CusToM : a Matlab toolbox for musculoskeletal simulation

Charles Pontonnier, Pierre Puchaud

CusToM : a Matlab toolbox for musculoskeletal simulation

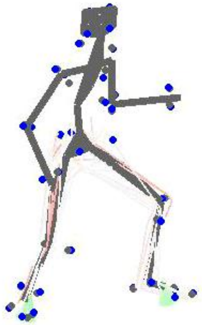
Introduction to musculoskeletal analysis

Charles Pontonnier, Pierre Puchaud

Introduction

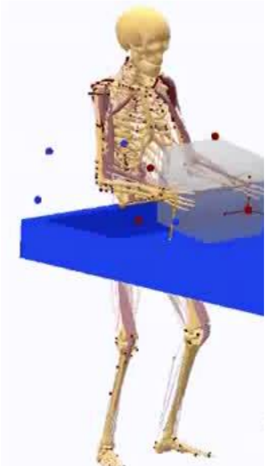
[Pouliquen2015]

[Murai2010]

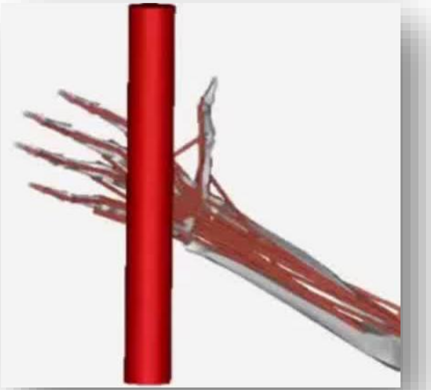


[Plantard2017a]

[Delp2007]

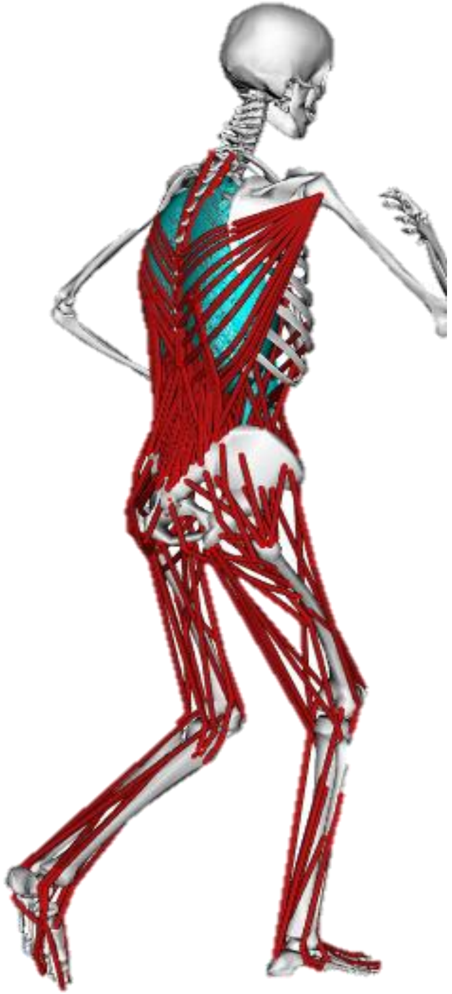


[Damsgaard2006]



[Vignais2014]

Musculoskeletal analysis



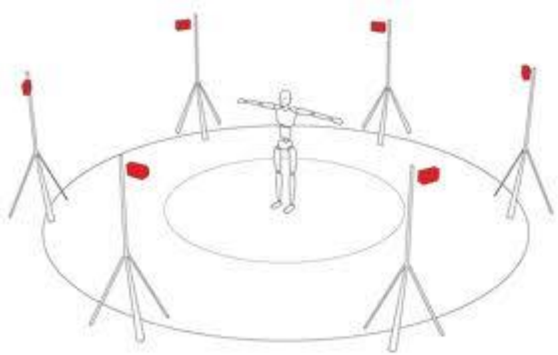
→ Angular trajectories

→ Joint forces

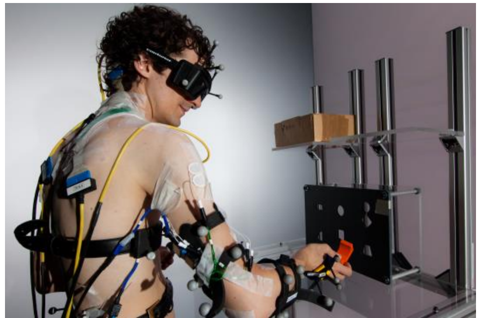
→ Muscle forces

Source : OpenSim

Input data: motion capture (and force platforms)

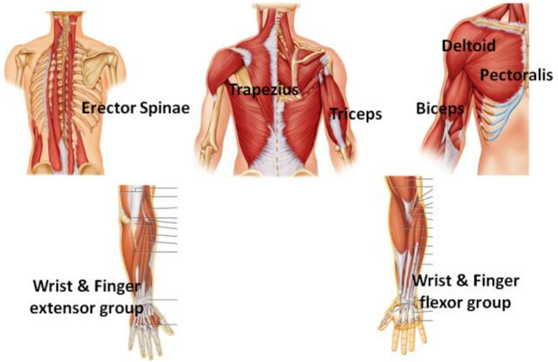


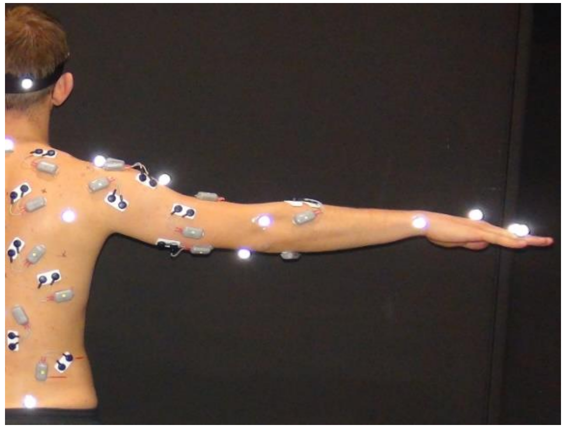
- Reflecting markers
- Infrared cams
- Triangulation



Input data (optional): sEMG

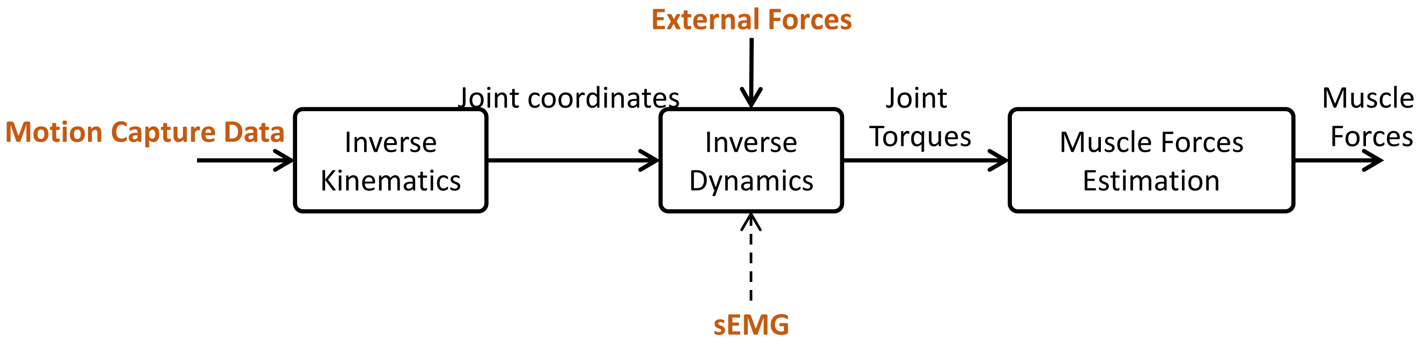
- Measuring electrical activity of muscles
- Classicaly voltage between two points of the muscle chief (bipolar)



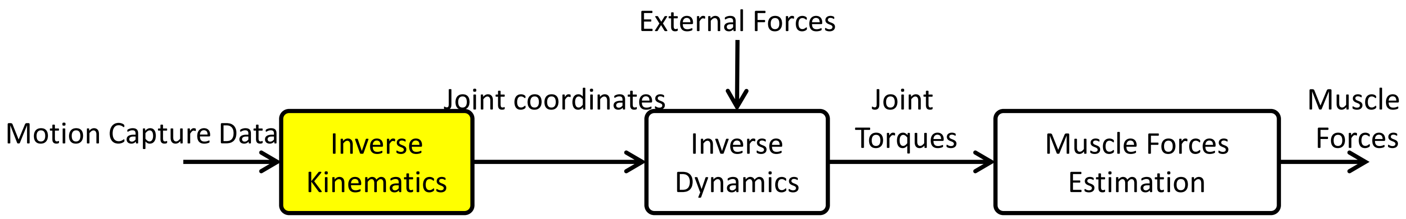


SENIAM, recommendation for electrode placements

Motion analysis (inverse dynamics approach)

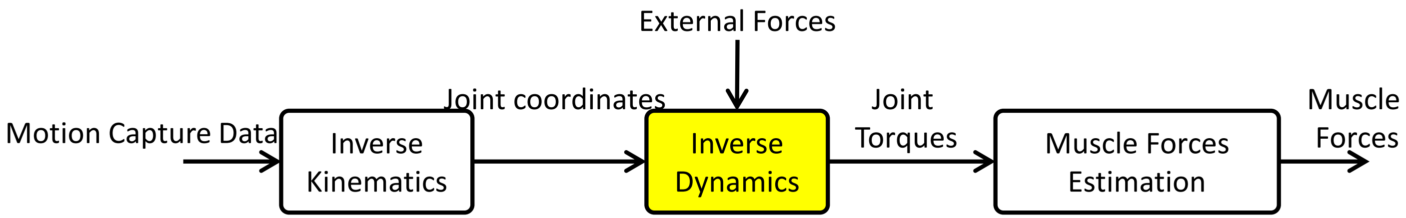


Inverse kinematics



- Joint coordinates computation
- Classically constrained optimization

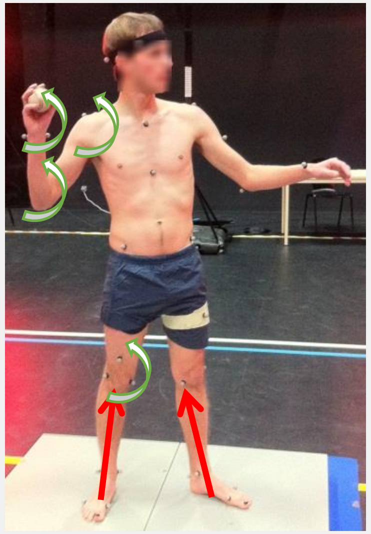
Inverse dynamics



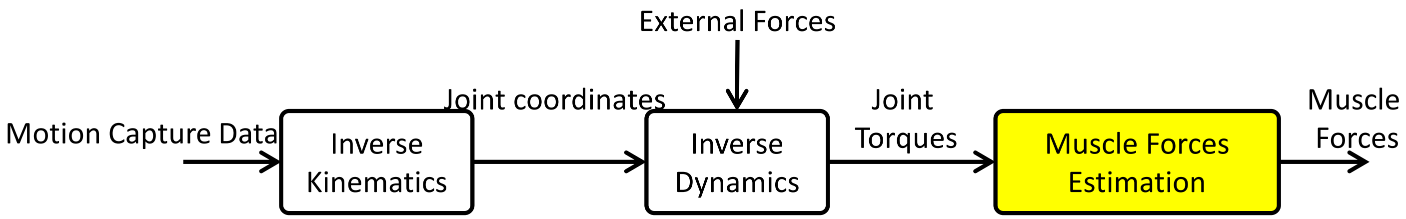
- Joint torques determination
- Classically Newton-Euler algorithm

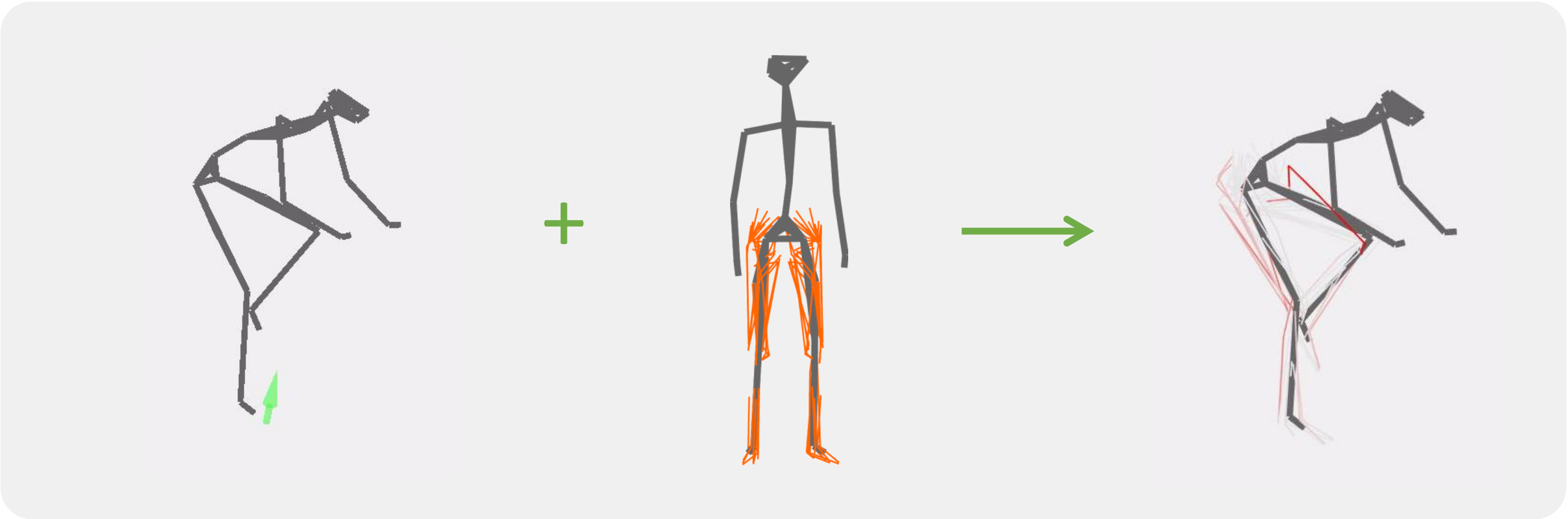
$$f_i = f_i^B - f_i^x + \sum_{j \in \mu(i)} f_i$$

External forces measures



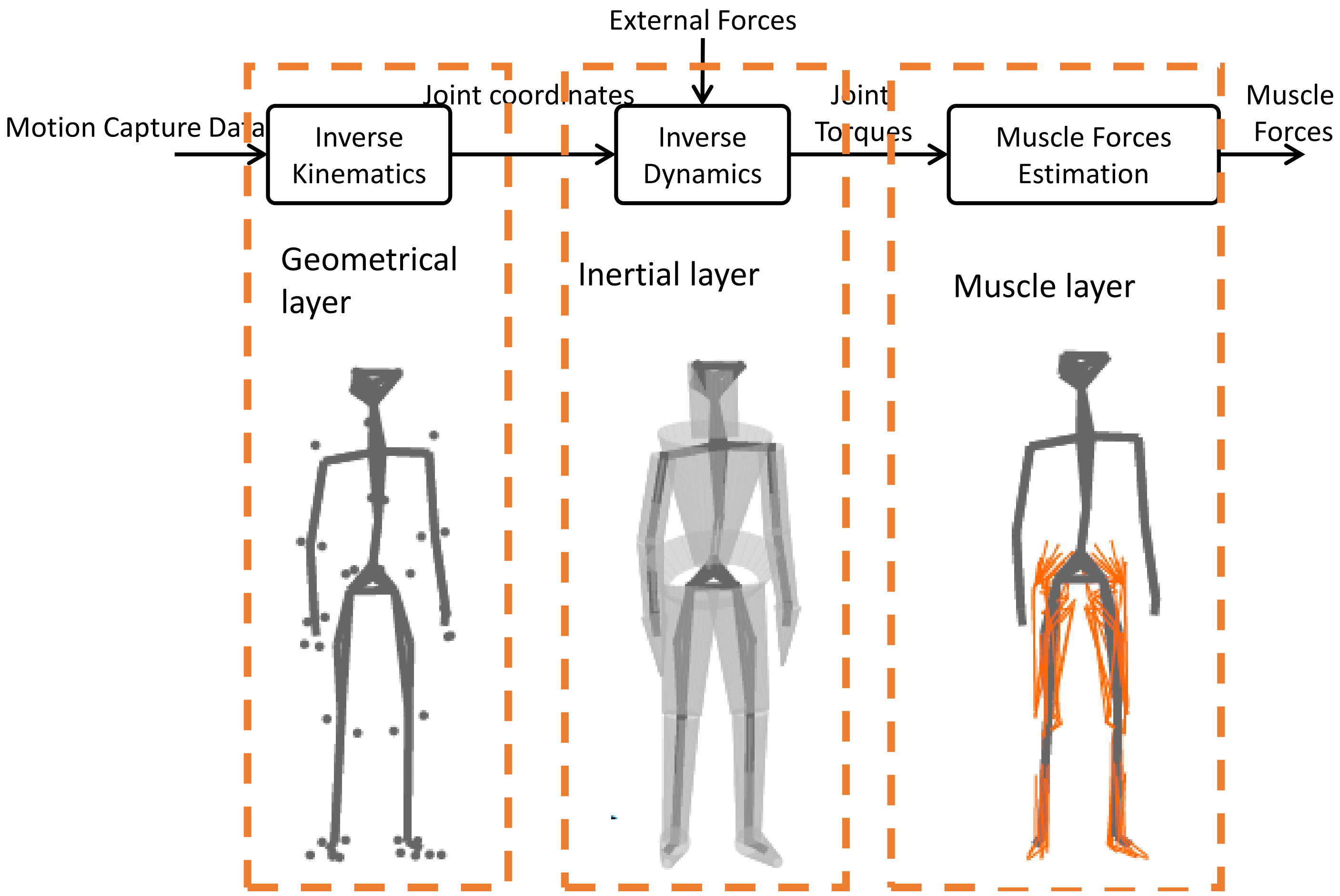
Muscle forces estimation





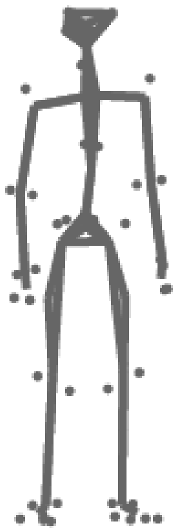
- Classically through non-linear constrained optimization

Musculoskeletal model



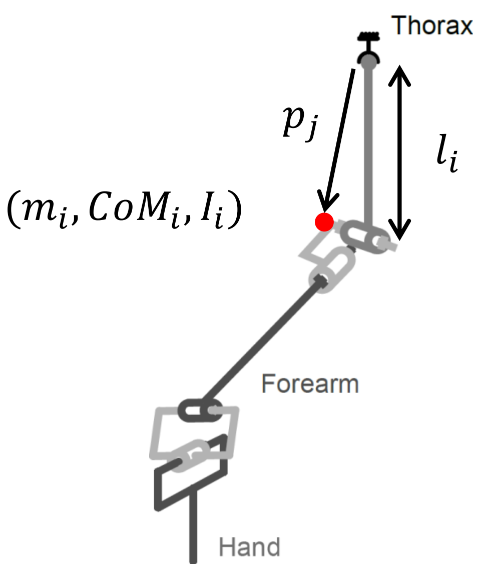
Geometrical layer

Geometrical layer



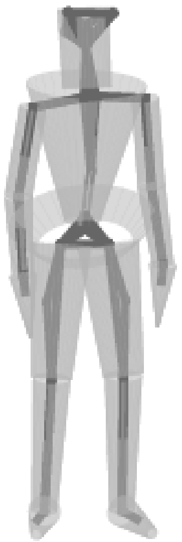
Oestoarticular model

- Polyarticulated rigid body system
- Kinematics joints
- Geometrical properties



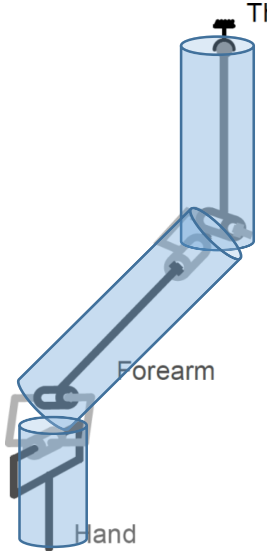
Inertial layer

Inertial layer



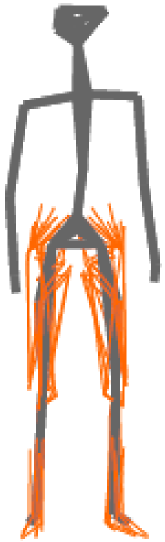
Oestoarticular model

- Inertial properties (mass, center of mass, inertia matrix)



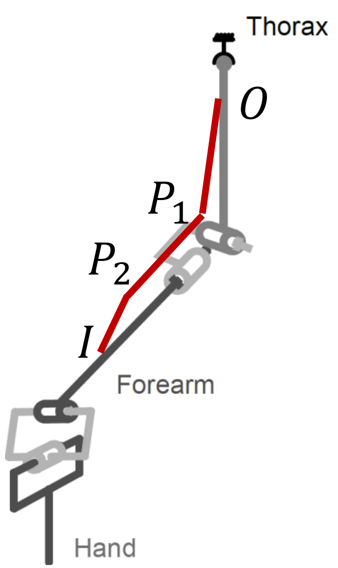
Muscle layer

Muscle layer



Muscle model

- Muscular topology



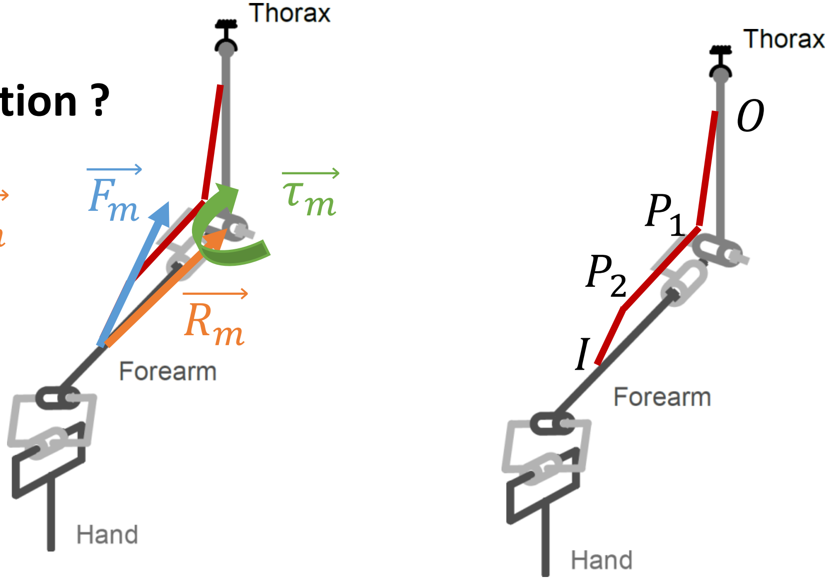
Muscle layer

Muscle model

- Muscular topology

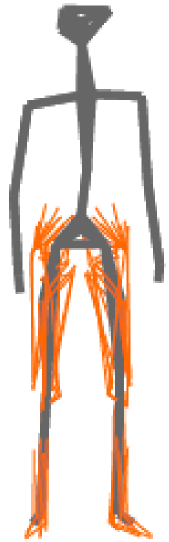
Muscle action ?

$$\overrightarrow{\tau_m} = \overrightarrow{F_m} \times \overrightarrow{R_m}$$



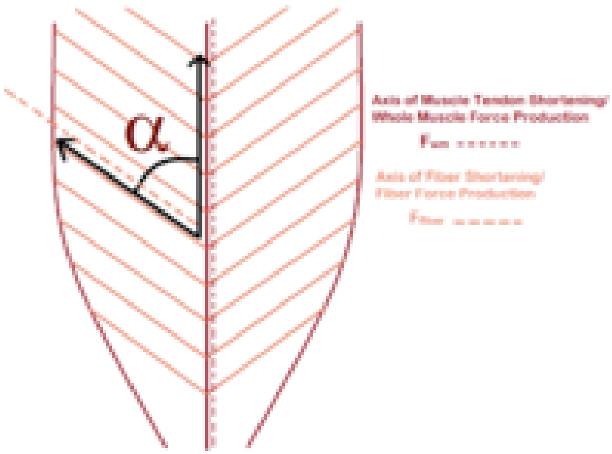
Muscle layer

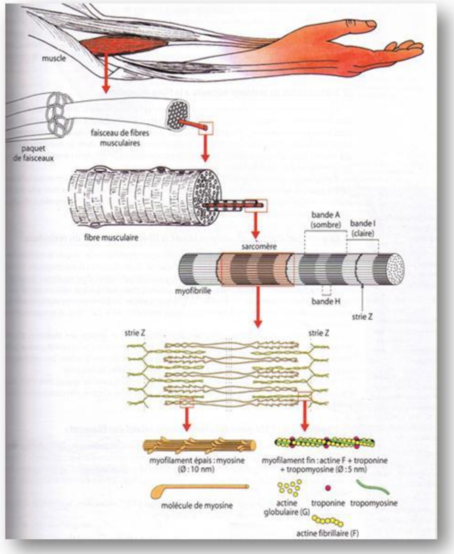
Muscle layer



Muscle model

- Force generation behavior

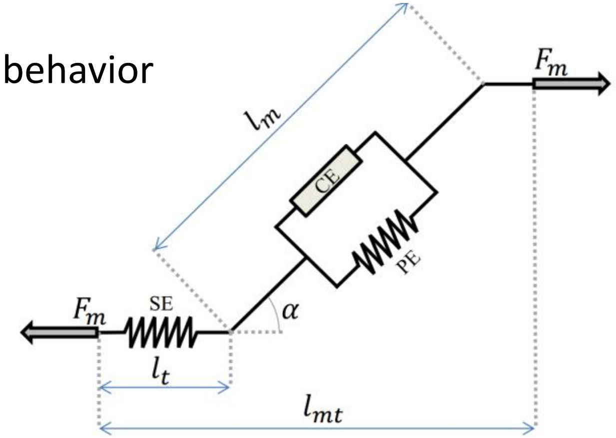




Muscle layer

Muscle model

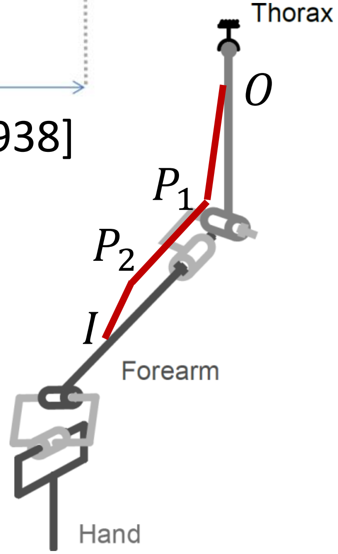
- Force generation behavior



Hill model [Hill1938]

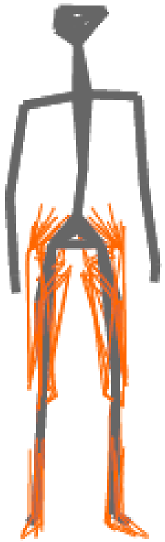
$$F_{m,j} = \left[f_p\left(\bar{l}_{m,j}\right) + f_a\left(a_j, \bar{l}_{m,j}, \dot{\bar{l}}_{m,j}\right) \right] F_{o,j}$$

Visco-elastic law



Muscle layer

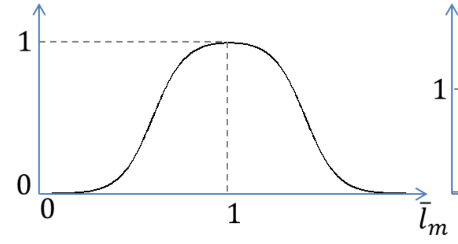
Muscle layer



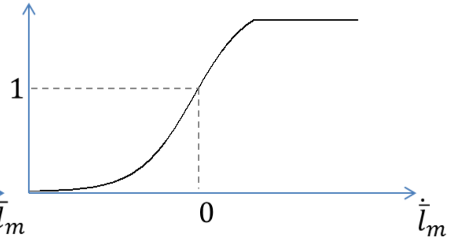
Muscle model

- Force generation behavior

Contractile element CE

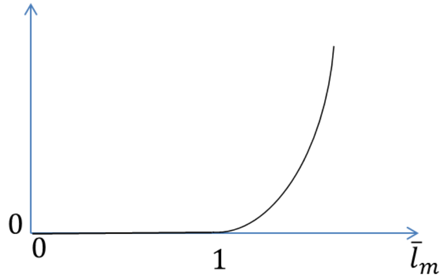


Force-Length relationship f_l



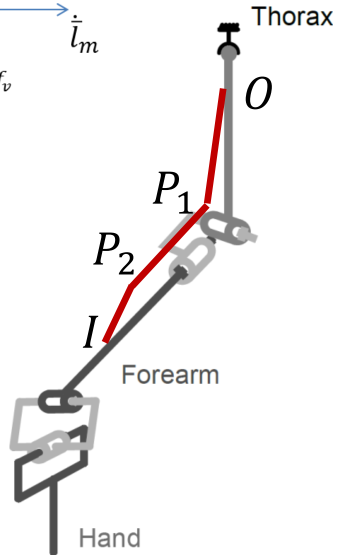
Force-Velocity relationship f_v

Passive element PE



Passive force relationship f_p

$$F_{m,j} = \left[f_p\left(\bar{l}_{m,j}\right) + f_a\left(a_j, \bar{l}_{m,j}, \dot{\bar{l}}_{m,j}\right) \right] F_{o,j}$$



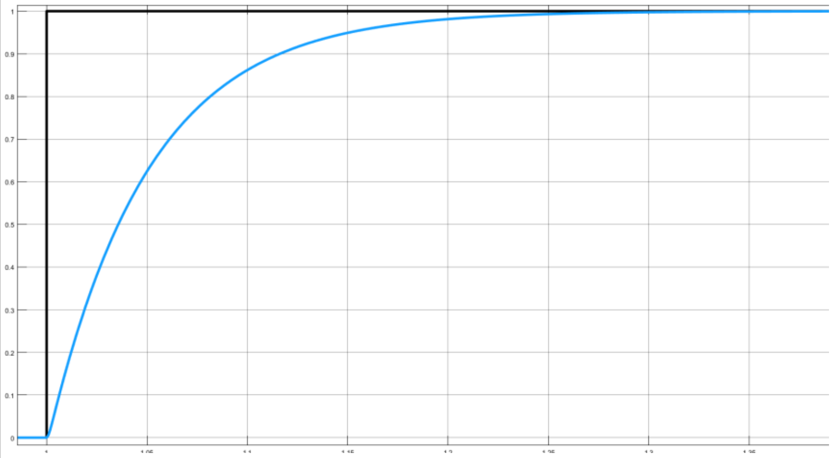
Muscle layer

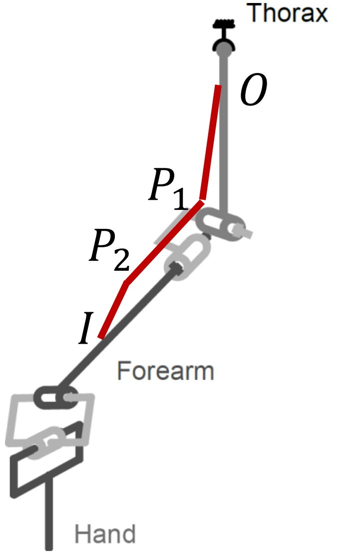
Muscle model

$$\dot{e}_j = (u_j - e_j)/\tau_{ne}$$

- Activation dynamics

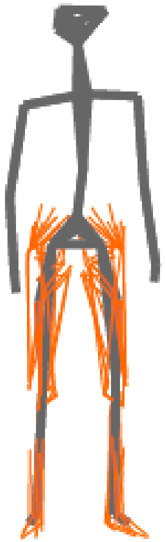
$$\dot{a}_j = \begin{cases} (e_j - a_j)/\tau_{act} & , \quad e_j \geq a_j \\ (e_j - a_j)/\tau_{deact} & , \quad e_j < a_j \end{cases}$$





Muscle layer

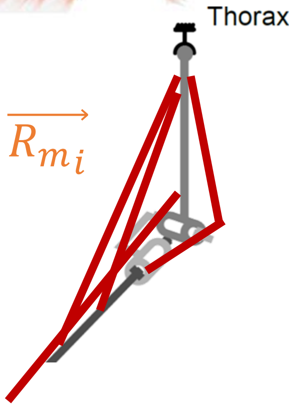
Muscle layer



Muscle model

- Motor control

$$\vec{\tau} = \sum_i \overrightarrow{F_{m_i}} \times \overrightarrow{R_{m_i}}$$

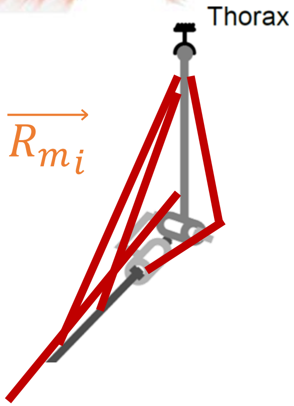


Muscular redundancy

Muscle layer

Muscle model

- Motor control



$$\vec{\tau} = \sum_i \overrightarrow{F_{m_i}} \times \overrightarrow{R_{m_i}}$$

Muscular redundancy

Muscle layer

Muscle model

- Motor control

→ minimising a function representing the motor control to define a muscle recruitment law

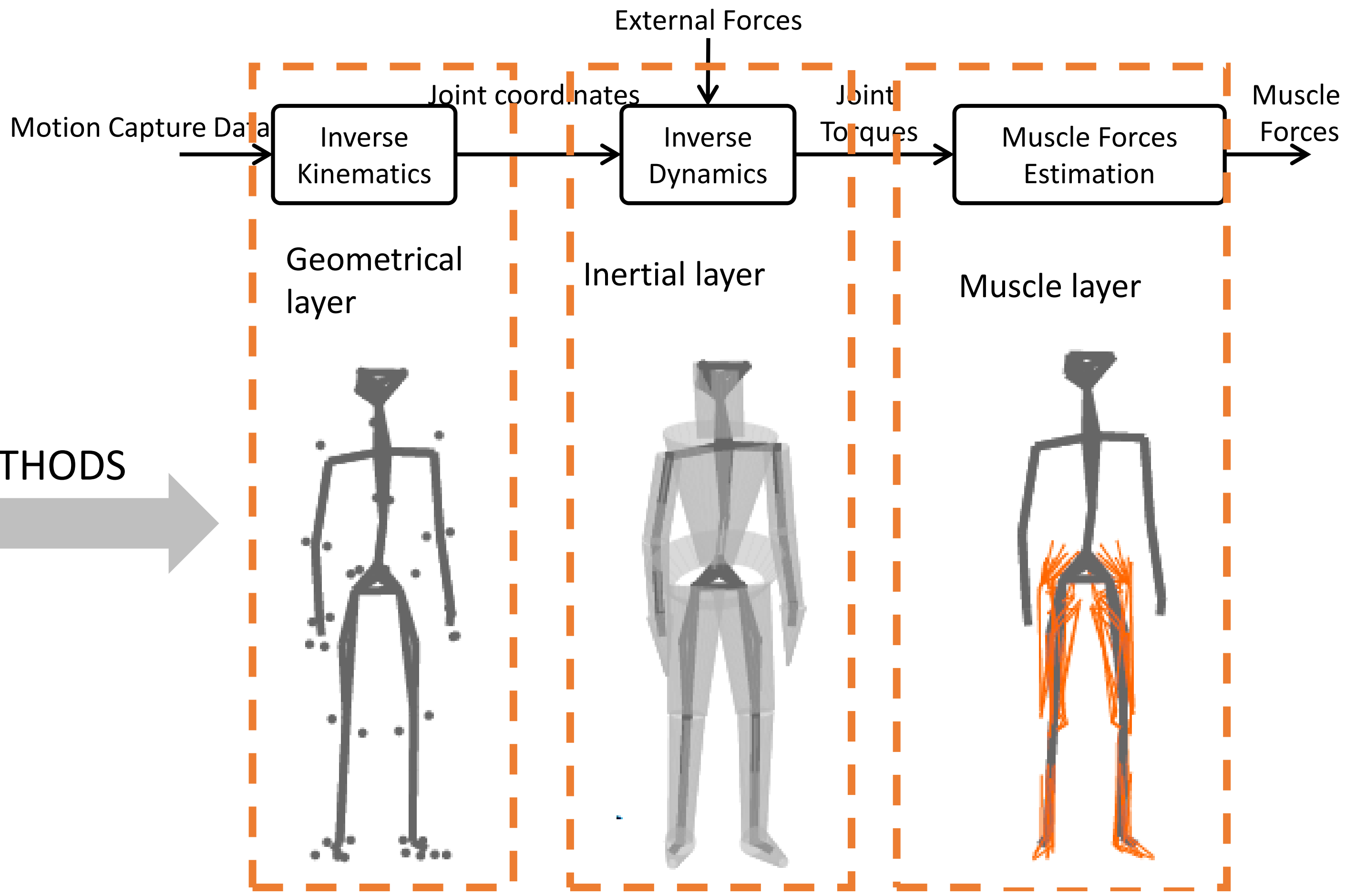
$$\min f(F) \xrightarrow{\text{classically}} f(F) = \sum_n \left(\frac{F_{m_i}}{F_{max_i}}\right)^p$$

s.t. $\vec{\tau} = \sum_i \overrightarrow{F_{m_i}} \times \overrightarrow{R_{m_i}}$

$$F_{min_i} < F_{m_i} < F_{max_i}$$

The more p is high, the more muscles acts in synergy
The more p is low, the more powerful muscles are preferably activated

Muscle layer



CALIBRATION METHODS

- Classically optimization under constraints

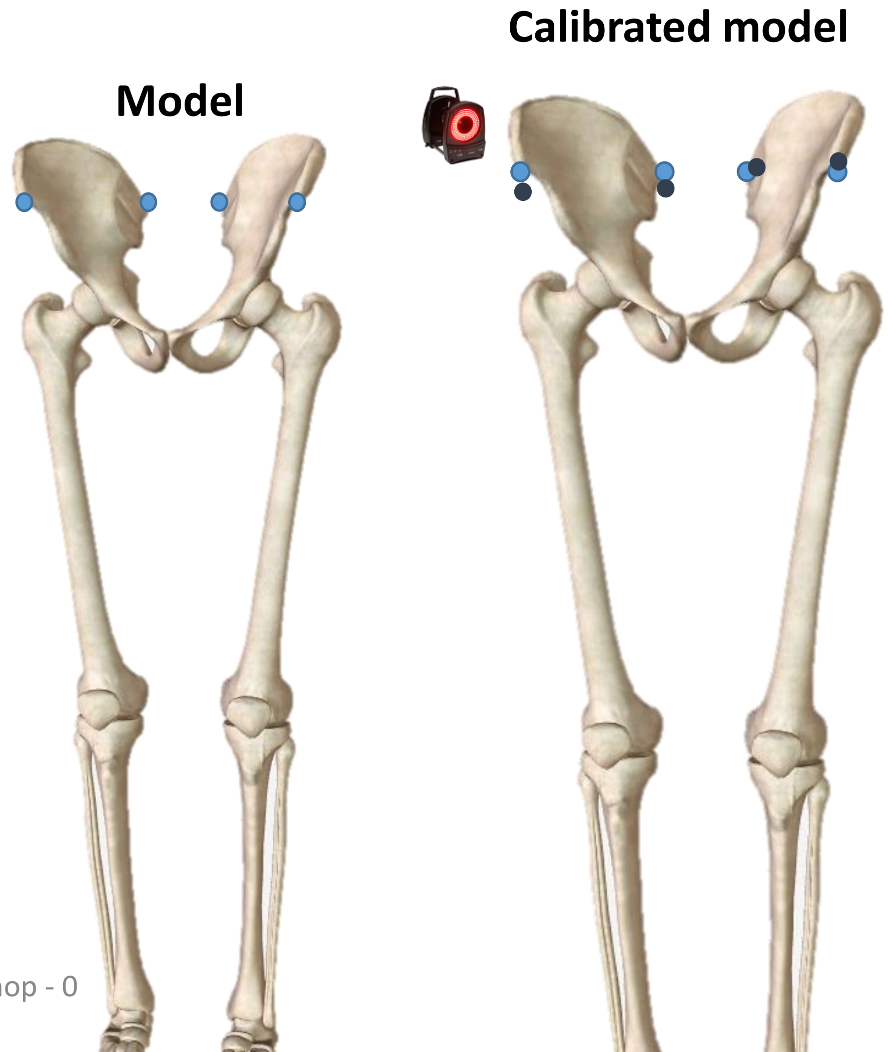
Geometrical calibration

Init: Anthropometrics tables [Winter 1955]
Marker-based [AnyBody, OpenSim]

Functional Optimization

$$\min_{k,\Delta p} \sum_{f}^{N_f} \sum_{m}^{N_m} ||\{X_{exp,m}(t_f)\} - \{X_{mod,m}^{global}(q(t_f), k, \Delta p)\}||_2^2$$

[Puchaud2018, Muller2015]



Inertial calibration

Init: anthropometrics tables [Dumas 2007, De Leva 1994]

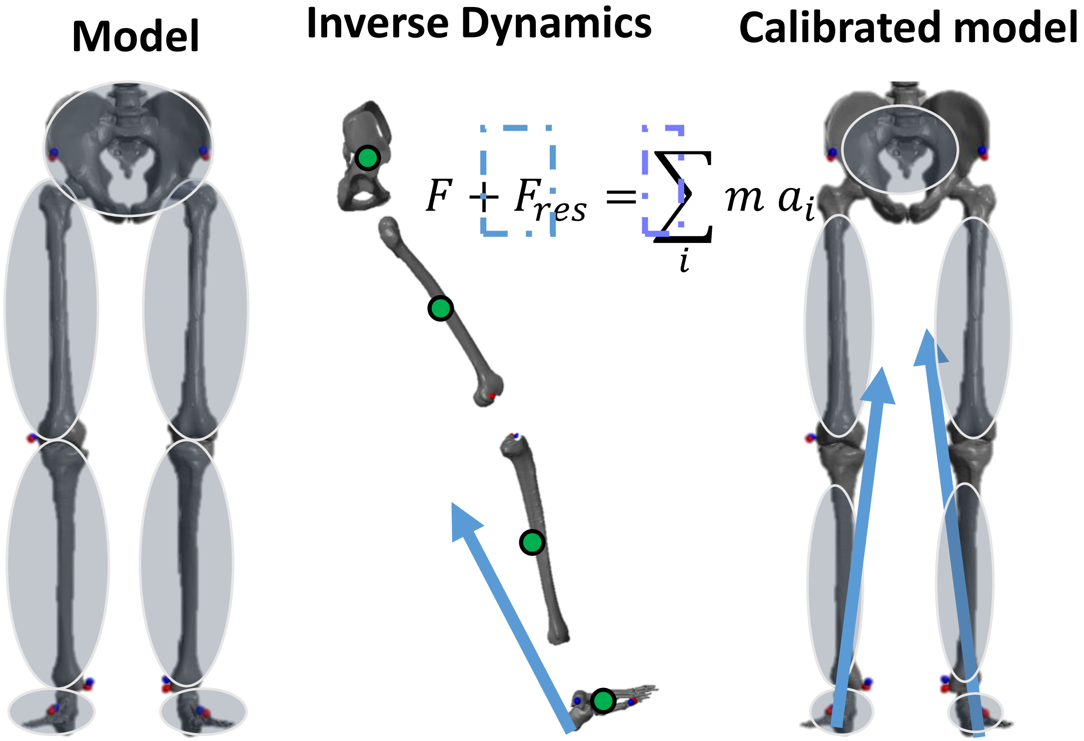
Optimisation

A. Muller 2017

Minimizing dynamics residuals

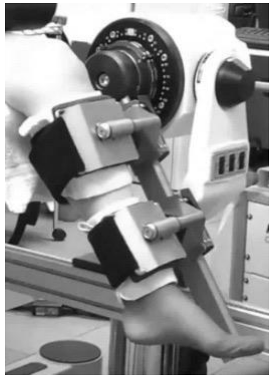
[Muller2017]

$$\min_{p} \sum_{f}^{N_f} \sum_{i}^{6} F_{res,i}(t_f)$$



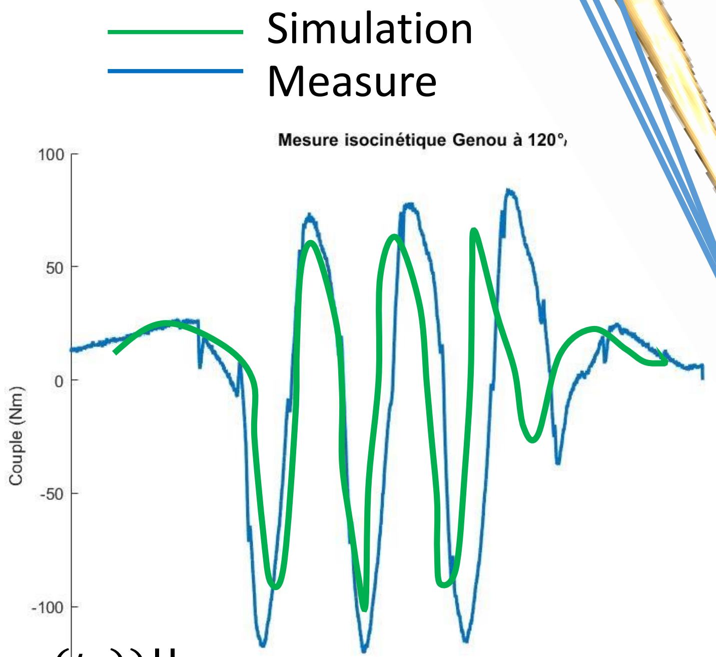
[Muller2017, Haering 2017]

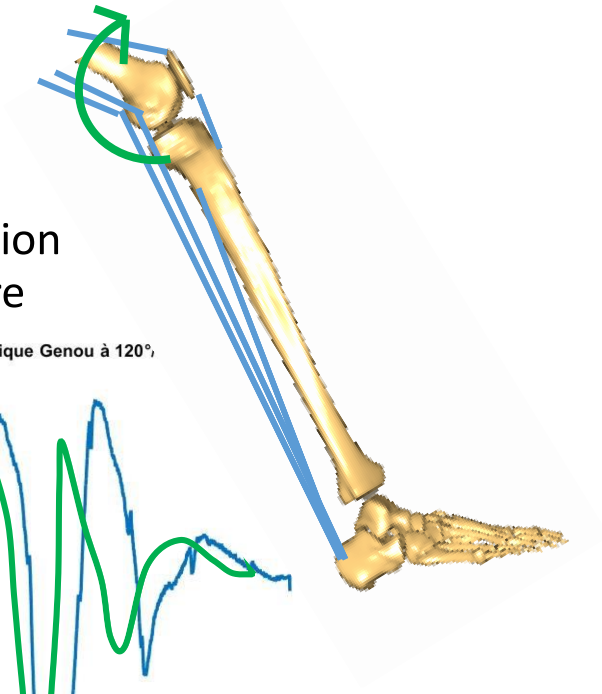
Optimization



Finding muscular parameters taht makes the resulting torque fitting the experimental data

$$\min_{P_{muscle}} \sum_{f}^{N_f} \sum_{i}^{3} ||C_{exp,i}(t_f) - C_{sim,i}(q(t_f), a(t_f))||$$

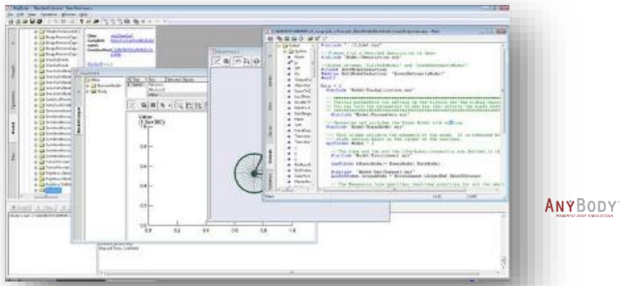




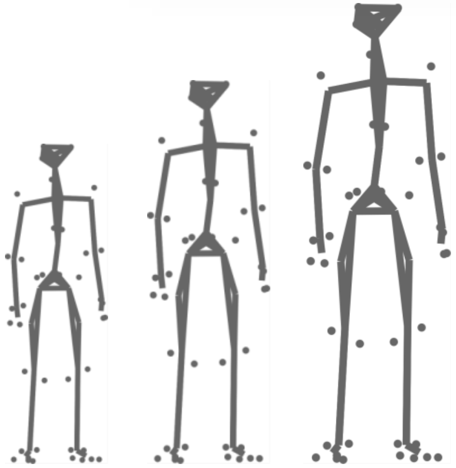
Mains issues

- Computational cost (optimization)
- Editing, assembling models
- Subject specific models
- Running multiple simulations

Heavy, expert software



Calibration



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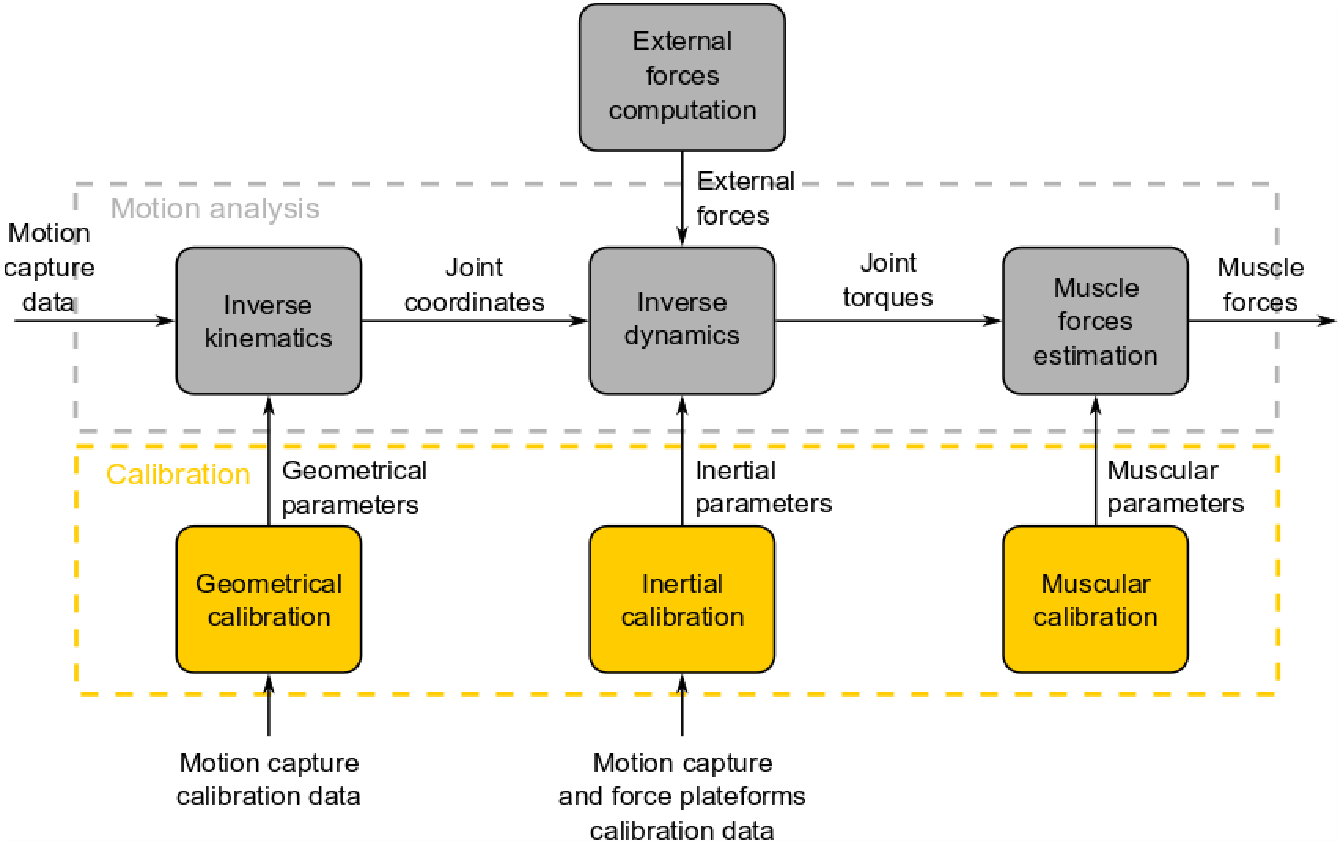
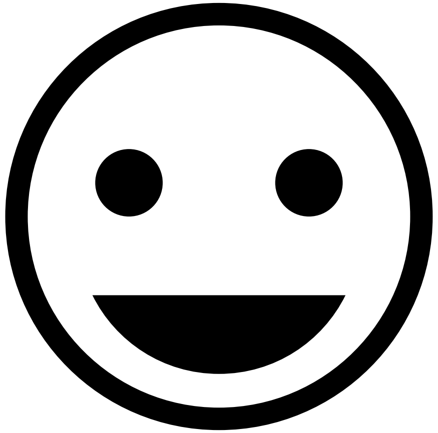
Introduction to CusToM

Charles Pontonnier, Pierre Puchaud

CusToM



https://github.com/anmuller/CusToM



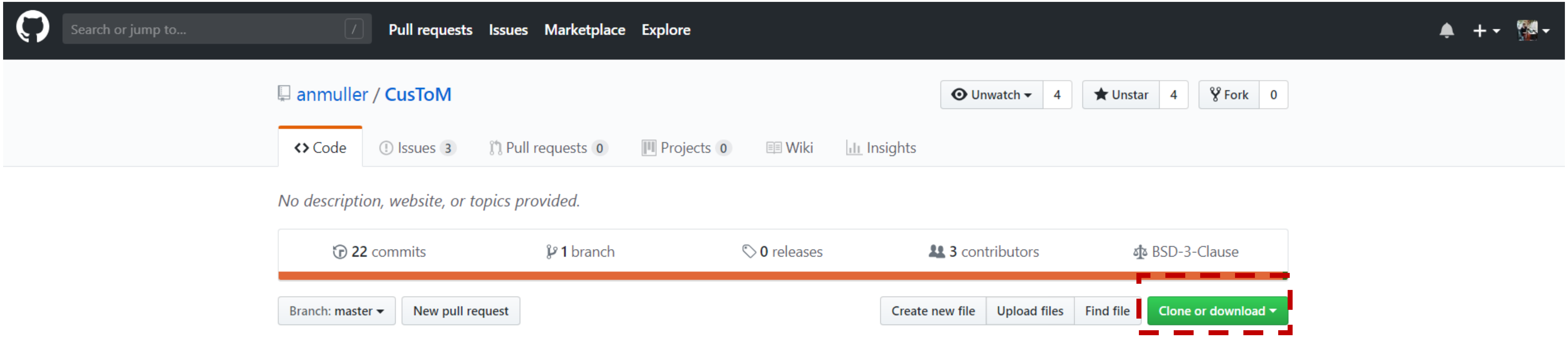
Please cite:

Muller, A., Pontonnier, C., Puchaud, P., Dumont, G., (2018). **CusToM : *a Matlab toolbox for musculoskeletal simulation*, in review.** Journal of Open Source Software.

Run on Matlab ®

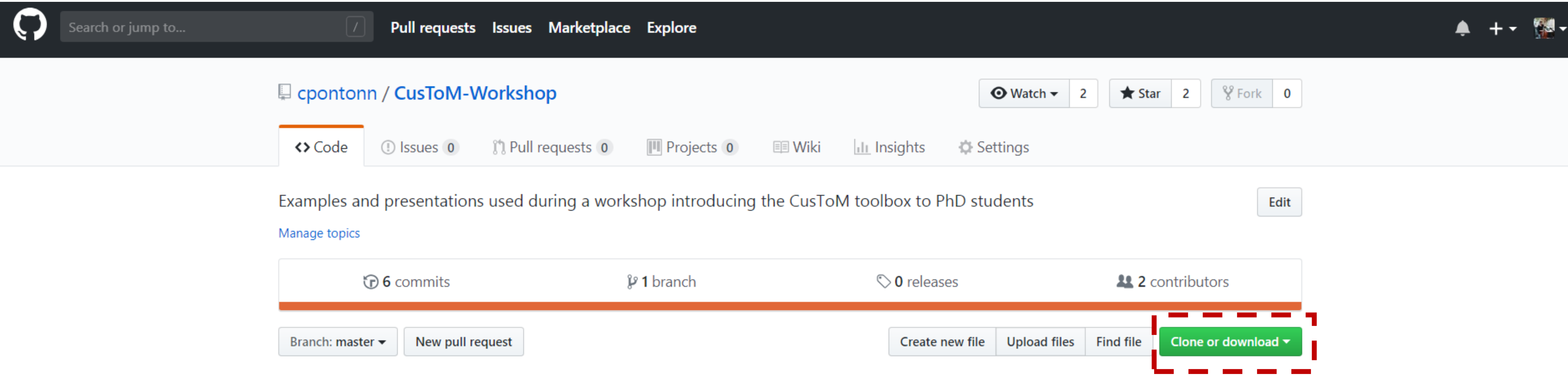
CusToM

https://github.com/anmuller/CusToM



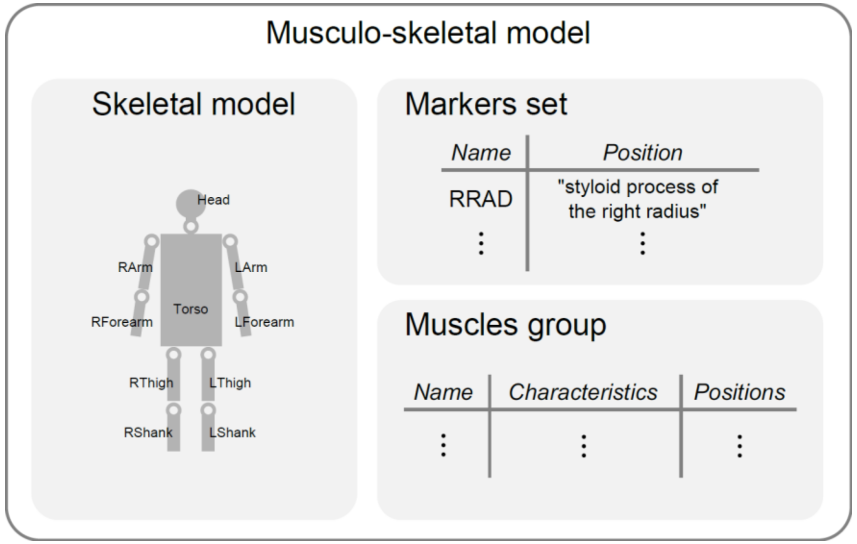
And for the workshop…

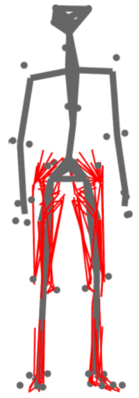
https://github.com/cpontonn/CusToM-Workshop



Until you’re done with CusToM

- **Modularity**



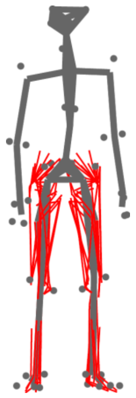


- **Model calibration**

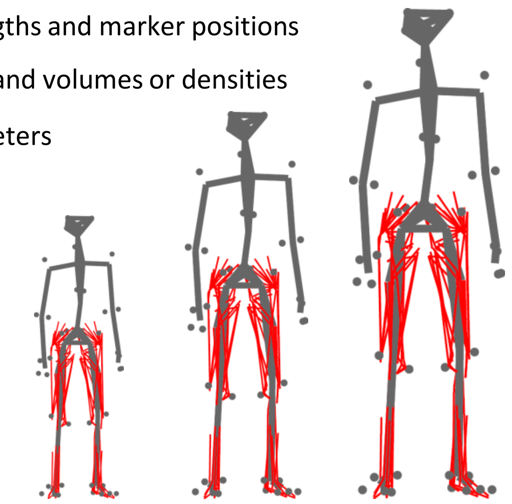
Geometrical: segment lengths and marker positions

Inertial: segment masses and volumes or densities

Muscular: Muscle parameters



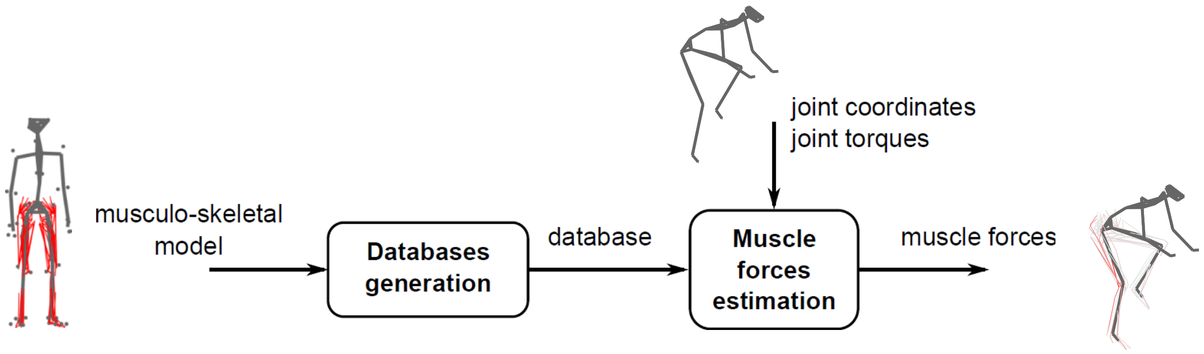
Use of
motion capture; external forces,
isokinetic ergometer data



MusIC method

2 main ideas:

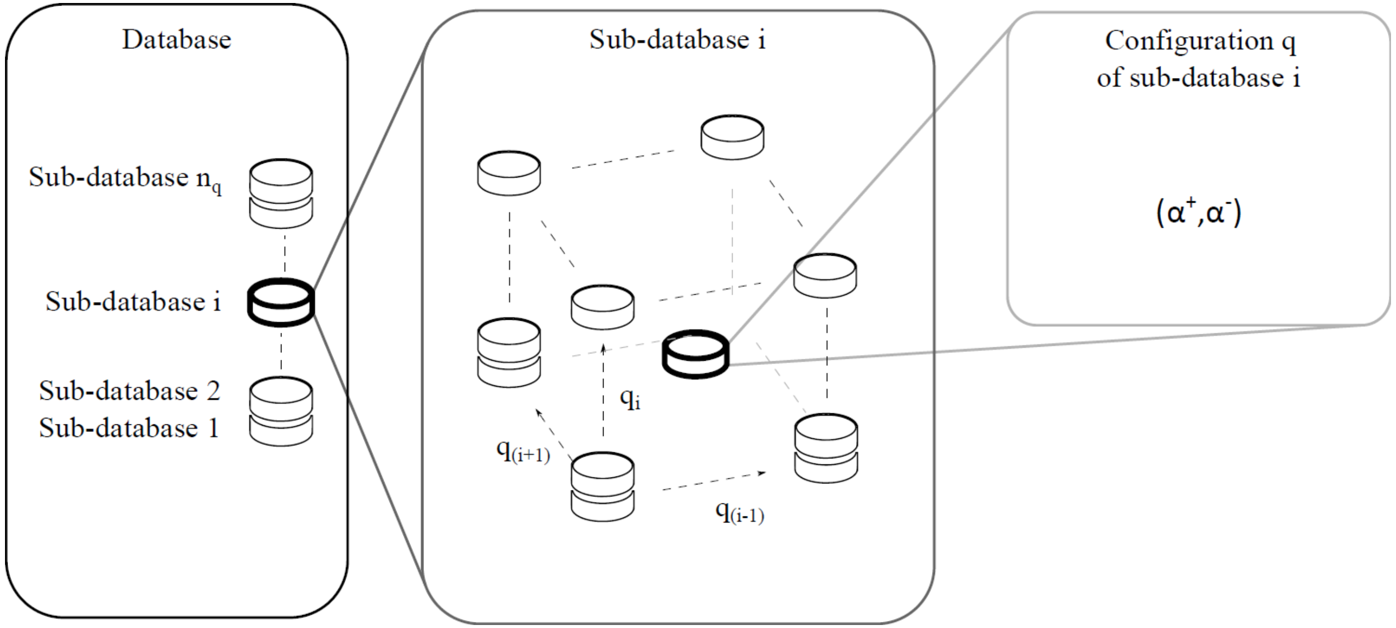
- Muscle contributions can be evaluated joint per joint in a decoupled manner
- Forces can be corrected a posteriori to fit dynamics

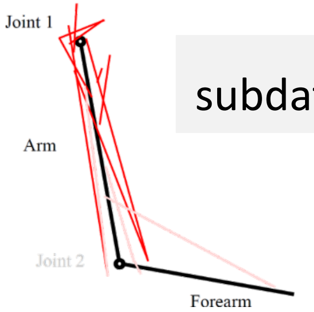


A database contains activation ratios α

$$\alpha = \frac{\frac{F}{F_{max}}}{\sum \frac{F}{F_{max}}}$$

MusIC method





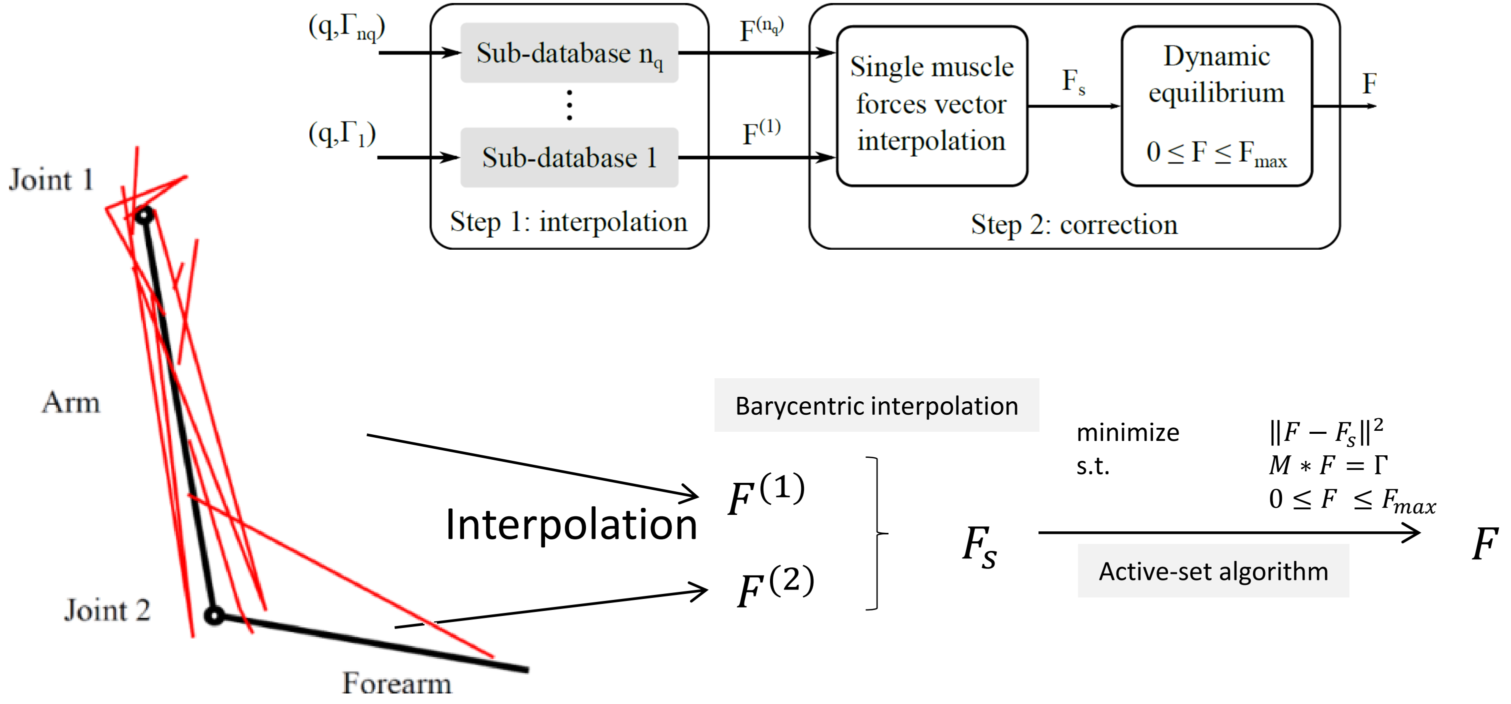
subdatabase

Solving:

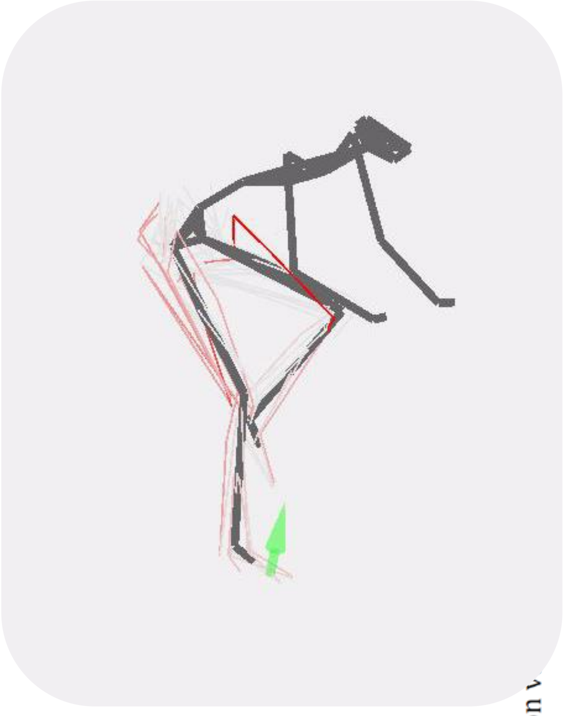
$$\begin{aligned} \text{min} \quad & f(F) \\ \text{s.t.} \quad & M * F = \pm\,\Gamma_{ref} \\ & F \geq 0 \end{aligned}$$

MusIC method

Compute forces from torques and joint configuration

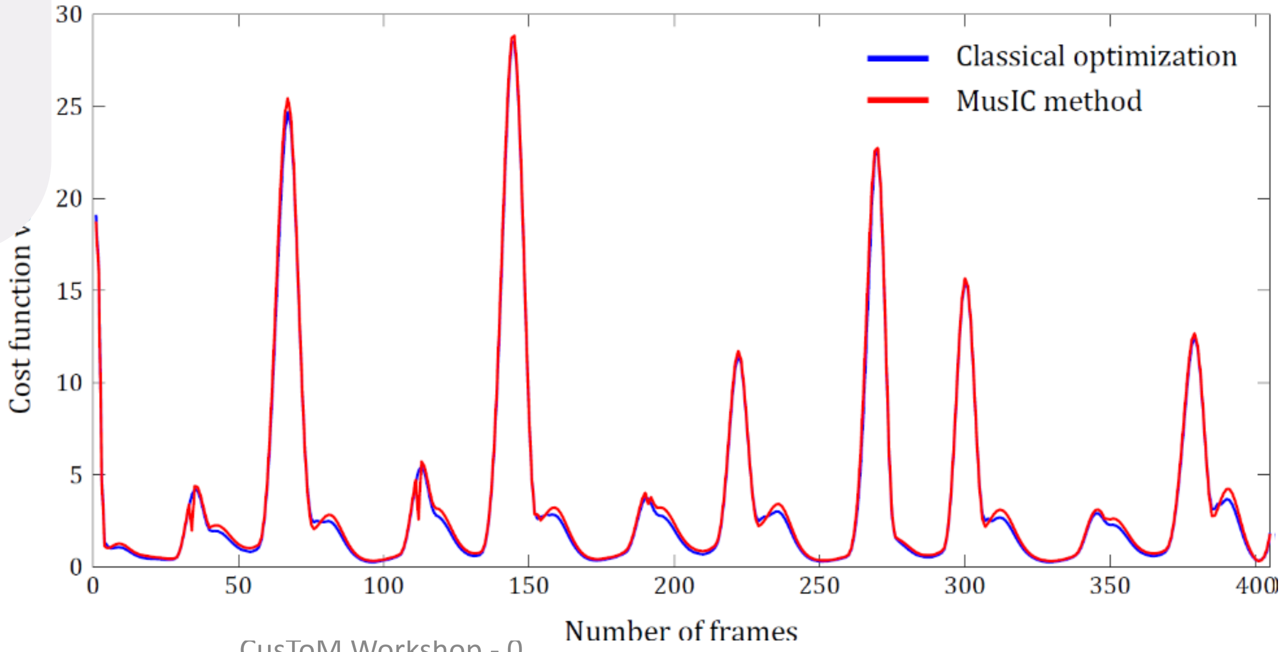


MusIC method

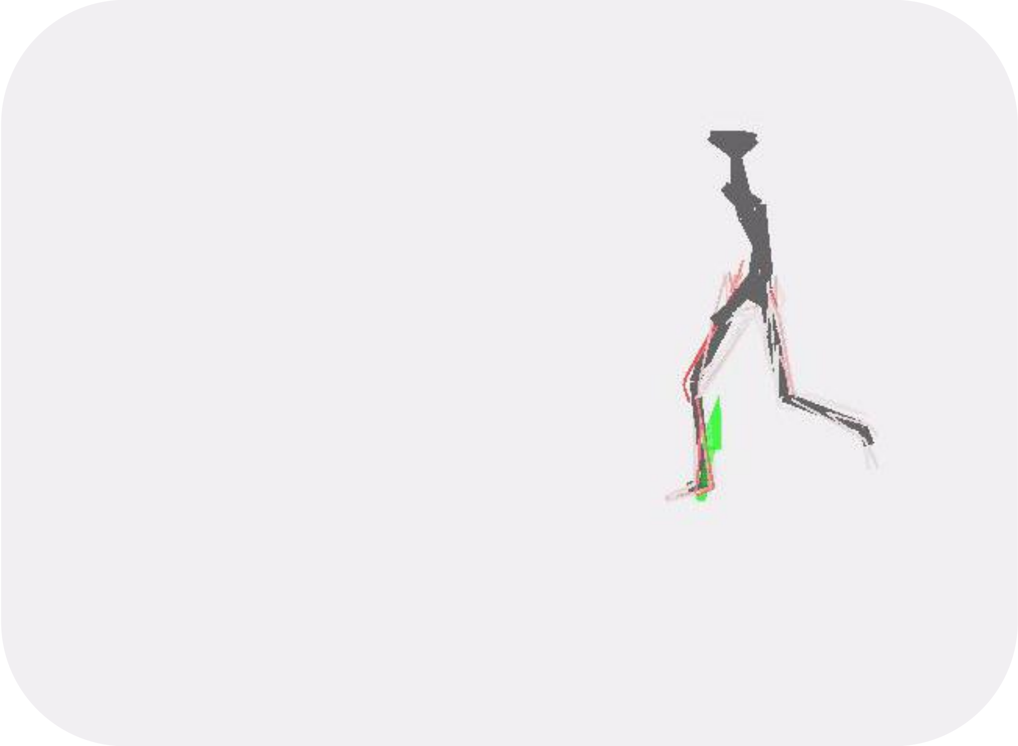


Computation frequency

- Optimization: 1,3 Hz
- MusIC : 27,5 Hz

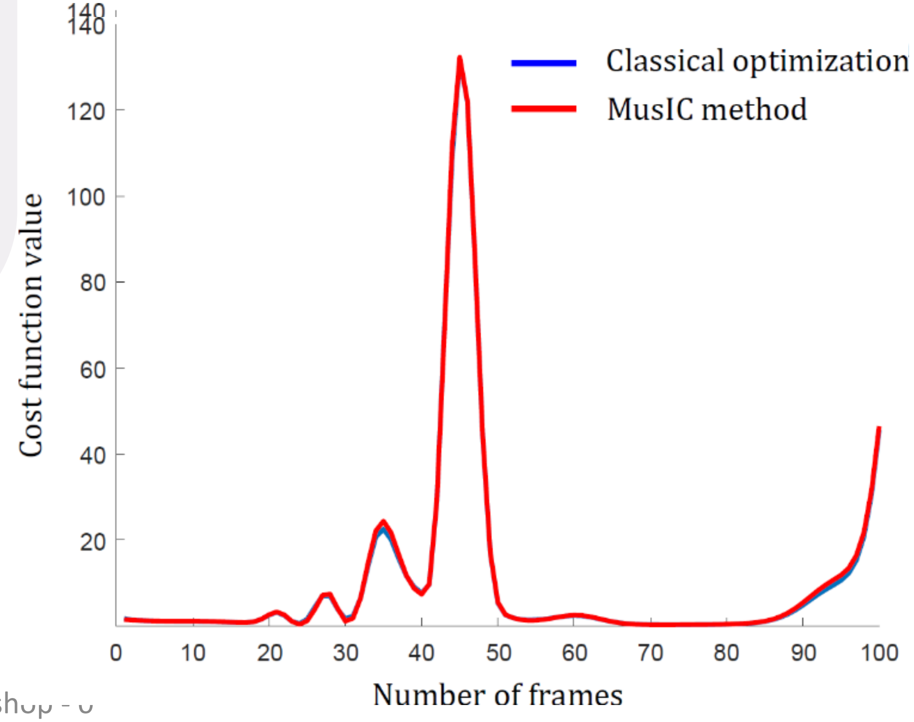


MusIC method



Computation frequency

- Optimisation: 1,6 Hz
- MusIC : 26 Hz



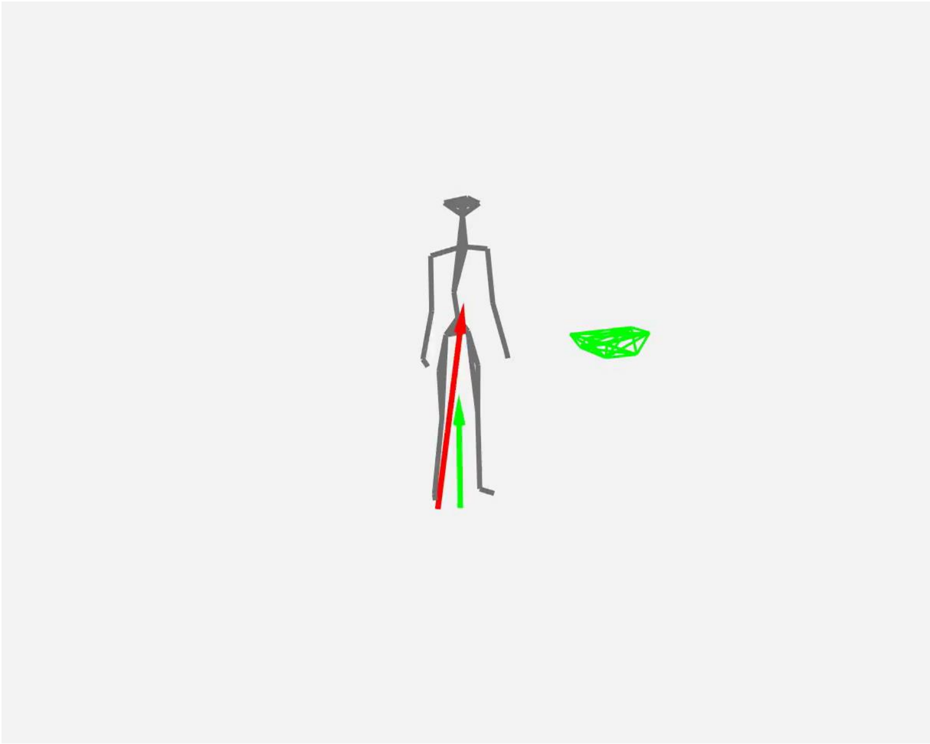
Force prediction

Contact forces prediction

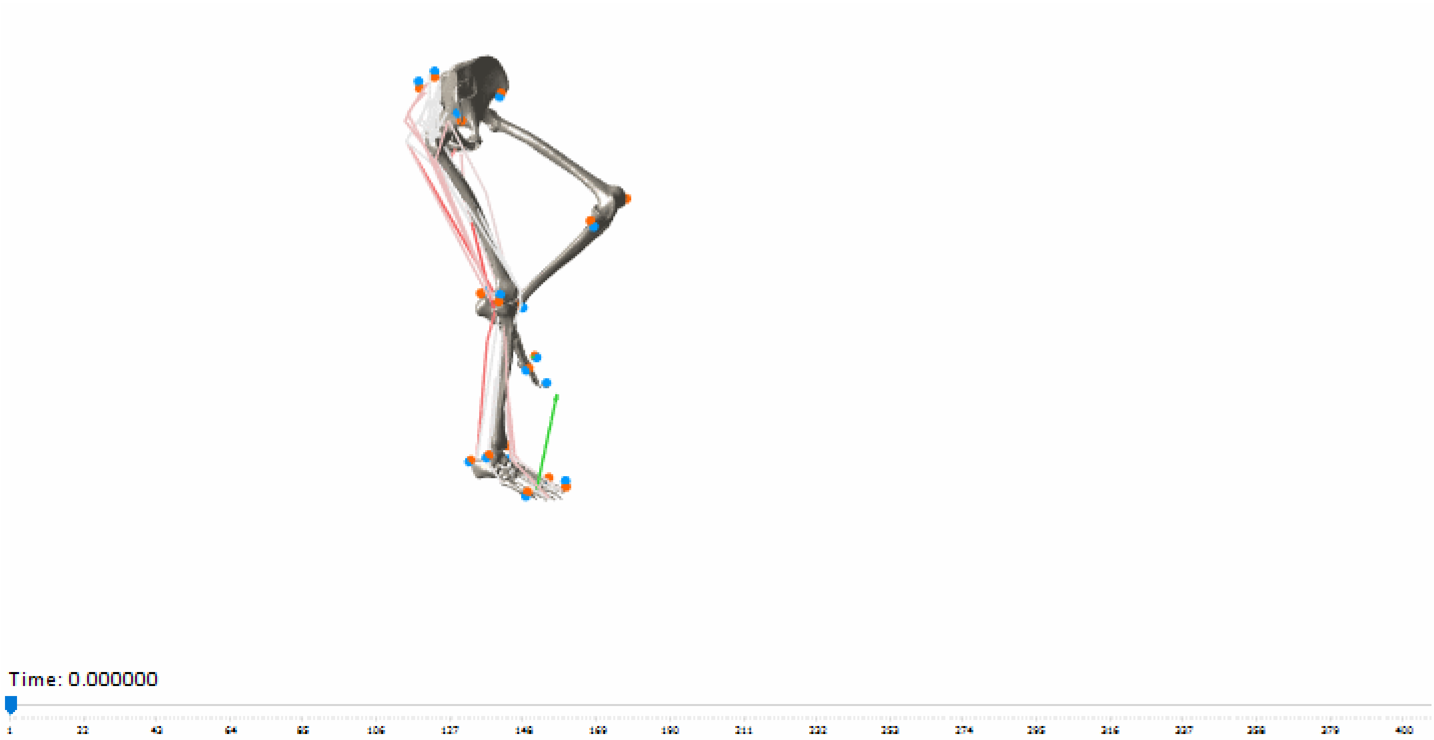
$$\min_{(\boldsymbol{\alpha},\boldsymbol{\beta},\boldsymbol{\gamma})} \sum_{i=1}^{2N_f} (\alpha_i^2 + \beta_i^2 + \gamma_i^2)$$

$$\text{t.q.} \quad \boldsymbol{M_s}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C_s}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{G_s}(\boldsymbol{q}) + \boldsymbol{\lambda_s} + \boldsymbol{E_s} = \boldsymbol{0};$$

$$\forall i \in [\![1, 2N_f]\!], (\alpha_i, \beta_i, \gamma_i) \in [-1, 1]^3$$



Vizualisation (thanks to GIBBON)



Now, let's learn how it works

Lesson #1: Kinematics and geometrical calibration
Lesson #2: Muscle forces estimation
Lesson #3: Force prediction and post-processing
Lesson #4: XSENS handling and model edition

References (work in and with CusToM)

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