

Vorlesung

Biorobotik

Unitnummer 473001

Modul 47300 ***Biorobotik***

Prüfungsnummer 47301

Vorlesung

Biorobotik

(1) Bitte die geänderten Startzeiten beachten:

Karlsruhe bleibt bei 10 Uhr

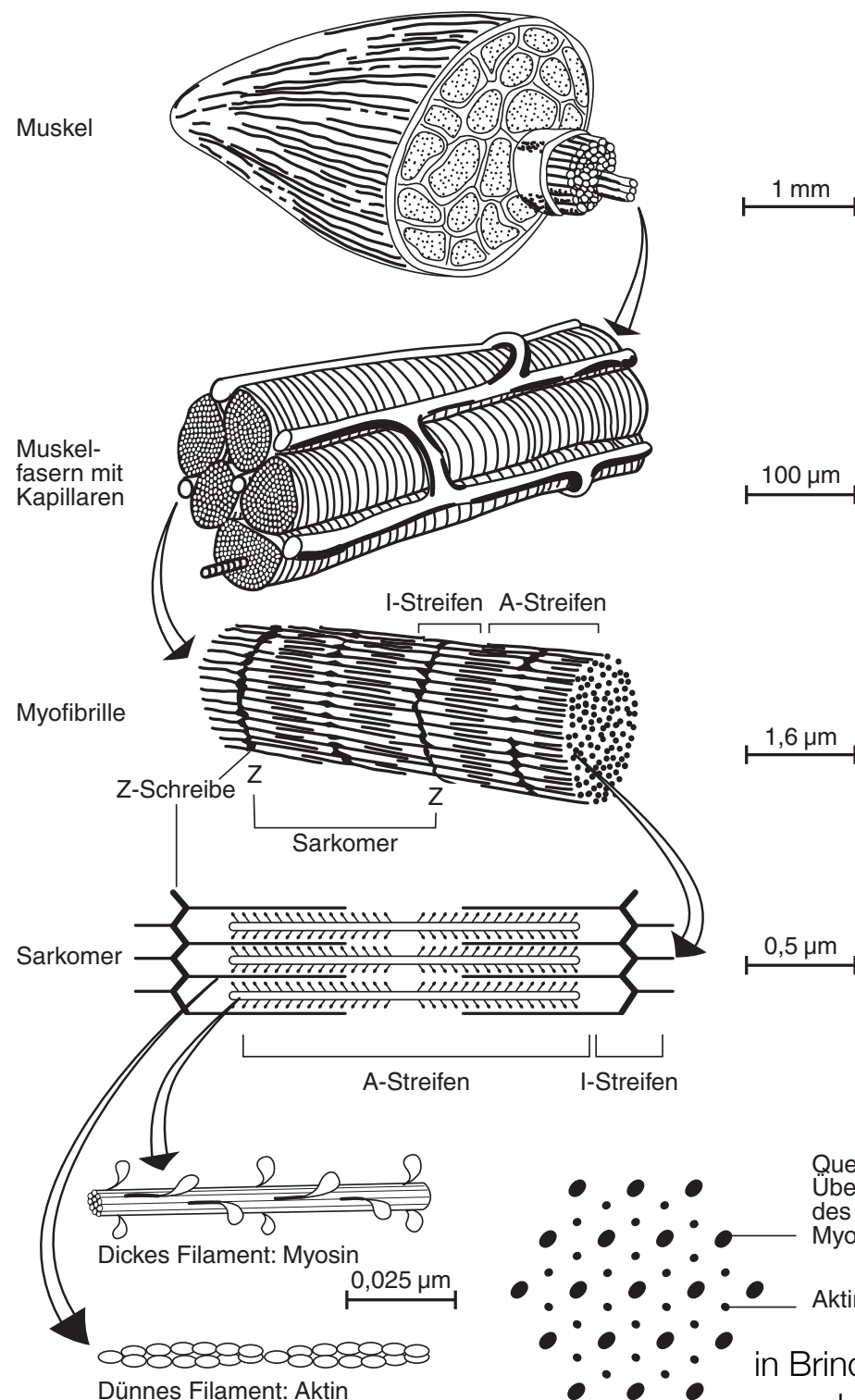
Stuttgart erst 10:45 Uhr (von Darmstadt so gewünscht)

Darmstadt 10:30 Uhr (aus organisatorischen Gründen von Darmstädter Seite)

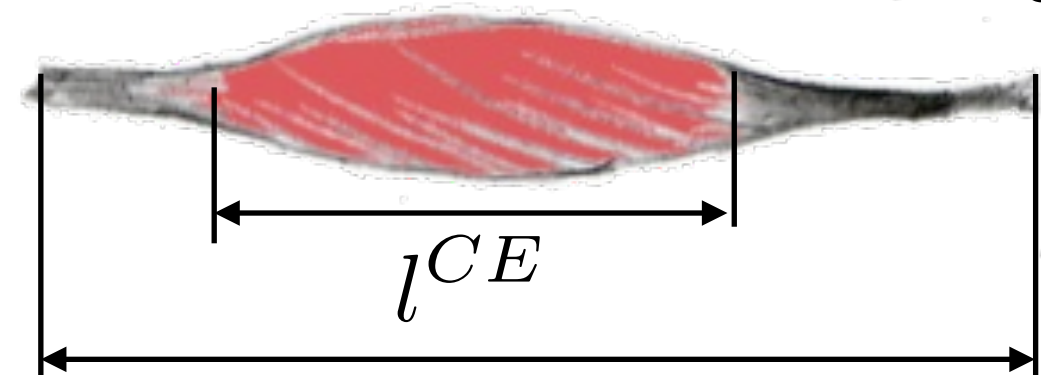
(2) Für den Termin in Stuttgart einen Laptop mit Matlab/Simulink inkl Simmechanics bzw. Sim Multibody toolbox mitbringen, wenn man direkt die Live-Demo mitmachen möchte.

Biologischer Muskel

Morphologie des Skelettmuskels



vereinfachte Darstellung



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

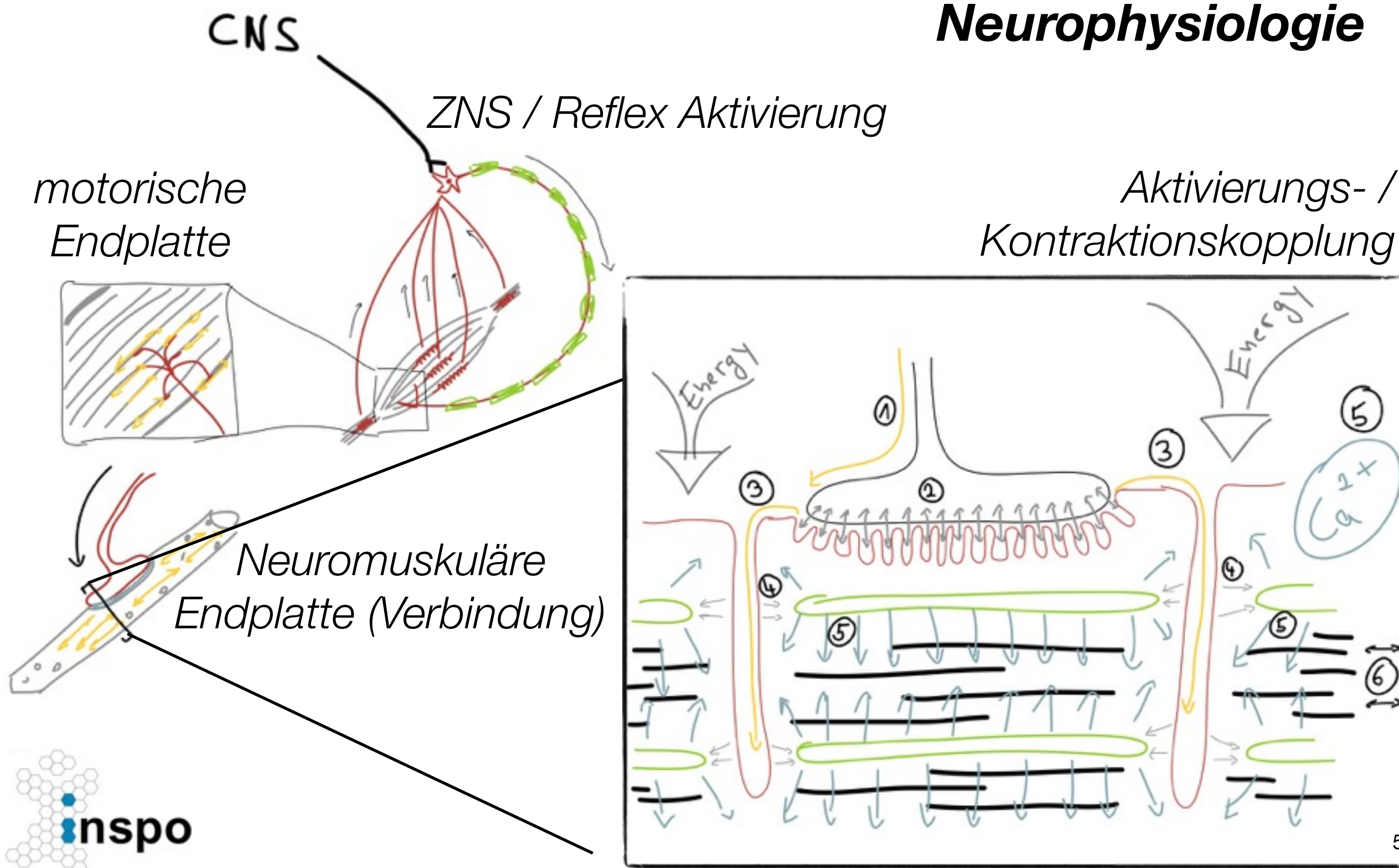
l^{CE} : Länge des kontraktiven Elements (Muskelfasern)

l^{mtc} : Länge des Muskel-Sehnen-Komplexes

in Brinckmann et al. (2012)
nach di Prampero (1985)

Physiologie des Skelettmuskels

Neurophysiologie



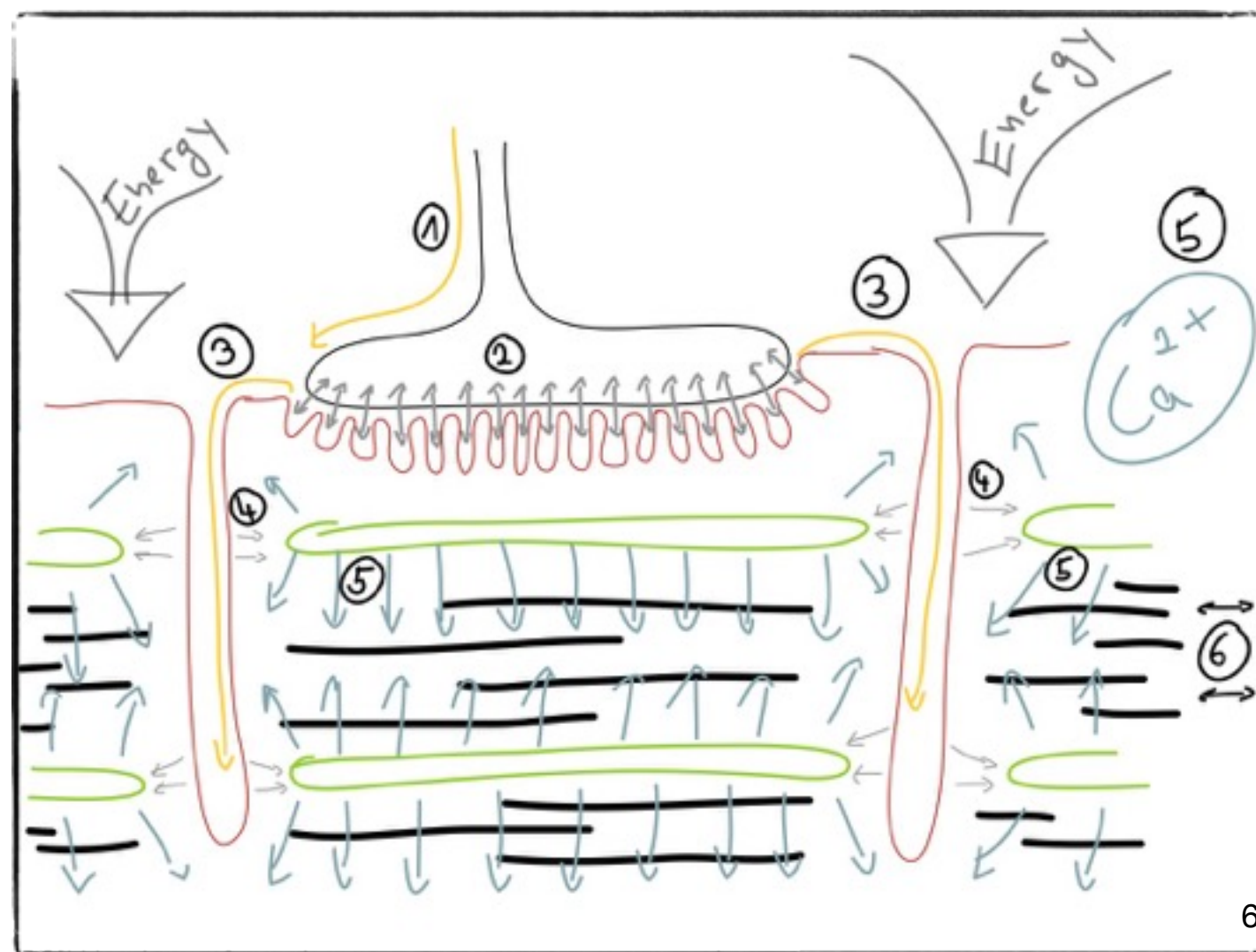
Physiologie des Skelettmuskels

Neurophysiologie

vereinfachte Darstellung

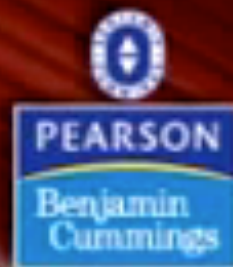
- (1) Elektromagnetische Aktivierung des **Motoneurons**
- (3) Elektromagnetische Aktivierung der **Muskelfaser** (EMG)
- (5) Biochemische Aktivierung des dünnen **Filaments** (Ca^{2+})

Aktivierungs- / Kontraktionskopplung



Physiologie des Skelettmuskels

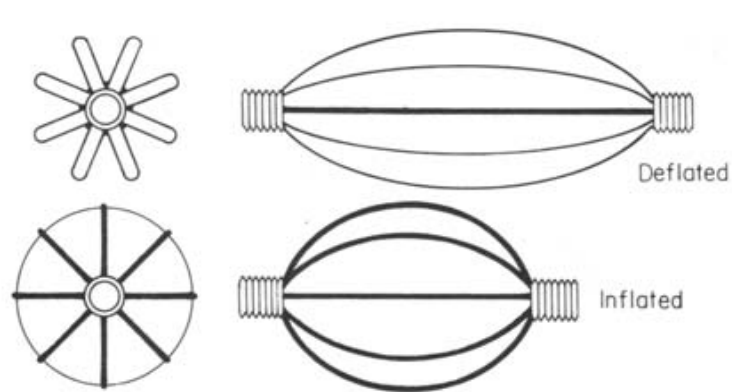
A&P Flix
Muscle Contraction Part 2:
Excitation-Contraction Coupling



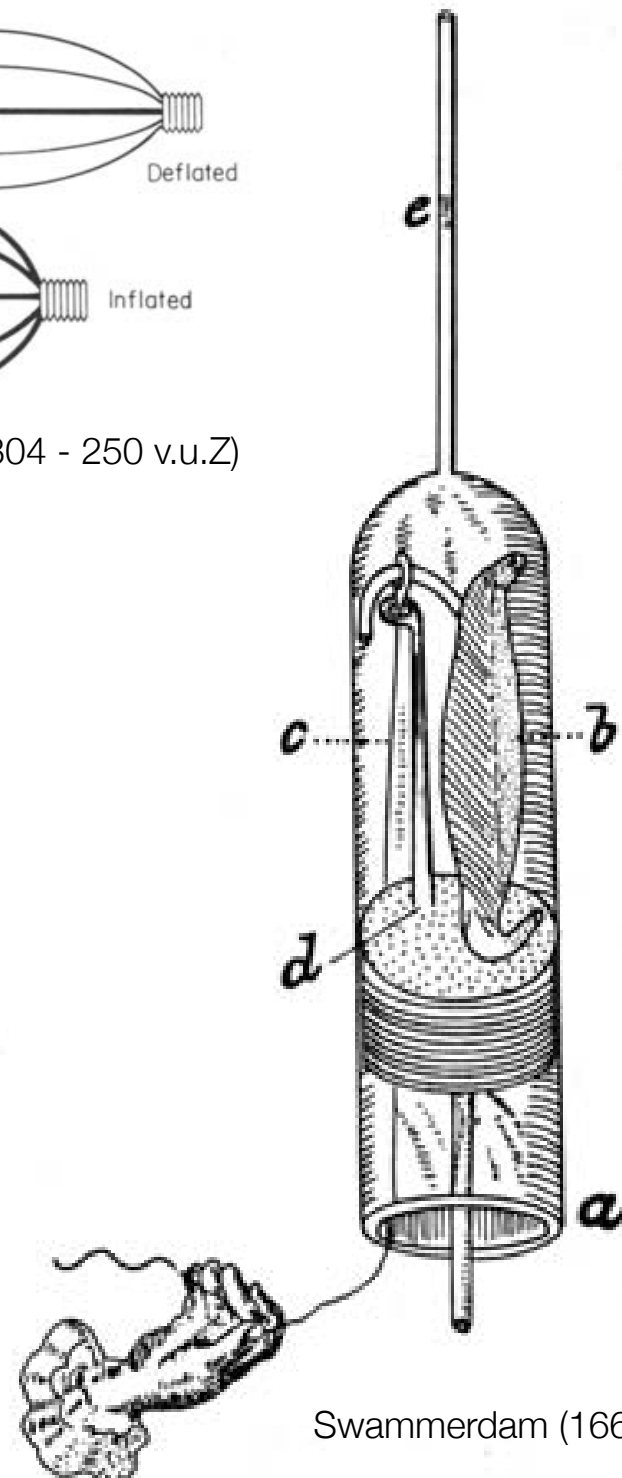
© 2009 Pearson Education, Inc.

Biologische und technische Muskelexperimente und Muskelmodelle

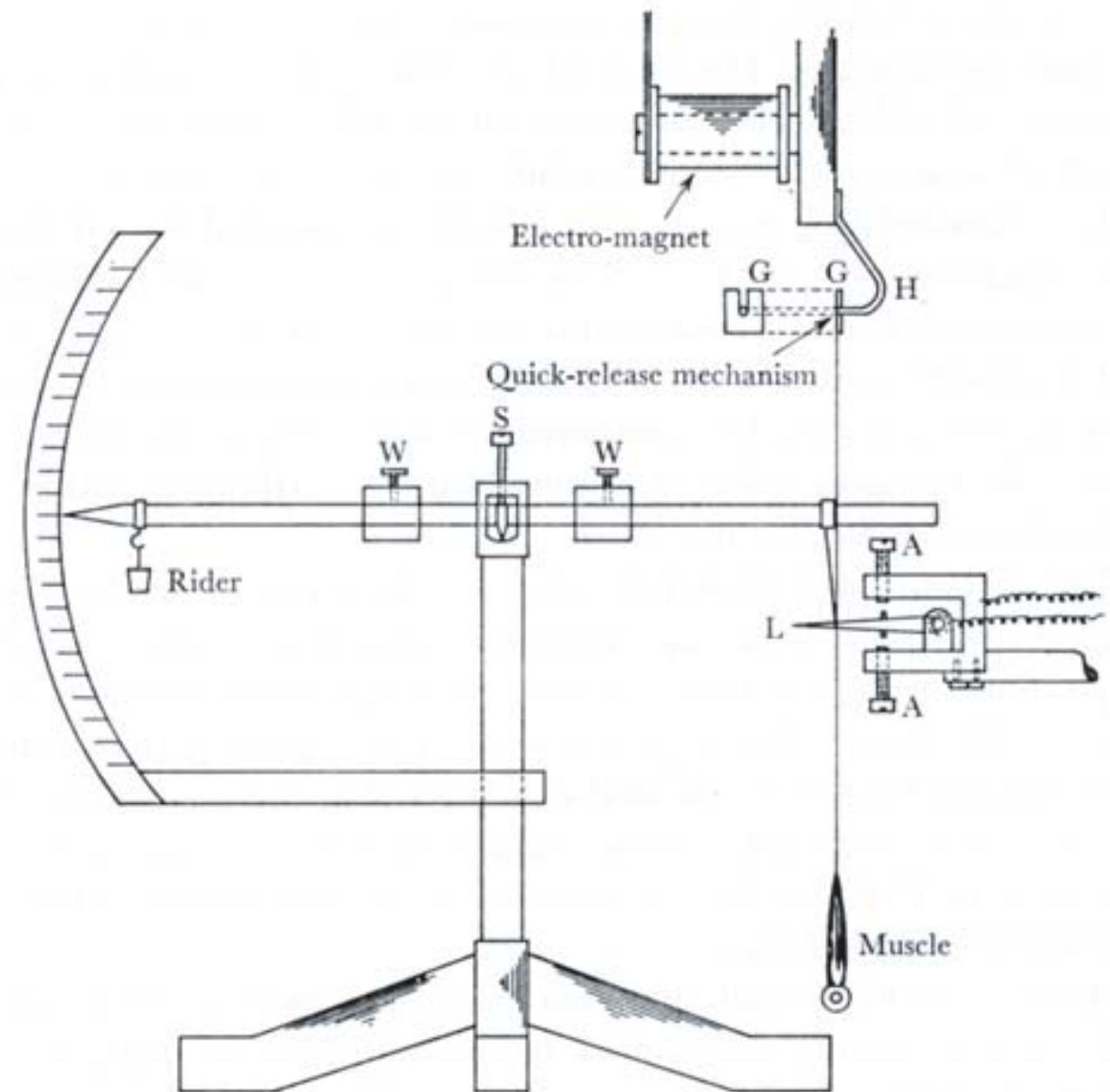
Historische Muskelexperimente



Erasistratos (304 - 250 v.u.Z)

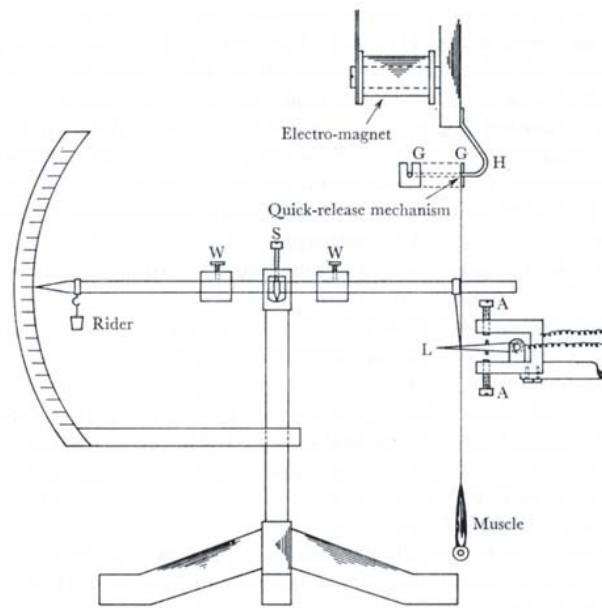


Swammerdam (1663)



Apparat von Hill um ca. 1910 (1970)

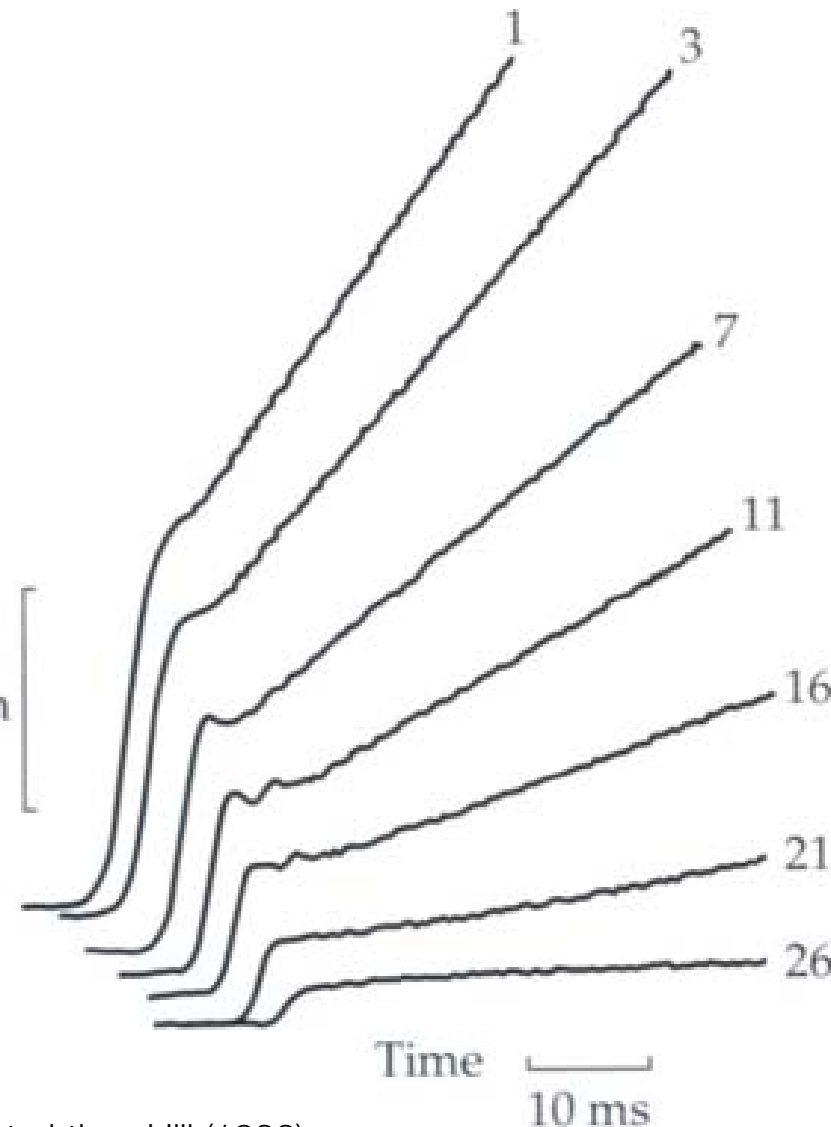
Historische Muskelexperimente



Apparat von Hill um
ca. 1910. Hill (1970)

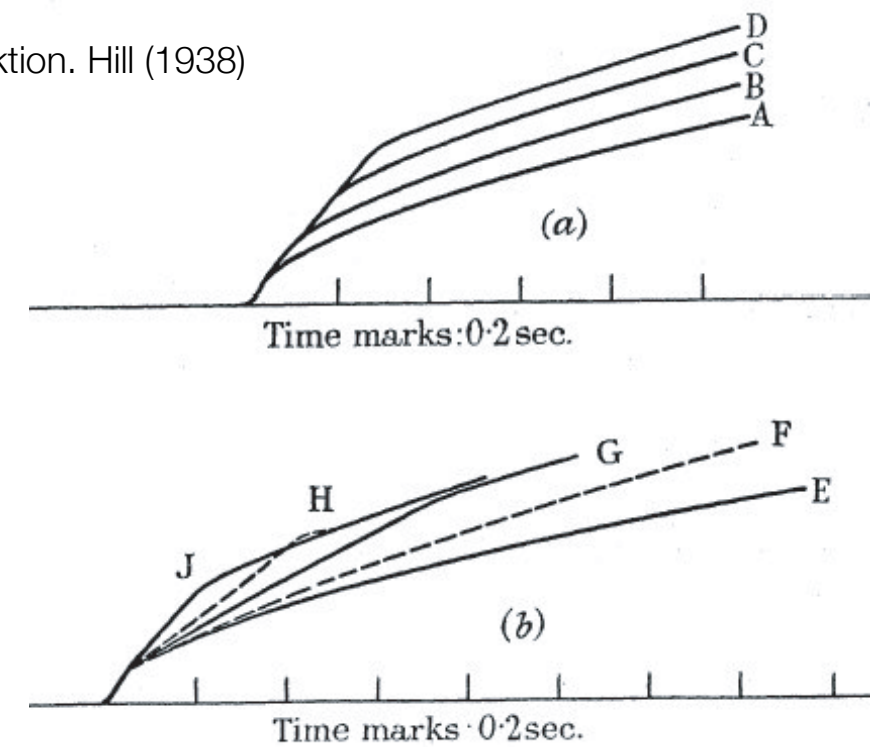
Length change

0.5 mm

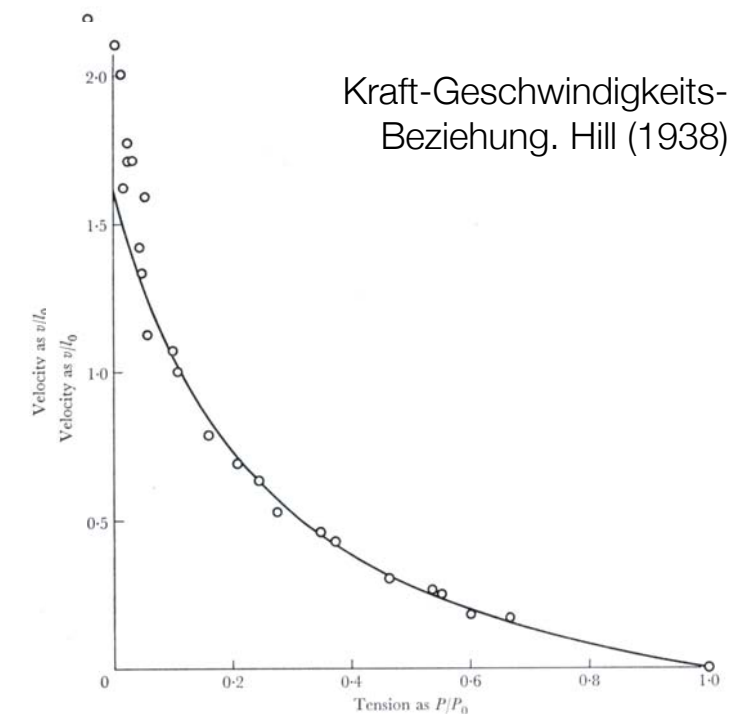


Muskelkontraktion. Hill (1938)

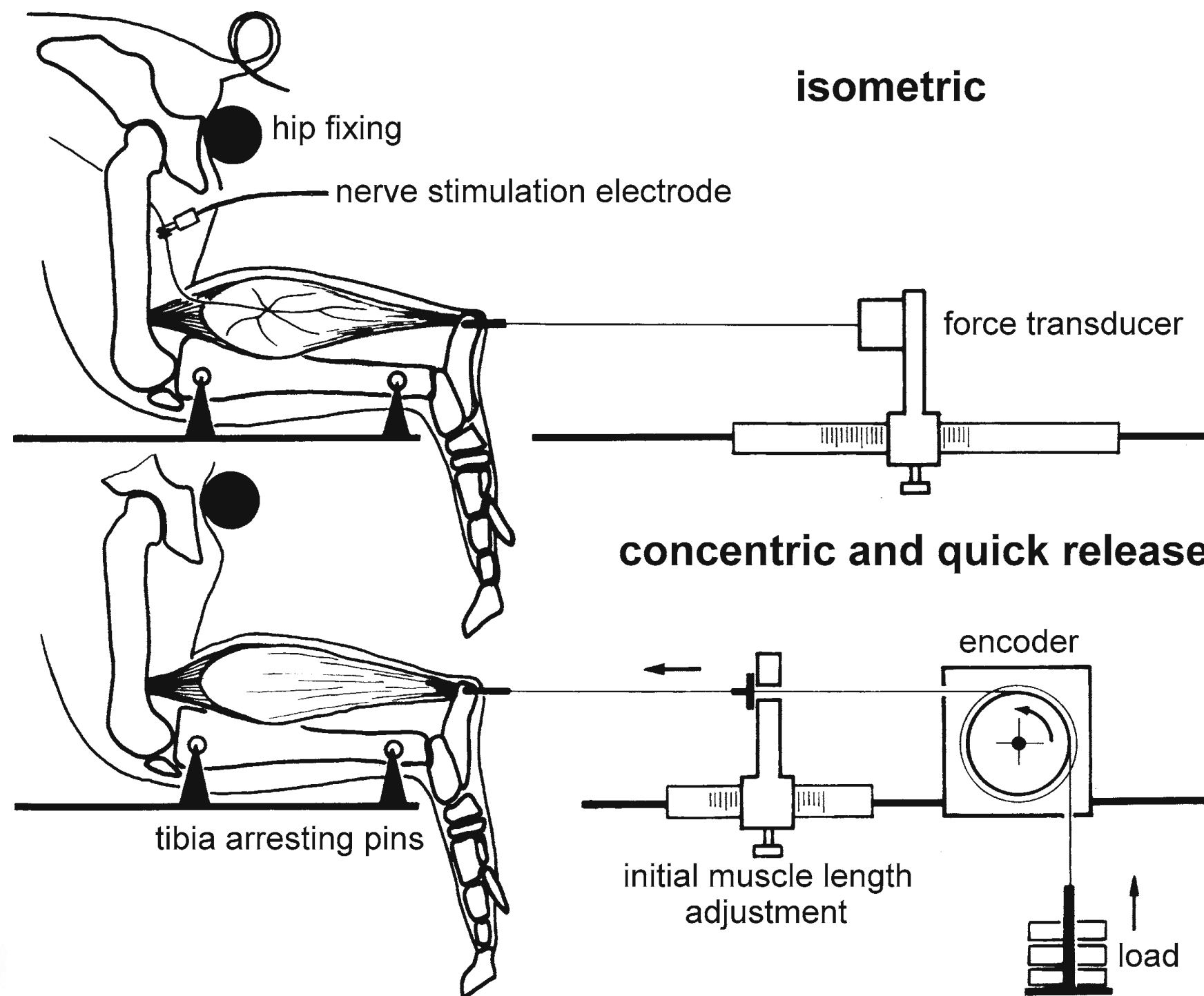
Wärmeproduktion. Hill (1938)



Kraft-Geschwindigkeits-
Beziehung. Hill (1938)



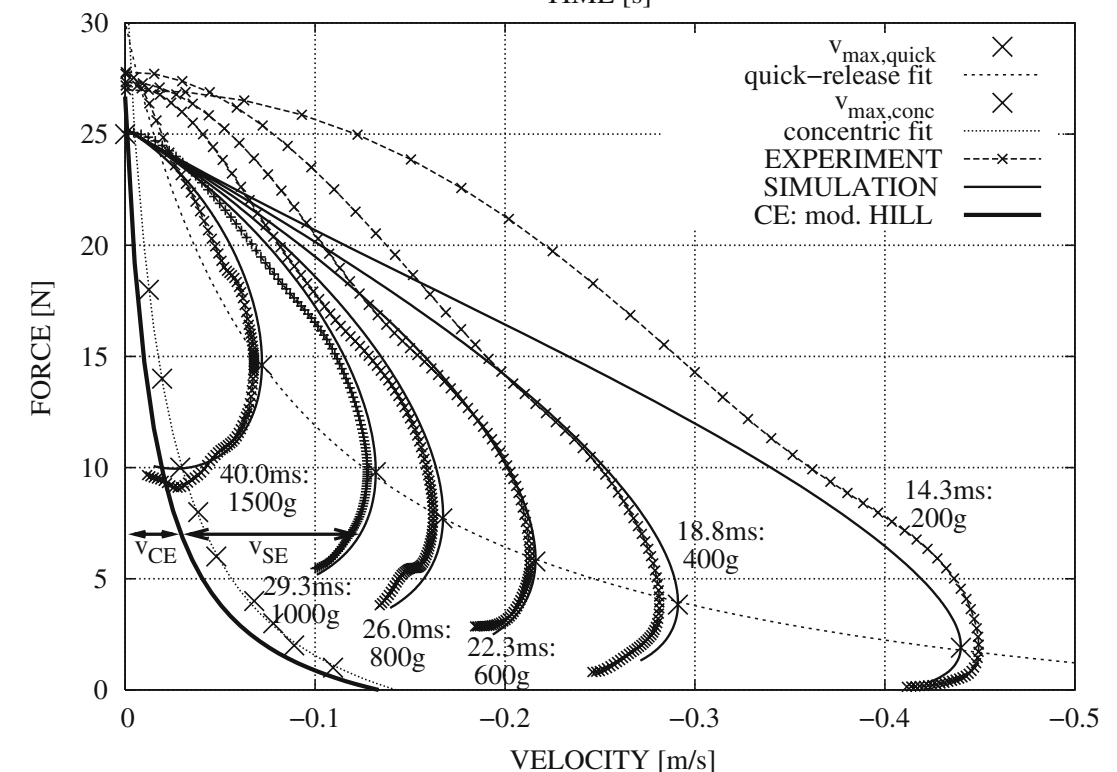
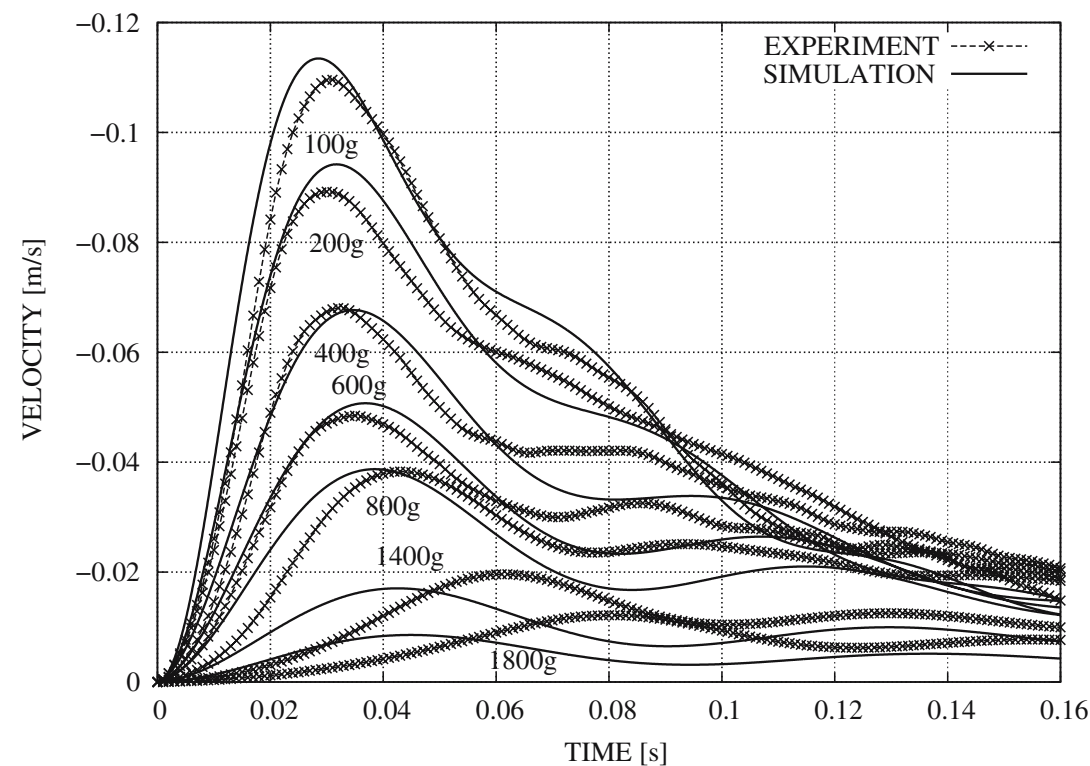
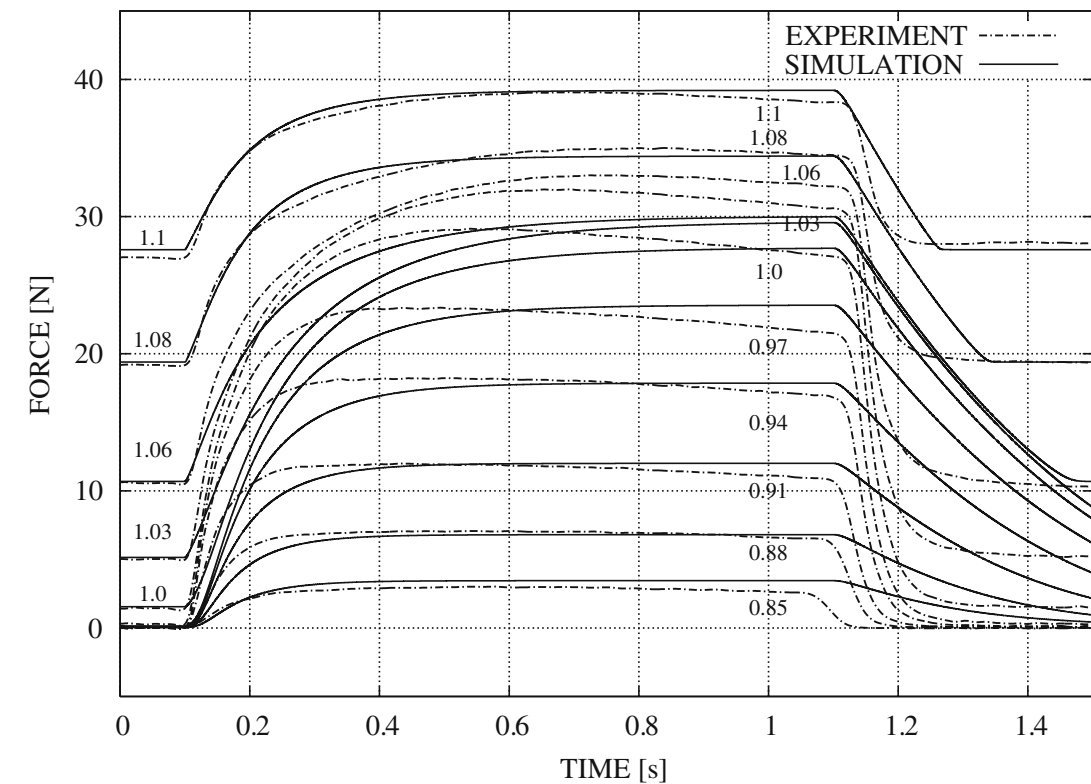
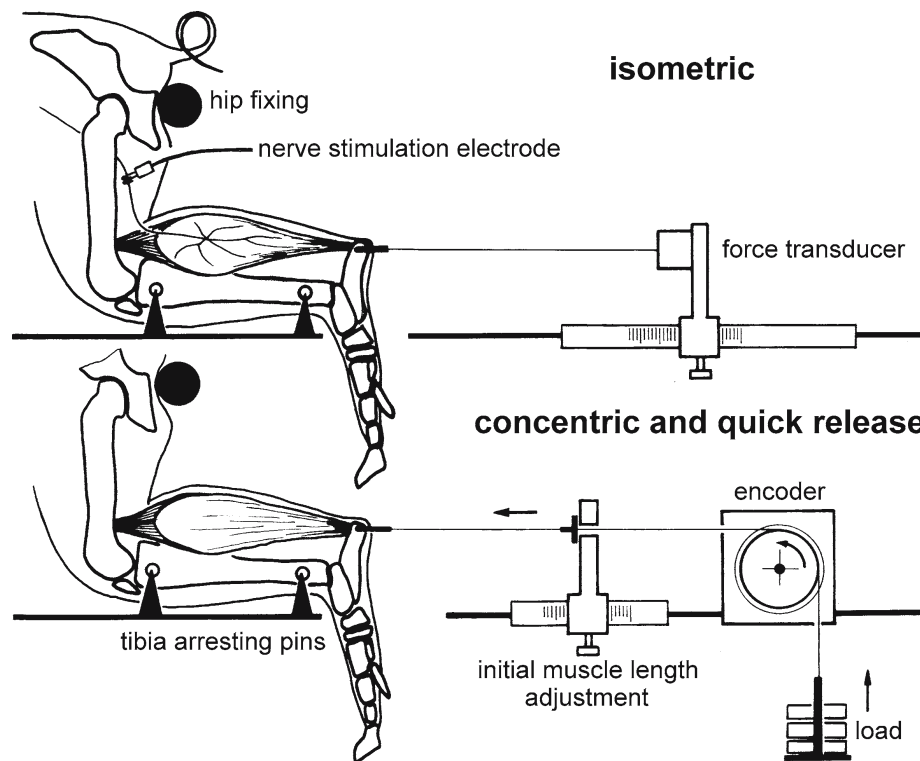
Biologische Muskelexperimente



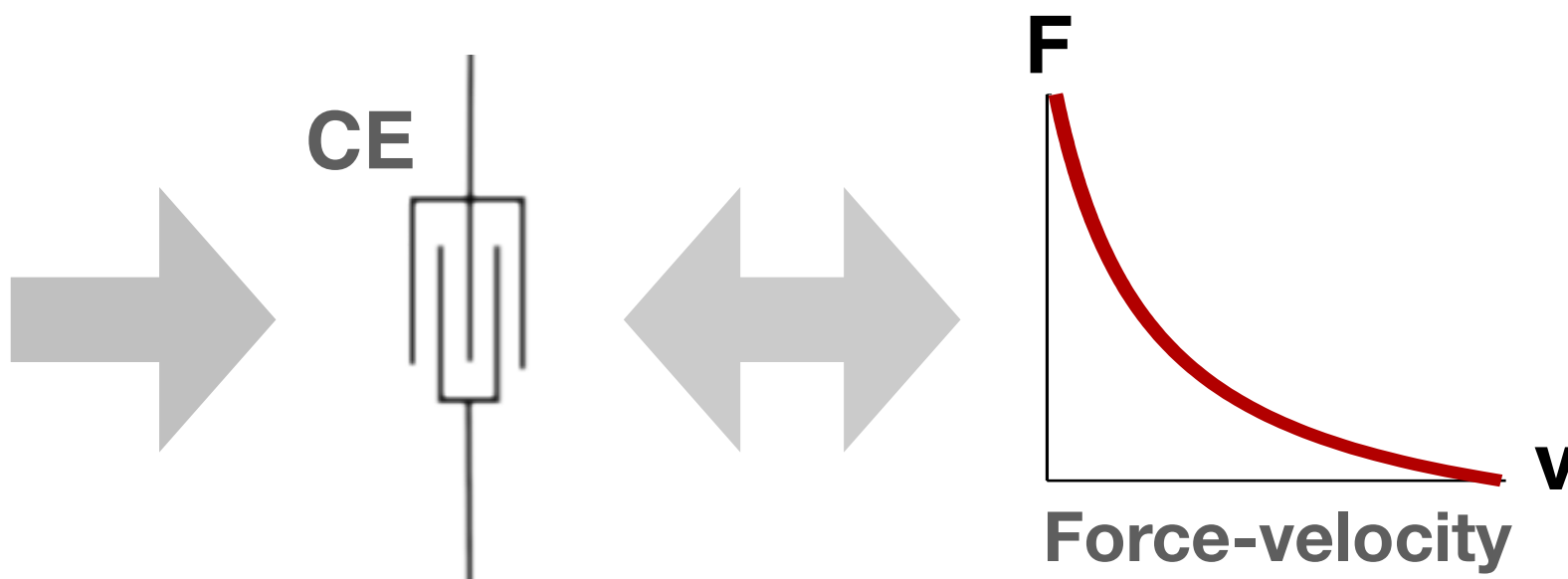
Günther, M, Schmitt, S, Wank, V. 2007. High-frequency oscillations as a consequence of neglected serial damping in Hill-type muscle models. *Biological Cybernetics*, 97:63–79.

Biologische Muskelexperimente

Günther, M, Schmitt, S, Wank, V. (2007)



Die Makrodynamik eines Skelettmuskels



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

Hilltyp Muskelmodelle beinhalten ein kontraktiles Element das die empirische Kraft-Geschwindigkeits-

Beziehung in sich trägt

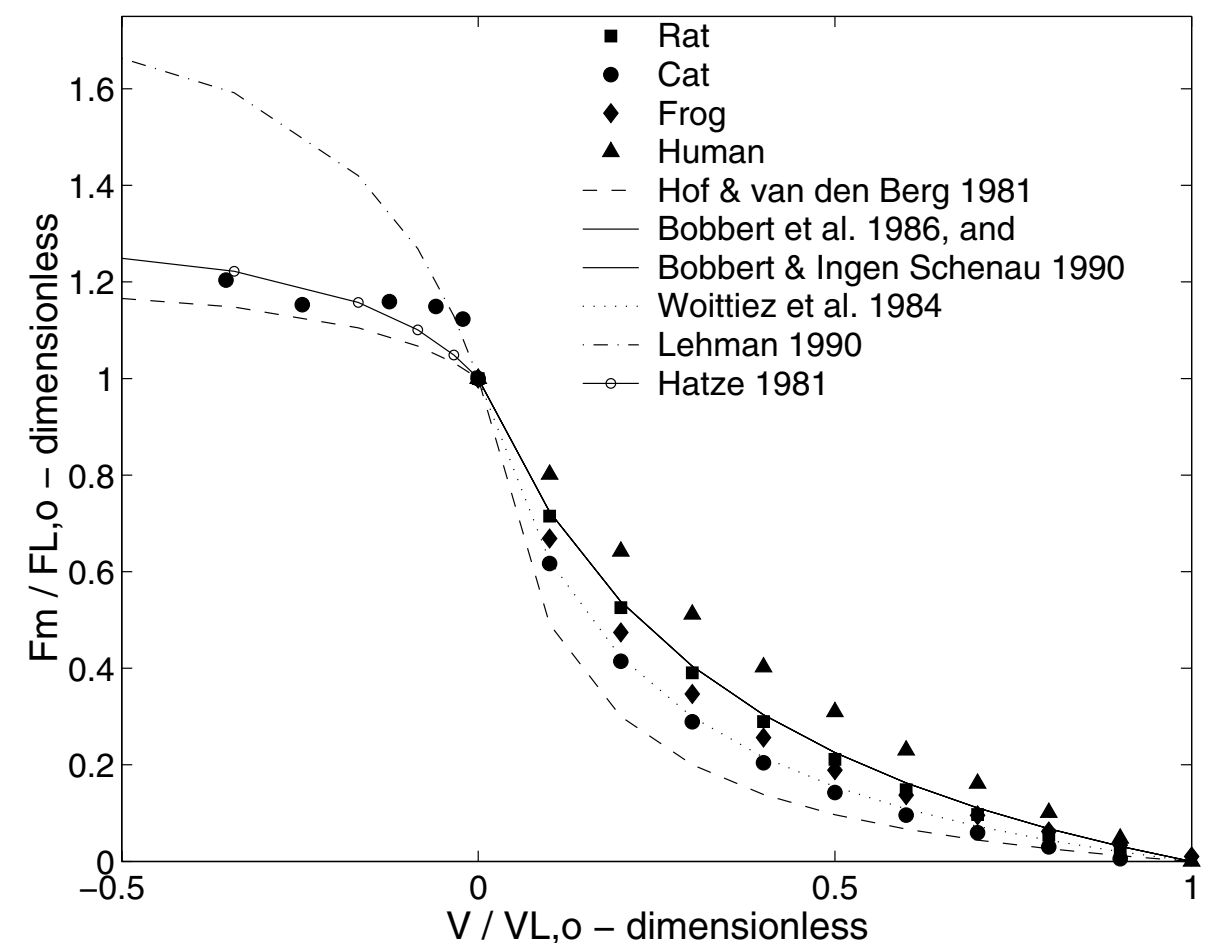
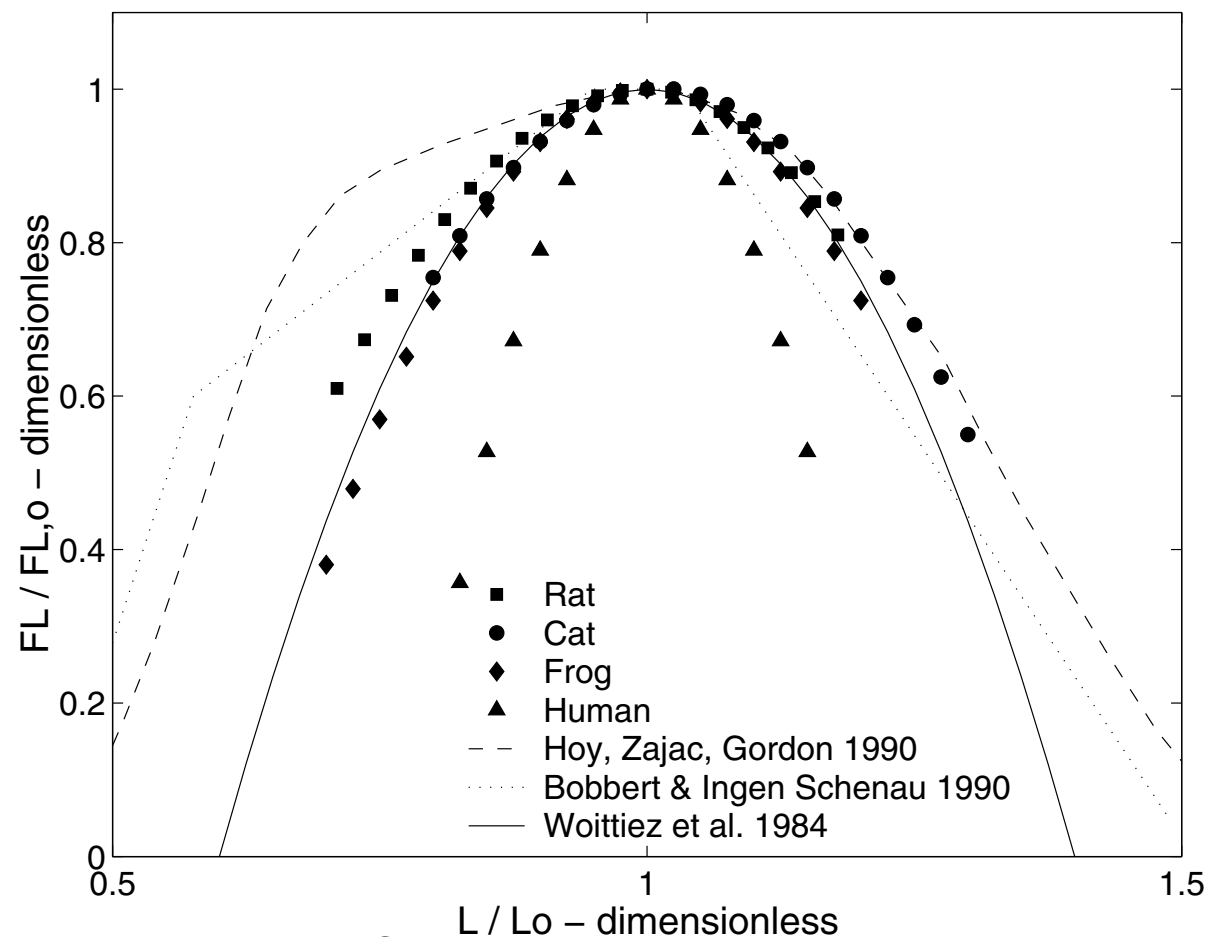


Archibald Vivian Hill

Nobelpreis 1922:

„ ... for his discovery relating to the production of heat in the muscle.“

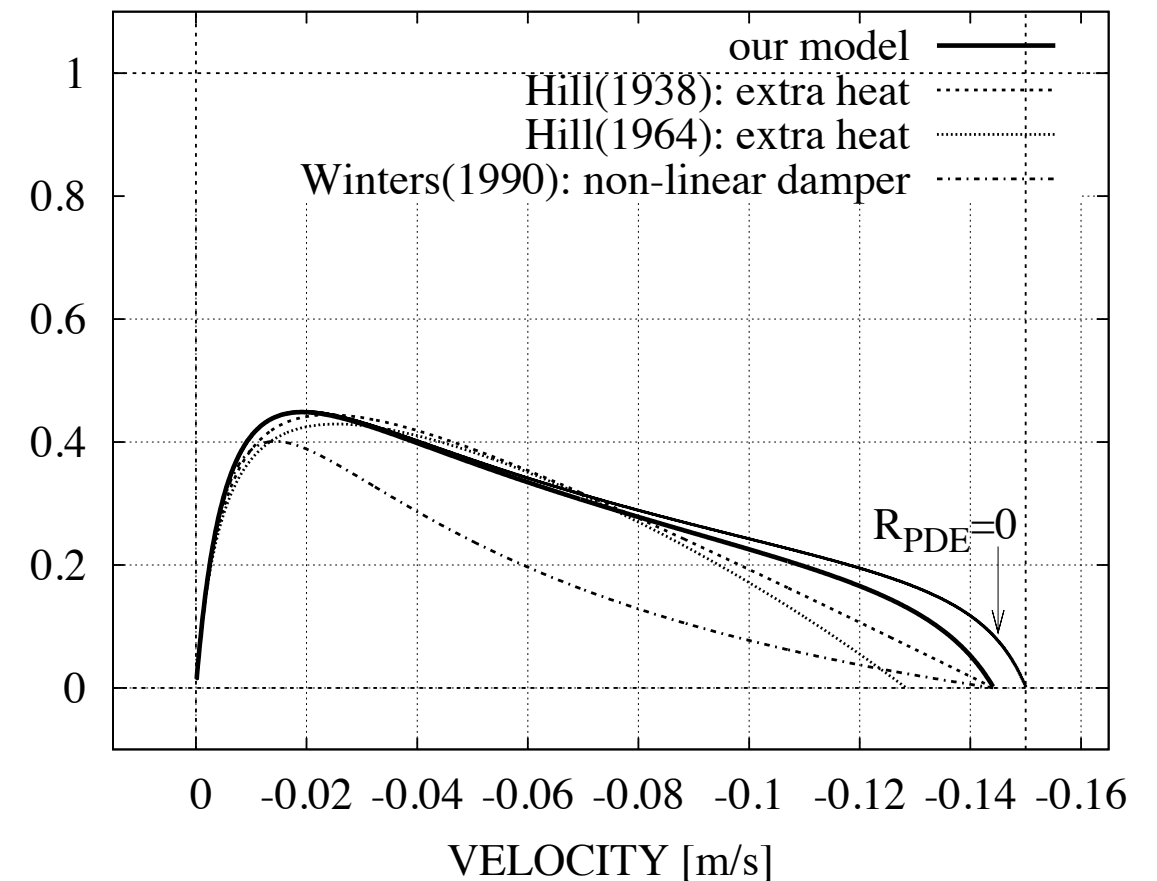
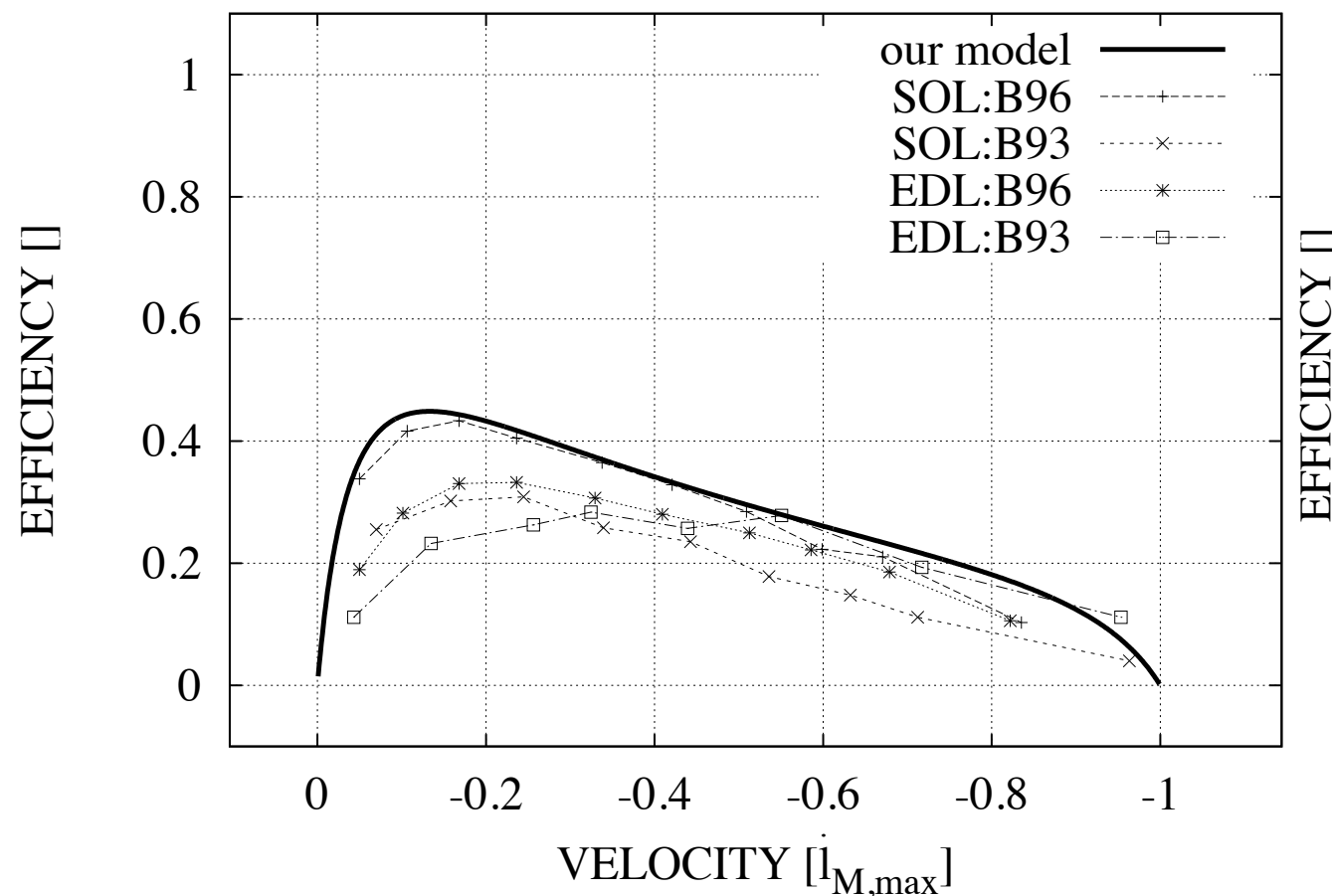
Mechanische Eigenschaften e. Skelettmuskels



	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	—

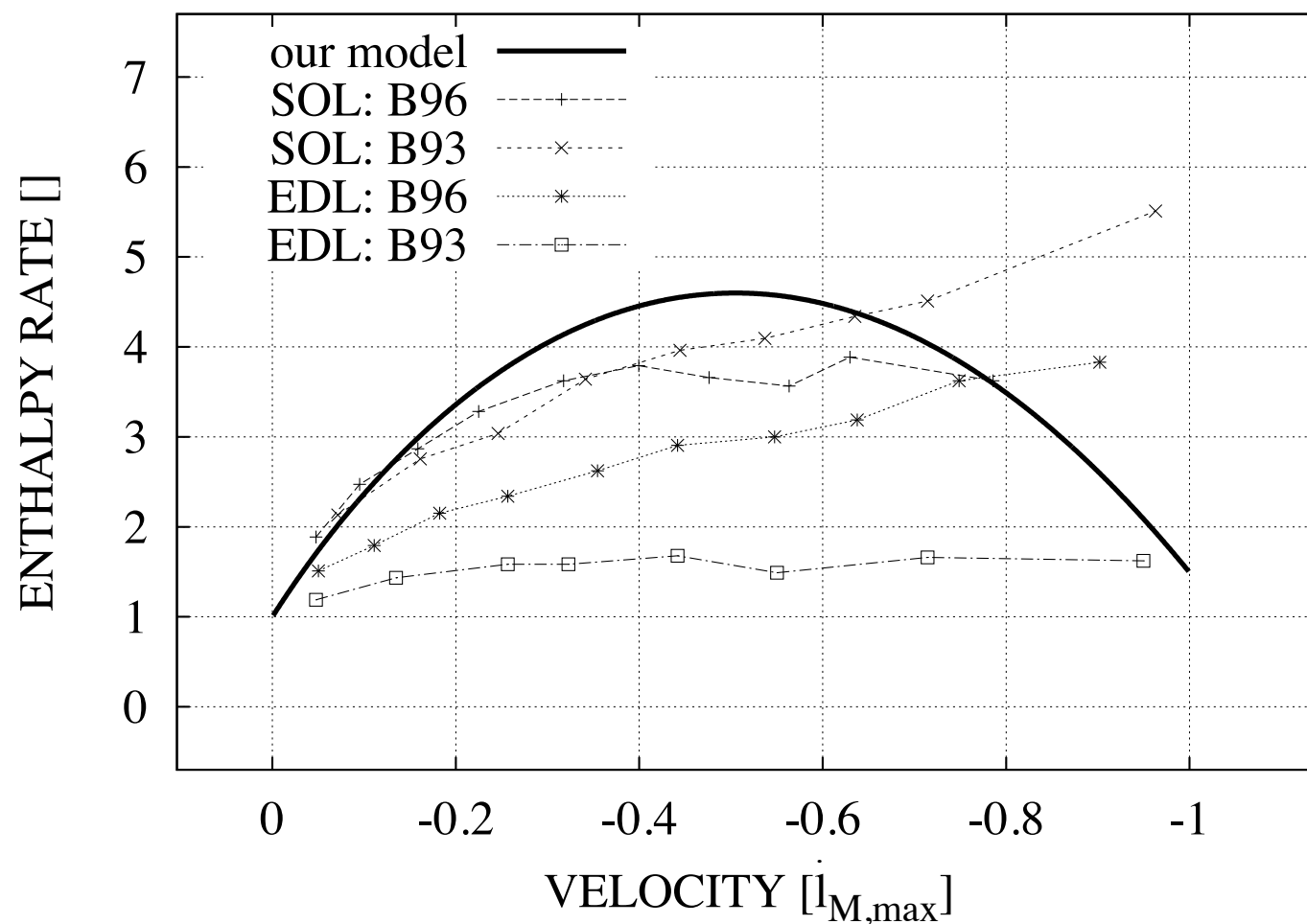
	$a / F_{L,o}$ dimensionless	$F_{L,o}$ N	$b / V_{L,o}$ dimensionless	$V_{L,o}$ mm/s
Rat ¹	0.356	4.30	0.38	144
Frog ²	0.27	0.67	0.28	42
Cat ³	0.27	0.18	0.30	191
Human ⁴	0.81	200	0.81	1115
Skeletal Muscle Model ⁵	0.224	—	0.224	—
Human ⁶	0.41	3000	0.39	756
Human ⁷	0.41	2430	0.41	780
Human ⁸	0.12	—	0.12	—

Mechanische Eigenschaften e. Skelettmuskels



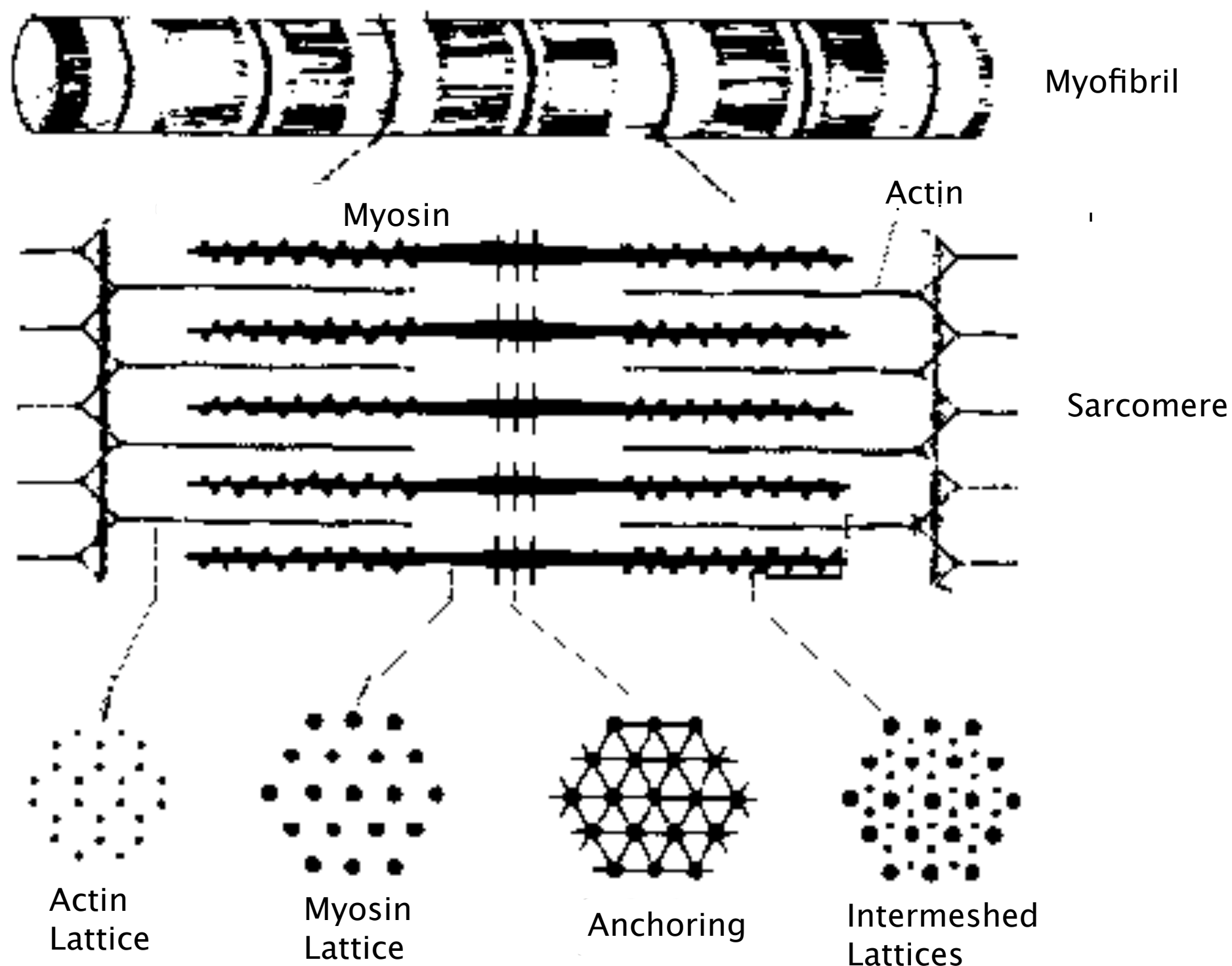
Efficiency = mech. energy output / mech. energy input

Thermodynamik eines Skelettmuskels



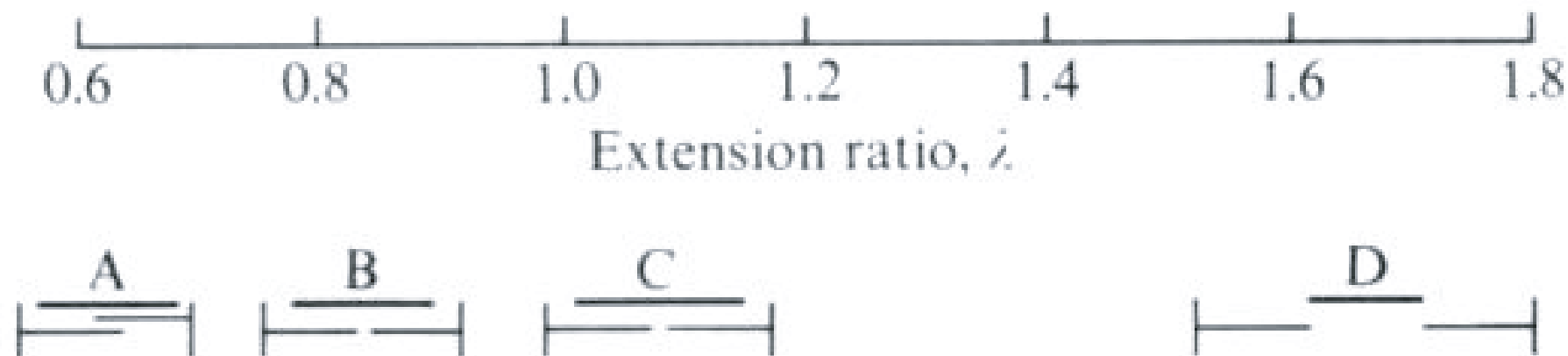
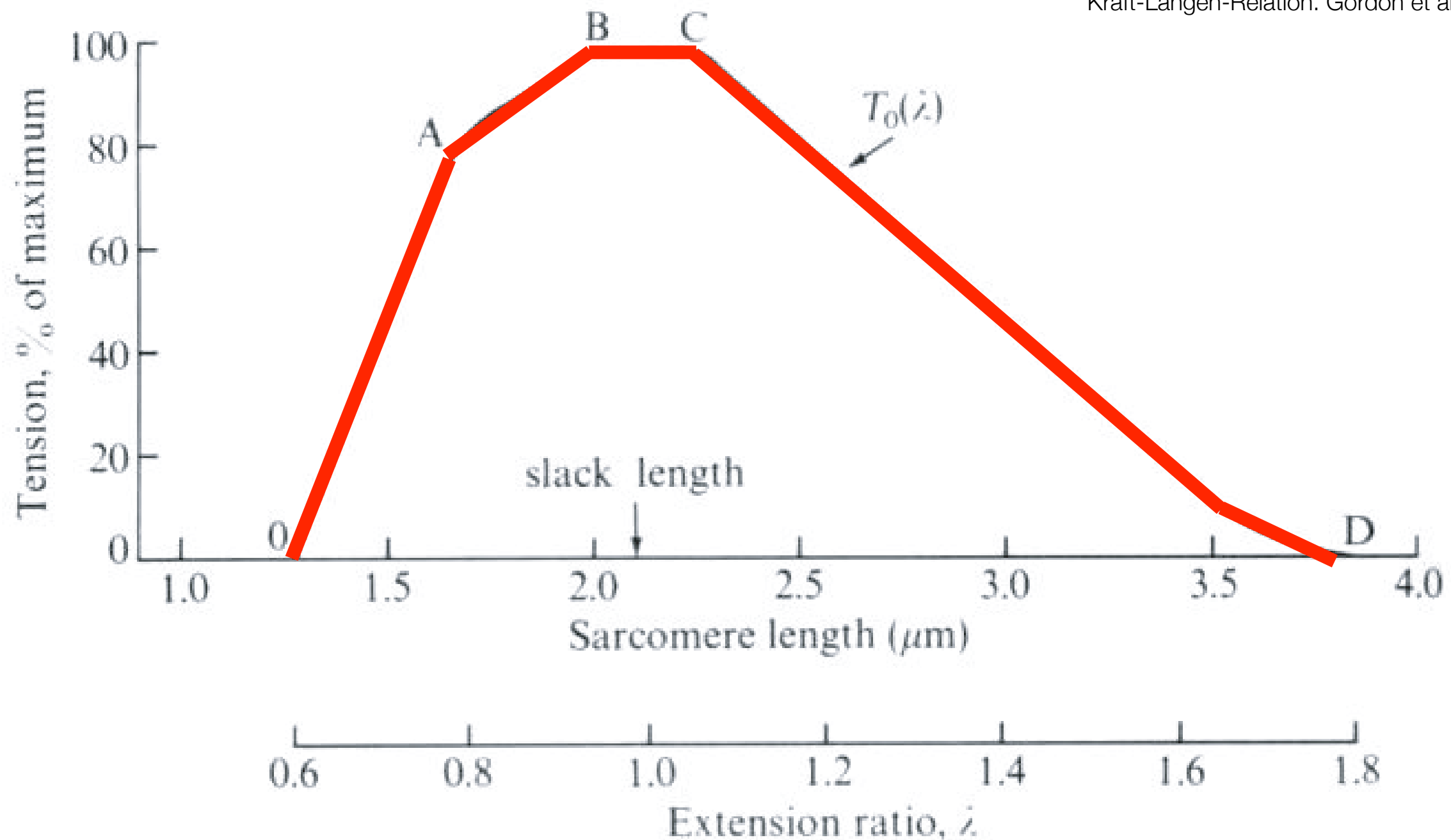
Enthalpy rate = power output * main. heat rate *
shortening heat rate

Das Sarkomer



Biologische Muskelexperimente

Kraft-Längen-Relation. Gordon et al. (1966)



Biologische Muskelexperimente

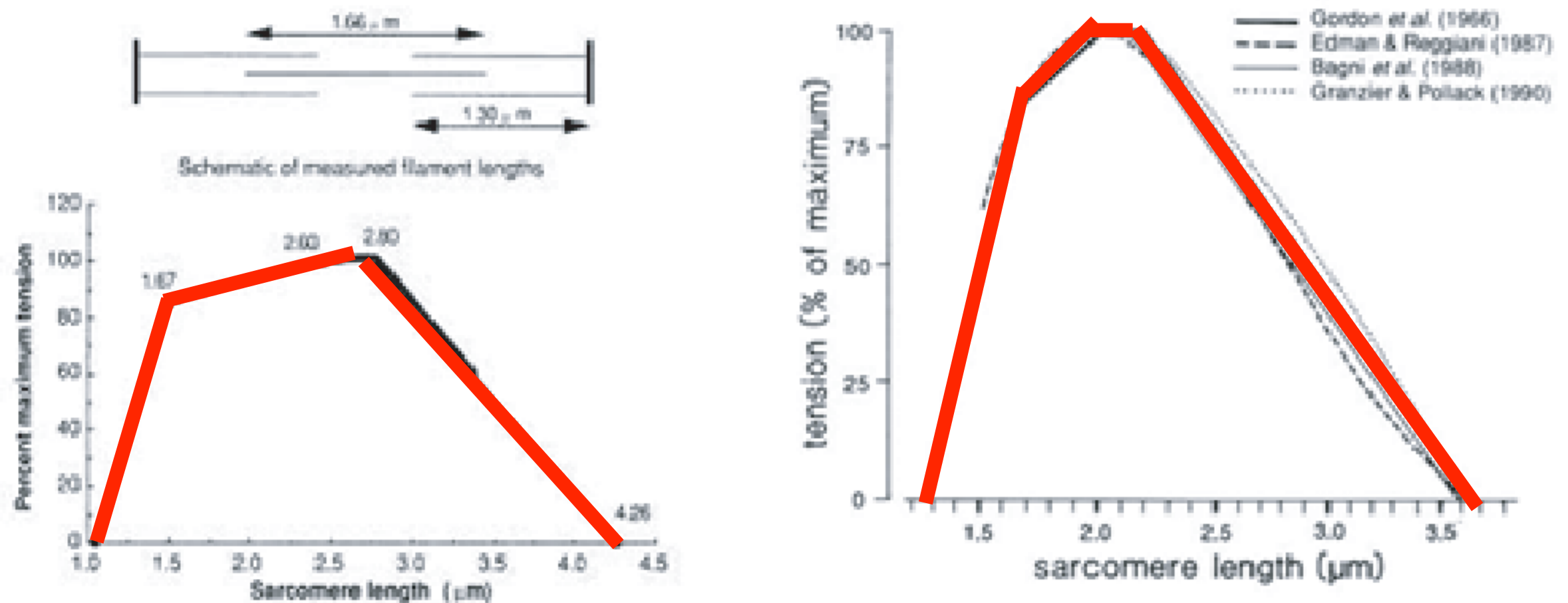
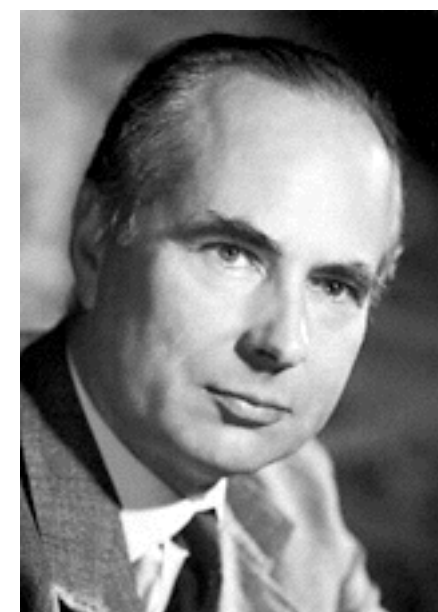
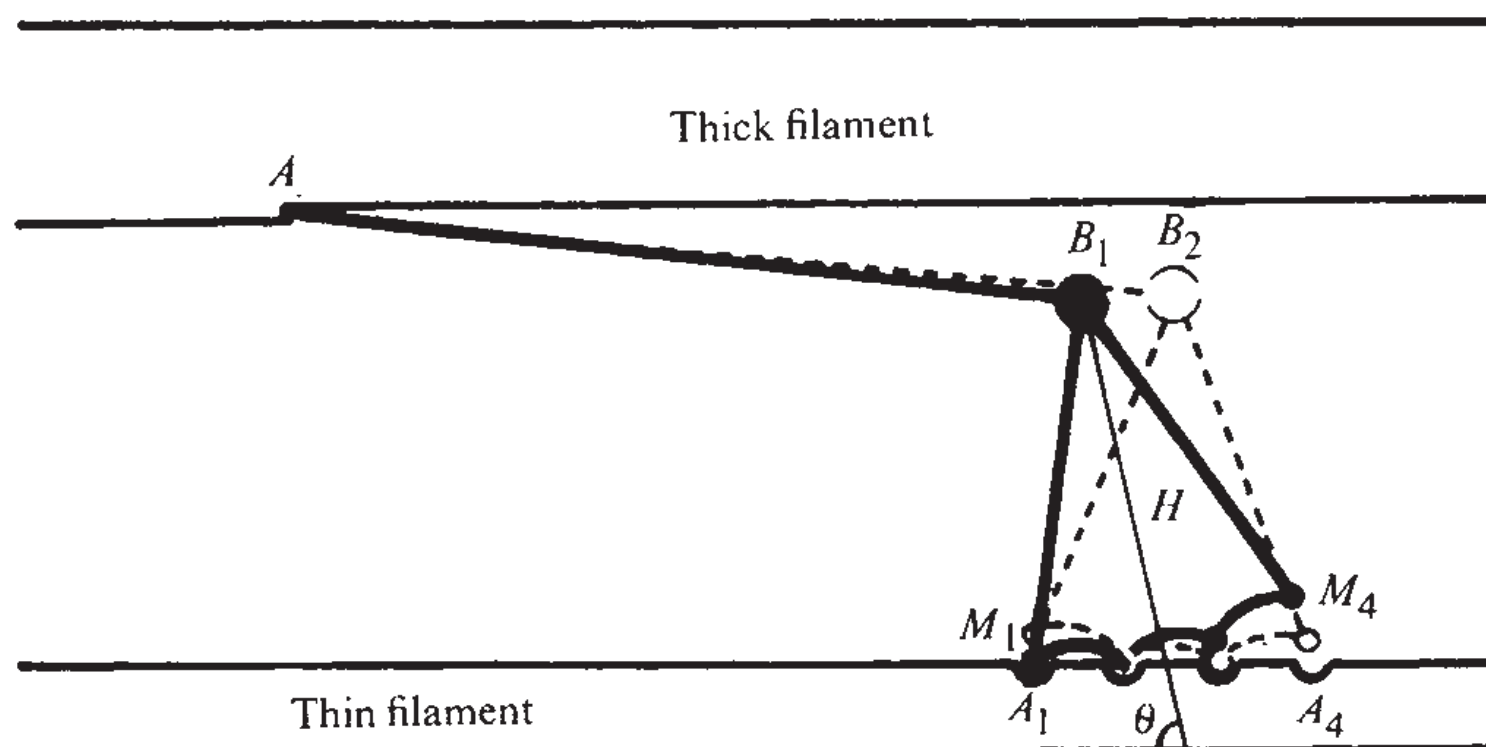


Abbildung 2.21: Die Kraft-Längen-Relation. Links: Die Relation für eine Faser des Menschen (Lieber et al., 1994). Rechts: Relation für eine Faser des Frosches von mehreren Autoren als Vergleich.

Mikrodynamik eines Skelettmuskels



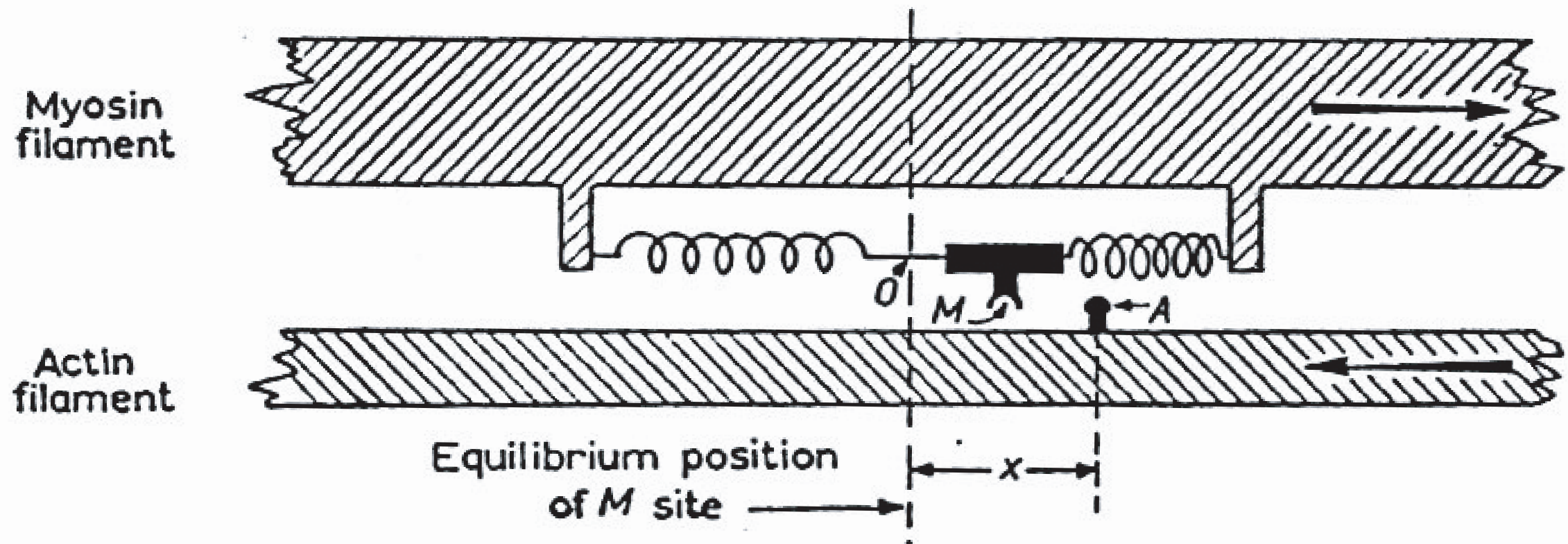
Andrew Fielding Huxley

Nobelpreis 1963:

„ ... for ... ionic mechanisms involved in excitation ... of the ... cell membrane.“

Huxleytyp Muskelmodelle erklären die Mechanik der Muskelkontraktion auf der Grundlage der Mikrostruktur („sliding filament theory“)

Die Theorie der gleitenden Filamente



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

m : Anzahl der Querbrücken pro Einheitsvolumen

s : Sarkomerlänge

k : Federkonstante

l : Abstand zweier M-Stellen

x : Auslenkung von Ruhelage

$n(x)$: Anzahl der gebundenen Zustände bei einer Auslenkung x

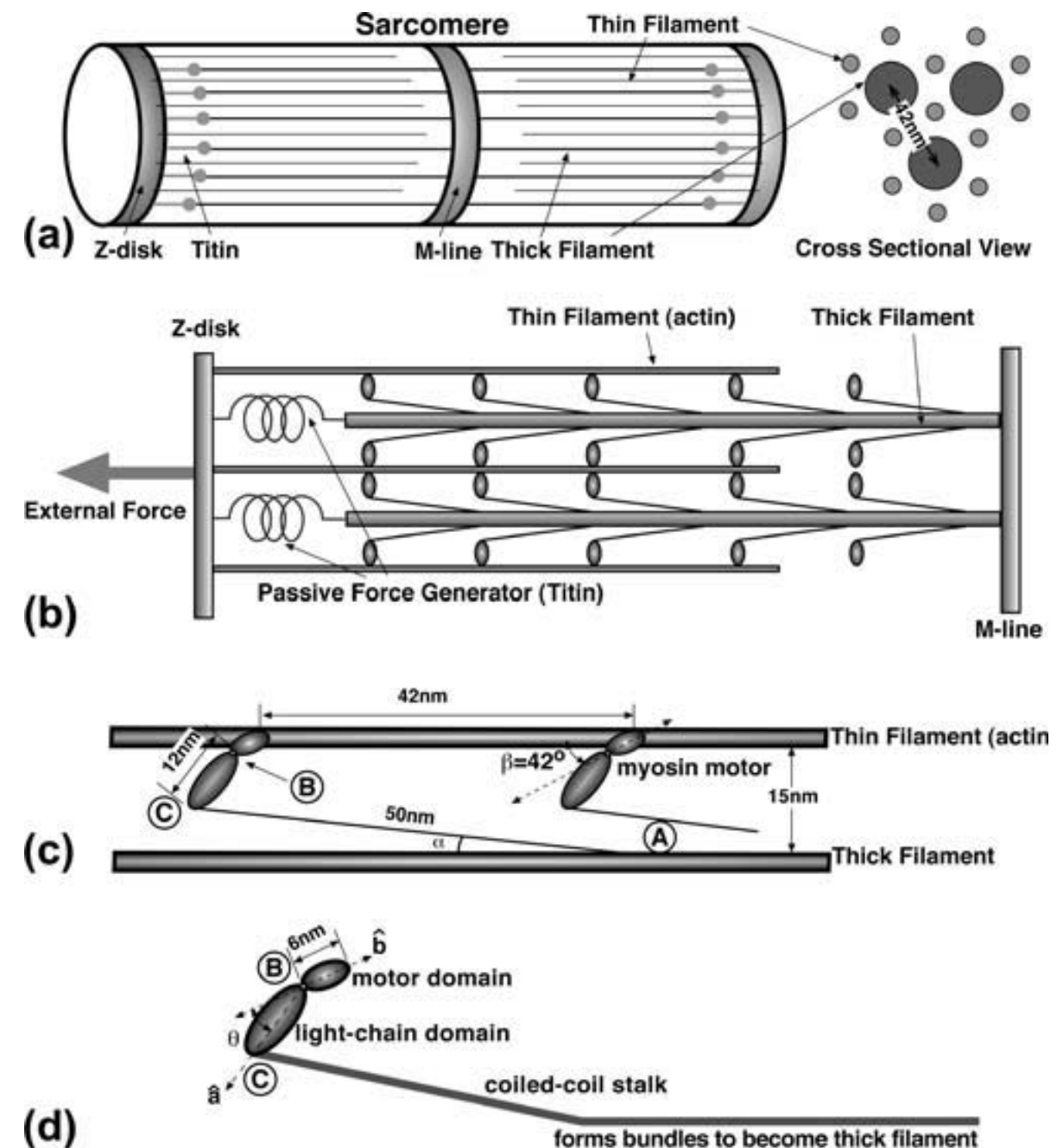
Mikrodynamik eines Skelettmuskels

Huxleytyp Modell beschreibt die Myosinkopf Bewegung

Beinhaltet molekulare Reibung, chemische Kinetik und stochastische Komponenten

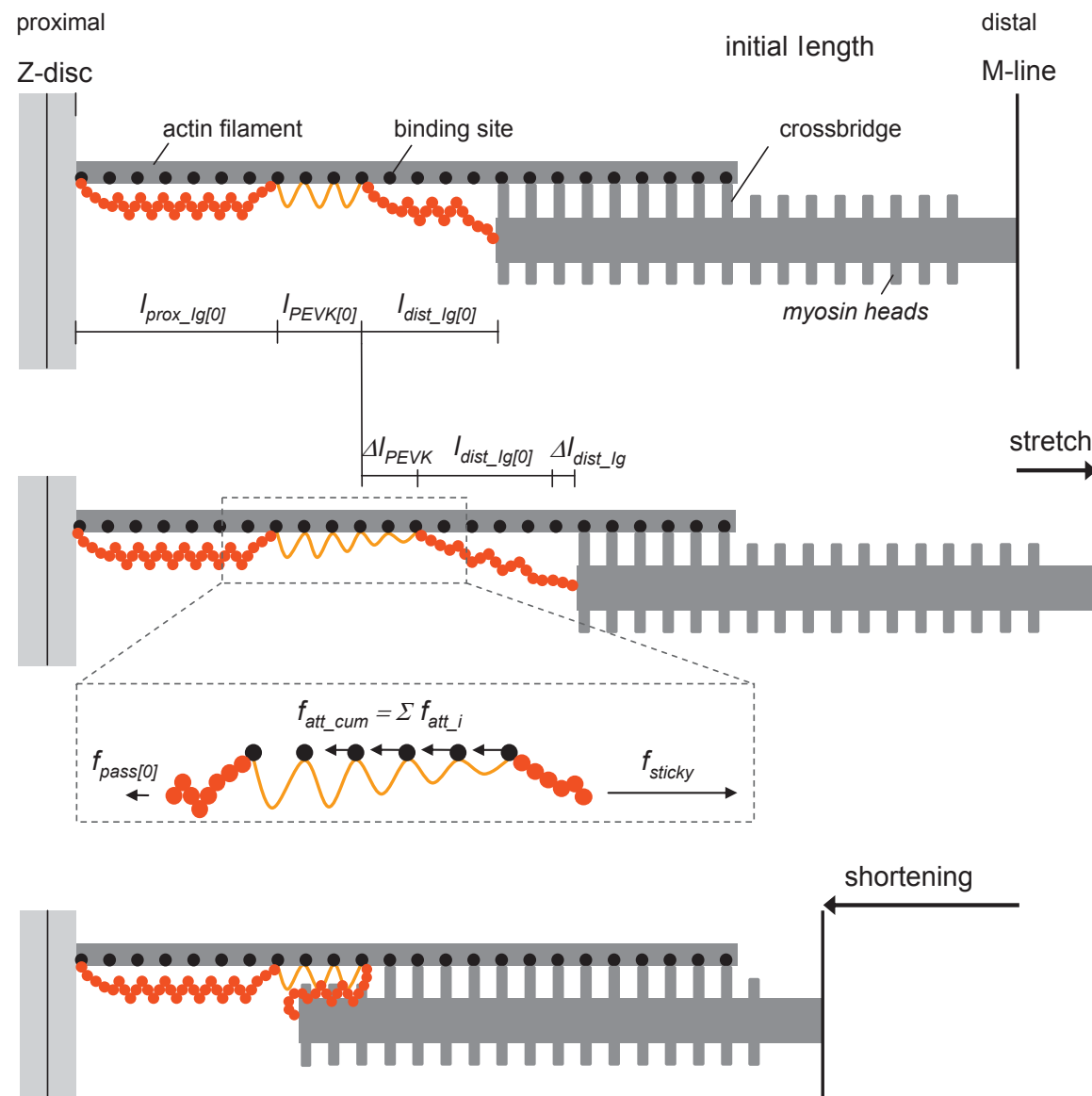
Sagt Änderung der Muskelkoordinate voraus (Winkel der Myosinköpfchen)

Benötigt Kraft und chemischen Zustand als Eingabedaten

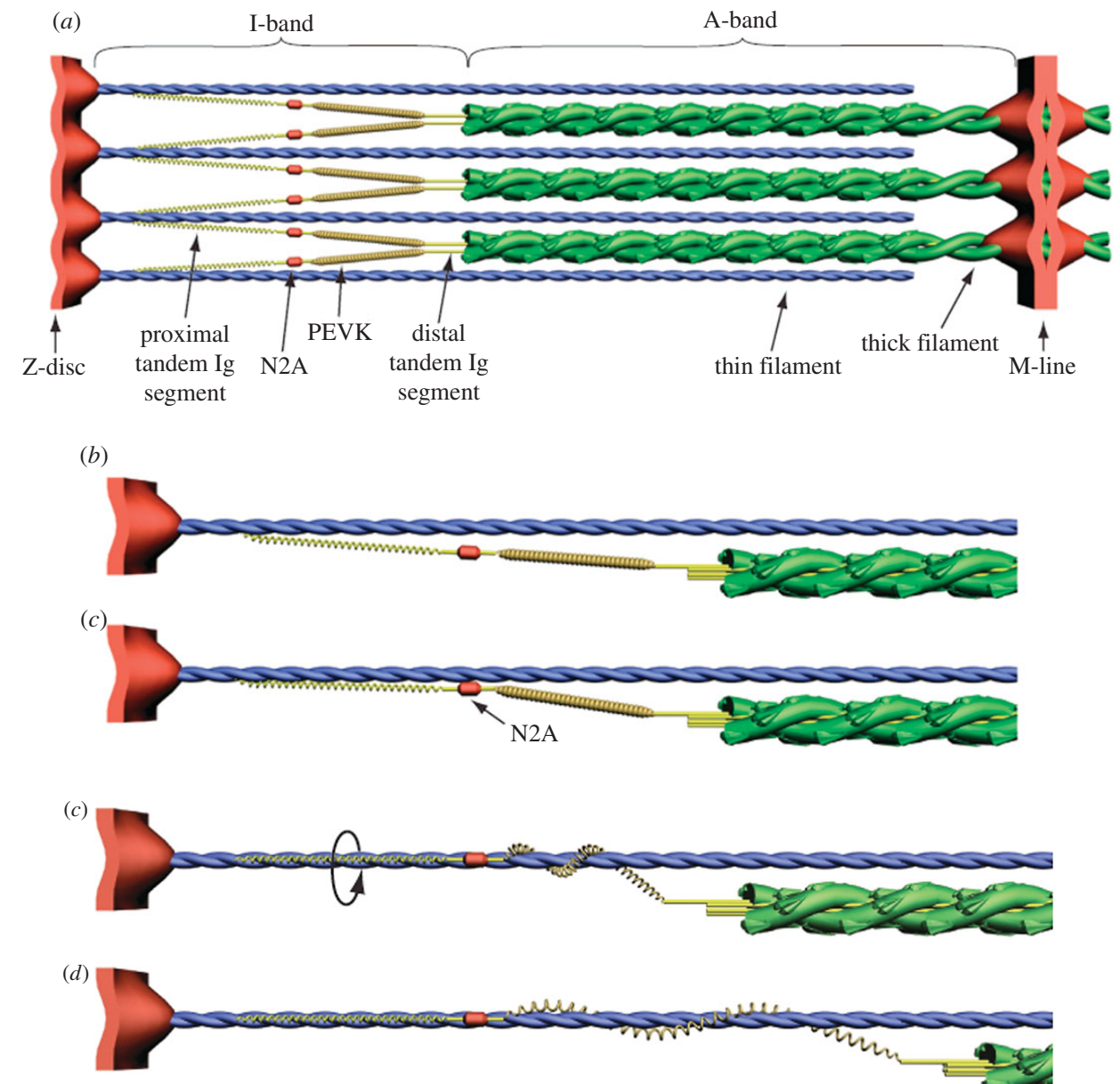


Lan, G., Sun, S., 2005. Dynamics of myosin-driven skeletal muscle contraction: I. Steady-state force generation. Biophysical Journal 88 (6), 4107– 4117.

Neue Hypothesen der Muskelkontraktion

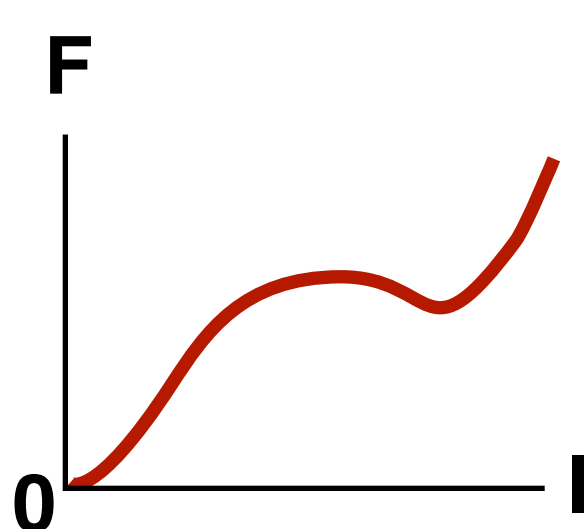


Rode, C., Siebert, T. Blickhan, R. 2009. Titin-induced force enhancement and force depression: A 'sticky-spring' mechanism in muscle contractions? *Journal of Theoretical Biology* 259 (2009) 350–360.

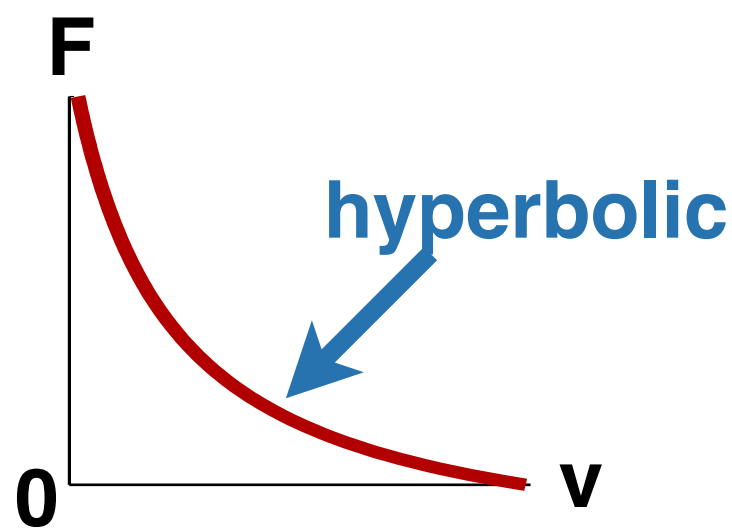


Kiisa C. Nishikawa, Jenna A. Monroy, Theodore E. Uyeno, Sang Hoon Yeo, Dinesh K. Pai and Stan L. Lindstedt 2012. Is titin a 'winding filament'? A new twist on muscle contraction. *Proc. R. Soc. B* 2012 279, 981-990

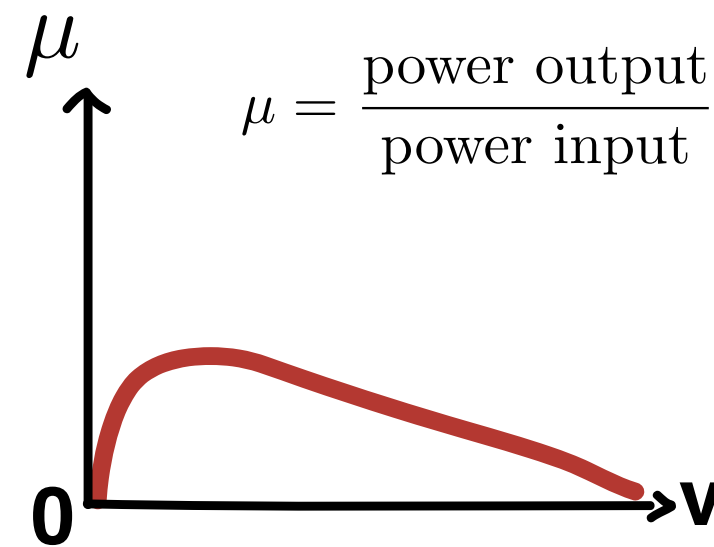
Kontraktionsdynamik des Skelettmuskels



**Kraft-Längen
Beziehung**

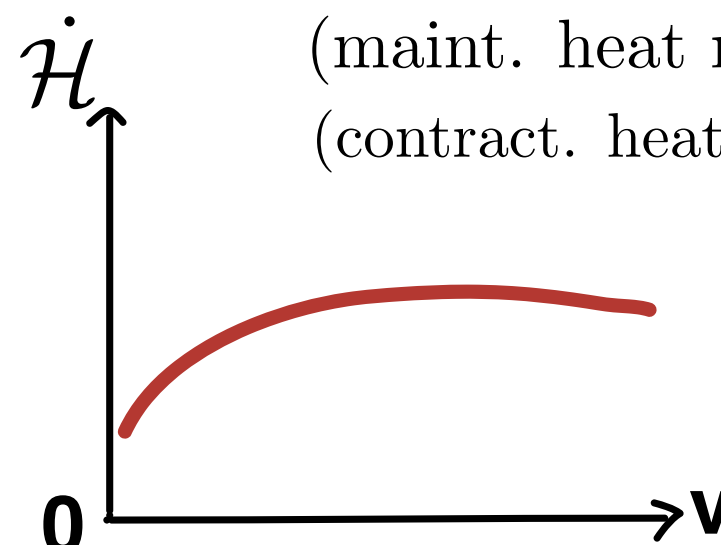


**Kraft-Geschwin-
digkeits Bez.**

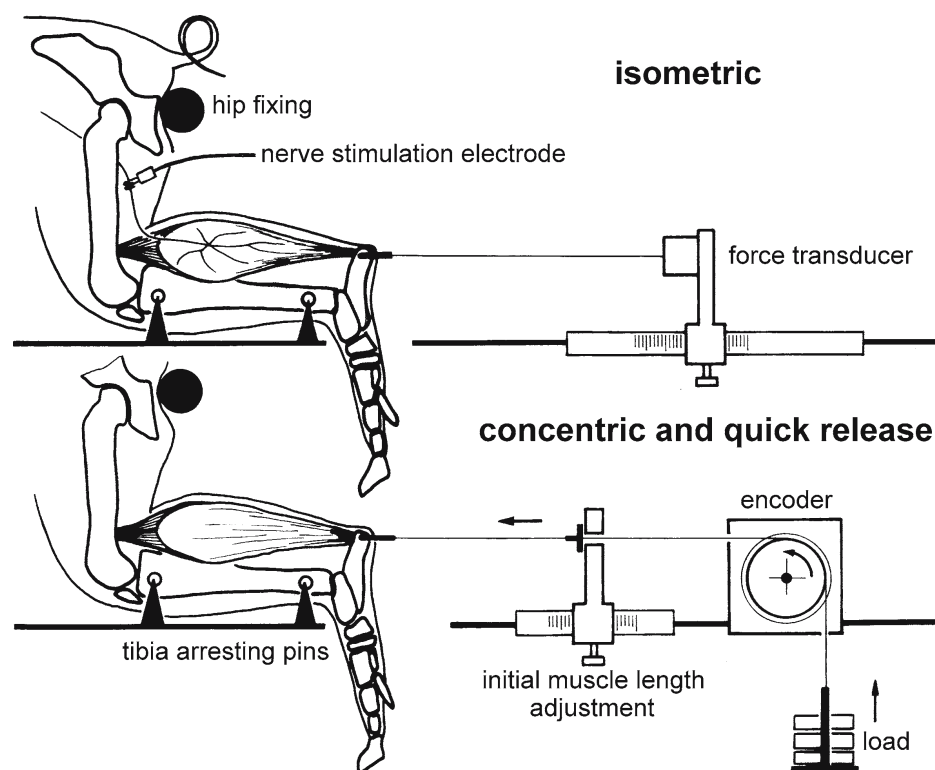


**Mechanische
Effizienz**

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



Enthalpierate



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.

Ist der Muskel der bessere Aktuator?

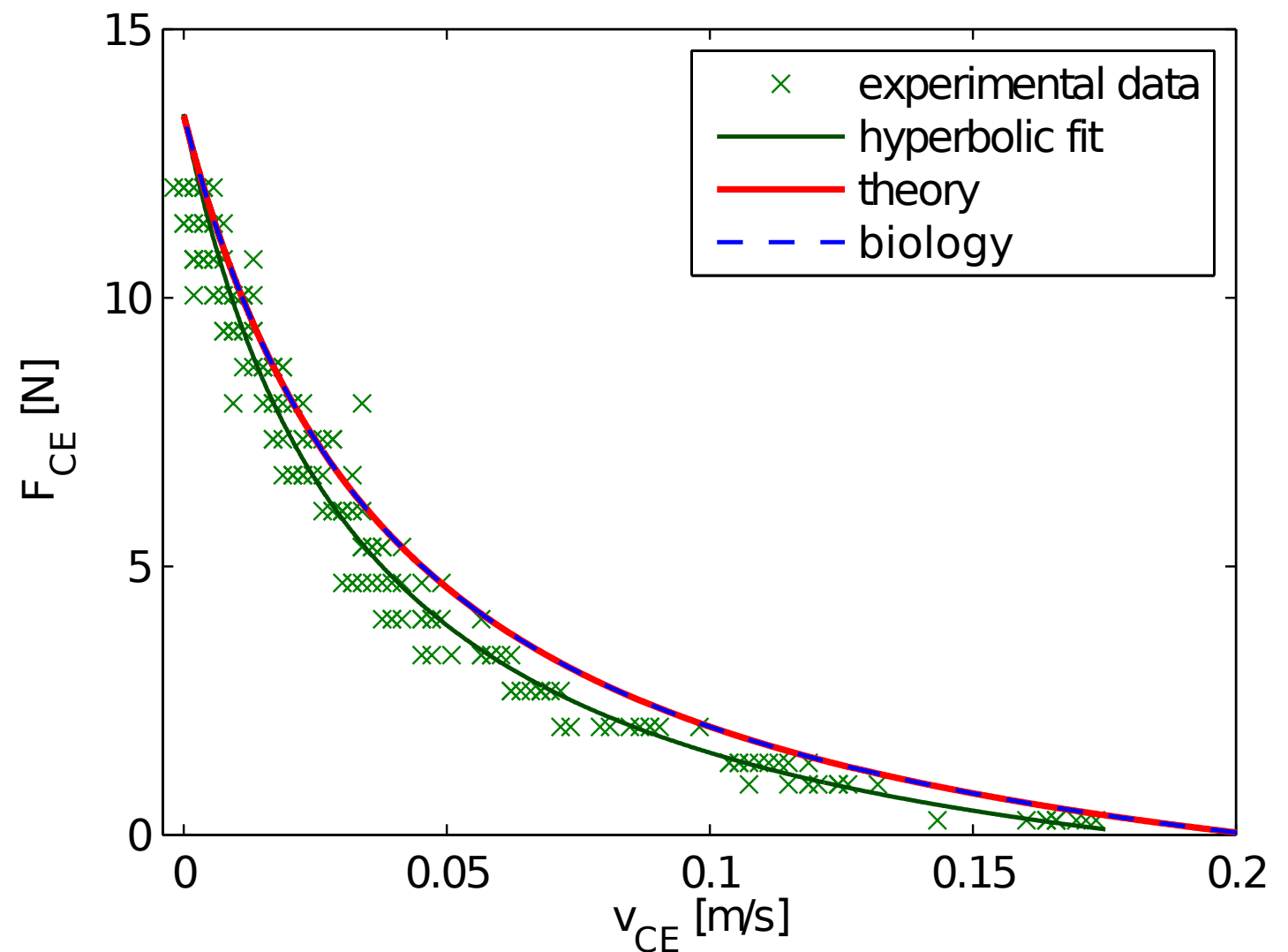
Biologischer Muskel als Vorlage für biomimetische Aktuatoren



Engineering



Biology



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

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

Modellsicht auf den biologischen Motor

Muskel

Hill-Typ Muskelmodell:

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

$$\dot{q}_j = f_q(q_j, \text{STIM}_j^i)$$

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

Günther, Schmitt, Wank (2007)

Skelett

Modell des mechanischen Systems:

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

Pandy (2001)

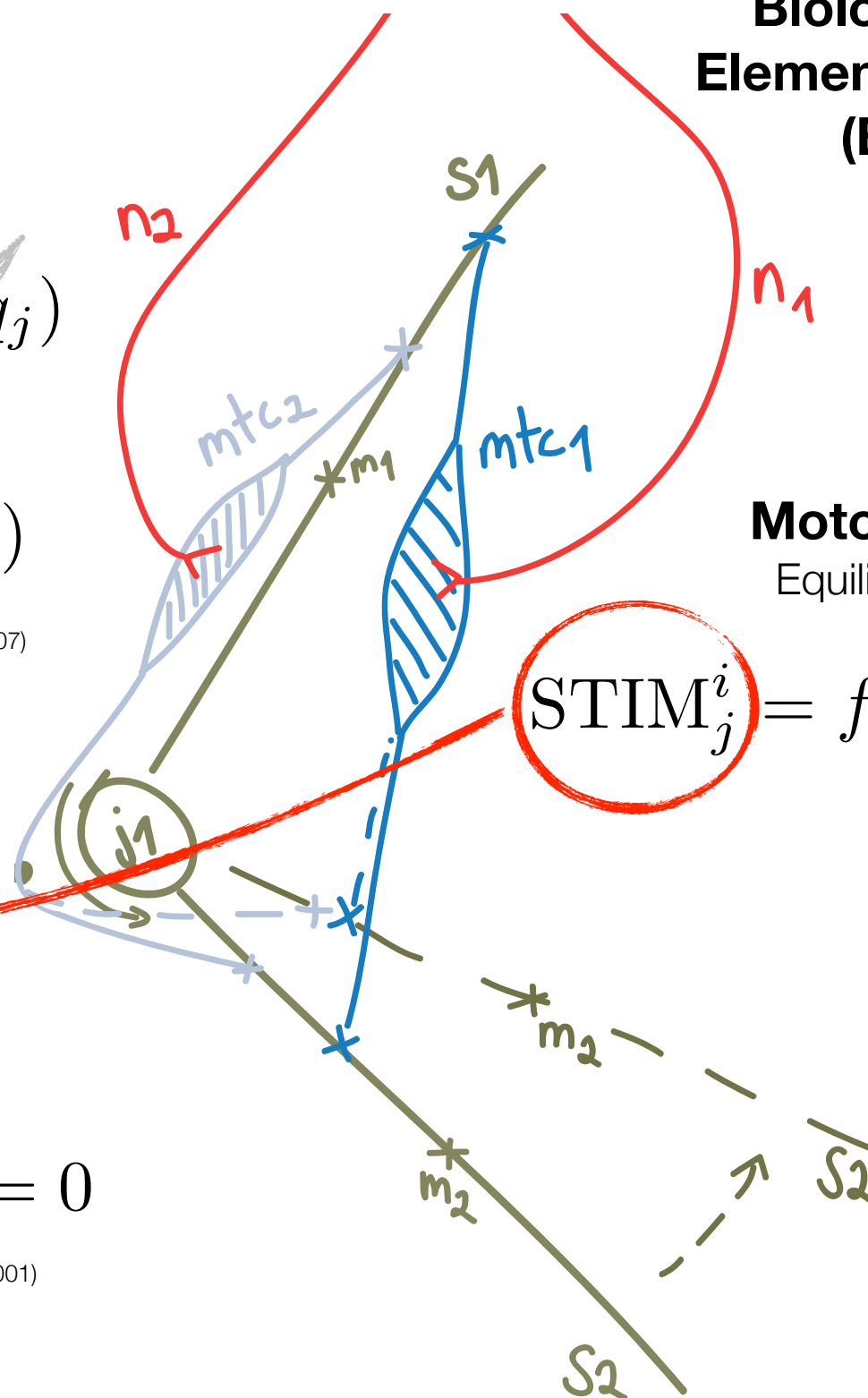
Biologischer Elementarantrieb (EBD)

Motorische Kontrolle

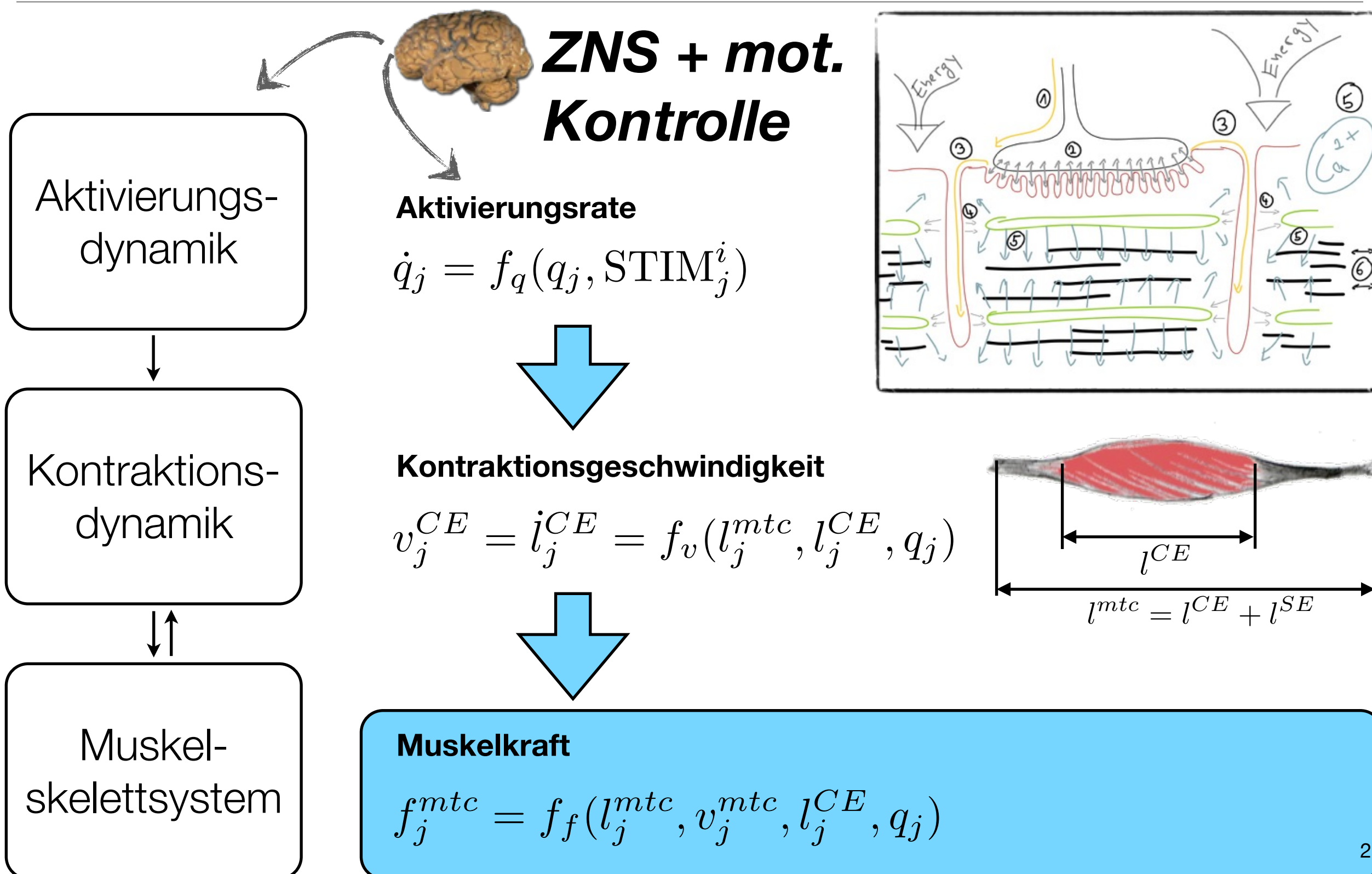
Equilibrium-Point-Control:

$$\text{STIM}_j^i = f_s(\lambda_j^i, l_j^{CE}, v_j^{CE})$$

Günther and Ruder (2003)



Muskelmodell auf makroskopischer Ebene



Beispiel eines Muskelmodells nach Hilltyp



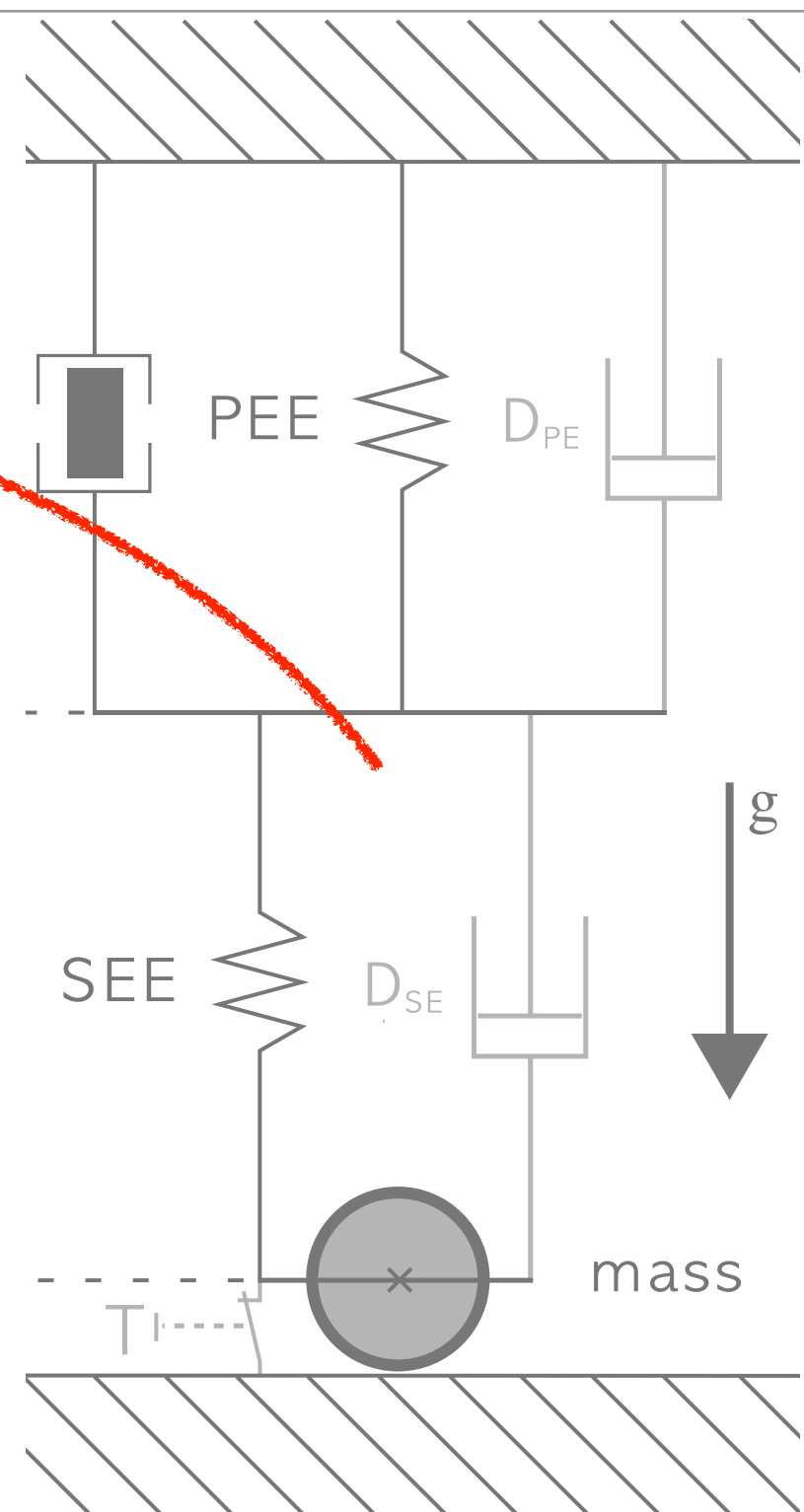
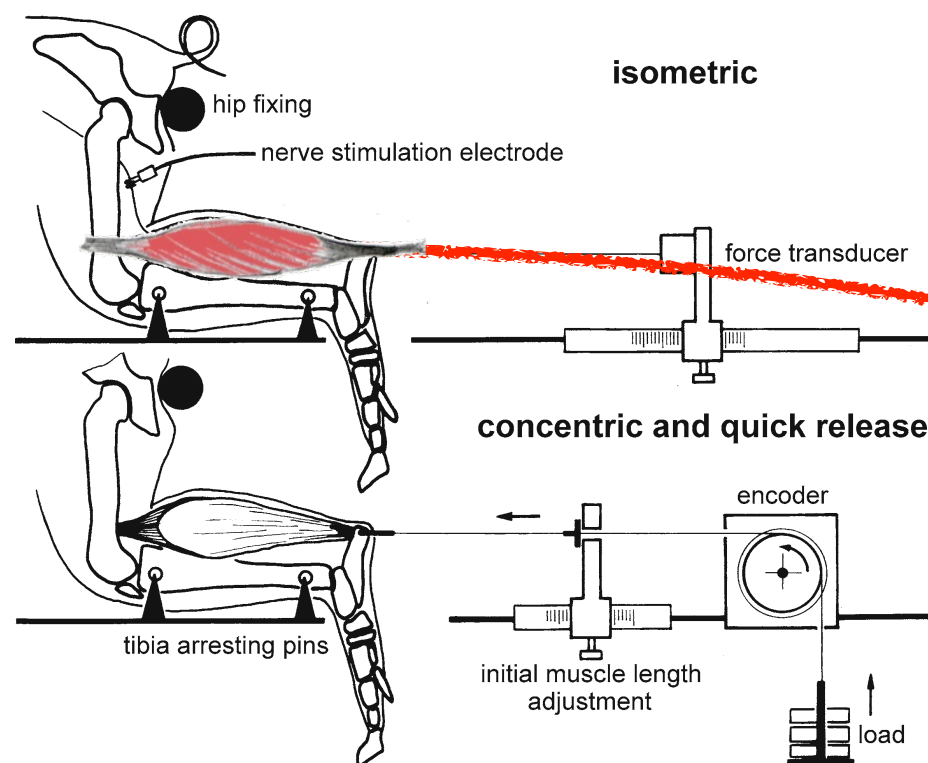
Biological Cybernetics
July 2007, Volume 97, Issue 1, pp 63-79

High-frequency oscillations as a consequence of neglected serial damping in Hill-type muscle models

Michael Günther, Syn Schmitt, Veit Wank

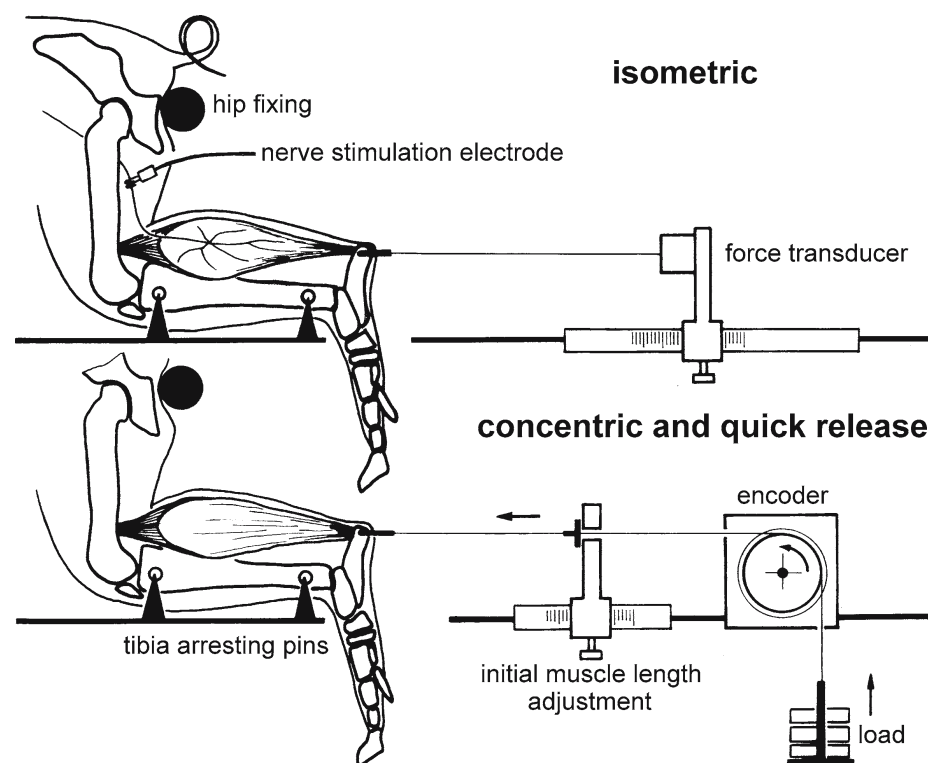
Modellskizze

Günther, M, Schmitt, S, Wank, V. (2007)

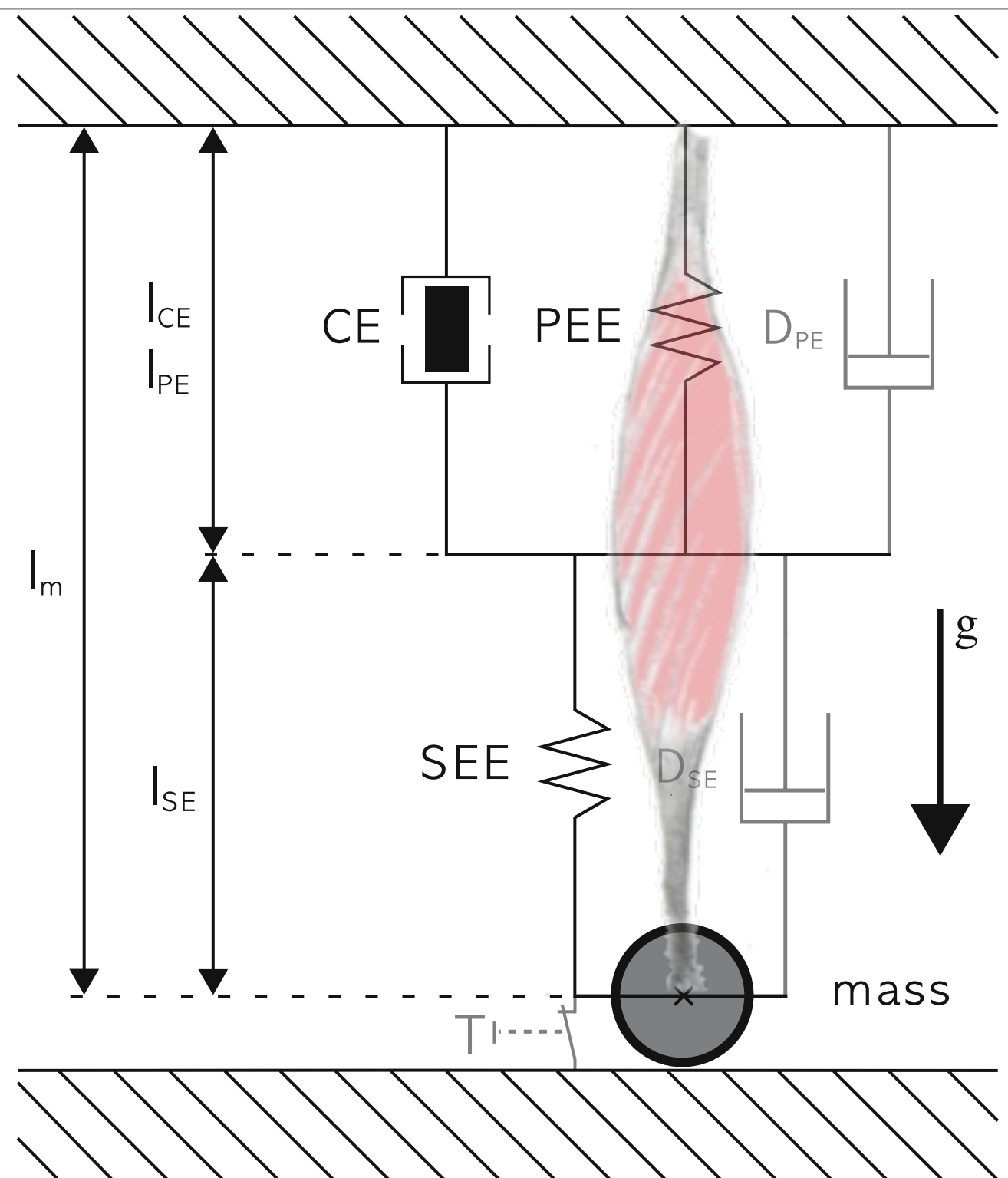


Modellskizze

Günther, M, Schmitt, S, Wank, V. (2007)



mass = 100,, 1800 g
g = Graviationsfeld der Erde



Modellskizze

Aktivierungsdynamik

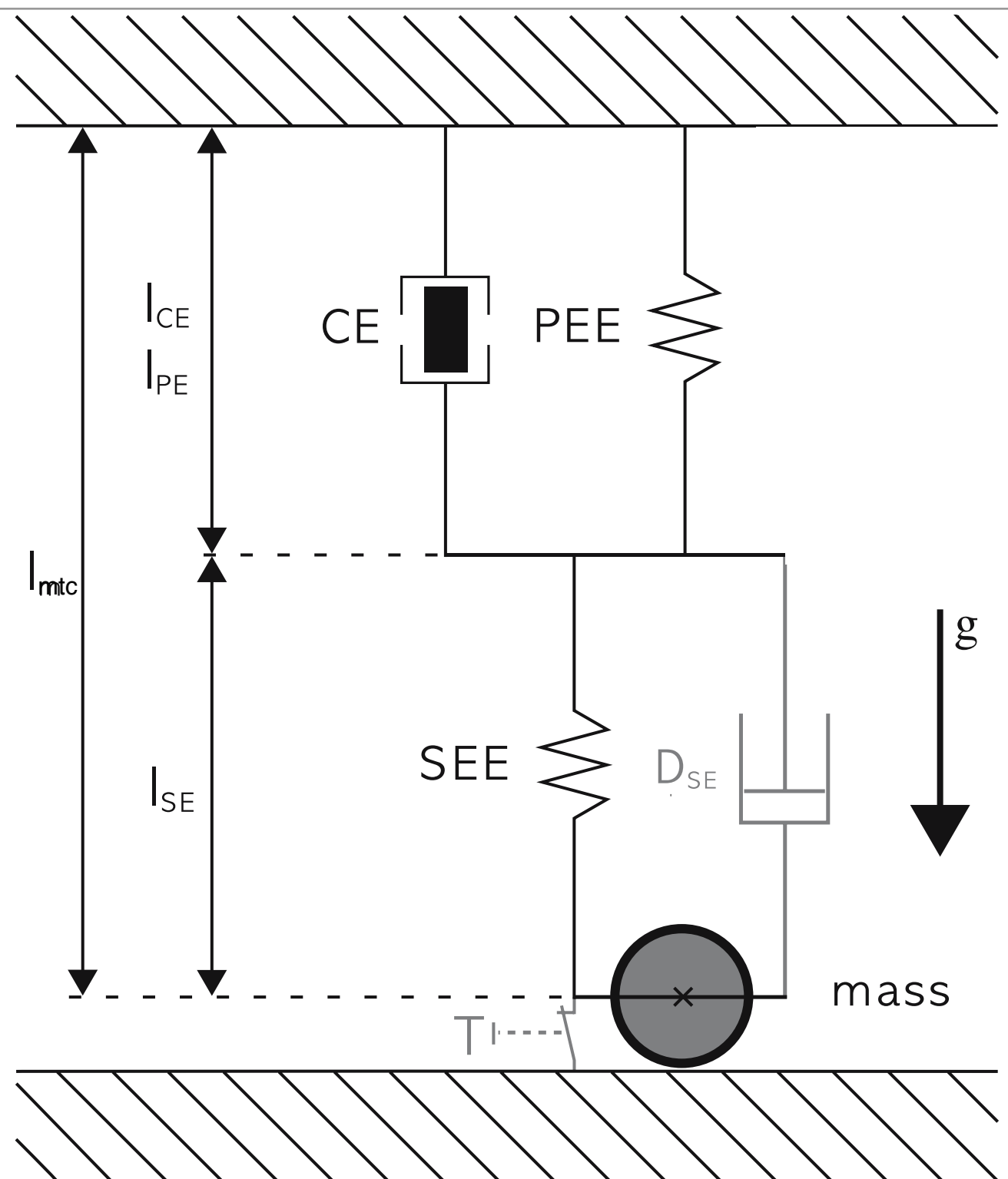
$$\dot{q}_j = f_q(q_j, \text{STIM}_j^i)$$

Kontraktionsdynamik

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

Muskel-Skelett-System

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



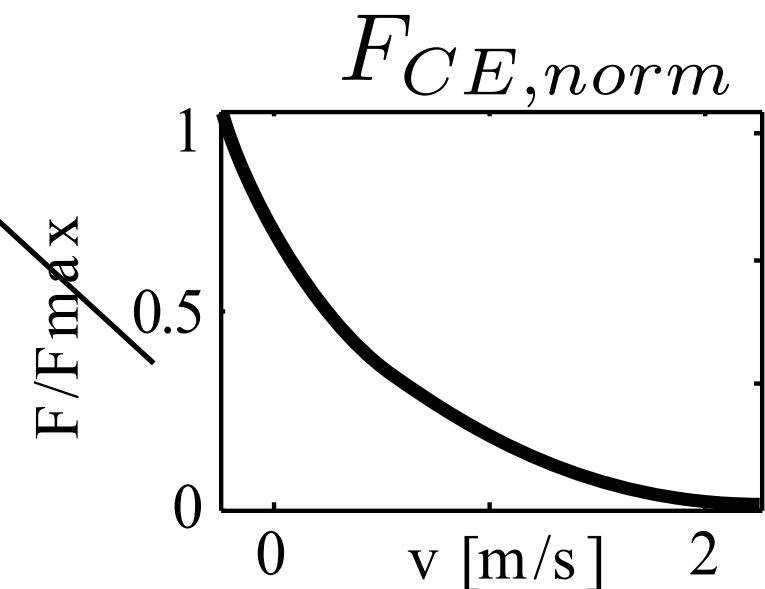
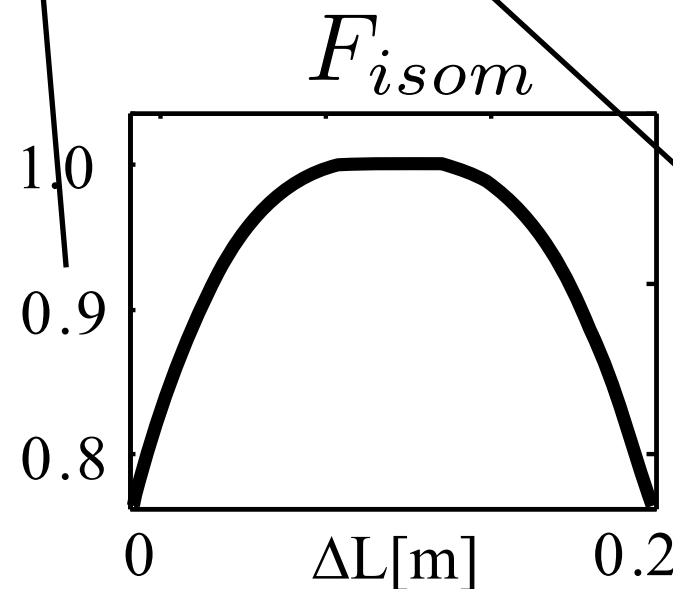
Modellierung des kontraktiven Elements

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

Produktansatz

Hill'sches
Muskel-Modell
Hill 1938

q
→ Aktivität [%]



Kontraktionsdynamik
Materialgesetze

Aktivierungsdynamik

Aktivierungsdynamik

$$\dot{q} = \frac{1}{\tau_q} \left(\text{STIM} - \text{STIM} \cdot (1 - \beta_q) \cdot (q - q_0) - \beta_q \cdot (q - q_0) \right)$$

mit $q_0 \leq q \leq 1$: Aktivierung der Muskulatur, Ca^{2+} - Konzentration

τ_q : Zeitkonstante für ansteigende Aktivierung

β_q : Verhältnis zwischen Zeitkonstante für ansteigende und abfallende Aktivierung

$0 \leq \text{STIM} \leq 1$: aktuelle, neuronale Stimulation des kontraktile Elements

Kontraktionsdynamik - Ausgangspunkt

nach Hill (1938)

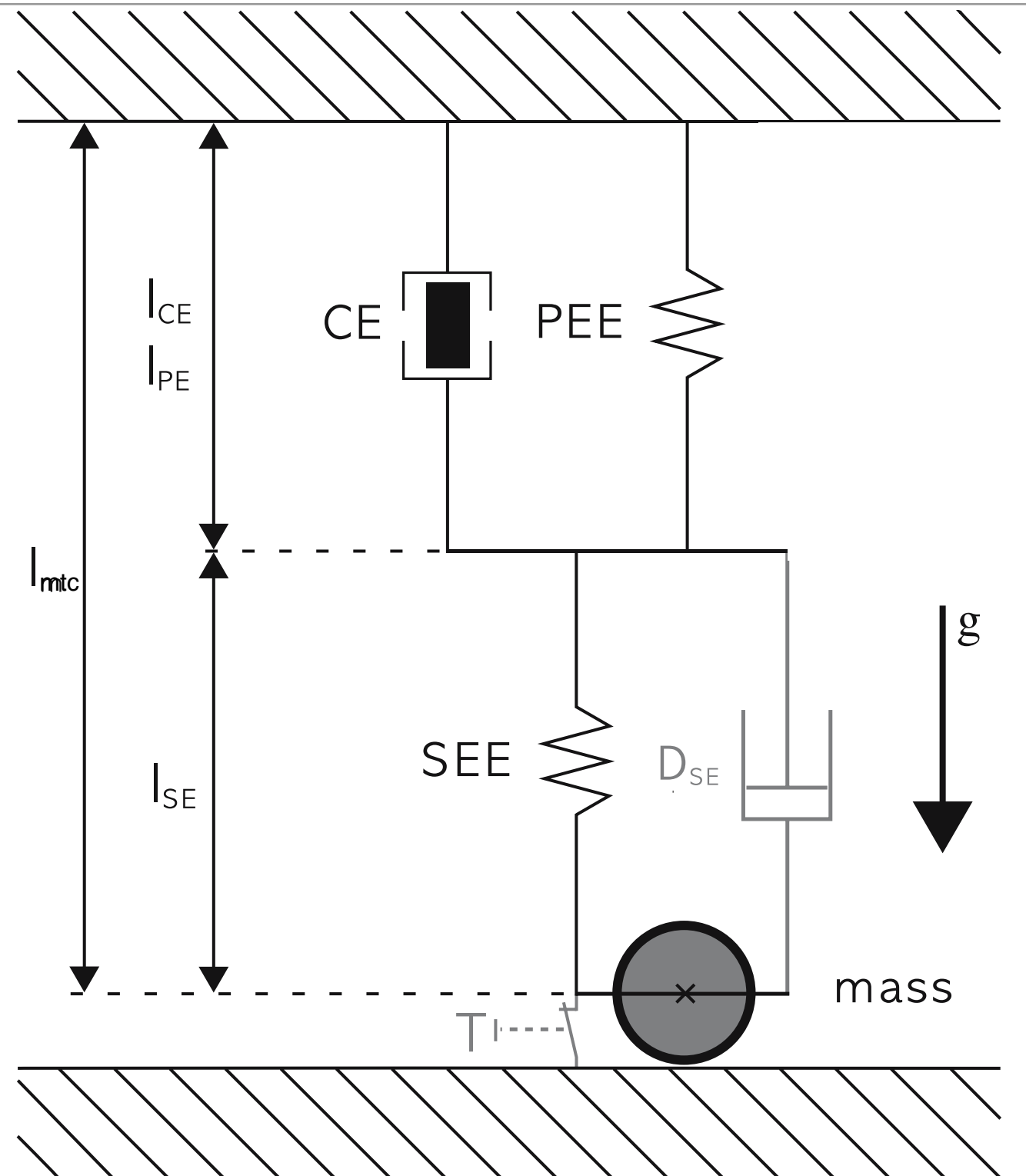
$$F_{mtc} = F_{mtc}(\dot{l}_{mtc})$$

unter Berücksichtigung des
Kraftgleichgewichts

$$F_{SDE}(l_{mtc}, l_{CE}) + F_{SEE}(l_{mtc}, l_{CE}) = F_{PEE}(l_{CE}) + F_{CE}(l_{CE}, \dot{l}_{CE}, q)$$

ergibt

$$\dot{l}_{CE} = \dot{l}_{CE}(l_{mtc}, l_{CE}, q)$$



Modellierung der Sehne - SDE

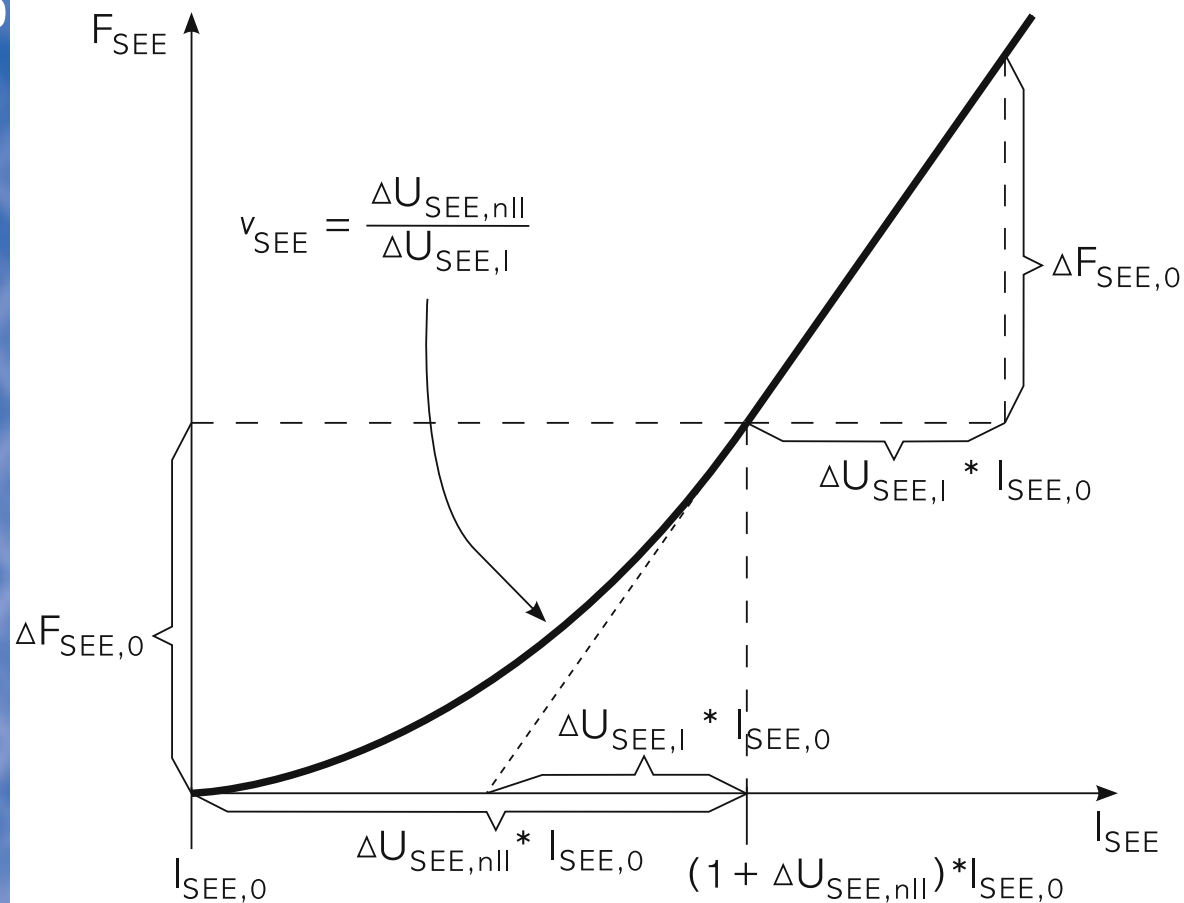
$$F_{SEE} + F_{SDE} = F_{PEE} + F_{CE}$$

$$F_{SDE} = d_{SE,max}(l_{CE}, q) \cdot \frac{F_{CE}(l_{CE}, \dot{l}_{CE}, q)}{F_{max}} \cdot \dot{l}_{SE}$$

mit

$$d_{SE,max}(l_{CE}, q) = D_{SE} \cdot \frac{F_{max} \cdot A_{rel,0}}{l_{CE,opt} \cdot B_{rel,0}}$$

Modellierung der Sehne - SEE



$$F_{SEE}(l_{SE}) = \begin{cases} 0, & l_{SE} < l_{SEE,0} \\ K_{SEE,nl} (l_{SE} - l_{SEE,0})^{\nu_{SEE}}, & l_{SEE,0} \leq l_{SE} < l_{SEE,nll} \\ \Delta F_{SEE,0} + K_{SEE,l} (l_{SE} - l_{SEE,nll}), & l_{SE} \geq l_{SEE,nll} \end{cases} \quad (4)$$

where $l_{SE} = l_{mtc} - l_{CE}$ is the length of the serial element (SE) and

$$l_{SEE,nll} = (1 + \Delta U_{SEE,nll}) l_{SEE,0}$$

$$\nu_{SEE} = \Delta U_{SEE,nll} / \Delta U_{SEE,l}$$

$$K_{SEE,nl} = \Delta F_{SEE,0} / (\Delta U_{SEE,nll} l_{SEE,0})^{\nu_{SEE}}$$

$$K_{SEE,l} = \Delta F_{SEE,0} / (\Delta U_{SEE,l} l_{SEE,0})$$

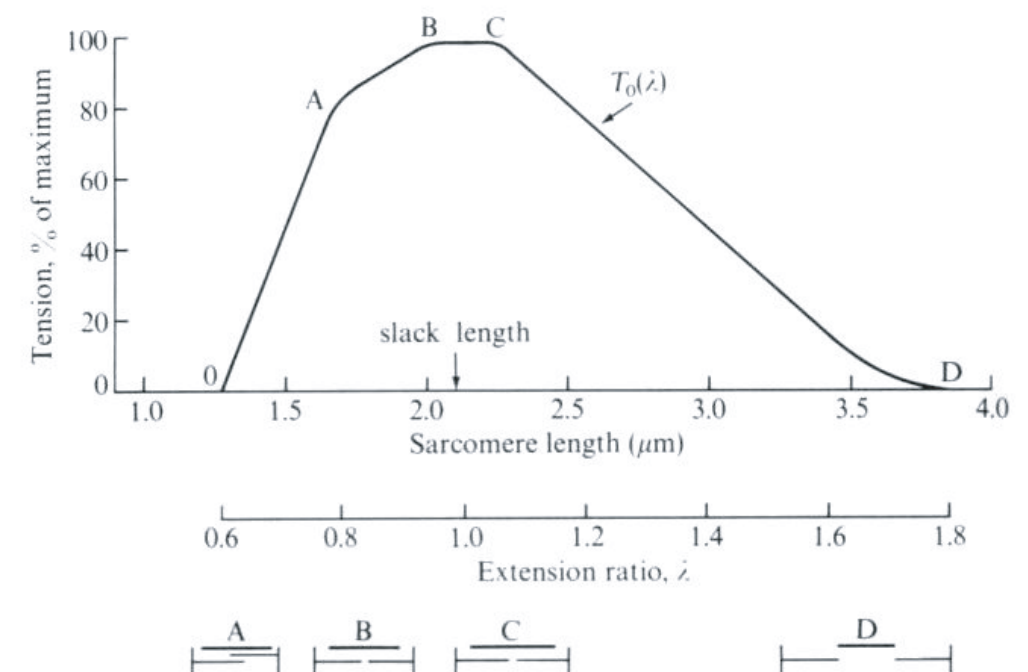
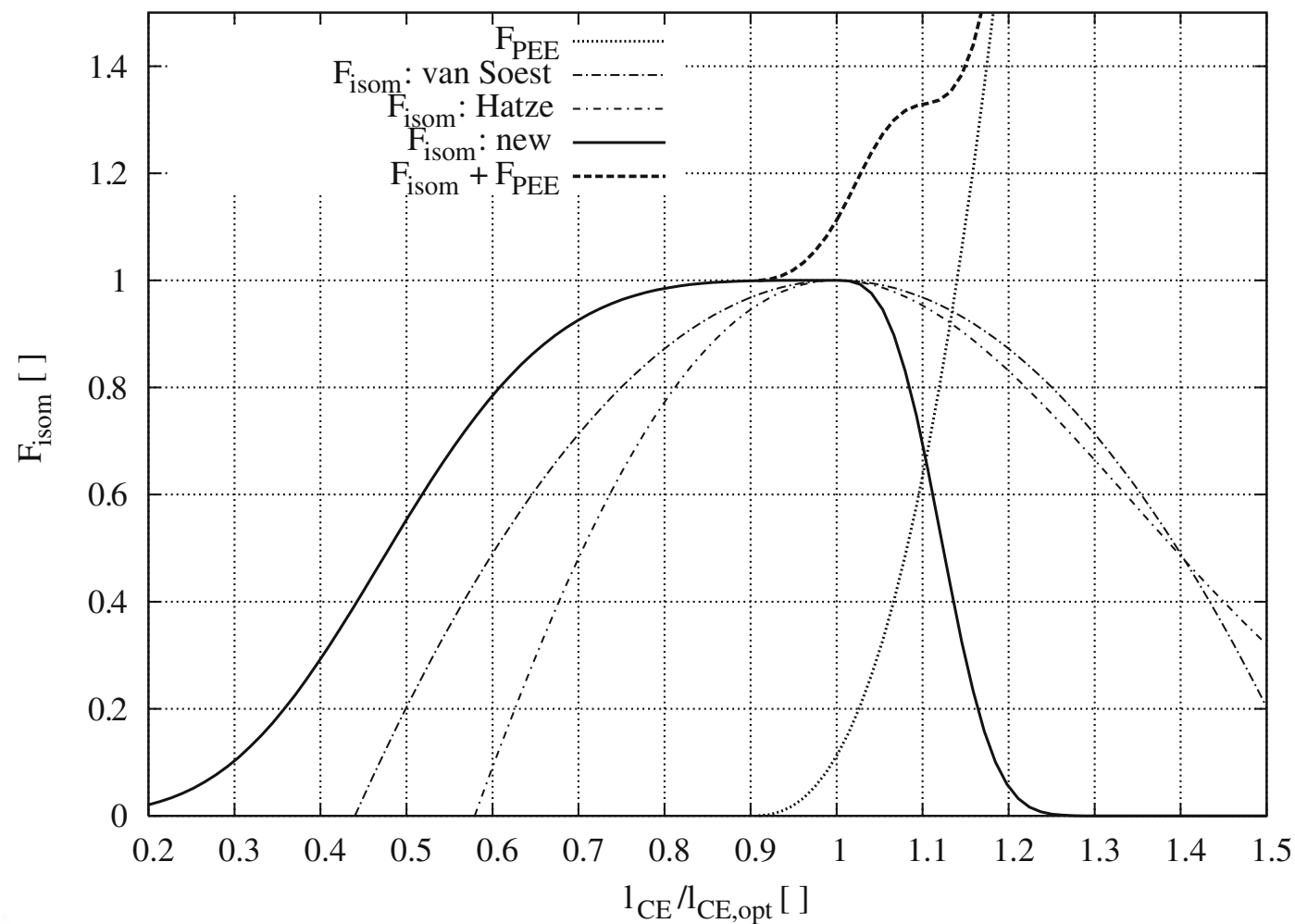
Modellierung des Bindegewebes - PEE

$$F_{\text{PEE}}(l_{\text{CE}}) = \begin{cases} 0, & l_{\text{CE}} < l_{\text{PEE},0} \\ K_{\text{PEE}} (l_{\text{CE}} - l_{\text{PEE},0})^{\nu_{\text{PEE}}}, & l_{\text{CE}} \geq l_{\text{PEE},0} \end{cases} \quad (14)$$

with $K_{\text{PEE}} = \mathcal{F}_{\text{PEE}} \frac{F_{\text{max}}}{(l_{\text{CE,opt}} (\Delta W_{\text{limb=des}} + 1 - \mathcal{L}_{\text{PEE},0}))^{\nu_{\text{PEE}}}}$ and $l_{\text{PEE},0} = \mathcal{L}_{\text{PEE},0} l_{\text{CE,opt}}$ with the three free parameters $\mathcal{F}_{\text{PEE}}$, $\mathcal{L}_{\text{PEE},0}$ and ν_{PEE} (Table 2).

Modellierung der Kraft-Längen-Beziehung

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



Modifizierte Hill-Gleichung

$$F_{SEE} + F_{SDE} = F_{PEE} + F_{CE}$$

Startpunkt Kraftgleichgewicht

$$0 = C_2 \cdot \dot{l}_{CE}^2 + C_1 \cdot \dot{l}_{CE} + C_0$$

Quadratische Gleichung der Kontraktionsgeschwindigkeit

$$\dot{l}_{CE} = \frac{1}{2 \cdot C_2} \cdot \left(-C_1 - \sqrt{C_1^2 - 4 \cdot C_2 \cdot C_0} \right)$$

für konzentrische Kontraktion ($\dot{l}_{CE} \leq 0$)

$$C_2 = d_{SE, \max}(l_{CE}, q) (R_{SE} - A_{rel} (1 - R_{SE}))$$

$$C_1 = -(C_2 \dot{l}_m + D_0 + F_{SEE}(l_m, l_{CE}) - F_{PEE}(l_{CE}) + F_{\max} A_{rel}(l_{CE}, q))$$

$$C_0 = D_0 \dot{l}_m + l_{CE, \text{opt}} B_{rel}(l_{CE}, q) \times (F_{SEE}(l_m, l_{CE}) - F_{PEE}(l_{CE}) - F_{\max} q F_{isom}(l_{CE}))$$

(24)

Kontraktionsdynamik ... aufgestellt!

nach Hill (1938)

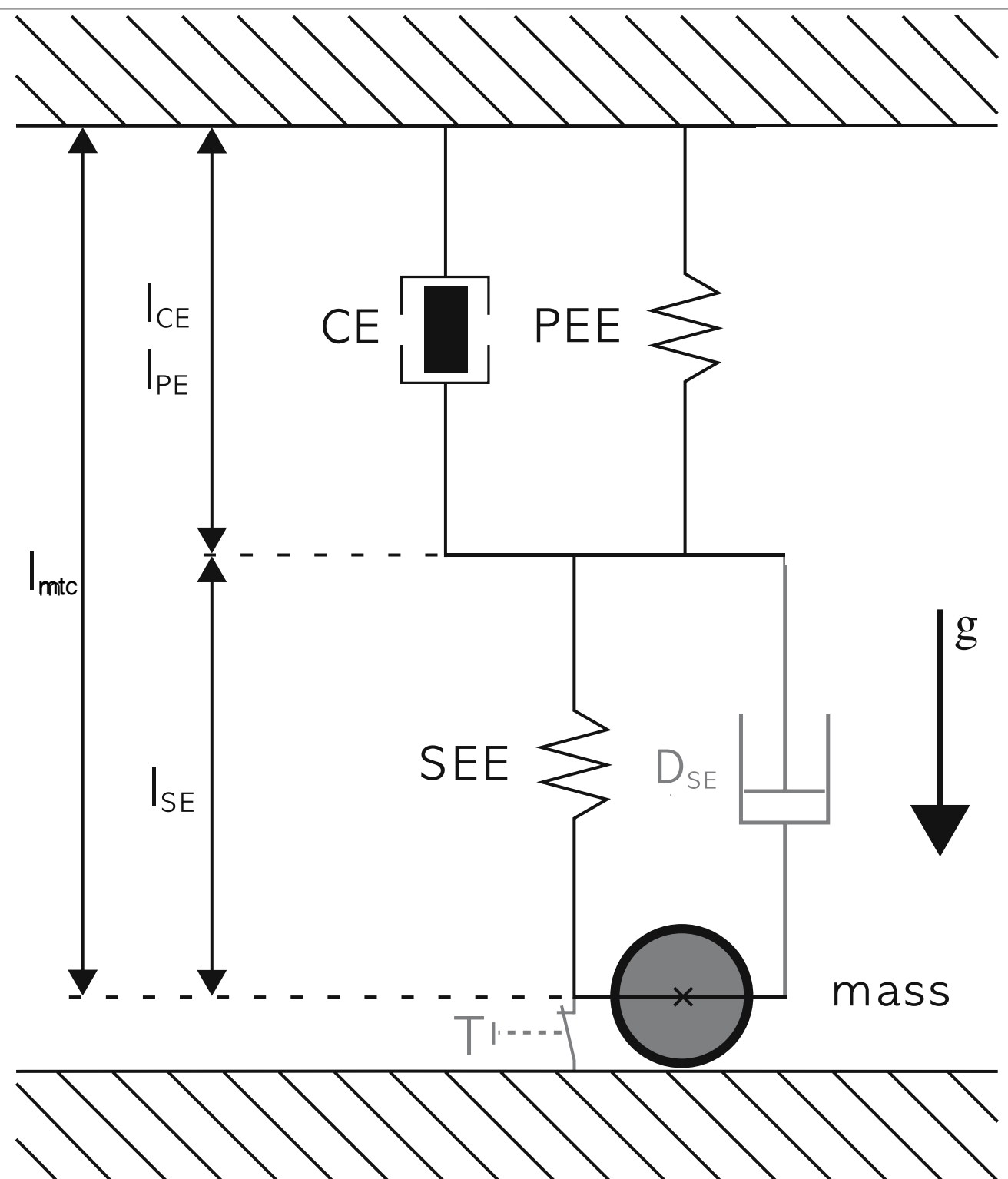
$$F_{mtc} = F_{mtc}(\dot{l}_{mtc})$$

unter Berücksichtigung des
Kraftgleichgewichts

$$F_{SDE}(l_{mtc}, l_{CE}) + F_{SEE}(l_{mtc}, l_{CE}) = F_{PEE}(l_{CE}) + F_{CE}(l_{CE}, \dot{l}_{CE}, q)$$

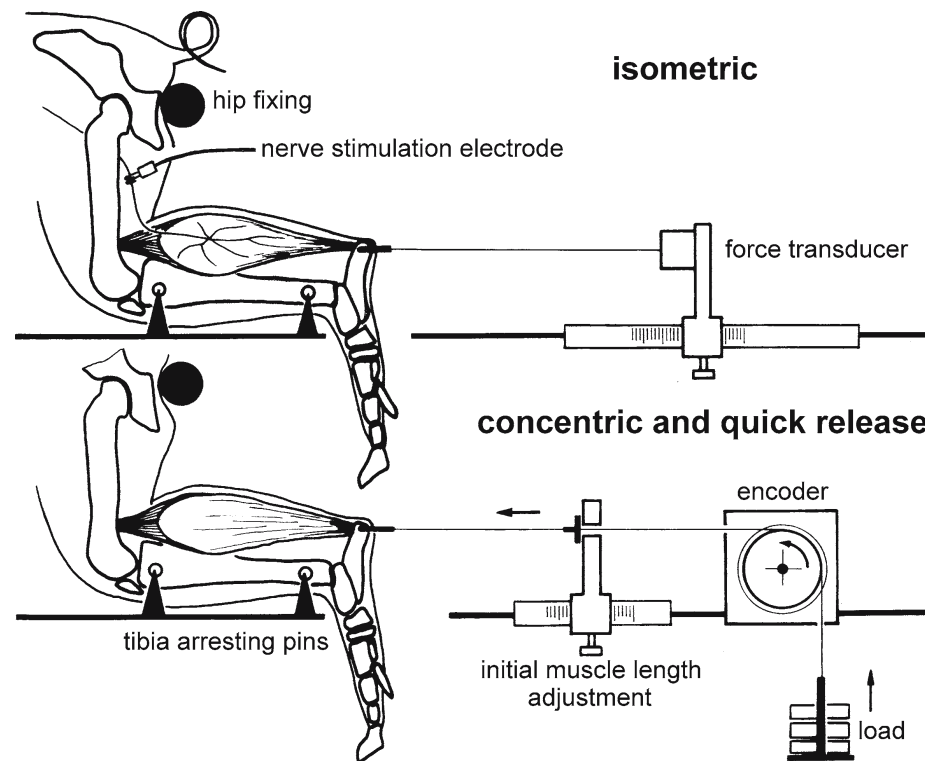
ergibt

$$\dot{l}_{CE} = \dot{l}_{CE}(l_{mtc}, l_{CE}, q)$$

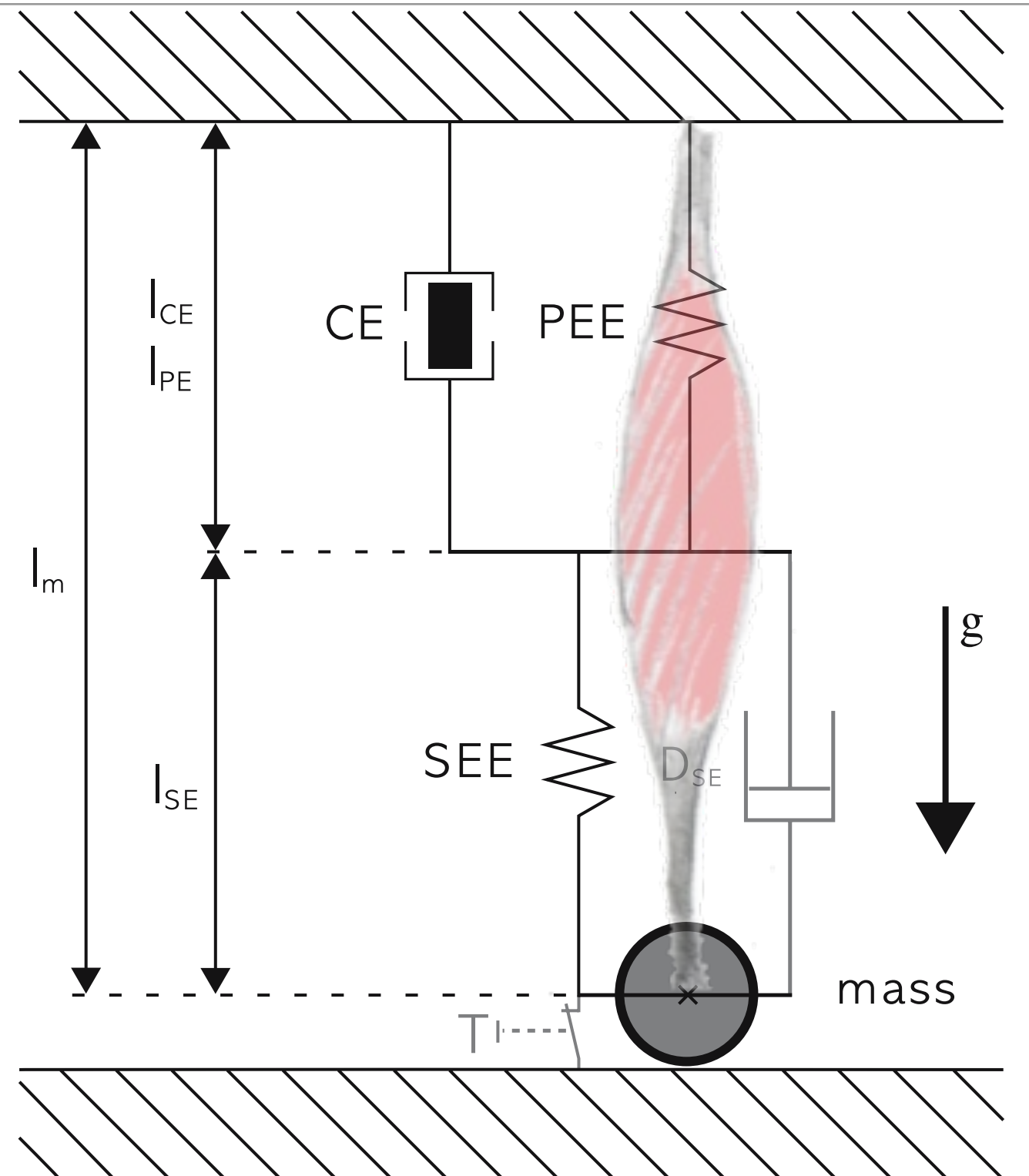


Experimentelle Bestimmung der Parameter

Günther, M, Schmitt, S, Wank, V. (2007)



mass = 100,, 1800 g
g = Graviationsfeld der Erde



Parameter des Muskelmodells

Table 2 Parameters of a lumped model MTC (GL, GM, SOL, FDS; compare Figs. 1, 2, 3) for a 1 day old piglet (body weight: 1,510 g) used in all simulations

Activation dynamics (Zajac)	$\tau_q(s)$ $\frac{1}{40}$	β_q 1.0	q_0 0.0001			
Isometric force	$F_{\max}(N)$ 30.0	$l_{CE,opt}(m)$ 0.015	ΔW_{des} 0.14	$\nu_{CE,des}$ 3.0	ΔW_{asc} 0.57	$\nu_{CE,asc}$ 4.0
Contraction dynamics (concentric: Hill) ^a	$A_{rel,0}$ 0.1	$B_{rel,0}(\frac{1}{s})$ 1.0				
Contraction dynamics (eccentric: van Soest)	S_{ecc} 2.0	$\mathcal{F}_{ecc}$ 1.8				
Parallel elastic element ^b	$\mathcal{L}_{PEE,0}$ 0.9	ν_{PEE} 2.5	$\mathcal{F}_{PEE}$ 1.0			
Serial elastic element ^c	$l_{SEE,0}(m)$ 0.045	$\Delta U_{SEE,nll}$ 0.1825	$\Delta U_{SEE,l}$ 0.073	$\Delta F_{SEE,0}(N)$ 60.0		
Damping parameters	$d_{PE}(Ns/m)$ 6.0	$d_{SE}(Ns/m)$ 6.0	D_{SE} 0.3	R_{SE} 0.01		

Dependent parameters:

^a $v_{\max,0} = \frac{B_{rel,0}}{A_{rel,0}} l_{CE,opt} = 0.15 \text{ m/s}$

^b $K_{PEE,nl} = 3.86 \times 10^7 \text{ N/m}^{2.5}$

^c $\nu_{SEE} = 2.5$, $K_{SEE,nl} = 9.82 \times 10^6 \text{ N/m}^{2.5}$, $K_{SEE,l}(30 \text{ N}) = 1.20 \times 10^4 \text{ N/m}$, $\Delta U_{SEE}(30 \text{ N}) = 0.138$

Vergleich Simulation und Experiment

Günther, M, Schmitt, S, Wank, V. (2007)

