Comparative Study of two Biomechanics Frameworks for Upper Limb Exoskeleton Simulations

12th ECCOMAS Thematic Conference on Multibody Dynamics

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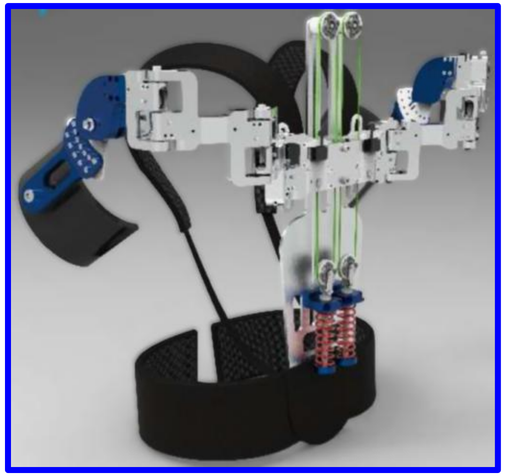
Benjamin Moreno, Valentin Sonneville, Léonore Foguenne,

Cédric Schwartz, Pierre Sacré, Olivier Brüls

Objective

Industrial exoskeleton:

- Purpose:
  Overhead work



Exo4Work
Van der Have 2022

For rehabilitation:

- Purpose:
  shoulder at 90°

Student project
Cottenier,
Hovhannisyan

For a task, predict:

- muscle forces
- excitations
- kinematic trajectories
- exoskeleton actuator inputs

→ **To what extent does the exoskeleton alleviate muscular load?**

Benchmarking example

- **Task**: Small shoulder flexion
  - Given: initial pose, final pose and time range

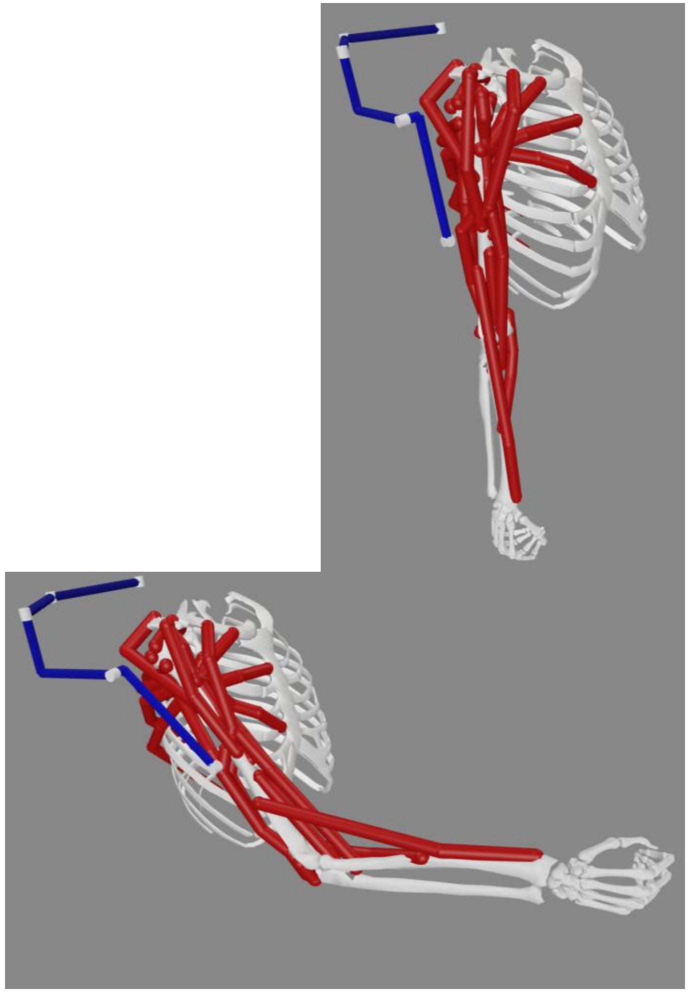
→ Constraints

- **Assumptions**:
  - Human motion minimizes an objective function
  - Ideal controller for exoskeleton that minimizes objective function

→ Optimal control problem

- **Objective function**:

$$\min_{\mathbf{u}} \sum_{k=0}^{N} \left(w_m \sum_{i=1}^{n_m} \left(a_i(t_k) \right)^2 + w_{exo} \sum_{i=1}^{n_u} \left(\tau_i(t_k) \right)^2 \right)$$



Where:

- a: muscle activations
- n_m: number of muscles
- N: number of timesteps
- $\mathbf{u} = (a_i(t_0), \tau_i(t_0) \ldots a_i(t_N), \tau_i(t_N))$
- w: weights
- n_u: number of actuators
- τ: exoskeleton control inputs

Required components

OpenSim {

Musculoskeletal (MSK) model
- Skeletal model
- Muscle model

Model of the exoskeleton
- Closed kinematic loop

↓

OpenSim / Odin {

Formulation of equations of motion

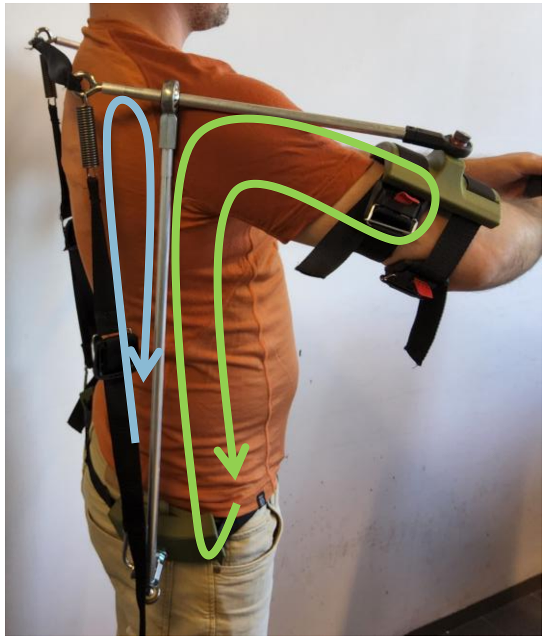
↓

Optimal control problem

↓

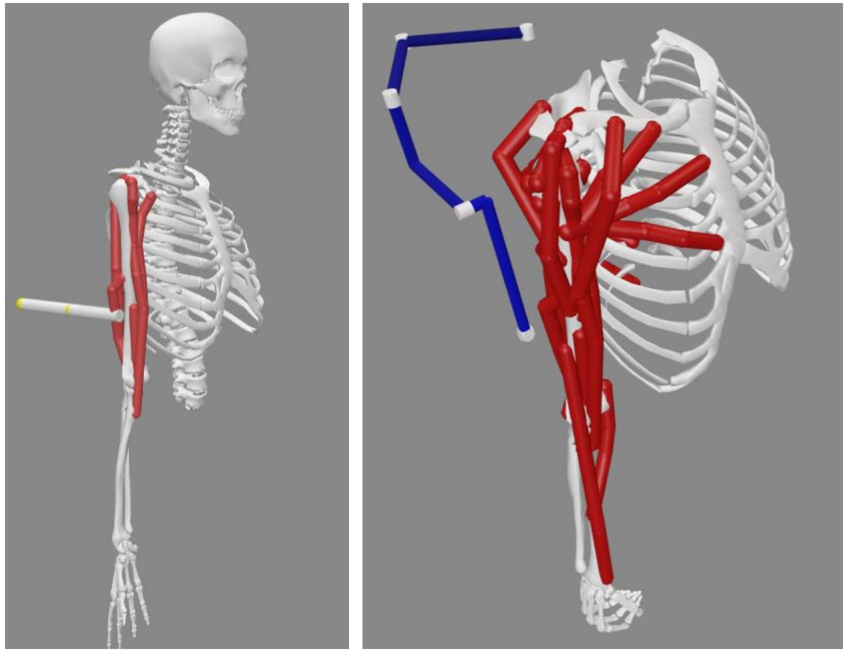
OpenSim {

Post-processing



Many biomechanical tools exist to solve the problem (Roupa 2022).
→ In this work we focus on two software: **OpenSim** and **Odin**

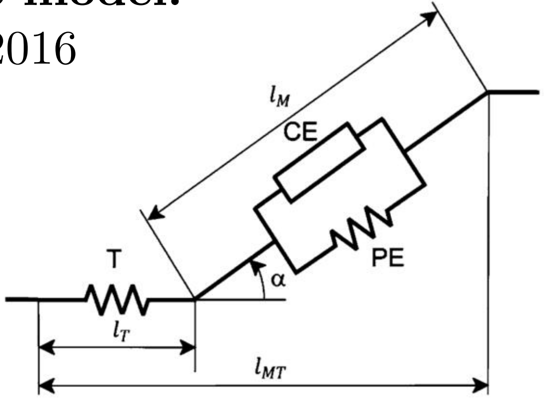
Models



Arm26	MoBL - ARMS
2 DOF, 6 muscles	4 DOF, 24 muscles
• Exo attached to the humerus and the trunk • Actuated slider joint	• Exo attached to the humerus and the trunk • 6 pin joints with the 4^{th} pin joint actuated

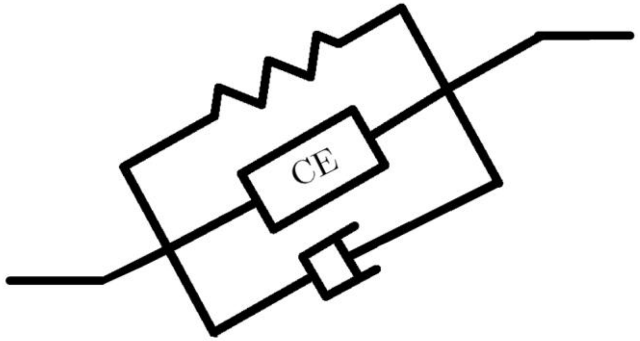
Hill type muscle model:

- DeGroteFregly2016



Current MSK model:

- Rigid tendons
- No activation dynamics
- No wrapping
- No ligaments
- Via points

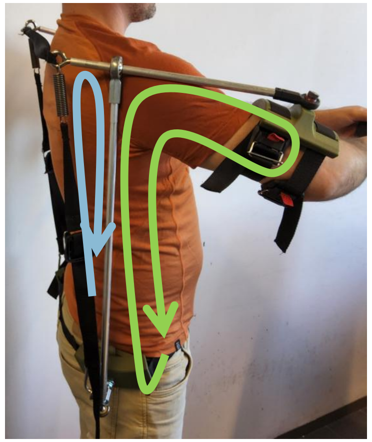


OpenSim:
A specialized toolbox for biomechanics

Code structure

- Oriented for biomechanics:
  - MSK models
  - Tools based on lab measurements

- Recursive formulation
  → closure constraint



Solvers

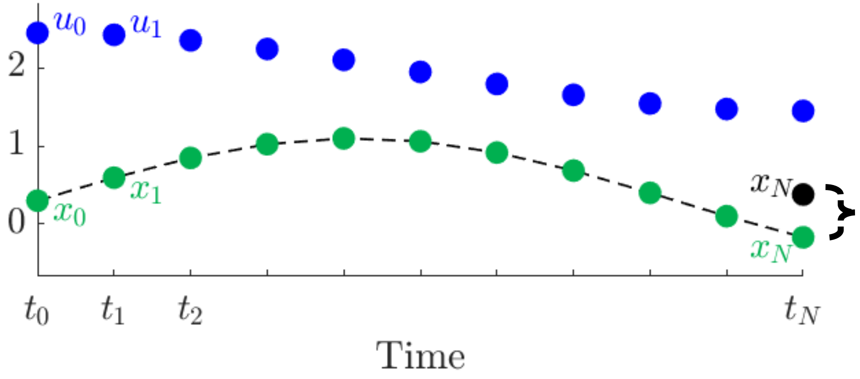
Forward dynamics solver

- Explicit integration

Optimal control with MOCO

- Direct collocation
- IPOPT
- All states and controls added to optimization at each mesh point
- Integration enforced via algebraic constraints

$$\begin{aligned} \min_{\mathbf{u}} \quad & J(\mathbf{u}), \\ \text{s.t.} \quad & \mathbf{x}(t_0) = \mathbf{x}_0, \\ & \mathbf{x}(t_N) = \mathbf{x}_N, \\ & \text{Equations of motion,} \\ & \text{Integration formulae.} \end{aligned}$$



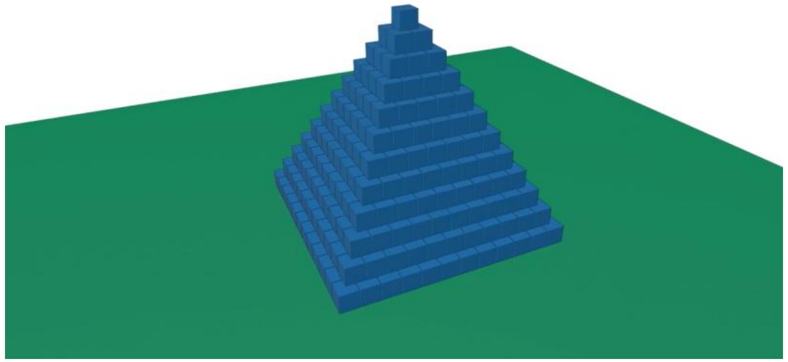
Odin: A multibody framework for complex biomechanical systems?

Code structure

- General multibody software:
  - FEM structure
  - Lie group SE(3)
  - Flexible elements and non-smooth contact available

  → Addition of muscle elements

- Absolute coordinates



Solvers

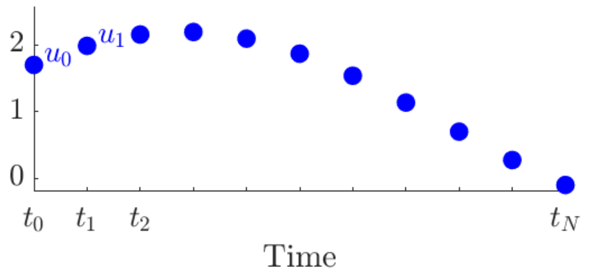
Forward dynamics (FD) solver

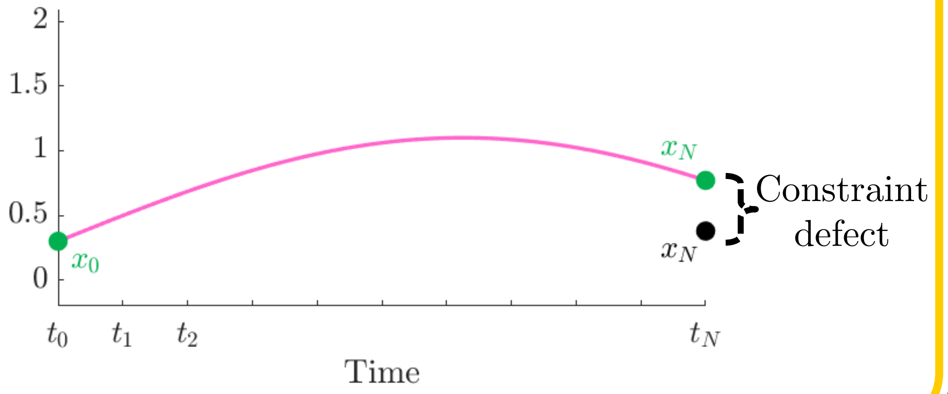
- Implicit generalized-α for DAE

Addition of optimal control capabilities

- Shooting method
- IPOPT
- Only **controls** as optimization variables
- States computed from FD integration

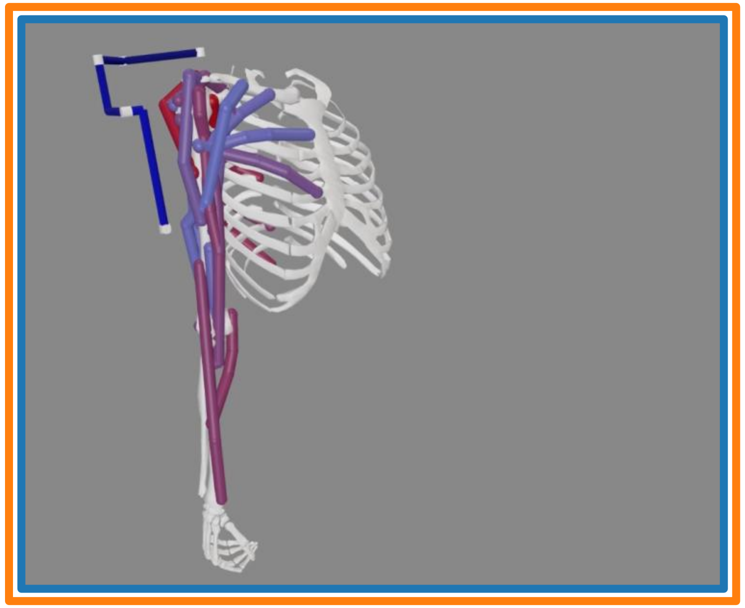
$$\min_{\mathbf{u}} \quad J(\mathbf{u}),$$
$$\text{s.t.} \quad \mathbf{x}(t_0) = \mathbf{x}_0,$$
$$\mathbf{x}(t_N) = \mathbf{x}_N.$$

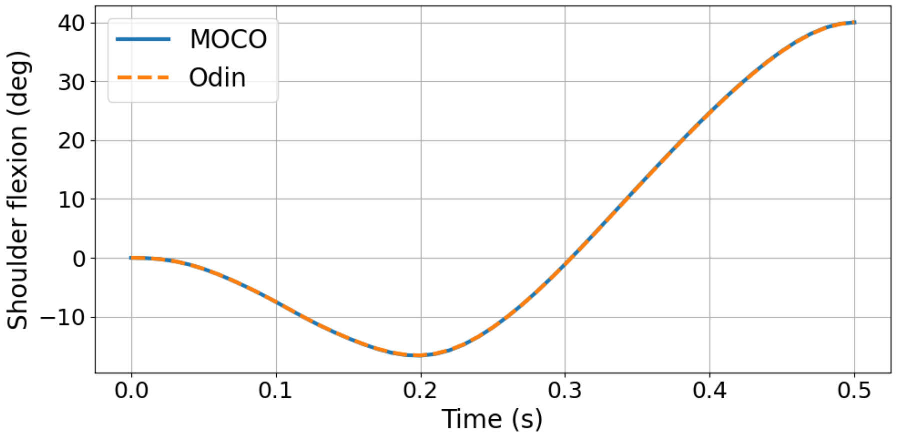


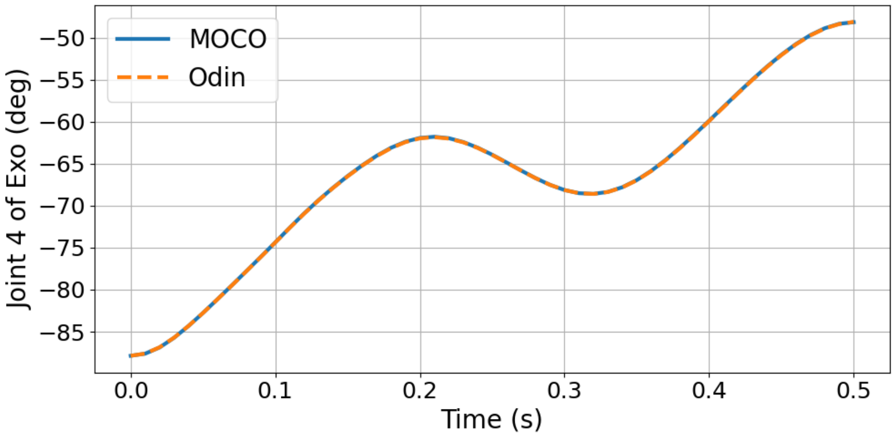


Forward dynamics: Verification

- Control inputs pre-computation:
  - Optimal solution found with **MOCO** for a small shoulder flexion with the exoskeleton.
  - Then applied as given control inputs in **Odin** for the forward simulation.



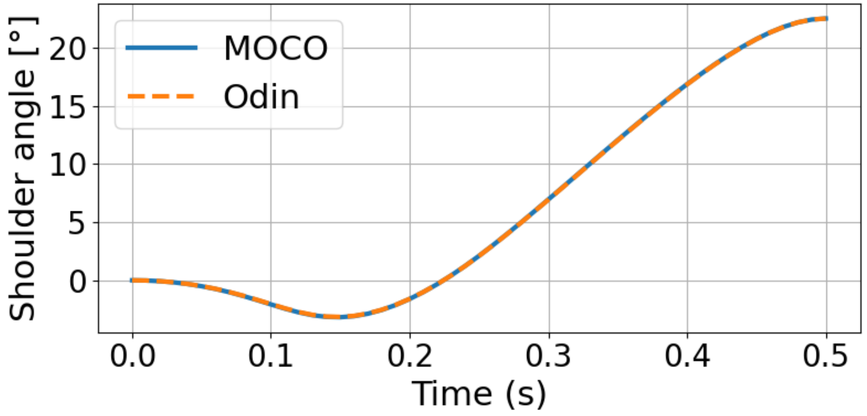


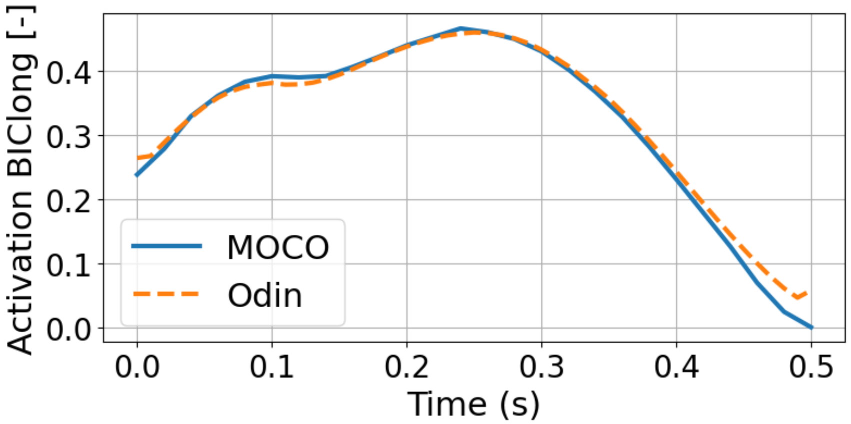


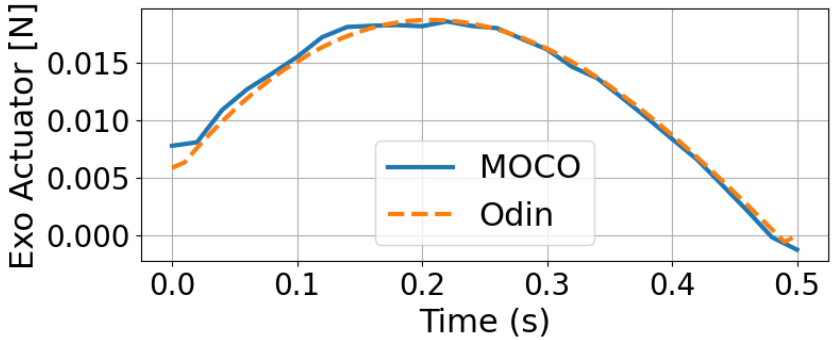
→ **Equivalence between the 2 formulations**

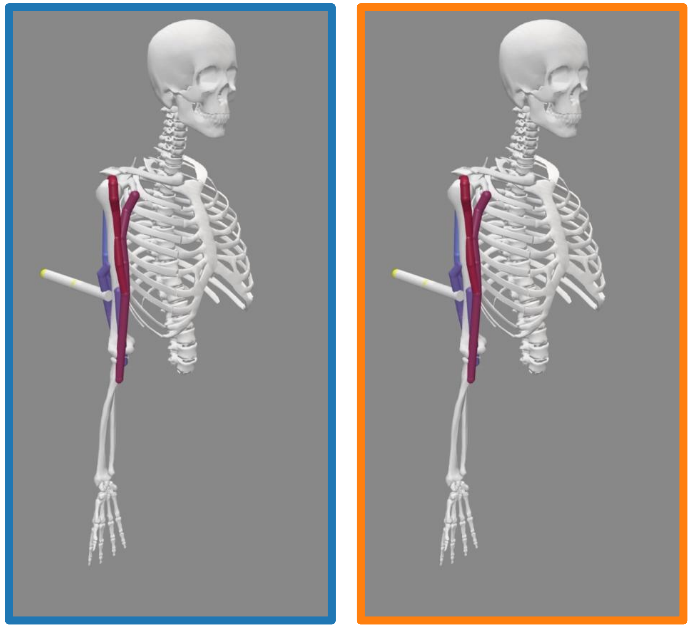
Optimal control: Verification

- Solution from **Odin** as guess in **MOCO**:





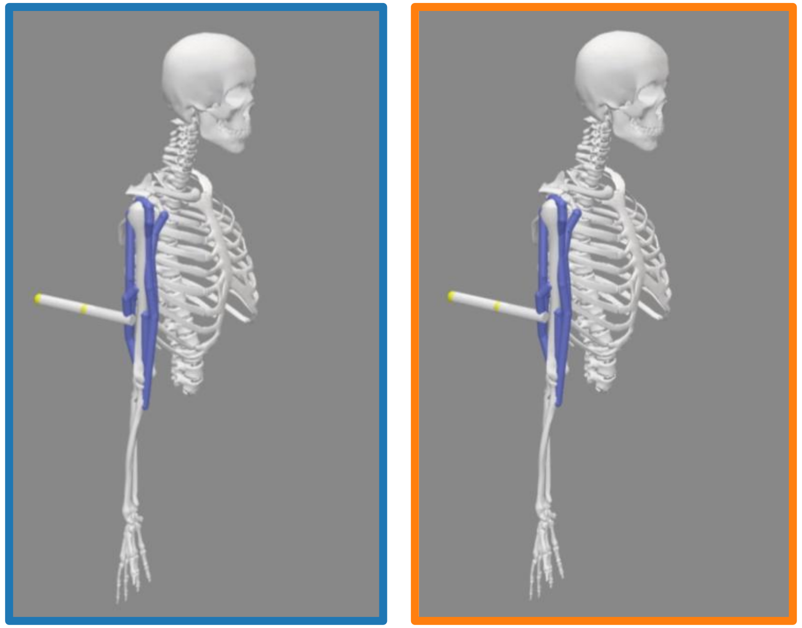


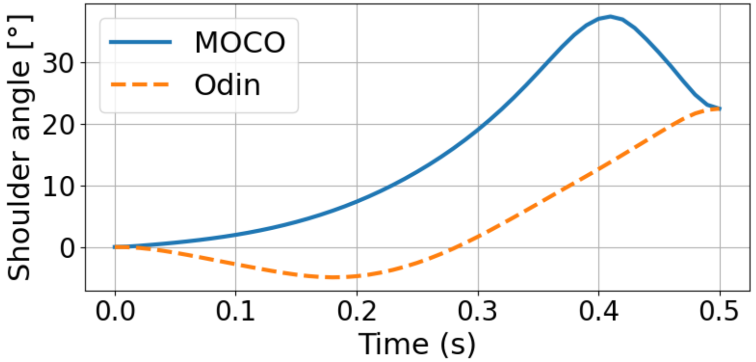


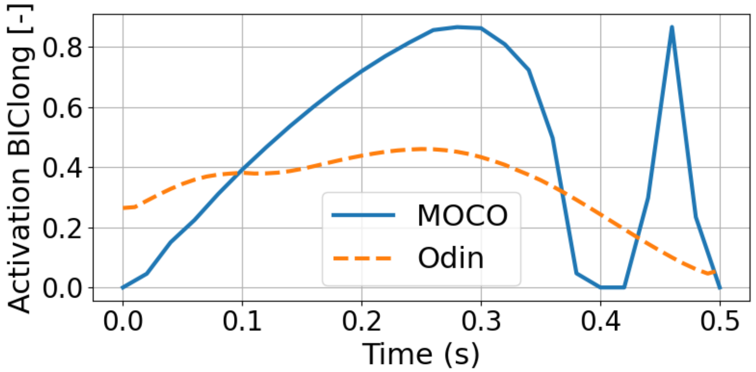
→ **Equivalent definition of the optimal control problem**

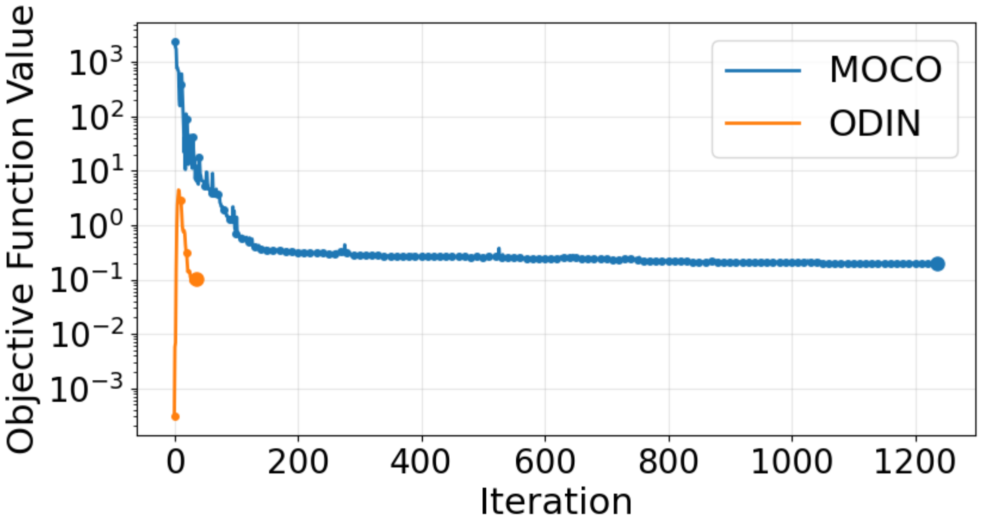
Optimal control solver: Influence of initial guess

- Default initial guesses:



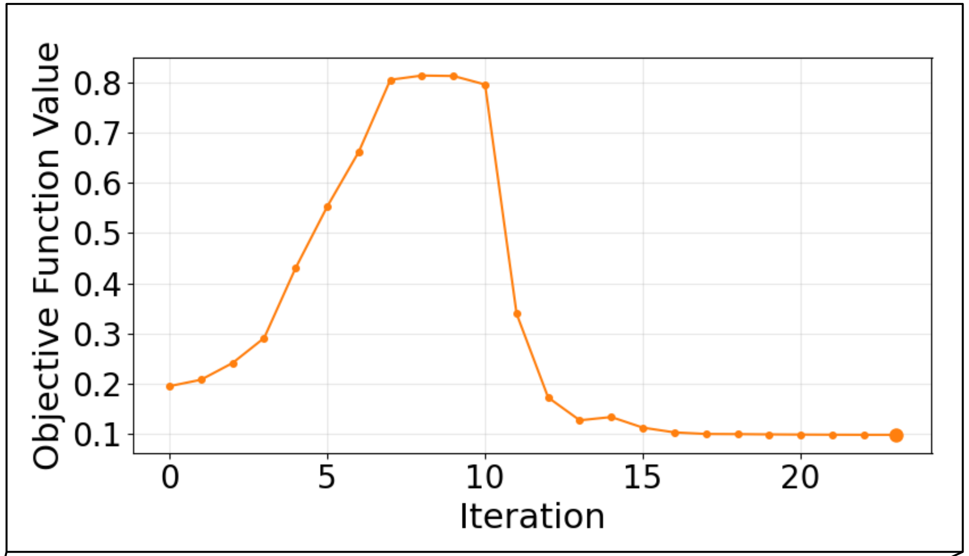


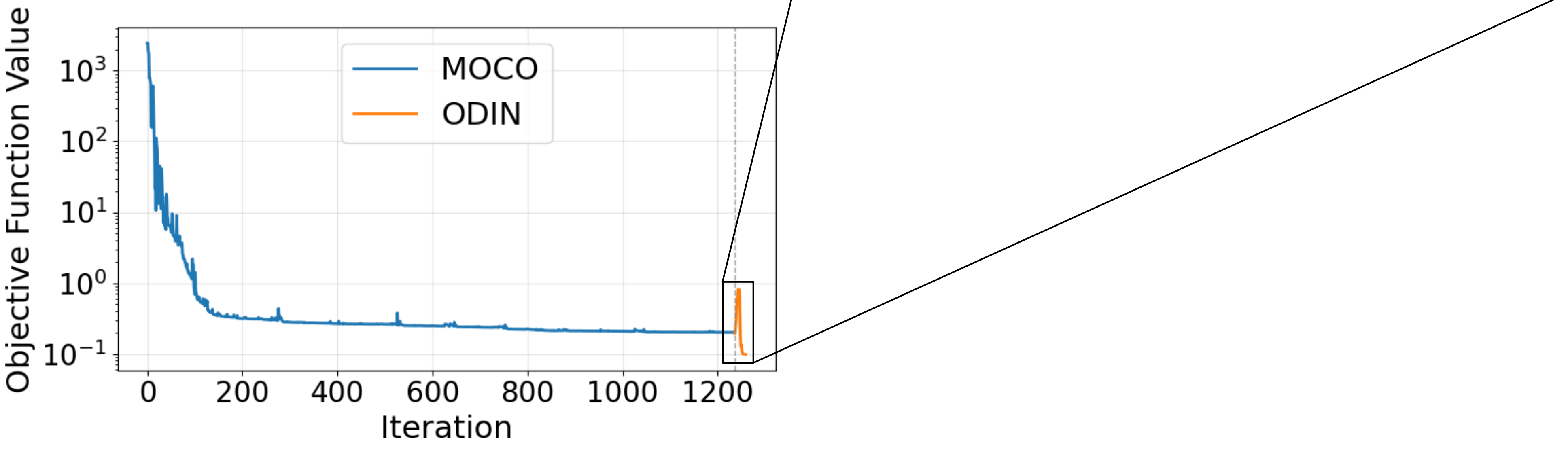


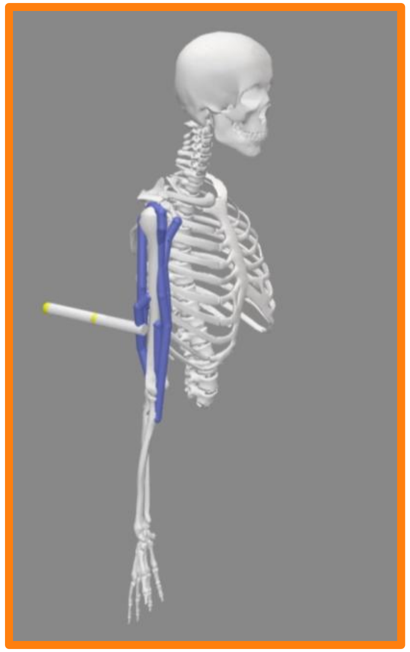


Difference in local minima

- Solution from **MOCO** as guess in **Odin**



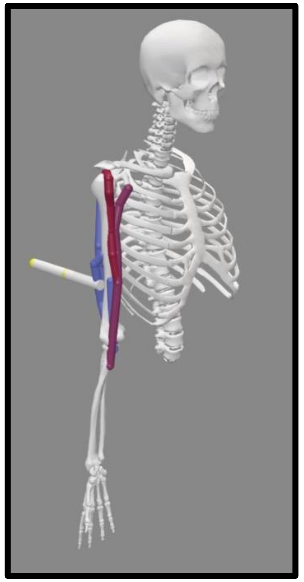




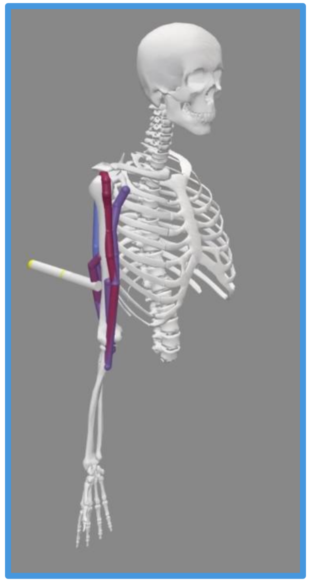
Influence of the exoskeleton weights

$$\min_{\mathbf{u}} \sum_{k=0}^{N} \left(w_m \sum_{i=1}^{n_m} \left(a_i(t_k) \right)^2 + w_{exo} \sum_{i=1}^{n_u} \left(\tau_i(t_k) \right)^2 \right)$$

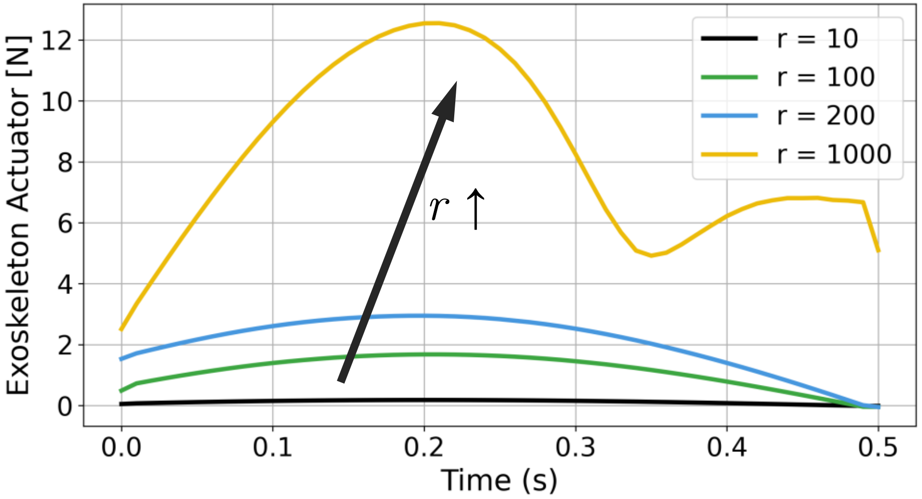
- We define: $r = \dfrac{w_m}{w_{exo}}$

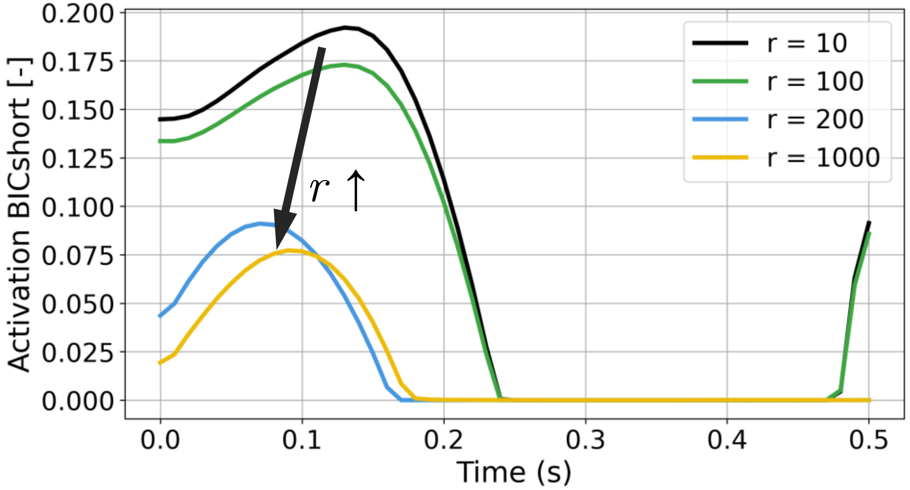


$r = 10$



$r = 200$





To what extent does the exoskeleton alleviate muscular load?

$$\min_{\mathbf{u}} \sum_{k=0}^{N} \left(w_m \sum_{i=1}^{n_m} \left(a_i(t_k) \right)^2 + w_{exo} \sum_{i=1}^{n_u} \left(\tau_i(t_k) \right)^2 \right)$$

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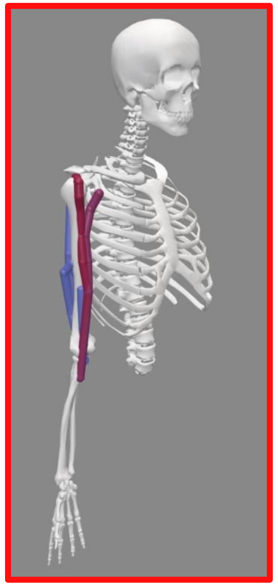
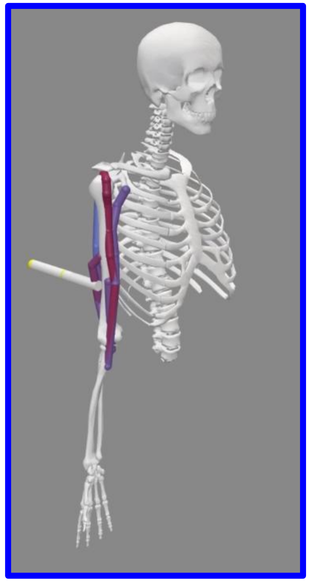
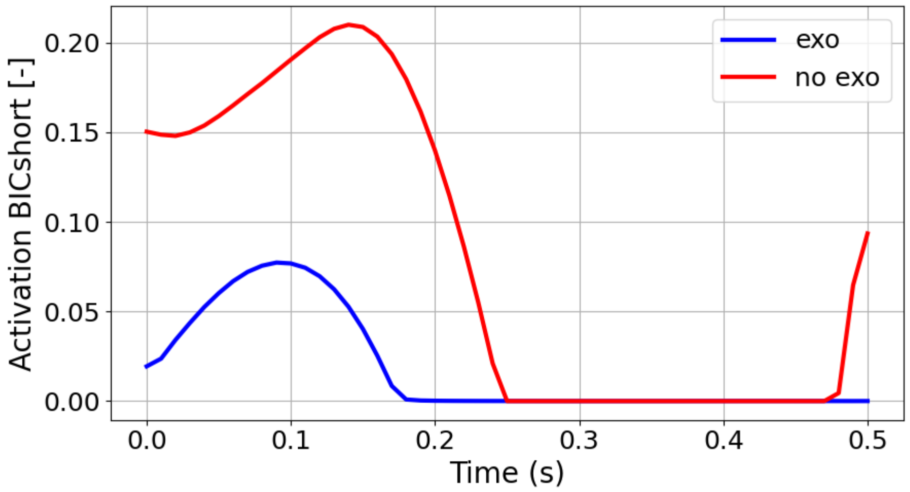
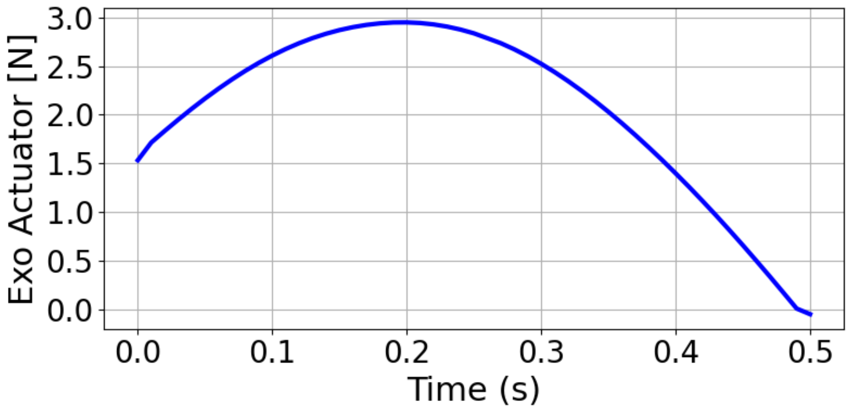




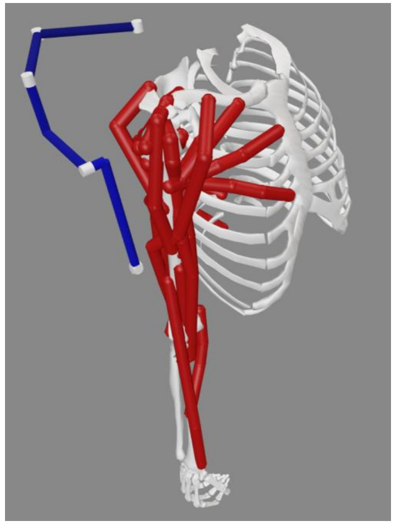
$r = 200$

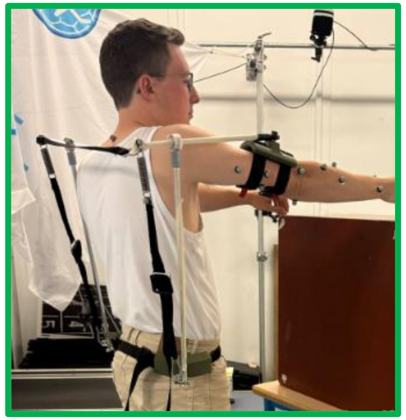




Ongoing work and perspectives

- More test cases
- Use semi-analytic differentiation
  - Compare computation time
- Extend the musculoskeletal modelling:
  - activation dynamics
  - ligaments
  - joints
  - compliant tendons
  - wrapping
- Compare the results with experimental data





Thank you for your attention!

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