Design, fabrication, and analysis of customized high-density MXene bioelectronics for upper and lower limb muscles

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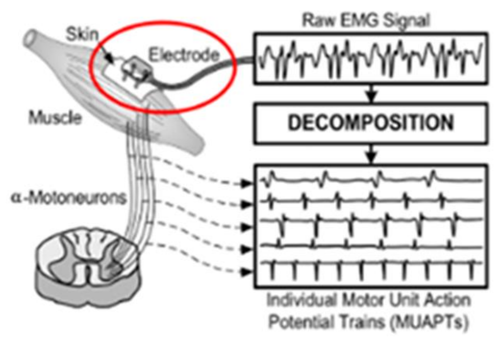
Introduction

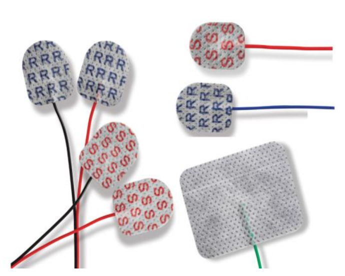
High-resolution $Ti_3C_2T_x$ MXene wearable bioelectronics are a novel technology that shows great advantages in the recording of high-density surface electromyography (HD-sEMG) data, useful to determine muscle activation patterns in the desired area as the patient moves. The goal of this project is to fabricate customized bioelectronics provide patients with an efficient alternative to conventional (EMG) technologies.

Shortcomings of current (EMG) technologies

- **Electromyography (EMG): is a technique for recording the electrical activity produced by muscles.**
  - Bipolar systems (two electrodes)
  - Standard array geometries
  - Need of uncomfotable abrasive gels
  - Individual wires
  - Limited use



J Neurophysiol. (2006) 96(3):1646-57.



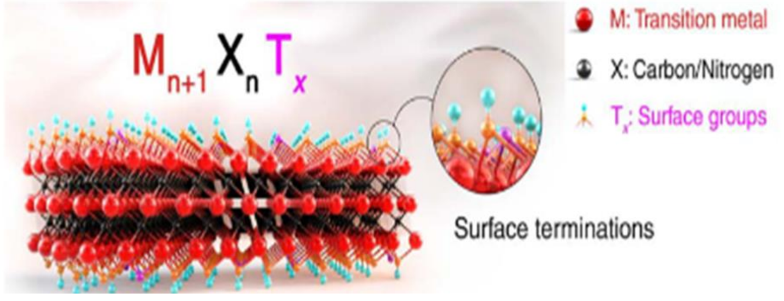
Adapted from: Rhythmlink Conditional Sticky Pad™ Electrodes

Disposable Ag/AgCl electrodes

Proposed Solution: Customized MXene Bioelectronics

What are $Ti_3C_2T_x$ MXenes?

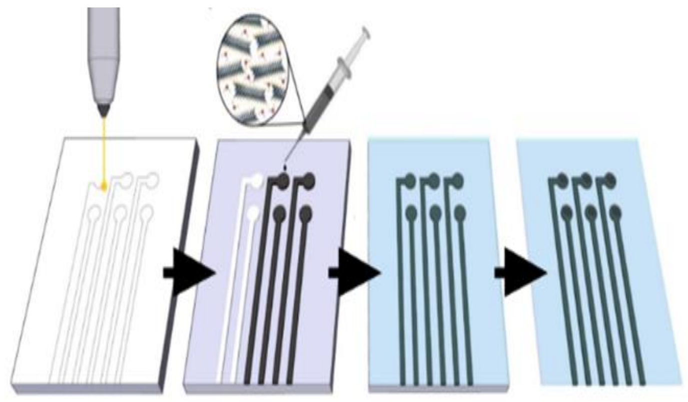
- MXenes refers to a large family of (**2D**) ceramics made from transition metal carbides, carbonitrides, and nitrides that usually take the form of $Ti_3C_2T_x$. Unlike most 2D ceramics, MXenes have good conductivity and excellent volumetric capacitance.



Science, 2021, 372(6547): abf1581

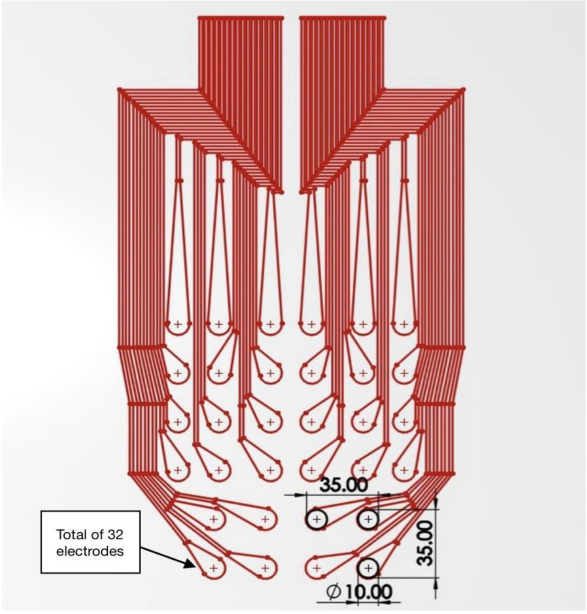
- Conductivity up to 20,000 S/cm
- High capacitance up to 1,500 F/cm[3]
- Hydrophilic material

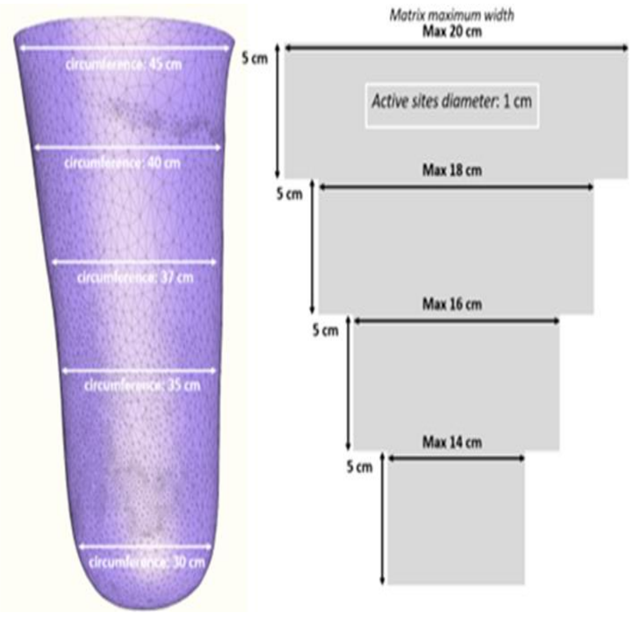
- Can be customized to the patient's measurements
- Can be fabricated for any part of the body
- Detailed (sEMG) recordings
- Cost-effective fabrication
- Skin conformability
- Biocompatibility
- Non-invasive



Driscoll N, Vitale F, et al., Sci. Trans. Med., 2021, 13(612): abf8629

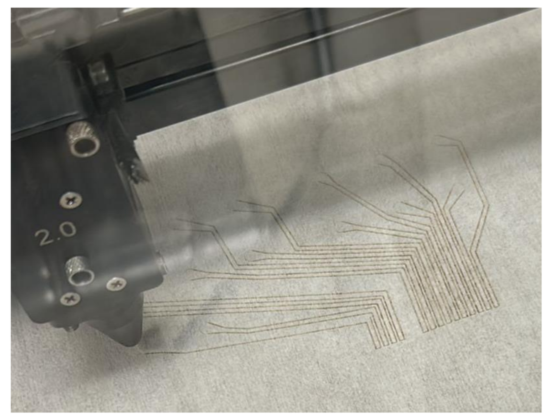
Customizing MXtrode designs for lower limb protheses



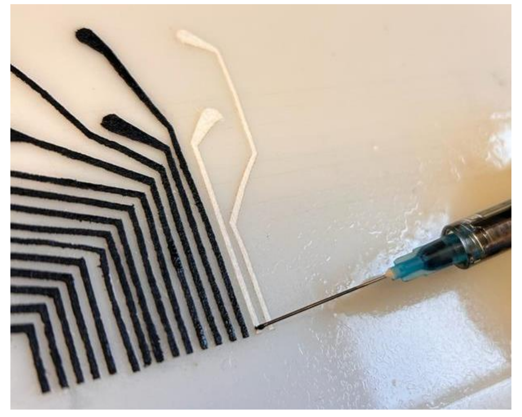


Adapted from: Micera lab, Scuola Superiore Sant'Anna

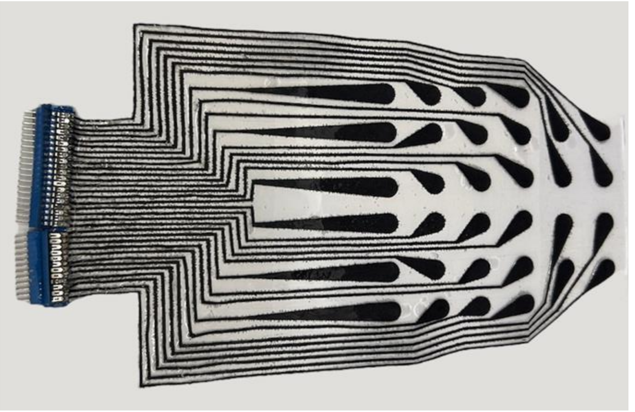
(i) Create customized design using CAD Software and upload it to a carbon dioxide (CO2) laser.



(ii) Laser pattern a nonwoven hydroentangled (60 to 40%) cellulose-polyester.



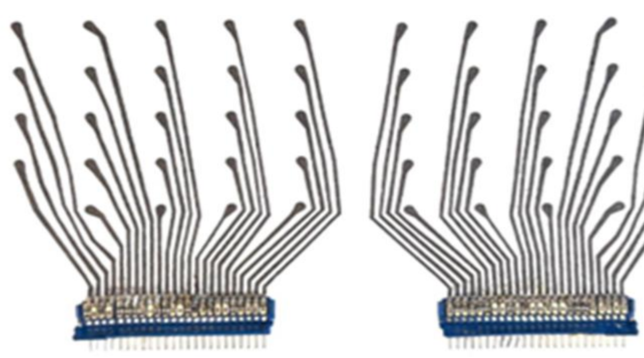
(iii) Place the porous absorbent substrate over a thin layer of polydimethylsiloxane (PDMS) and infuse it with a water-based $Ti_3C_2T_x$ ink.



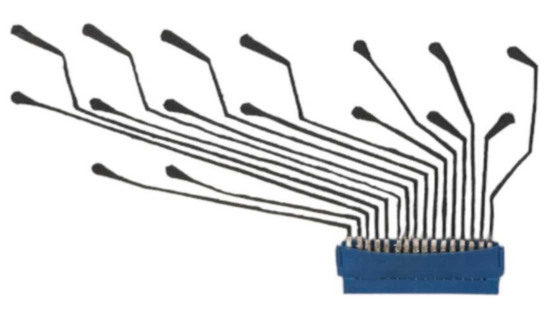
(iv) Attach Flexible Flat Cable Connectors (FFC) with a silver conductive epoxy.

(v) Encapsulate the resulting conductive composite in polydimethyloxane (PDMS) and expose electrodes sites.

Additional MXtrode designs for upper limb protheses

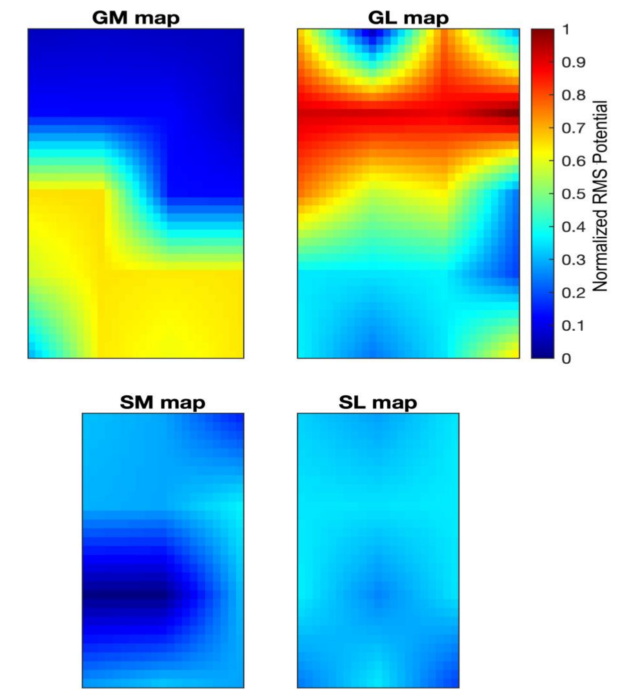


Upper arm (HDsEMG) MXene arrays

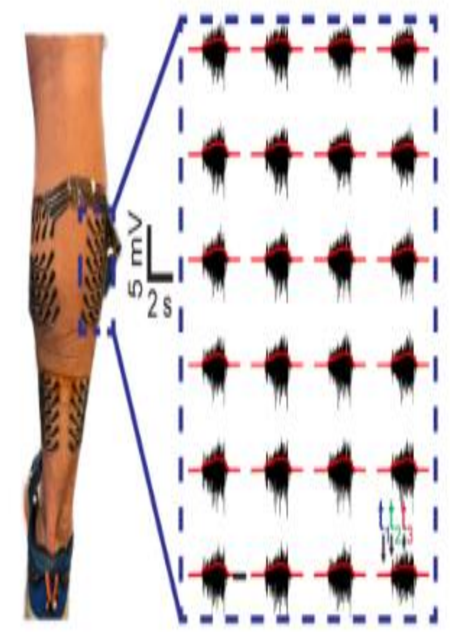


Lower arm (HDsEMG) MXene arrays

MXtrode applications

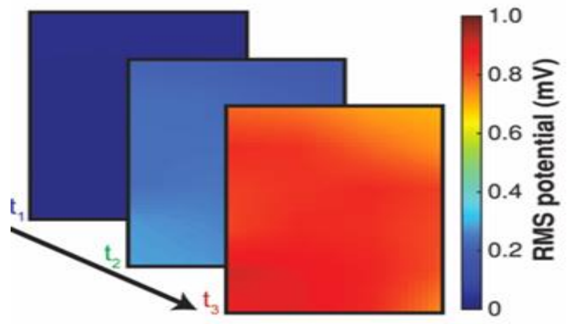


Adapted from: Maggie Wagner, [Unpublished figure]



Adapted from: Garg et al., Small Methods., (2022)

- **Spatial colormaps:** allow us to visualize the (HDsEMG) muscle activation patterns across time during a voluntary muscle contraction. Specific differences in activation patterns can be seen during a maximum isometric contraction. The scale is normalized between minimum and maximum activation potential (0-1).

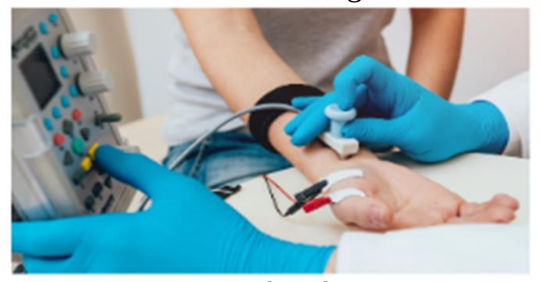


Adapted from: Garg et al., Small Methods., (2022)

Conclusion and Future Directions

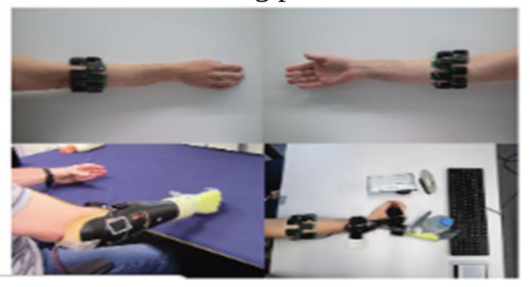
- **Conclusion:** High-density MXene wearable electrodes have proven to be a customizable, low-cost, gel-free, skin conformable option compared to commercially available electrodes.
- **The next steps:** Test the fabricated MXtrode designs on patients and create spatial maps to distinguish muscle activation patterns and eventually use this information to provide medical diagnostics and apply the use of assistive technologies like the control of prosthetics.

Neuromuscular diagnosis



Texas Orthopedics

Controlling prosthetics



IEEE T. Neur. Sys. Reh., 2019, 13; 28(2):508-18. Raghav Garg, University of Pennsylvania

Acknowledgements

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[2] R. Garg *et al.*, "Wearable High-Density MXene-Bioelectronics for Neuromuscular Diagnostics, Rehabilitation, and Assistive Technologies," *Small Methods*, p. 2201318, Dec. 2022, doi: 10.1002/smtd.202201318.

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