Estimation of joint torque and muscle fatigue for assistive technology applications using a wearable ultrasound system

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Introduction

Many assistive technologies to restore function for neuromuscular deficits require a robust sensing of muscle activity and fatigue. The conventional standard for sensing muscle activity, surface electromyography (sEMG), has well-documented limitations including its incompatibility with electrical stimulation (ES). ES is commonly used for physical rehabilitation for stroke and SCI and increasingly in assistive technologies such as exoskeletons. However, ES causes rapid muscle fatigue and currently there exists no reliable, real-time indicator for ES-induced muscle fatigue. We hypothesized that muscle activity and fatigue can be inferred from diagnostic ultrasound imaging. Here we used continuous wave (CW) Doppler ultrasound to create a wearable, low power muscle fatigue monitor. This could ultimately provide a useful wearable biosignal sensing method for rehabilitation and assistive technologies, especially when paired with ES.

Methods

Experimental setup: Subjects were recruited to perform prone isometric plantar flexion. We used electrical stimulation (ES) to stimulate their calf muscles to fatigue and quantified muscle movement with a continuous wave (CW) ultrasound probe along with the joint torque (Fig 1).

Experimental protocol: We first established the subject’s maximum voluntary isometric torque (MVIT) and the stimulation level to produce 20% of their MVIT. We then stimulated 50 times over a period of 60 seconds. The muscle was then allowed to rest for two minutes, and the 60-second stimulation period was repeated for a total of five times. Audio output signal from the CW Doppler instrument was recorded continuously throughout.

Analysis: We calculated the spectrogram (Fig 2) and spectral entropy of the CW Doppler signal to analyze signal duration at the onset of muscle contraction. We compared the signal duration first and 60th stimulation period and performed a simple linear regression between the signal duration and peak plantar flexion torque for stimulation cycles 1, 11, 21, 31, 41, 51, and 60 for each of the five ES trials.

Results – Signal Duration with Torque

We also performed a simple linear regression between signal duration and peak plantar flexion torque for each subject. We found that if all ES trials were included, the average R² value was 0.504 ± 0.159, meaning that 50.4% of the torque variability could be explained by the signal duration. The initial ES trial did not follow the same pattern as trials 2-5 (see Fig 4). If trials 2-5 were analyzed without trial 1, the mean R² increased to 0.661 ± 0.0957, indicating that 66.1% of the torque variability could be explained by the signal duration. This could indicate that the muscle needed a warm-up period before they start producing more consistent results.

Results – Signal Duration after Fatigue

We found that CW Doppler signals at both the onset phase and release phase of force, were force/fatigue dependent (Fig 3). In general, as the muscles fatigued, the audio signal durations continually got shorter during both phases and tended to drop below detectable levels for the release phase. For the first stimulation period, the contraction signal was on average 133.5 ms ± 36.05 ms. By the 60th stimulation period, the muscle had fatigued and the signal duration dropped to 52.16 ms ± 20.24 ms. This change was statistically significant (p = 0.012, paired 2-tailed t-test). This indicates that the signal duration is correlated with peak plantar flexion torque.

Conclusions

Continuous wave Doppler ultrasound is portable, low power, and provides real-time information about muscle activation, fatigue, and recovery that is compatible with ES. This could provide a useful wearable biosignal sensing method for use in conjunction with assistive technologies such as hybrid exoskeletons combining ES and actuators, and therapeutic electrical stimulation. This method overcomes many of the limitations of other sensing modalities.

Future Directions

• Incorporate machine learning
• Integrate the portable CW Doppler system into a hybrid ES exoskeleton

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