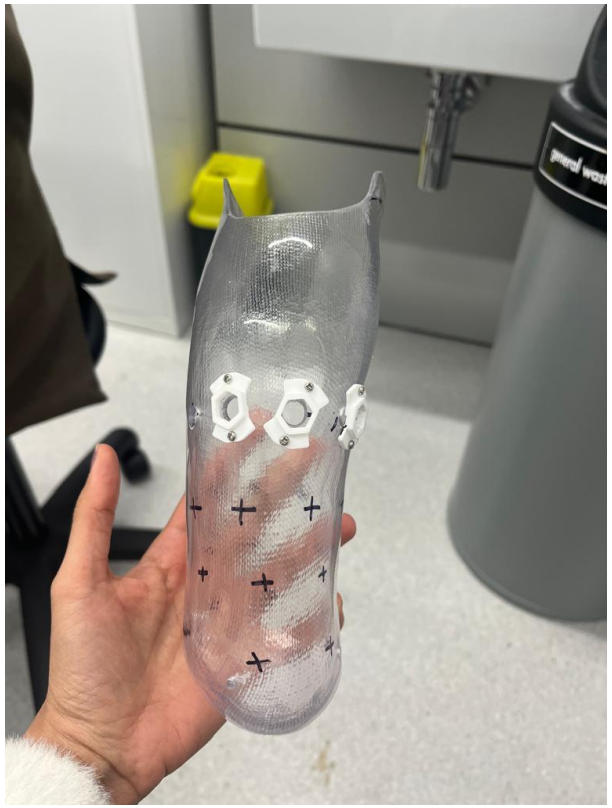
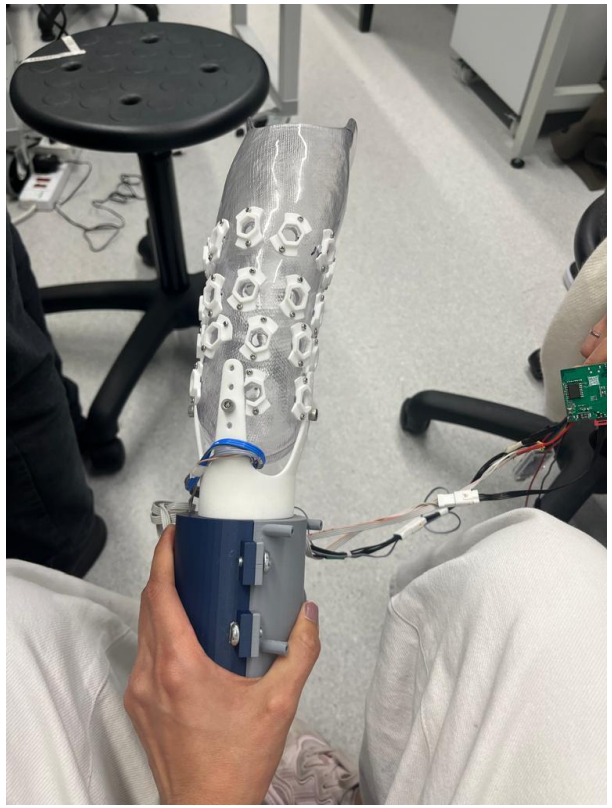
Sgambato et al. Towards Natural Multi-DoF Prosthesis Control with Distributed Ultrasound (In Preparation)

Towards validation on Prosthesis

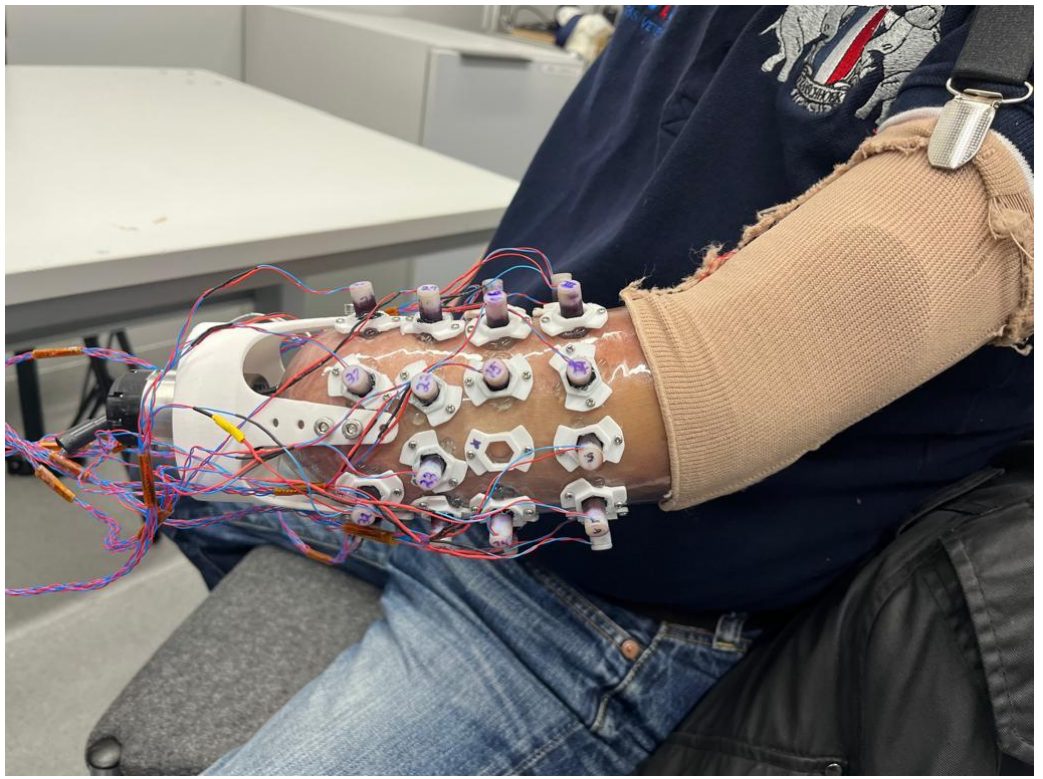
HYBRID NEURO

Traditional Thermoplastic Socket Fabrication





Individualised design of a “constellation of sensors”



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Sgambato et al. Towards Natural Multi-DoF Prosthesis Control with Distributed Ultrasound (accepted lecture IEEE IUS)

Towards validation on Prosthesis

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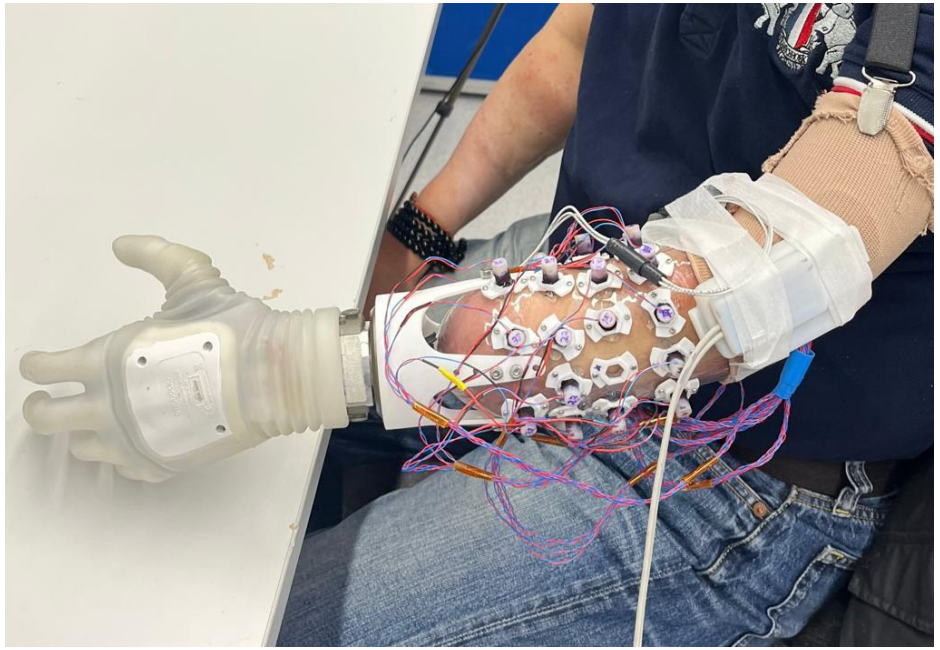
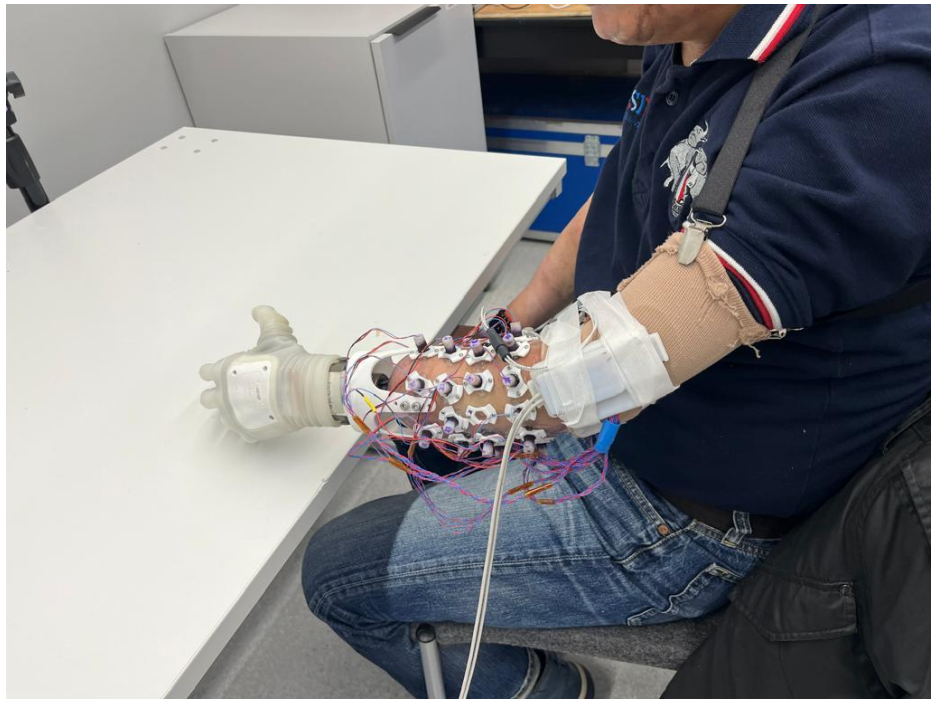
Traditional Thermoplastic Socket Fabrication



Individualised design of a “constellation of sensors”



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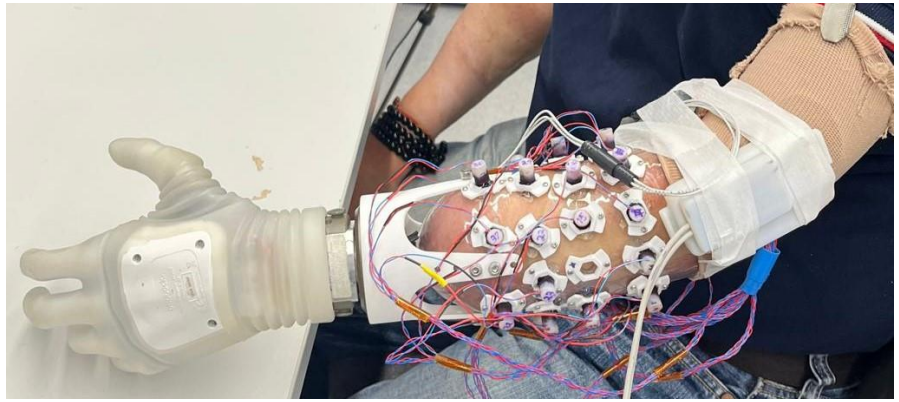
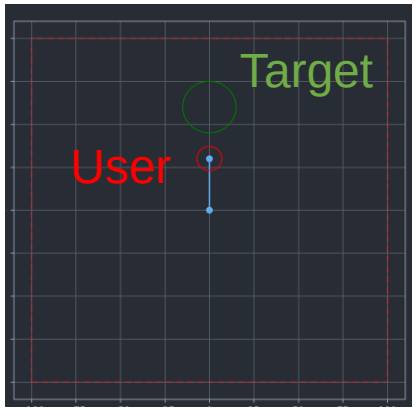
a.



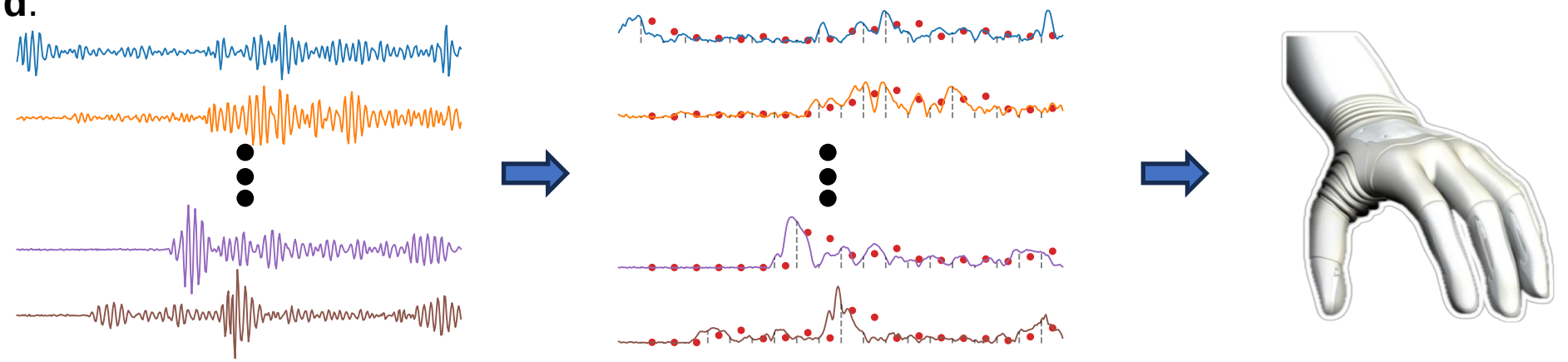
b.



c.

	Participant Results
Offline	0.66 ± 0.12 r^2
TAC Test	11 out 18 Targets (61%)
Box and Blocks	7 ± 1 blocks in 60 seconds
Clothespin Relocation	15 ± 3 seconds per clothespin (9 successes out of 10)

d.



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Topics

1. Motivation
2. What is Ultrasound?
3. Application 1. Motor Unit Decomposition via Ultrafast Ultrasound
4. Break Time
5. Translational challenges: Laboratory → Real-World
6. Application 2. Interfacing with Wearable A-mode Ultrasound
7. **Questions and Answers**

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Acknowledgment

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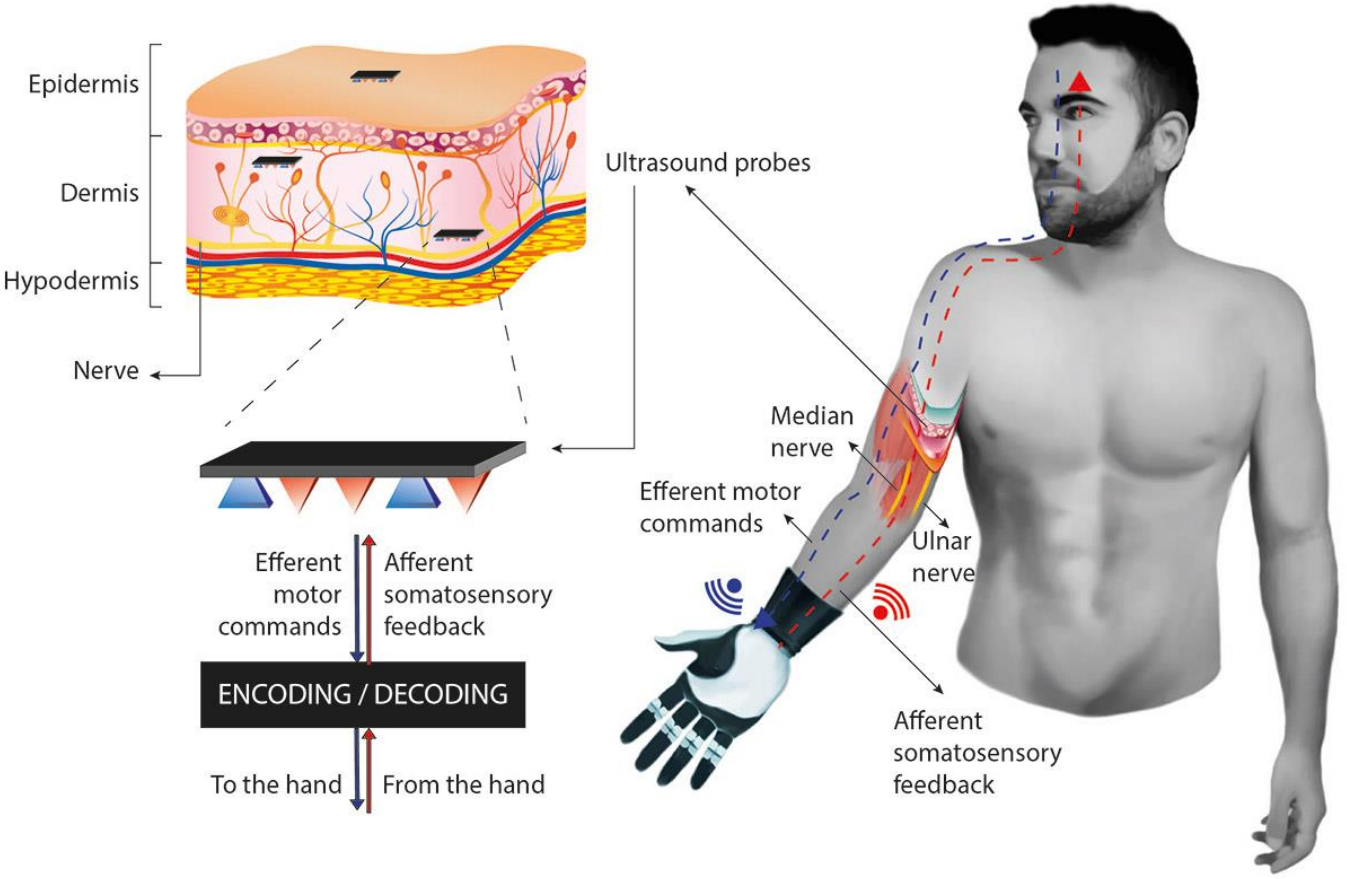
SOMA



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HORIZON 2020

Thank you for the Attention

HYBRID NEURO

Questions?

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- Dario Farina

And many others!!!

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