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A Unified Human-Robot Simulation Enables Modulation of Supraspinatus Muscle Activation

Pierre Schegg[a*], Pierre Puchaud[b], François Bailly[a]

[a] CAMIN, Inria, Univ Montpellier, Montpellier, France
[b] AUCTUS, Inria, Bordeaux, France
* Corresponding author: pierre.schegg@inria.fr

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1. Introduction

Orthopedic rehabilitation can benefit from using robotic devices, however, current robot-assisted physiotherapy methods (e.g. exoskeletons) often only implement impedance control or gravity compensation and do not explicitly include biomechanical information in their control systems (Dalla Gasperina et al., 2021). This abstract presents an automated approach that adjusts the robot's controls to modulate the maximum level of muscle activity with a single parameter $\boldsymbol{R}$, applied to a rotator cuff tendon rehabilitation scenario. Using a unified framework co-simulating a musculoskeletal (MSK) model of the shoulder and elbow and a collaborative robotic arm, we solve an optimal control problem to define assistive robot torque trajectories that achieve a targeted level of muscle activations along a predefined trajectory.

2. Methods

We used an upper limb MSK model from (Bailly et al., 2021) with 3 shoulder (glenohumeral) and 1 elbow rotational degrees of freedom (DoF), incorporating 19 muscles and the Unified Robot Description Format of a 7-DoF Kuka iiwa robot to combine them in a unified format with biobuddy (Charbonneau et al., 2025) and enable their mutual simulation in Bioptim (Michaud et al., 2022), a Python numerical optimal control package for biomechanics. The combined model is displayed in Figure 1a.

In the simulation, both the robot and the human state and control variables are part of a single trajectory optimization problem. This provides a bidirectional sensitivity between the robot and human decision variables (positions, velocities, torques or muscles). As such, constraints and objectives set on the MSK model influence the robot's control law and state, and vice versa. The interaction between the human and the robot was modeled using holonomic constraints (Docquier et al., 2013), transmitting forces between the wrist and robot end-effector.

We prescribed an elliptical trajectory (70 cm × 35 cm) in a plane rotated 30° from the sagittal plane about the anteroposterior axis, which spanned a large part of the combined robot and MSK model workspace, and naturally resulted in maximal Supraspinatus muscle activation during 48% of the trajectory in a simulation without robotic assistance. The simulated movement lasted 1 second and was optimized using direct collocation with 40 intervals. We assume that a human is not able to isolate and control the activation of the Supraspinatus alone, as such we grouped its activation with its synergists involved in the humerus elevation in the sagittal plane: Pectoralis Major clavicular (PMc) and Deltoid Anterior (DA).

The objective function is comprised of two main terms: minimizing the robot joint torques (weight $w_\tau = 1$) and minimizing the humerus elevator muscles' activation (weight w_{he}, applied to Supraspinatus, PMc and DA).

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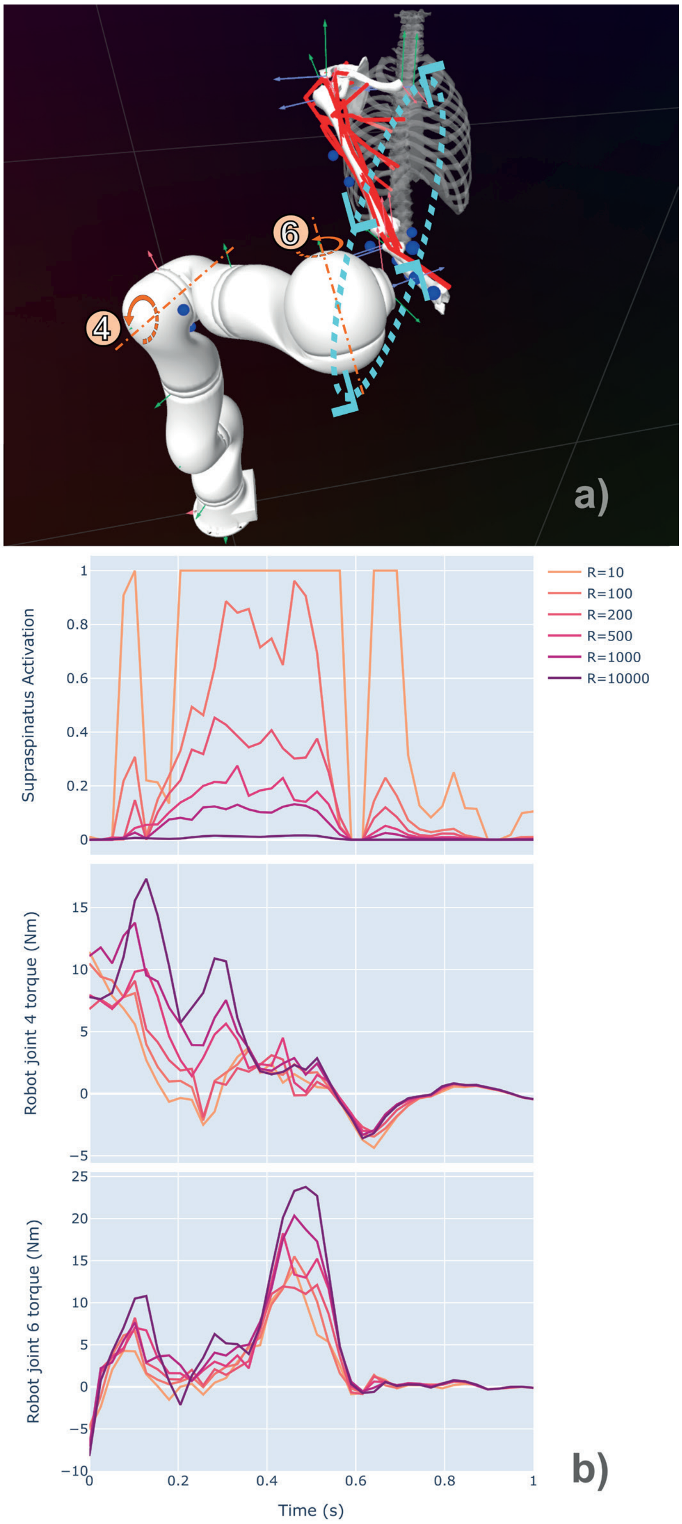

Figure 1. a) Combined MSK and robot model configuration at the tenth interval of the simulation. Prescribed trajectory is represented in blue. b) Supraspinatus activation and robot joint torques (4th and 6th axes) along the trajectory, comparison of six R parameter values.

Their relative importance is tuned by the parameter $\boldsymbol{R}$, defined as $w_{he} \triangleq \boldsymbol{R} \times w_{\tau}$, so that larger values of $\boldsymbol{R}$ correspond to greater assistance (more muscle activation reduction). The three remaining terms track the trajectory, minimize the robot joint velocities and minimize the 16 other muscle activations.

Six simulations are performed with R={10, 100, 200, 500, 1000, 10000}.

Table 1. Six R parameter values and corresponding Supraspinatus Maximum Activation.

Parameter R	Supraspinatus Maximum Activation
10	1.0
100	0.96
200	0.47
500	0.27
1000	0.13
10000	0.02

3. Results and discussion

Simulation convergence time was 17±2 minutes.

Preliminary results demonstrate that our formulation reliably adapts the robot control law to modulate activation of the three muscles, in particular Supraspinatus. Increasing R yields progressively lower activation and non-trivially redistributes the load across the robot joints depending on the trajectory phases (joint 4 handles the first Suprastinatus activation peak around 0.1s and joint 6 the second around 0.5s). Figure 1b illustrates how Supraspinatus activation and torques at robot joints 4 and 6 co-vary with R; analogous activation patterns were observed for PMc and DA. Robot joints 4 and 6 display the most visible changes along the trajectory when modifying R. The correspondance between the R parameter value and obtained maximum Supraspinatus activation is given in Table 1.

While the elliptical trajectory chosen to illustrate this abstract was designed to span the workspace and strongly activate target muscles, it does not reflect motions typically used in physical therapy. However, modifying the trajectory is straightforward and can be adapted for specific applications.

Additionally, this study is purely simulation-based. As such, we cannot confirm whether the predicted muscle activations accurately reflect those observed in real-world scenarios when applying the robot control laws. Experiments including electromyography measurements are required and planned as future validation work.

4. Conclusions

We demonstrated that a single optimal control program can be used to integrate biomechanics constraints into the computation of a robot's control law in the context of human-robot interaction, exemplified here in rotator cuff tendon rehabilitation.

An extension of this work lies in movement assistance applications (e.g. muscle dystrophy or hemiplegia), where robotic devices could provide individualized support based on a personalized MSK model and optimal control strategies.

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Conflict of Interest Statement

None.

Contributor Roles

PS: Conceptualization, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. PP: Methodology, Software, Writing – review & editing. FB: Conceptualization, Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing.

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