Evaluating Calf Muscle Activation for Applications to Achilles Tendinopathy Patients

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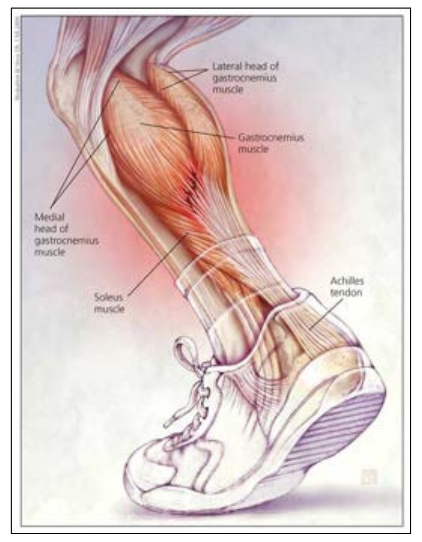
Background



Adapted from: Equilibrium Sports and Spinal Clinic

The Achilles tendon enables multiple types of dynamic movement, but is one of the most fragile structures in the body. It extends from mid-calf to just above the heel and acts in conjunction with two muscles, the gastrocnemius (located mid-calf) and the soleus (behind the gastrocnemius). Specific motor tasks activate the gastrocnemius and soleus differently, generating stress on the Achilles tendon.

Achilles tendinopathy refers to the various pathological changes that reduce the functionality of the Achilles tendon, resulting in chronic pain and impairments in the ability to move. Successful recovery of the tendon requires continuous monitoring of the loads that the calf muscles are imparting on it to avoid further detriment, but a method of monitoring this is yet to exist.

Research Questions

- Can the spatial maps generated by MXene-based high-density surface electromyography (HDsEMG) differentiate between specific activation patterns across the three calf muscles during each exercise?
- Do these activation patterns correspond to different degrees of Achilles tendon loading in patients?

Shortcomings of Existing Technologies

Current Achilles Tendon Imaging:

- Radiography is efficient, readily available, and captures bone erosion and displacement well to indicate ossification
  - Lacks soft tissue contrast, preventing insight into muscle activation
- MRI and ultrasound (shown on the right) have high sensitivity, but cannot capture motion
  - Are thus limited in assessing tendon strain through stages of movement

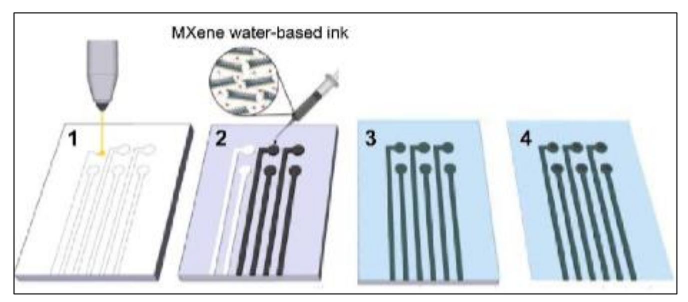
Adapted from: Szaro et al., European Journal of Radiology., (2021)

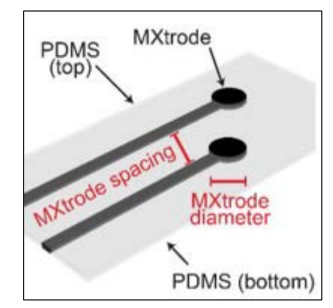
Adapted from: Compex Electrode Systems

Electromyography (EMG): technique for recording the electrical activity produced by muscles

- Current EMG systems are bipolar (two-electrode), meaning it becomes harder to capture accurate data if even a single electrode stops working
- Also use abrasive gels and wires

Materials: What's Different About Our Electrodes?





Adapted from: Driscoll et al., Sci. Trans. Med., (2021)

MXenes: 2D transition metal carbides and nitrides, usually taking the form $Ti_3C_2T_x$

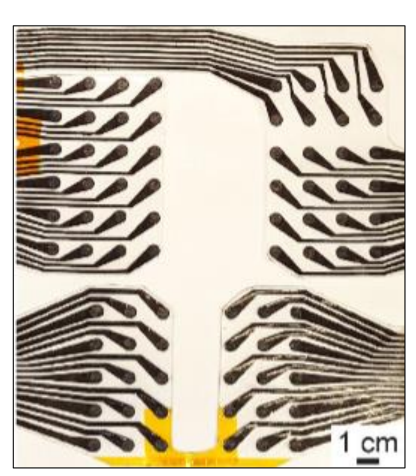
- Produce biocompatible films with high electronic conductivity, skin conformability, and sEMG signal intensity
- Flexible, gel-free HDsEMG arrays composed of MXene electrodes (MXtrodes) were found to discriminate between activity within small muscle groups
- Yield high-resolution, patient-customizable wearable sensors

Fabrication of MXtrodes:

The arrays are first laser cut from textile and placed upon cured PDMS (a silicon-based polymer) using a bioadhesive. 20 mg/ml large flake MXene is then used to ink the textiles. Connectors are applied to the ends of the MXtrodes using silver epoxy, and the entire array is coated in PDMS, cut out, and biopsy punched at the electrode heads to expose the MXene.

Methodology

The HDsEMG array used in this study consists of 78 MXene electrodes spanning the medial and lateral gastrocnemius (24 electrodes on each) and lower soleus (30 electrodes) muscles.



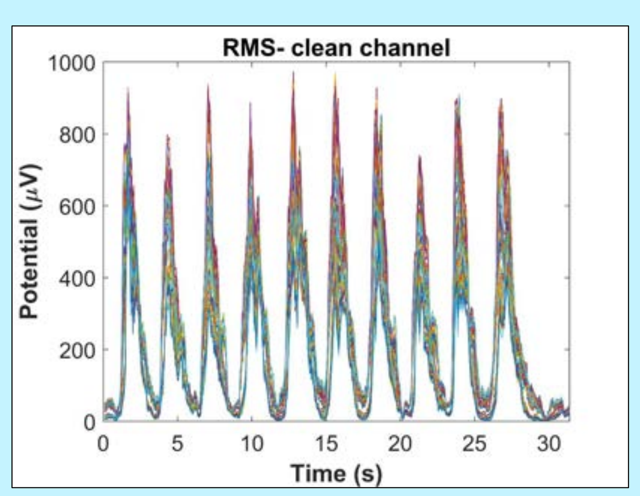
Designing a Wireless System

- Previous designs involved connecting 78 wires to electrodes, which could lead to significant breakage and data loss
- Connected to a wired, non-portable system, restricting subject movement

In our wireless system, we instead attached electrodes to PCBs (dim: 5.4 x 2.55 cm) using soldered connectors. The connectors were then attached to flex cables that connect to the Ripple Grapevine Neural Interface Processor, a wireless EMG voltage recording system.

Signal Analysis

- EMG recordings gave Potential (μV) vs. Time (s) data for each electrode channel
- Data filtered to remove noise and non-functional electrodes, after which the root mean square (RMS) signals were calculated
- MATLAB algorithms for interpolation then implemented to compensate non-functional electrodes the creation of spatial activation maps



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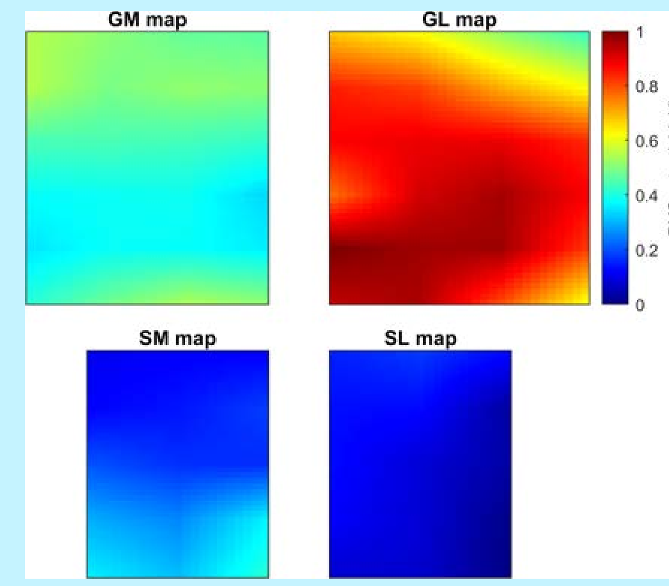
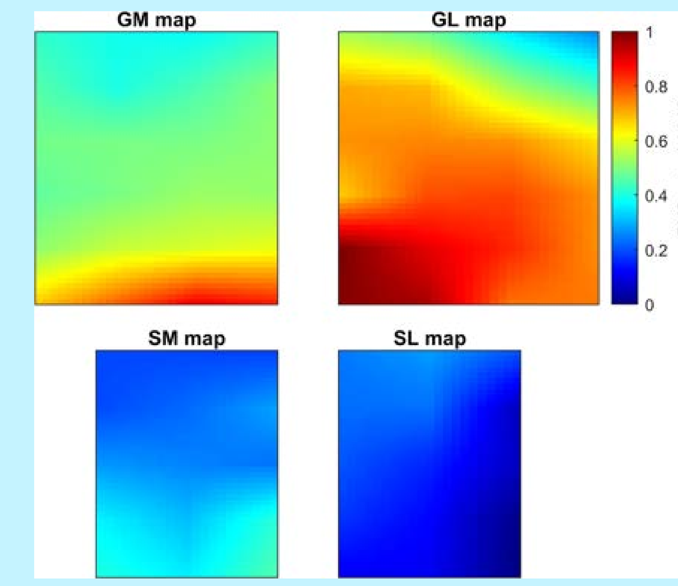
Results

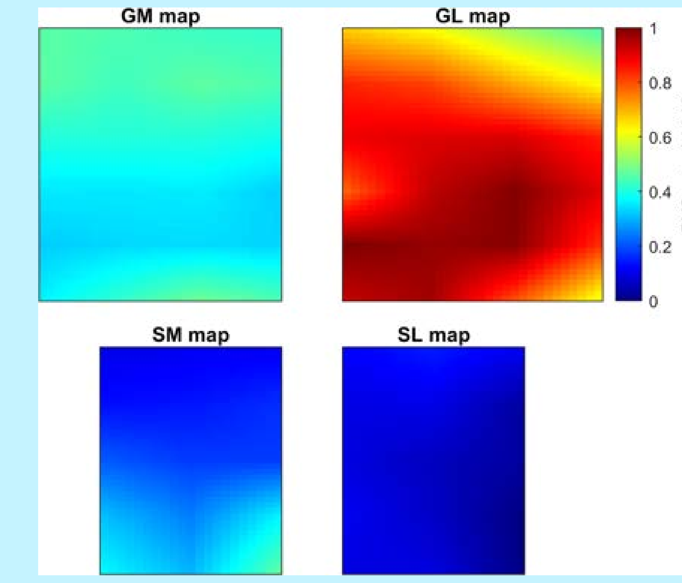
HDsEMG Calf Muscle Activity Across Calf Raises at Varying Ankle Positions



Neutral Calf Raises



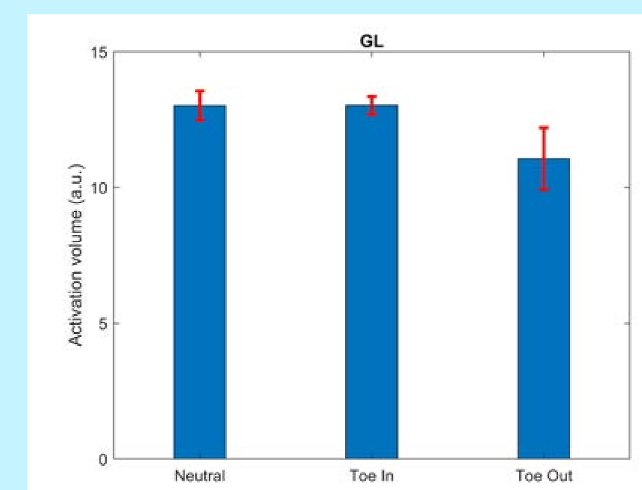
Calf Raises with Toe Out



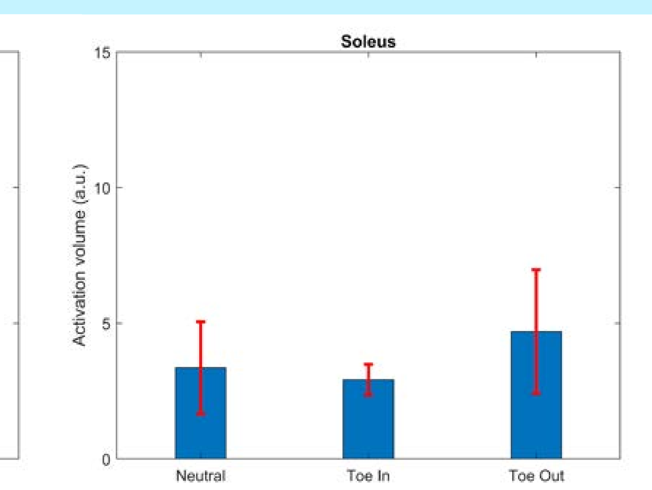
Calf Raises with Toe In

These spatial colormaps show HDsEMG activity for a representative subject. Average RMS muscle potential activity at the maximum voluntary contraction (MVC) points across ten calf raises was computed for these spatial maps. Specific differences in activation across the calf muscles can be seen. In this calf raises exercise, the lateral gastrocnemius shows the highest activation, suggesting it is the source for the majority of the strain on the Achilles tendon at this point.

Muscle Activation Volume Across Calf Raises at Various Ankle Positions



Lateral Gastrocnemius Activation Volume



Soleus Activation Volume

These bar graphs compare activation volume for each muscle at various ankle positions. Activation volume was computed by integrating over the spatial maps for each muscle at the MVC point across each calf raise and taking the average. Differences in activation volume across each ankle position can be observed to determine whether this affects the activity of certain muscle regions, and therefore loading on the tendon.

Conclusion

- MXtrode arrays serve as a gel-free, highly skin-conformable, and customizable option for capturing EMG measurements across the calf muscles
- Mapping spatial activation across the sections of calf muscles has shown distinctions in muscle activity across various activities with a high degree of specificity
- This ability provides great implications for physical therapy and restoration of the Achilles tendon

References

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Next Steps

Now that this robust model of EMG analysis has been validated, the next step would be its utilization to discover potential muscle activation trends for different motor tasks. This would involve generating spatial maps for large numbers of healthy subjects, to establish a baseline, and then conducting trials with patients with Achilles tendinopathy, successively.

- For patients with tendinopathy, the MXtrode arrays will reside inside a boot in conjunction with the wireless Ripple System to provide stability during healing
- The portability and customizability of these MXtrode arrays enables clinicians to be able to track the physiology and structure of the tendon real time to monitor healing progress specific to individual patients
- These arrays can be applied to other parts of the body to distinguish activation patterns across other muscle groups as well

Acknowledgements

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