

Motivation

The literature reports a variety of adaptations in motor unit (MU) firing behavior during muscle fatigue, including a decrease [1] and an increase [2] in MU firing rates. The inconsistency among previous studies is due primarily to the limited number of MUs available for analysis, and to the practice of analyzing MU data grouped from different subjects, contractions, and force levels [1,2,3].

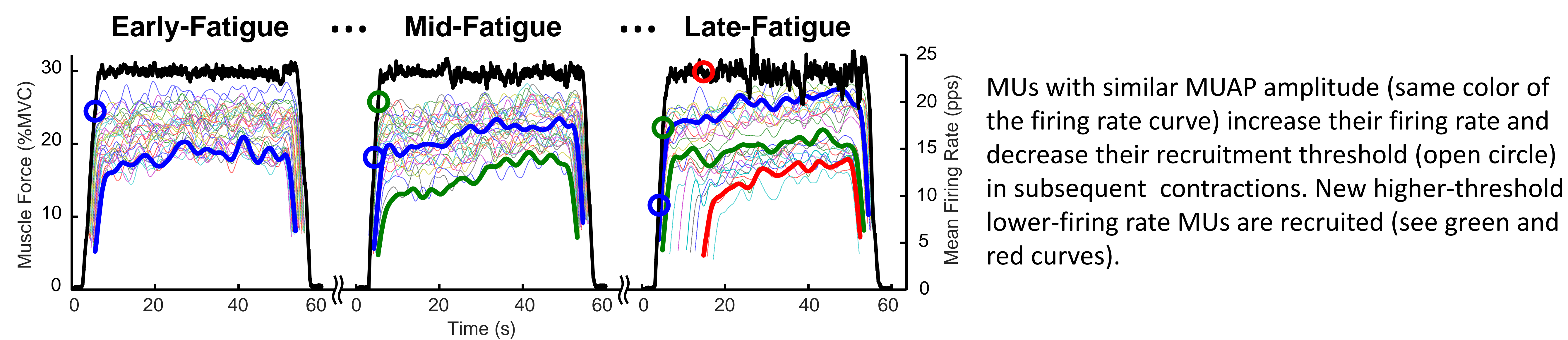
Aim: establish a clear understanding of MU behavior during fatigue by investigating the firing adaptations of MUs in individual subjects and contractions during a fatigue protocol in the Vastus Lateralis (VL) muscle.

Methods

- **Subjects:** Five healthy young (24-33 years old) subjects
- **Muscle:** Vastus Lateralis (VL)
- **Protocol:** Voluntary isometric contractions sustained at 30 % MVC for 60 s and repeated to the endurance limit
- **Analysis:** MU firing rates, MU recruitment threshold, MU action potential (MUAP) amplitude were extracted using the dEMG System from Delsys, Inc (Natick, MA)

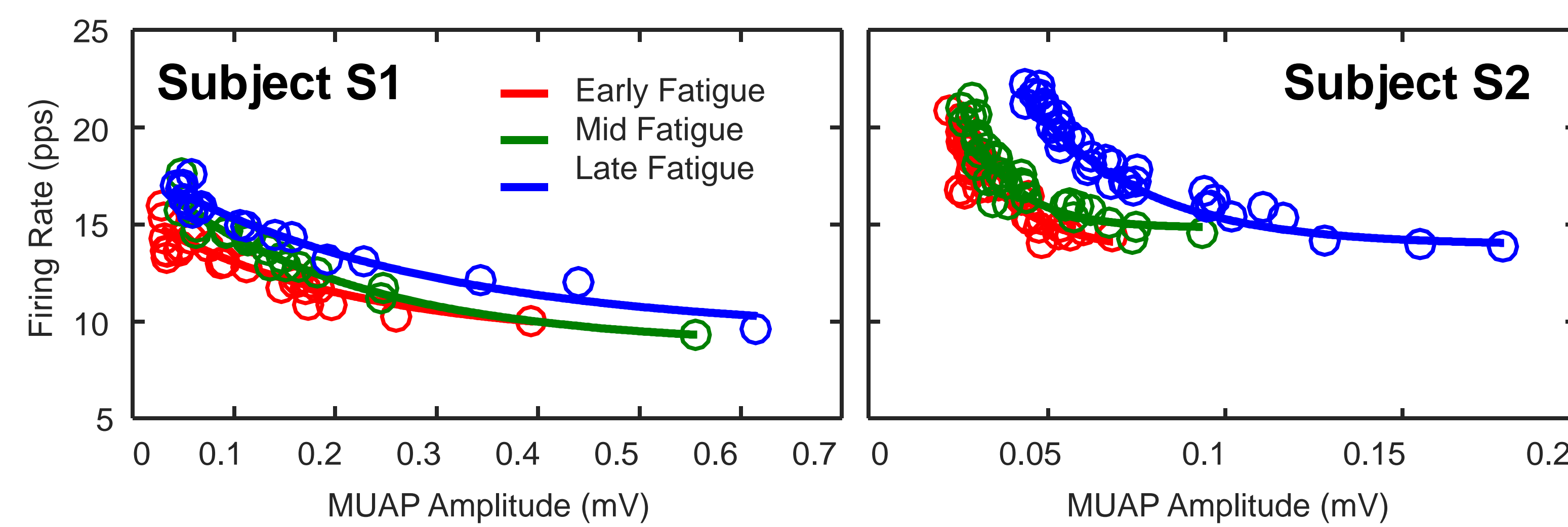
Results - Empirical Study

During fatigue, MU firing rates increase, MU recruitment threshold decrease, and new MUs are recruited



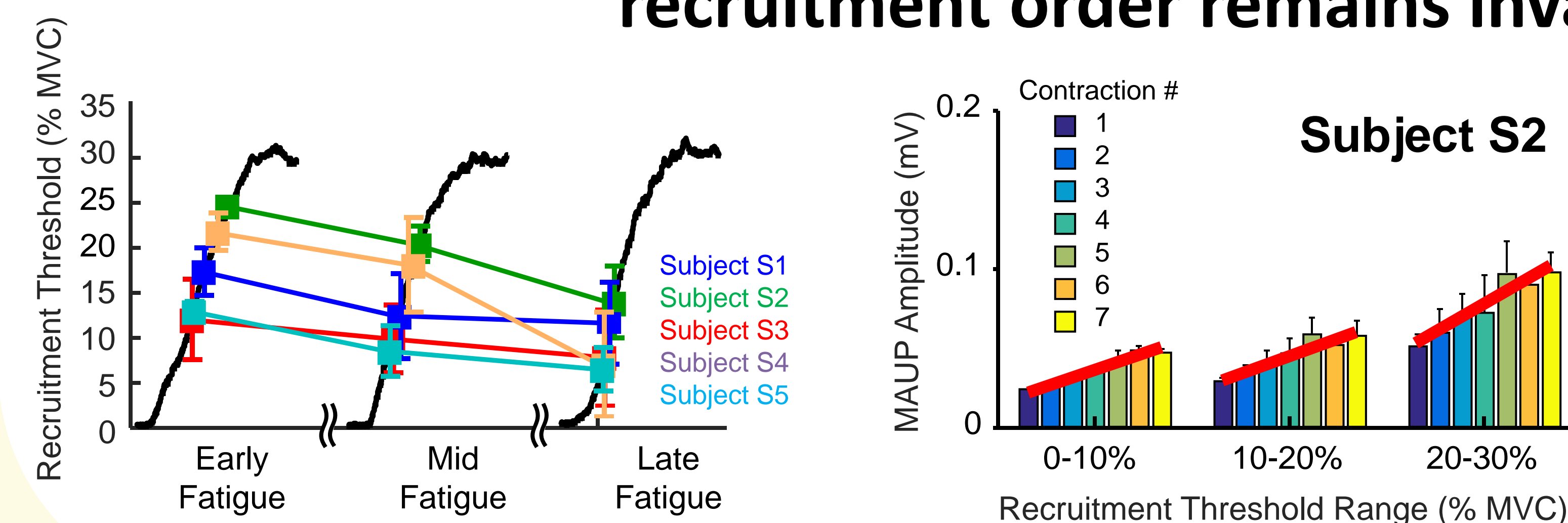
MUs with similar MUAP amplitude (same color of the firing rate curve) increase their firing rate and decrease their recruitment threshold (open circle) in subsequent contractions. New higher-threshold lower-firing rate MUs are recruited (see green and red curves).

The increase in MU firing rate is subject-dependent, but the firing rate scheme remains invariant with fatigue



The regression curves between MU firing rate and MUAP amplitude show a subject-dependent upward shift from early to mid to late-fatigue, but the inverse relation between MUAP amplitude and MU firing rate, known as the Onion-Skin property of MU firings [4], is maintained ($R^2 = 0.74 - 0.97$).

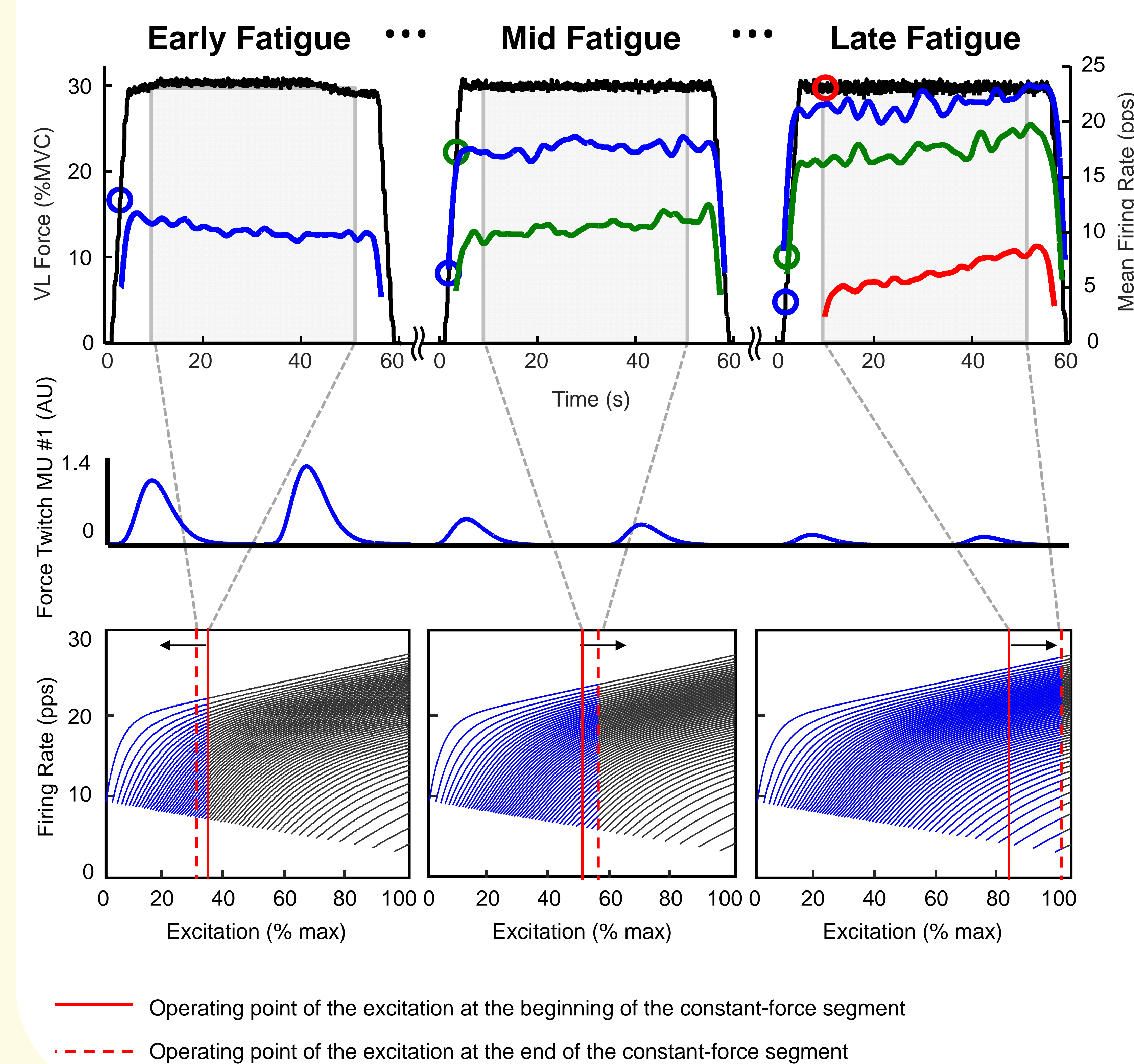
The decrease in MU recruitment threshold is subject-dependent, but the recruitment order remains invariant with fatigue



Left) Subject-dependent decrease in the average recruitment threshold of MUs with similar-amplitude MUAPs from early to late-fatigue. Right) The direct relation between MUAP amplitude and recruitment threshold is maintained with fatigue (Size-Principle of MUs [5]) (see the increasing height of similarly colored bars).

Results - Simulation Study

During fatigue, MU firing rates increase, MU recruitment threshold decrease, and new MUs are recruited in response to decreasing muscle force generation capacity



When the protocol was replicated with a model [6] that simulates the force and firing behavior of MUs in the VL, all empirically observed adaptations in MU firing were replicated:

- MU firing rates increased (see the firing rate curves of three selected MUs shown in different colors)
- MU recruitment threshold decreased
- New higher-threshold lower-firing rate MUs were recruited (see green and red curves).

Muscle fatigue was simulated as a time-varying decrease in the amplitude of the MU force twitches. The force twitch increased only during the initial 60-s of the fatigue protocol to replicate muscle potentiation [6].

In response to the fatigue-induced decrease in MU force twitches, the operating point of the excitation to the motoneuron pool (red lines) increased from early to mid to late-fatigue. The right-ward shift in the operating point caused: recruitment of new MUs (active MUs are indicated in blue), increase in MU firing rates (indicated by the intersection of the firing rate curves with the excitation line), and decrease in MU recruitment threshold.

References

- [1] Kelly et al. *J Neurophysiol.* (2013)
- [2] deRuiter et al. *Eur J Appl Physiol.* (2005)
- [3] Enoka et al. *J Neurophysiol.* (1989)
- [4] De Luca & Erim. *Trends Neurosci.* (1994)
- [5] Henneman. *Science.* (1957)
- [6] Contessa & De Luca. *J Neurophysiol.* (2013)

Acknowledgments

This work was funded in part by the National Institute of Neurological Disorders and Stroke (R43NS093651, R44NS077526).