A New Simulation Framework for the Design of Human–Robot Controllers in Elderly Care

Parsa Jafarian[1] Mostafa Kaviri[1] Wael Suleiman[2] Guillaume Durandau[1]

Motivation

- Physical human–robot interaction (pHRI) helps older adults live independently [1].
- Typical task: a robot and an older adult jointly carry a heavy object via admittance/impedance control [2].
- Tremor is a major safety concern: naively following tremor-induced motion can be unsafe [3].

Open Challenges

- Most HRI research relies on physical experiments, limiting scale and accessibility.
- Robot simulators (MuJoCo [4], Gazebo [5], PyBullet [6]) and biomechanics platforms (OpenSim [7]) remain separate – no coupled human–robot dynamics.
- Existing work targets general HRI, not elderly-specific tremor mitigation.

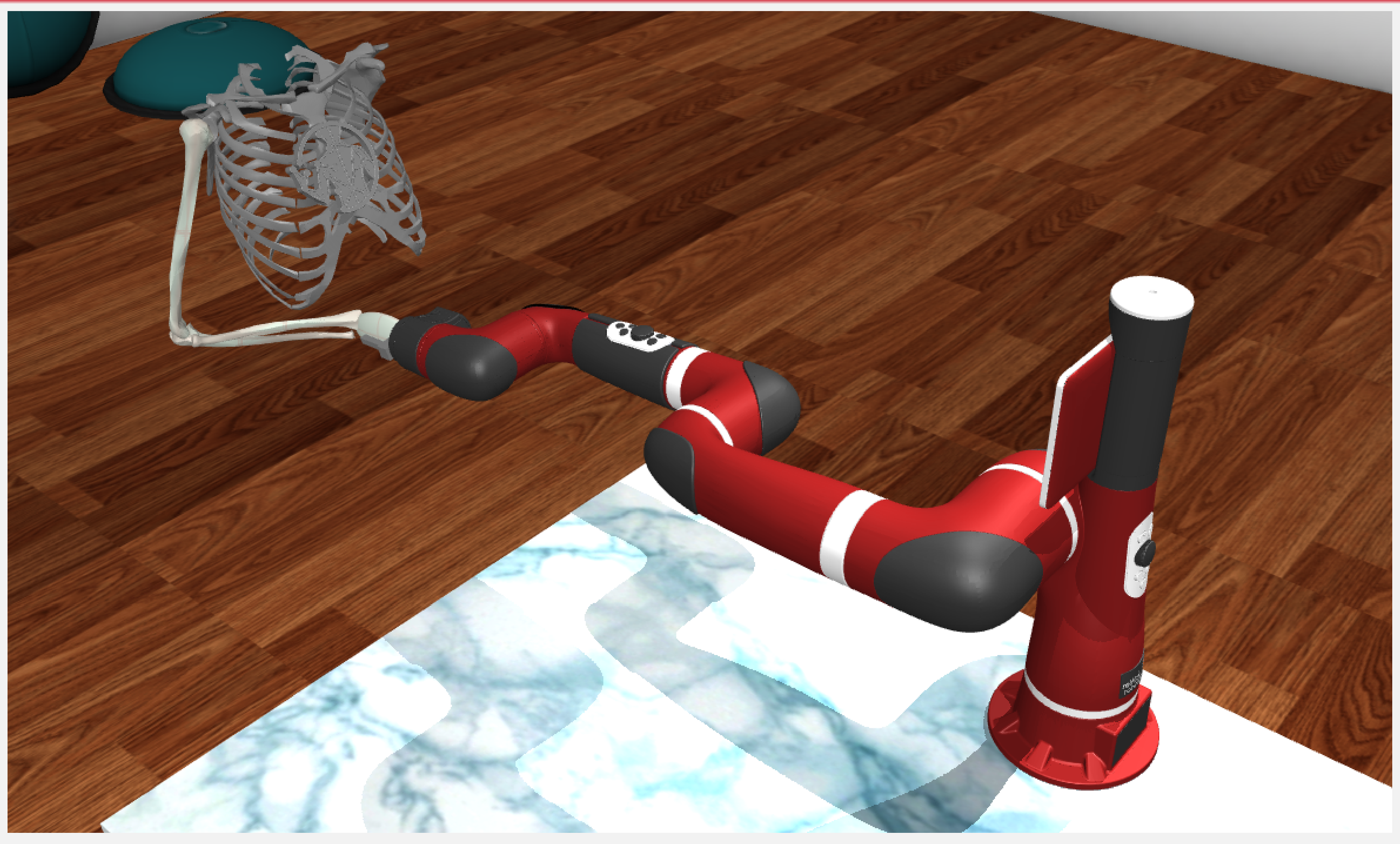
Our Approach

- Accessible HRI framework: **MyoSuite** [8] musculoskeletal MyoArm + **Rethink Sawyer** robot in **MuJoCo** [4].
- A **series admittance–impedance controller** [9] for flexible tremor mitigation on Sawyer's torque-based actuators.
- Sawyer (7 DoF): joint angles $\mathbf{q} \in \mathbb{R}^7$; end-effector position $\mathbf{x} \in \mathbb{R}^3$.
- Total force $\mathbf{F}_{\text{ext}} = \mathbf{F}_h + \mathbf{F}_l$: intent $\mathbf{F}_h$ + object load $\mathbf{F}_l = mg(0,0,-1)^\top$ ($m = 5\,\text{kg}$).
- $\mathbf{F}_h$ (load subtracted) drives the controller; $\Delta t = 2\,\text{ms}$.

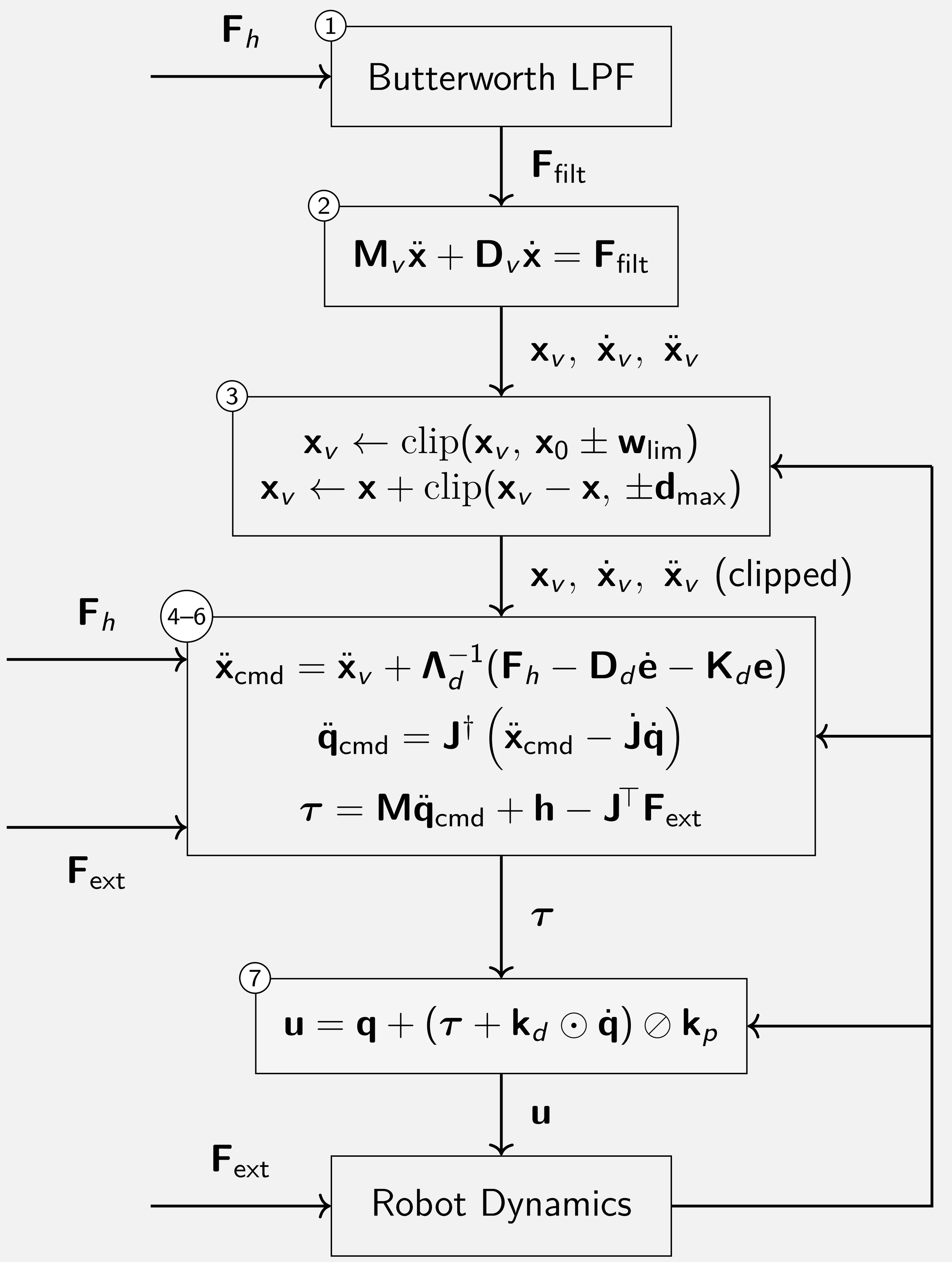
Code & simulation environment

github.com/NeuRoC-Lab/HRI-controller

Simulation Setup



Admittance–Impedance Controller



1. Butterworth filter. A 2nd-order Butterworth LPF [10] ($f_c = 2\,\text{Hz}$, $\Delta t = 2\,\text{ms}$) filters $\mathbf{F}_h$: cutoff $\omega_n = f_c/(0.5/\Delta t) = 0.008$, response $|H(f)| = (1 + (f/f_c)^4)^{-1/2}$, attenuating 9 Hz tremor [3] to $|H(9)| \approx 0.02$ ($-34\,\text{dB}$, $\sim$2% residual).

2. Admittance. $\mathbf{F}_{\text{filt}}$ maps to virtual target $\mathbf{x}_v$ via admittance [2] ($\mathbf{M}_v = 1.5\mathbf{I}_3$, $\mathbf{D}_v = 8\mathbf{I}_3$), discretized by semi-implicit Euler [11].

3. Stability clipping. $\mathbf{x}_v$ is clipped element-wise: workspace $\mathbf{w}_{\text{lim}} = 0.6(1,1,1)^\top$ m about $\mathbf{x}_0$; divergence limit $d_{\max} = 5/40\,\text{cm}$ (intent/passive) from $\mathbf{x}$.

4–6. Impedance tracking. Tracking error $\mathbf{e} = \mathbf{x} - \mathbf{x}_v$ drives desired dynamics ($\mathbf{\Lambda}_d = 2\mathbf{I}_3$, $\mathbf{D}_d = 30\mathbf{I}_3$, $K_d = 150/500\,\text{N/m}$ intent/passive) into a commanded acceleration, mapped to joint space via the damped pseudoinverse [12]

$$\mathbf{J}^\dagger = \mathbf{M}^{-1}\mathbf{J}^\top\left(\mathbf{J}\mathbf{M}^{-1}\mathbf{J}^\top + \lambda^2\mathbf{I}\right)^{-1}, \quad \lambda = 0.05, \tag{1}$$

then to joint torques via inverse dynamics ($\mathbf{M}$: inertia; $\mathbf{h}$: Coriolis/centrifugal/gravity).

7. Actuator mapping. $\mathbf{u} \in \mathbb{R}^7$ inverts Sawyer's joint PD servos ($\mathbf{k}_p, \mathbf{k}_d \in \mathbb{R}^7$: per-joint gains).

Force profiles & metric. Ramp $f_{\text{ramp}}(t) = \text{clip}(1.5t, 0, 12)$ or sinusoid $f_{\sin}(t) = 5\sin(\pi t)$ intent, plus 9 Hz tremor and onset ramp: $\mathbf{F}_h(t) = o(t)\big(\mathbf{f}(t) + \boldsymbol{\epsilon}(t)\big) \odot \mathbf{m}(t)$. 14 configs (single/double/triple-axis X/Y/Z); RMSE normalized by the virtual target's peak-to-peak range:

$$\text{RMSE}_i = \frac{\sqrt{\frac{1}{N}\sum_{t=1}^{N}\left(x_i^{(t)} - x_{v,i}^{(t)}\right)^2}}{\max_t x_{v,i} - \min_t x_{v,i}} \times 100\%. \tag{2}$$

Results

Axis	Ramp RMSE (%)	Sinusoidal RMSE (%)
X	5.9	8.3
Y	6.9	4.0
Z	3.8	7.5
X / Y	5.8 / 5.5	5.7 / 5.2
X / Z	4.3 / 6.4	5.3 / 6.0
Y / Z	8.8 / 14.2	6.8 / 7.8
X / Y / Z	9.3 / 9.5 / 8.8	6.2 / 4.3 / 5.3

$\sim$**98% tremor attenuation** | 4–14% **RMSE across all 14 configurations**

Discussion

- Single-axis tracking reaches 4–9% RMSE; multi-axis configurations are similar.
- Worst case: YZ ramp, Z axis (14.2%) – combined Y+Z intent and Z load exposes feedforward error at $K_d = 150\,\text{N/m}$.
- Ramp and sinusoidal inputs are comparable except XYZ (ramp $\sim$9% vs. sinusoid $\sim$5%).

Conclusion & Future Work

- First MuJoCo-based HRI framework coupling a musculoskeletal arm and a torque-controlled robot for elderly tremor mitigation.
- Controller achieves 4–14% RMSE tracking with $\sim$98% tremor attenuation across 14 configurations; interaction forces emerge naturally from physics.
- **Future work:** adaptive/ML parameter tuning, full human–robot coupling, real-world validation.

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[1]NeuRoC Lab, McGill University & Feil & Oberfeld CRIR – Jewish Rehabilitation Hospital Research Center. [2]Université de Sherbrooke. Corresponding author: guillaume.durandau@mcgill.ca | Supported by the FRQNT INTER program and an NSERC Discovery Grant.