JNRH'2023 : Journées Nationales de la Robotique Humanoïde
5-7 juil. 2023 Bordeaux (France)

Muscle modeling: a short introduction

Charles Pontonnier

(thanks to Nicolas Bideau & Claire Livet for sharing some slides)

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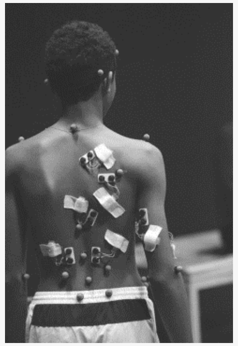
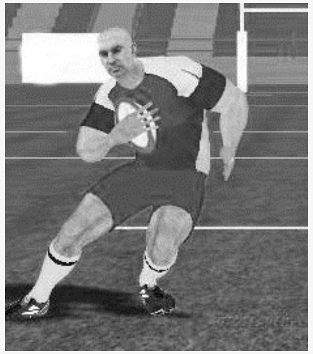
Motion analysis



Motion analysis in complex environments and ecological conditions

Autonomous virtual humans



Simulation/motion synthesis

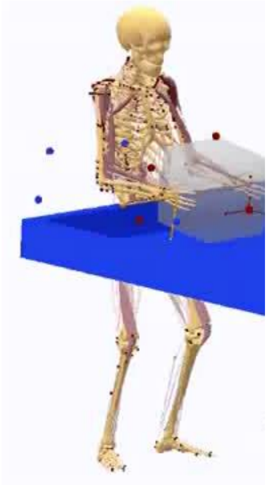
Physical activity in virtual reality

Analysis/synthesis control
Sport training

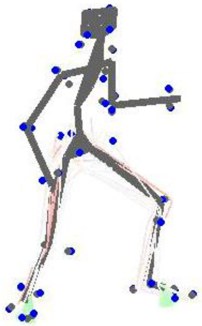
Musculoskeletal Analysis

[Pouliquen2015]

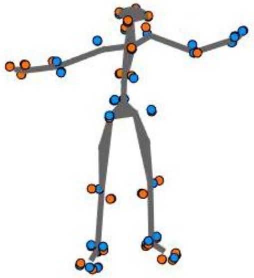
[Damsgaard2006]

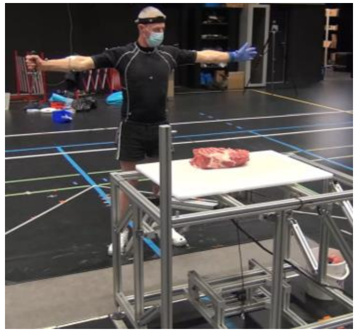


[Murai2010]

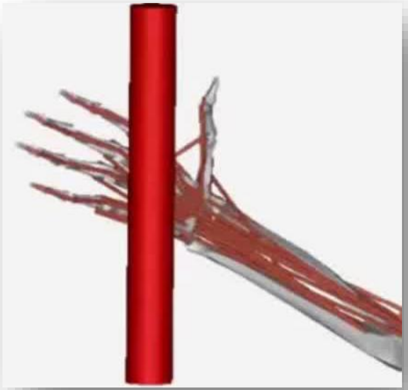


[Pontonnier2019]





[Chander2022]



[Vignais2014]

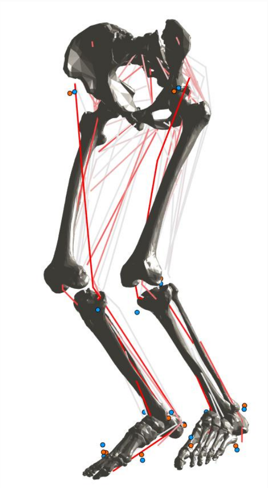
Musculoskeletal analysis

Get biomechanical quantities from motion and force data

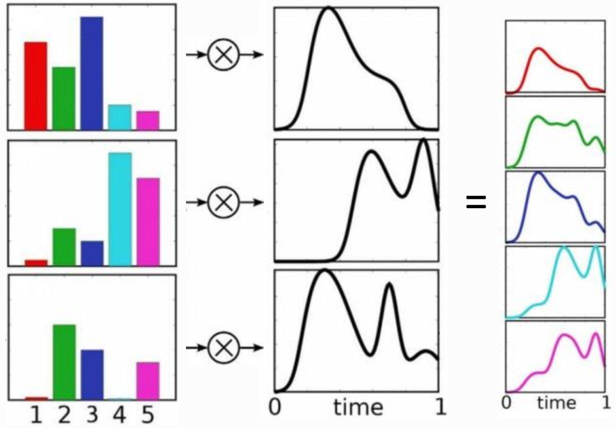
Motion data

Force data

$M(\boldsymbol{q})\ddot{\boldsymbol{q}} + C(\boldsymbol{q},\dot{\boldsymbol{q}}) = \boldsymbol{\tau} + \boldsymbol{F}_{\boldsymbol{ext}}$ *Equations of motion*



MS model



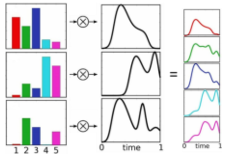
Motor control model

Joint quantities
(angles, torques, joint compression forces)

Muscle quantities
(lengths, forces, activations)

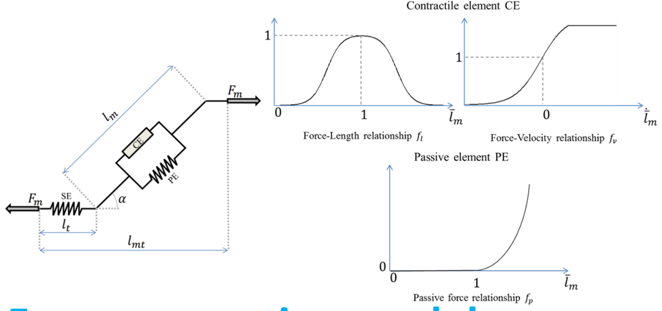
Scientific issues

[And some PhD related work]



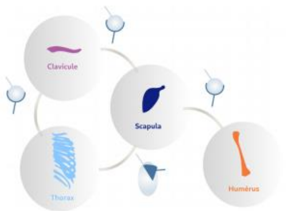
Motor control models

[Livet 2022]
[Morin 2023]



Force generation model

[Puchaud 2020]
[Livet 2022]



Osteoarticular model

[Muller 2017]
[Puchaud 2020]
[Livet 2022]
[Rouvier 2023]

$$\min_{\boldsymbol{F},\boldsymbol{\lambda}} f(\boldsymbol{F})$$

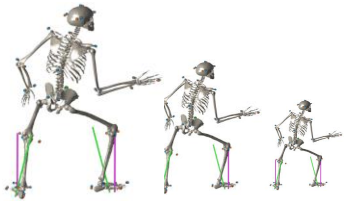
s.t. $$H(\boldsymbol{q})\ddot{\boldsymbol{q}} + C(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + G(\boldsymbol{q}) = \boldsymbol{f_e} + \boldsymbol{RF} + \boldsymbol{K^t\lambda}$$

$$\boldsymbol{h}(\boldsymbol{F}) = \boldsymbol{0}$$

Muscle redudancy

$\boldsymbol{F} > \boldsymbol{q}$

[Muller 2017]
[Livet 2022]

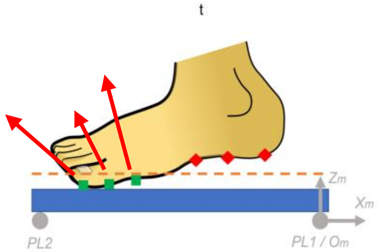


Model calibration

[Muller 2017]
[Puchaud 2020]
[Livet 2022]

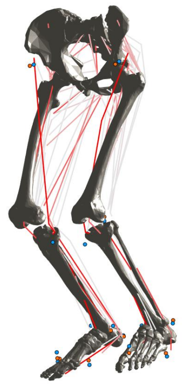
External forces estimation

[Muller 2017]
[Demestre 2022]
[Morin 2023]



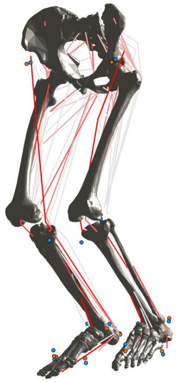
Muscle path

[Puchaud 2020]
[Livet 2022]
[Rouvier 2023]



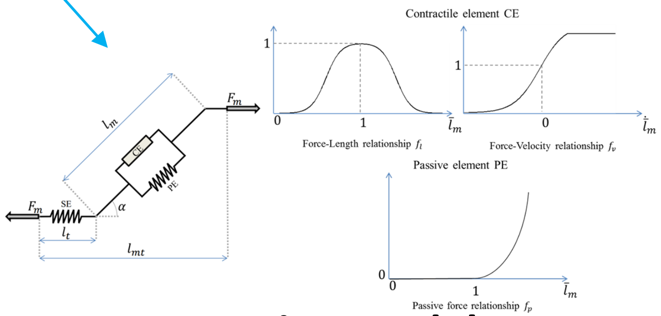
Aim

Striated skeletal muscles



Muscle path

[Puchaud 2020]
[Livet 2022]
[Rouvier 2023]

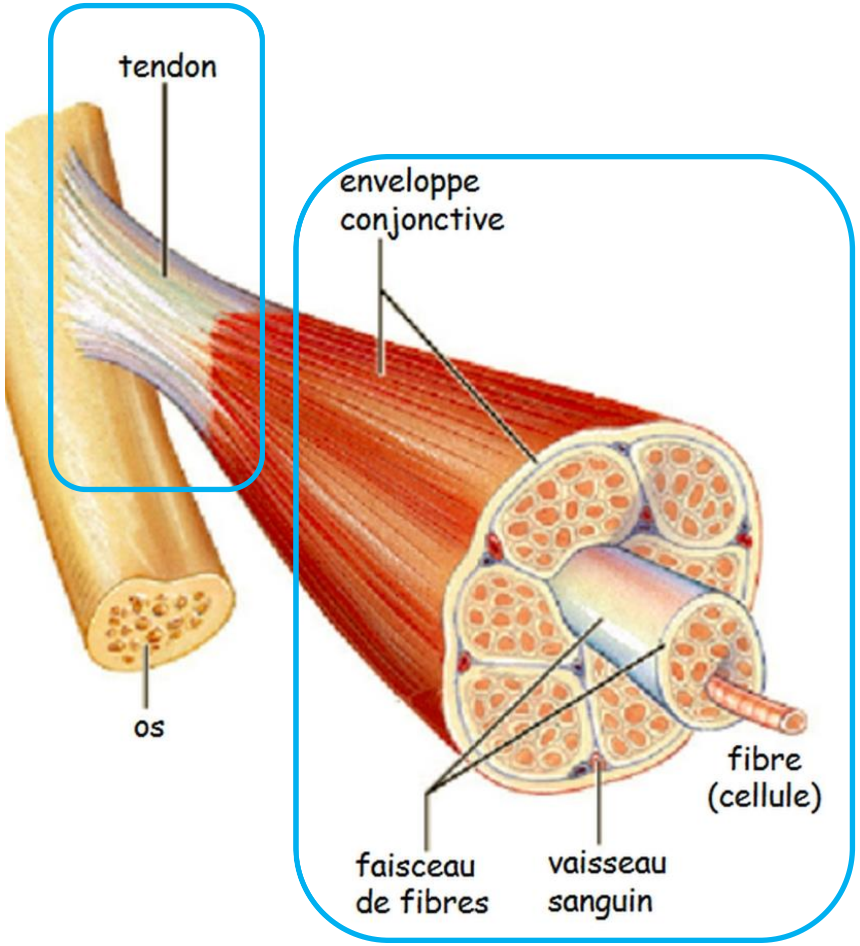


Force generation model

[Puchaud 2020]
[Livet 2022]

Striated skeletal muscles (short)

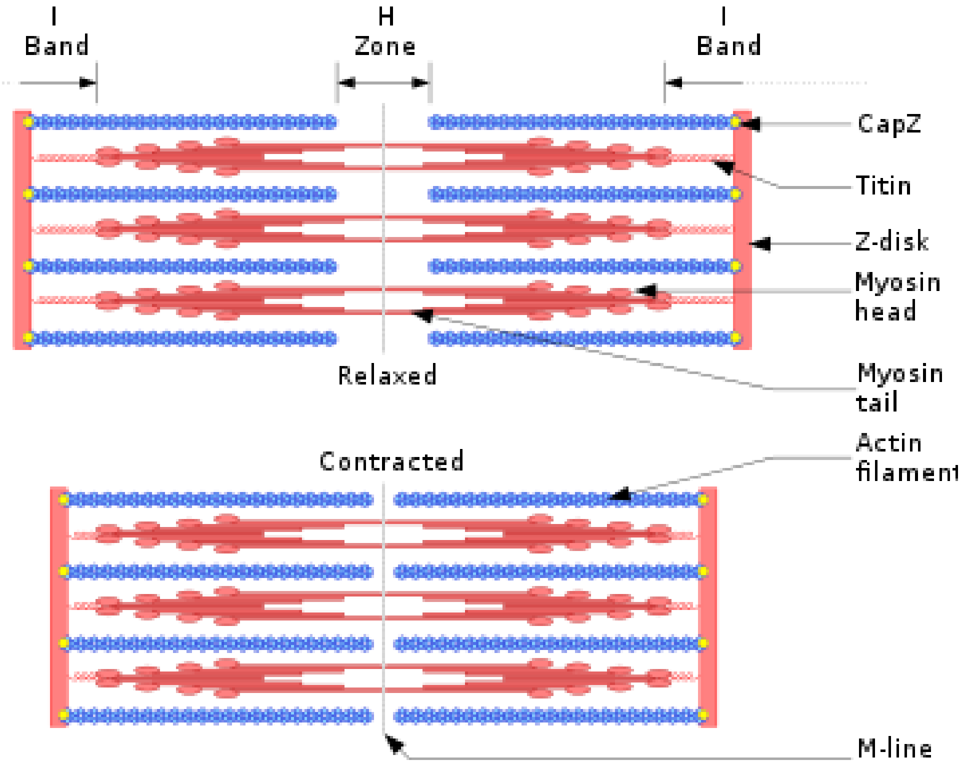
Musculotendon system



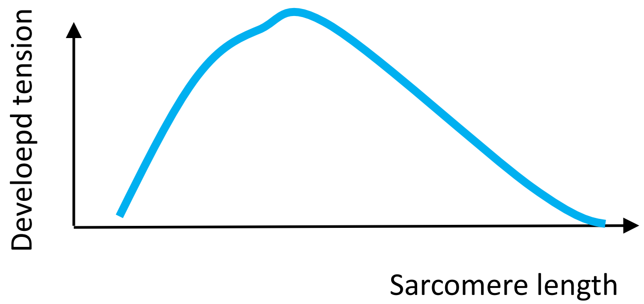
d'après Benjamin Cummings (2001)

- Tendinous tissue **Passive**
- Muscle tissue **Active**

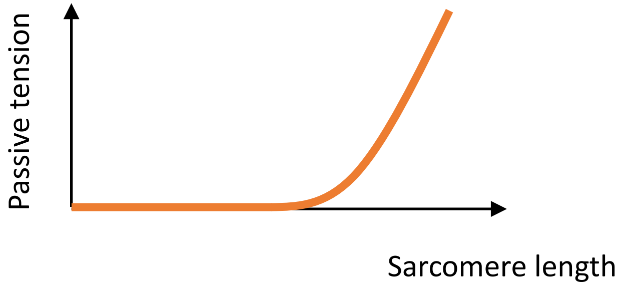
Sarcomere



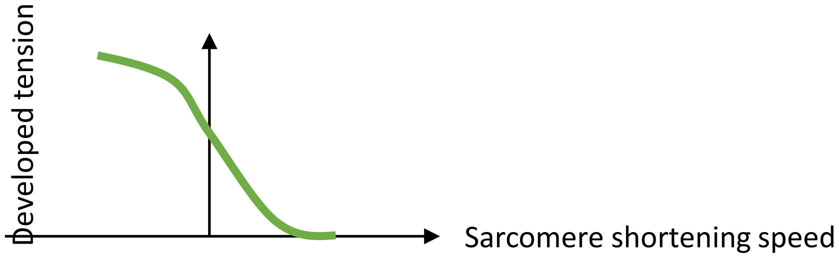
Calcium ions disinhibit the actin-myosin interaction



The active force (length) is generated by the actin-myosin cross-bridges

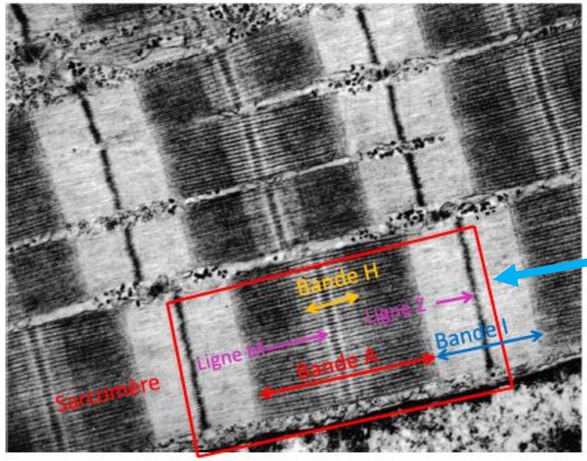


The passive force is generated by the titin lenghtening

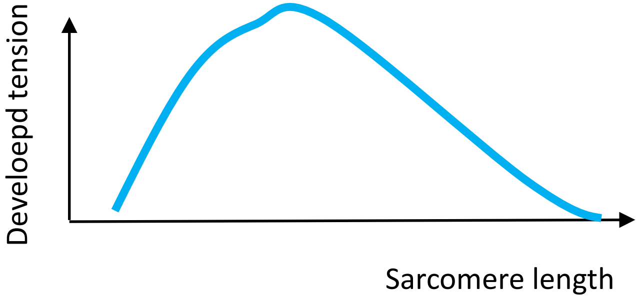


The active force (velocity) is generated by the difference in sarcomere shortening speed and the cross-bridge creation rate

Skeletal striated muscle



Sarcomeres are assembled in parallel and serial structures → similar behavior at the muscle scale



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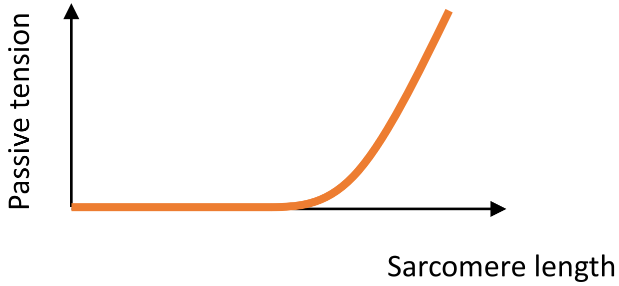

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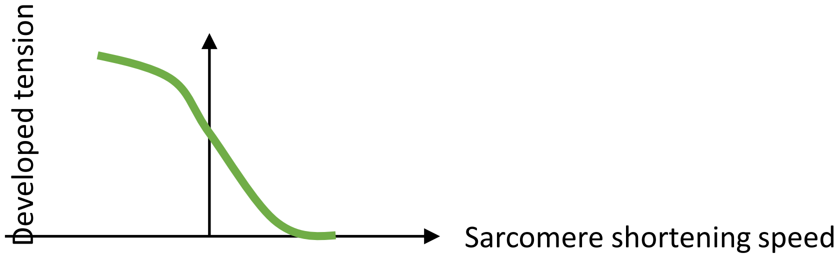
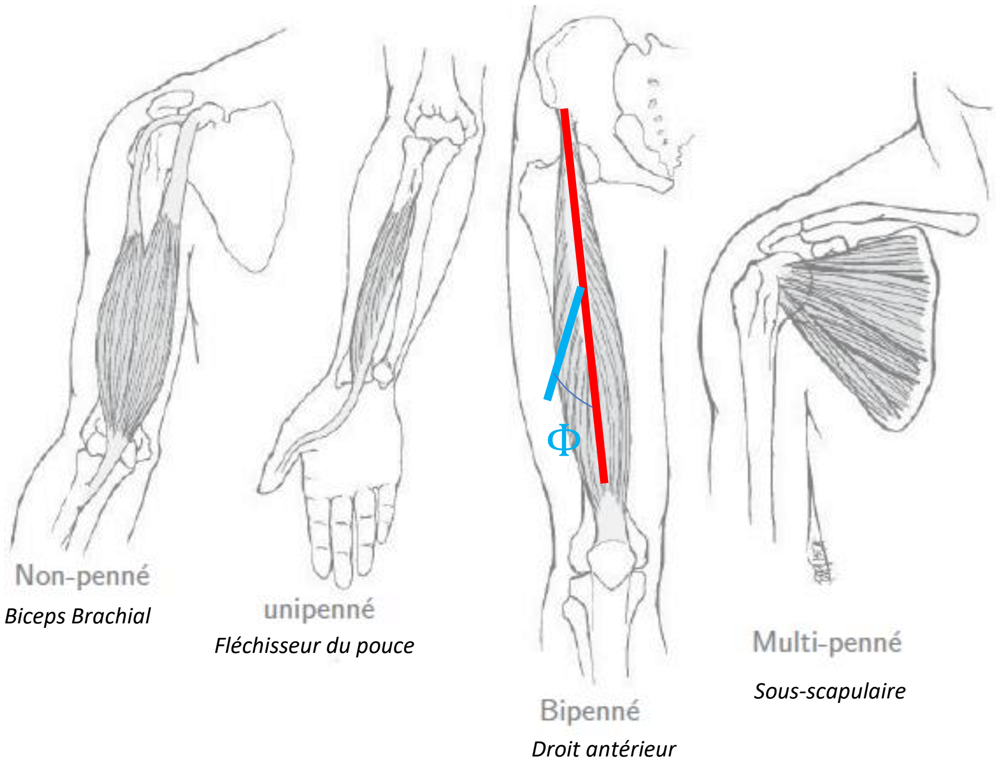


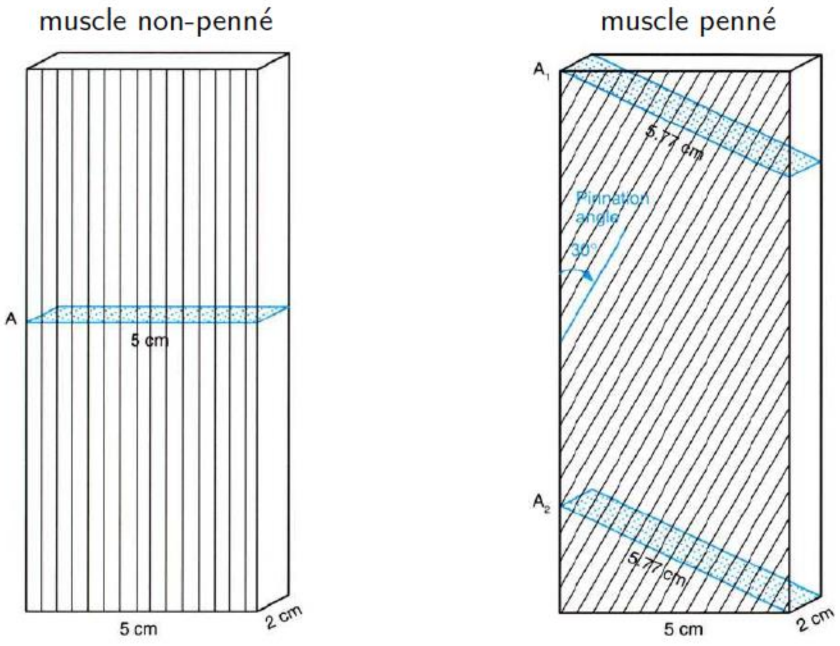
The active force (velocity) is generated by the difference in sarcomere shortening speed and the cross-bridge creation rate

Fiber orientation & PCSA

The fiber orientation is not always the same as the muscle action line (pennate muscle)

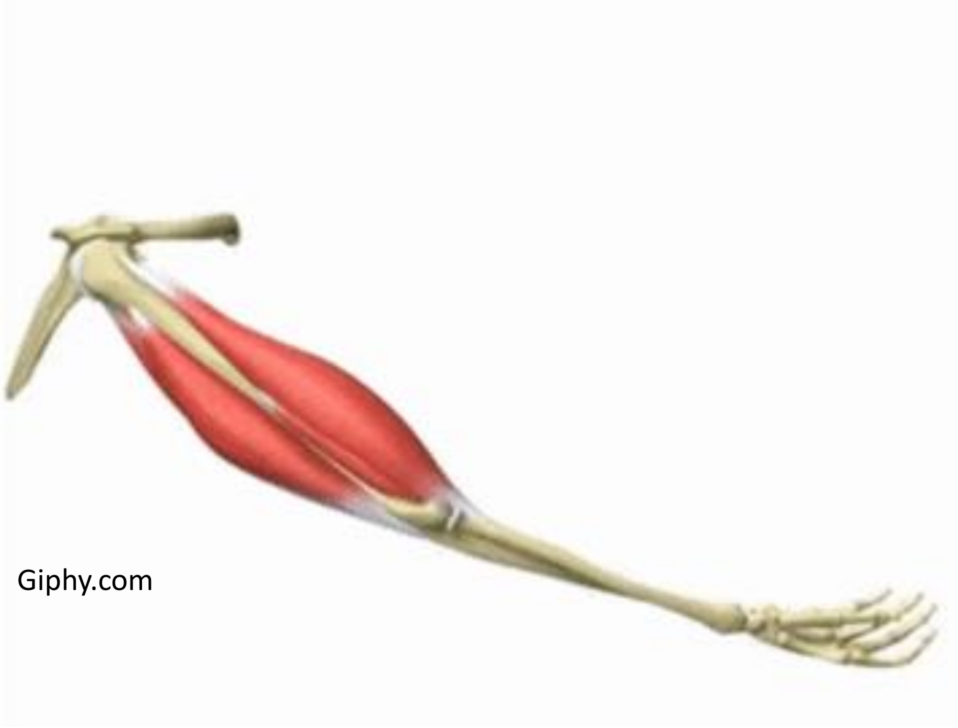


Φ optimal length pennation angle



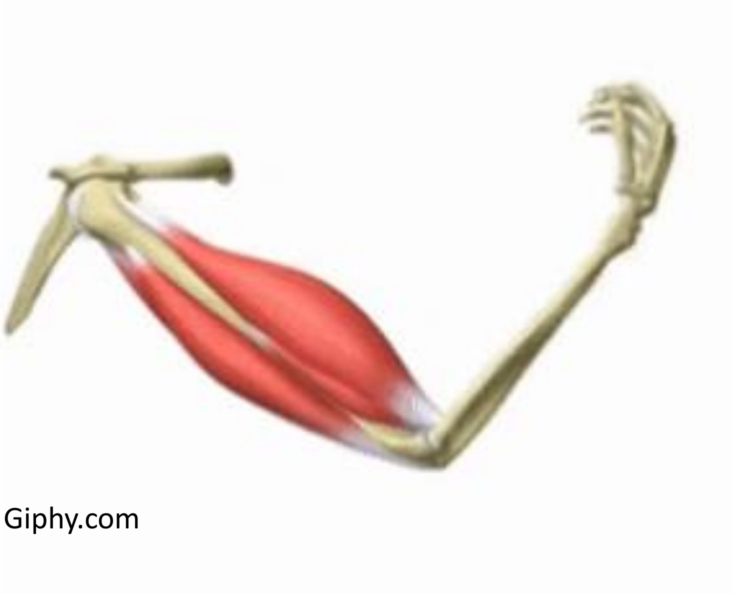
Pennate muscles exhibit higher PCSA

Striated skeletal muscles as actuators

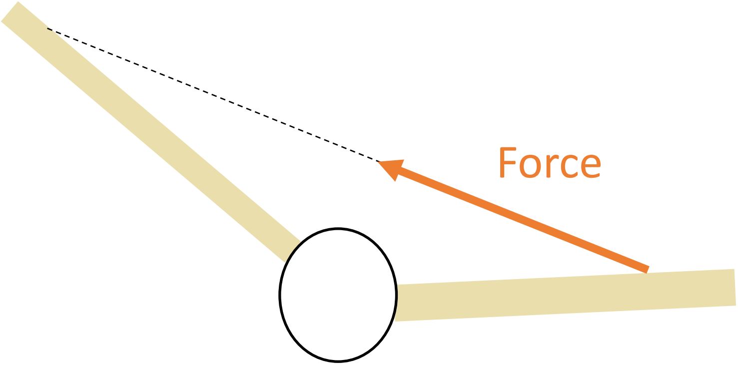


Giphy.com

Striated skeletal muscles as actuators



Giphy.com



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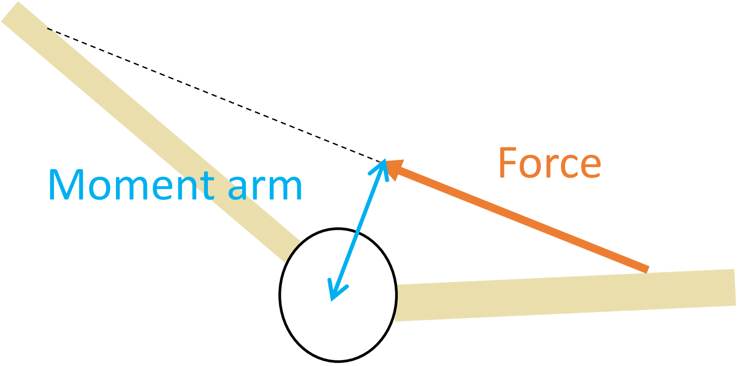

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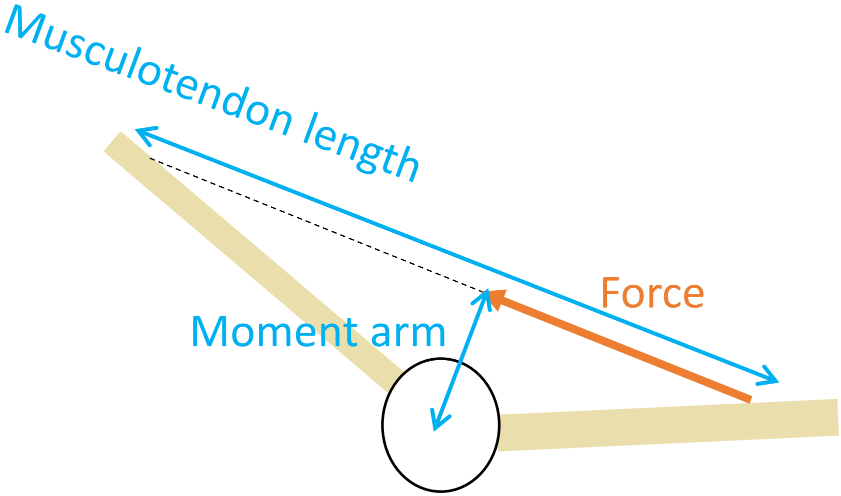

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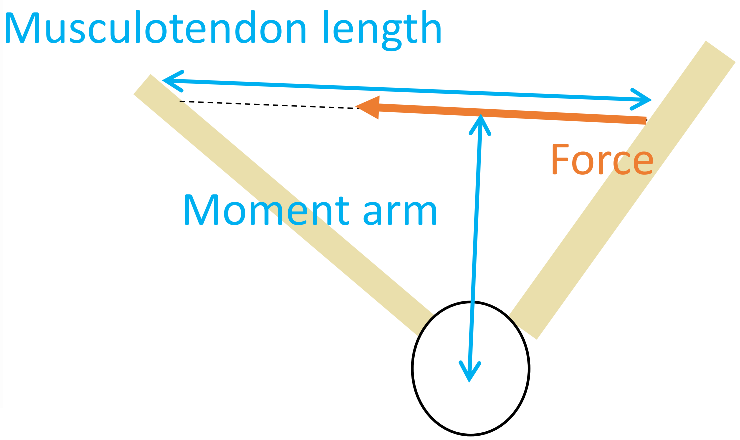
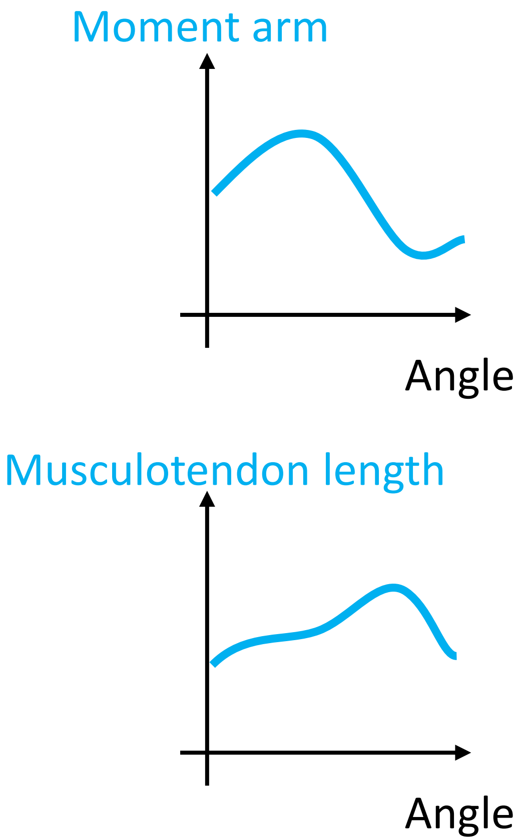
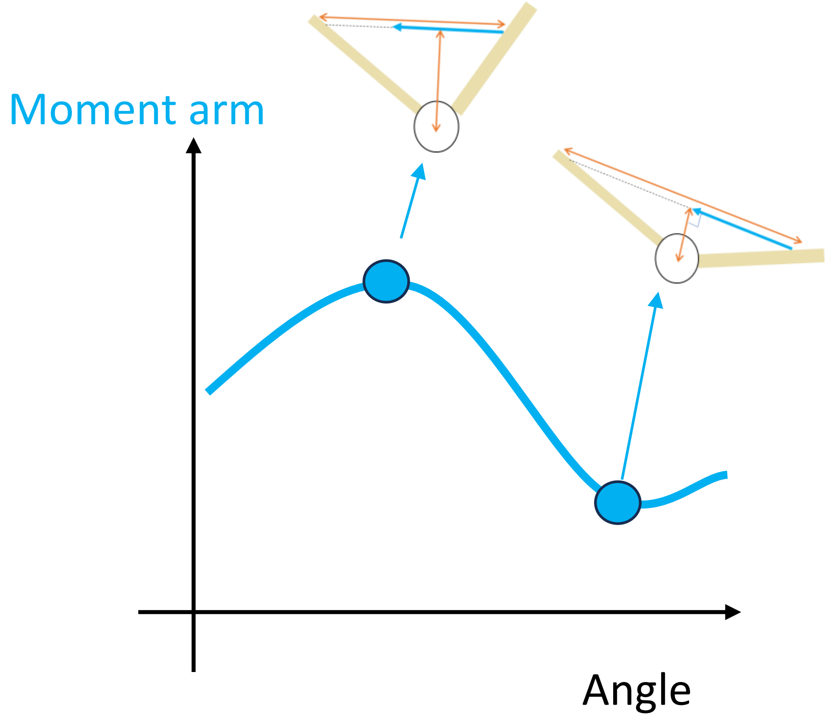
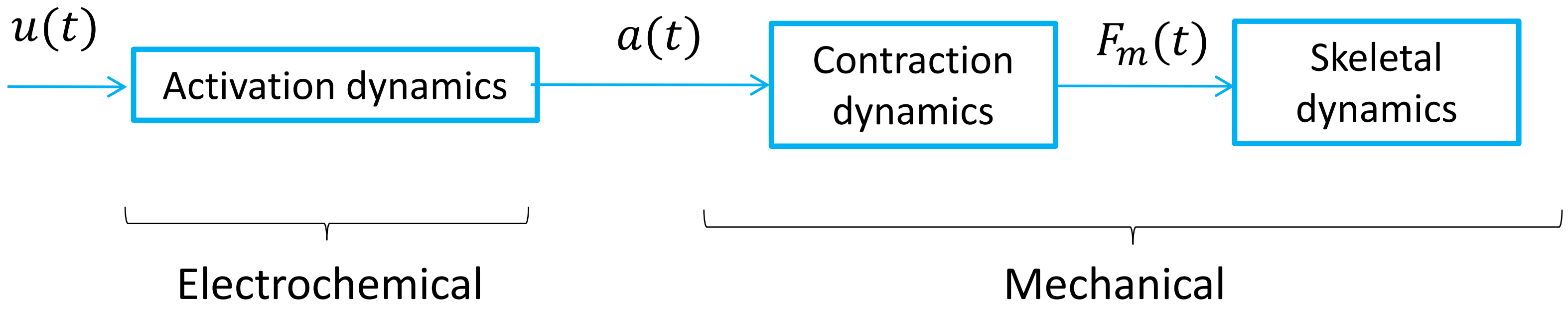




Striated skeletal muscles as actuators

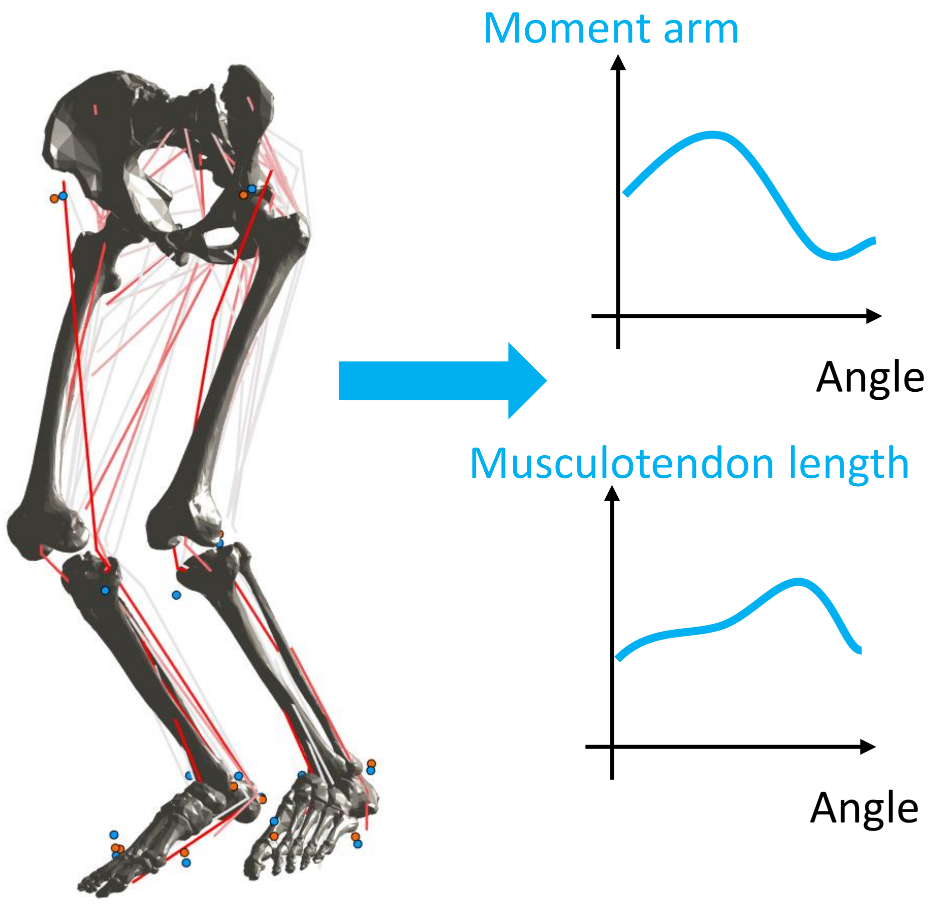
- Linear actuator acting on revolute joints (non linear moment arm)
- Non-linear visco-elastic force generation behavior
- Multiscale actuation dynamics





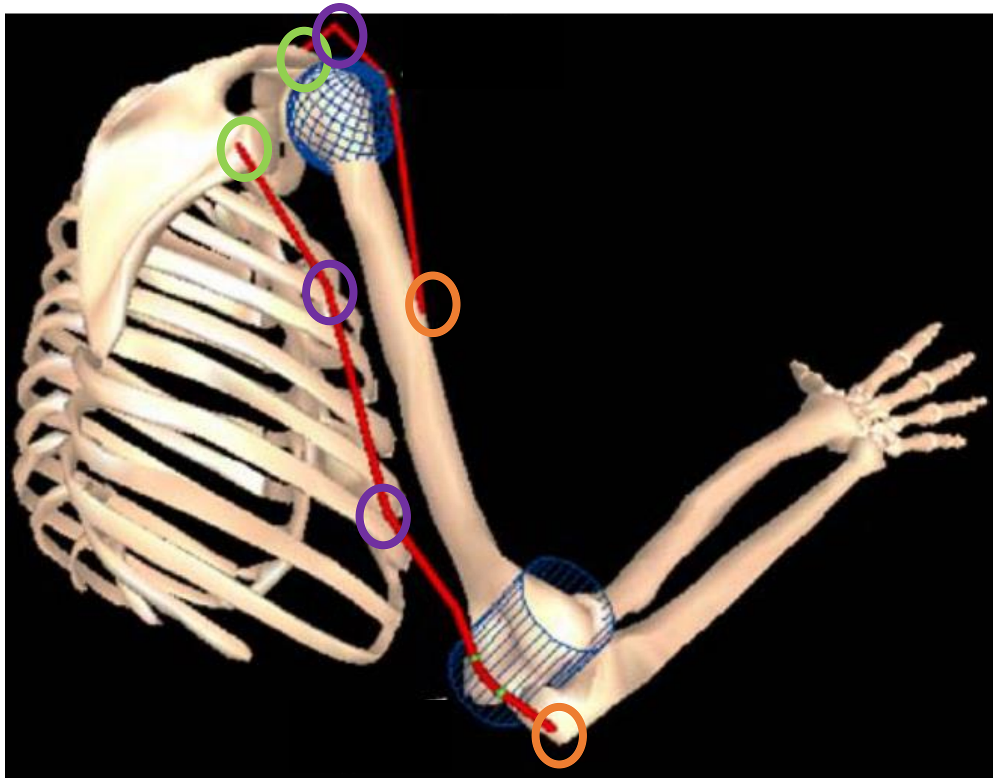
Muscle path

[Puchaud 2020]
[Livet 2022]
[Rouvier 2023]



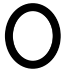
Muscle path

Muscles are divided into heads (independently from their actual chiefs)
Each head has a path defined by **an origin, an insertion** and **some path elements mimicking obstacles (bones, soft tissues, muscle volume)**

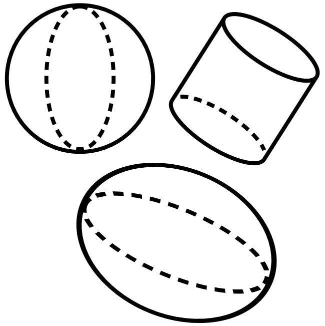


[Gatti2009]

[Favre2010]



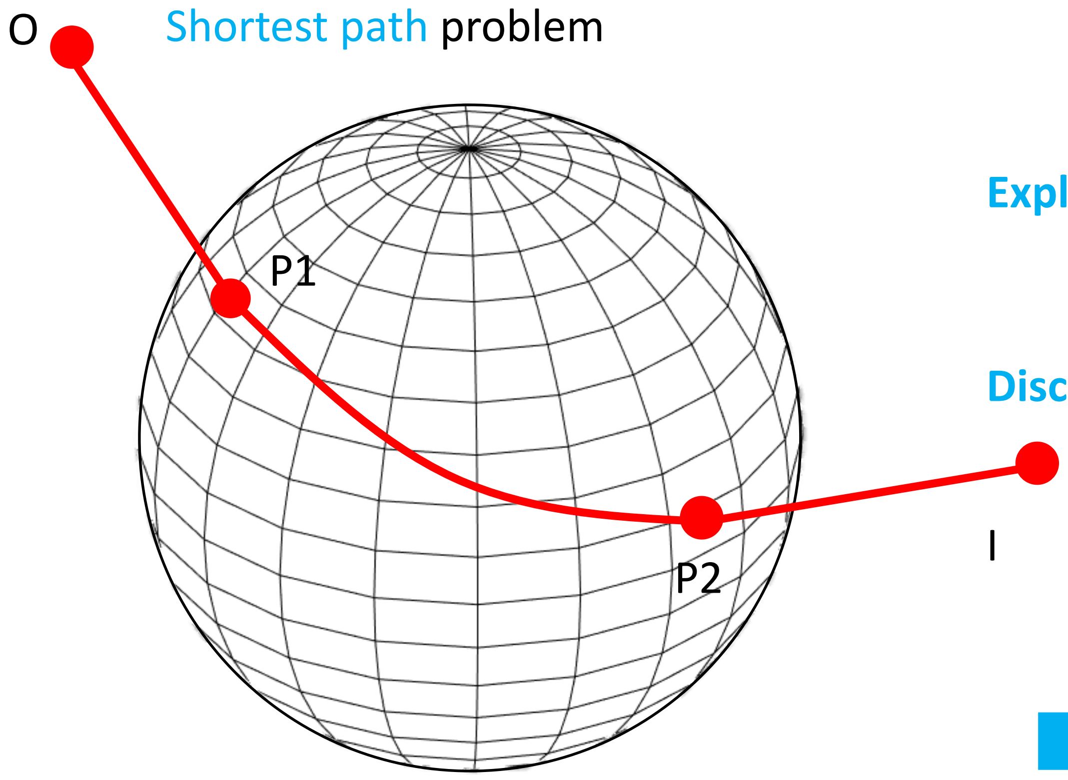
Via points



Wrapping objects (wraps)

Wrapping objects (wraps)

Shortest path problem



Explicit methods

+ continuous derivatives
- simple geometries, multiple obstacles, computation cost

Discrete methods

+ fast, multiple obstacles, applicable to meshes
- discontinuous derivatives (muscle state)

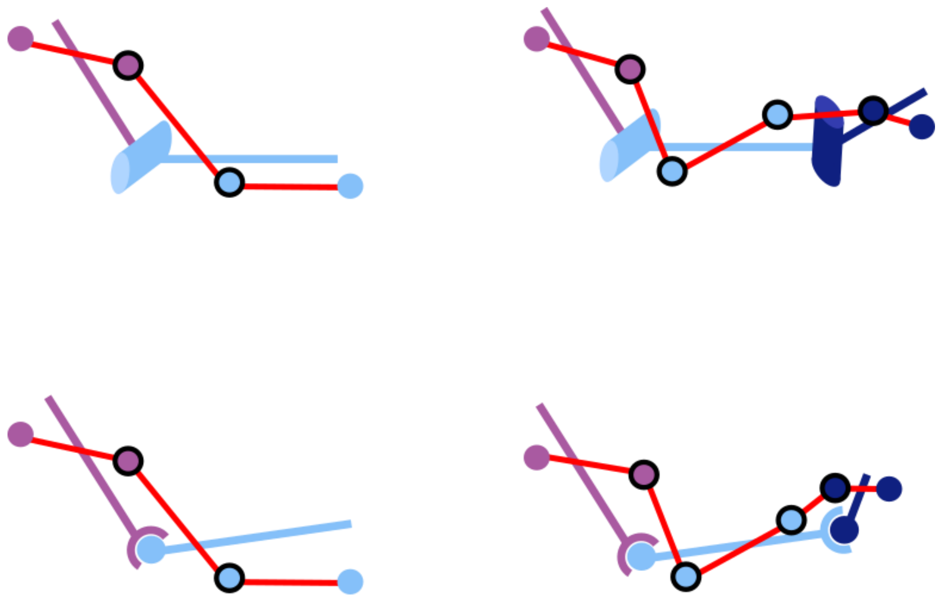
How to scale that ?

Scholz, A. (2016). *Fast differential-geometric methods for continuous muscle wrapping over multiple general surfaces* (Doctoral dissertation, Duisburg, Essen, 2016).

Systematic via points
[Livet et al. 2022]

A generic and systematic muscle path without wraps

2 via points per dof



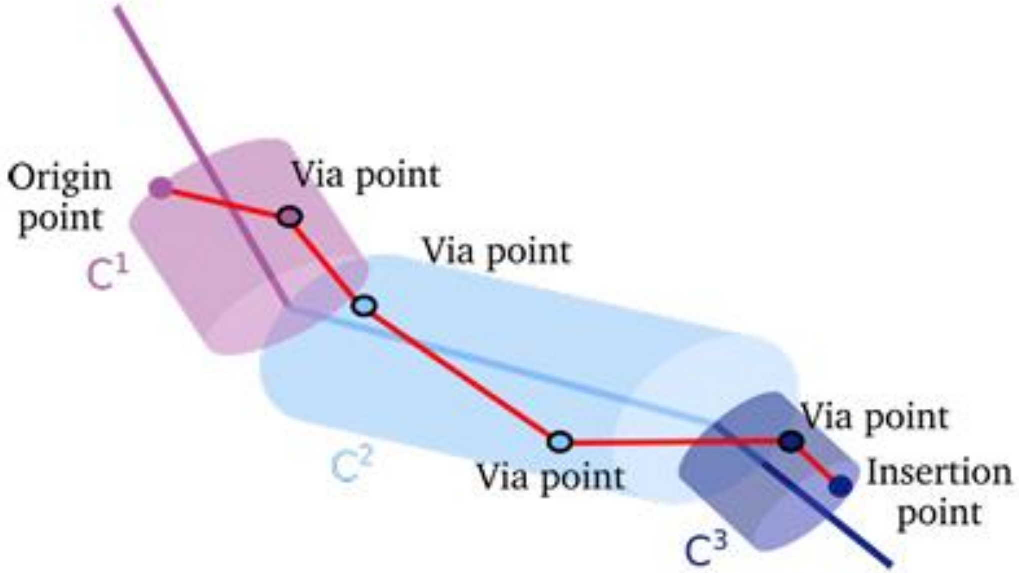
Livet, C., Rouvier, T., Dumont, G., & Pontonnier, C. (2022). An Automatic and Simplified Approach to Muscle Path Modeling. *Journal of Biomechanical Engineering*, *144*(1), 014502.

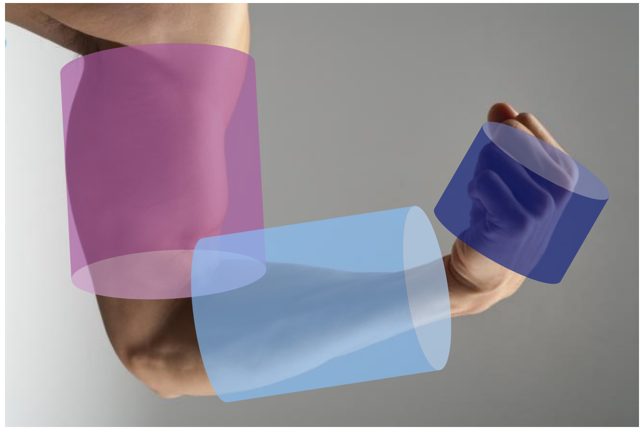
Systematic via points

A generic and systematic muscle path without wraps

2 via points per dof

All via points included into the segment volume



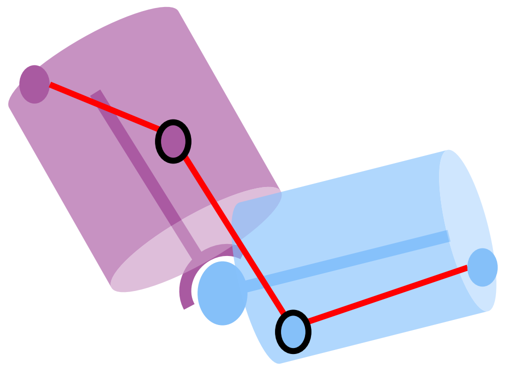


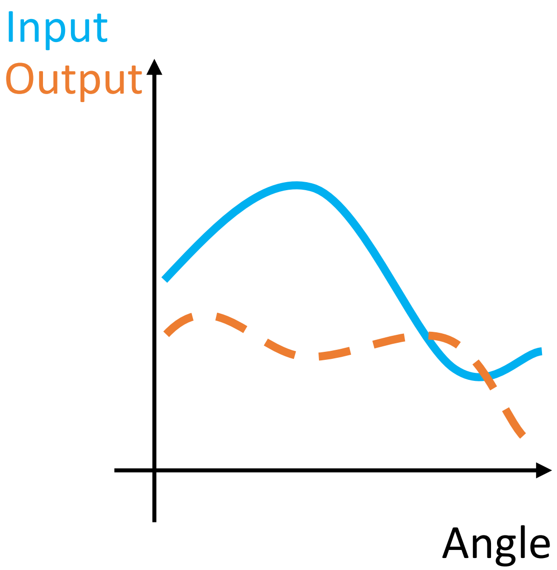
Pixabay.com

Systematic via points

Moment arm optimization

Placing via points into the segment volume to follow the moment arm





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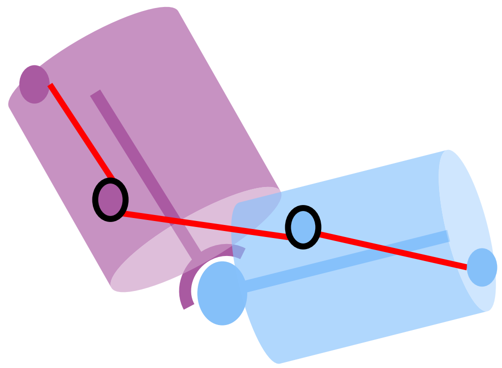

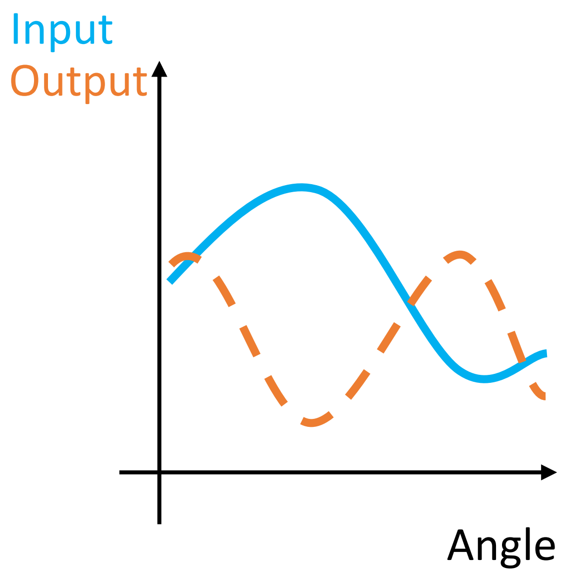

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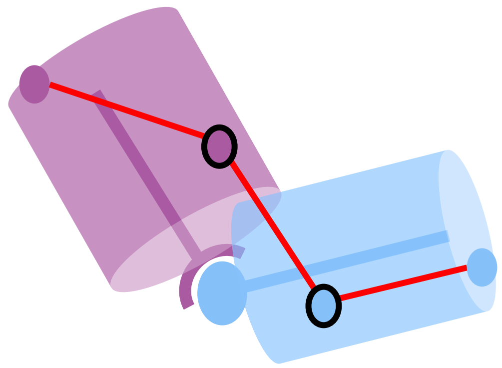

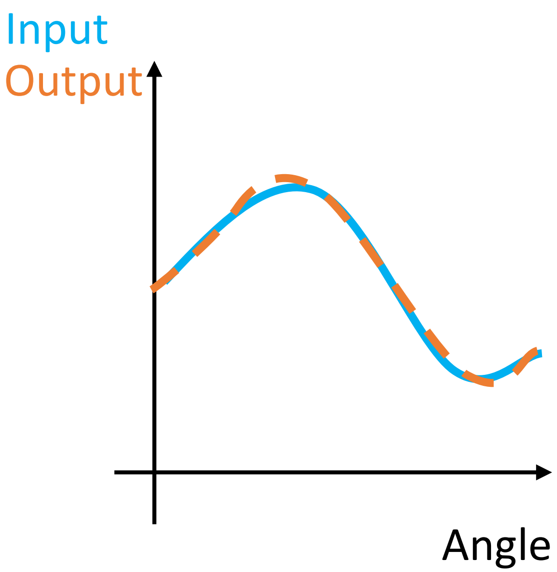

Systematic via points

Musculotendon length

- Moment arm = derivative of the length with regard to the angle
- A correct moment arm means a correct length to within a constant

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Optimisation of the musculotendon length

- Placing origin and insertion points at a corrected distance of the via points

Systematic via points

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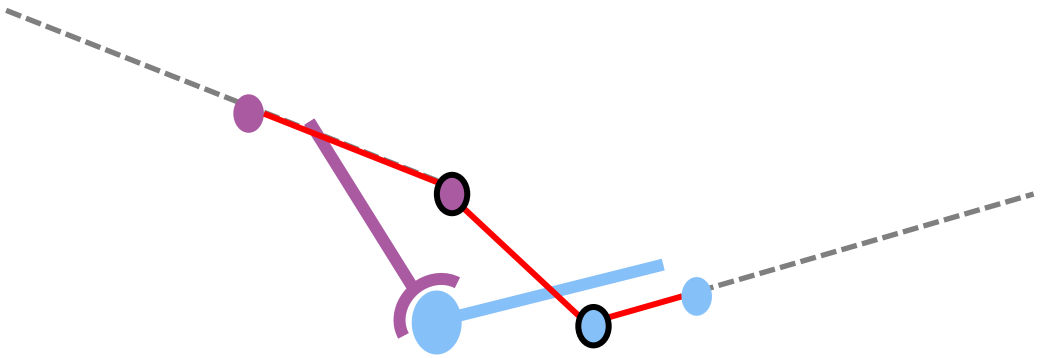

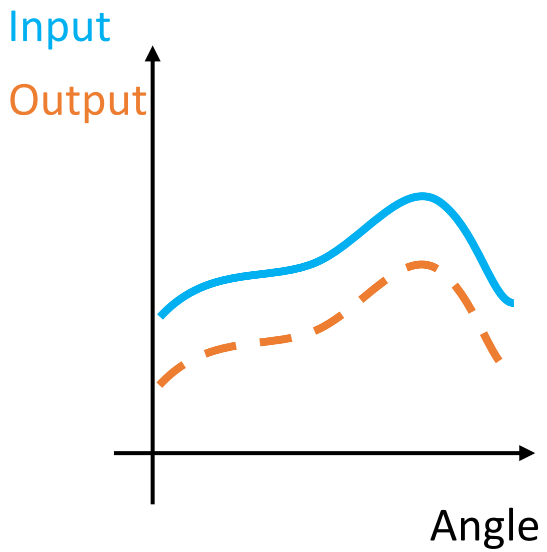

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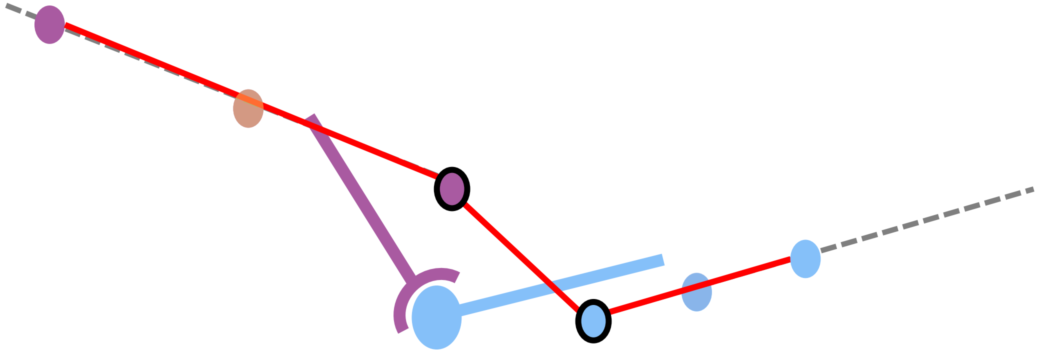

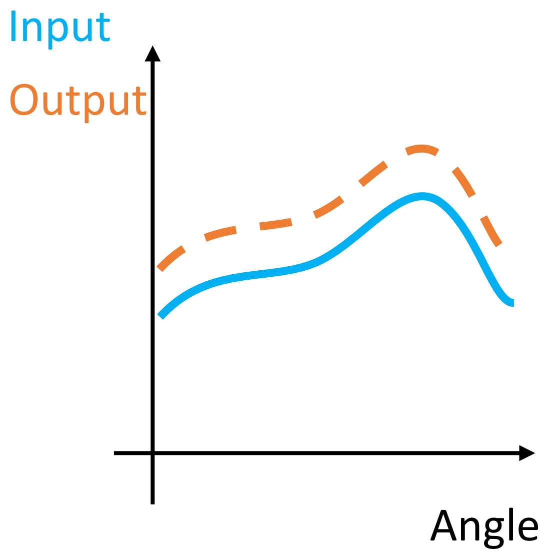

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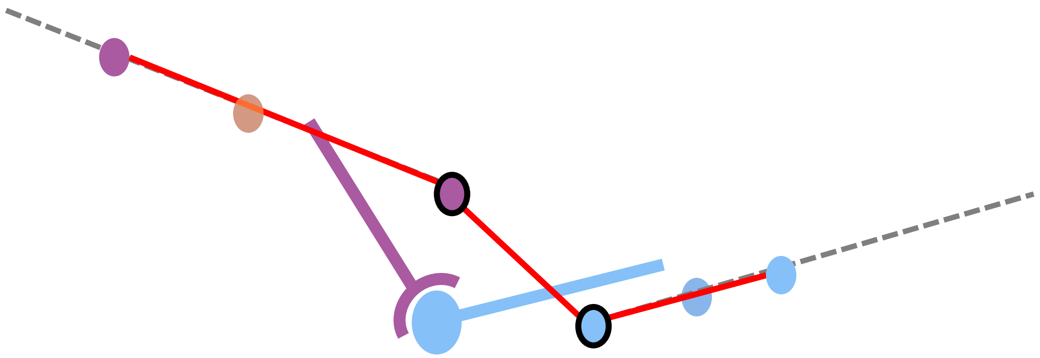
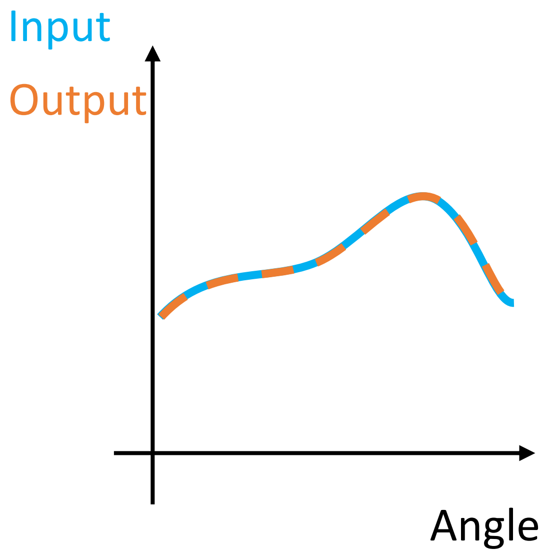
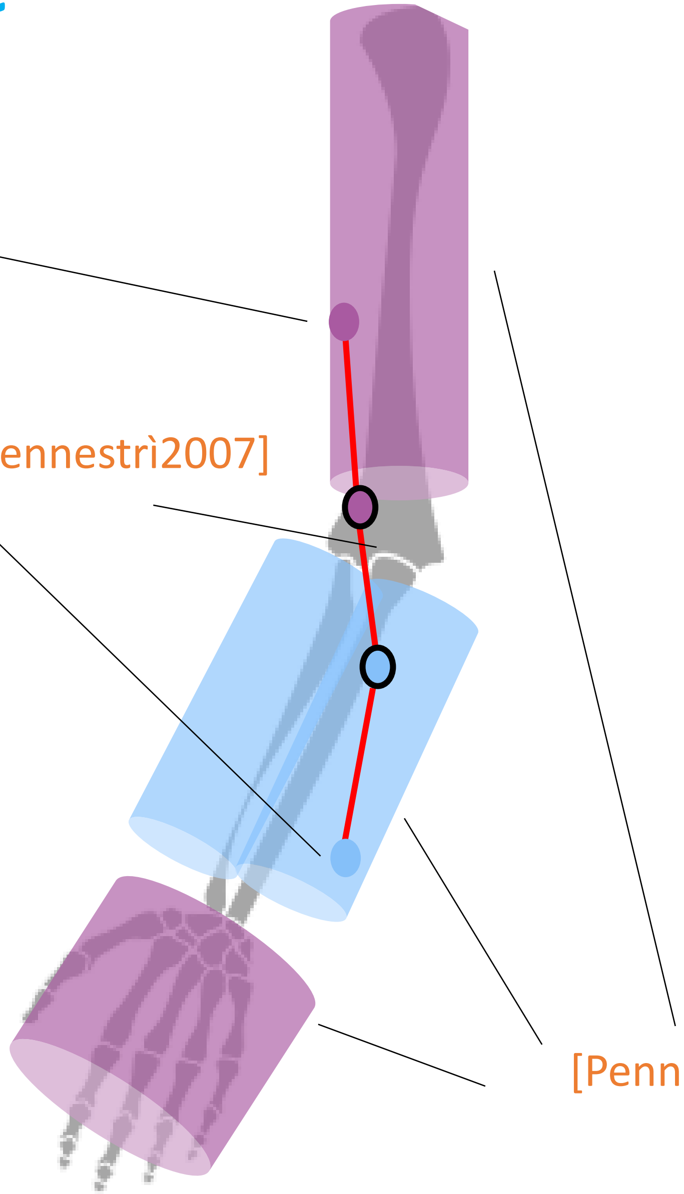
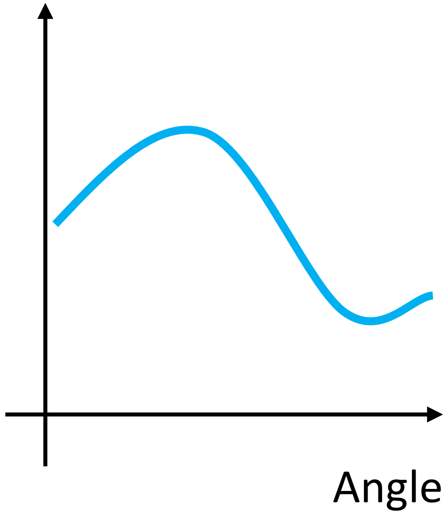




Example



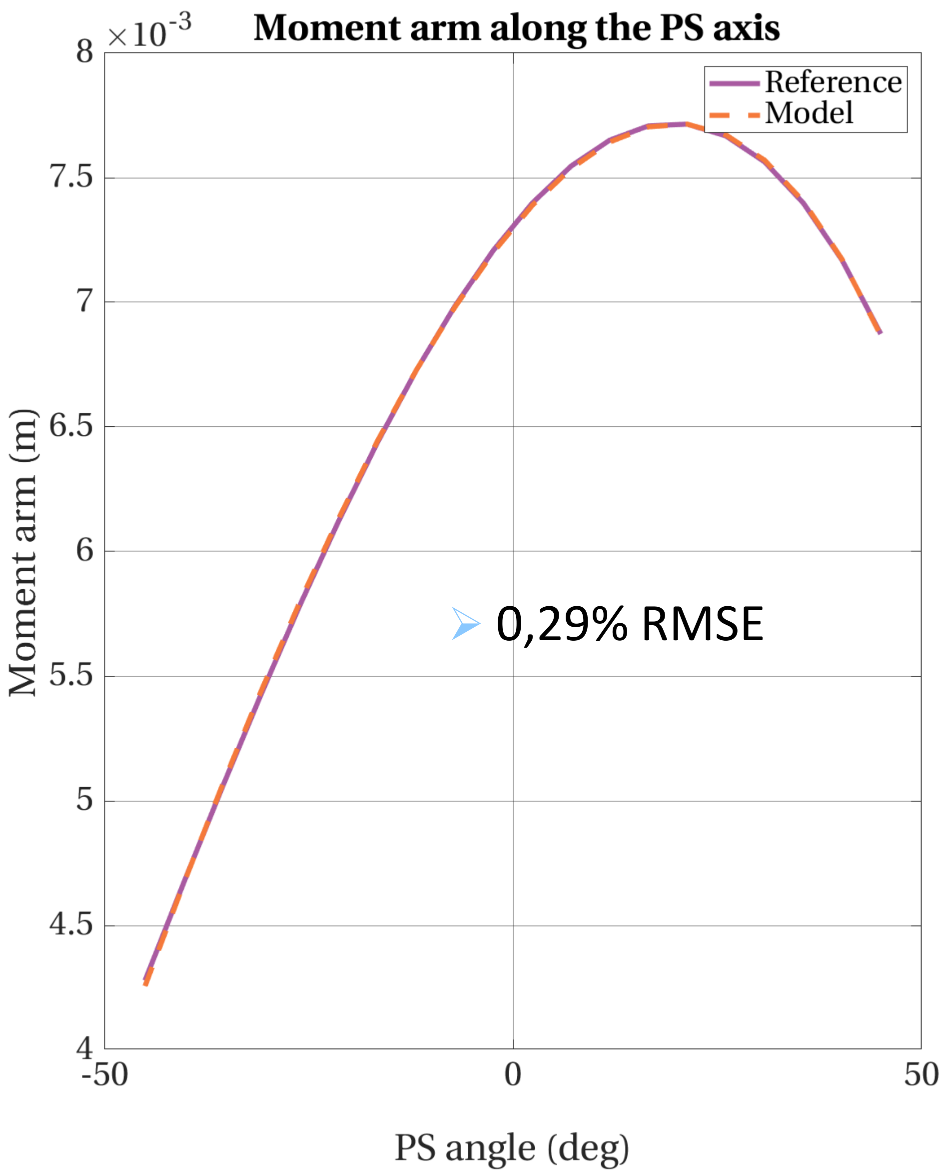
[Holzbaur2005]
[Pennestrì2007]
[Pennestrì2007,Dumas2007,Yeadon1990,Holzbaur2005]

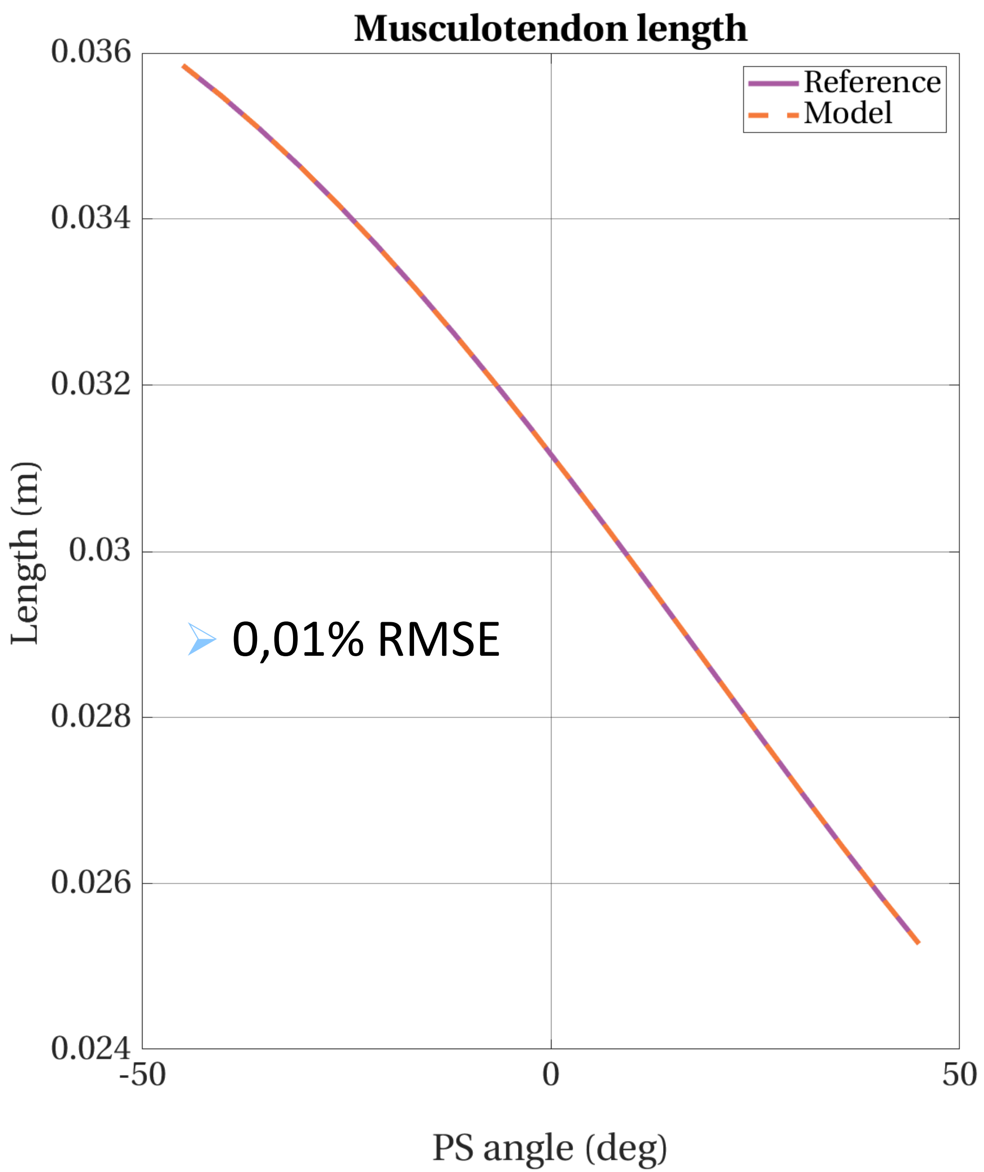


Musculotendinous data
[Rankin2012]
Angle

Results

Pronator Quadratus (2 obstacles)

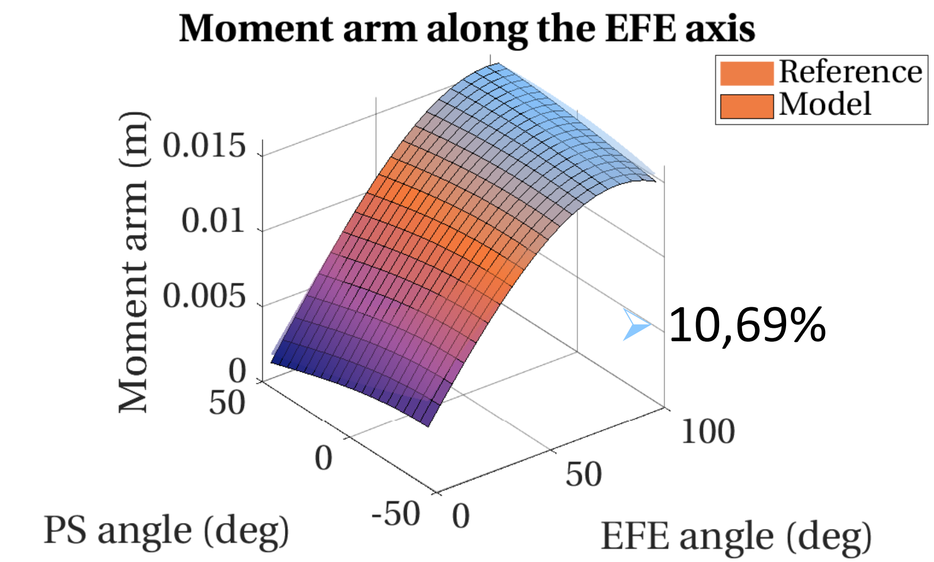




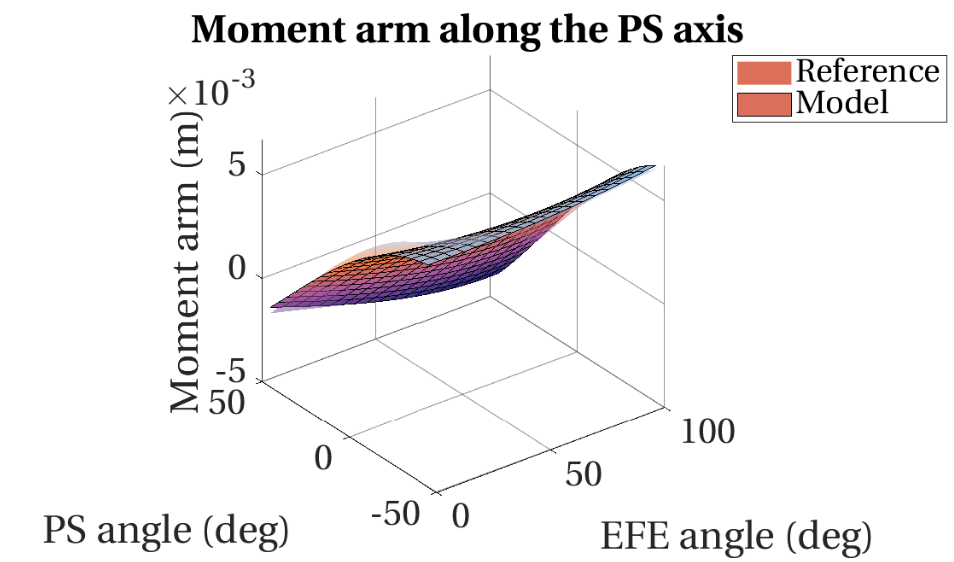
Results

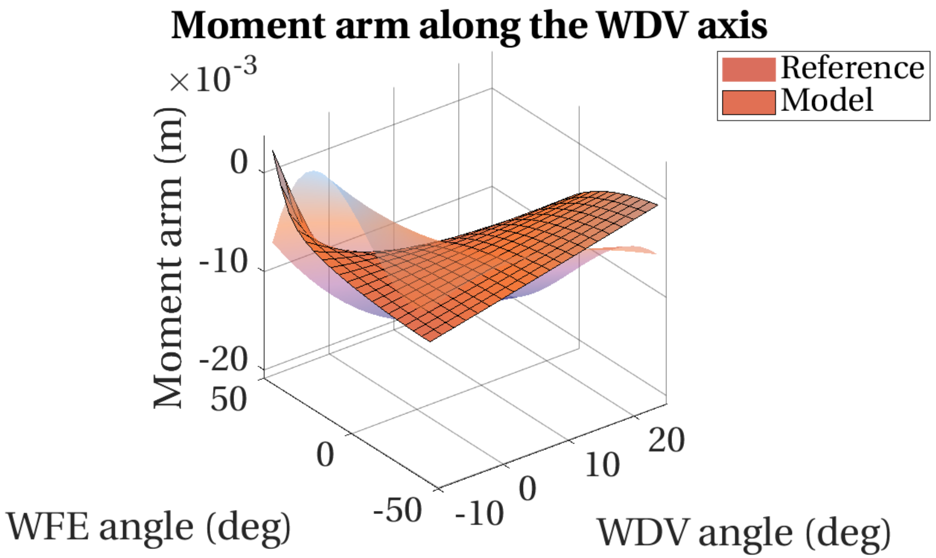
Palmaris Longus

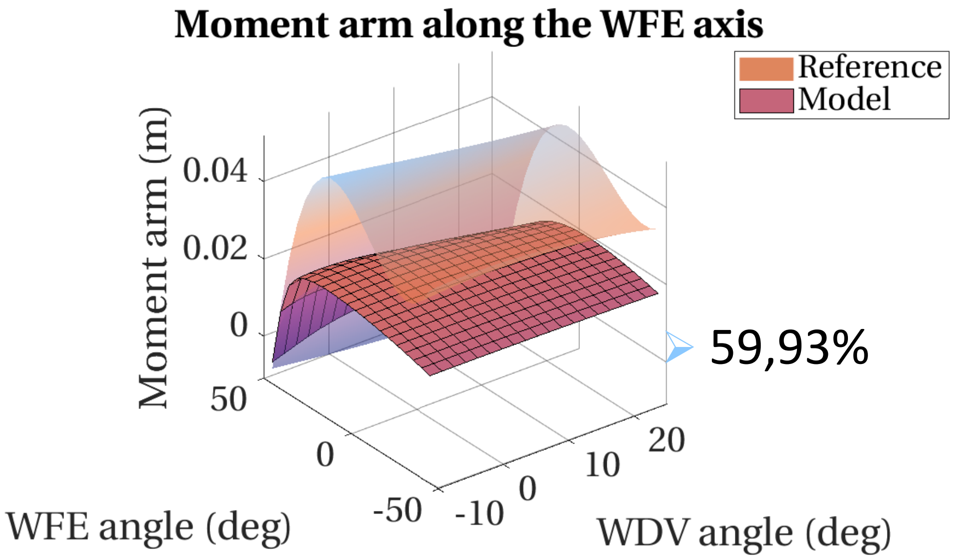
(2 obstacles + 2 via points)



10,69%



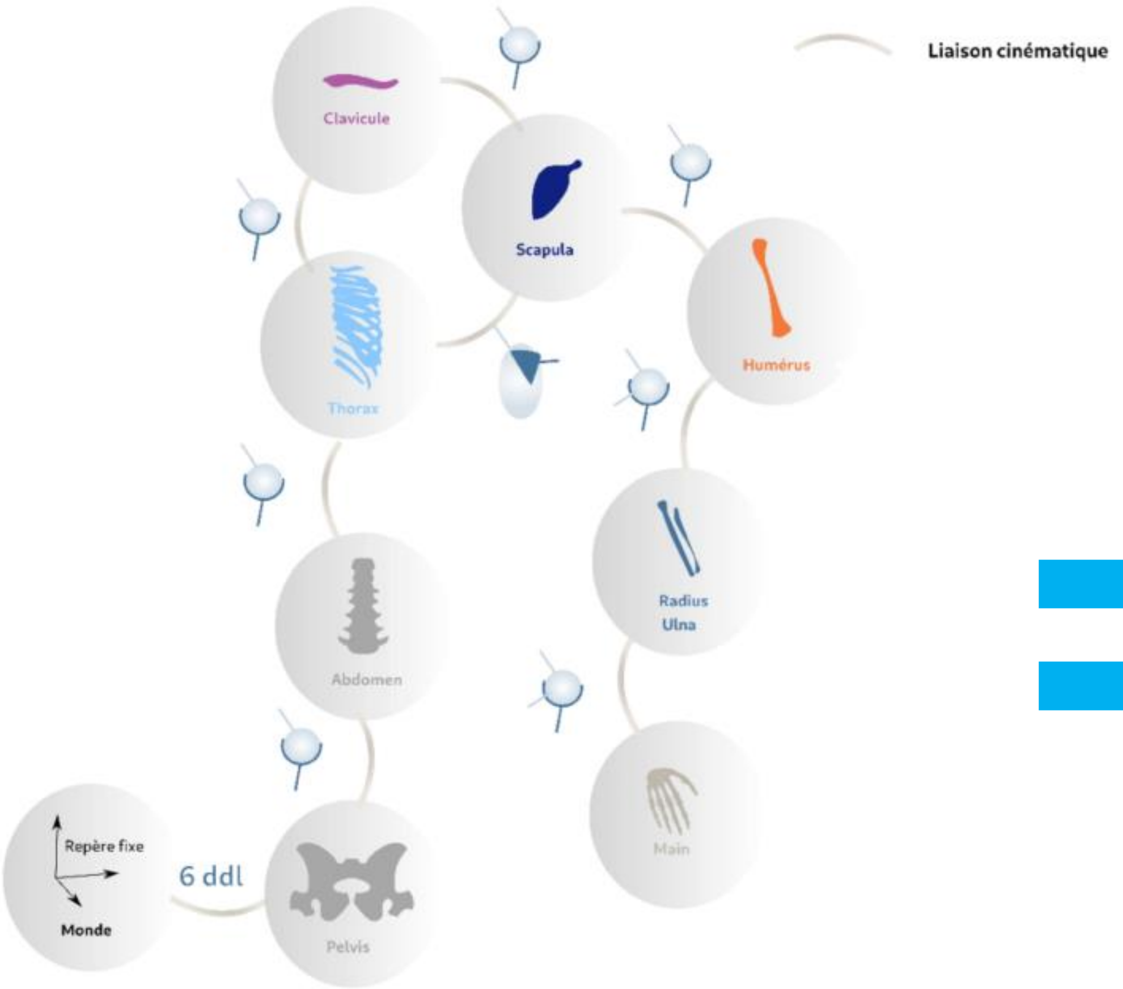


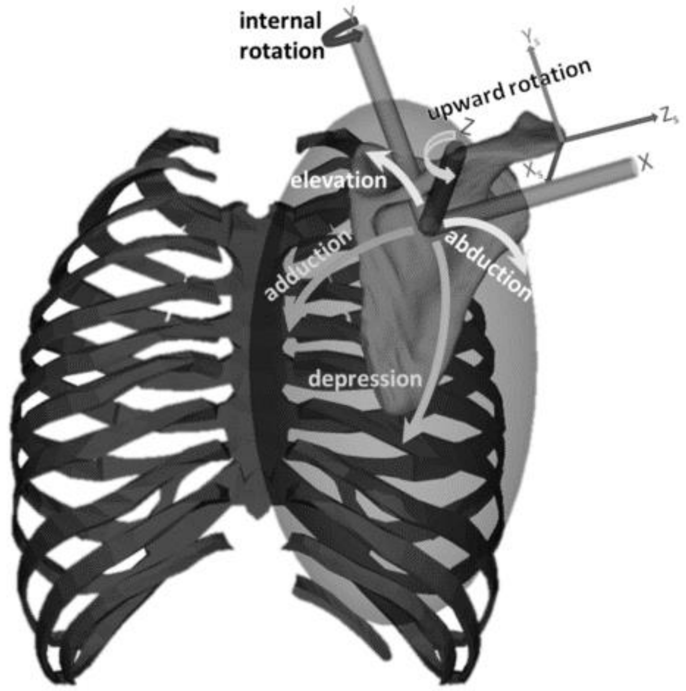


59,93%

Another example

[Rouvier 2023]





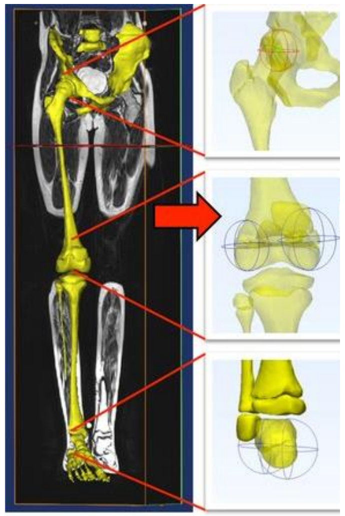
[Seth et al. 2016] [Holzbaur et al. 2005] [Saul et al.2015]

- RMSE <10% fort most moment arms
- Reproduces physiological non-senses

Scaling

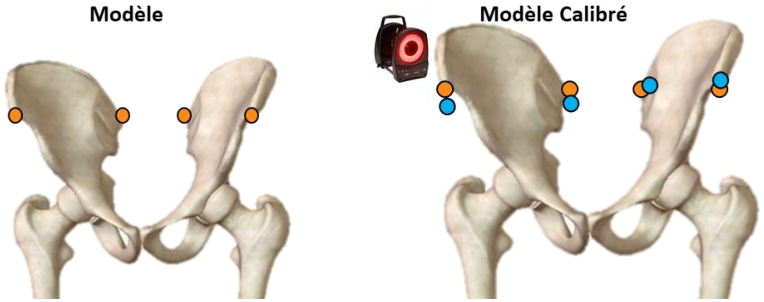
Calibrate **segment lengths, rotation axes, anatomical positions**

From medical imagery



[Kainz 2016]

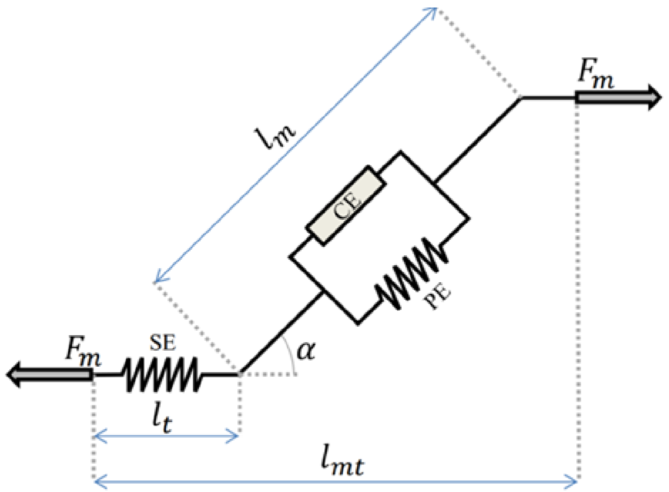
From motion capture

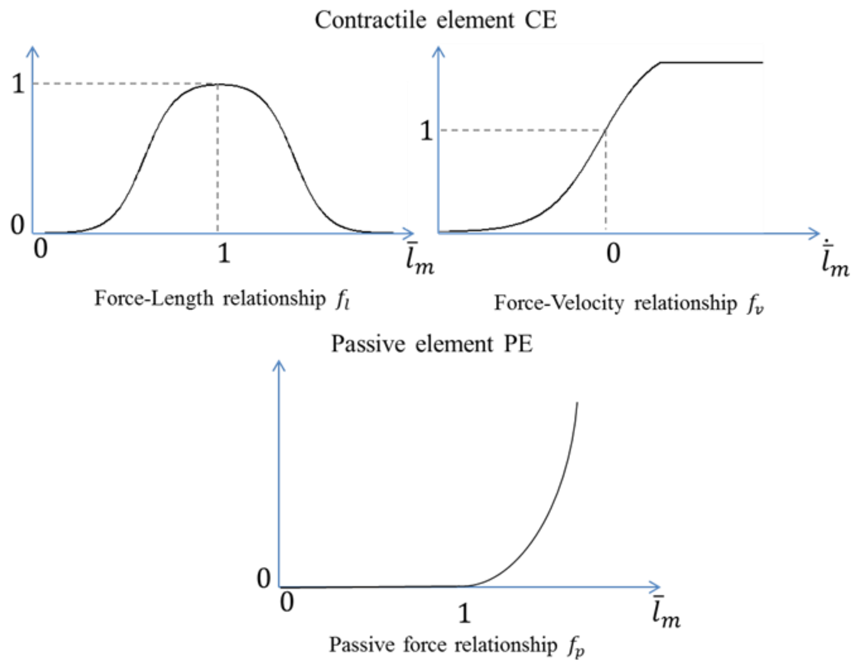


$$\min_{\boldsymbol{p}} \sum \left\| \boldsymbol{X}_{\boldsymbol{exp}} - \boldsymbol{X}_{\boldsymbol{mod}}(\boldsymbol{q}, \boldsymbol{p}) \right\|$$

[Puchaud et al. 2020]

- Muscle geometry is affected by anatomical changes
- Scaling wraps ?
- Statistical modeling and AI methods





Force generation model

[Puchaud 2020]
[Livet 2022]

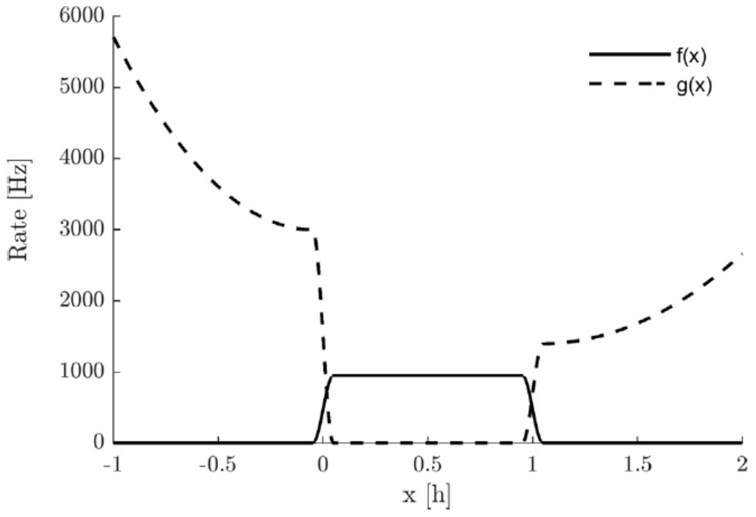
Hodgkin-Huxley Model

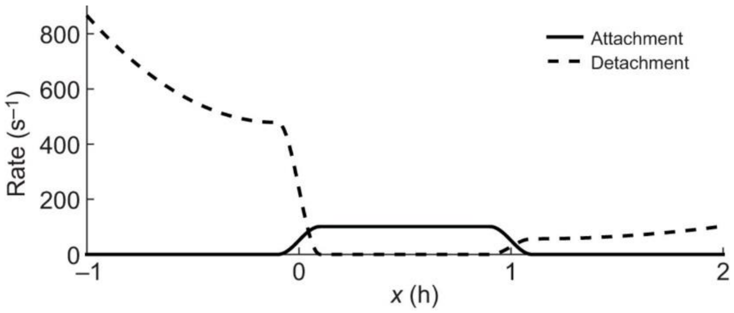
[Huxley 1969]

Sliding filaments model
Microscopic model

$$\frac{\partial n(x,t)}{\partial t} - v(t)\frac{\partial n(x,t)}{\partial t} = f(x)\big(f(x) + g(x)\big)n(x,t)$$

$n(x,t)$ Proportion of actine and myosine filaments compromised the union gate process
$v(t)$ Sarcomere shortening speed
$f(x)$ Cross-bridges creation rate
$g(x)$ Cross-bridges destruction rate





Advantages

Discontinuous effects
Isolated muscle scale

Drawbacks

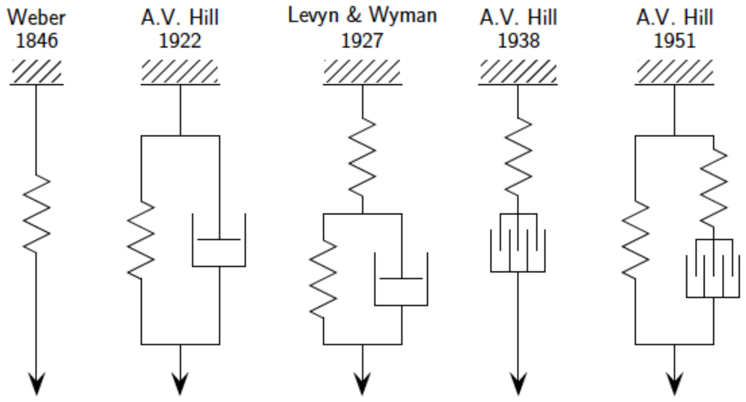
Model parameters tuning
Computation costs

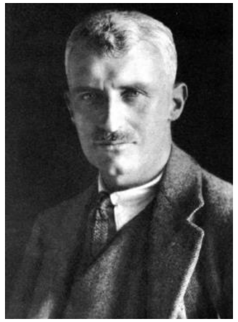
Hill Model

[Hill 1938]

Elementary mechanical components assembly

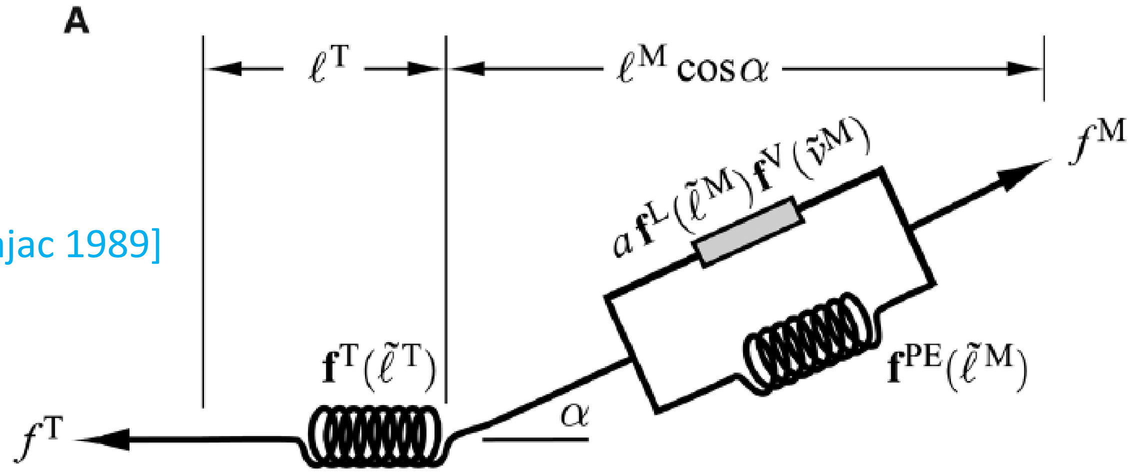
Macroscopic model





A.V. Hill 1886-1977

Under its most common form [Zajac 1989]



Hill Model

[Hill 1938]

$$f^M = F_0^M[af^L(\tilde{l}^M)f^V(\tilde{v}^M) + f^{PE}(\tilde{l}^M)]$$

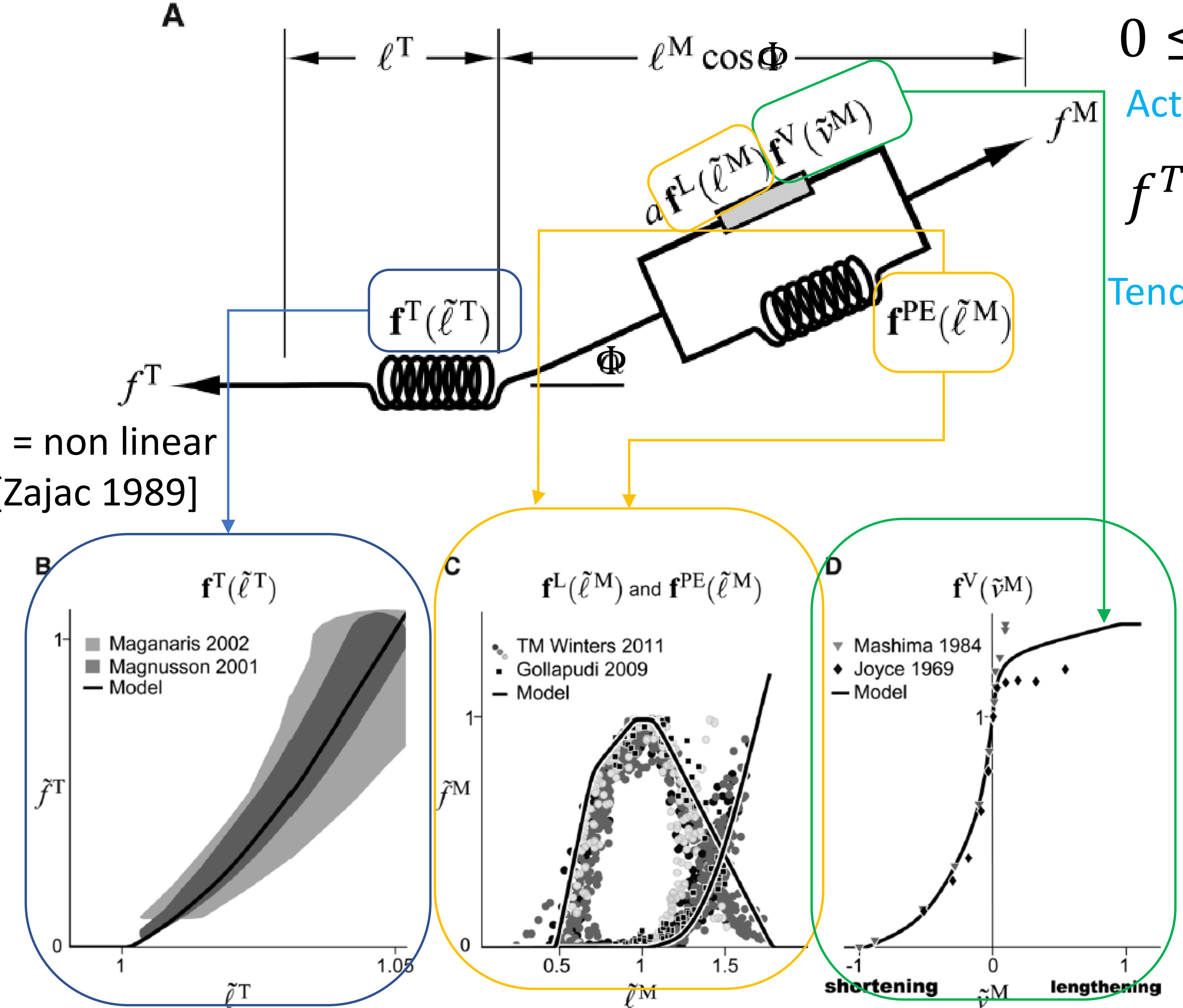
Muscle force

$$0 \le a \le 1$$

Activation

$$f^T = F_0^M f^T(\tilde{l}^T)$$

Tendinous force



Tendon = non linear spring [Zajac 1989]

Transposing sarcomere behavior to the muscle scale [Zajac 1989]

Scaling

Numerous parameters

l_0^M optimal fiber length

Φ_0 pennation angle

F_0^M Maximal isometric force $\quad F_0^M = \mathrm{PCSA} * \tau_{max}$

35 to 137 $\mathrm{N/cm^2}$
[Buchanan2004]

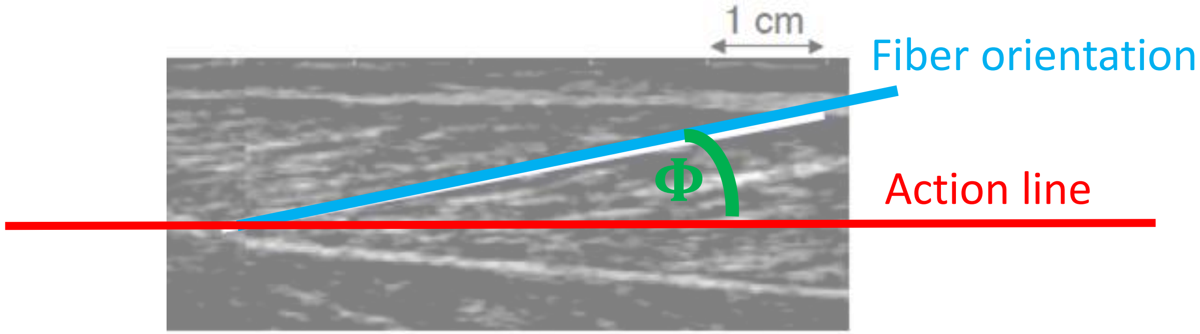
v_{max}^M maximal shortening speed

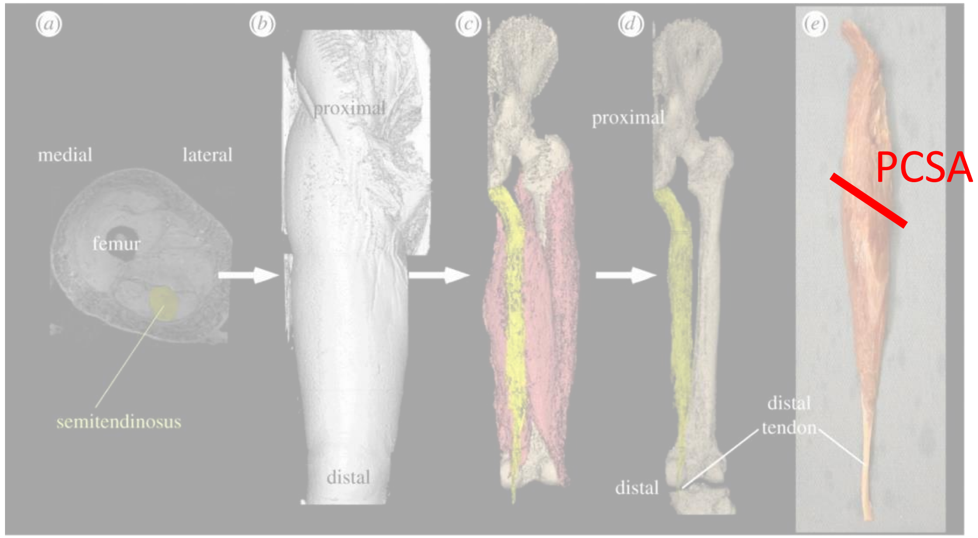
l_s^T tendon slack length

➡ Long, invasive, costly, incomplete

➡ Realistic, accurate

Medical imagery $(\Phi, PCSA, l_s^T)$
[Marra et al. 2018] [Modene et al. 2016]





Scaling

Isokinetic joint strength $(\mathrm{T}(q, \dot{q}))$

[Haering et al. 2019][Muller et al. 2017] [Puchaud 2020]

Numerous parameters

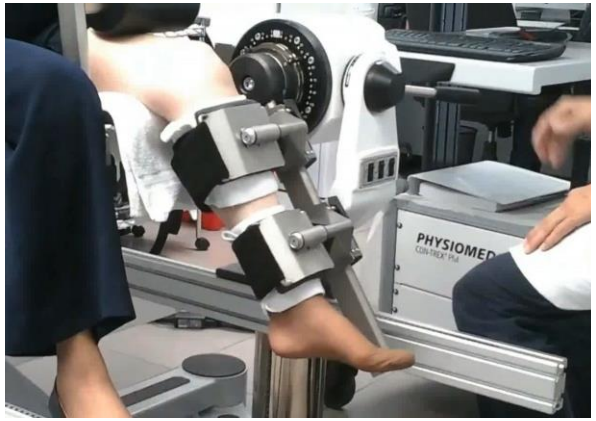
l_0^M optimal fiber length

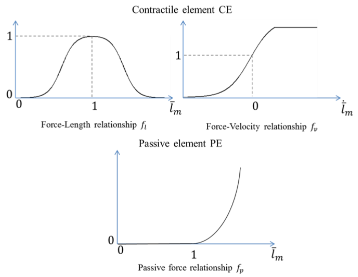
Φ_0 pennation angle

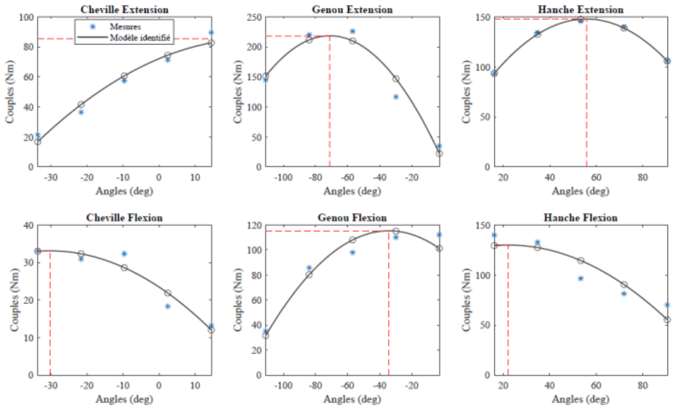
F_0^M Maximal isometric force

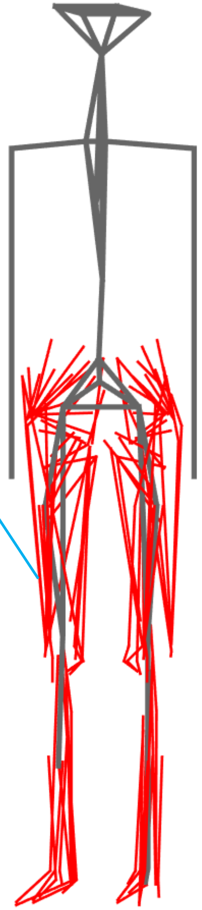
v_{max}^M maximal shortening speed

l_s^T tendon slack length







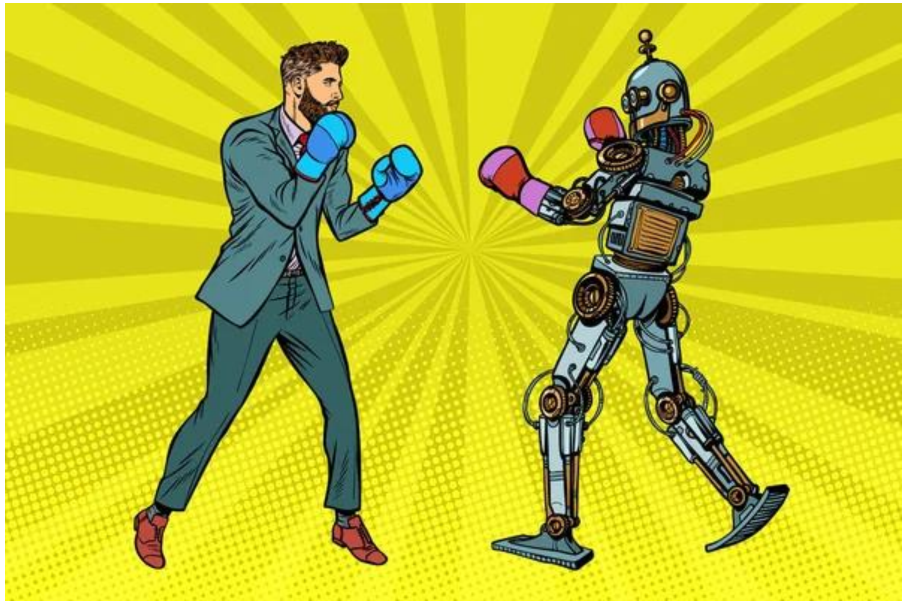


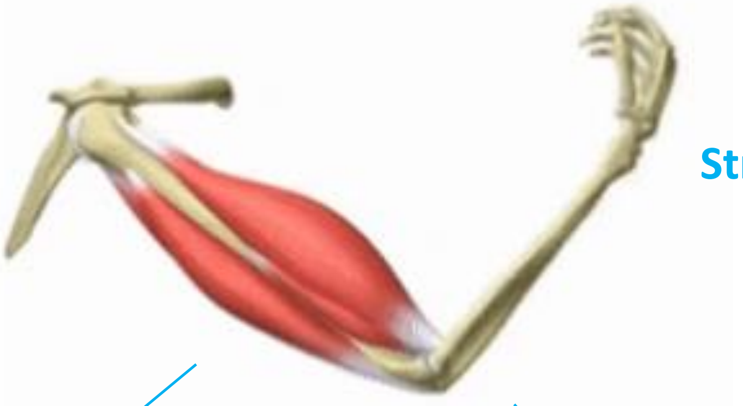
→ Long, tedious, submaximal, undetermined

→ Non invasive, generalizable, viscous effects

$$\min \|\boldsymbol{\Gamma}_{ex} - \boldsymbol{\Gamma}_{sim}\|^2$$

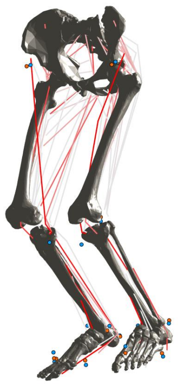
To summarize





Striated skeletal muscle

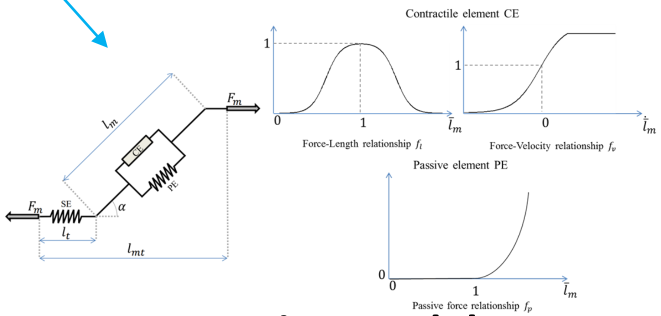
Scaling and specification



Muscle path

[Puchaud 2020]
[Livet 2022]
[Rouvier 2023]

Wrapping objects
Via points
Learning paths
Statistical approaches

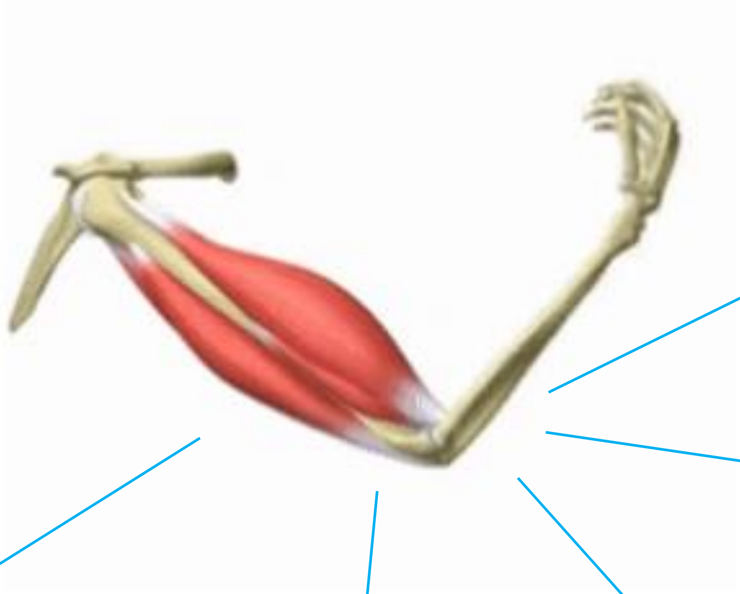


Force generation model

[Puchaud 2020]
[Livet 2022]

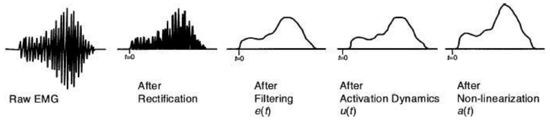
Macroscopic models
Numerous parameters

Simulation ?



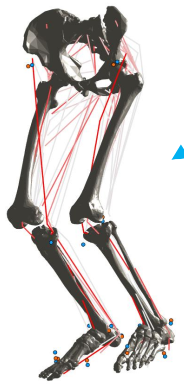
Activation and contraction dynamics

Electromechanical delay



Motor control model

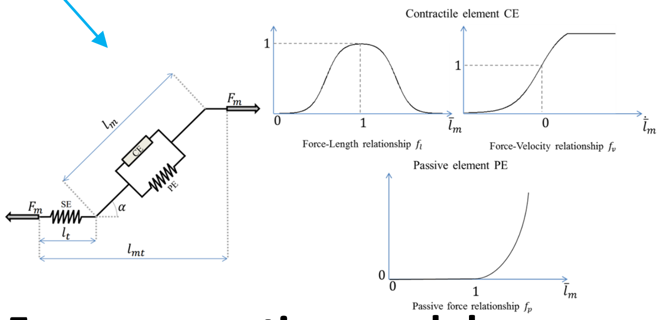
$$\min f\big(\boldsymbol{F}(t)\big)$$



Muscle path

[Puchaud 2020]
[Livet 2022]
[Rouvier 2023]

Musculotendon equilibrium & **temporal integration**



Force generation model

[Puchaud 2020]
[Livet 2022]

JNRH'2023 : Journées Nationales de la Robotique Humanoïde

5-7 juil. 2023 Bordeaux (France)

Thanks !

We have a temporary position (research and teaching) in mechanics /robotics for one year, starting in september 2023 !

Please contact me ☺

charles.pontonnier@ens-rennes.fr