Quantitative Assessment of Change in Muscle Contractility Due to Fatigue During NMES: An Ultrasound Imaging Approach

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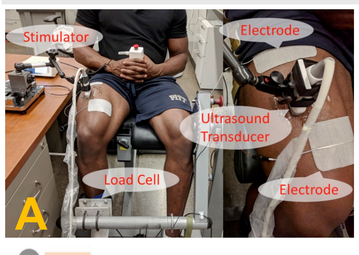
Motivation

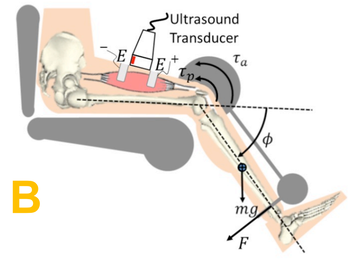
- Neuromuscular electrical stimulation (NMES) artificially excites motor nerves and can be used to restore limb function in persons with neurological disorders.
- However, **NMES-induced muscle fatigue** is a major technical hindrance that significantly limits its operation time and causes ineffective closed-loop control.
- A sensing modality to directly assess the NMES-induced fatigue can provide effective closed-loop NMES control.
- **Ultrasound (US) imaging** is proposed as a new-type of sensing modality for **direct fatigue assessment.**
- Methods to integrate US-based fatigue sensing in NMES control are under development in our laboratory.

Methods

Our recent research results indicate US can be used to predict NMES-induced muscle fatigue.

- **Knee extension experiments** on a human participant were conducted to record synchronized isometric knee force data and ultrasound images of the electrically stimulated quadriceps muscle.
- The data was firstly collected in a **pre-fatigue stage** and then in a **post-fatigue stage**.
- During the transition period, a **fatiguing protocol** was applied. Decay of the normalized joint torque curve indicates the attainment of post-fatigue stage.
- Ultrasound images were processed using a **contraction rate adaptive speckle tracking algorithm**. A 2D strain measure field was constructed based on the muscle displacement tracking results.
- Analysis of the strain measure with synchronized force data provides implications of **NMES-induced muscle fatigue**.





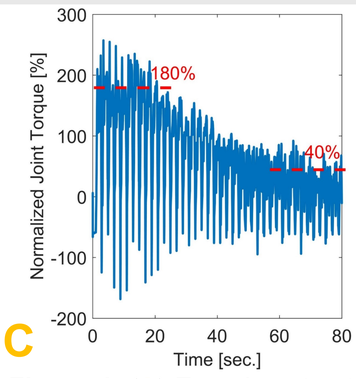
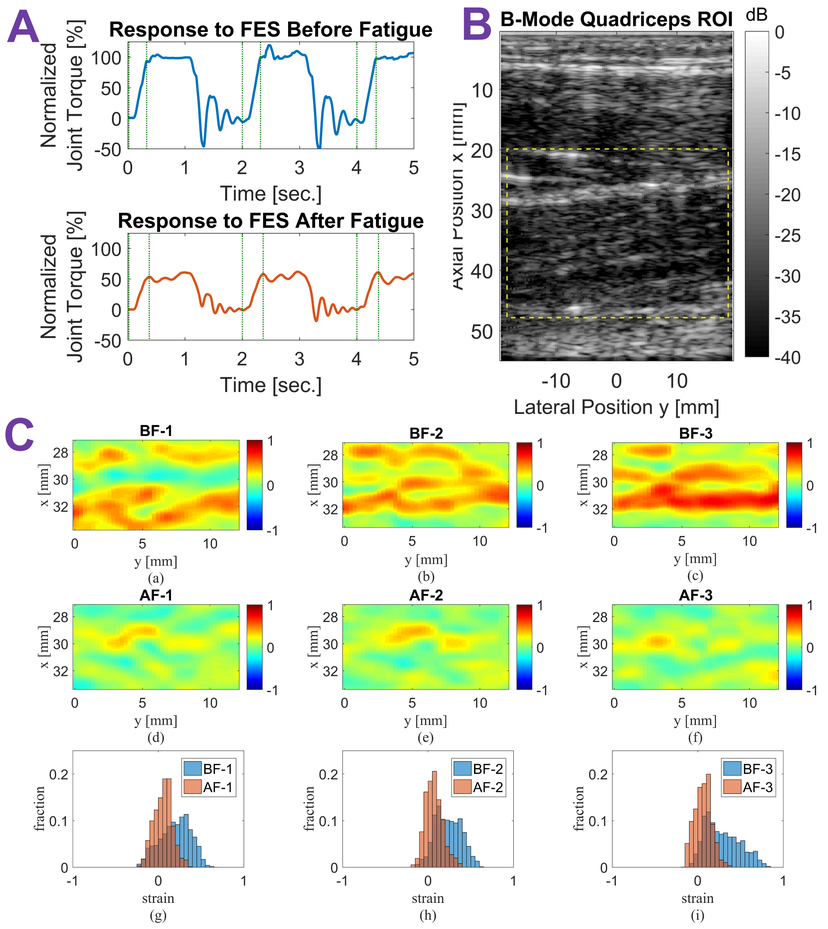
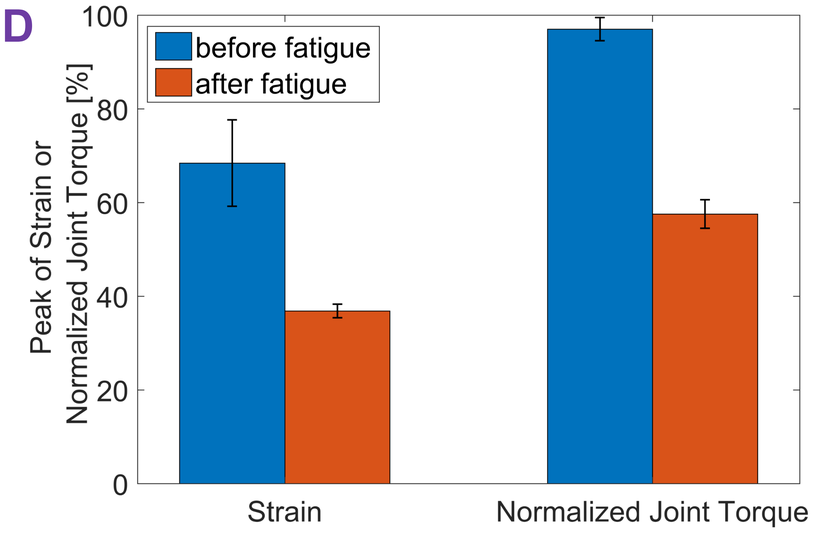


Figure 1. (**A**) Experiment setup. (**B**) Sketch of the knee extension. (**C**) Transition period and decay of the normalized joint torque under the fatiguing protocol.

Analysis of the Strain Measure between Pre-fatigue and Post-fatigue Stage

Maximum Strain Images





Temporal Strain Curves of a Local Region

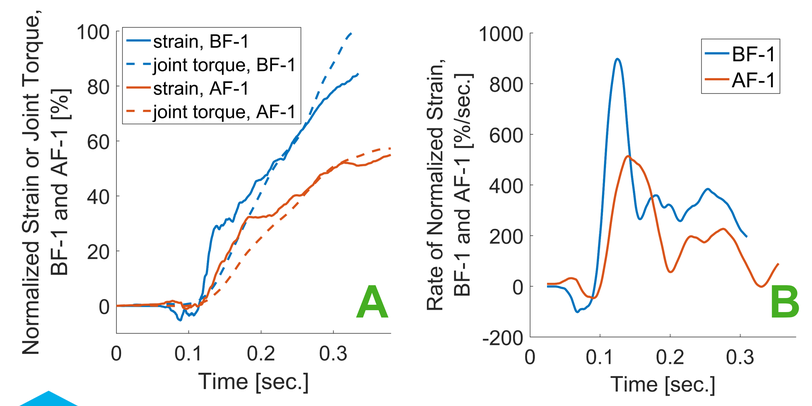


Figure 3. (**A**) Temporal curves of the **normalized strain** and **joint torque**, compared between data set **BF-1** at a position around $(x, y) = (31.1080,\ 5.3)$ mm and data set **AF-1** at a position around $(x, y) = (29.0675,\ 5.3)$ mm. (**B**) **Rate of the normalized strain** curves compared between data set **BF-1** and **AF-1**. When muscle is fatigued, the initial peak not only has a noticeable reduction but also appears slightly later during the contraction process.

Figure 2. (**A**) **Normalized force data** before (**BF**: top) and after (**AF**: bottom) fatiguing protocol. Among the three contraction cycles, the rising periods marked by the dotted lines were extracted, matched with their synchronized strain data and marked as **BF-1,2,3** (pre-fatigue stage), **AF-1,2,3** (post-fatigue stage), respectively. (**B**) Region of interest (ROI) of the stimulated quadriceps muscle (yellow rectangular box). (**C**) **Maximum strain field** images (a-f), compared between **BF-1,2,3** and **AF-1,2,3**, respectively, and **histograms** (g-i) showing a noticeable change in **spatial distributions of the maximum strain field**. (**D**) Comparison of **peak reductions** of both strain and normalized joint torque. The maximum strain value decreases from $\mathbf{68.4 \pm 9.23\%}$ in the pre-fatigue stage to $\mathbf{36.9 \pm 1.46\%}$ in the post-fatigue stage. The maximum torque decreases from $\mathbf{97.0 \pm 2.47\%}$ to $\mathbf{57.5 \pm 3.05\%}$.

Conclusions

- NMES-induced change in muscle contractility and fatigue effect can be quantified by the reduction in strain peak during each stimulated contraction.
- A noticeable difference in strain distributions can be used as the 2nd quantitative assessment of muscle contractility change.
- Temporal properties of the strain measure can be the 3rd way to capture fatigue effect: the initial high peak of a strain rate curve is reduced and slightly delayed in the post-fatigue stage.

Future work: The proposed ultrasound imaging based methodology assesses changes in muscle contractility and indicates fatigue. This methodology will be used to predict NMES-induced muscle fatigue in closed-loop hybrid neuroprosthetic systems. A switched control scheme that uses this fatigue feedback is under investigation on a hybrid walking exoskeleton.