Adaptive Torque Control of Exoskeletons under Spasticity Conditions via Reinforcement Learning

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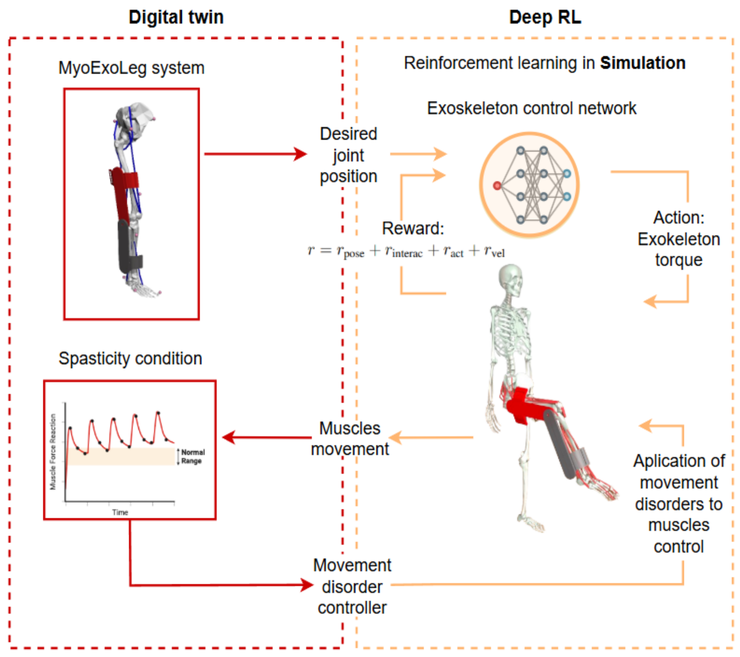
1. MOTIVATION AND OBJECTIVE

Spasticity is a neurological impairment consequence of an upper motor neuron syndrome defined by James Lance in 1980 as "a motor disorder characterized by a velocity-dependent increase in tonic stretch reflexes with exaggerated tendon jerks, resulting from hyperexcitability of the stretch reflex" [1].

Wearable robots (WRs). The use of WRs under spasticity conditions has shown that intensive early rehabilitation, revealing intrasession changes in muscle resistance in elbows and limb joints [2].

Torque control of WRs with RL. Market-available solutions are primarily PID open-loop driven [3]. RL controllers are capable to **interact with the environment and learning from it** [4].

- **Adaptative WRs with RL**. The aim of the study is develop an adaptative RL torque controller which employs a **single agent** and compare it to a classical control method optimized for a single spasticity level.
- **Ensuring safety**. The primary goal of WRs in movement disorders is **not performance** but to ensure safety, reducing undesired interaction forces.



2. SPASTIC DIGITAL TWIN

- **Realistic MS-Exo coupling.** With **4 DoF**, 1 for Exo knee joint and 3 DoF simulating a soft coupling with straps.
- **Spasticity levels.** Based on the **Modified Asworth Scale (MAS)** with a **joint range** and **velocity** dependency.

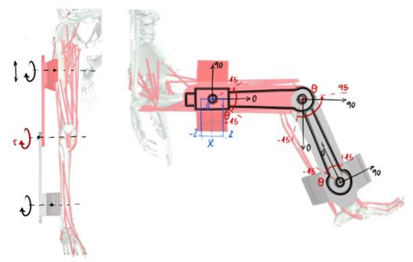


TABLE I
SPASTICITY LEVELS AND CORRESPONDING PARAMETERS

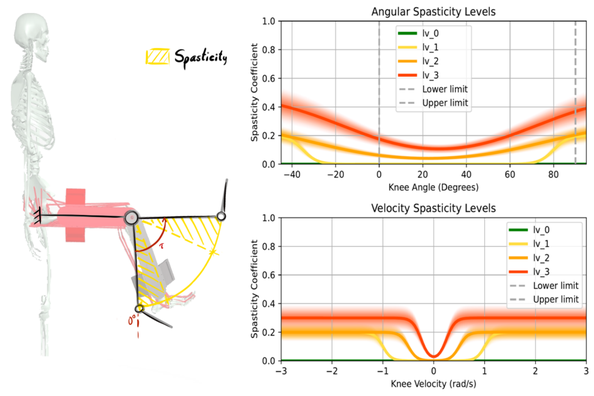
Lv	Muscular activation range limits	Activation coefficient
0	Knee joint range: [-45, 95]° Velocity limit: [-10, 10] rad/s	Angular Spasticity: 0 Velocity Spasticity: 0
1	Knee joint range: [-35, 80]° Velocity limit: [-1, 1] rad/s	Angular Spasticity: 0.2 Velocity Spasticity: 0.2
2	Knee joint range: [-30, 75]° Velocity limit: [-0.5, 0.5] rad/s	Angular Spasticity: 0.3 Velocity Spasticity: 0.3
3	Knee joint range: [-15, 60]° Velocity limit: [-0.25, 0.25] rad/s	Angular Spasticity: 0.3 Velocity Spasticity: 0.5
4	Not Implemented	

$$SC_{total} = sc_{angular}(\theta) + sc_{velocity}(v) \quad (1)$$

$$\phi(k, \beta, \beta_0) = \frac{1}{1 + e^{k(\beta - \beta_0)}} \quad (2)$$

$$sc_a(\theta) = S_{\theta Max}\left[1 - \left(\phi(k_{ang}, \theta, \theta_{flexion}) - \phi(k_{ang}, \theta, \theta_{extension})\right)\right] \quad (3)$$

$$sc_v(v) = S_{vMax}\left[1 - \left(\phi(k_{vel}, v, v_{lower}) - \phi(k_{vel}, v, v_{upper})\right)\right] \quad (4)$$



- **Spasticity coefficient** (SC). Normalized measure of the **percentage of maximum isometric force** generated by each muscle. Implemented in **11 muscles** involved in knee joint flexion-extension movement.
- **Individual subjects.** To ensure the robustness of the model we introduce intersubject variability by introducing **Gaussian noise** with a standard deviation of **10%** in equations (3) and (4).

3. SIMULATION SETUP AND RL LEARNED BEHAVIOURS

- **Experimental procedure. Knee extension** begins at a 90º knee flexion position up until a total knee extension rotation of 83º to avoid the risk of knee hyperextension.
- **Soft Actor Critic (SAC)** trained for 50M steps = 10,000 full knee extensions.
- **Reward function** :

$$r = r_{pose} + r_{inter} + r_{vel} + r_{act} \quad (5)$$

  - Learning to reach a specific angular joint position.

$$r_{pose} = \exp\left(-\frac{e_{pose}}{2\sigma^2}\right) - \|e_{pose}\| \quad (6)$$

  - Reducing undesired Human-Exo interaction forces.

$$r_{inter} = \begin{cases} \left\|\nabla_{exo_{torque}}\right\|^2, & if\ \tau_{exo_{torque}} \leq \tau_{threshold} \\ \left\|\nabla_{exo_{torque}}\right\|^2 + \tau^2_{exo_{torque}}, & if\ \tau_{exo_{torque}} > \tau_{threshold} \end{cases} \quad (7)$$

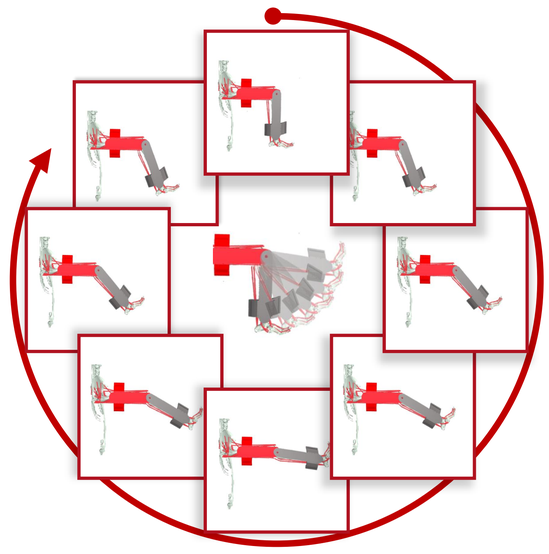
  - Minimizing joint velocity.

$$r_{vel} = \left\|\nabla_{knee_{vel}}\right\|^2 \quad (8)$$

  - Ensuring smooth Exo actuation (user comfort)

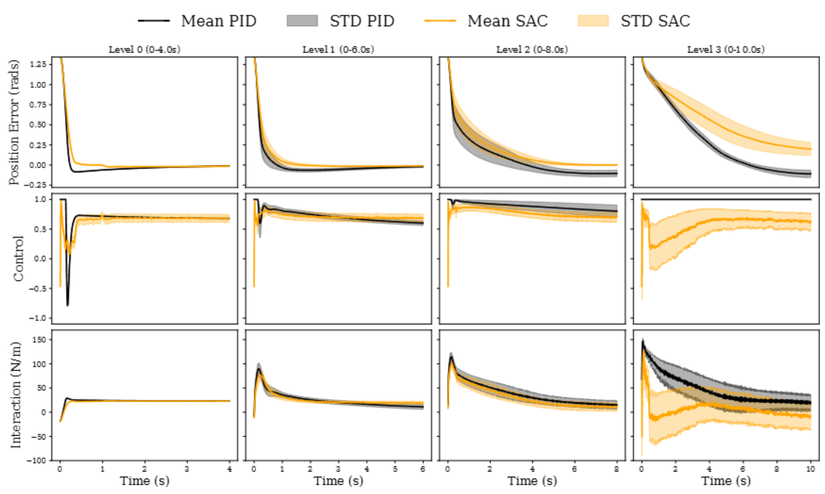
$$r_{act} = \left\|\nabla_{exo_{control}}\right\|^2 \quad (9)$$

- **Environment Observations.** Learning from for joint **positions, velocities** and **torques**. No EMG or information about muscles activation.
- **Environment Action**: Knee exoskeleton **torque**.



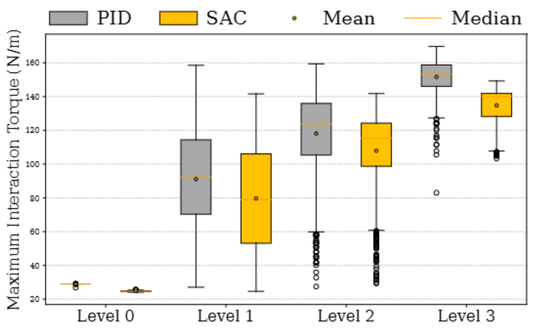
4. RESULTS

SAC / PID torque controller comparison

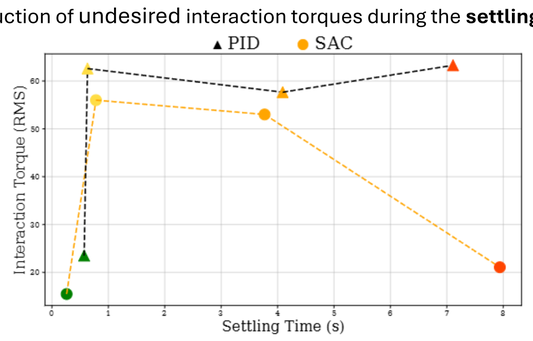


Interaction torque analysis

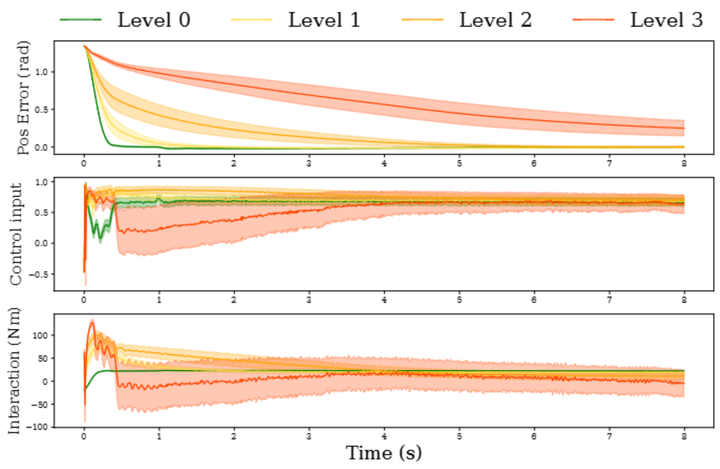
Reduction of the **maximum force applied**



Reduction of undesired interaction torques during the **settling interval**



SAC learned behaviours over spasticity levels



5. DISCUSSION

Spastic Digital twin

- **Soft coupling Human-Exo system** that accounts for joint misalignments and relative human-exoskeleton displacements due to soft tissues.
- **Spasticity differentiable model** with 4 different levels of spasticity based on a Spasticity Coefficient and a Gaussian Noise randomization.

Adaptive RL WR torque controller

Improved compliant control of spasticity compared to a standard PID torque controller in an environment that presents motor disorders and muscle position-velocity changing dynamics.

- **Reducing maximum torques** applied to the human knee joint under spastic conditions by an average of **10.6%** .
- **Faster and reduced effort. Decreasing the root mean square** (RMS) of the torque until the settling time by **8.9%**. The **settling time** in these cases shows **reductions at levels 0 and 2** and similar values at level 1.
- **User safety over task performance**. Particularly noticeable in level 3, where the SAC controller prioritized not achieving the target position due to the excessive torque required.

6. FUTURE WORK

- **Physical deployment.** Future deployment in physical exoskeleton systems and eventual application in human trials.
- **Personalized Digital twins.** This approach enables the simulation to capture natural variations observed across individuals, providing a more realistic representation of subject-specific dynamics.
- **Motor disorders.** To address a broader spectrum of motor disorders, such as ataxia and tremor.
- **Complex tasks.** We plan to develop a new controller capable to learn more complex task like gait, running, up stairs...



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[3] A. Rodríguez-Fernández, J. Lobo-Prat, and J. M. Font-Llagunes, "Systematic review on wearable lower-limb exoskeletons for gait training in neuromuscular impairments," *Journal of NeuroEngineering and Rehabilitation*, vol. 18, no. 1, p. 22, Dec. 2021.

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