Modeling and Switching Control of an Input Delayed Hybrid Exoskeleton for Lower-limb Function Restoration

Zhiyu Sheng[1], Kang Kim[1, 2, 3, 5] and Nitin Sharma[1, 2, 4]

[1]Department of Mechanical Engineering and Materials Science, University of Pittsburgh School of Engineering.
[2]Department of Bioengineering, University of Pittsburgh School of Engineering.
[3]Center for Ultrasound Molecular Imaging and Therapeutics, Department of Medicine and Heart and Vascular Institute, University of Pittsburgh School of Medicine and University of Pittsburgh Medical Center.
[4]Joint Department of Biomedical Engineering, North Carolina State University.
[5]McGowan Institute for Regenerative Medicine, University of Pittsburgh and University of Pittsburgh Medical Center.

SHARMA LAB NEUROMUSCULAR CONTROL AND ROBOTICS | SWANSON ENGINEERING
Multi-modality Biomedical Ultrasound Imaging (Kim) Lab

Introduction

- **Spinal cord injuries** (SCI) or **stroke** result in impaired limb functions and mobility disorders.
- **Hybrid exoskeleton**: a wearable robotics device for function restoration via **functional electrical stimulation** (FES) + **electrical motors.**
  - **FES** activates the paralyzed or paretic muscles. Users gain training and therapeutic benefits. However, **quick onset of muscle fatigue** due to non-physiological muscle recruitment limits the FES applications.
  - **Electrical motors** provide more **predictable torque** to assist the movements. **Less stimulation** is required due to a shared workload with the electrical motors and FES-induced muscle fatigue can be **maintained in a desired range**.
- Modeling of the human-in-the-loop wearable robotics system considers:
  - the **electromechanical delay** of the muscle's torque response to a stimulation input;
  - switched activations in each **agonist-antagonist muscle pair** to actuate joint movements in both directions;
  - formulation of a **hybrid dynamical system to integrate two control modes** that activates in turns.
- Stability analysis via a **multiple Lyapunov functional** (MLF) approach

Control Design and Experiments

Block diagram of the control design and the hybrid dynamical system model

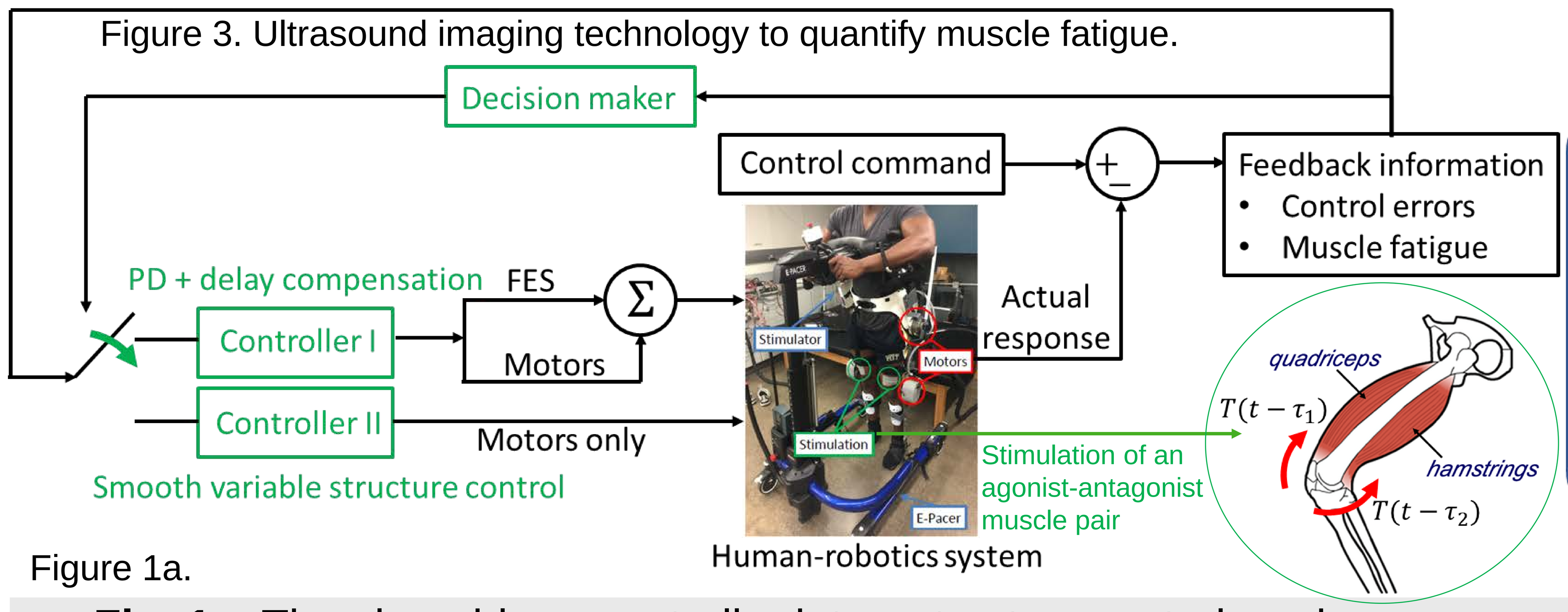


Figure 1a.

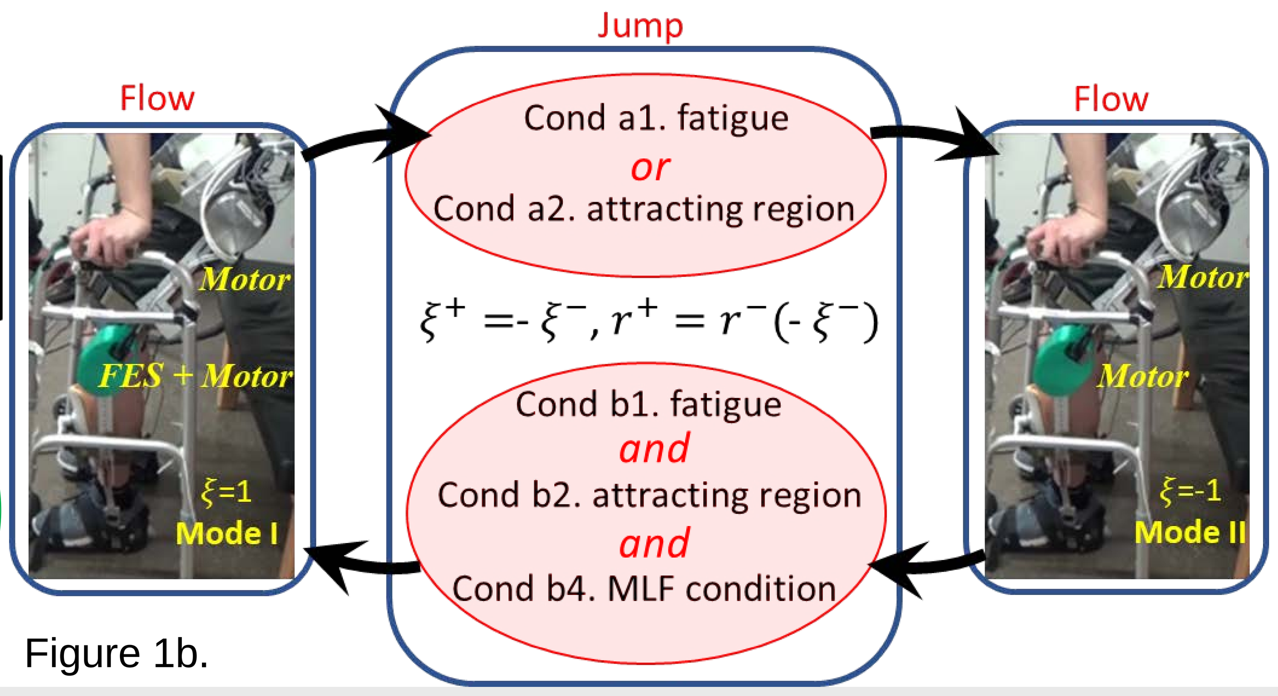


Figure 1b.

- **Fig. 1a**: The closed-loop controller integrates two control modes:
  - (I. non-fatigued) a **PD-based robust controller** with **delay compensation vectors** to control **FES + electrical motors;**
  - (II. fatigued) a smooth **variable structure controller** (VSC) to control **electrical motors**.
- **Fig. 1b**: Switches between control mode I and II follows the flows and jumps of the **hybrid dynamical system model**.

Control of a hybrid exoskeleton that integrates FES and electrical motors

Figure 2. sit-to-stand experiments.

- A **sit-to-stand** task assisted by the hybrid exoskeleton.
- Online trajectory planning based on **virtual constraints from a normal sit-to-stand profile.**

Conclusions: Results of the Stability Analysis and Experiments

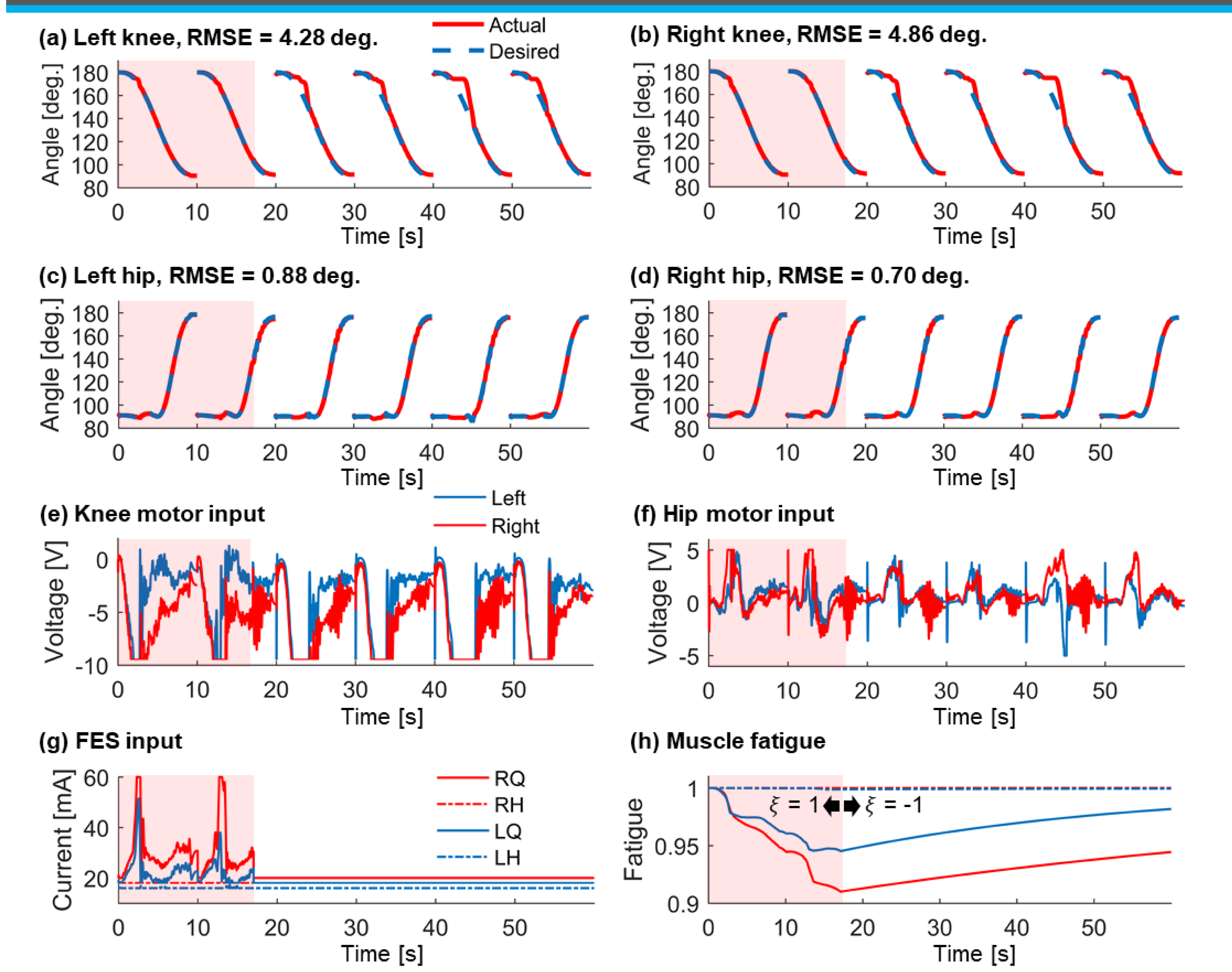


Figure 3. Performance of the hybrid exoskeleton during **repeated sit-to-stand** experiments. $\xi = 1$ (shadowed region) indicates that FES inputs are active while $\xi = -1$ indicates that there is no FES contribution. (Muscles are at rest and recovering toward a pre-fatigue stage.)

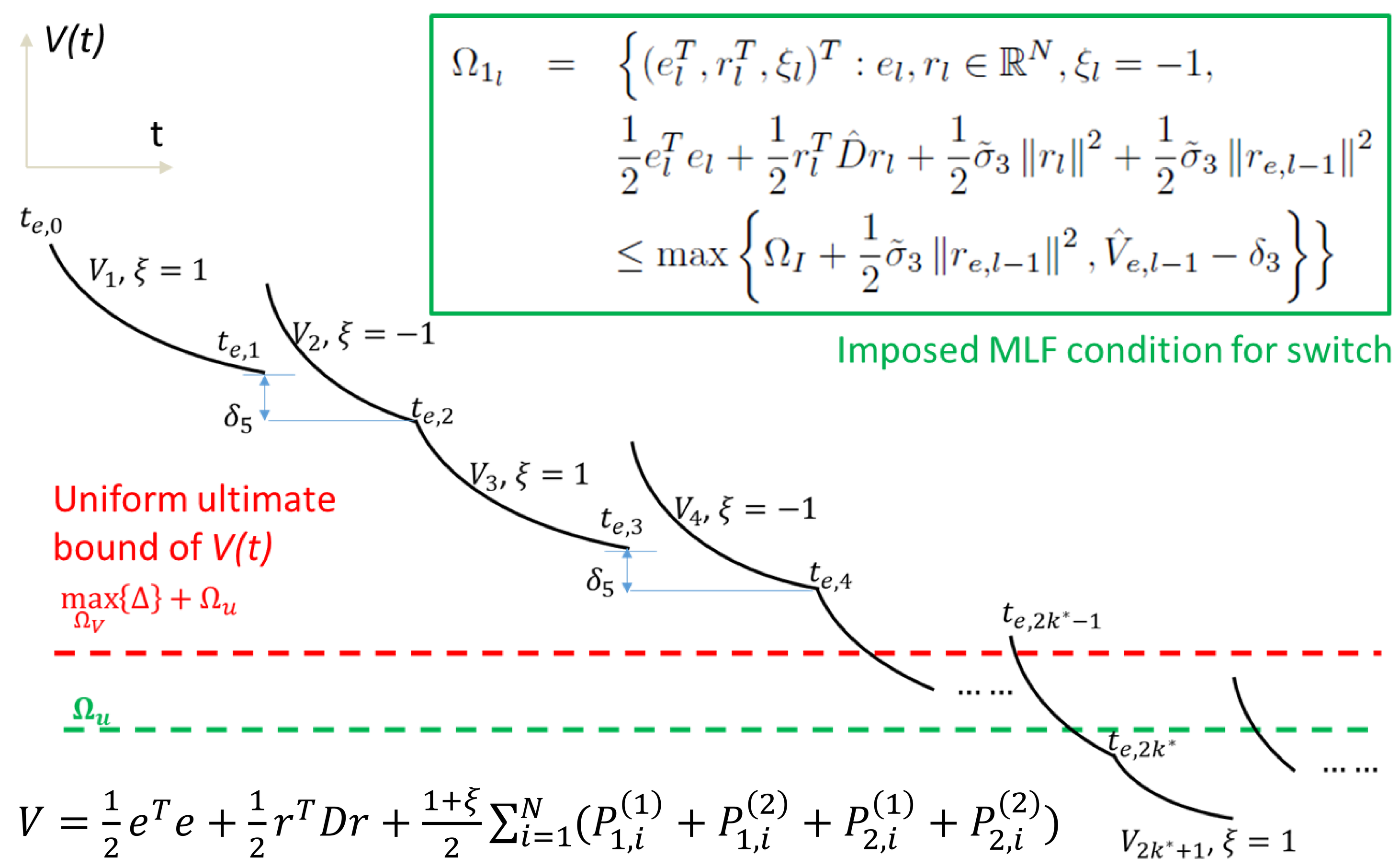
- **Stability results:**
  - mode I: **Semi-globally uniformly ultimately bounded** (*s. G. U. U. B*)

$$V(t) \le V_0 e^{-\frac{\lambda_3}{\lambda_2}t} + \frac{\lambda_2 \Psi^2}{4\lambda_3 K_2}\left(1 - e^{-\frac{\lambda_3}{\lambda_2}t}\right)$$

  - mode II: ***s. G. U. U. B***

$$V(t) \le V_0' e^{-\frac{\lambda_4}{\lambda_2}t} + \frac{\lambda_2 \Psi''}{\lambda_4}\left(1 - e^{-\frac{\lambda_4}{\lambda_2}t}\right)$$

  - $y = \left(e^T, r^T, \mu^{(1)^T}, \mu^{(2)^T}, \xi\right)^T$, the state vector of the hybrid dynamical system model, converges to a set **in finite time**, if the switches satisfy the MLF condition



- **Control accuracy** of the hybrid exoskeleton in a sit-to-stand task:
  - knee joints **RMSE < 5.00°.**
  - hip joints **RMSE < 1.00°.**
- Muscle fatigue was maintained in a desired range by intermittently activating two control modes. The decision making of activating either of the control mode depends on:
  - pre-defined fatigue and recovery thresholds;
  - attracting regions of control mode I and II;
  - Imposed MLF stability conditions.