Velocity error damping admittance control **increased** the **force transparency** of our **upper-limb rehabilitation exoskeleton.**

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Comparison of Admittance Control Dynamic Models for Transparent Free-Motion Human-Robot Interaction

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Objective: Investigate transparent physical human-robot interaction (pHRI) force environments for BLUE SABINO, a robot for stroke rehabilitation and assessment of the upper limb, to facilitate accurate and precise patient evaluation.

Problem: External forces can disrupt natural motor control, hindering assessment accuracy and patient engagement.

Approach: Tested four admittance control modes on a five-degree-of-freedom arm exoskeleton: Low-Mass, High-Mass, Velocity-Damping, and Velocity-Error-Damping.

Experiments:

- High-Repetition Motion (20 repetitions of reach-and-return at 3 tempos to a single target)
- Low-Repetition-Distributed Motions (2 repetitions of reach-and-return to 13 different targets).

Evaluation: Admittance control modes compared for vibration transparency, naturalness of motion, and user work.

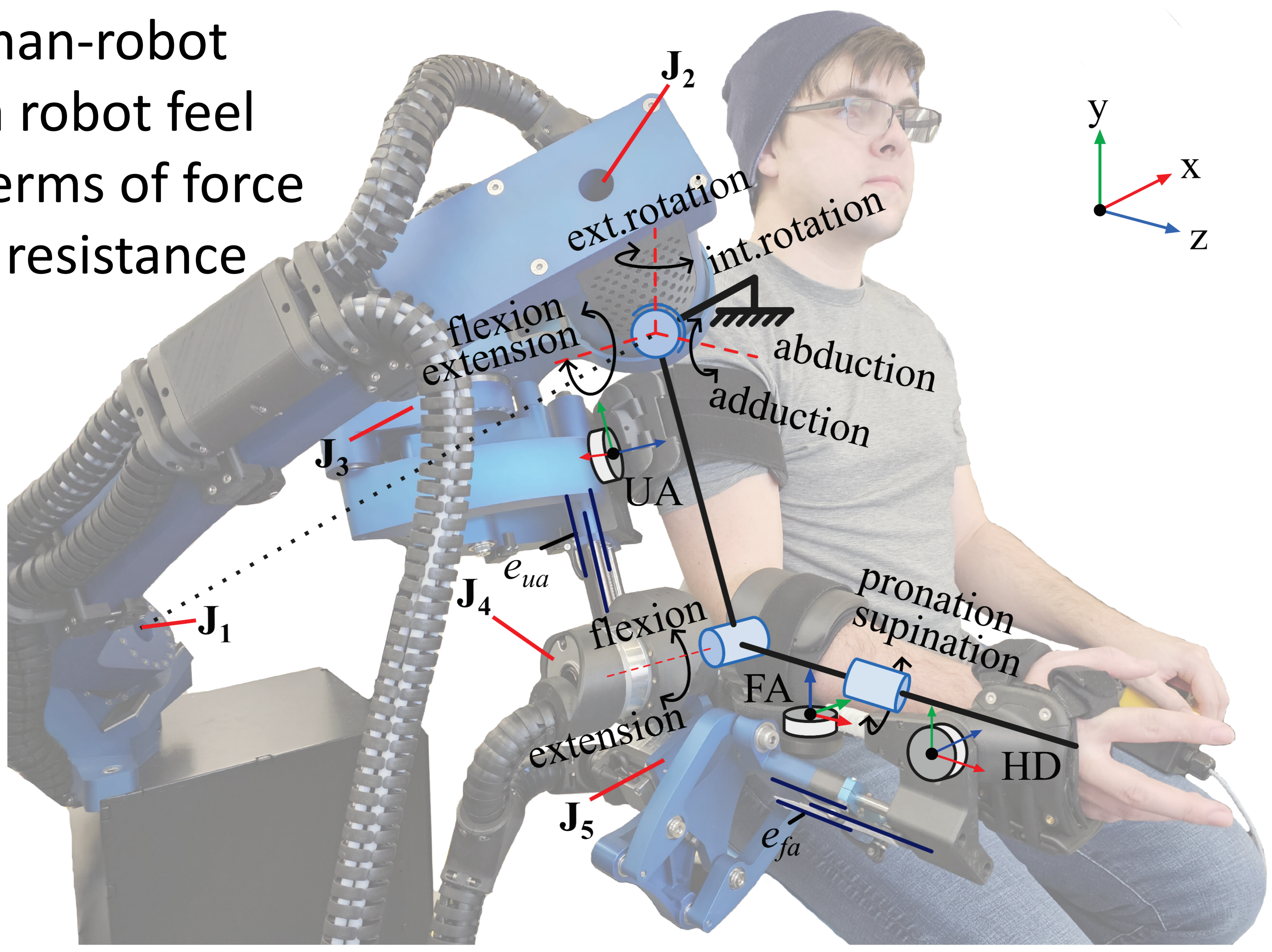
Findings:

- Velocity-Error-Damping mode is the most transparent, requiring 23.8% less user effort than High-Mass and reducing vibration power by 70% compared to Low-Mass.
- Alternate modes have *task-specific advantages*: Low-mass mode improves target accuracy and reduces effort for low-speed motions.

Future Research: Explore variable admittance control, expand studies to more healthy and impaired subjects, and investigate real-time mode transitions to align with task goals.

"A ***transparent*** human-robot interaction makes a robot feel nearly invisible in terms of force when assistance or resistance isn't needed"

Bi-
Lateral
Upper-Limb
Exoskeleton for
Simultaneous
Assessment of
Biomechanical and
Neuromuscular
Output



The BLUE SABINO Exoskeleton. The 5-DOF kinematic structure includes three actuators ($J_{1\text{-}3}$) which allow shoulder rotation, one (J_4) for elbow rotation, and one (J_5) for forearm pronation/supination.

Control Design

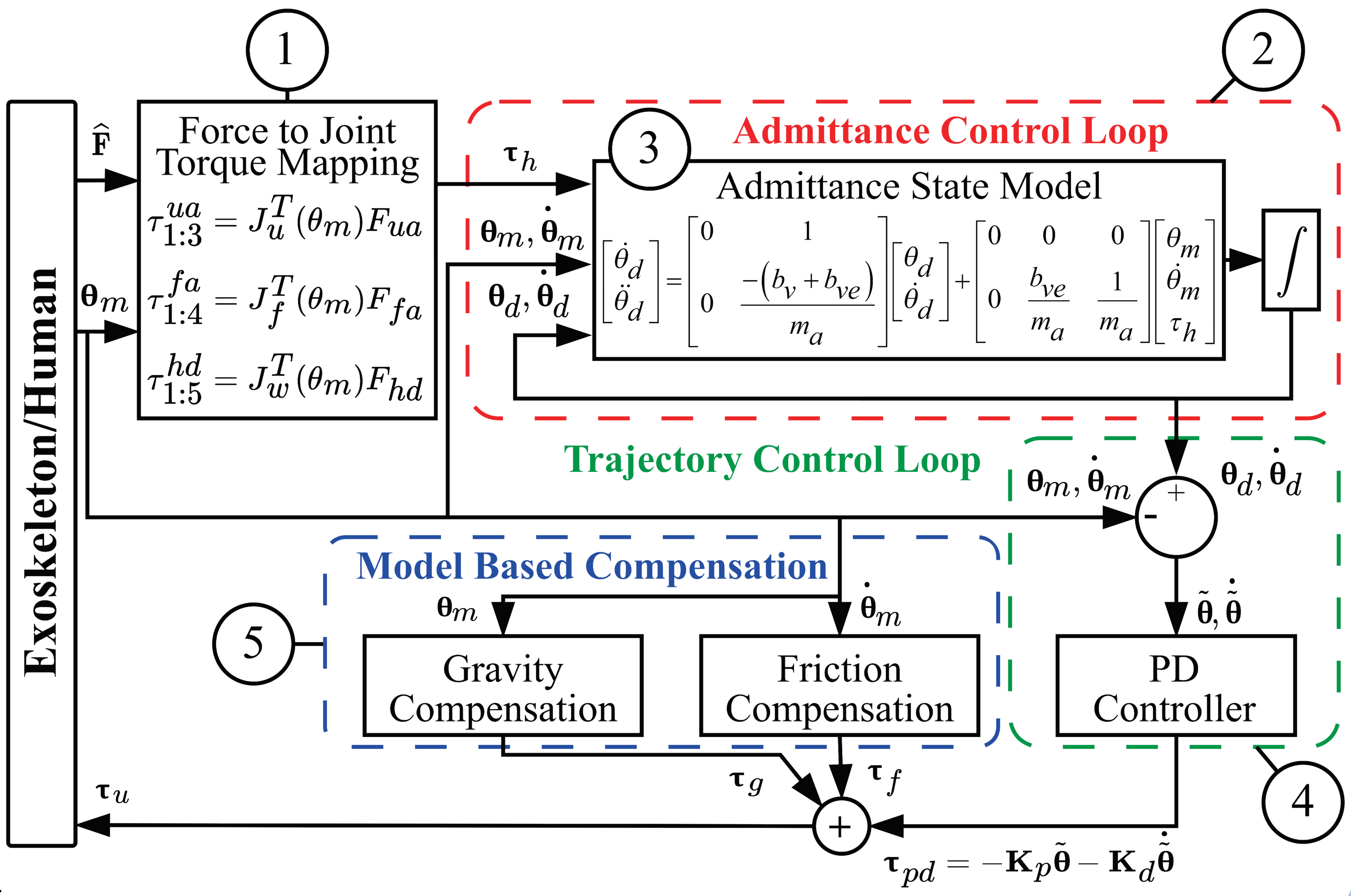
Overview

1. User-applied forces are converted to human joint torques, $\boldsymbol{\tau}_h$.
2. Admittance-control loop uses $\boldsymbol{\tau}_h$ to set target states.
3. Joint-level admittance model includes inertia, $\boldsymbol{m}_a$ velocity damping, $\boldsymbol{b}_v$, and velocity error damping, $\boldsymbol{b}_{ve}$ (Table 1).
4. Trajectory control loop computes proportional-derivative (PD) admittance-state-tracking control torques, $\boldsymbol{\tau}_{PD}$.
5. Model-based compensation for friction, and gravity, are added to the control torques, $\boldsymbol{\tau}_u$.

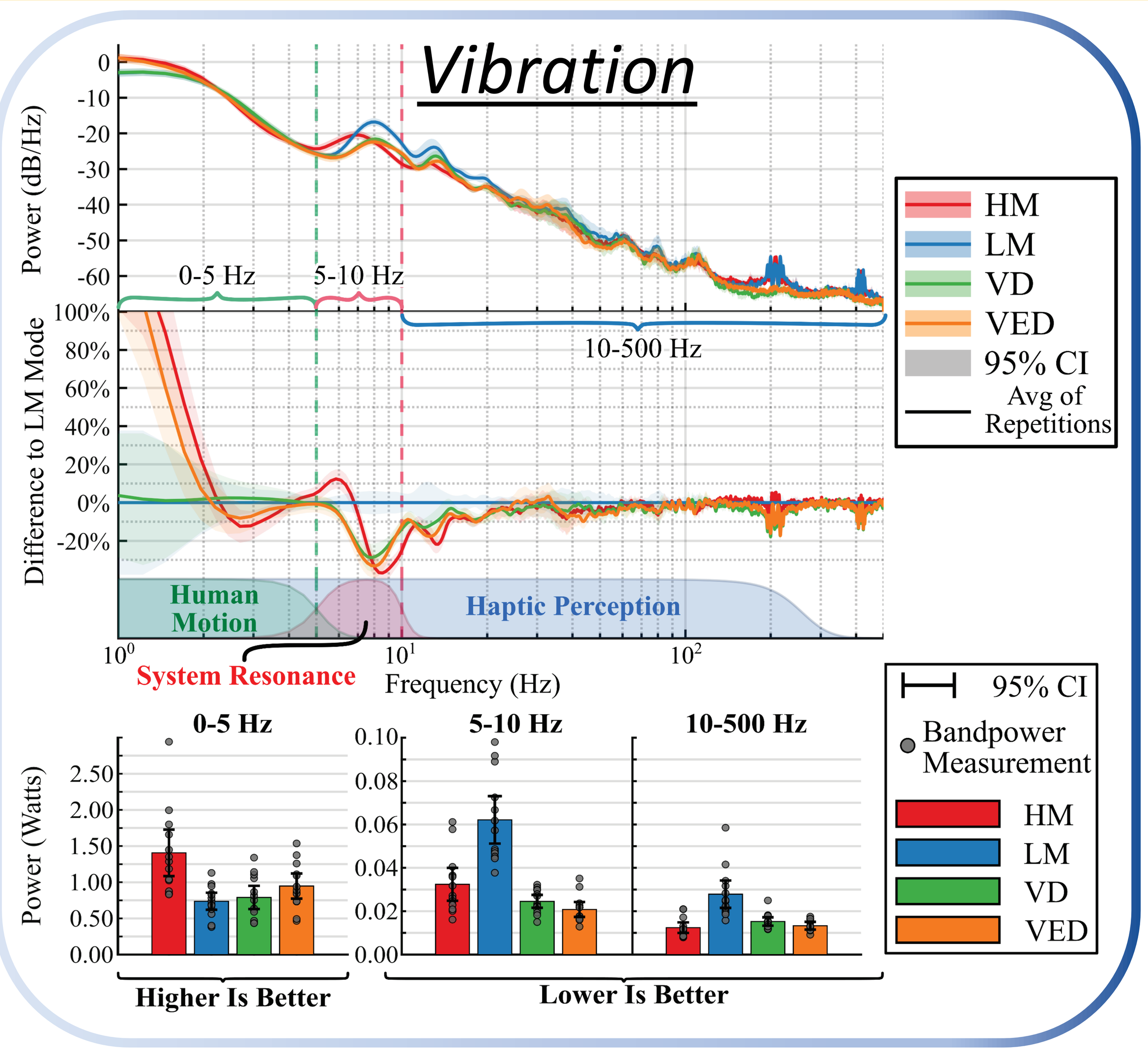
TABLE 1. ADMITTANCE PARAMETERS

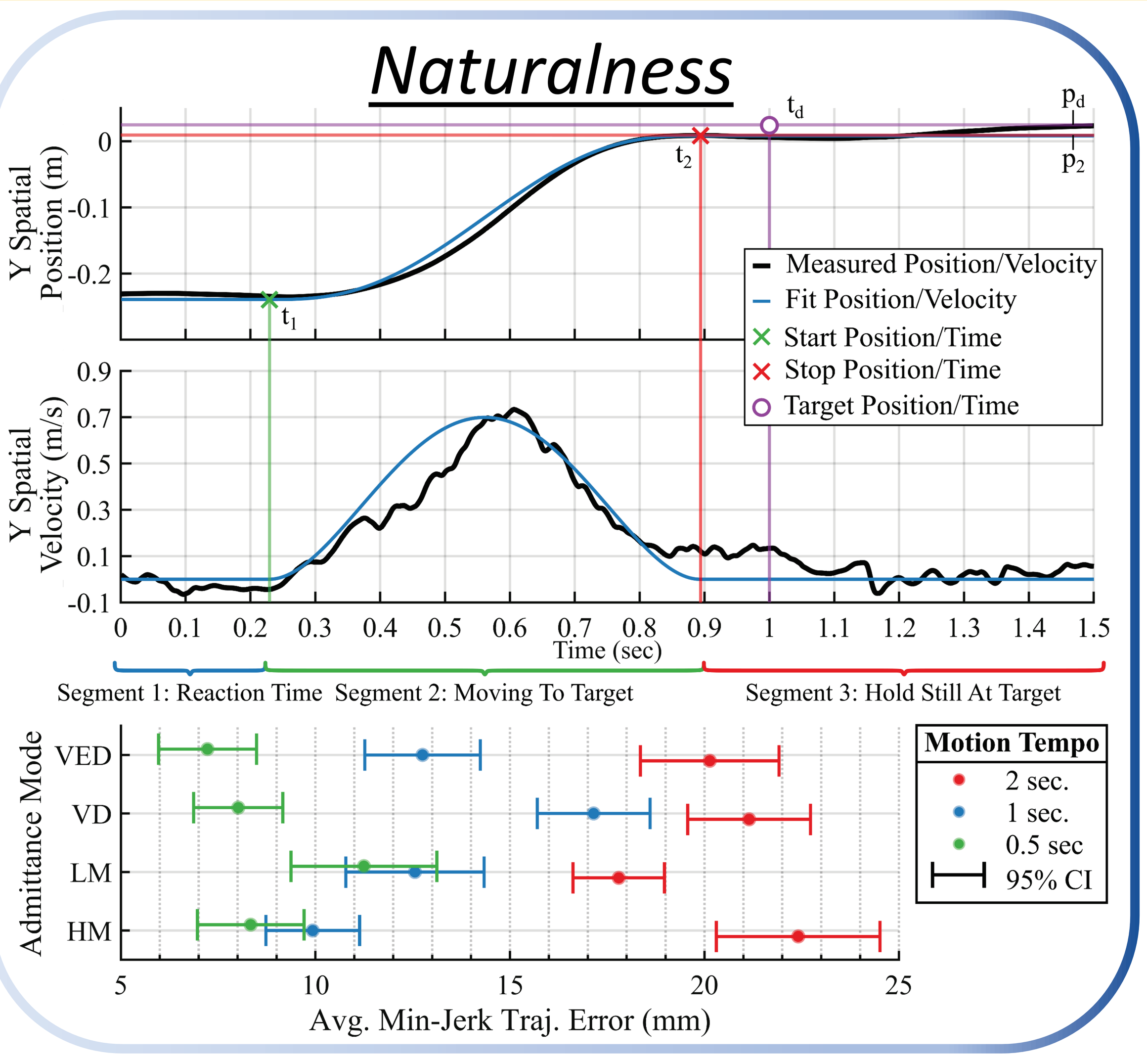
Mode	Abbr.	Term[a]	Unit	Joint J_1	J_2	J_3	J_4	J_5
High-Mass	*HM*	$\mathbf{m}_a$	kg·m	1.2	1.2	0.6	0.6	0.6
Low-Mass	*LM*	$\mathbf{m}_a$	kg·m	0.6	0.6	0.3	0.1	0.01
Velocity-Damping	*VD*	$\mathbf{m}_a$	kg·m	0.6	0.6	0.3	0.1	0.01
		$\mathbf{b}_v$	kg·m/s	5	5	3	3	0.5
Velocity-Error-Damping	*VED*	$\mathbf{m}_a$	kg·m	0.6	0.6	0.3	0.1	0.01
		$\mathbf{b}_{ve}$	kg·m/s	15	15	9	9	1.5
All Modes[b]		$\mathbf{K}_p$	N·m/rad	4000	4000	3000	3000	320
		$\mathbf{K}_d$	N·m·s/rad	200	200	40	40	1

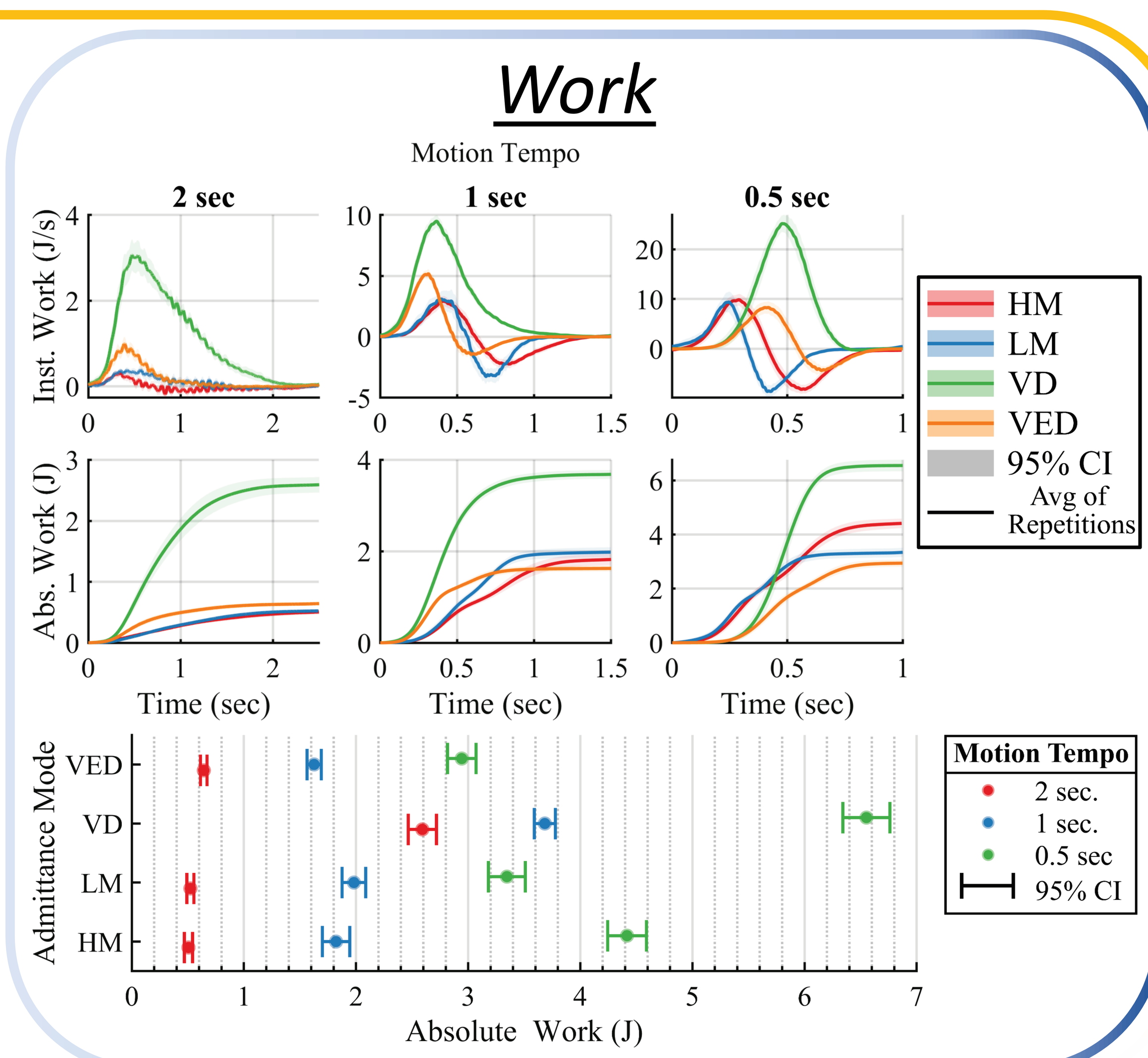
a. Terms not listed for a mode are set to 0.
b. $\mathbf{K}_p$ and $\mathbf{K}_d$ are set to the same values for all modes.



Results







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