Data-Integrated Simulation Science A
Elsa Bunz, Schmitt Group

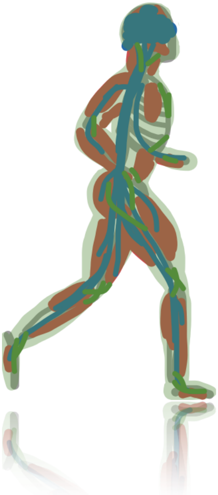
Lecture 2: Modelling muscles and ligaments

University of Stuttgart
Institute for Modelling and Simulation
of Biomechanical Systems

SimTech

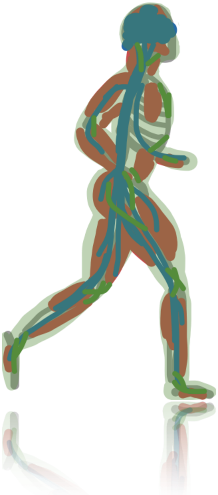
cbb Computational Biophysics and Biorobotics

What is required for such a model?



	Bones Structure	Rigid bodies	Lecture 1
	Ligaments, cartilage, fat Springs	Passive force	
	Muscles Motors	Active force	
	Neurons Wires, CPU	Reflexes, commands	

What is required for such a model?



Bones Structure	Rigid bodies
Ligaments, cartilage, fat Springs	Passive force
Muscles Motors	Active force
Neurons Wires, CPU	Reflexes, commands

Lecture 2

What is required for such a model?

Model of high-level motor control

EP control

$$\Lambda_i^{\text{move}} = \{\vec{\lambda}_1, \vec{\lambda}_2, \vec{\lambda}_3, \dots, \vec{\lambda}_n\}$$

Joint space control

- continuous vs. intermittent
- ***model-based control***
- ***learning-based control***

Model of skeletal muscle

Hill-type model

$$F_j^{\text{MTU}} = f_f(l_j^{\text{MTU}}, \dot{l}_j^{\text{MTU}}, l_j^{\text{CE}}, a_j)$$

$$\dot{l}_j^{\text{CE}} = f_v(l_j^{\text{MTU}}, \dot{l}_j^{\text{MTU}}, l_j^{\text{CE}}, a_j)$$

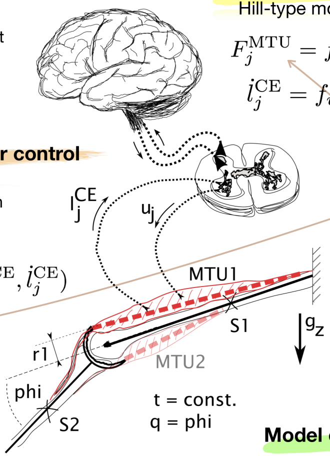
$$\dot{a}_j = f_a(a_j, l_j^{\text{CE}}, u_j)$$

Model of low-level motor control

monosynaptic reflex
alpha-gamma co-activation

$$u_j = u_j^{\text{open}} + u_j^{\text{closed}}$$

$$u_j^{\text{closed}} = f_n(\kappa, \lambda_j^{\text{CE}}, l_j^{\text{CE}}, \dot{l}_j^{\text{CE}})$$



Numerical solution

$$\vec{q}(t) = ?$$

Parameters
Initial conditions

Model of skeletal structure

$$M(q)\ddot{q} = C(q)\dot{q}^2 + E(q,\dot{q}) + G(q) + R(q)F^{\text{MTU}}$$

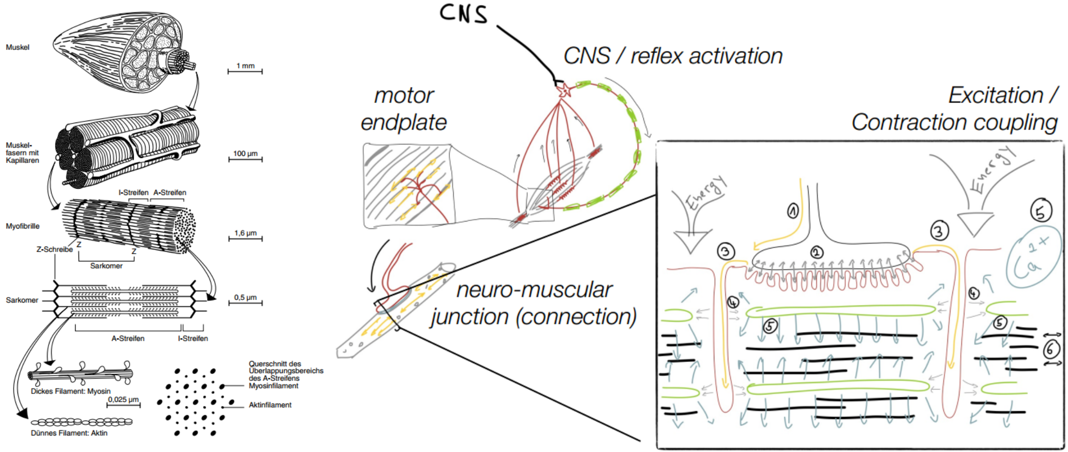
Schmitt, Günther, and Häufle [1]

Model of muscle-tendon unit

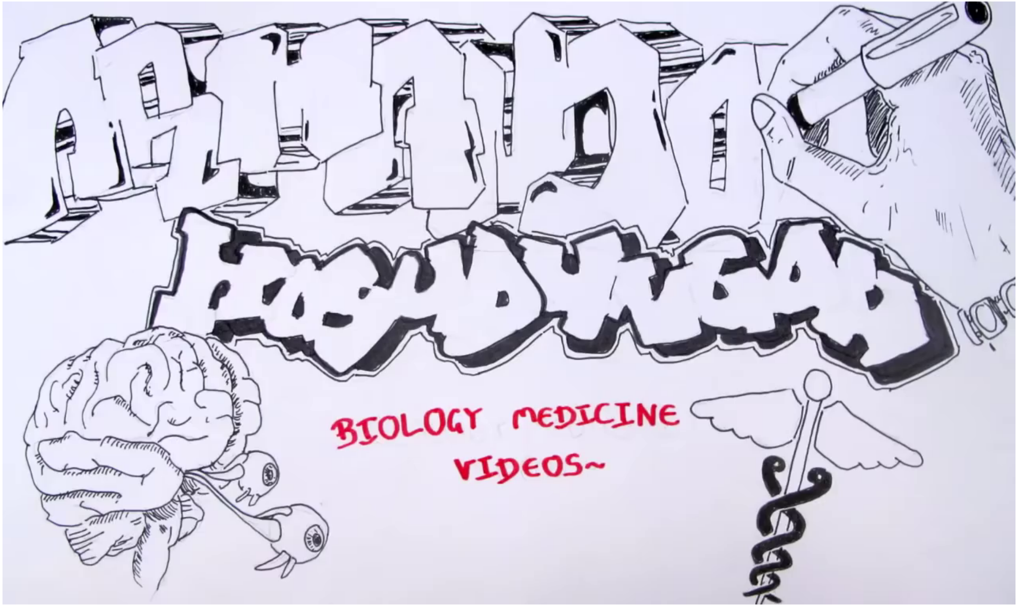
What we will look at today:

- Muscle physiology + morphology
- Microscopic vs. macroscopic model
- Muscle experiments
- Important muscle properties
- Hill-type muscle model

Muscle morphology + physiology



in Brickmann et al. (2012) mod. di Prampero (1985)



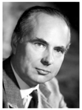
Video source: Hasudungan [2]

Microscopic modelling

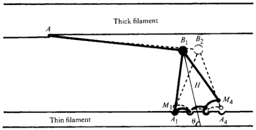
Huxley-type muscle models

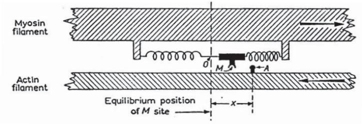
Andrew Fielding Huxley

Nobel prize 1963



- Explain the mechanism of force generation known as the "sliding filament theory" based on microstructure
- Look at one muscle in detail
- Require a lot of parameters
- Difficult to scale to a bigger system with several muscles





$$F = \frac{m \cdot s \cdot k}{2 \cdot l} \int_{-\infty}^{\infty} n(x) \cdot x \cdot dx$$

m: number of cross bridges per unit
s: sarcomere length
k: spring constant
l: distance between two M positions
x: elongation from rest length
n(x): Anzahl der gebundenen Zustände bei einer Auslenkung x

Huxley and Niedergerke [3]

Macroscopic modelling

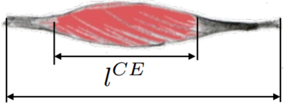
Hill-type muscle models

Archibald Vivian Hill

Nobel prize 1922

- Include a contractile element which represents empirical data
- Phenomenological models
- Model the important characteristics
- Reduced number of necessary parameters
- Can be used in a system with several muscles

simplified sketch



$$l^{MTU} = l^{CE} + l^{SE}$$

l^{CE}: *length of contractile element (muscle fibre)*

l^{MTU}: *length of the muscle-tendon unit*

Macroscopic modelling

CNS + mot. control

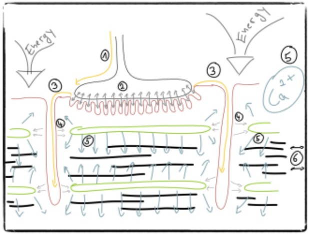
activation dynamics

contraction dynamics

musculo-skeletal system

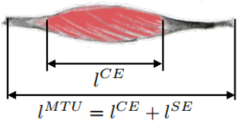
activation rate

$$\dot{a}_j = f_a(a_j, l_j^{CE}, u_j^{CE})$$



contraction velocity

$$\dot{l}_j^{CE} = f_v(l_j^{MTU}, v_j^{MTU}, l_j^{CE}, a_j)$$



muscle force

$$F_j^{MTU} = f_f(l_j^{MTU}, v_j^{MTU}, l_j^{CE}, a_j)$$

Macroscopic modelling

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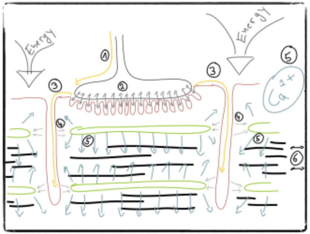

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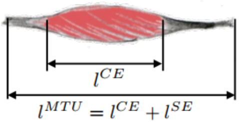


muscle force

$$F_j^{MTU} = f_f(l_j^{MTU}, v_j^{MTU}, l_j^{CE}, a_j)$$

Macroscopic modelling

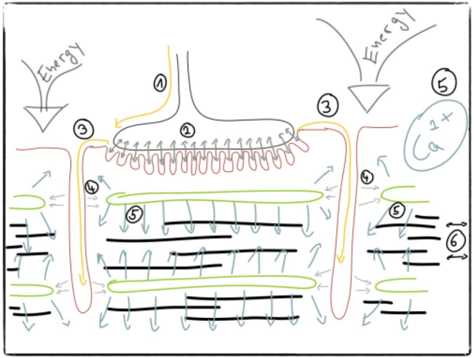
simplified view

(1) Electro-magnetic activation of the **motoneurons**

(3) Electro-magnetic activation of the **muscle fibre** (EMG)

(5) Bio-chemical activation of the thin **filaments** (Ca^{2+})

Excitation / Contraction coupling



Activation Dynamics (Hatze)

Sought-after: a relation of the neural stimulation **u** and muscle activity **a**

$\dot{\gamma} = m \cdot (u - \gamma)$ free Calcium ion concentration

$$\boxed{a_{(Hatze)}(l_{CE}\gamma) = \frac{a_0 + (\rho(l_{CE})\gamma)^3}{1 + (\rho(l_{CE})\gamma)^3}}$$

with $$\rho(l_{CE}) = c \cdot \eta \cdot \frac{(k-1)}{(k - \frac{l_{CE}}{l_{CE,opt}})} \frac{l_{CE}}{l_{CE,opt}}$$

After Hatze [4]. A simplification can be found in Rockenfeller and Günther [5].

Macroscopic modelling

CNS + mot. control

activation dynamics

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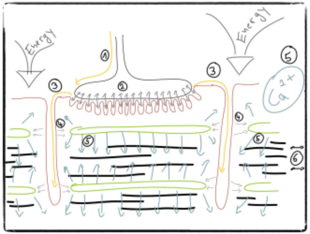
$$\dot{a}_j = f_a(a_j, l_j^{CE}, u_j^{CE})$$



contraction velocity

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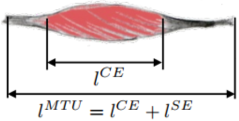
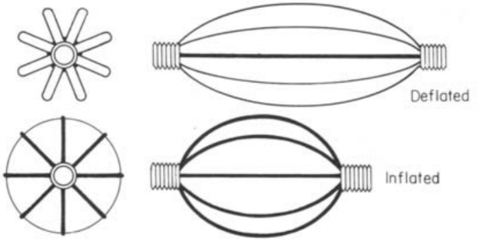


muscle force

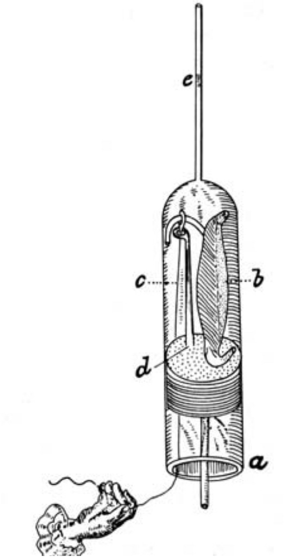
$$F_j^{MTU} = f_f(l_j^{MTU}, v_j^{MTU}, l_j^{CE}, a_j)$$

Muscle experiments

Volume constancy



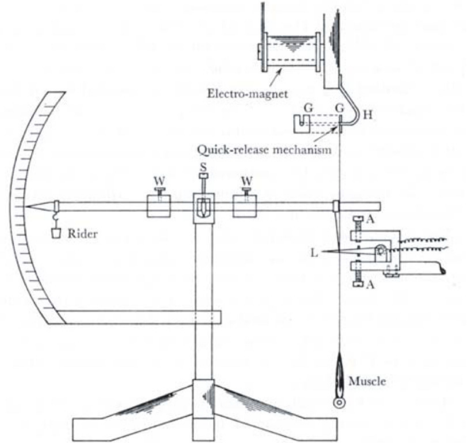
Erasistratus (304-250 BC)



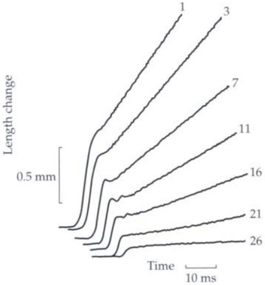
Swammerdamm (1663)

Muscle experiments

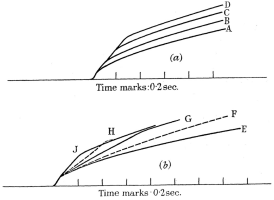
Quick release experiments



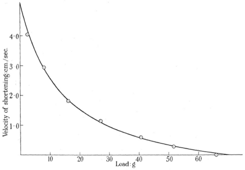
Apparatus of Hill approx. 1910



Muscle contraction



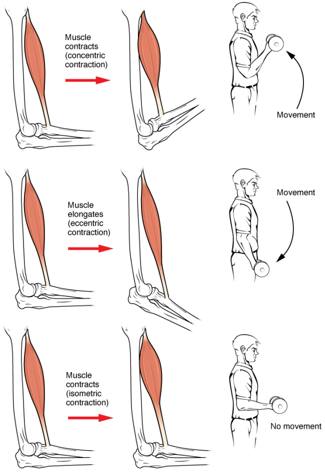
Heat production



Force-velocity-relation

Hill [6, 7]

Muscle experiments



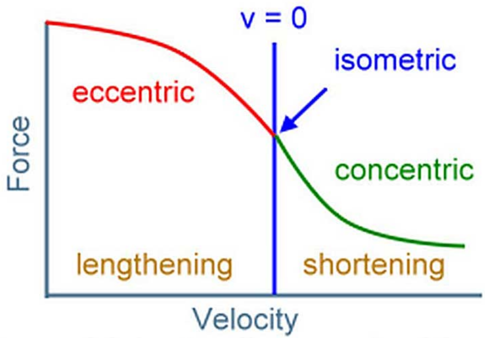
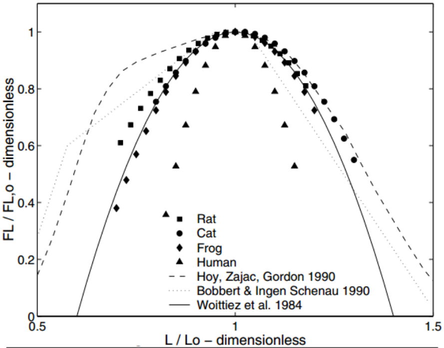
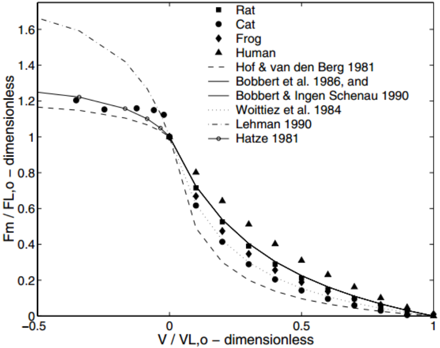


Image sources: [8, 9]

Muscle experiments



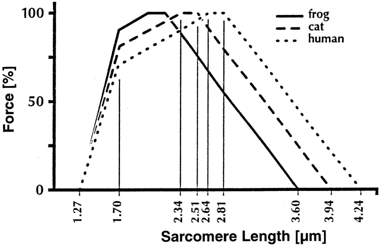
	k_1	k_2	k_3	L_o	$F_{L,o}$	
Rat[1]	−4.50	8.95	−3.45	27.0 mm	0.29 N	$p \leq 0.001$
Frog[2]	−6.79	14.69	−6.88	31.0 mm	0.67 N	$r^2 = 0.96$
Cat[3]	−5.71	11.52	−4.81	31.9 mm	0.18 N	$r^2 = 0.99$
Human[4]	−13.43	28.23	−13.96	215.9 mm	193.1 N	$r^2 = 0.75$
Skeletal Muscle Model[5]	−6.25	12.50	−5.25	60.0 mm	3000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

Klute, Czerniecki, and Hannaford [10]

Muscle experiments



Rassier, MacIntosh, and Herzog [11]

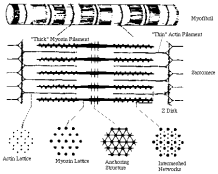
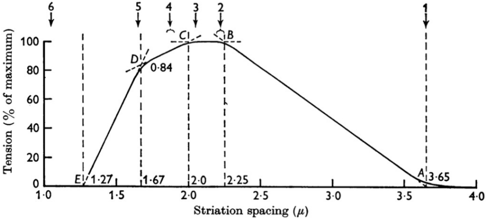
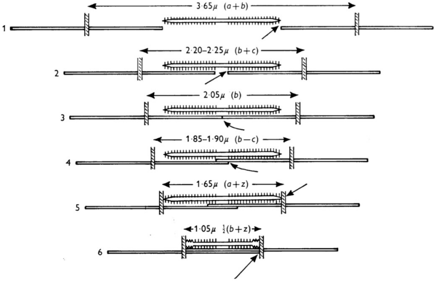


Image source: [13]

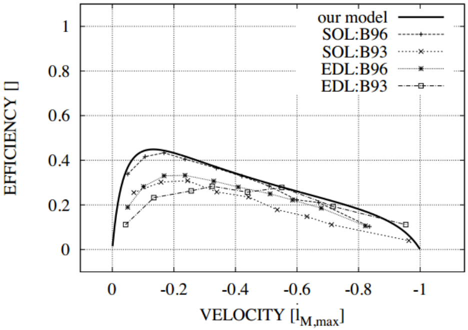


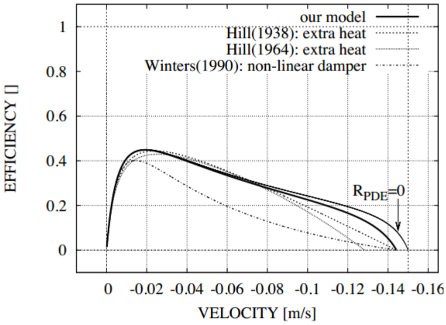
Gordon, Huxley, and Julian [12]



Gordon, Huxley, and Julian [12]

Muscle experiments

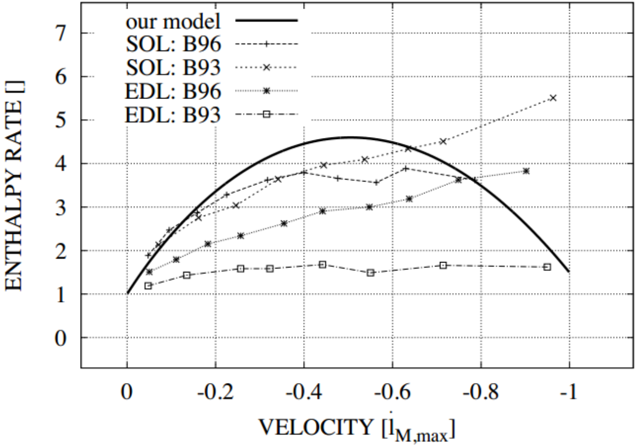




$$\text{Efficiency} = \frac{\text{power output}}{\text{power input}}$$

Günther and Schmitt [14]

Muscle experiments

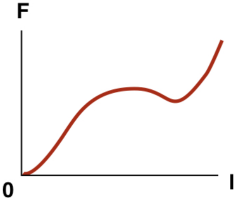


Enthalpy rate = (mech. power output) + (maint. heat rate) + (contract. heat rate)

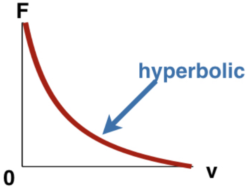
Günther and Schmitt [14]

Muscle properties

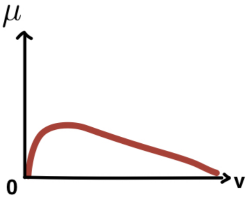
... that need to be reproduced in a macroscopic model



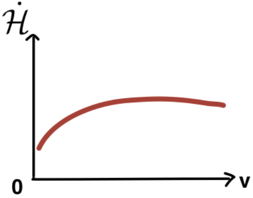
Force-length relationship



Force-velocity relation



Mechanical efficiency



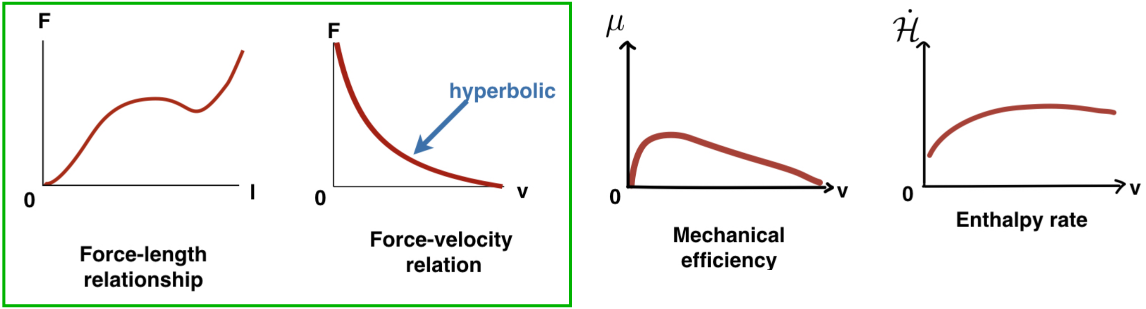
Enthalpy rate

$$\mu = \frac{\text{power output}}{\text{power input}}$$

$$\dot{H} = (\text{mech. power output}) + (\text{maint. heat rate}) + (\text{contract. heat rate})$$

Muscle properties

... that need to be reproduced in a macroscopic model



$$\mu = \frac{\text{power output}}{\text{power input}}$$

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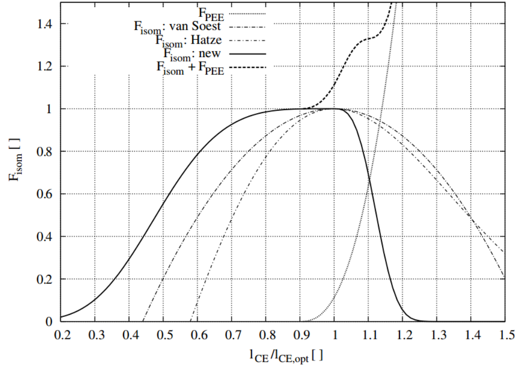
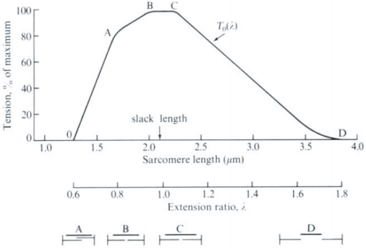
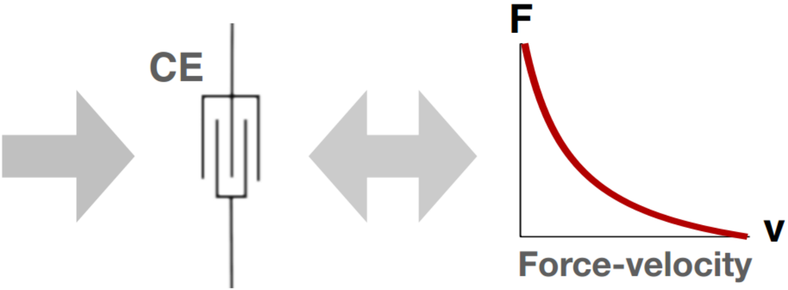
Force-length relationship





Besides the muscle fibers also the surrounding soft tissue develops force leading to the difference in the force-length relationship of a sarcomere and a muscle.

Hill-type muscle model

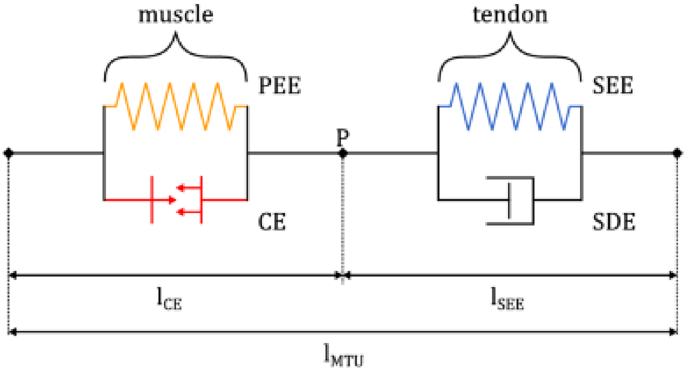


$$(F + a) \cdot v = b \cdot (F_{\text{max}} - F)$$

Hill [7]

Hill-type muscle model

Muscle-tendon unit (MTU)



Martynenko et al. [15] and Haeufle et al. [16]

Macroscopic modelling

CNS + mot. control

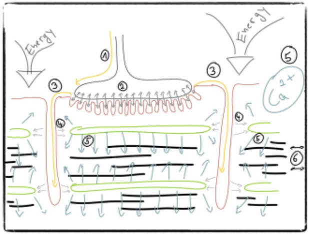
activation dynamics

contraction dynamics

musculo-skeletal system

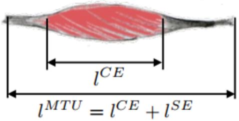
activation rate

$$\dot{a}_j = f_a(a_j, l_j^{CE}, u_j^{CE})$$



contraction velocity

$$\dot{l}_j^{CE} = f_v(l_j^{MTU}, v_j^{MTU}, l_j^{CE}, a_j)$$

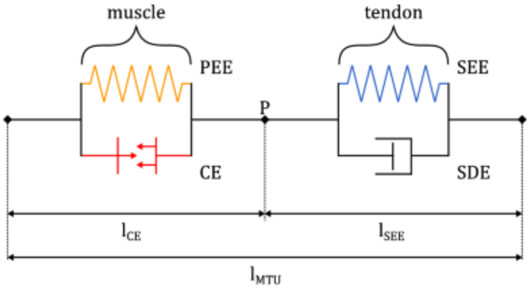


muscle force

$$F_j^{MTU} = f_f(l_j^{MTU}, v_j^{MTU}, l_j^{CE}, a_j)$$

Force of muscle-tendon unit F_{MTU}

1. Force equilibrium:
   $F_{CE} + F_{PEE} = F_{SEE} + F_{SDE}$
2. Define equations for F_{CE}, F_{PEE}, F_{SEE} and F_{SDE} and rearrange to obtain equation for $\dot{l}_{CE}$.
3. Use $\dot{l}_{CE}$ to calculate forces
4. $F_{MTU} = F_{SEE} + F_{SDE}$



Martynenko et al. [15] and Haeufle et al. [16]

Force of the contractile element F_{CE}

$$F_{CE} = A \cdot F_l \cdot F_v \cdot f_{max}$$

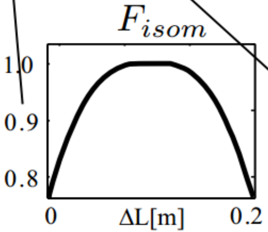
product approach

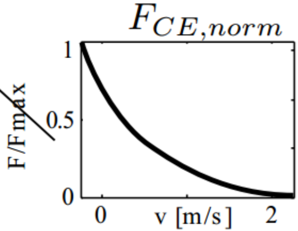
Hill type
muscle model

Hill 1938

a
→ activity [%]

activation dynamics





contraction dynamics
material laws

Force of the contractile element F_{CE}

Equations in Haeufle et al. [16]

$$F_{\mathrm{CE,c}}(\dot{l}_{\mathrm{CE}} \leq 0) = F_{\mathrm{max}}\left(\frac{qF_{\mathrm{isom}} + A_{\mathrm{rel}}}{1 - \frac{\dot{l}_{\mathrm{CE}}}{B_{\mathrm{rel}}\, l_{\mathrm{CE,opt}}}} - A_{\mathrm{rel}}\right)$$

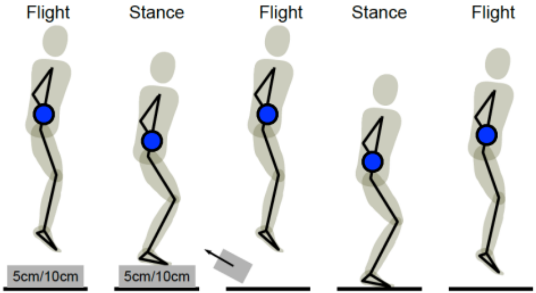
with

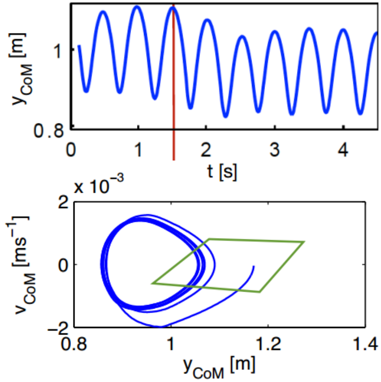
$$F_{\mathrm{isom}}(l_{\mathrm{CE}}) = \exp\left\{-\left|\frac{\frac{l_{\mathrm{CE}}}{l_{\mathrm{CE,opt}}} - 1}{\Delta W_{\mathrm{limb}}}\right|^{\upsilon_{\mathrm{CE,limb}}}\right\}$$

with activation q, maximum isometric force F_{max}, F_{isom} representing the force-length relation and $A_{\mathrm{rel}}, B_{\mathrm{rel}}$ being the normalized Hill parameters.

Benefits of biological muscles

Increased stability

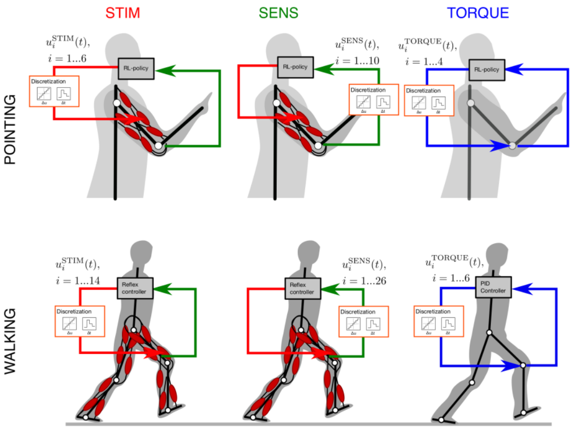


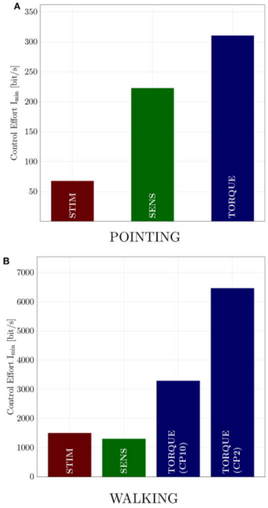


Haeufle et al. [17], Haeufle, Grimmer, and Seyfarth [18], and Kalveram et al. [19]

Benefits of biological muscles

Reduced control effort

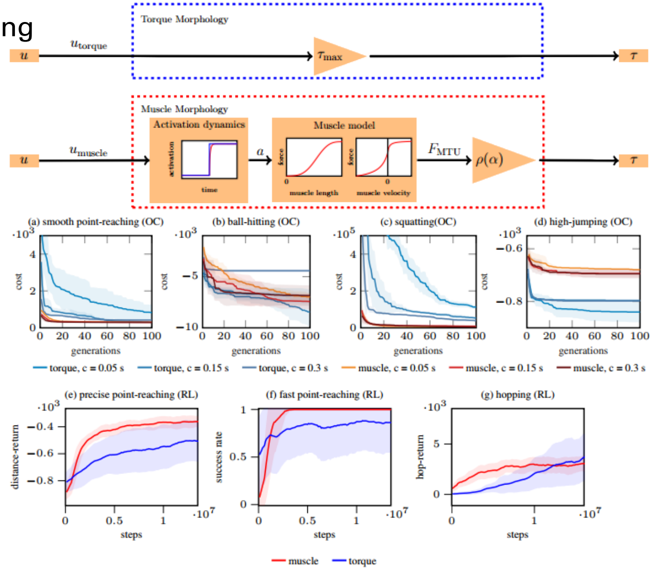




Haeufle et al. [20]

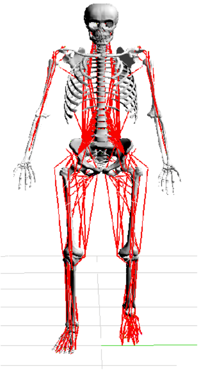
Benefits of biological muscles

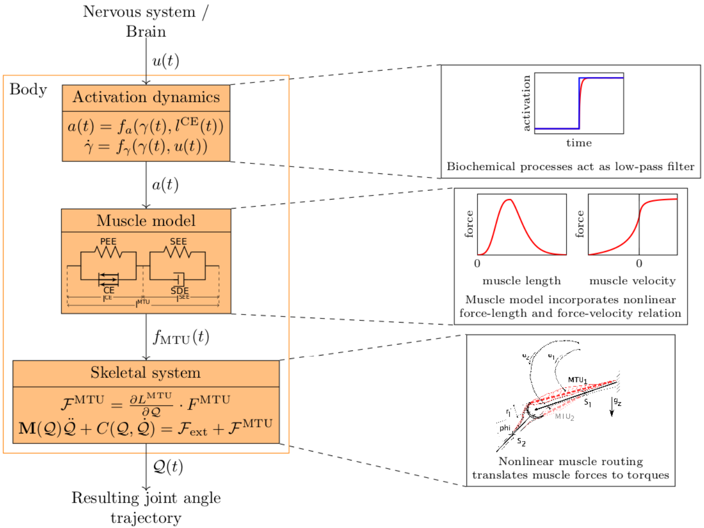
Improved learning



Wochner et al. [21]

Summary + Discussion





Summary + Discussion

Do we miss/ neglect any typical characteristics of a biological muscle?

Age

Reservoir chemical substrates

Fatigue

History effects

Training

???

Outlook

For the next exercise: Download the Matlab implementation of the muscle model of Häufle et al. (2014)

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Short communication

Hill-type muscle model with serial damping and eccentric force–velocity relation

CrossMark

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