CPS:Synergy: Collaborative Research: Closed-loop Hybrid Exoskeleton Utilizing Wearable Ultrasound Sensors for Measuring Fatigue

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Objective: Develop closed-loop exoskeletons for restoring function


Fig. 1

The focus of our work is on hybrid systems that utilize external actuators in conjunction with the force generated by the subject's own muscles, augmented by electrical stimulation. Engaging a subject's own muscles via functional electrical stimulation (FES) can lead to improved functional outcomes compared to mechanical assistance alone, but repeated stimulation tends to rapidly induce muscle fatigue.

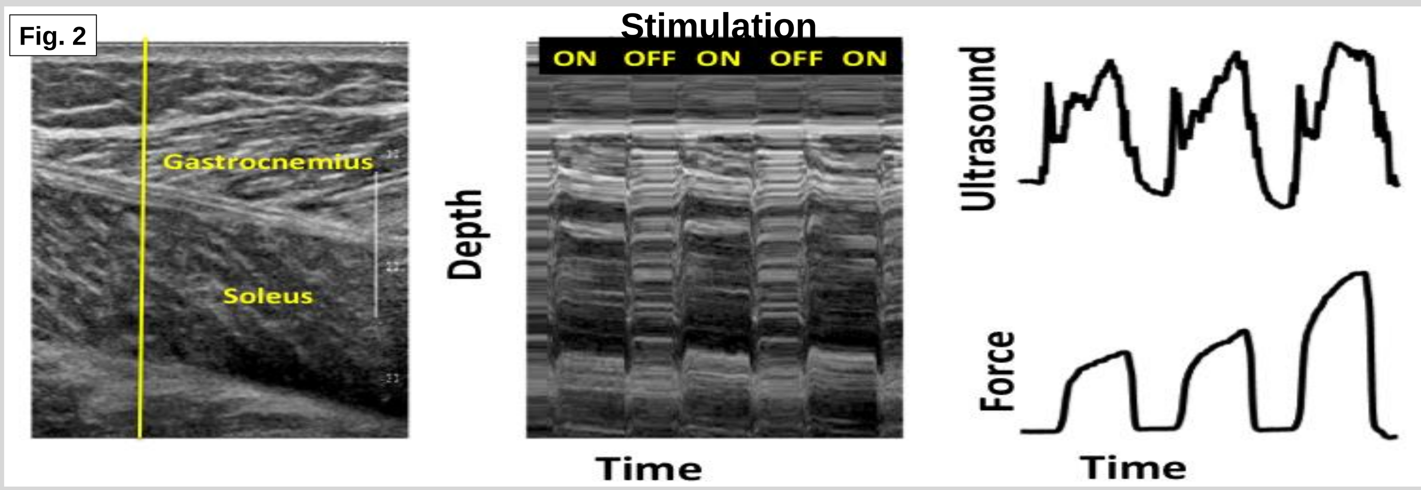
We are developing a closed-loop hybrid exoskeleton that utilizes ultrasound imaging of the muscle to provide closed-loop feedback of volitional motor intent and muscle fatigue.

The specific aims of the project are:

1. **Novel Sensing**: Develop and evaluate wearable imaging sensors for sensing muscle function.
2. **Novel Control**: Closed-loop control allocation to minimize fatigue.
3. **System Integration and Testing**: Integrate sensing and control with a closed-loop hybrid exoskeleton system and evaluate on patients.

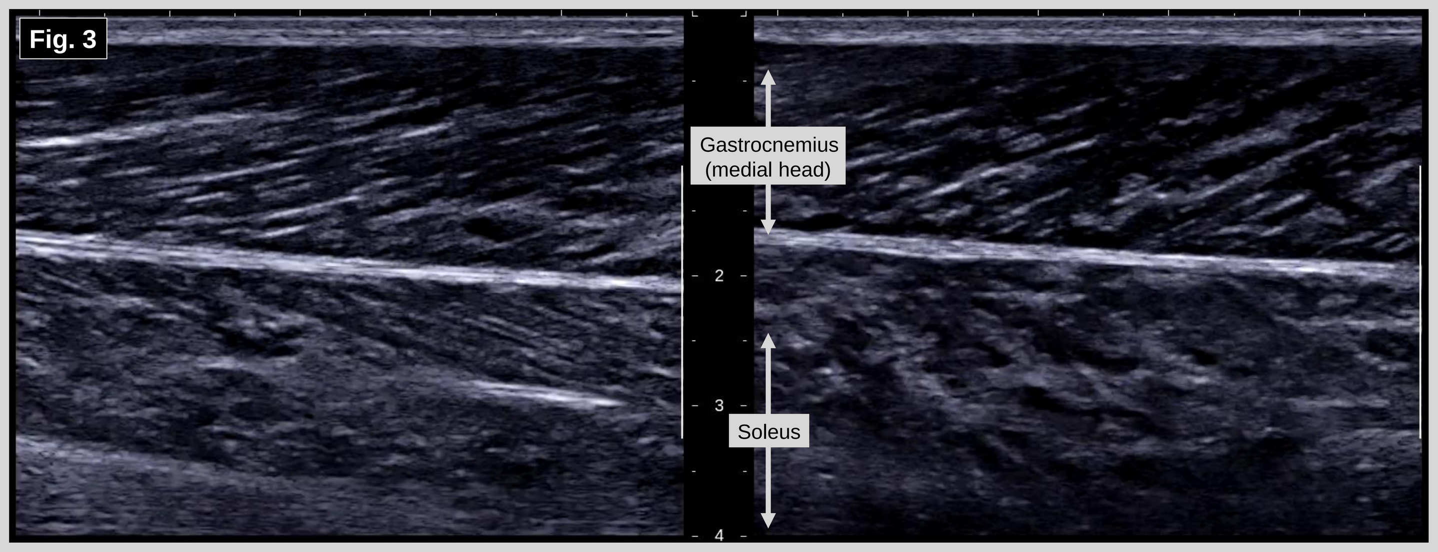
Predicting joint force from ultrasound imaging of calf muscles during functional electrical stimulation (FES)

One of the significant drawbacks of conventional electrical monitoring of muscle activity using electromyography (EMG) is that it cannot be utilized in conjunction with electrical stimulation. Our ultrasound-based methods can be utilized during stimulation as there is no electrical interaction. Preliminary experiments during functional electrical stimulation and simultaneous ultrasound imaging demonstrate changes in muscle thickness and brightness during stimulation compared to rest. Fatigue was not induced for this trial (Fig. 2).

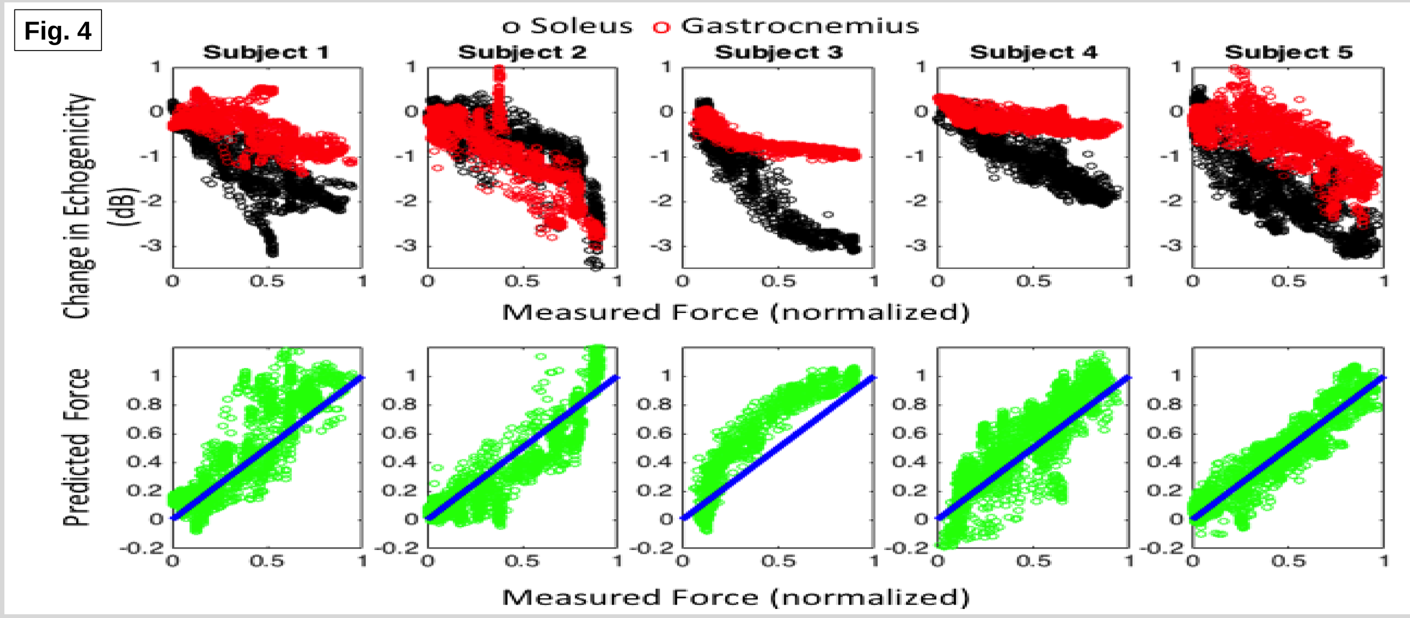


Predicting joint force from ultrasound imaging of calf muscles during voluntary tasks

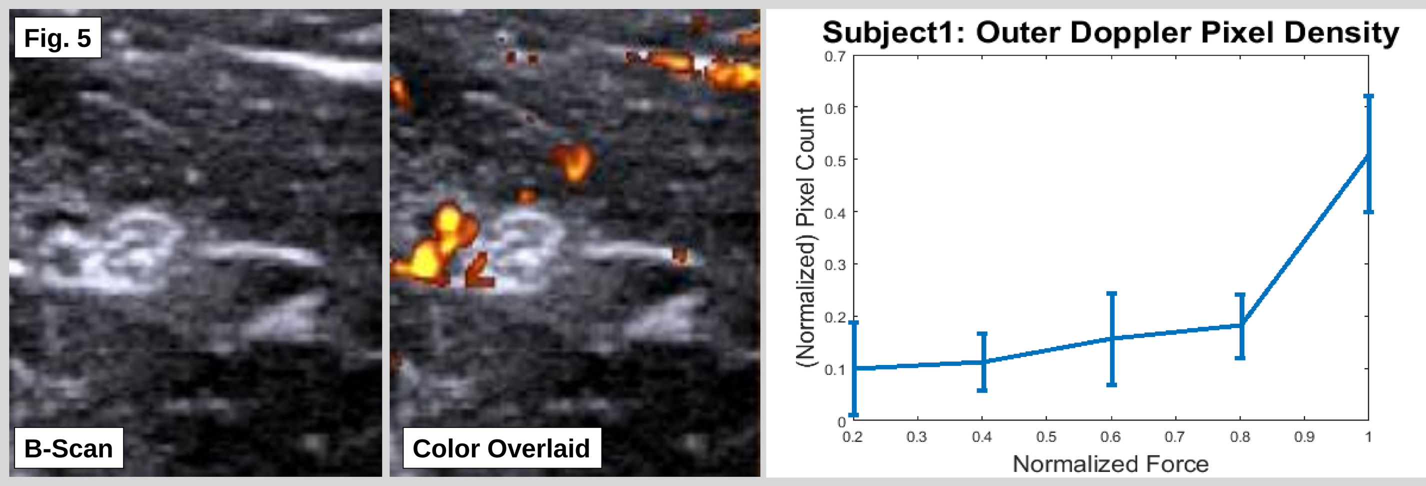
Muscle tension correlates with fiber angle in pennate muscles (Fig. 3,4). Changes in fiber angle alter echogenicity – mean intramuscular image intensity is therefore a potential low-cost surrogate for pennate muscle force.



Longitudinal view of the gastrocnemius and soleus in a relaxed state (Fig. 3 left) and during isometric plantarflexion (Fig. 3 right).

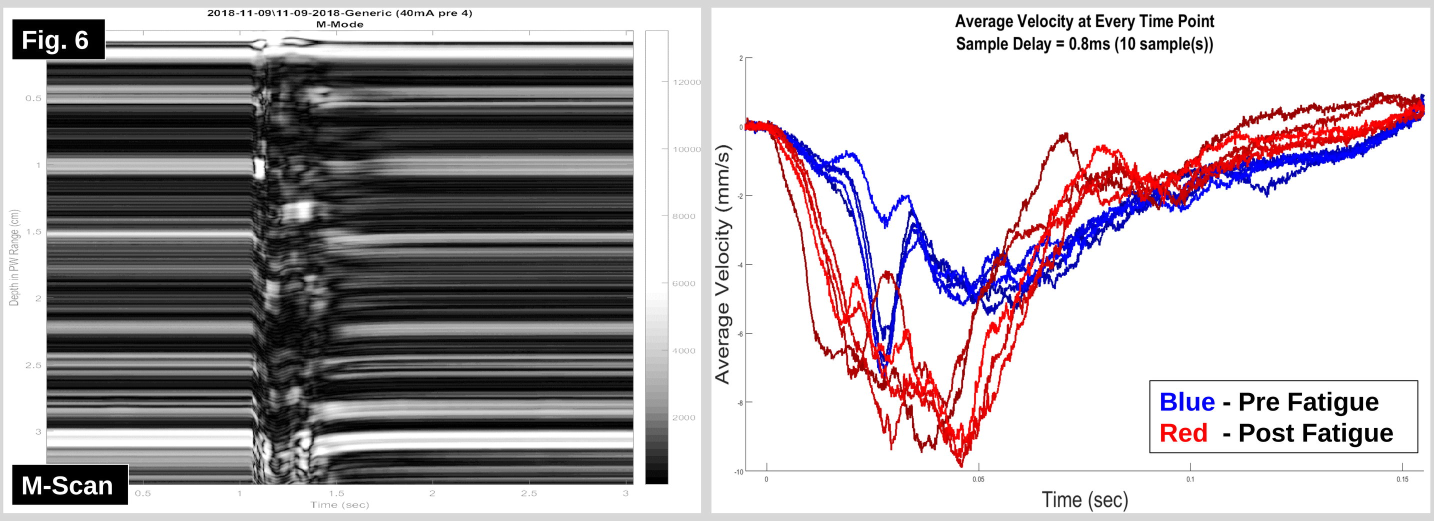


We utilized brightness as an indicator of force (Fig. 4), but a number of other such measures exist, which may be better suited in muscles with a shallower pennation angle. These include the muscle's cross-sectional area, fascial vibrations observed in mechanomyography, and certain approaches in quantitative ultrasound. Color Doppler imaging proved to correlate with muscle force from hand grasp (Fig. 5).



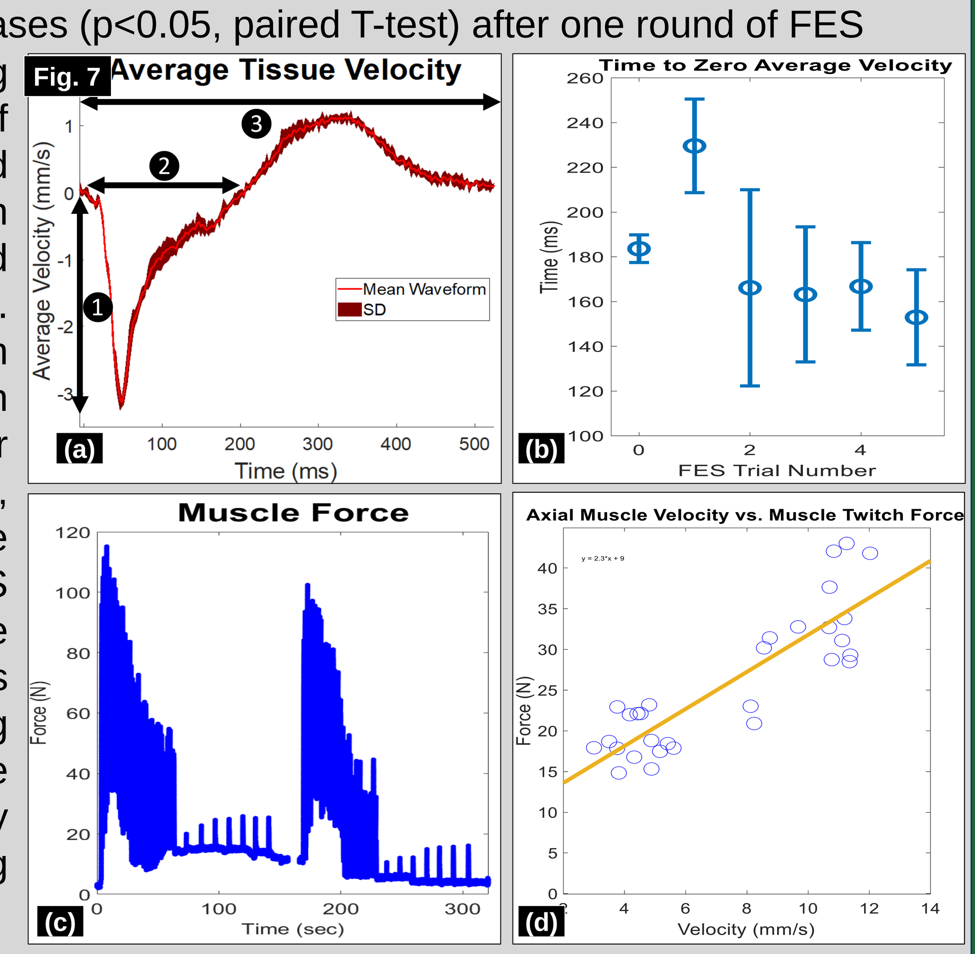
Predicting fatigue using pulse wave Doppler ultrasound and FES muscle twitch

Tissue Doppler imaging (TDI, a form of pulse wave Doppler) is commonly used to quantify heart muscle kinetics during the cardiac cycle. We evaluated pulse wave (PW) Doppler to quantify gastrocnemius muscle twitch to identify muscle fatigue. Below (Fig. 6) we show the PW signal recorded from an FES induced muscle twitch both before and after MVIC induced fatigue.



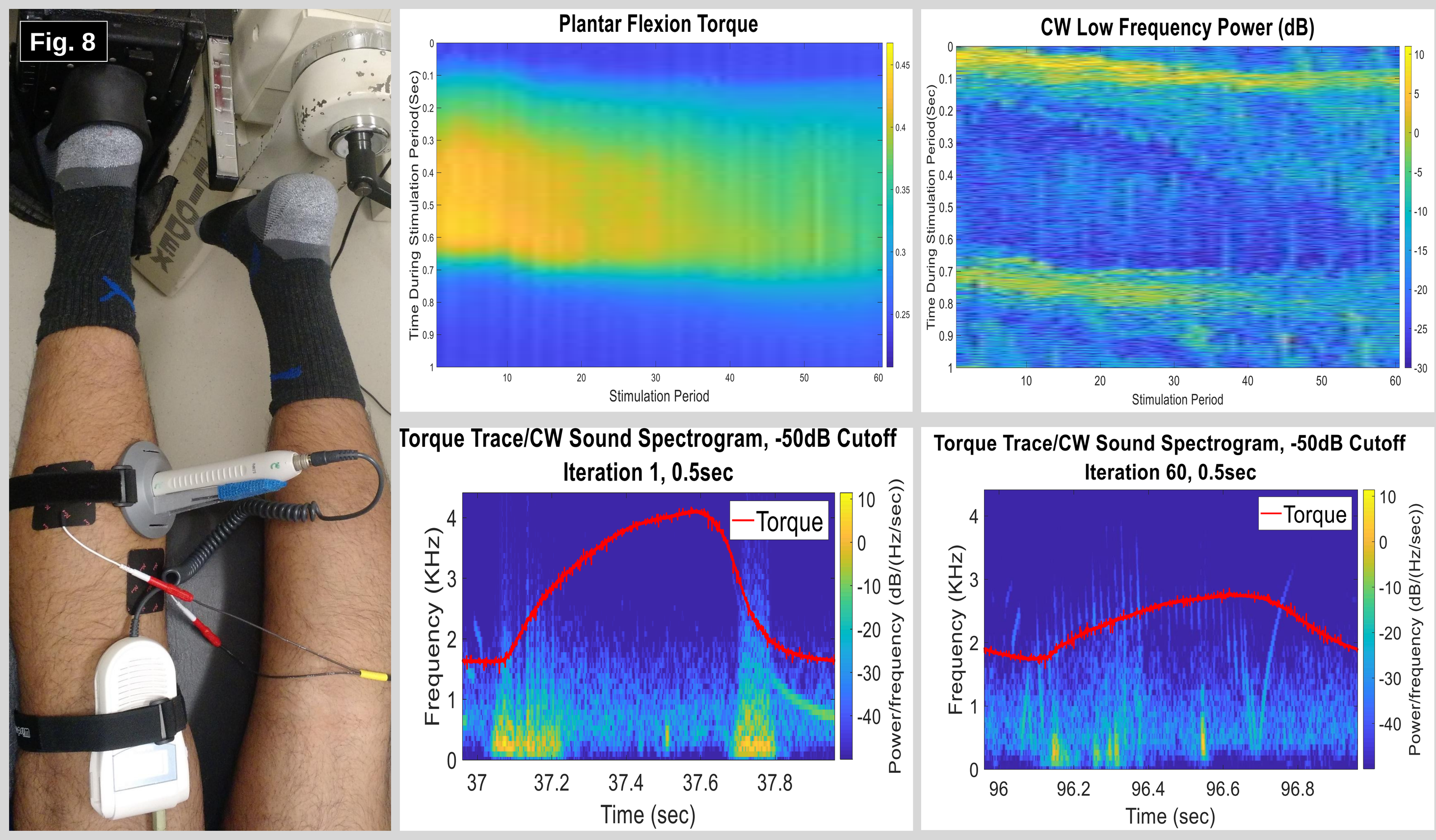
Results indicate a higher peak muscle velocity, twitch duration, and peak displacement after one round of FES fatigue, indicating muscle potentiation. With repeated trials of FES, fatigue eventually dominates. These measures may also indicate fatigue recovery.

Figure 7. (a)Diagram of tissue velocity phases. 1 indicates the peak velocity, 2 indicates the expansion phase ("time to zero velocity"), 3 indicates twitch duration. Displacement (not shown) is the integral of velocity. All four measures showed statistically significant increases ($p<0.05$, paired T-test) after one round of FES fatigue, indicating potentiation. (b)Effect of muscle potentiation and fatigue on the twitch response with repeated fatigue/recovery cycles. Initially, potentiation increases muscle twitch activity, but after subsequent FES trials, fatigue dominates. (c)Force trace with two FES fatigue/recovery trials. Note that muscle twitches increase in force during recovery. (d)Muscle velocities during recovery correlate with recovering muscle force.



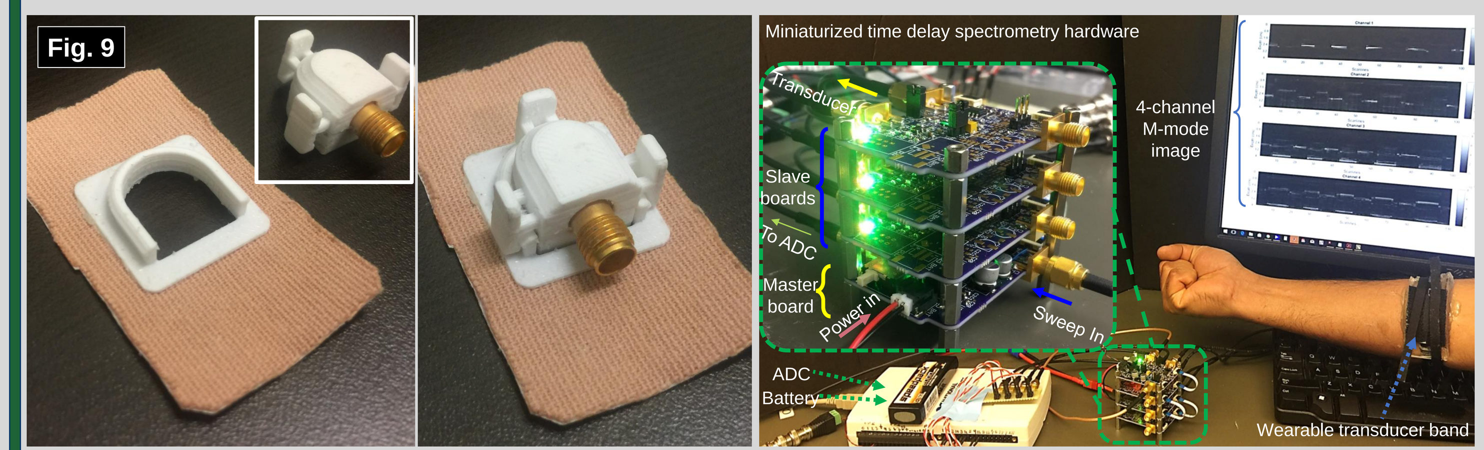
Predicting fatigue using continuous wave Doppler ultrasound

Continuous wave (CW) Doppler is another commonly used ultrasound technique for measuring blood flow. Unlike PW Doppler, CW can be done with a low powered, wearable device using much lower sample rates. We repeated the previous experiment with a portable CW Doppler system and found comparable results. Lower sample rates allowed us to measure force during production in addition to muscle twitches. We found that sound duration at the onset decreases with muscle fatigue, and can drop off entirely as the muscle relaxes (Fig. 8).



Fabricating ultraportable ultrasound imaging hardware

Integrating ultrasound into a hybrid exoskeleton will require ultraportable ultrasound hardware. We are currently developing custom wearable ultrasound transducers and miniaturized electronics for both exoskeleton and prosthetics applications. These include 3D printed clip-on adhesive transducers (Fig. 9, left) as well as wearable band arrays (Fig. 9, right). We are also developing custom PCB boards for miniaturizing the underlying electronics required for ultrasound imaging and image/signal processing.



Developing a portable pneumatic upper limb exoskeleton

Exoskeletons are not limited to restoring gait. We are developing a hybrid FES/pneumatic upper limb exoskeleton to assist with arm and torso motion for a functional reaching task with stroke patients. In our design, a portable air compression fills air bladder to elevate the arm (Fig. 10) while FES is used for forward reaching.


Fig. 10

Future Plans

- Incorporate machine learning
- Integrate ultrasound fatigue measures into closed-loop exoskeleton

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