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The biological motor

Syn Schmitt

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Stuttgart Research Centre for Simulation Technology, University of Stuttgart
Pfaffenwaldring 5a

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The Human Movement Simulation Lab

SimTech
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The biological skeletal muscle's ...

anatomy, physiology, and metabolism.

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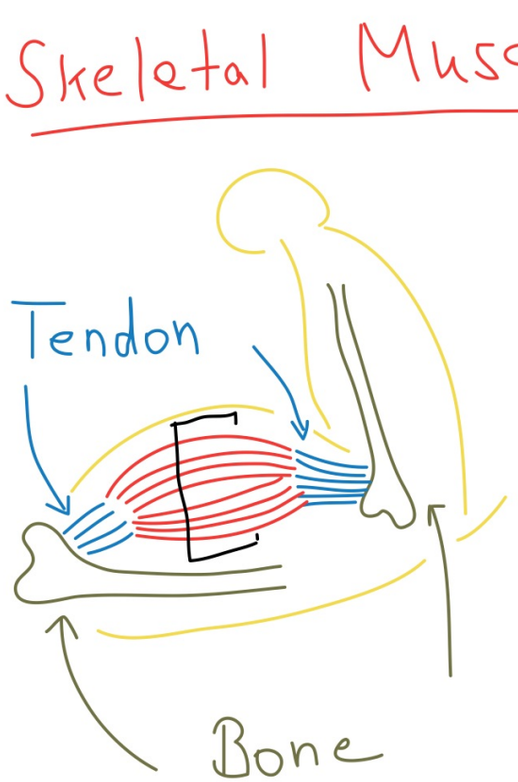
Biological skeletal muscle's anatomy



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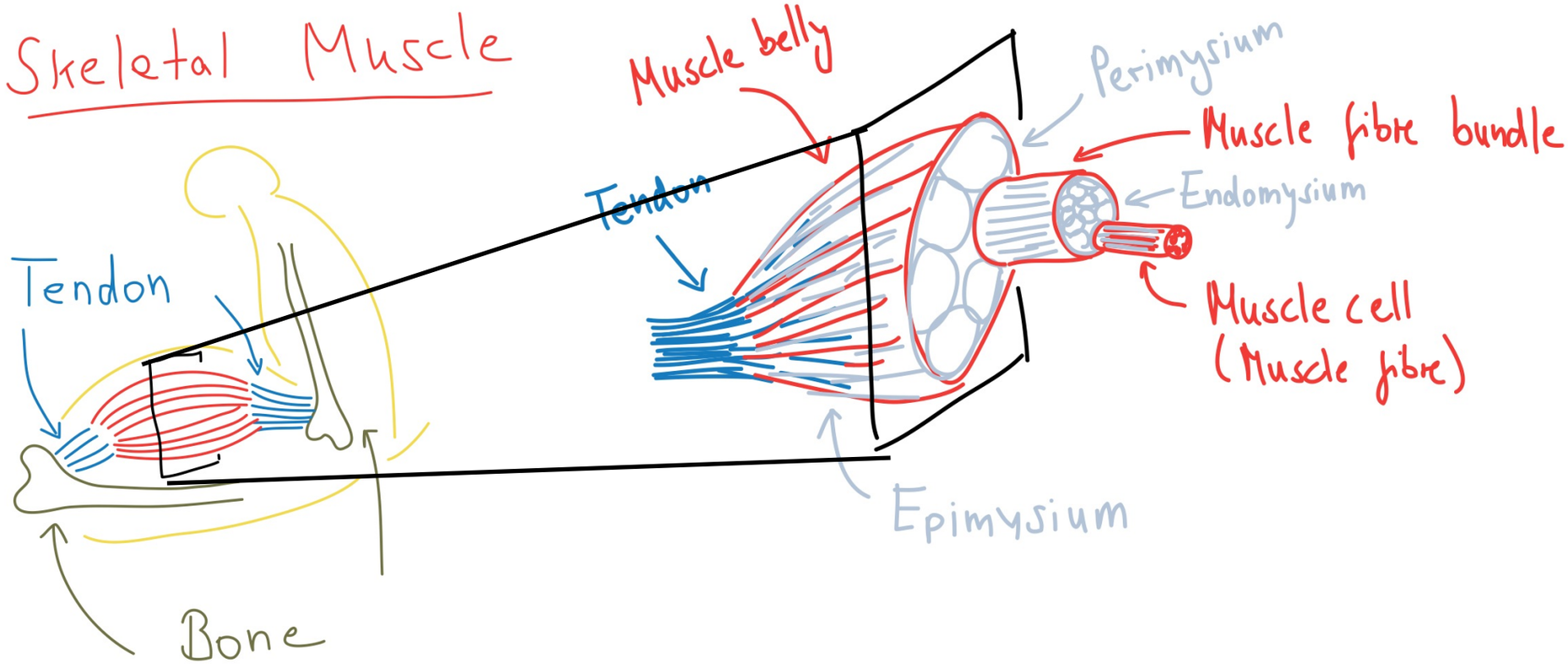
Biological skeletal muscle's anatomy



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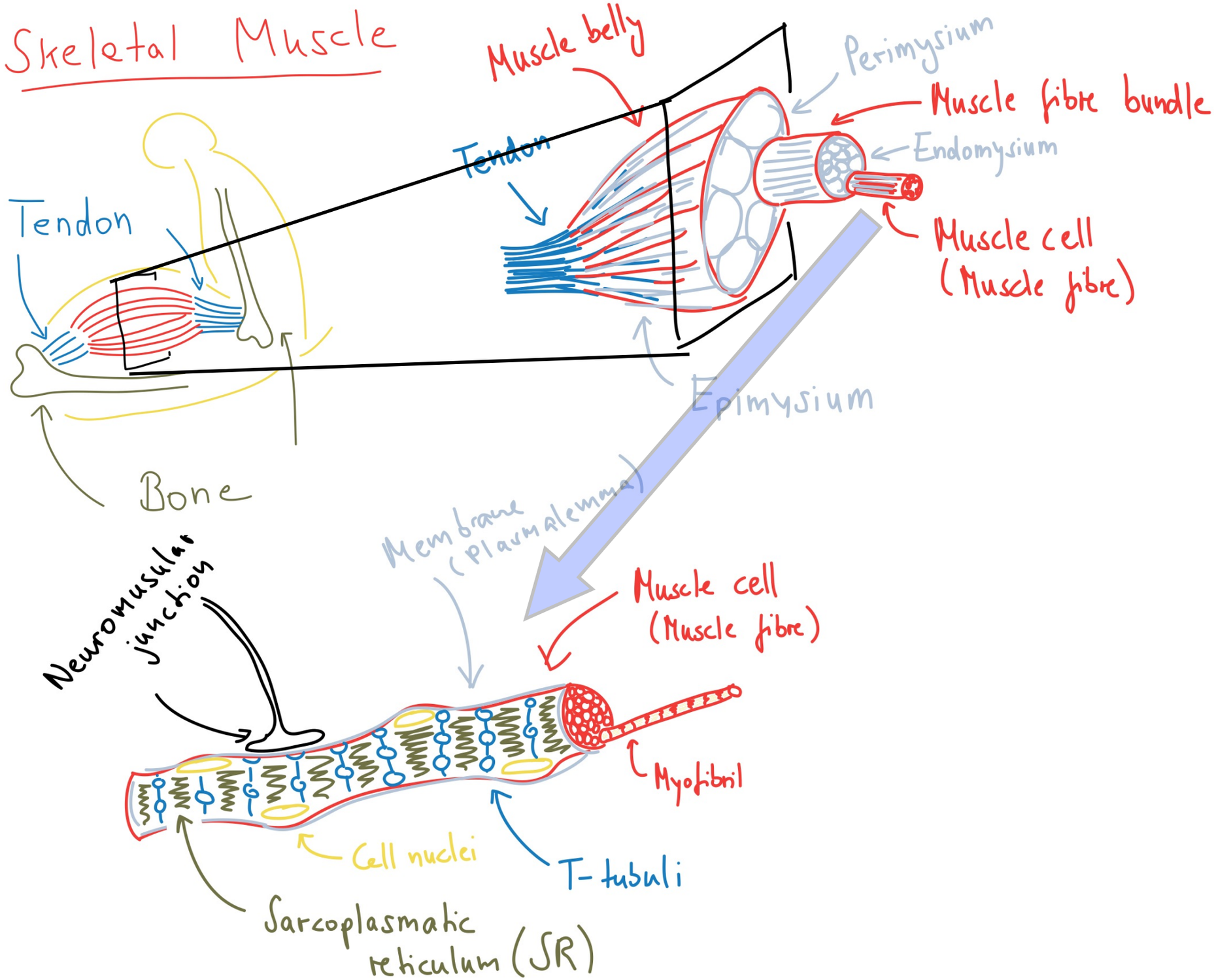
Biological skeletal muscle's anatomy



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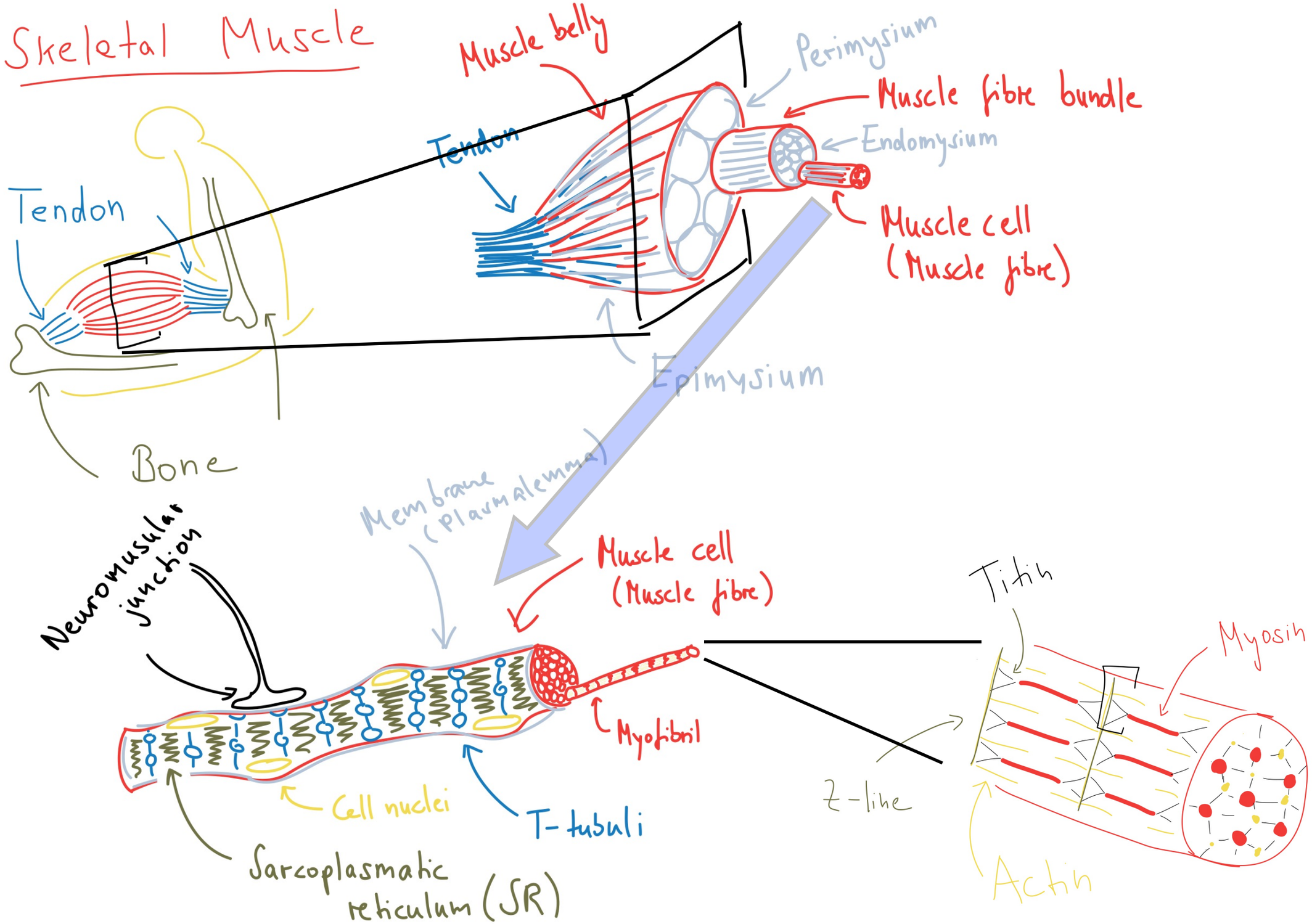
Biological skeletal muscle's anatomy



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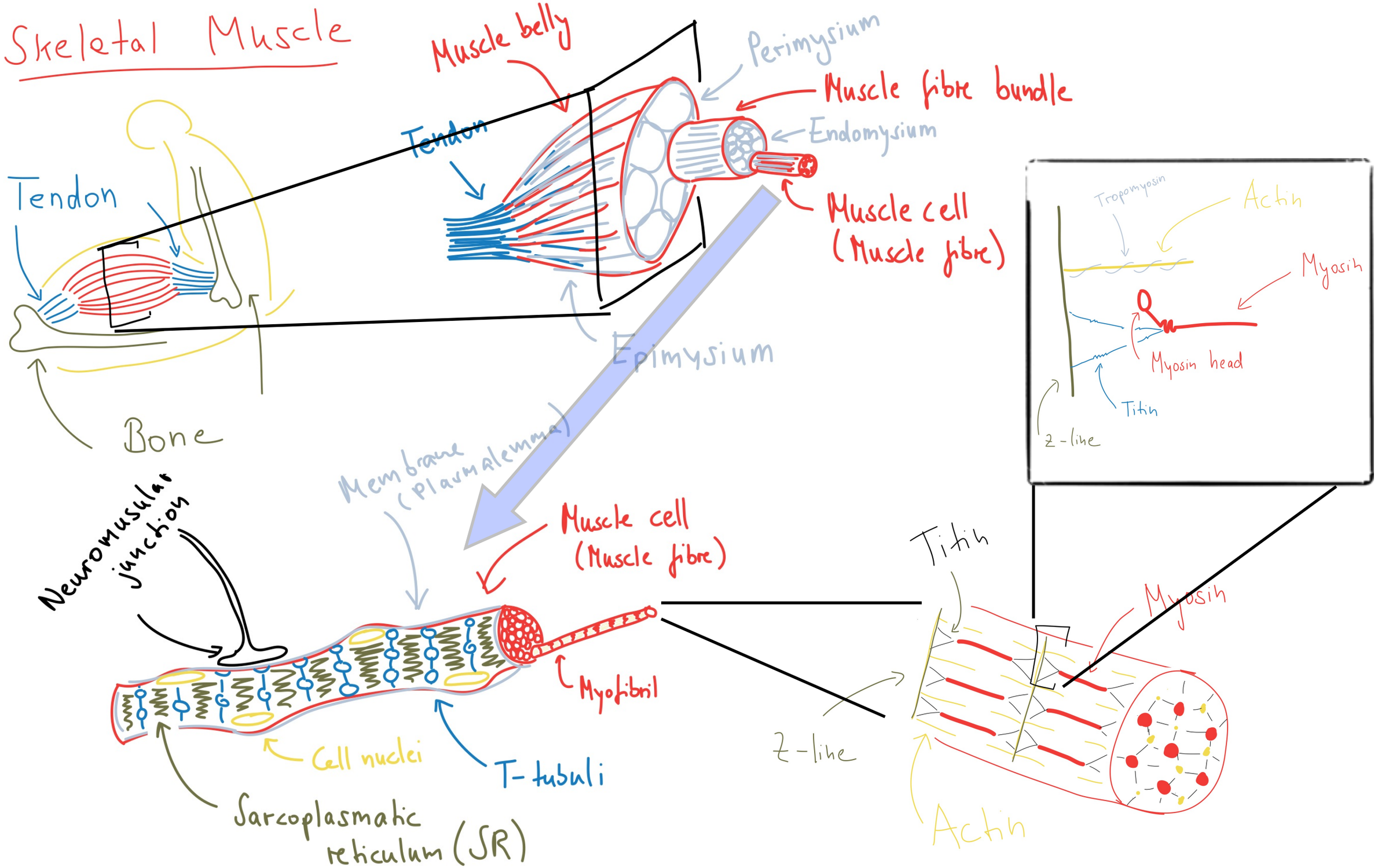
Biological skeletal muscle's anatomy



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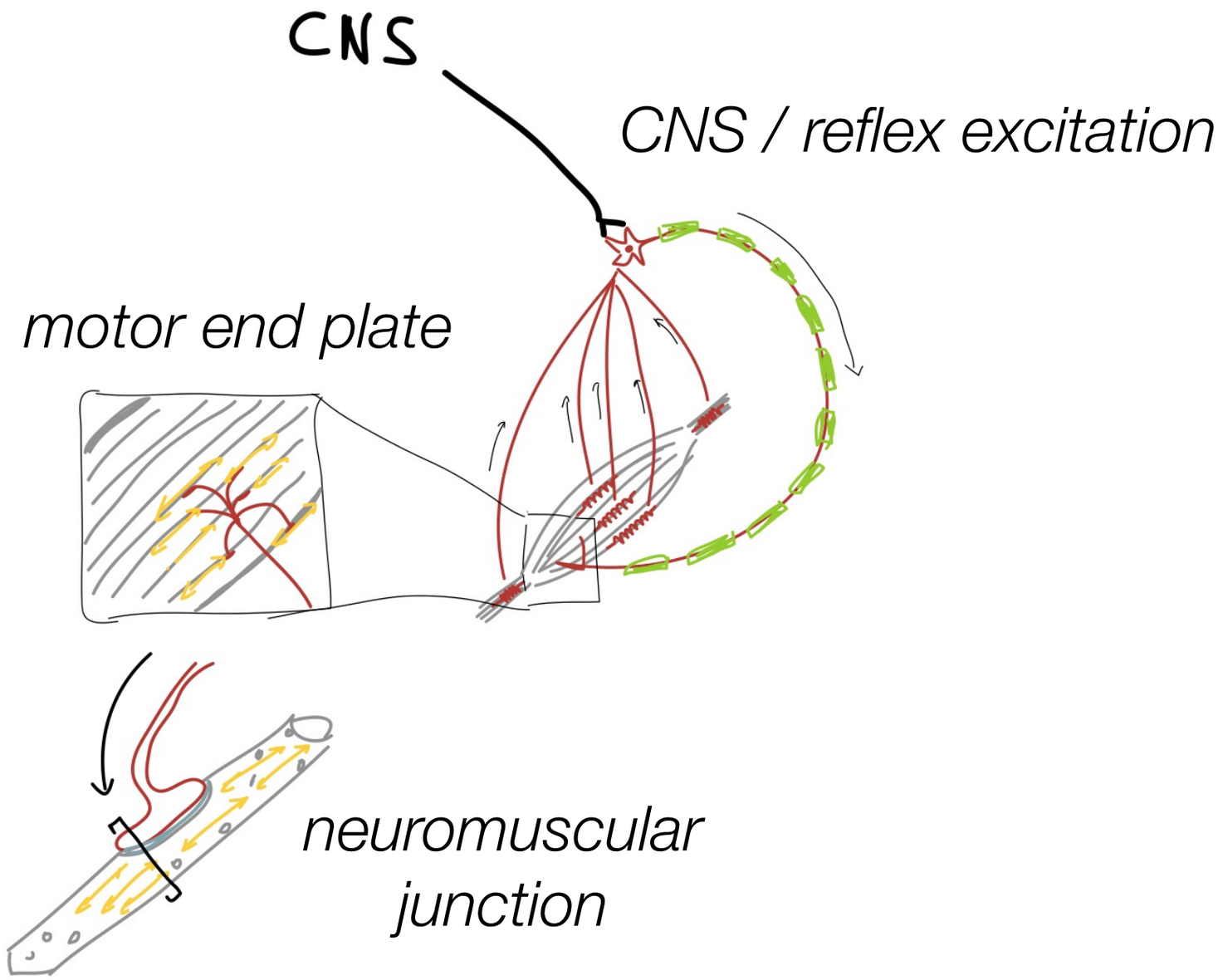
Biological skeletal muscle's physiology



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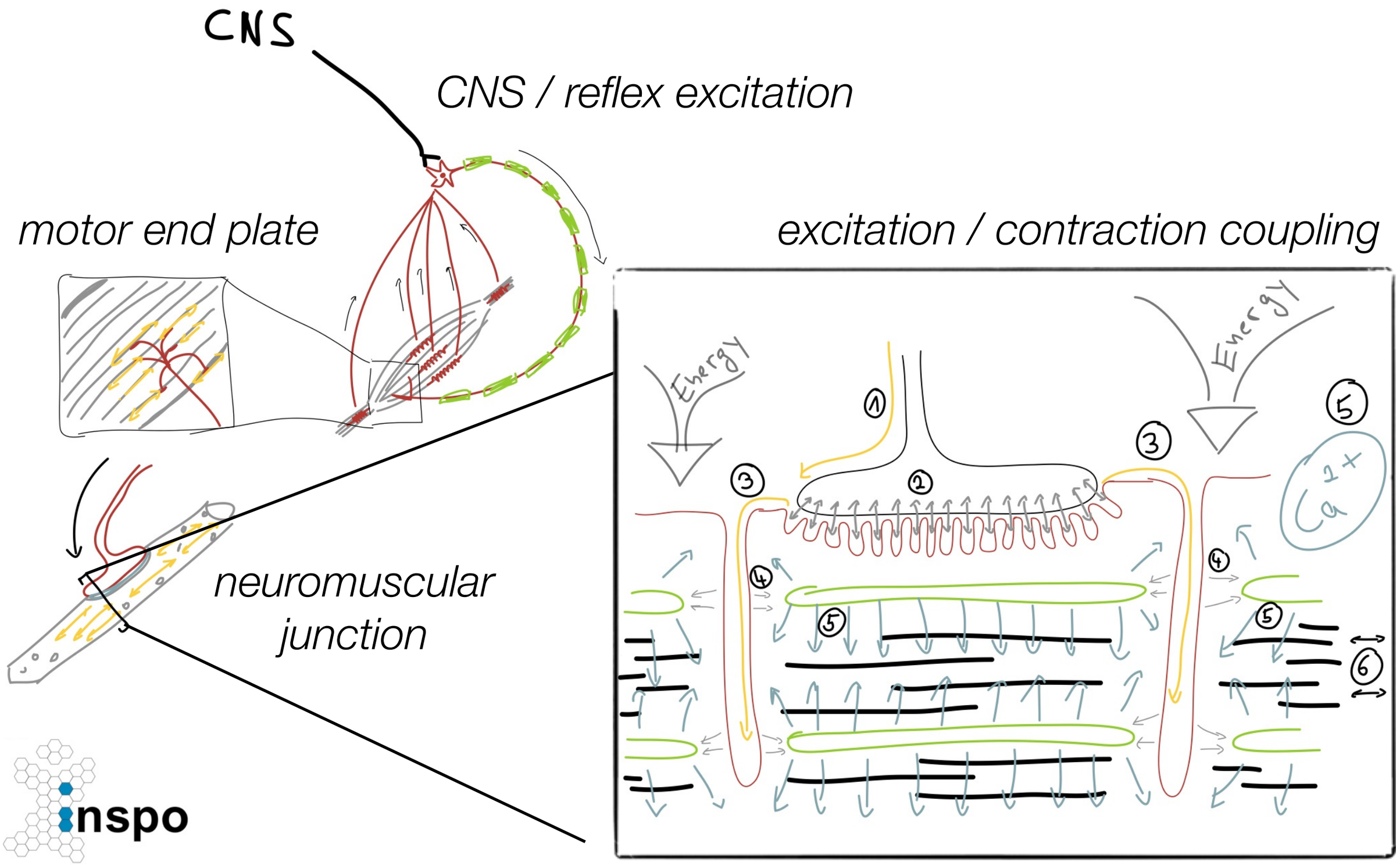
Biological skeletal muscle's physiology



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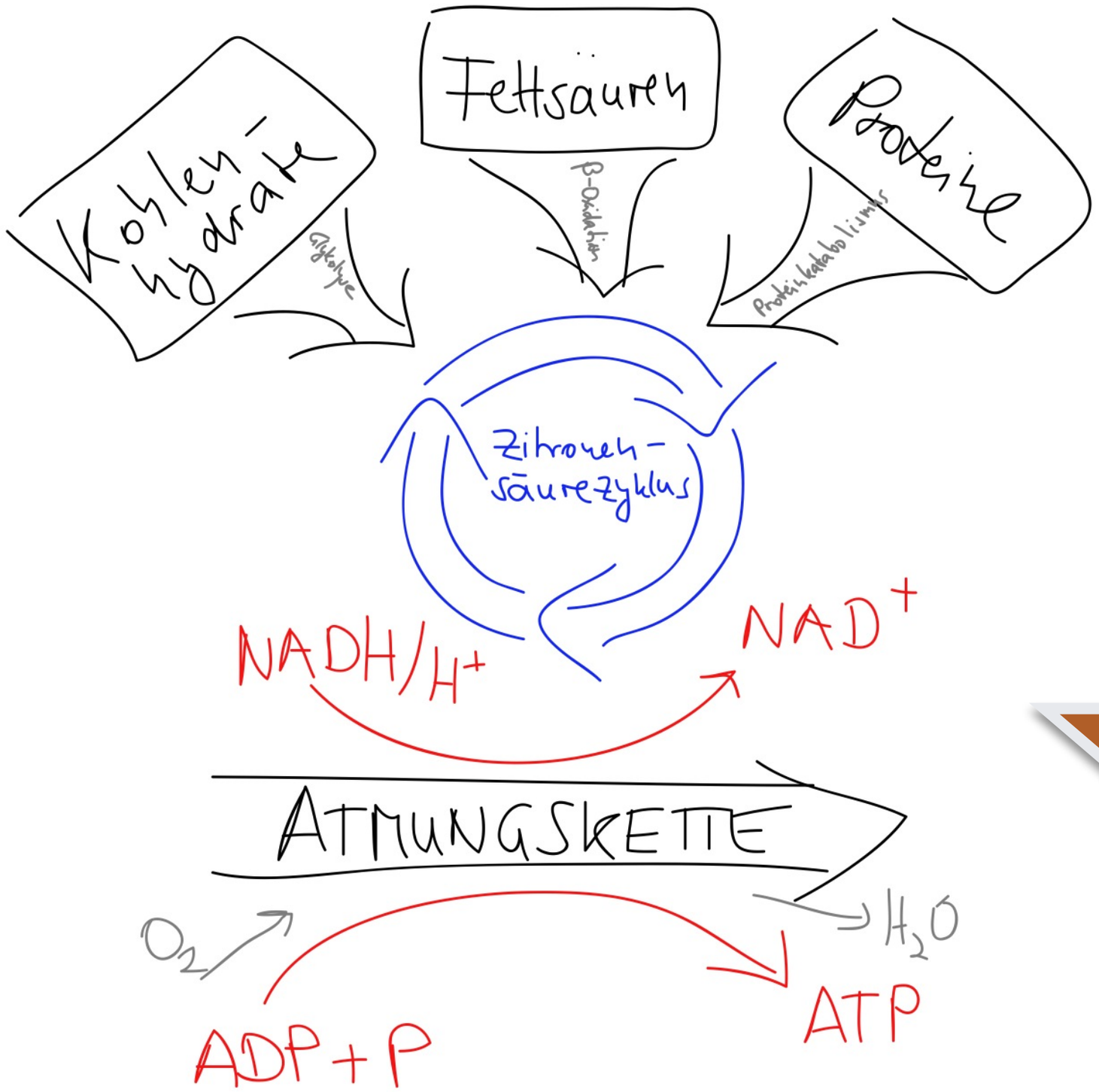
Biological skeletal muscle's metabolism



Fuel / energy supply

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The biological skeletal muscle's ...

mechanics and thermodynamics.

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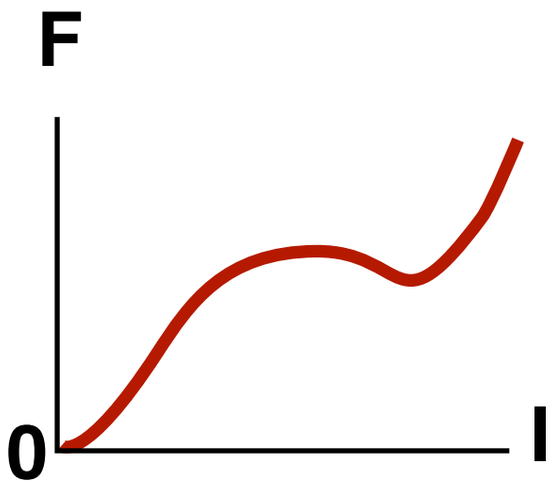
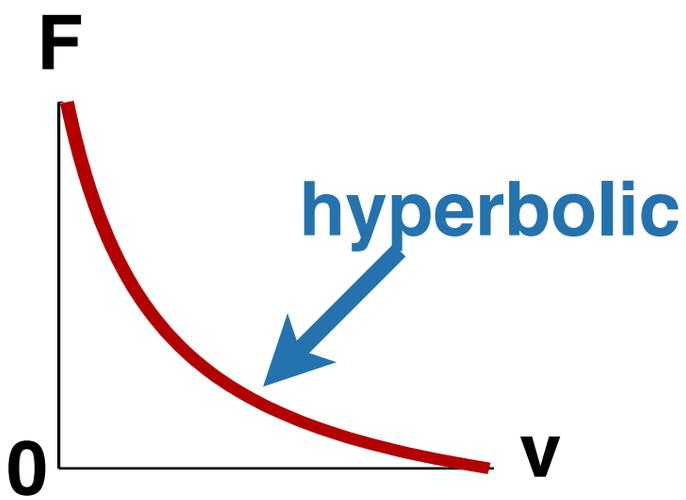
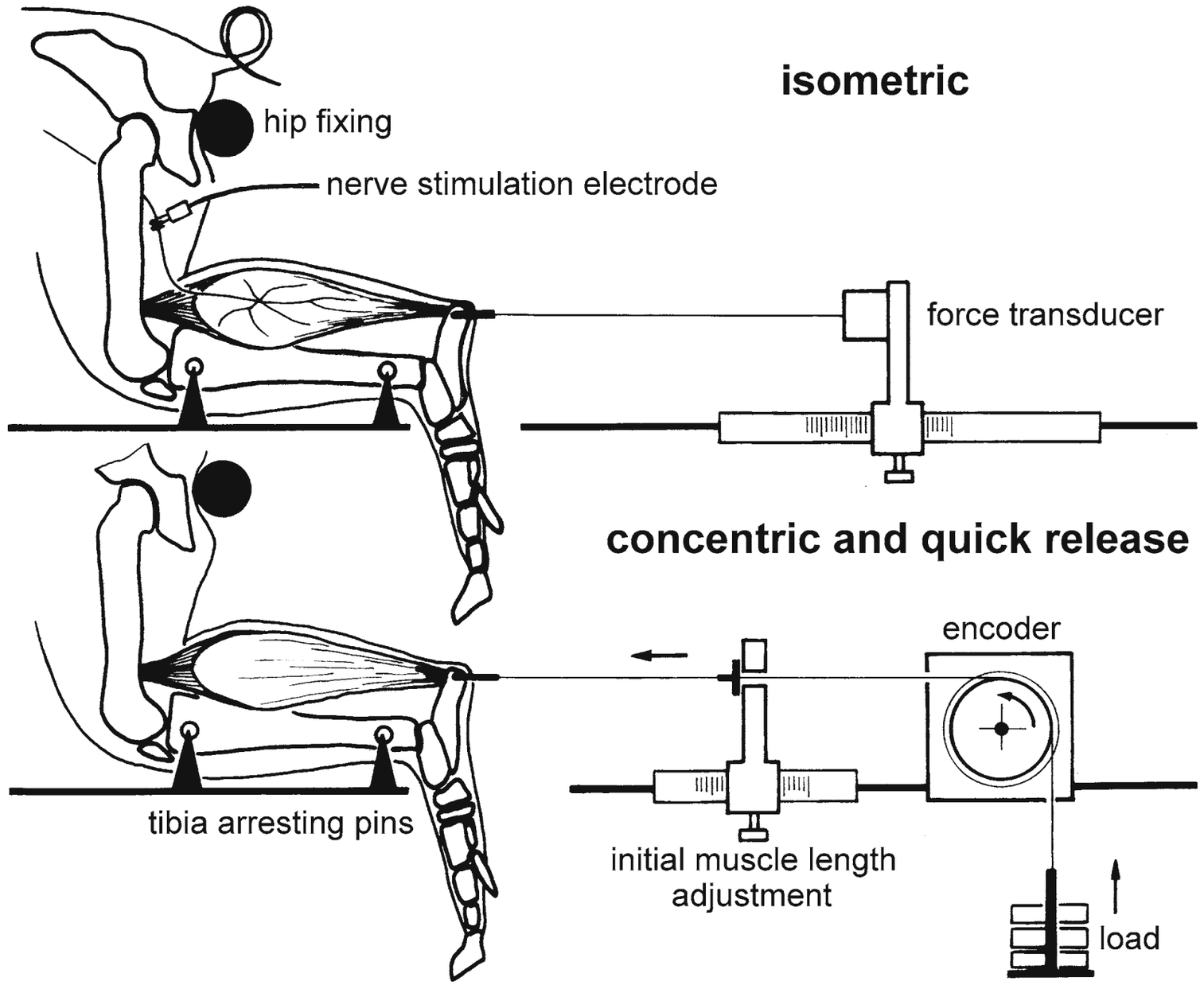
Skeletal muscle‘s mechanical characteristics



Force-length relationship



Force-velocity relation



Günther, M, Schmitt, S, Wank, V. 2007. High-frequency oscillations as a consequence of neglected serial damping in Hill-type muscle models. Biological Cybernetics, 97:63–79.

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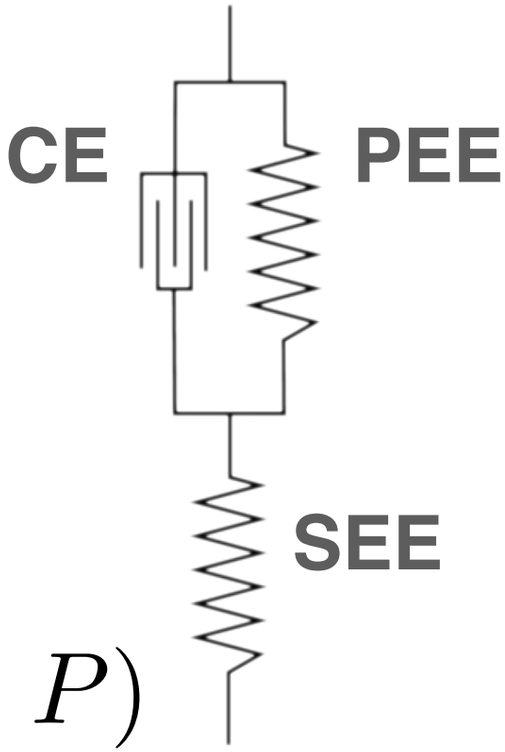
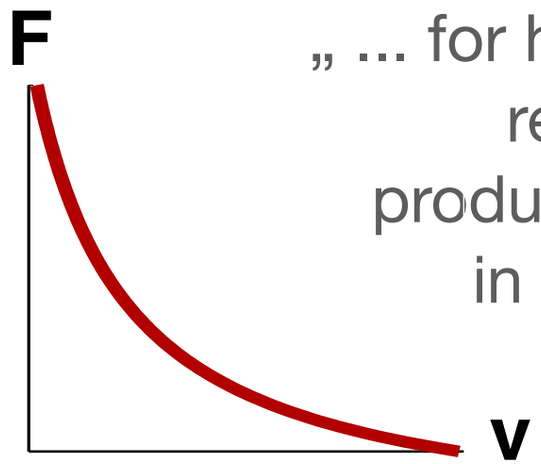
Skeletal muscle‘s mechanical characteristics



$$(P + a) \cdot v = b \cdot (P_0 - P)$$

Archibald Vivian Hill
Nobel Prize 1922:
„ ... for his discovery relating to the production of heat in the muscle.“



Force-velocity

Hill, A., 1938. The heat of shortening and the dynamic constants of muscle. Proceedings of the Royal Society of London B 126, 136–195.

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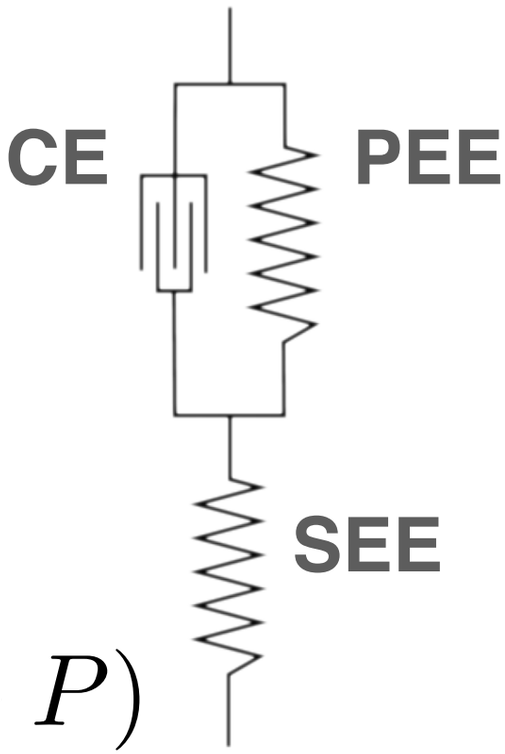
Skeletal muscle‘s mechanical characteristics



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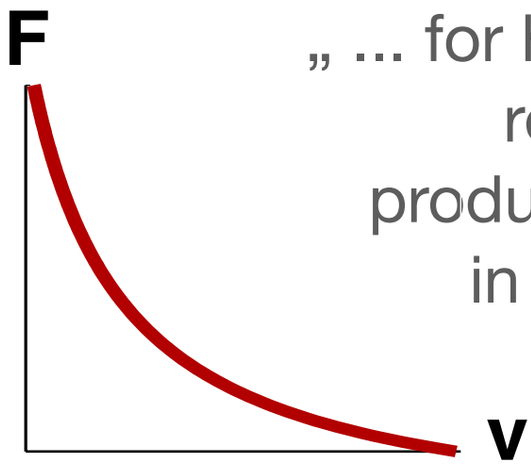
Hill-type muscle models include a contractile element which represents the empirical force-velocity data



Force-velocity

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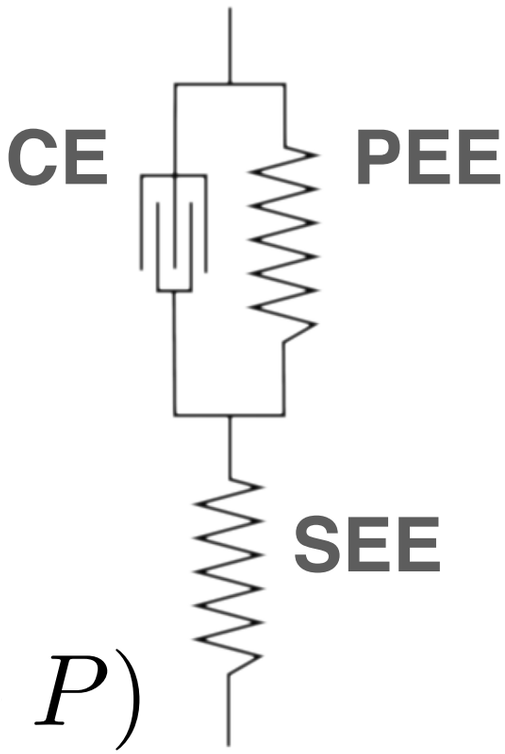
Skeletal muscle‘s mechanical characteristics



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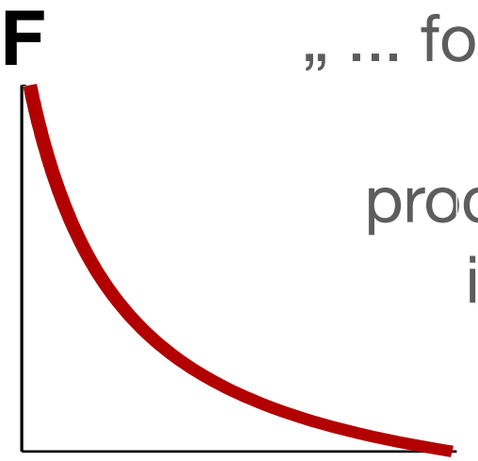

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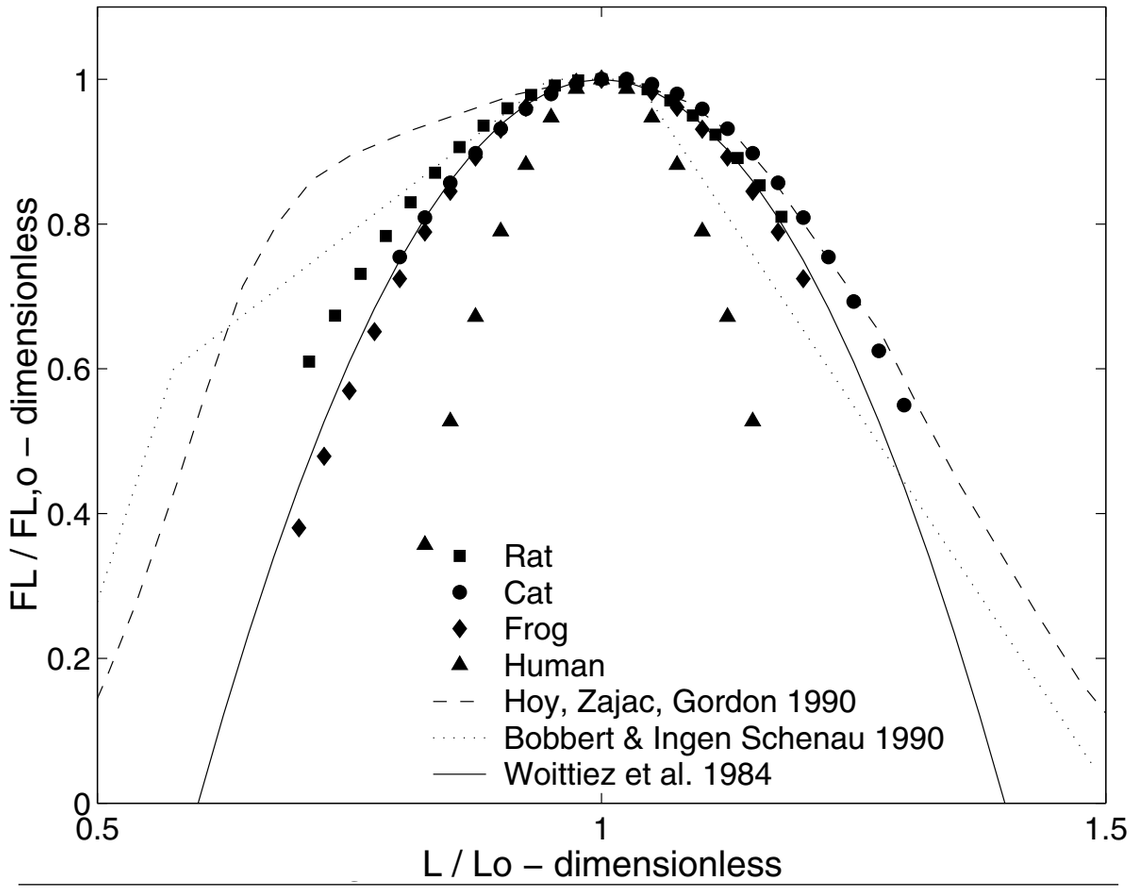
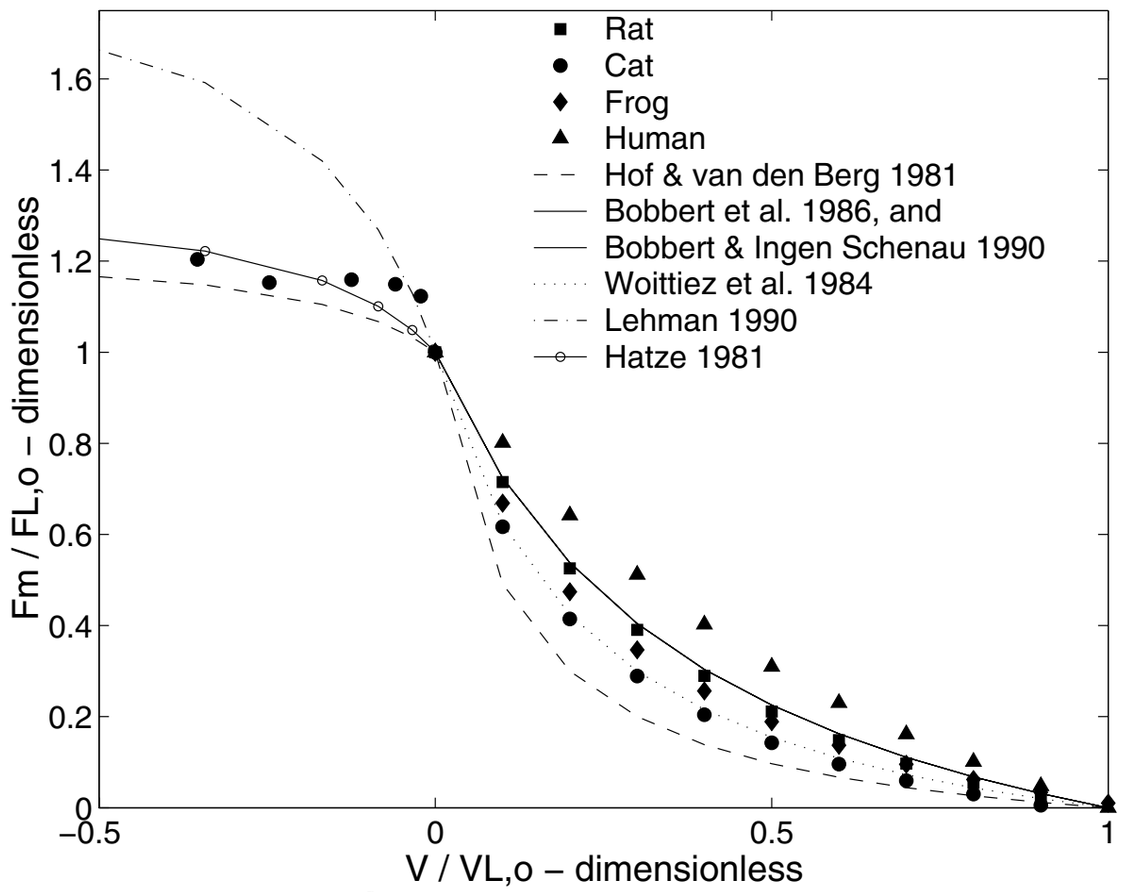


	k_1	k_2	k_3	L_o	$F_{L,o}$	
Rat[1]	–4.50	8.95	–3.45	27.0 mm	0.29 N	$p \leq 0.001$
Frog[2]	–6.79	14.69	–6.88	31.0 mm	0.67 N	$r^2 = 0.96$
Cat[3]	–5.71	11.52	–4.81	31.9 mm	0.18 N	$r^2 = 0.99$
Human[4]	–13.43	28.23	–13.96	215.9 mm	193.1 N	$r^2 = 0.75$
Skeletal Muscle Model[5]	–6.25	12.50	–5.25	60.0 mm	3000 N	—



	$a/F_{L,o}$ dimensionless	$F_{L,o}$ N	$b/V_{L,o}$ dimensionless	$V_{L,o}$ mm/s
Rat[1]	0.356	4.30	0.38	144
Frog[2]	0.27	0.67	0.28	42
Cat[3]	0.27	0.18	0.30	191
Human[4]	0.81	200	0.81	1115
Skeletal Muscle Model[5]	0.224	—	0.224	—
Human[6]	0.41	3000	0.39	756
Human[7]	0.41	2430	0.41	780
Human[8]	0.12	—	0.12	—

GK Klute, JM Czerniecki, B Hannaford (2002) Artificial Muscles: Actuators for Biorobotic Systems. The International Journal of Robotics Research, 21: 295.

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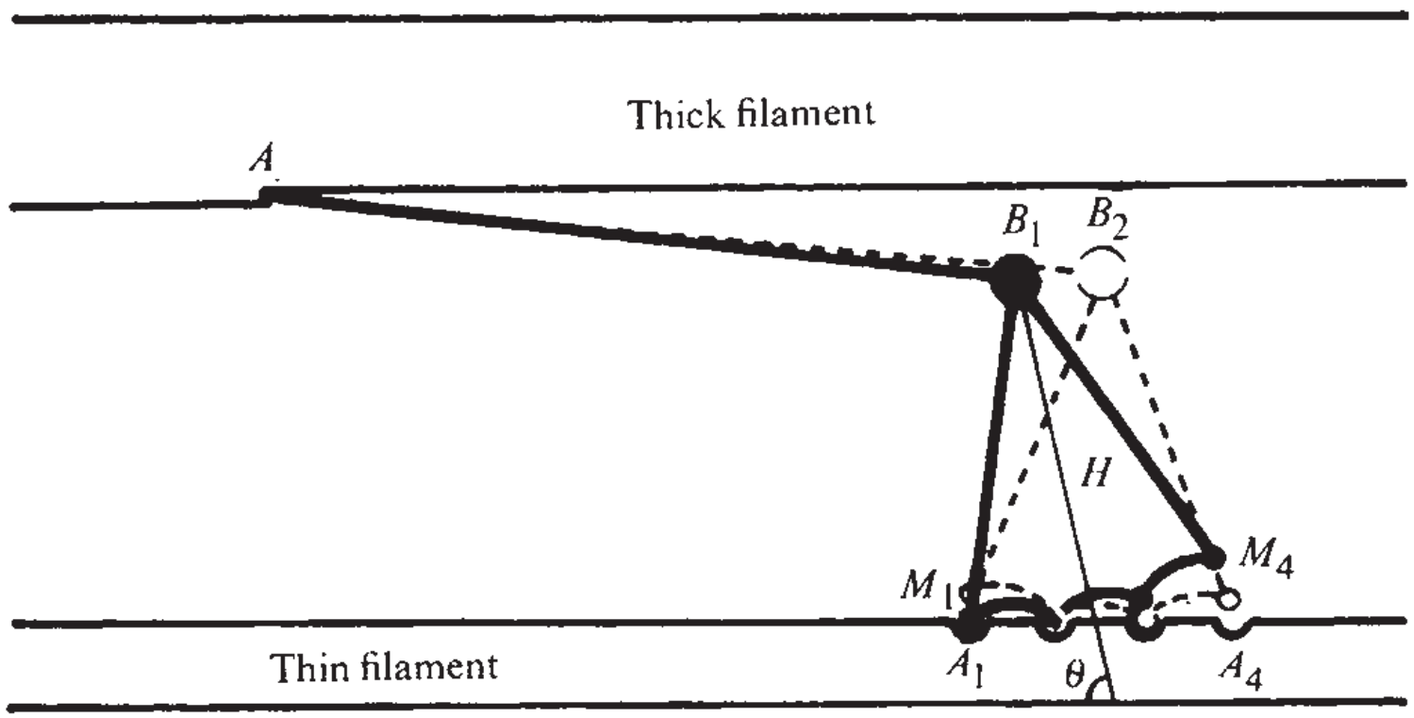
Skeletal muscle‘s mechanical characteristics



Andrew Fielding Huxley
Nobel prize 1963:
„ ... for ... ionic mechanisms involved in excitation ... of the ... cell membrane.“

Huxley, A. F., Niedergerke, R., 1953. Structural changes in muscle during contraction. Interference microscopy of living muscle fibres. Nature 173 (4412), 971–973.

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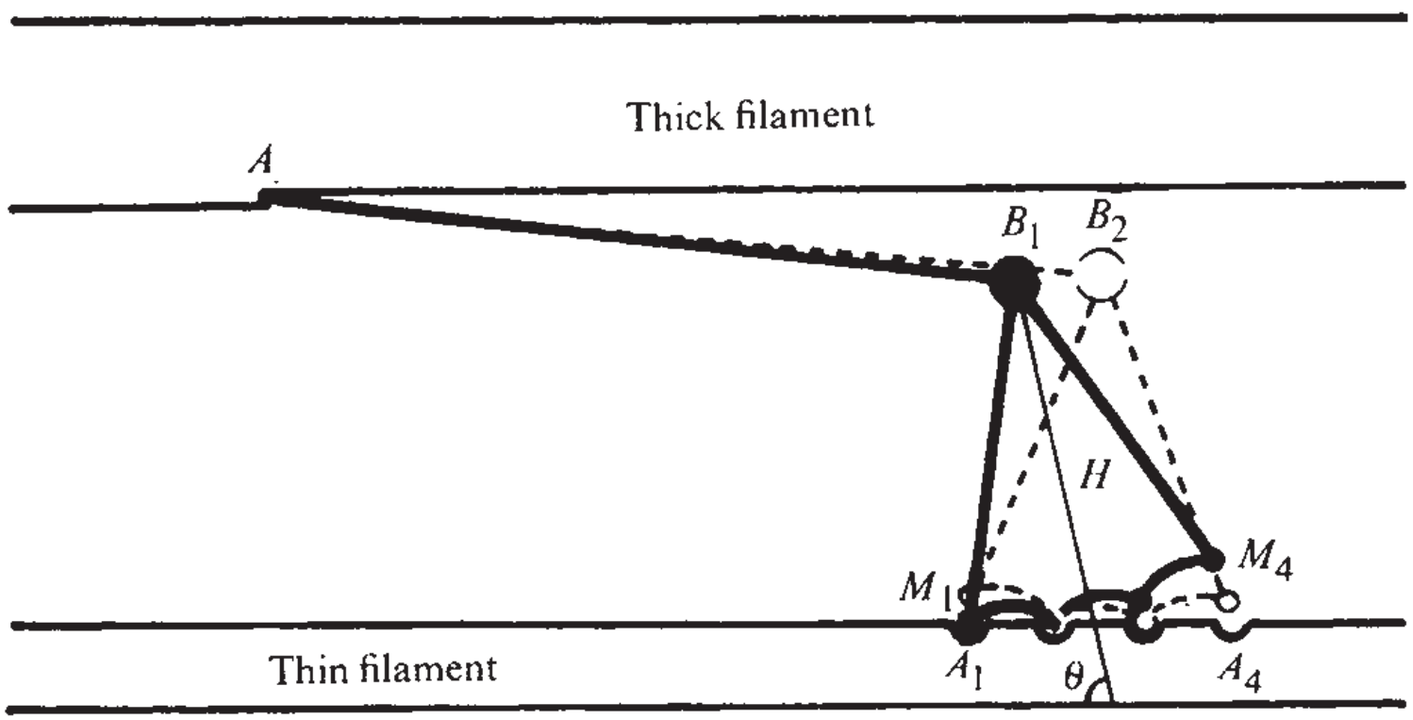

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Huxley-type muscle models explain the mechanism of force generation known as the „sliding filament theory“ based on microstructure

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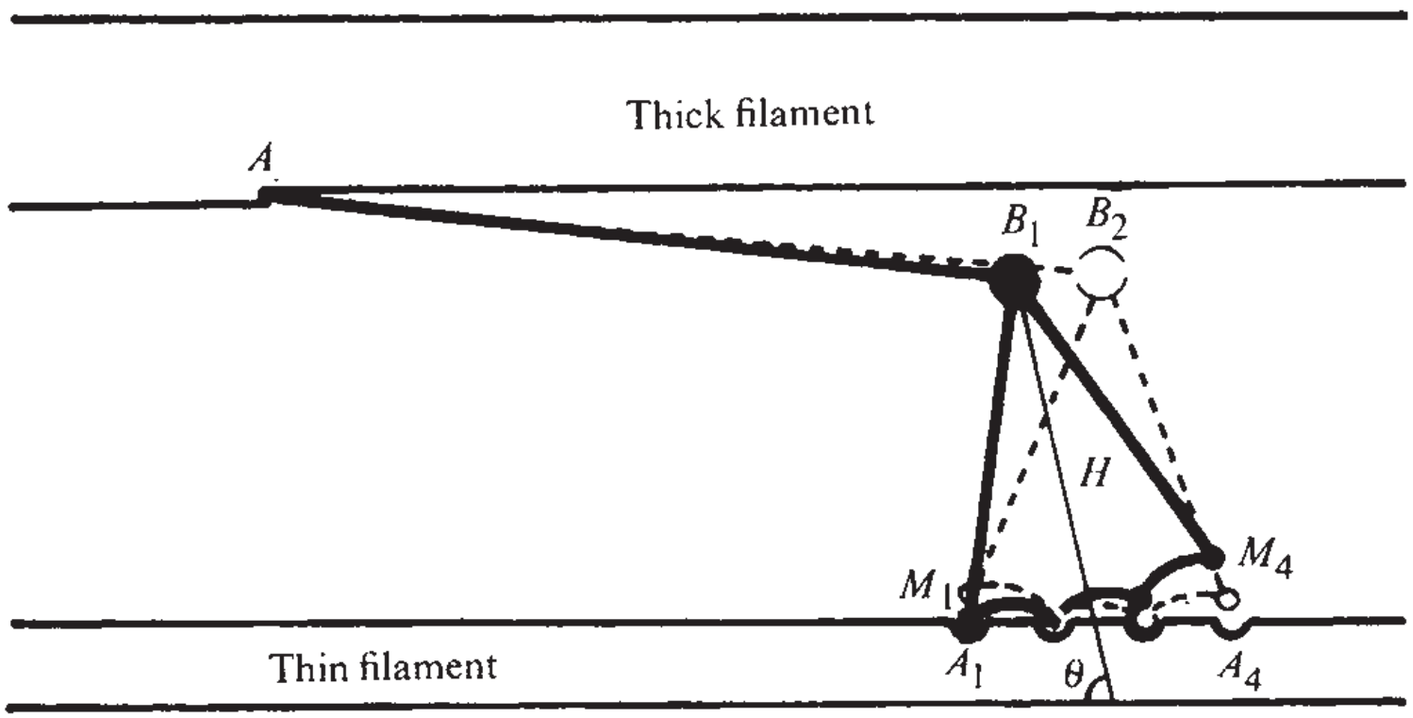

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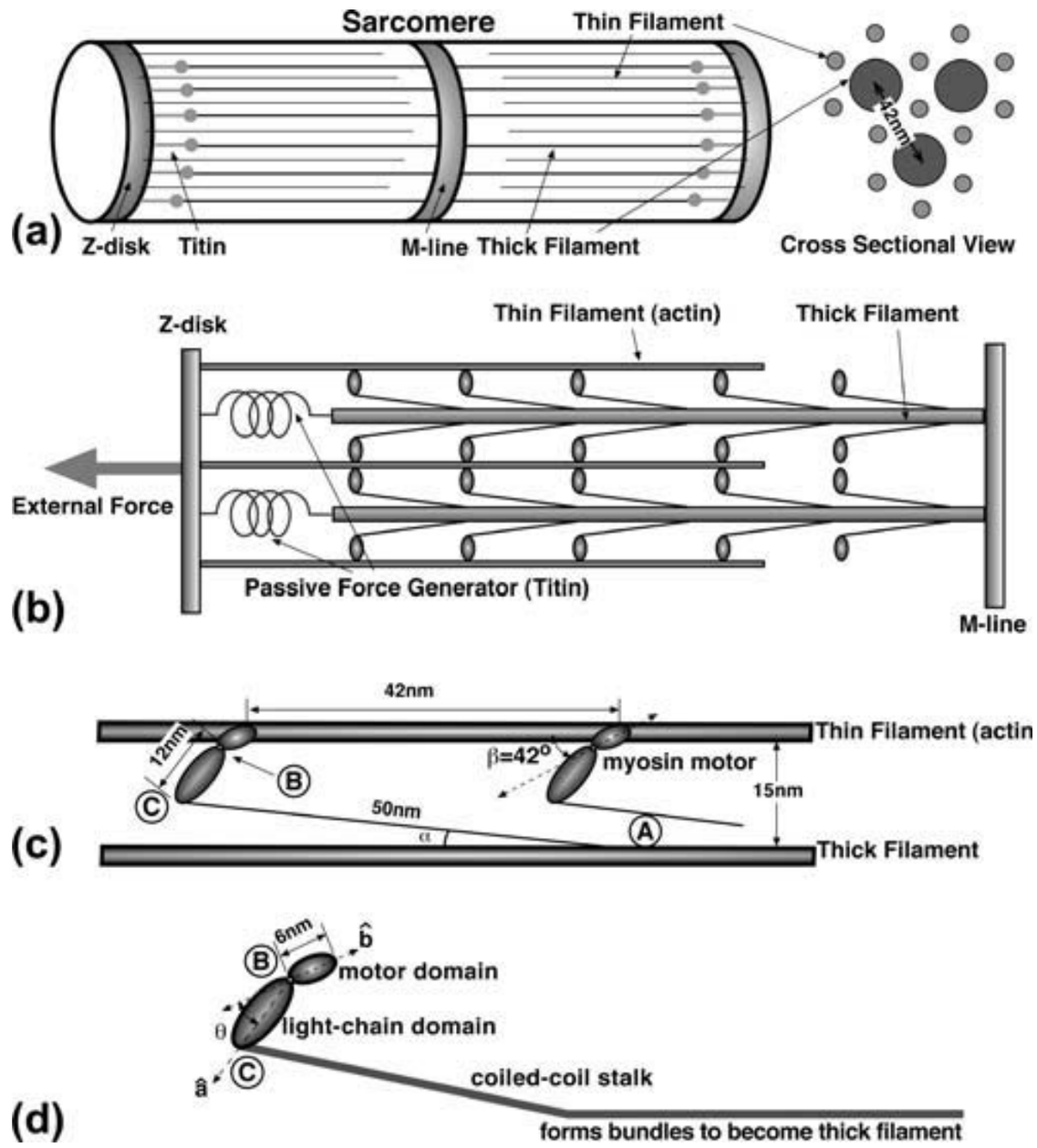

Lan, G., Sun, S., 2005. Dynamics of myosin-driven skeletal muscle contraction: I. Steady-state force generation. Biophysical Journal 88 (6), 4107– 4117.

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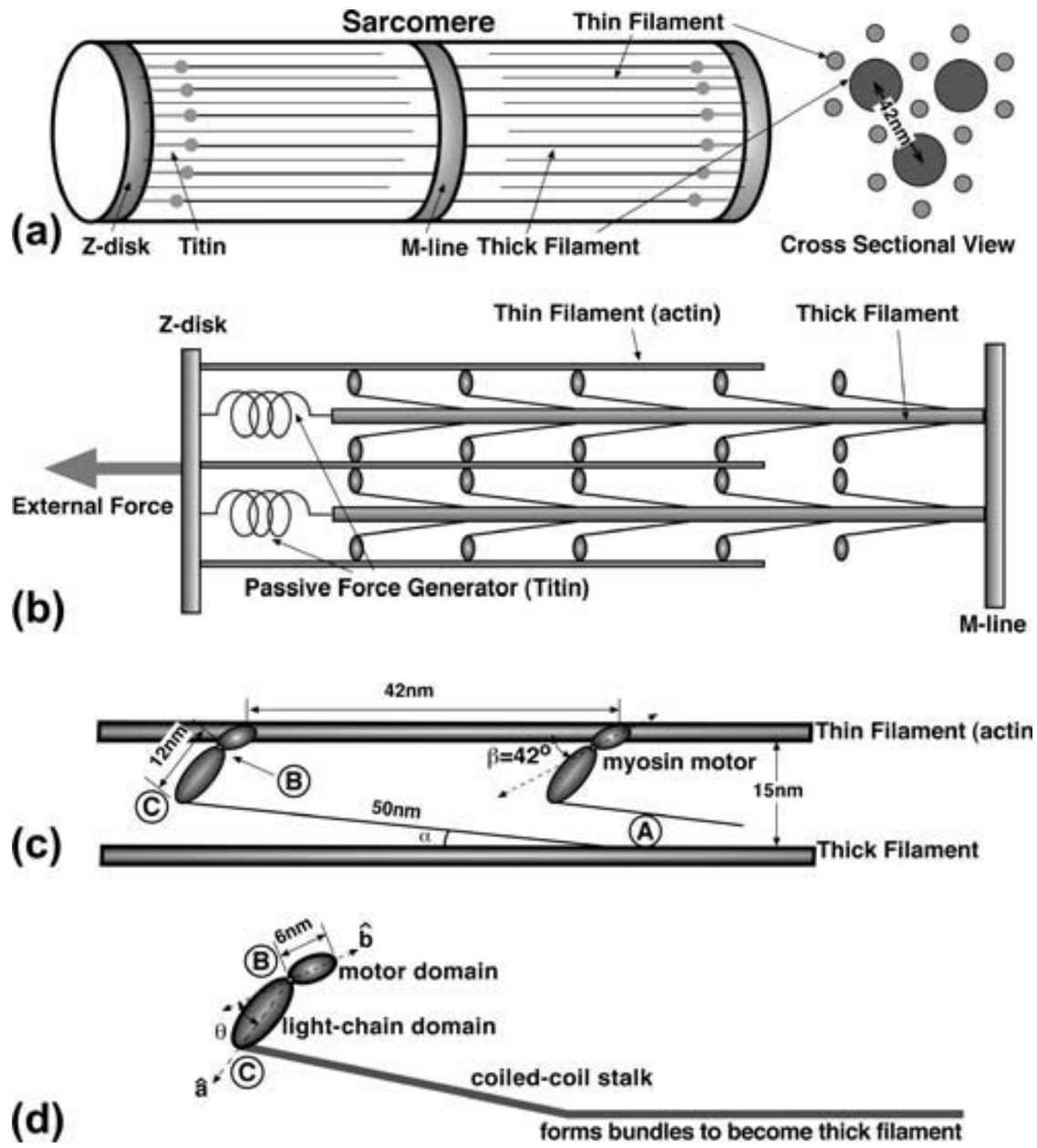
Skeletal muscle‘s mechanical characteristics

Huxley-type model describing myosin head movement

Presets force and chemical state

Include molecular friction, chemical kinetics and a stochastic component

Predicts change of muscle coordinate (angle of myosin heads)



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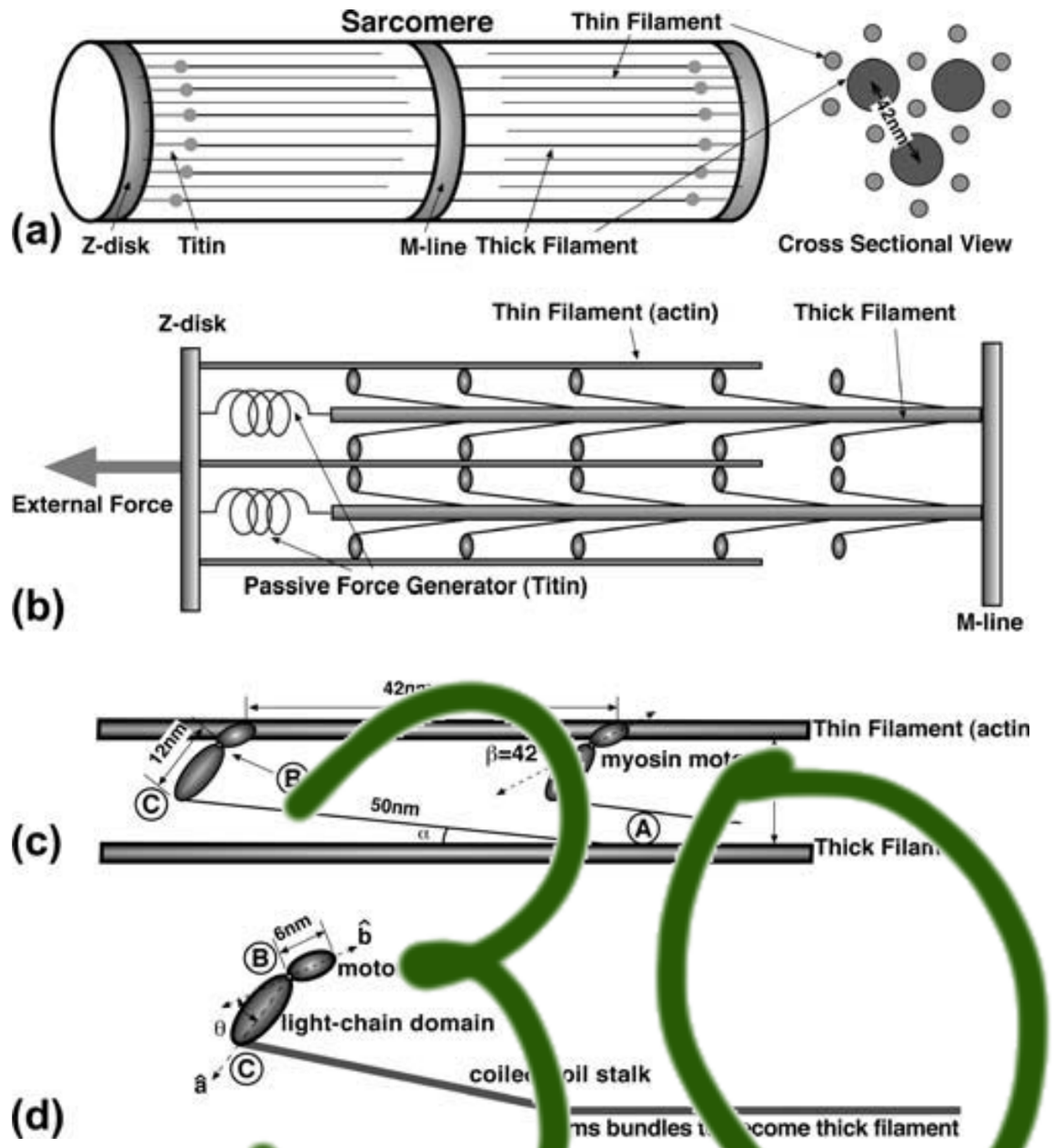

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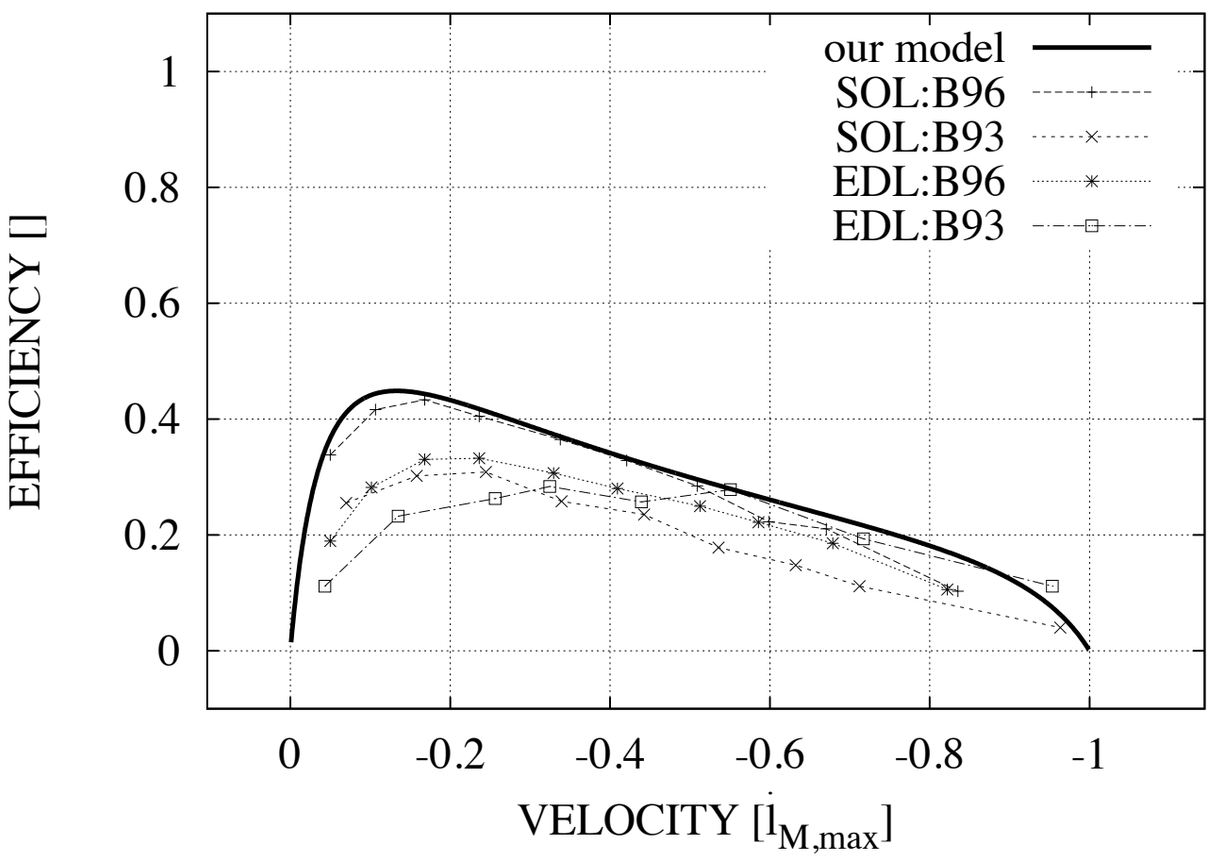
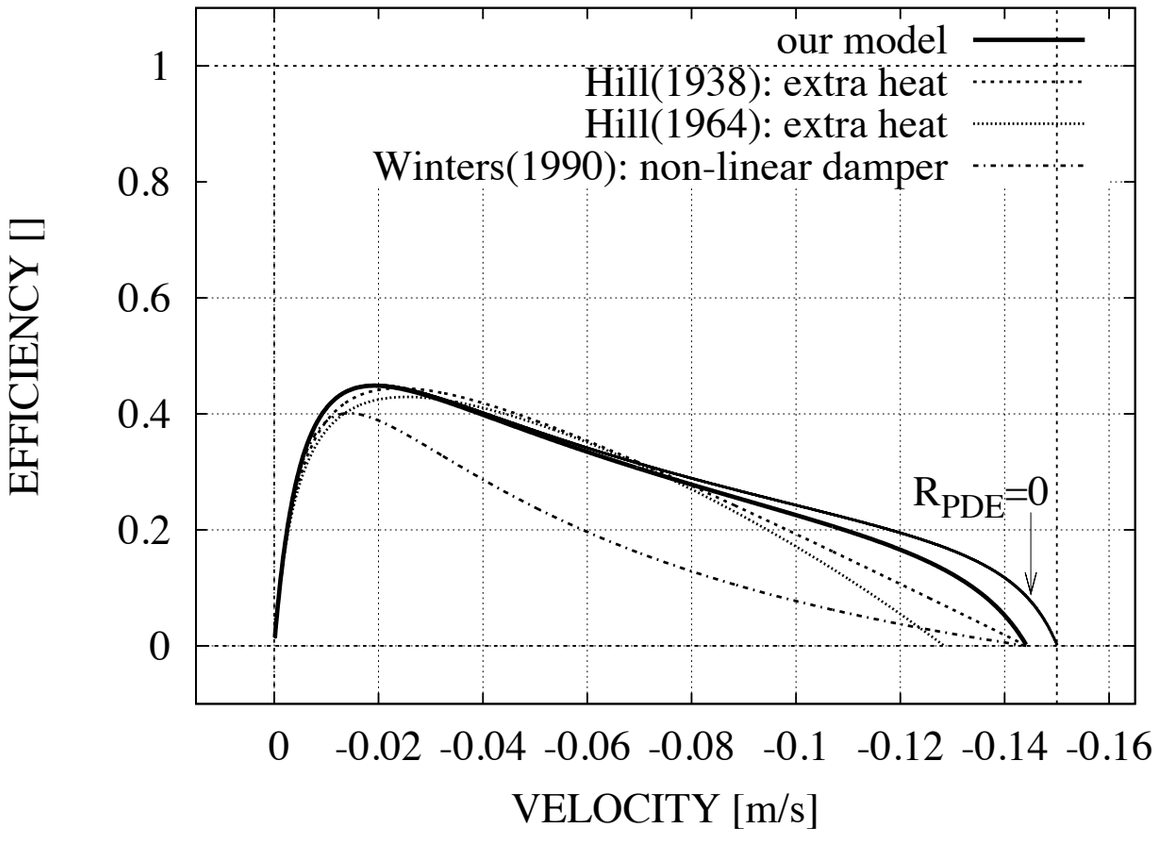
Skeletal muscle‘s mechanics





Efficiency = mech. energy output / mech. energy input

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Günther, M, Schmitt, S. 2010. A macroscopic ansatz to deduce the Hill relation. Journal of Theoretical Biology, 263(4), 407–18.

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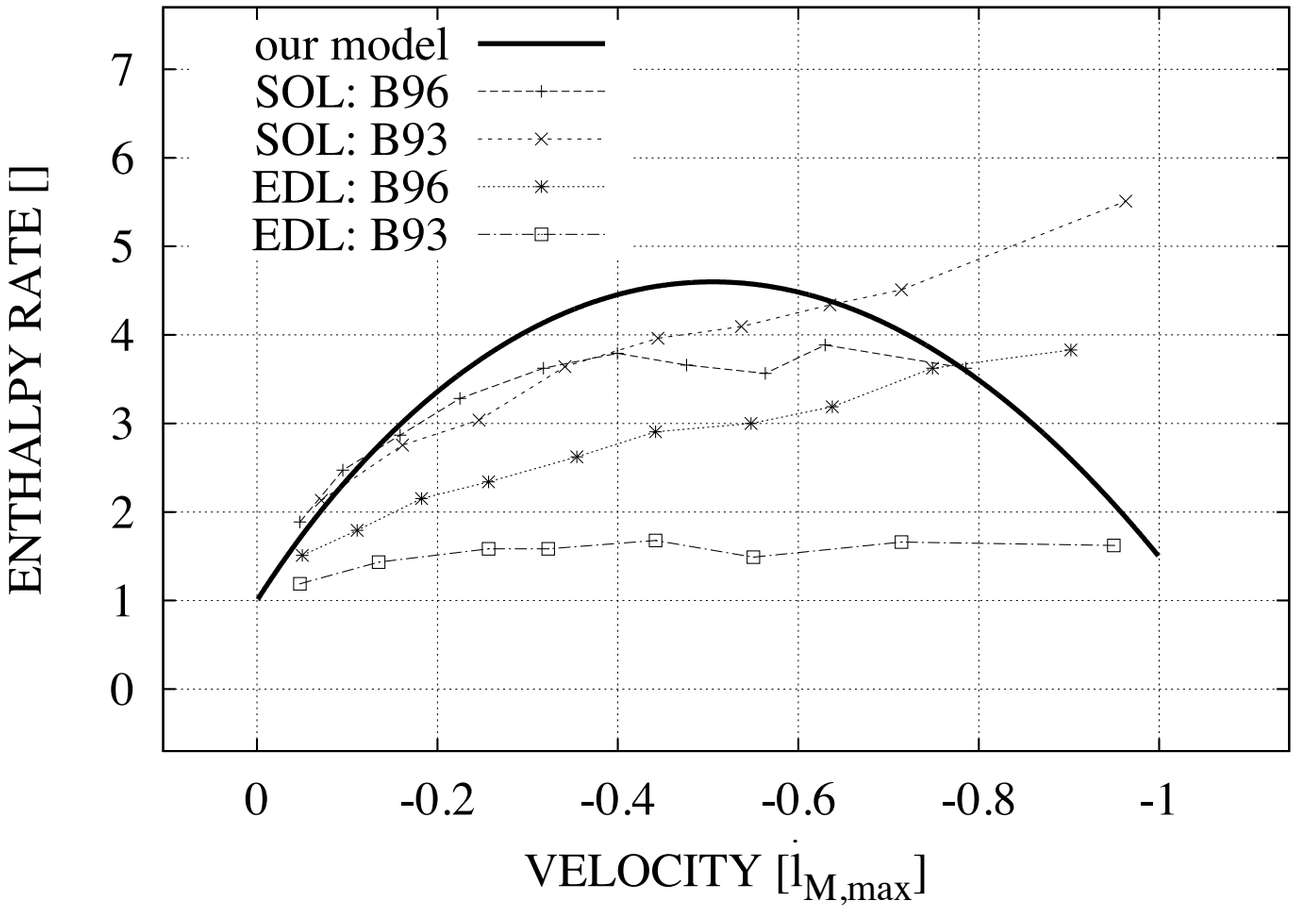
Skeletal muscle‘s thermodynamics



Enthalpy rate = power output * main. heat rate * shortening heat rate

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Günther, M, Schmitt, S. 2010. A macroscopic ansatz to deduce the Hill relation. Journal of Theoretical Biology, 263(4), 407–18.

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The biological skeletal muscle's ...

design and functioning.

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The biological skeletal muscle's ...

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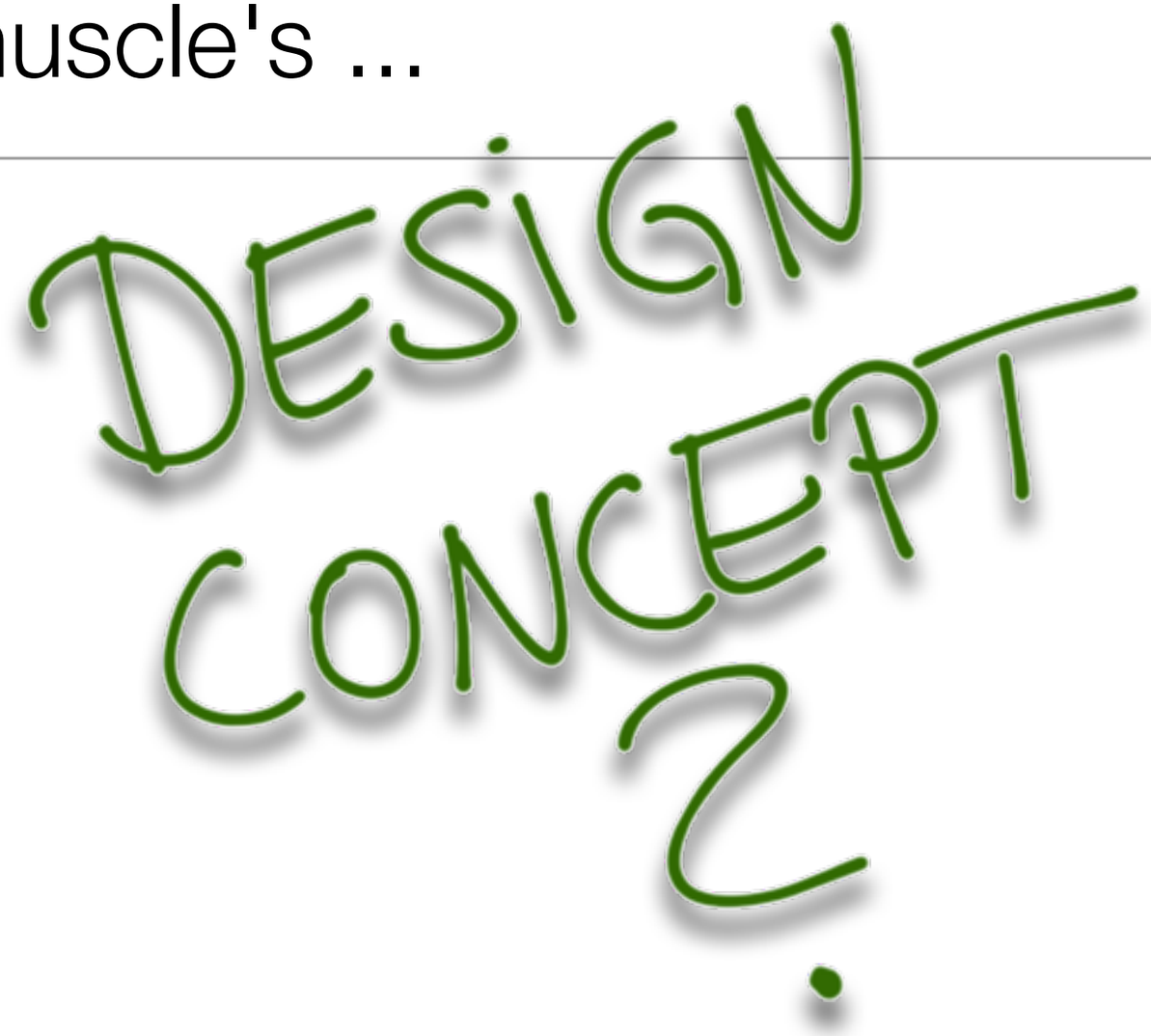

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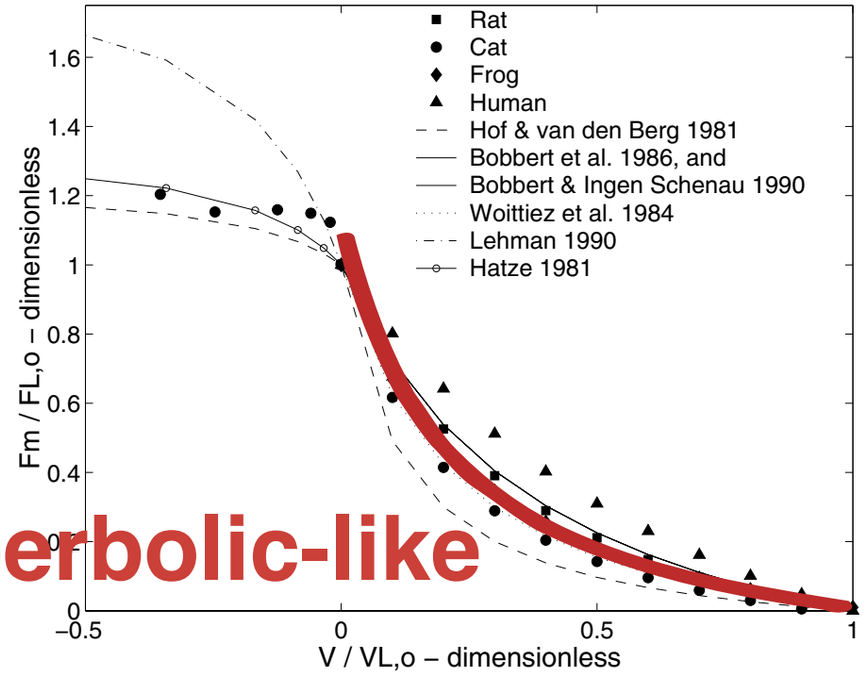
Design - from biological to artificial muscle ?

Engineering

←

?

Klute et al. (2002)



hyperbolic-like

↕

Hill-type muscle models so far ...

Biology

explain predict +√

account for structure ✗

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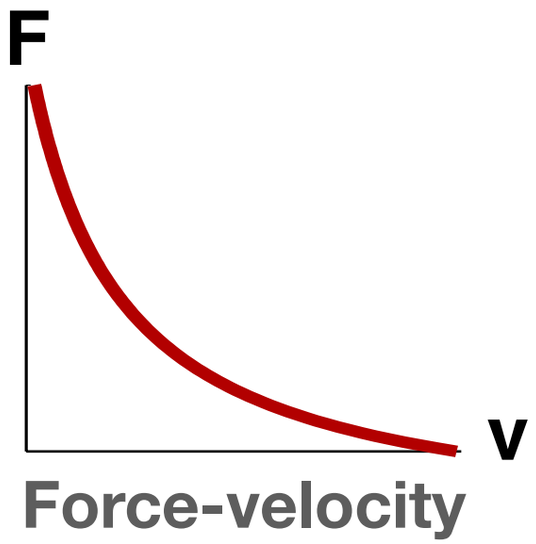
A macroscopic ansatz to derive the Hill relation

classical Hill-type models

data

fit



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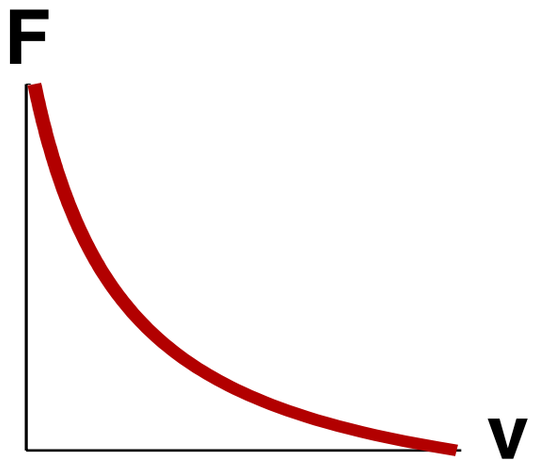
A macroscopic ansatz to derive the Hill relation

inspiration

data

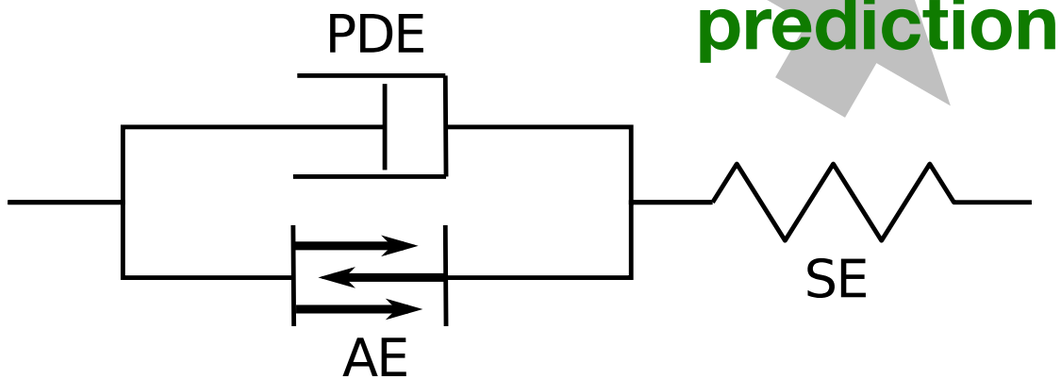
classical Hill-type models

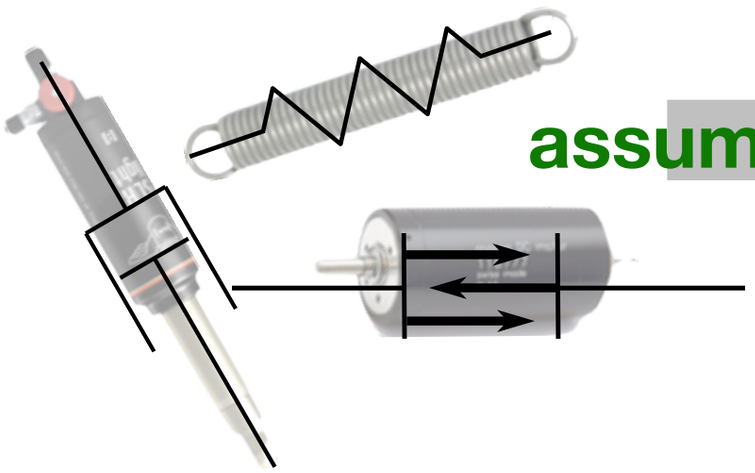
fit



Force-velocity

prediction





assumptions

first principle: force equilibrium

force law for damper

define introduced dof

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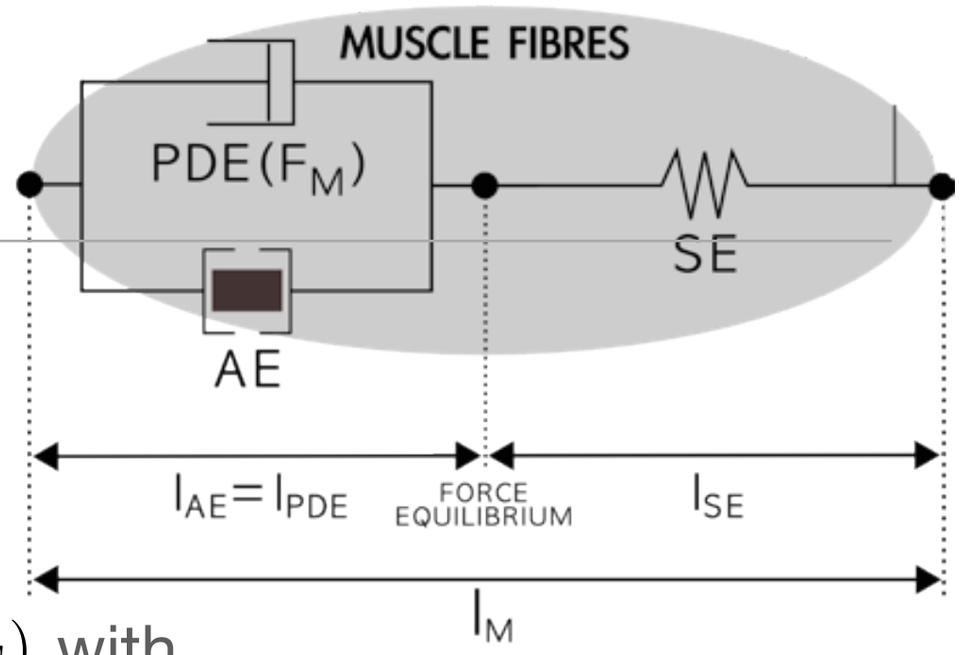
Analytical model



A1: Structure + first principle:

$$F_M = F_{SE} = F_{AE} + F_{PDE}$$

A2: Choice of a simple force law:

$$F_{PDE} = d_{PDE} \cdot \dot{l}_{PDE} = d_{PDE}(F_M) \cdot (\dot{l}_M - \dot{l}_{SE}) \text{ with}$$

$$d_{PDE}(F_M) = D_{PDE,max} \cdot ((1 - R_{PDE})F_M / F_{AE,max} + R_{PDE})$$

A3: Internal degree of freedom:

$$\kappa_v = \dot{l}_{SE} / \dot{l}_M$$

nspo

Günther, M, Schmitt, S. 2010. A macroscopic ansatz to deduce the Hill relation. Journal of Theoretical Biology, 263(4), 407–18.

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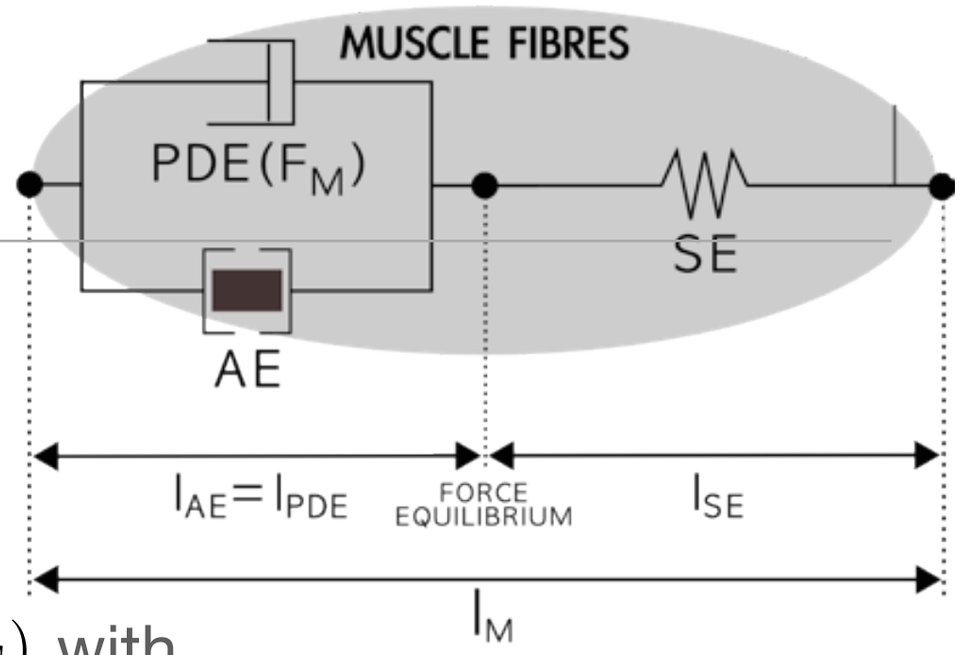
Analytical model



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A3: Internal degree of freedom:

$$\kappa_v = \dot{l}_{SE} / \dot{l}_M$$

After some mathematics we get:

$$\boxed{(F_M + A) \cdot \dot{l}_M = -B \cdot (F_{M,0} - F_M)}$$

with

$$A = \frac{R_{PDE}}{1 - R_{PDE}} \cdot F_{AE,max}$$

$$B = \frac{1}{1 - R_{PDE}} \cdot \frac{1}{1 - \kappa_v} \cdot \frac{F_{AE,max}}{D_{PDE,max}}$$

nspo

Günther, M, Schmitt, S. 2010. A macroscopic ansatz to deduce the Hill relation. Journal of Theoretical Biology, 263(4), 407–18.

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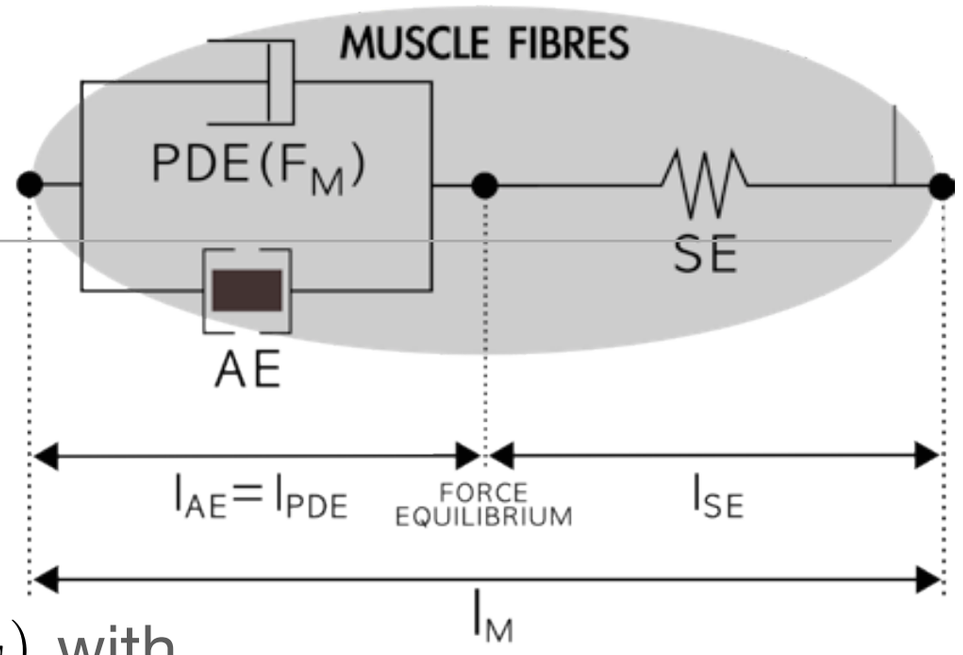
Analytical model



A1: Structure + first principle:

$$F_M = F_{SE} = F_{AE} + F_{PDE}$$

A2: Choice of a simple force law:

$$F_{PDE} = d_{PDE} \cdot \dot{l}_{PDE} = d_{PDE}(F_M) \cdot (\dot{l}_M - \dot{l}_{SE}) \text{ with}$$

$$d_{PDE}(F_M) = D_{PDE,max} \cdot ((1 - R_{PDE})F_M / F_{AE,max} + R_{PDE})$$

A3: Internal degree of freedom:

$$\kappa_v = \dot{l}_{SE} / \dot{l}_M$$

- **After some mathematics** we get:

$$\boxed{(F_M + A) \cdot \dot{l}_M = -B \cdot (F_{M,0} - F_M)}$$

with

$$A = \frac{R_{PDE}}{1 - R_{PDE}} \cdot F_{AE,max}$$

$$B = \frac{1}{1 - R_{PDE}} \cdot \frac{1}{1 - \kappa_v} \cdot \frac{F_{AE,max}}{D_{PDE,max}}$$

$\Longleftrightarrow$

- **Hill's original formulation** to fit his experimental results

$$(P + a) \cdot v = b \cdot (P_0 - P)$$

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Günther, M, Schmitt, S. 2010. A macroscopic ansatz to deduce the Hill relation. Journal of Theoretical Biology, 263(4), 407–18.

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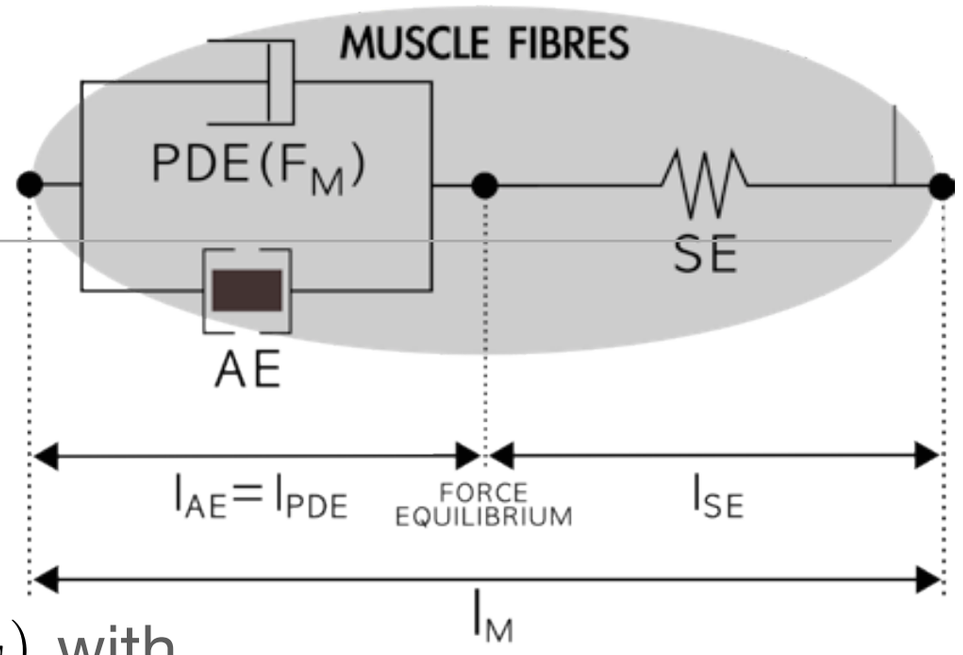
Analytical model



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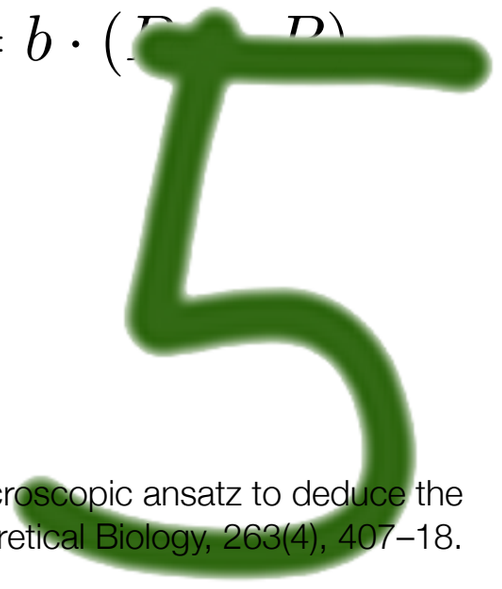

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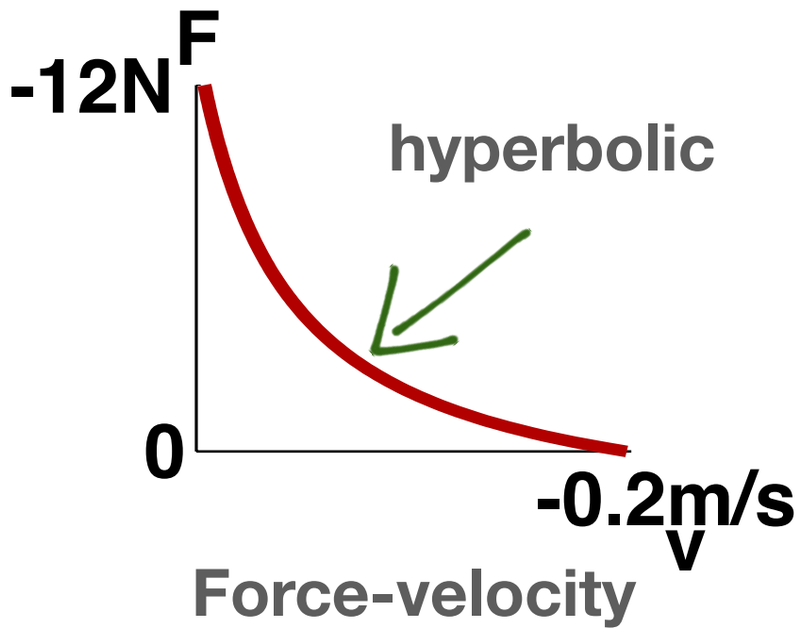
Choice of biological muscle (experimental data)



Rat gastrocnemius
A = 2.68 N
B = 0.042 m/s
F_{max} = 13.4 N
$l_{CE,opt}$ = 0.013 m

van Zandwijk et al. 1996

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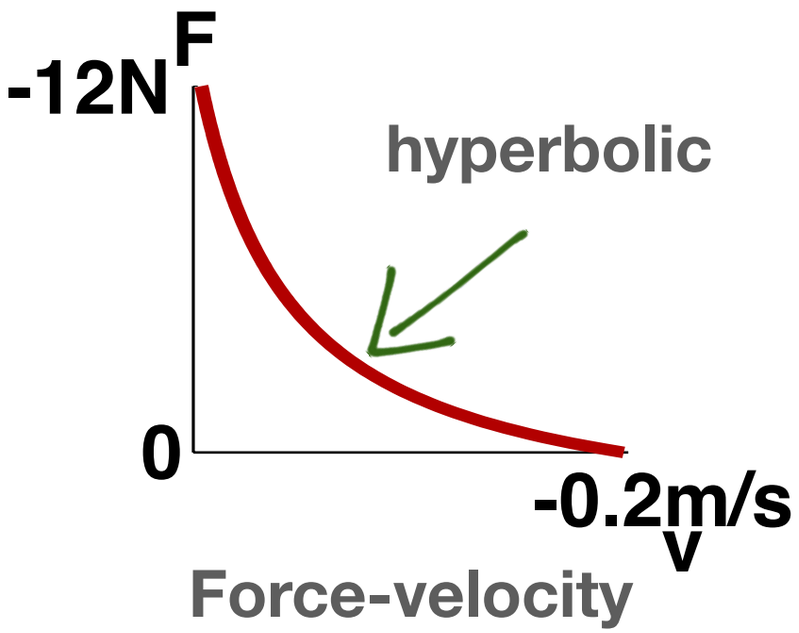
Choice of biological muscle (experimental data)



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A = 2.68 N
B = 0.042 m/s
F_{max} = 13.4 N
$l_{CE,opt}$ = 0.013 m

van Zandwijk et al. 1996

analytical model

$kappa_v$ = 0.15

$F_{AE,max} = F_{max}$

$F_{M,0} = F_{AE,max}$

analytical model

Mechanical parameters PDE
R_{PDE} = 0.2
$D_{PDE,max}$ = 386 Ns/m

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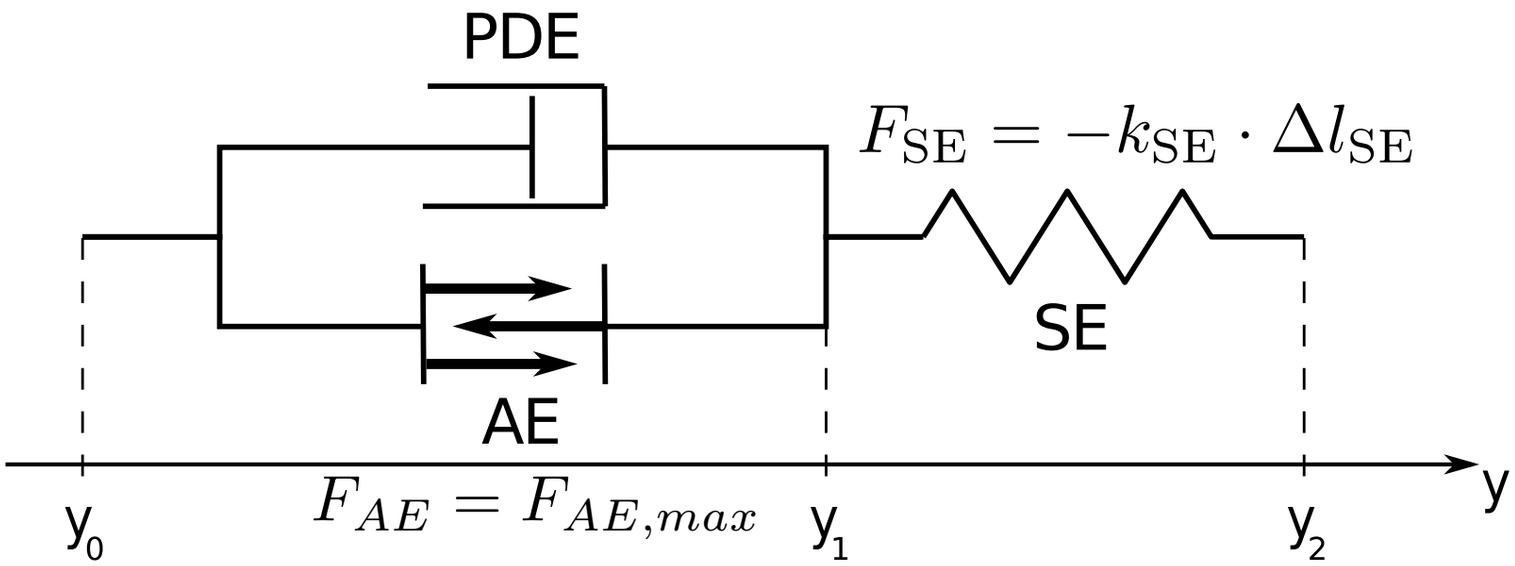
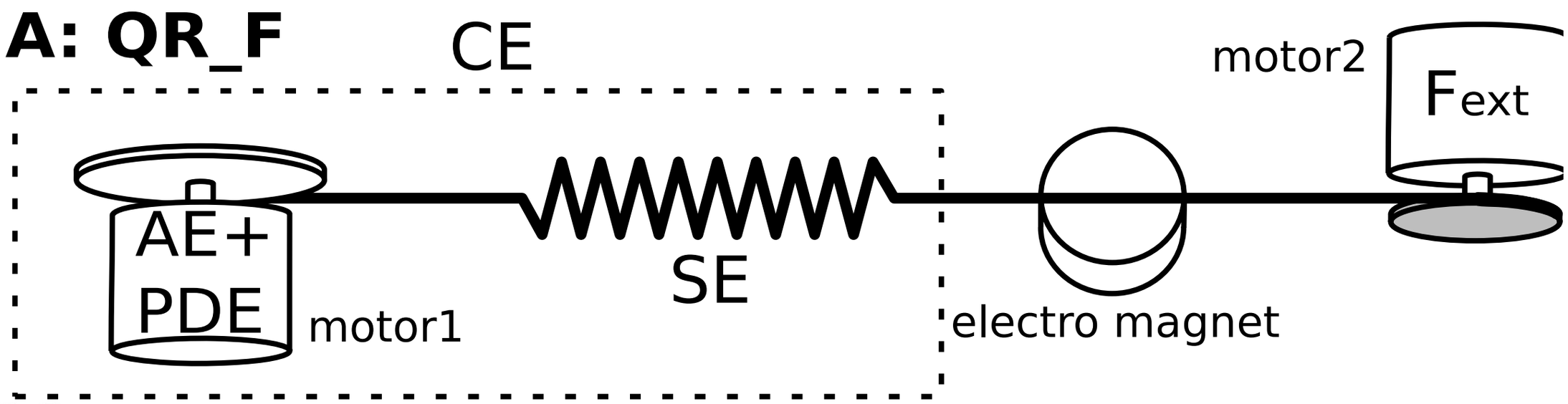
Numerical model and hardware experiment



$$\dot{y}_1 = \frac{F_{AE} - F_{SE}}{d_{PDE(F_M)}}$$

$$\ddot{y}_2 = g + \frac{1}{m} F_{SE}$$

using same parameters



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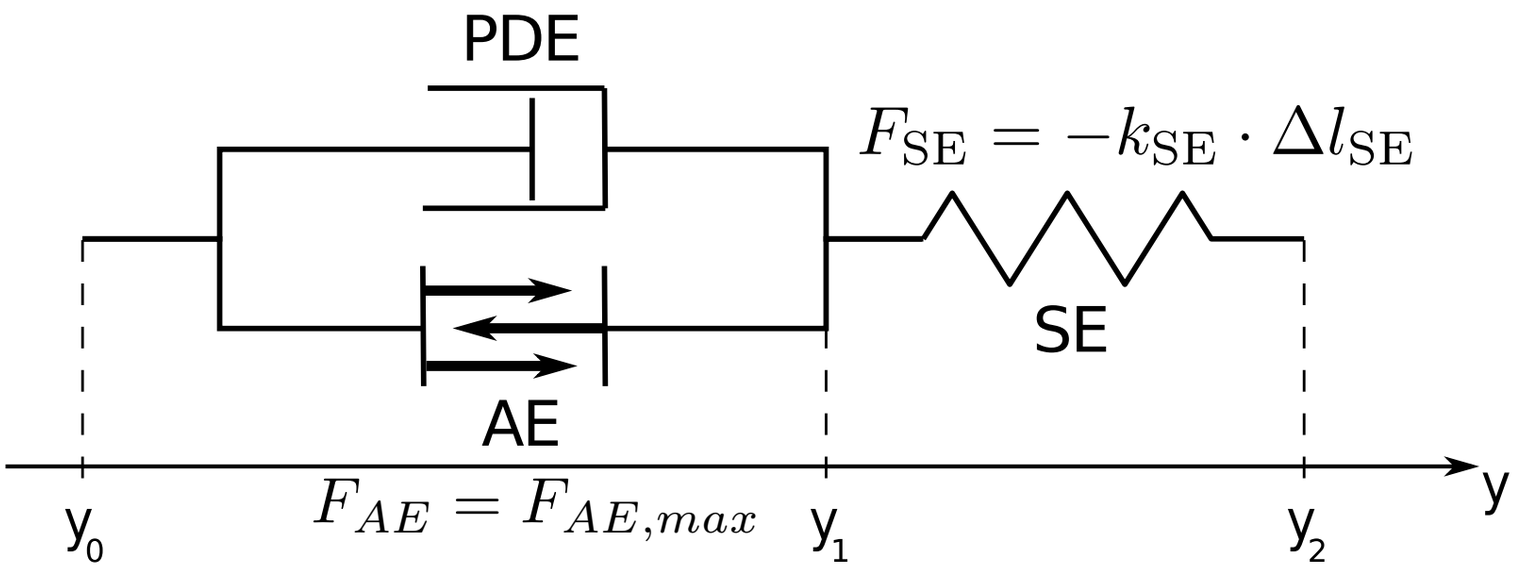
Numerical model and hardware experiment



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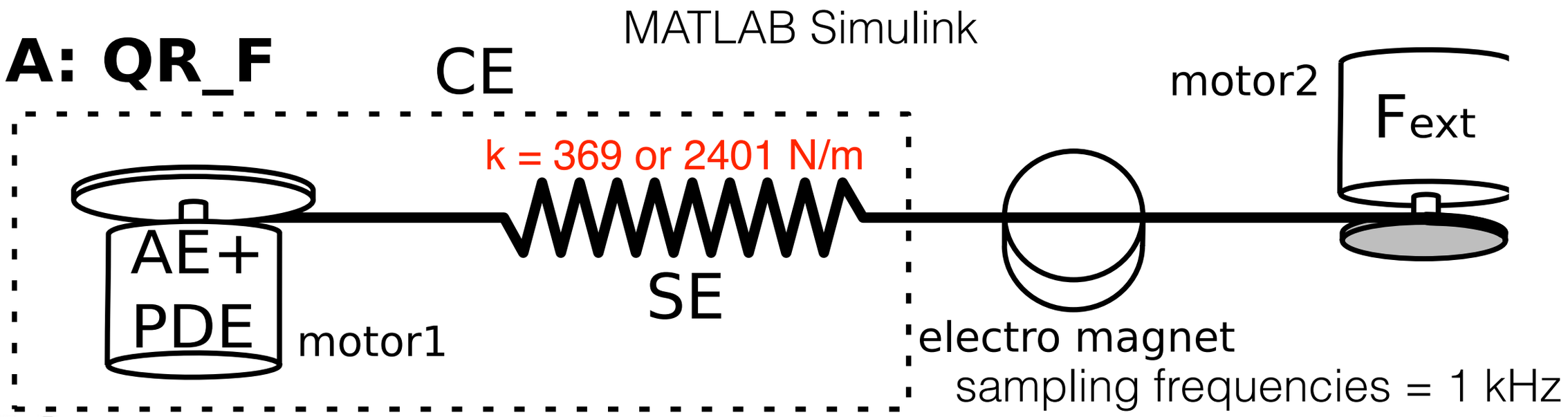

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Quick release contractions

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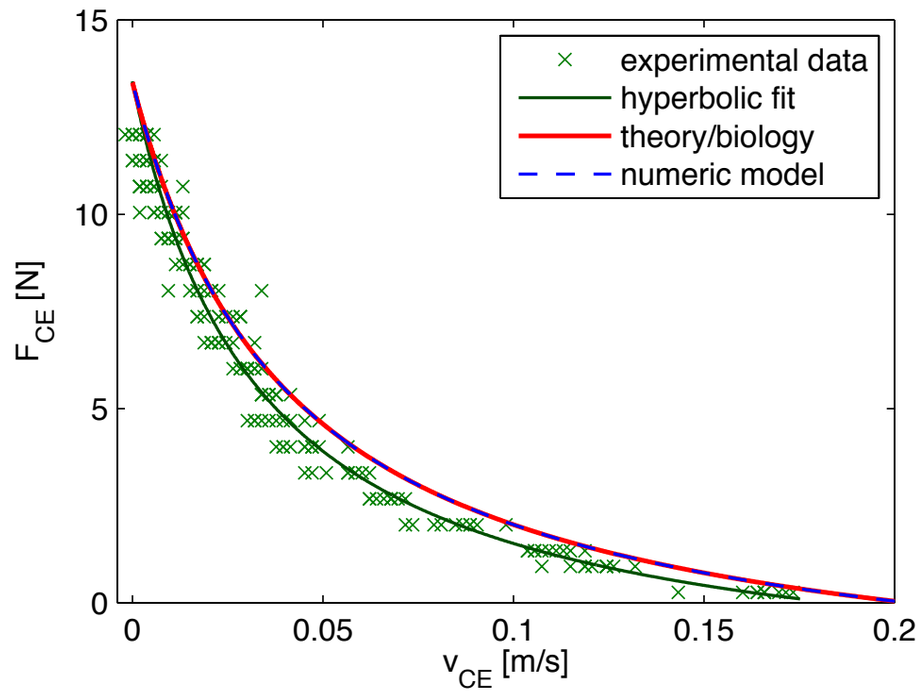
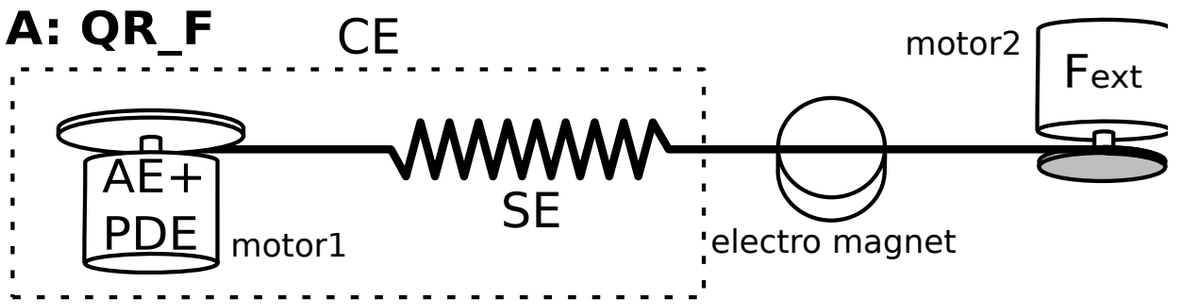
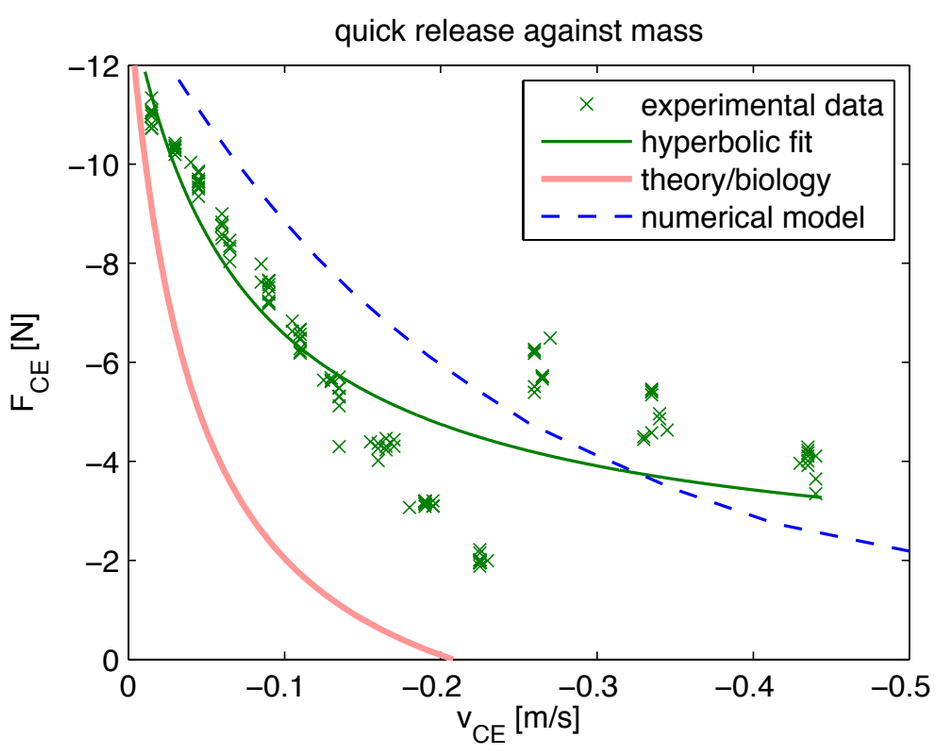
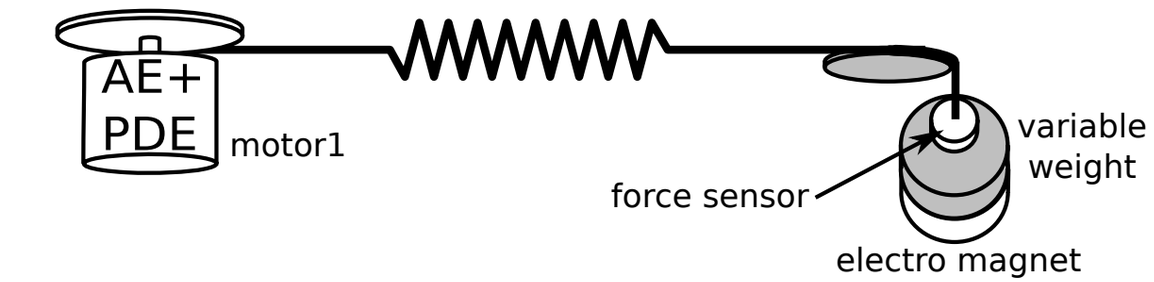
Hyperbolic force velocity relation









Haeufle, D.F.B., Günther, M., Blickhan, R., Schmitt, S. (2012). Can Quick Release Experiments Reveal the Muscle Structure? A Bionic Approach. Journal of Bionic Engineering, 9(2), 211-223

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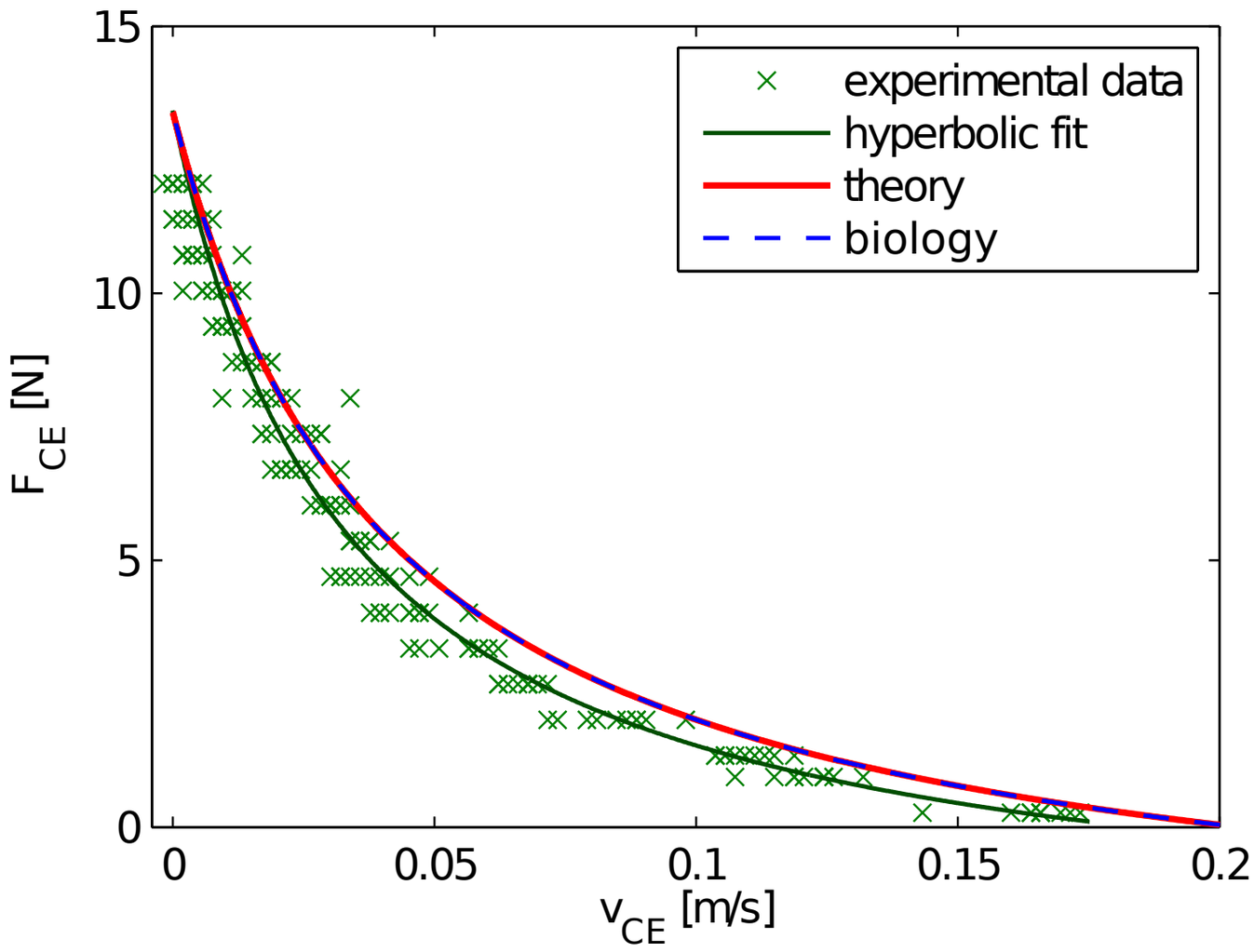
Biological muscle is the better actuator!

Engineering

Biology



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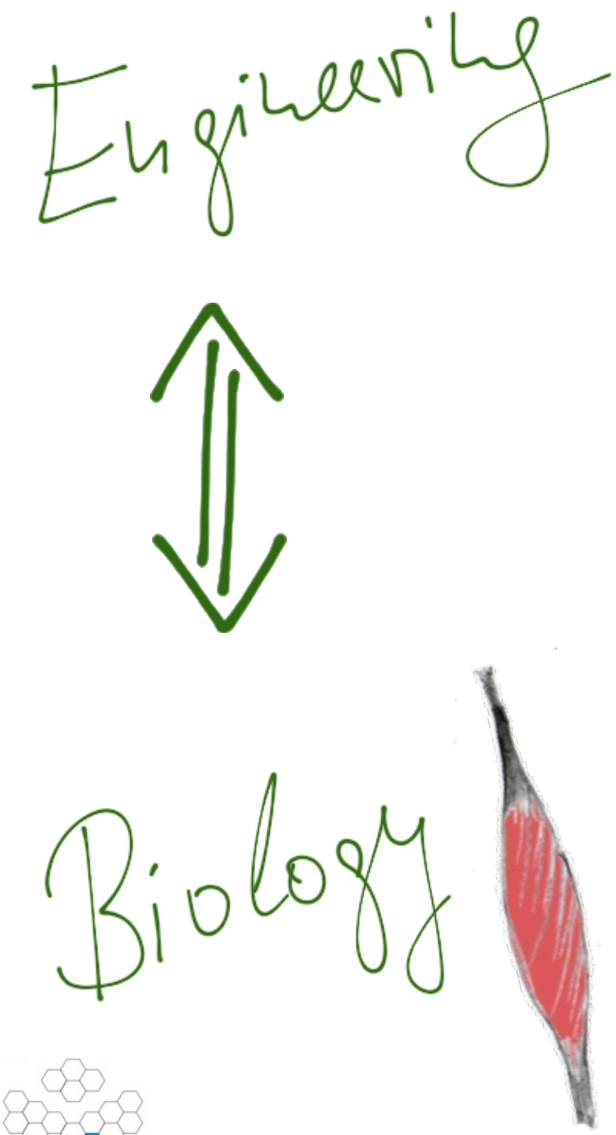

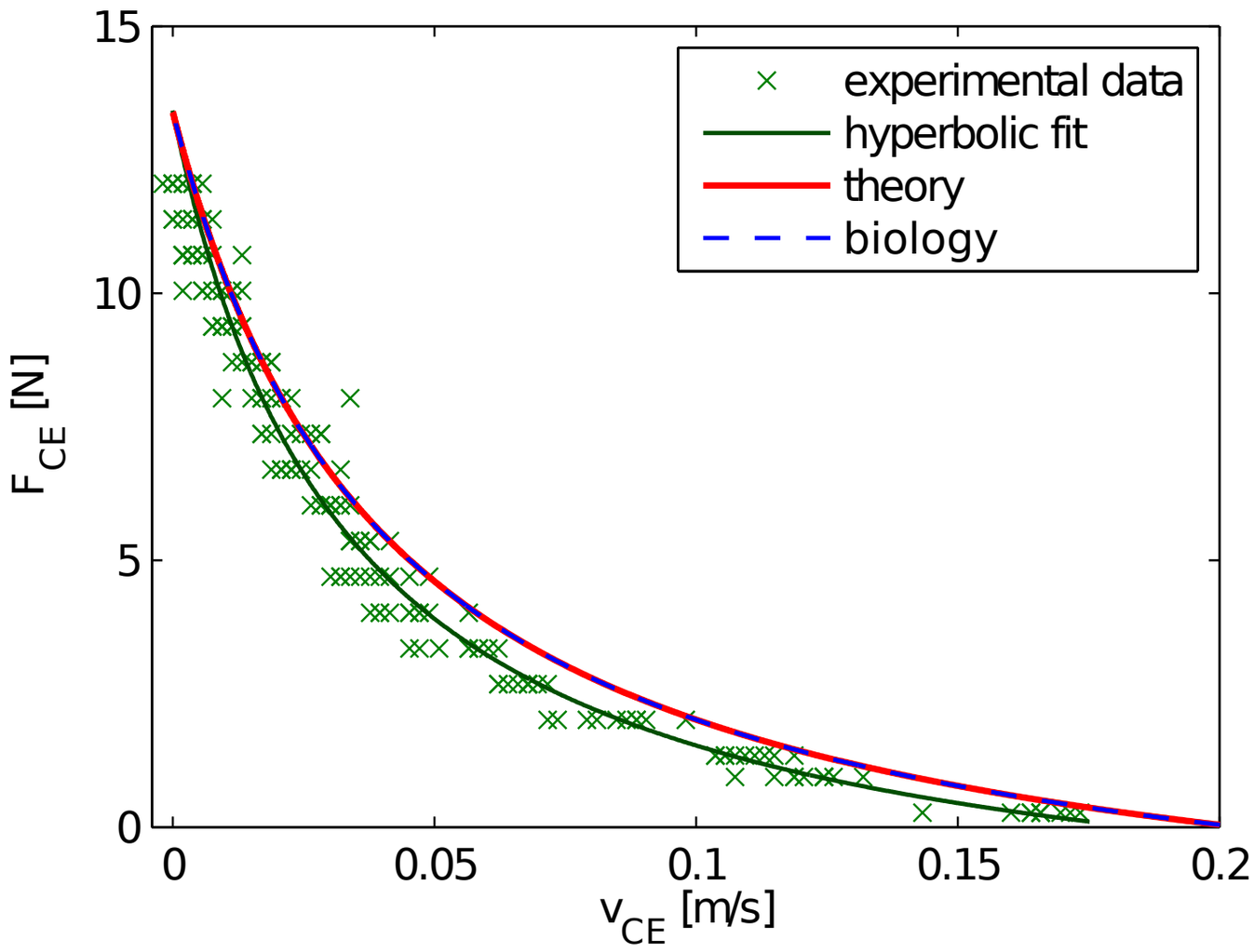

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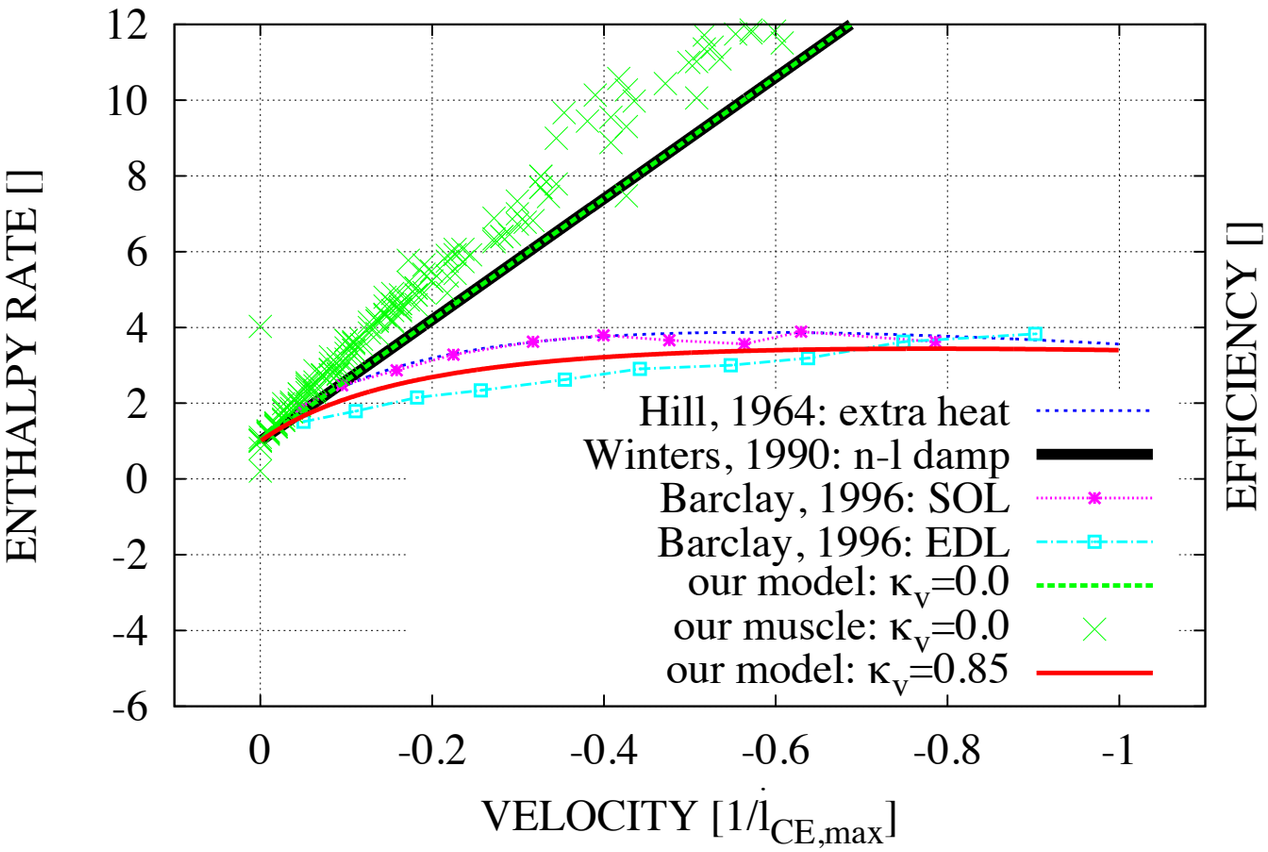
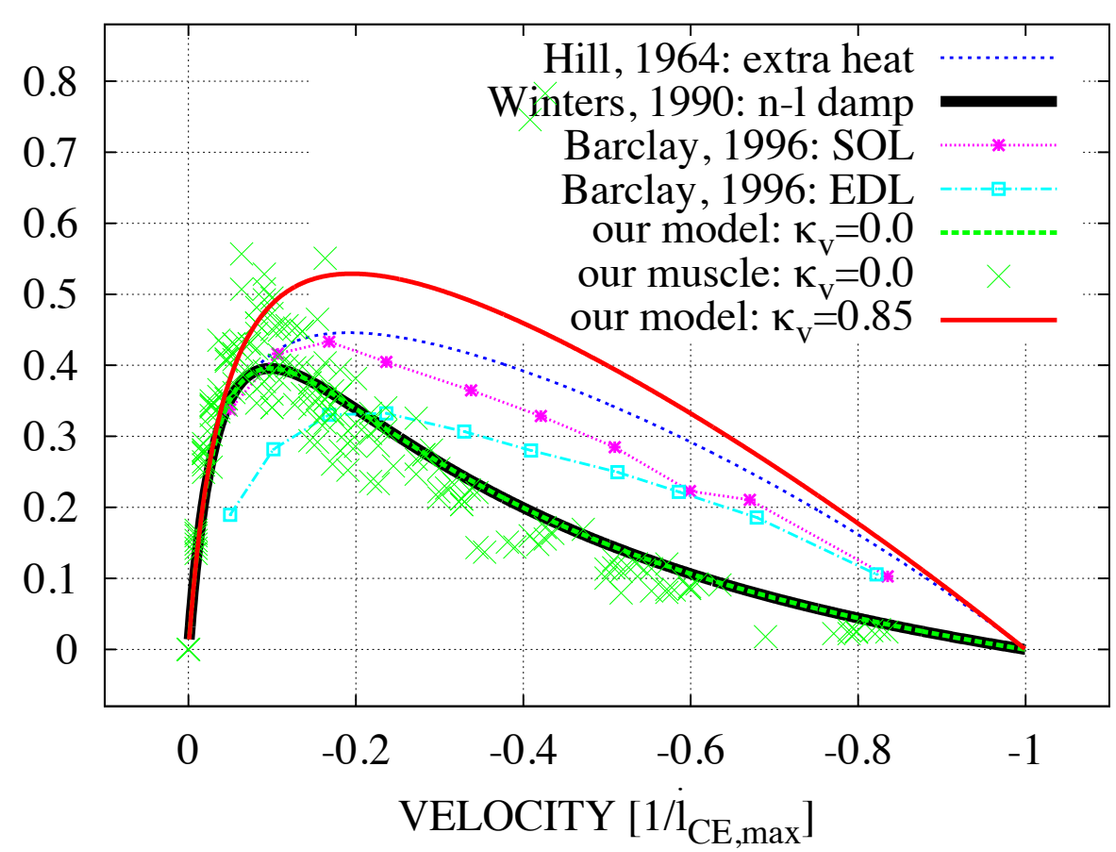
Is biological muscle the better actuator?





Enthalpy rate = energy balance including heat rates

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Schmitt, S., Häufle, D.F.B., Blickhan, R., Günther, M. (2012). Nature as an engineer: one simple concept of a bio-inspired functional artificial muscle. Bioinspiration & Biomimetics, 7 036022

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What to do with this knowledge?

Build computer models of the biological system, which then can be activated and validated, realistically!

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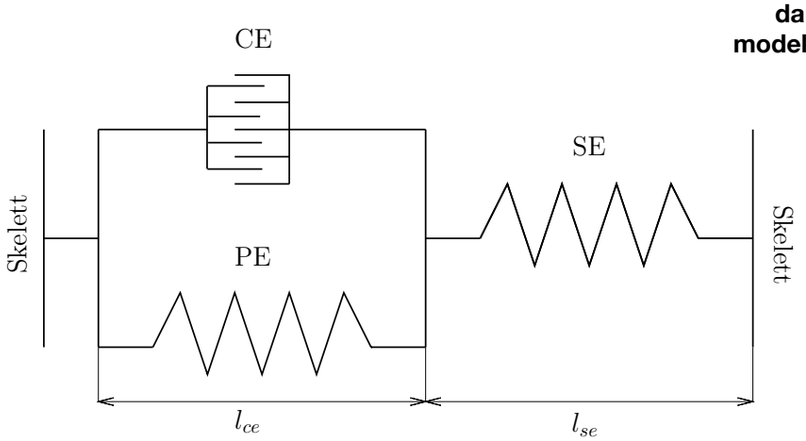
Our view on the biological motor ...

Muscle

Hill-type muscle model:



Günther, Schmitt, Wank (2007). **High-frequency oscillations as a consequence of neglected serial damping in Hill-type muscle models.** Biological Cybernetics, 97(1), 63-79..

$$v_j^{CE} = f_v(l_j^{mtc}, l_j^{CE}, q_j)$$

$$f_j^{mtc} = f_f(l_j^{CE}, v_j^{CE}, q_j)$$

$$\dot{q}_j = f_{qd}(l_j^{mtc}, l_j^{CE}, STIM_j^i)$$

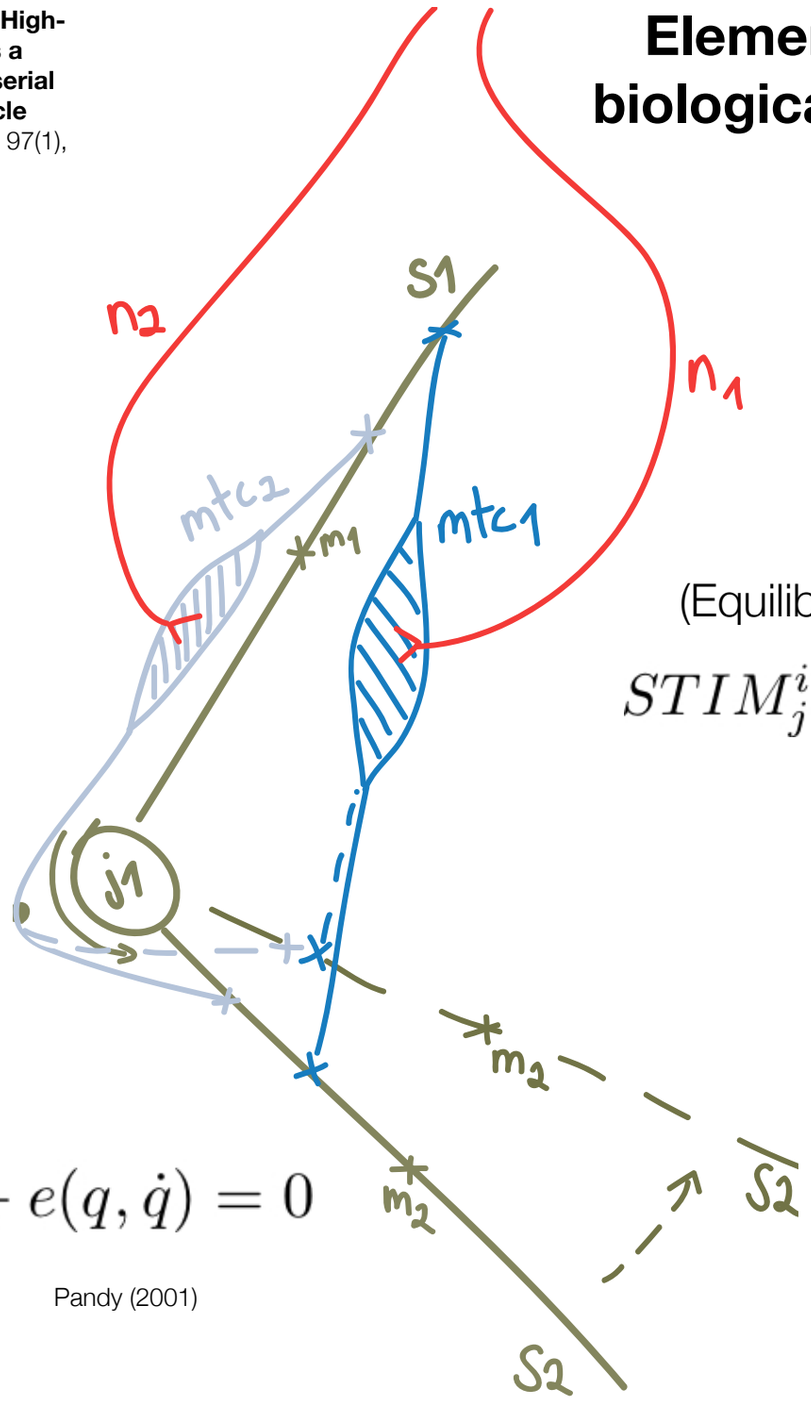
Skeletal apparatus

Model of the mechanical system:

$$M(q)\ddot{q} + C(q)\dot{q}^2 + g(q) + R(q)f^{mtc} + e(q,\dot{q}) = 0$$

Pandy (2001)

Elementary biological drive



Motor control

(Equilibrium-Point-Theory, EPT):

$$STIM_j^i = f_s(\lambda_j^i, l_j^{CE}, v_j^{CE})$$

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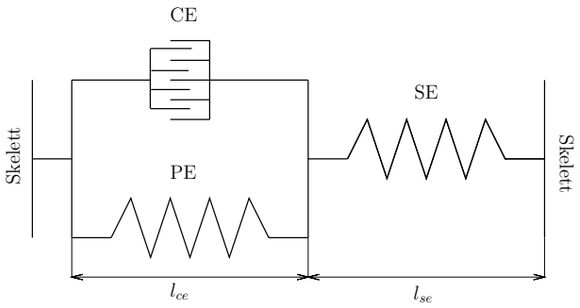
Modelling and simulation - our approach

Muscle

Hill-type muscle model:



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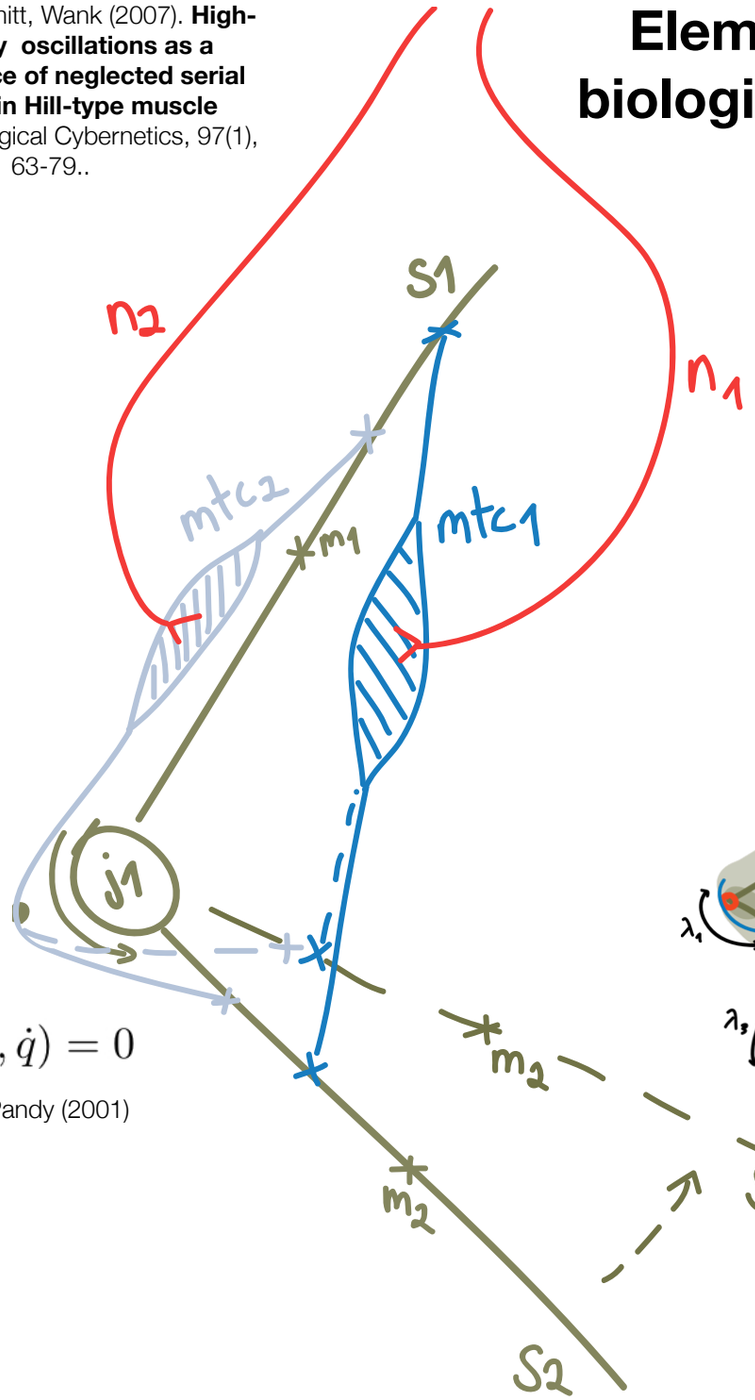

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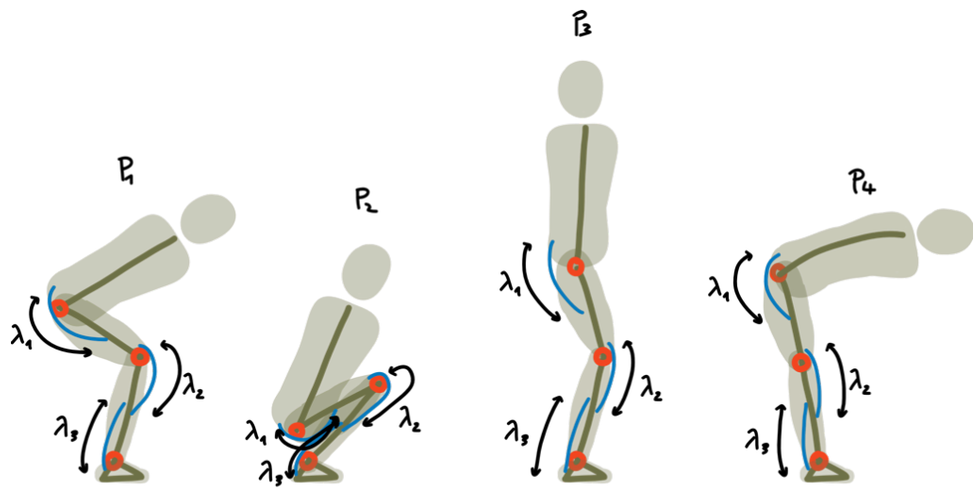

P1	P2	P	P3	P4
λ_1	λ_1	λ_1	λ_1	λ_1
λ_2	λ_2	λ_2	λ_2	λ_2
λ_3	λ_3	λ_3	λ_3	λ_3

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Modelling and simulation - motor control

multiple EBDs (single joint drives)

+

more complex drives (multi joint drives)

+

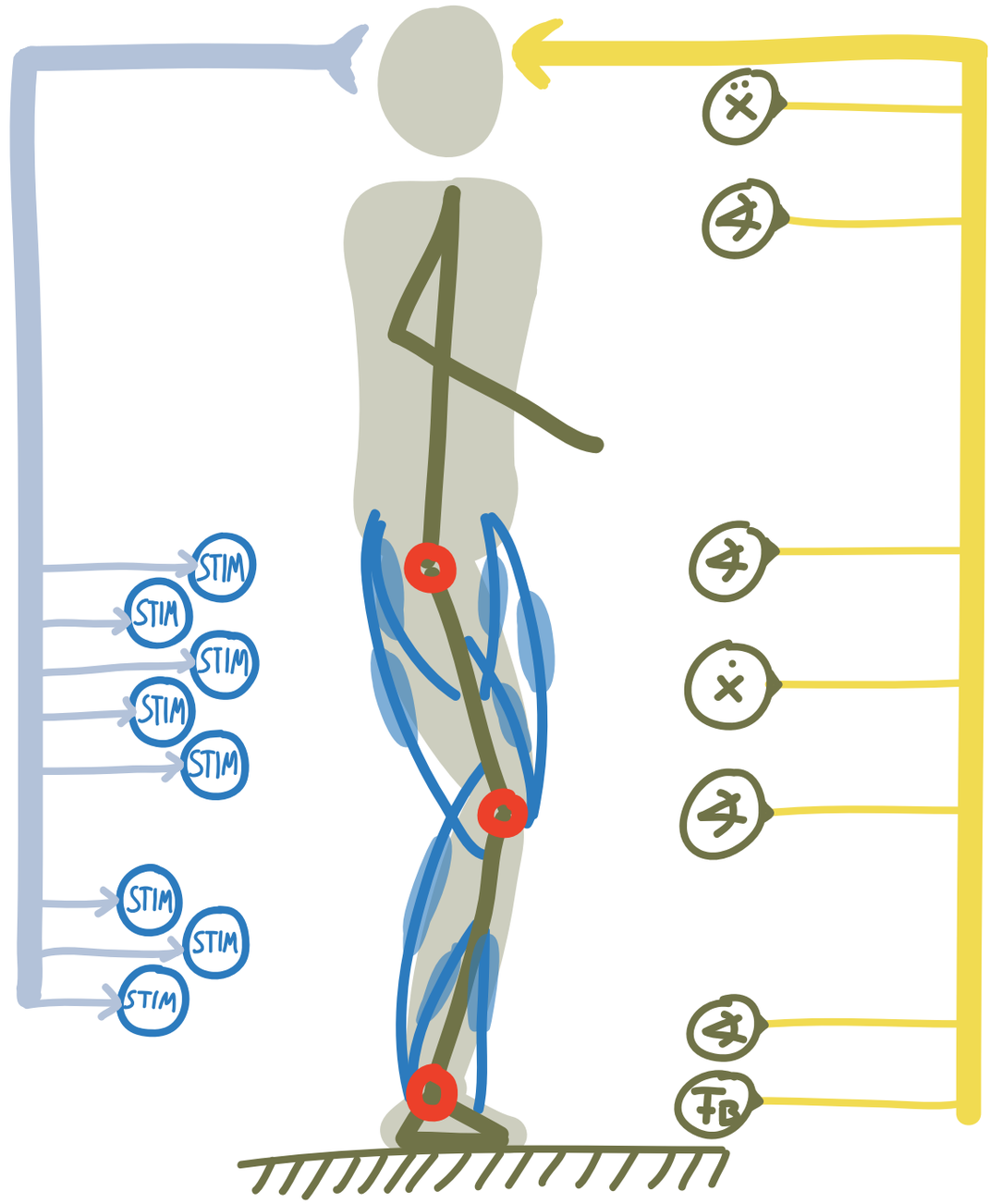
well tuned control (all drives)

+

movement tasks (daily living, ...)

+

disturbances (uneven ground, impact forces, ...)



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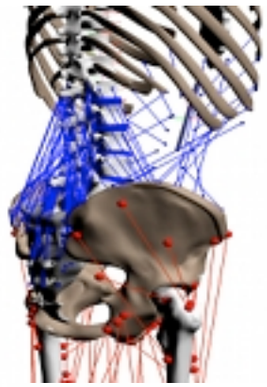
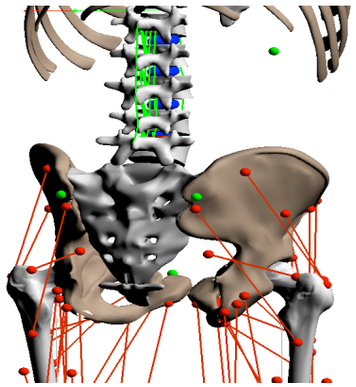
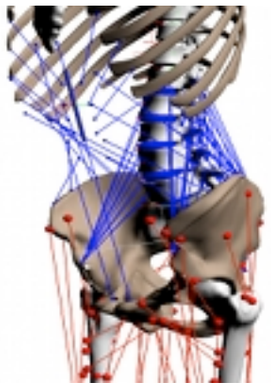
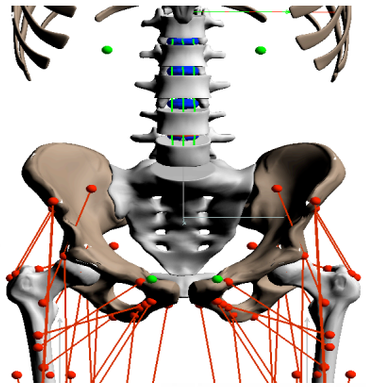
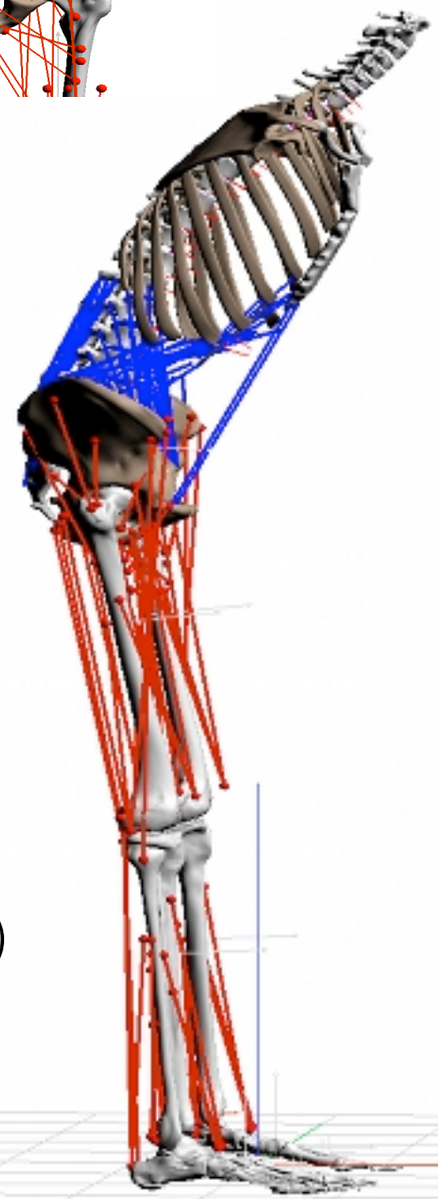
Modelling and simulation of human lumbar spine



450	degrees of freedom
48	mechanical dofs
202	Muscle-tendon complex (active, Hill-type)
58	non-linear ligaments
5	intervertebral discs (non-linear, coupled)

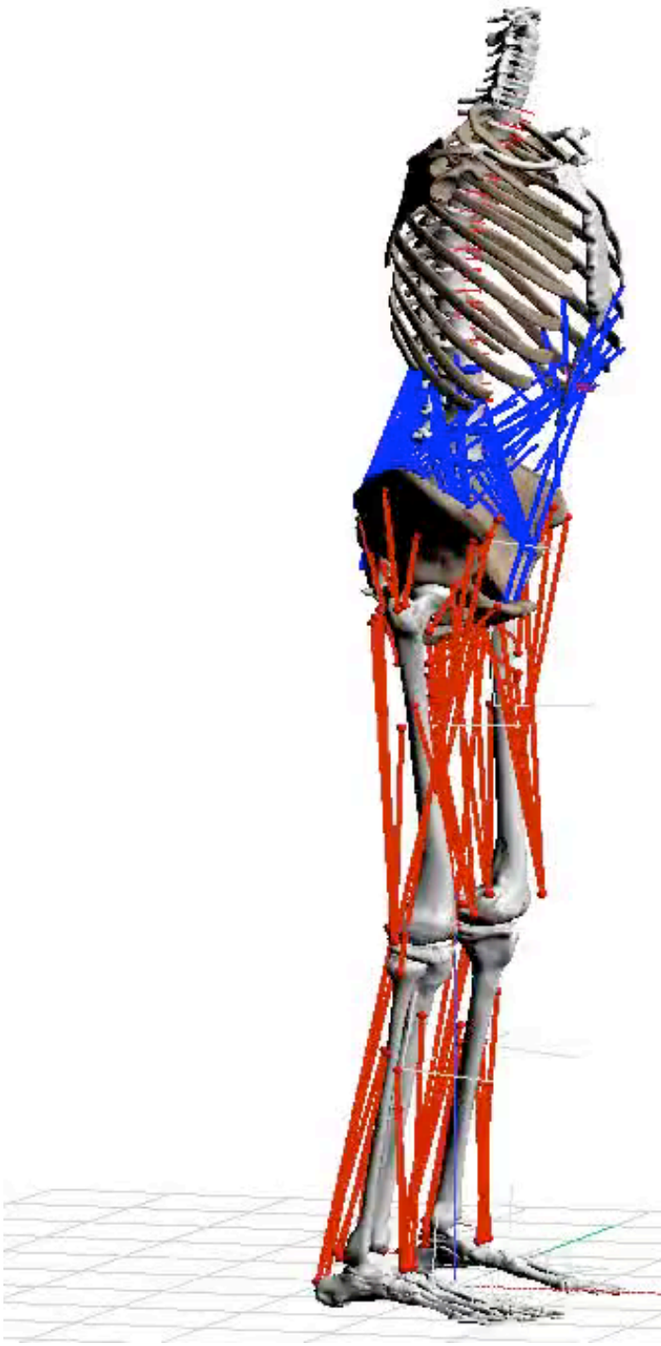
Anatomy of skeleton: m, 68kg, 1,78m (NASA, 1978)

Ligaments: Anatomy (Panjabi, 1982), physiology (Chazal, 1985)

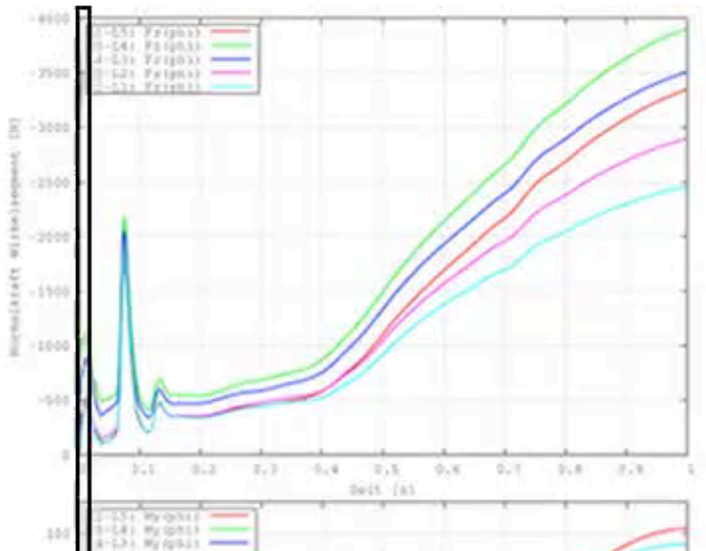
Muscles: Anatomy and physiology (Bogduk, 1992a,b, 1998; Hansen, 2006; Christophy, 2012)

Modelling and simulation of human lumbar spine

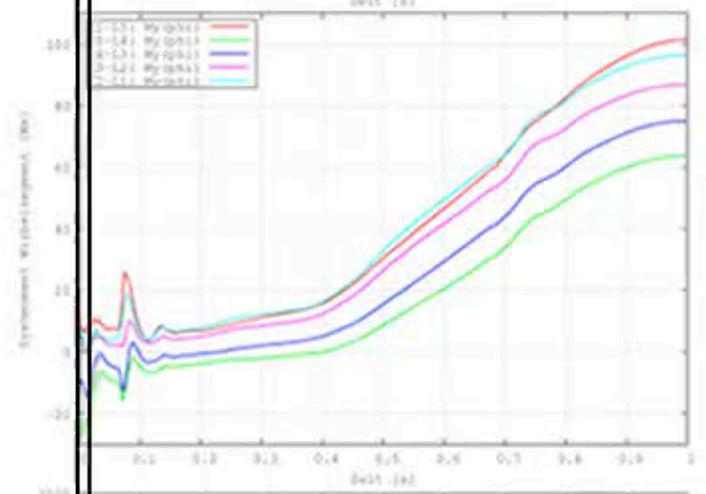
University of Stuttgart
Germany



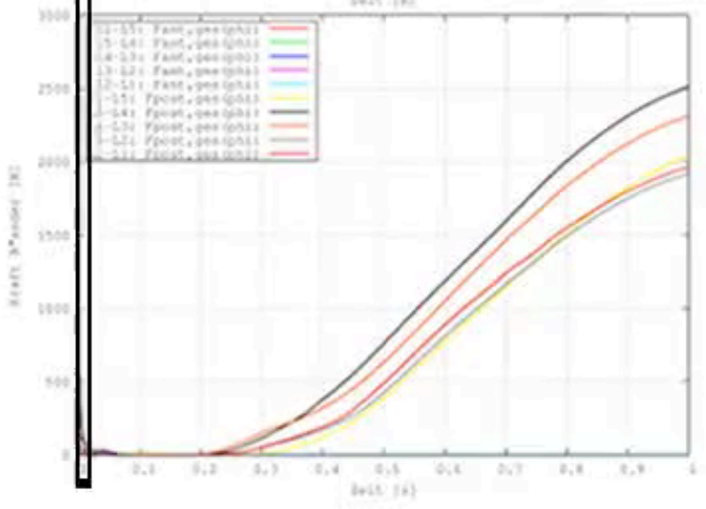
IVD Force normal dir.



IVD Torque



LIG Force posterior



The Human Movement Simulation Lab

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Motions in Man and Machine

A joint task for two groups:
(1) Computer simulation of an arm movement
(2) 3-d movement analysis of an arm movement

Project work will be to do (1) and (2)
and compare simulation and experiment

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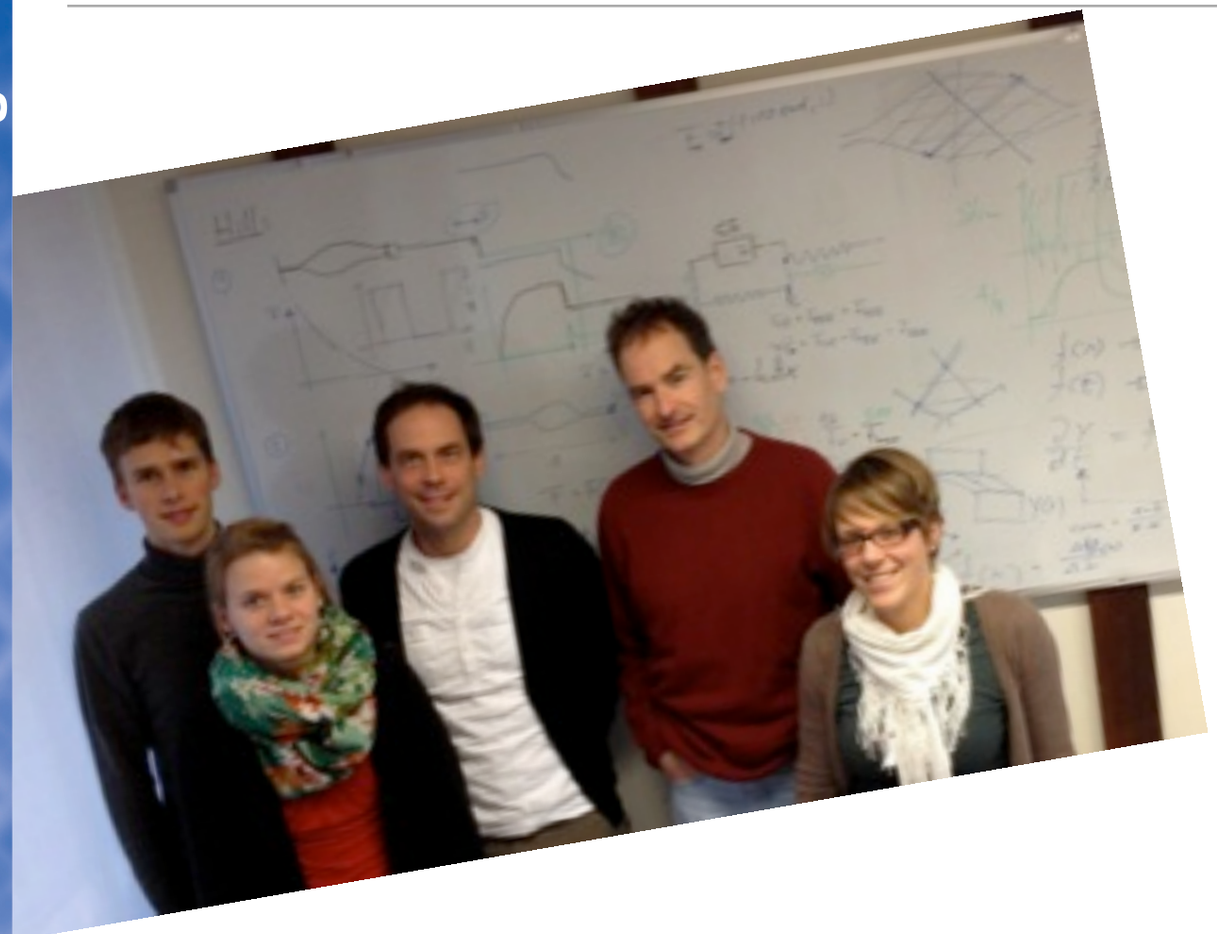
The **Human Movement Simulation** Lab



Alexandra Bayer
Michael Günther
Daniel Häufle
Tille Rupp
Syn Schmitt

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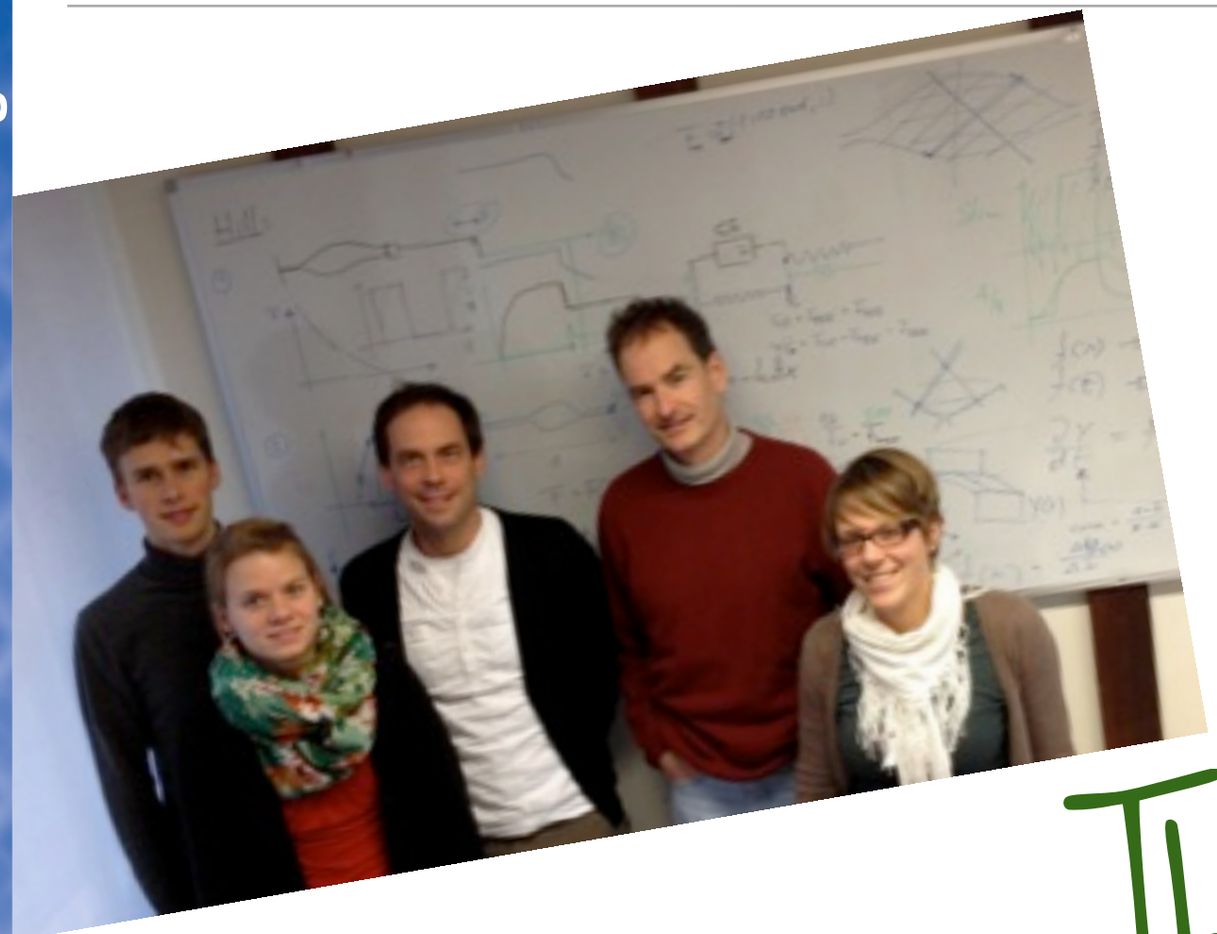
The **Human Movement Simulation** Lab



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Thank you for your attention !

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