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ÉCOLE POLYTECHNIQUE
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Faculty of Mathematics,

Biomechanical model of the primates’ upper limb

Pierre Kibleur

Prof. Auke Ijspeert
Marco Caprogrosso
Nathan Greiner
Shravan Tata Ramalingasetty

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Introduction

Motivation

Worldwide, **50 000 people a year** suffer a Spinal Cord Injury (SCI), with **lifetime consequences**.
Half of the patients are **under 30 years old**.
The injury is often **localized**, leaving hope to one day find a treatment.
But after 40 years of research, we cannot restore **basic limb functionality**.

Motivation

Instead, Grégoire Courtine's **pragmatical** approach focuses on electrically stimulating the proprioceptive feedback into the spinal cord below the SCI, in order to **recruit the reflex loop**. It has been shown to **restore walking capabilities** in humans with partial SCI.

Prof. Courtine

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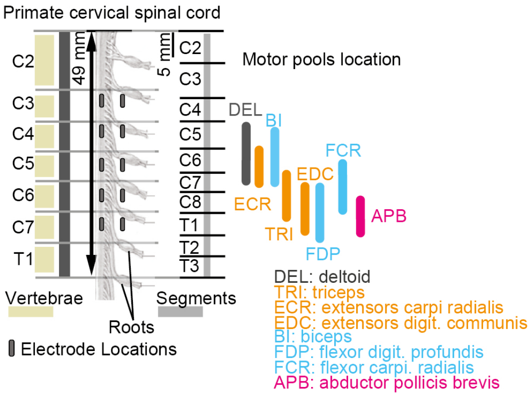
Instead, Grégoire Courtine's **pragmatical** approach focuses on electrically stimulating the proprioceptive feedback into the spinal cord below the SCI, in order to **recruit the reflex loop**. It has been shown to **restore walking capabilities** in humans with partial SCI.

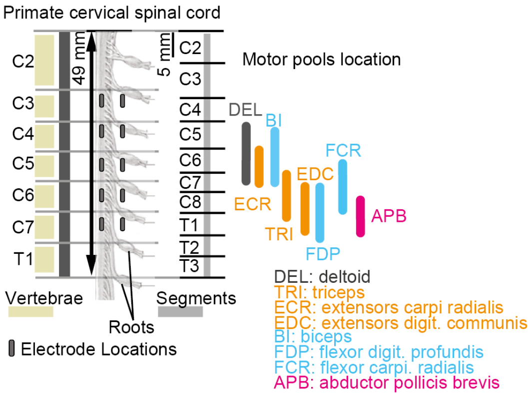
Prof. Courtine

Adapt the methodology to stereotypical motion of the upper limb.
Start with Non Human Primates (NHP).



An epidural electrode stimulates groups of actuators' sensory neurons' afferent fibres' firing rates, to recruit the sensorimotor limb control.

Electrical Epidural Stimulation (EES)



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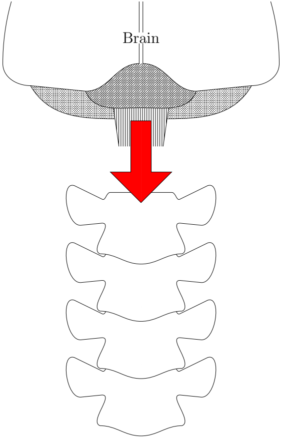
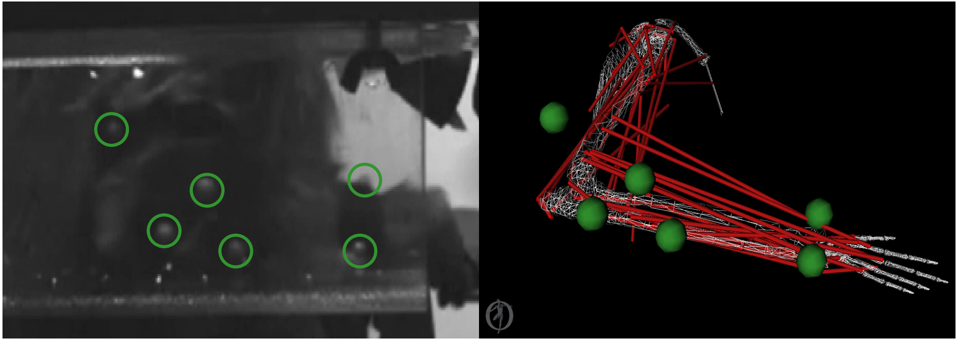


Produces motion if synchronous with descending modulation from the brain.

What are the patterns of afferents' firing rates?

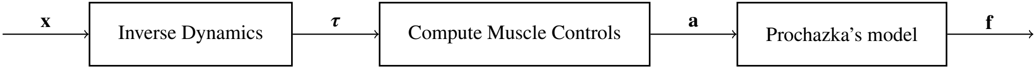
Biomechanical model



Kinematic recordings are reproduced in **OpenSim** simulations in order to predict them.

Computational model

3 algorithms to process the recorded kinematics into the afferents' firing rates:



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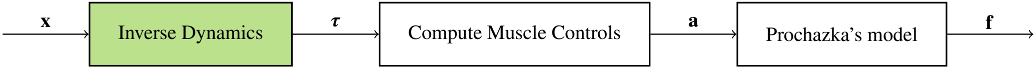
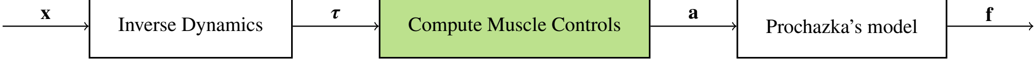


Joint angles that minimize the error in marker position are used to calculate joint torques.

$$\mathbf{q} = \arg\min_{\mathbf{q}} \sum_i \omega_i \left\| \mathbf{x}_i^{exp} - \mathbf{x}_i(\mathbf{q}) \right\|^2,$$

$$\boldsymbol{\tau} = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q}).$$

3 algorithms to process the recorded kinematics into the afferents' firing rates:

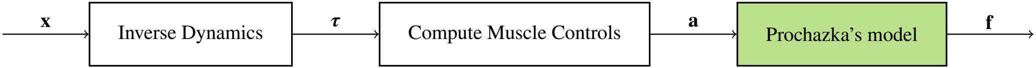


Muscle activations able to render the torques minimize muscle fatigue (Anderson, 2001).

$$
\begin{aligned}
\text{min} \quad & \sum_m a_m^2 + \sum_i \omega_i (\ddot{q}_i^* - \ddot{q}_i)^2, \\
\text{s. t.} \quad & \tau_j = \sum_m F_m(t) \cdot r_{j,m}(\mathbf{q}).
\end{aligned}
$$

Computational model

3 algorithms to process the recorded kinematics into the afferents' firing rates:



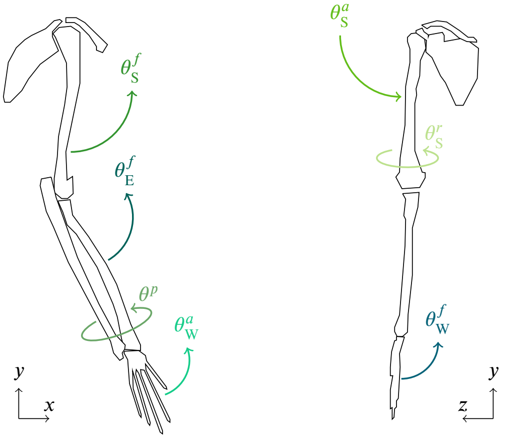
Afferent firings are estimated from stimuli different fibres respond to (Prochazka, 1999).

$$\begin{pmatrix} f_{\mathrm{Ia}} \\ f_{\mathrm{Ib}} \\ f_{\mathrm{II}} \end{pmatrix} = \begin{pmatrix} \alpha_l & \alpha_v & \alpha_a & 0 & c_{\mathrm{Ia}} \\ 0 & 0 & 0 & \beta_F & 0 \\ \gamma_l & 0 & \gamma_a & 0 & c_{\mathrm{II}} \end{pmatrix} \begin{pmatrix} \Delta l \\ v^p \\ a \\ F \\ 1 \end{pmatrix} = \mathbf{A}\zeta_m(t).$$

Modelling

Imported **SIMM** arm model (Chan, 2006):

- ***Macacca Mulatta***
- Right arm
- 7 bones (6 monkey + human hand)
- 3 of them **fixed**
- 7 degrees of freedom
- 39 musculo-tendon units
- 18 of them **unparametrized**

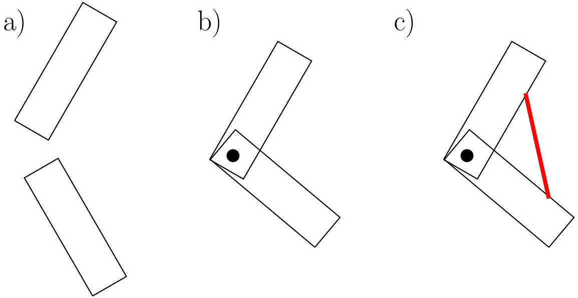


Geometry, leeway of the modelled arm.

Model adaptations

Fix the model in OpenSim in order to use it for the computations, at different levels of the musculoskeletal modelling.

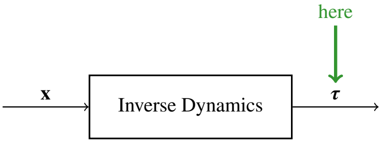
Segments -> Joints -> Actuators:



Segments	Joints	Actuators
- length	- operating range	- optimal fibre length
- mass	- joint coupling	- tendon slack length
- CoM	- damper	- pennation angle
- Inertia	- ligament	- maximal isometric force

Validation

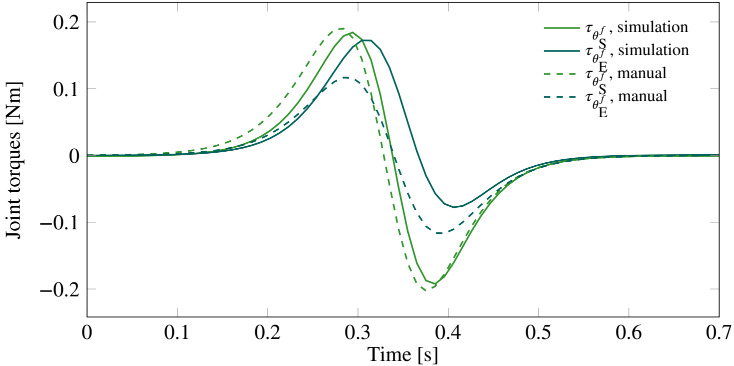
Where to validate the model?



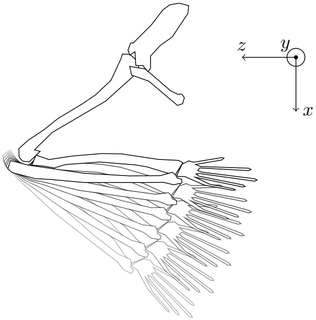
- Validate the torques, before even trying to compute muscle activities

Published results of the study of humans' **planar elbow flexion** are used (Gribble, 1999).

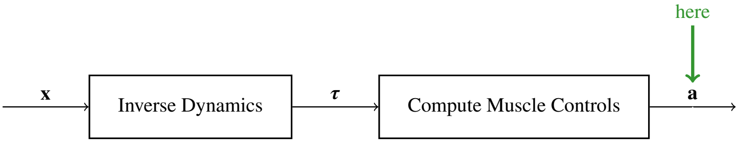
Compare torques manually computed with OpenSim's:



Task:



Where to validate the model?

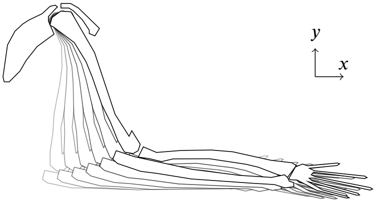


- Validate the torques, before even trying to compute muscle activities
- Validate individual actuators' properties (Hicks, 2015)

  Recently enforced by implementation (Millard, 2013)
- Validate the muscle activities

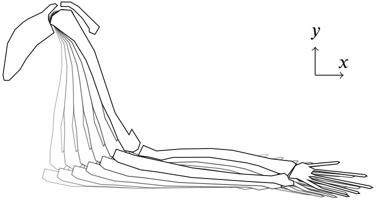
Muscular model validation: data

69 EMG-kinematic simultaneous recordings of NHP frontal centre-out tasks are shared with us (Miller, Chowdhury, 2017). **22 muscles are monitored.**

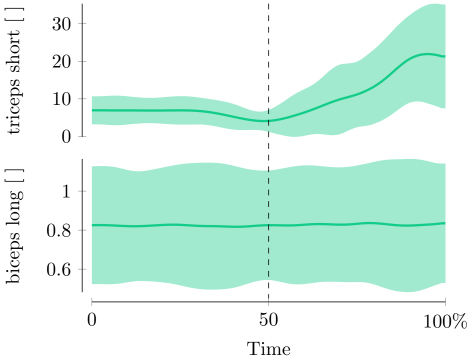


Frontal centre-out task.

69 EMG-kinematic simultaneous recordings of NHP frontal centre-out tasks are shared with us (Miller, Chowdhury, 2017). **22 muscles are monitored.** Find the important ones.



Frontal centre-out task.



Example (filtered) EMG signals.

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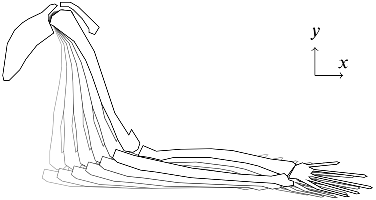
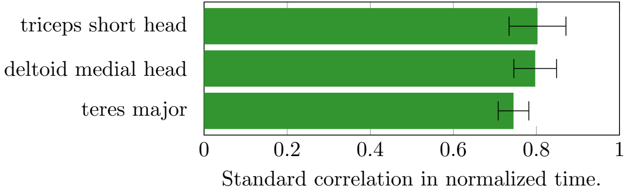
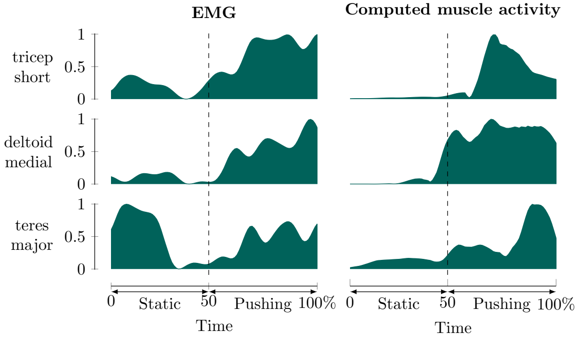


Frontal centre-out task.



Mean and variance of the correlation between all EMG recordings.

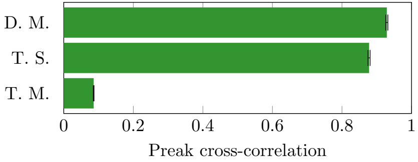
Compare EMGs of important muscles to computed controls.



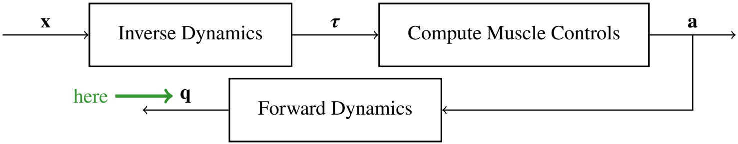
Profiles of muscle activity, recorded and computed.

Allow the computed activity to be earlier than the EMG: $\Delta t \leq .1$s (Miller, 1993).

$$\max_{\Delta t} \int_{t_0}^{t_f} \mathrm{EMG}(t) \cdot a(t + \Delta t) dt,$$



Where to validate the model?



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- Validate individual actuators' properties (Hicks, 2015)

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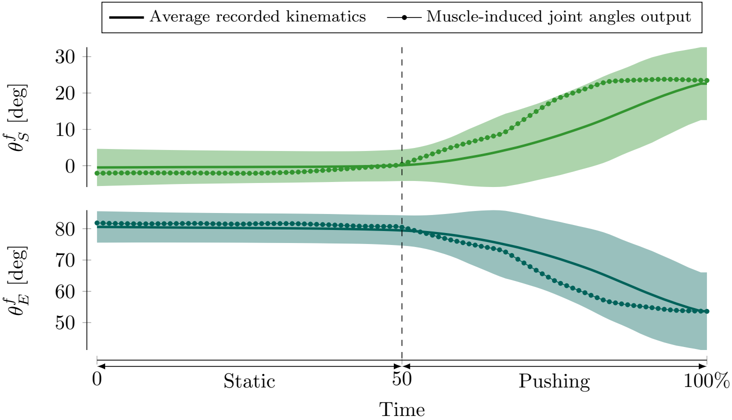
- Validate the muscle activities
- Validate the inversibility of computations if possible

Model validation: feed-forward kinematics

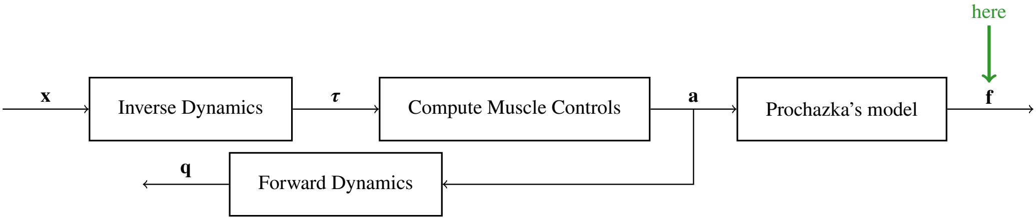


Principal joint angle evolutions, frontal-centre out task.

a → **τ** → **q**

Inverting the previous computations enables us to feed the model muscle activities, and observe the resulting kinematics.

Where to validate the model?



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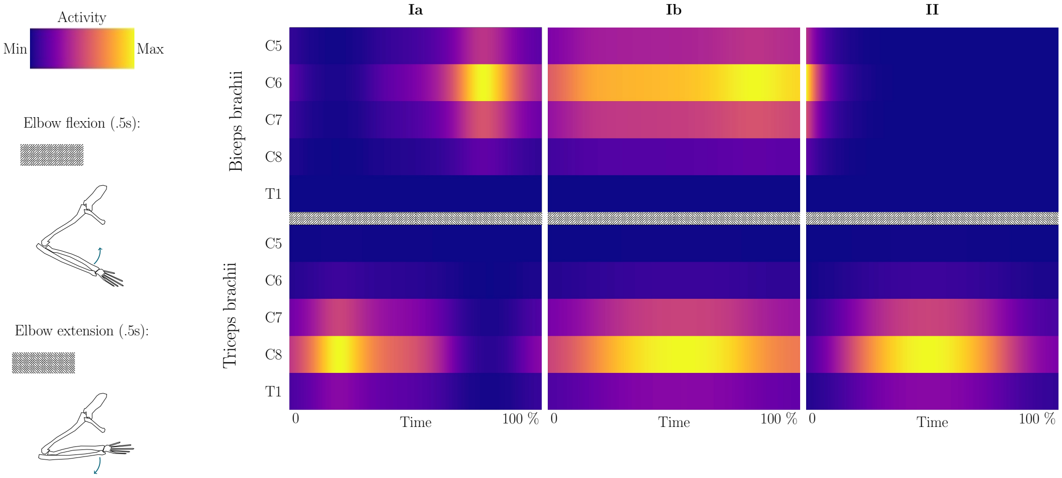
- Validate the muscle activities
- Validate the inversibility of computations if possible
- Validate the firing rates

Validation: firing rates predictions



Afferent fibres activities with parameters tuned to the cat's normal locomotion (Prochazka, 1999), based on motor pools distributions in the Non Human Primate (Jenny, 1983).

Experiments

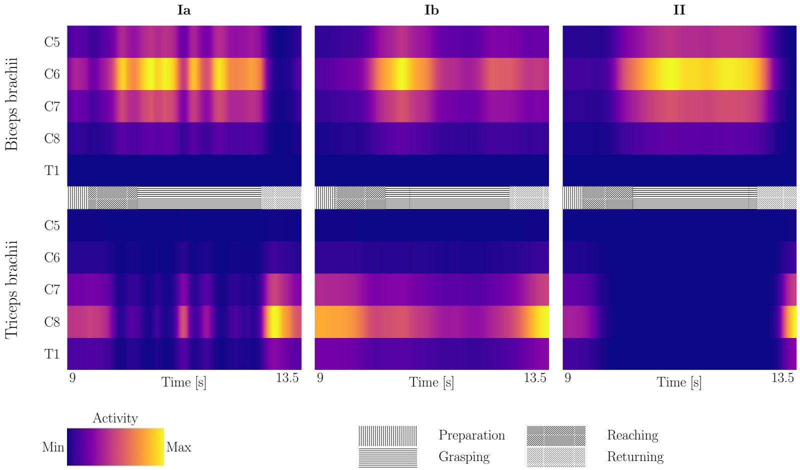
Experiment: reaching & grasping task

Recorded kinematics

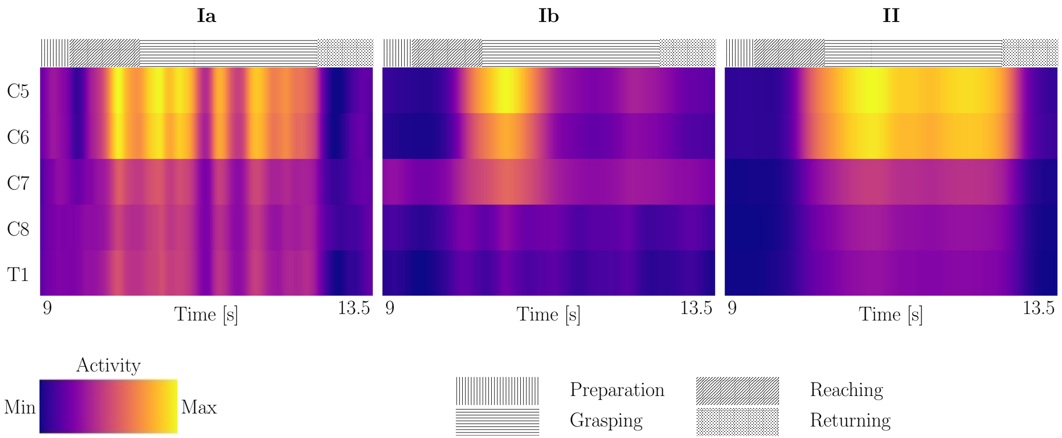
Forward control

Principal joint angle evolutions, reaching & grasping task.

Biceps and Triceps afferent activities



Averaged afferent activities



Afferent fibres activities with parameters tuned to the cat's normal locomotion, based on motor pools distributions in the NHP.

Conclusion

Current State:

- Macacca fascicularis right arm
- Fully parametrized
- Integrated in computations chain
- Estimates sensorineural activity

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Future developments:

1. Add functionality
2. Improve physiological correctness
3. Replace cost function
4. Use spinal maps to tune the EES

THANK YOU!