



Laboratoire
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Le muscle un système rétroagit: vers une approche thermodynamique de la réponse force- vitesse

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Comparaison bio-inspirée

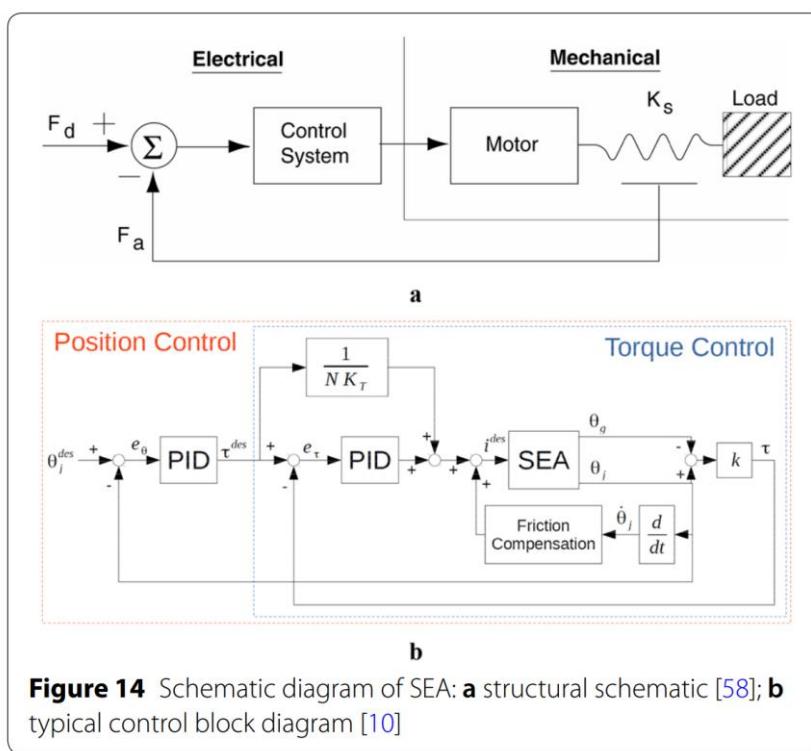
REVIEW

Open Access

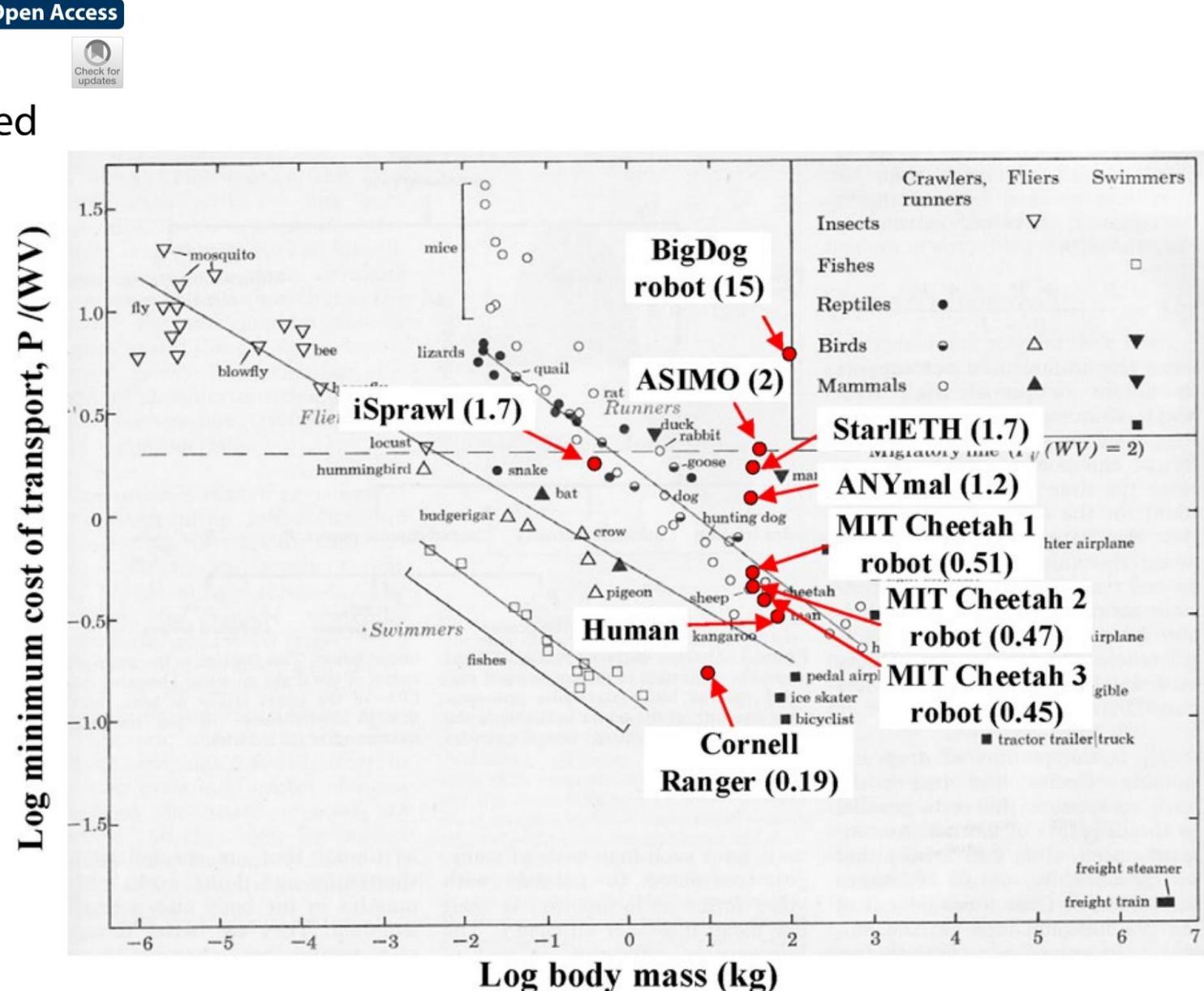


Mechanism, Actuation, Perception, and Control of Highly Dynamic Multilegged Robots: A Review

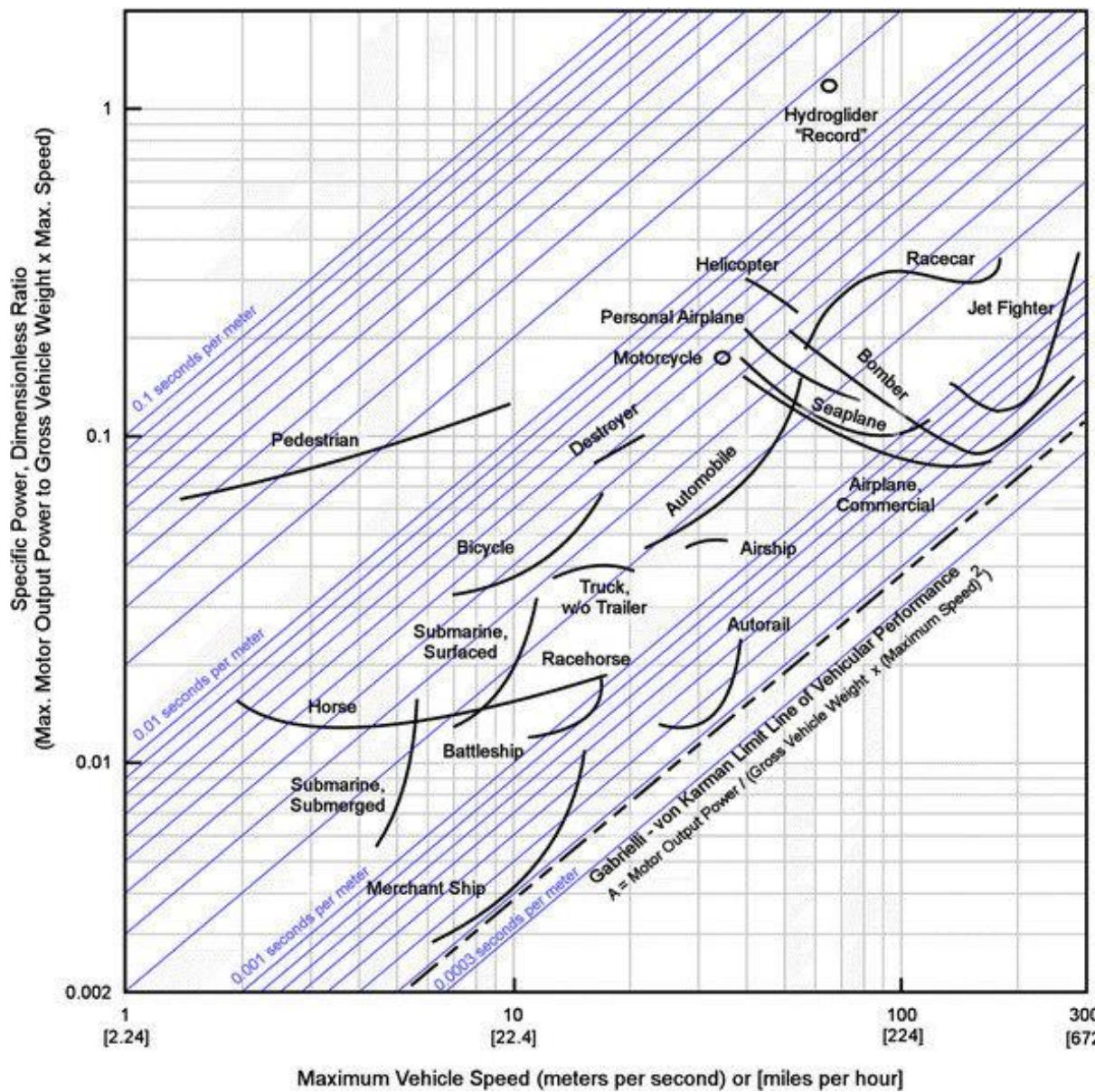
Jun He and Feng Gao*



Serial elastic actuation (SEA)

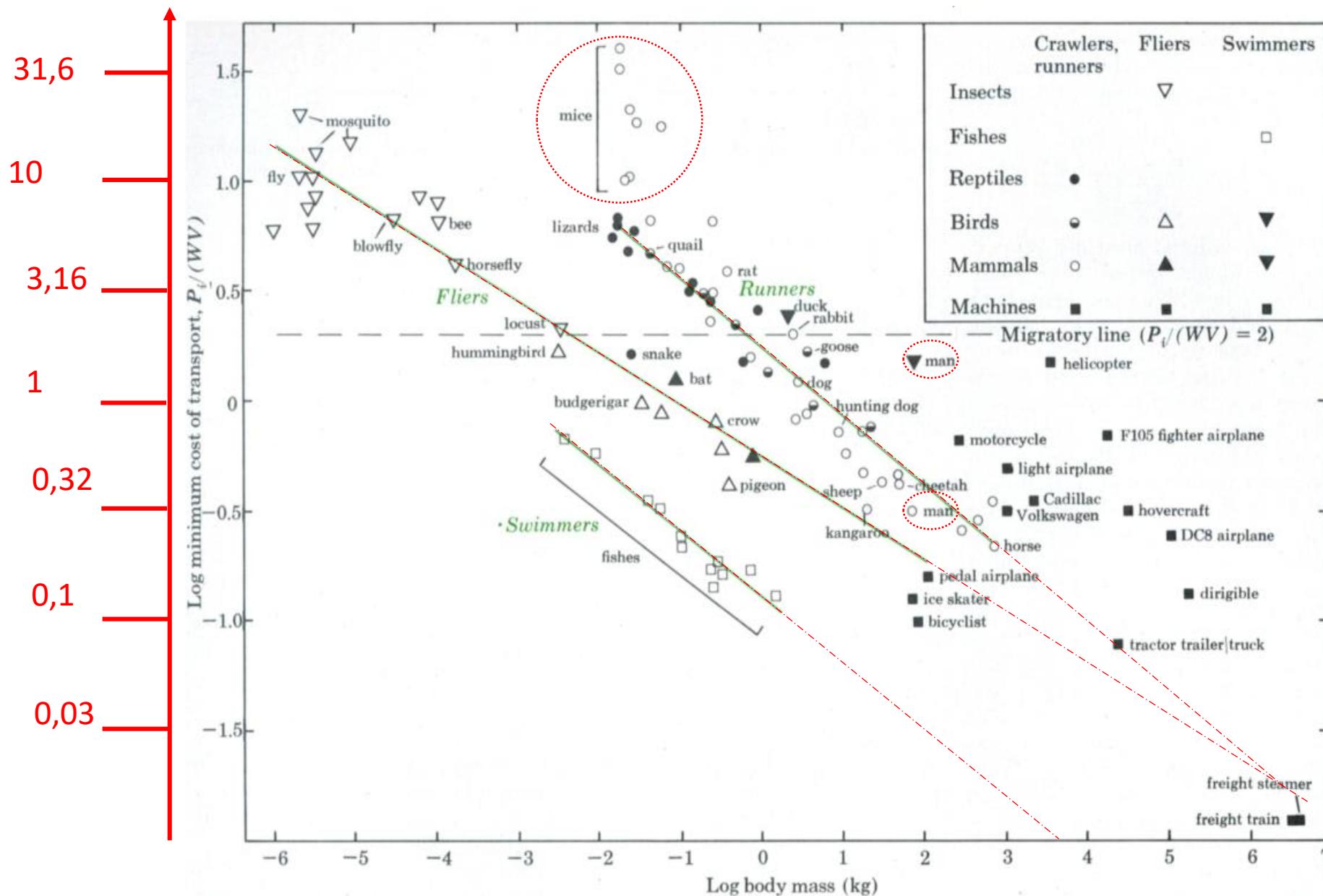


von Kármán–Gabrielli diagram



$$COT = \frac{P}{mgV}$$

Historical reference



V. A. Tucker

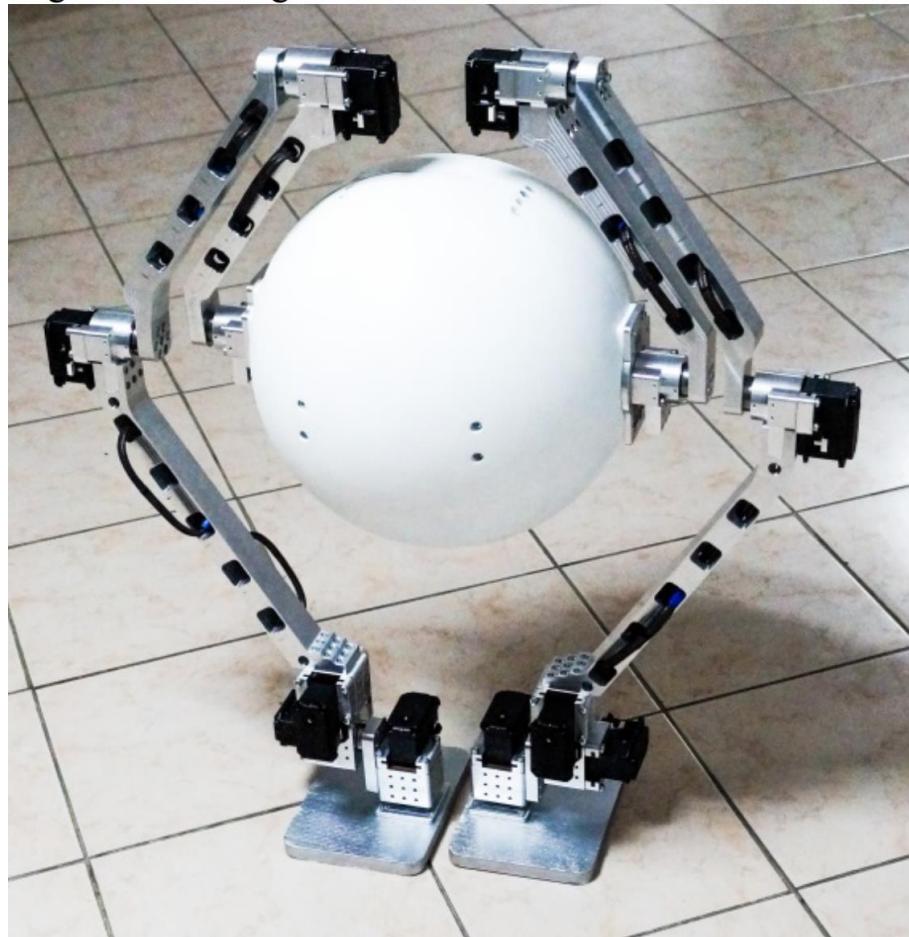
Energetic Cost of Moving About

ig and running are extremely inefficient if locomotion. Much greater efficiency is ed by birds, fish—and bicyclists

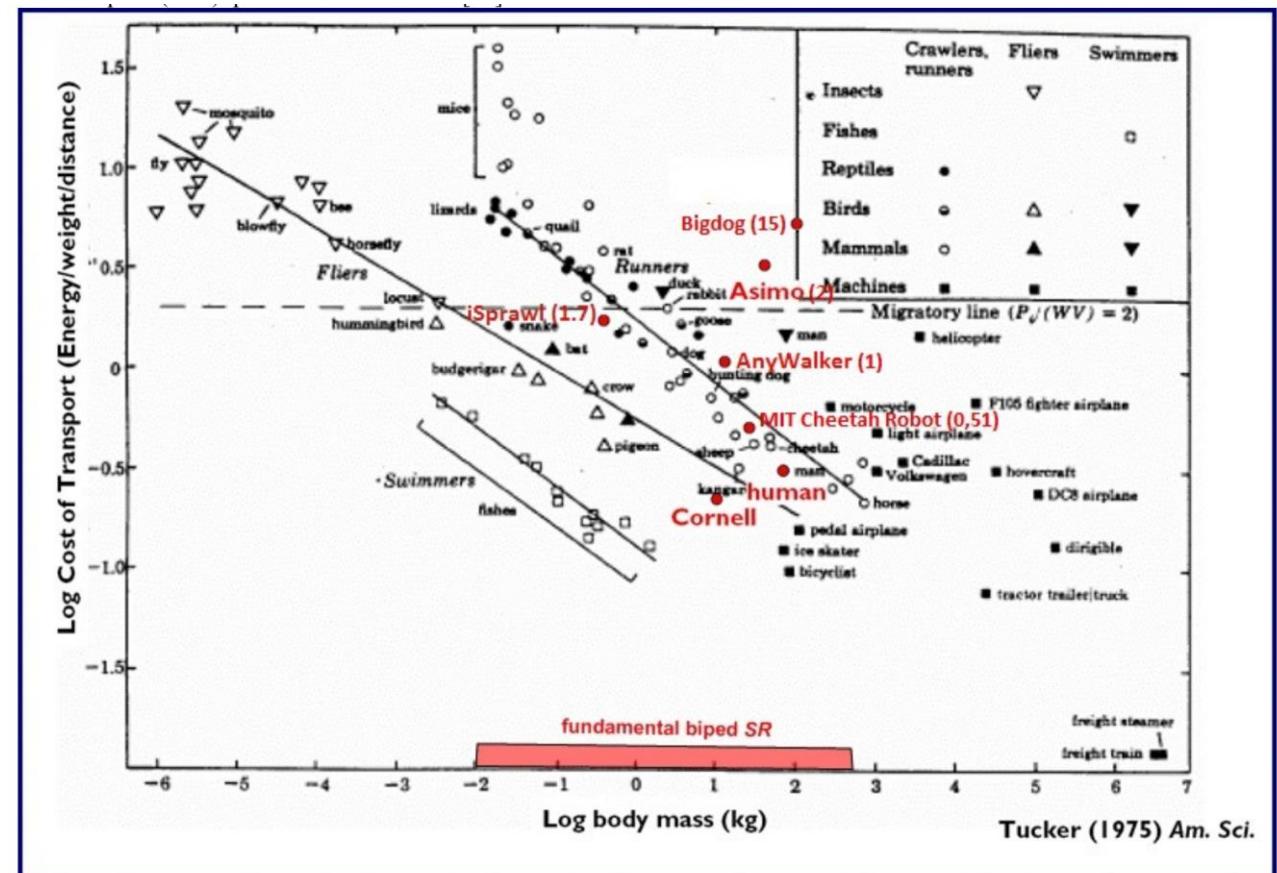
Stabilization System of a Bipedal non-anthropomorphic Robot AnyWalker

I. Ryadchikov¹, S. Sechenev¹, M. Drobotenko¹, A. Svidlov¹, P. Volkodav¹, R. Vishnykov¹, D. Sokolov²
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Received 20 November 2017; Accepted 22 November 2018



Walk



Design Principles for Energy Efficient Legged Locomotion and Implementation on the MIT Cheetah Robot

Sangok Seok¹, Albert Wang¹, Meng Yee (Michael) Chuah¹, Dong Jin Hyun¹, Jongwoo Lee¹, David Otten², Jeffrey Lang², and Sangbae Kim¹

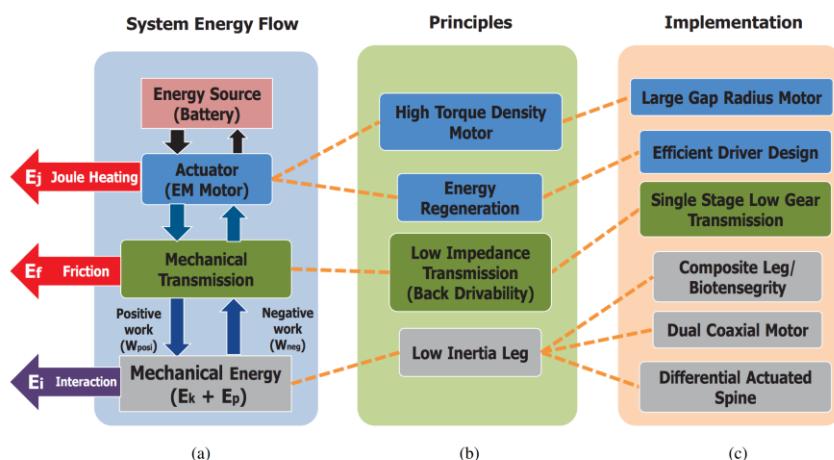
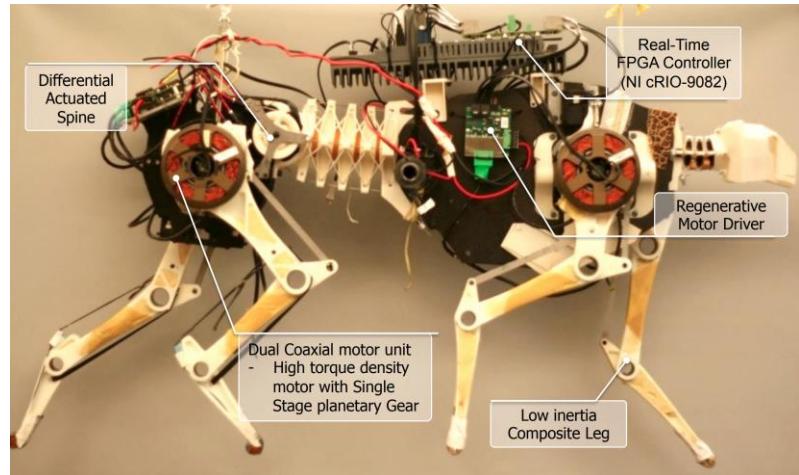


Fig. 2: (a) Energy flow diagram of the robot showing energy flows between the source and mechanical energy. Joule heating loss occurs at the motor, friction loss occurs in the mechanical transmission and interaction loss reduces the total mechanical energy. (b) Design principles to improve efficiency at the sources of energy loss. (c) Strategies for implementing the design principles for efficiency used on the MIT Cheetah Robot.

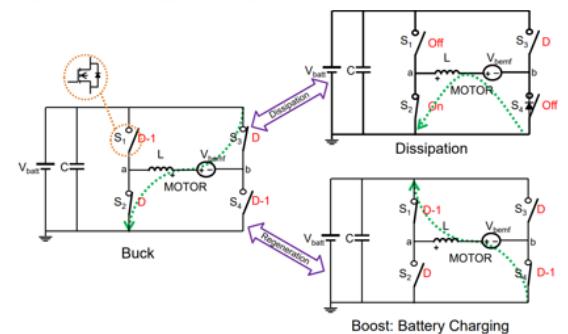
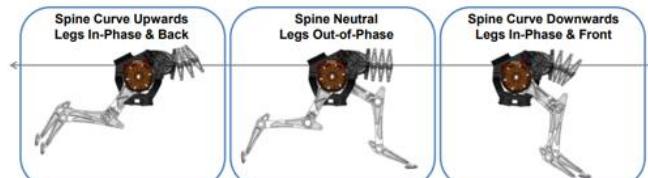
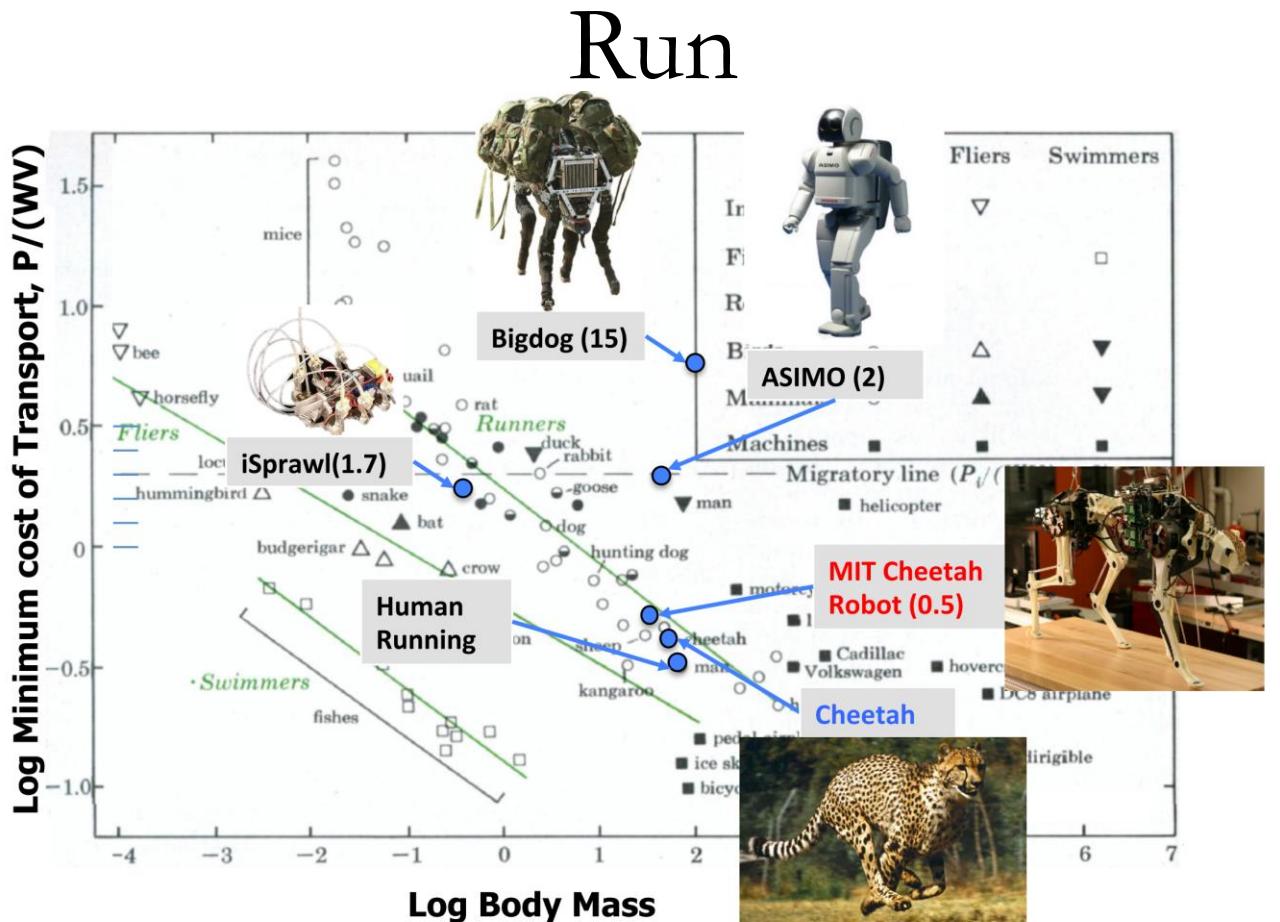
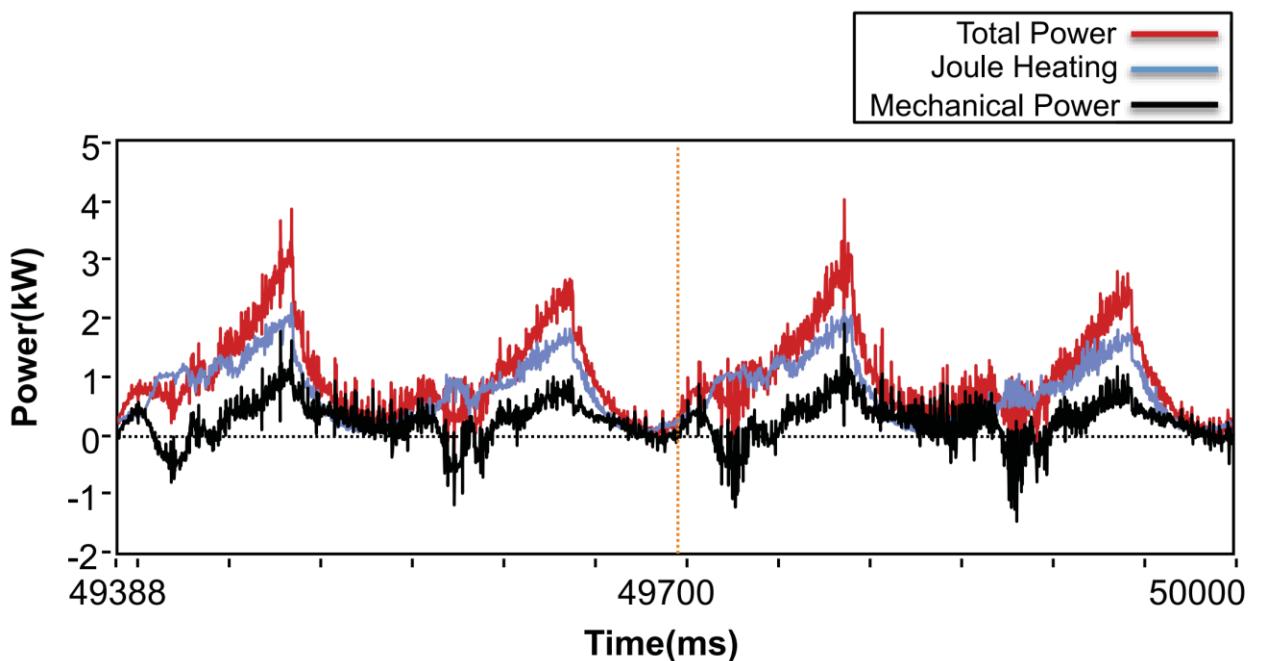
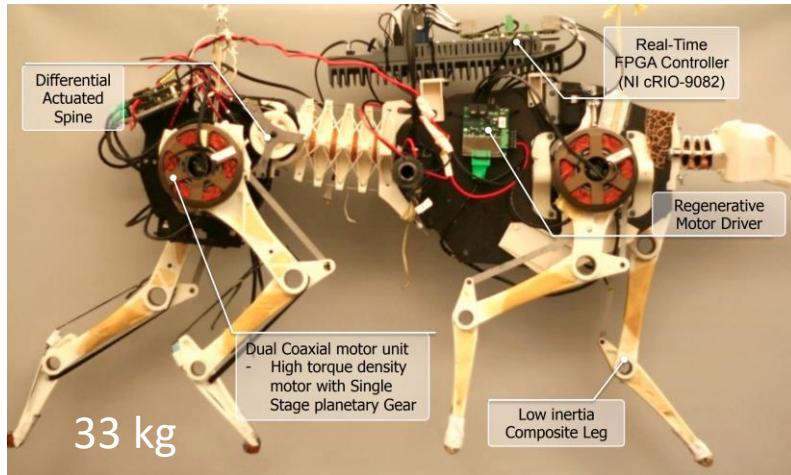
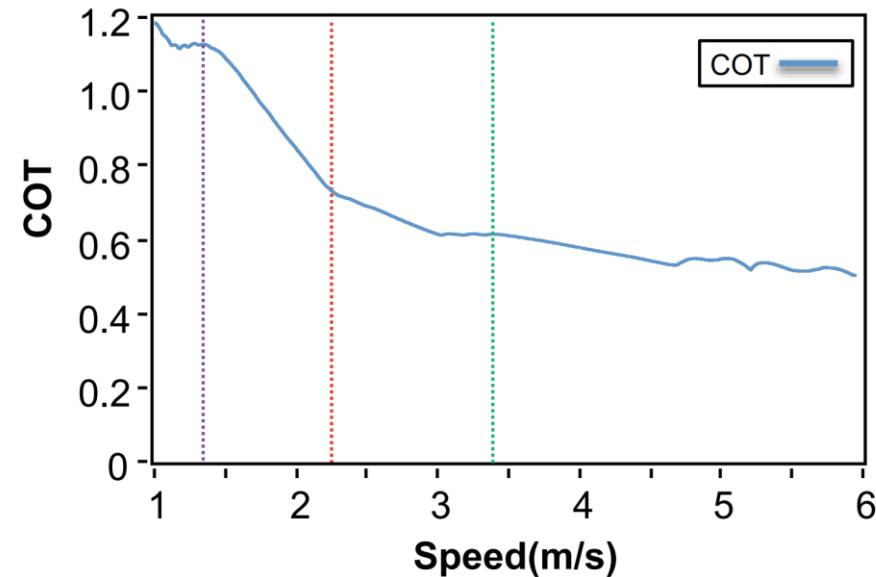


Fig. 6: Energy flow in a Bidirectional Buck Boost Converter.

COT study



Total Power	Joule Heating	Mechanical Power	COT	with 3 Kg Battery (465 Whrs)	
				Running Time	Distance
973 W	739 W (76%)	234 W (24%)	0.5	0.48 Hrs	10.3 km
		Positive 292 W	Negative -58 W		



Minimal COT... minimal range of application

ENERGY-EFFICIENT, DYNAMIC WALKING ROBOT

Pranav A. Bhounsule, Jason Cortell and Andy Ruina

*Biorobotics and Locomotion Laboratory,
306 Kimball Hall, Cornell University,
Ithaca, NY 14853, USA*

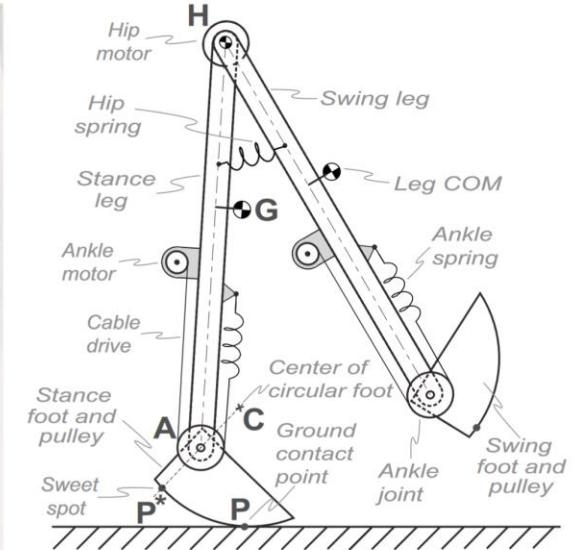
E-mail: pab47@disneyresearch.com, jbc2@cornell.edu, ruina@cornell.edu

We present the design and control of an energy-efficient, knee-less, essentially planar, four-legged bipedal robot called Ranger. In separate trials, Ranger: 1) walked a 40.5 mile ultra-marathon on a single charge and without human touch, setting a robot distance record; and 2) walked stably at Total Cost Of Transport (TCOT= total energy used per unit weight per unit distance travelled) of 0.19, apparently less than that of any other legged robot to date. Key design features are: a light weight and high strength box body, low-inertia leg design for fast and efficient swing, foot actuation that combines toe-off and ground clearance, a steering mechanism that enables turning of this essentially planar robot, and a low-power modular networked electronics hardware system. The model-based control approach uses a simplified offline trajectory optimization with a reflex-based feedback controller for stabilization. Ranger's reasonable success suggests that these design and control ideas could be extended to the development of an energy-efficient higher degree of freedom, 3-D bipedal robot.

a) Robot



b) Schematic



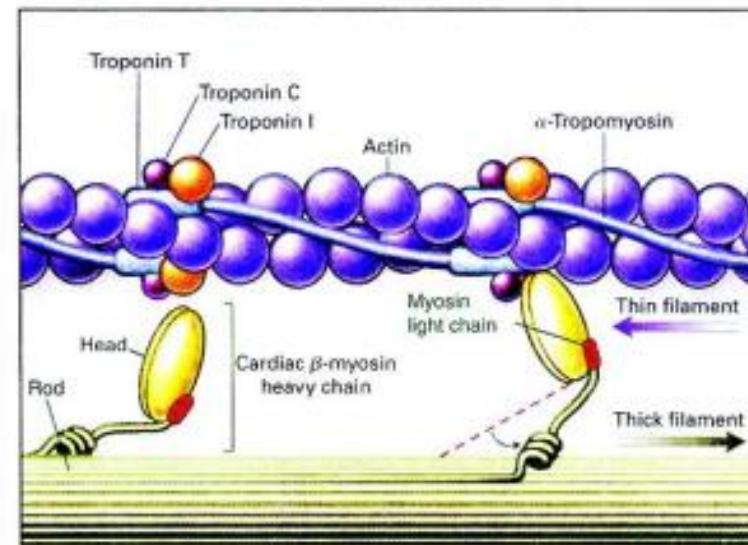
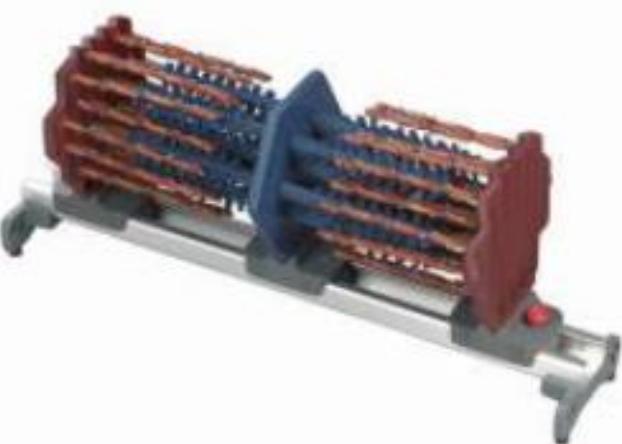
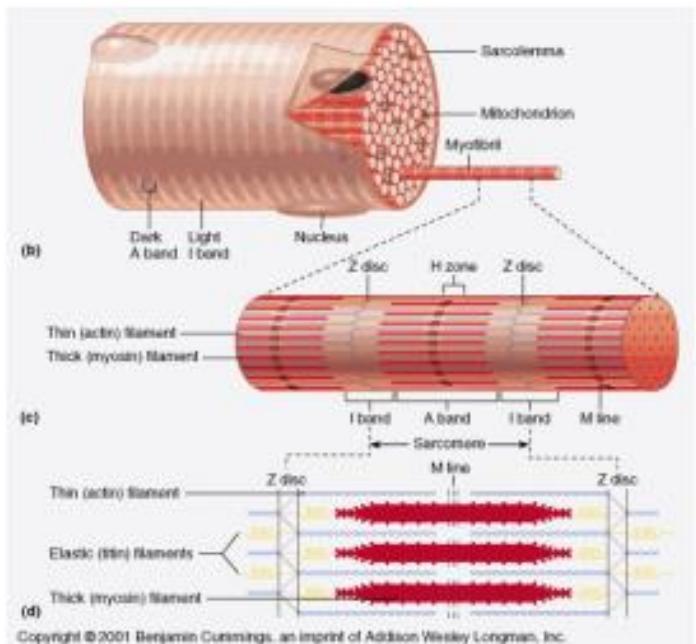
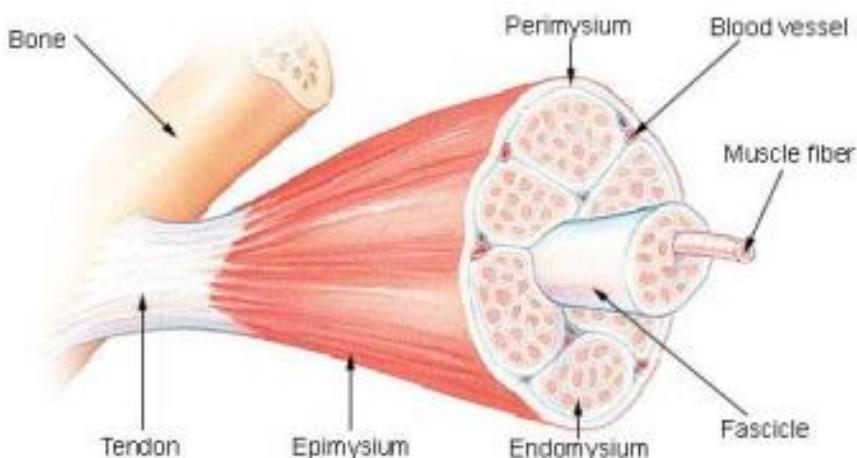
Gait Parameter	Fine-grid	Coarse-grid	Experiment
Total COT	0.167	0.180	0.190
Motor COT	0.087	0.100	0.110
Overhead COT	0.083	0.080	0.080
Hip COT	0.019	0.018	0.030
Ankle COT (push-off)	0.029	0.052	0.046
Ankle COT (foot-flip)	0.039	0.029	0.034
Step Length	0.38	0.39	0.38
Step Velocity	0.64	0.66	0.62
Step Time	0.60	0.60	0.61
Double Stance (%)	9.5	5.0	3.0
Control Parameters	126	15	30

The question of the muscle description

THE Muscle

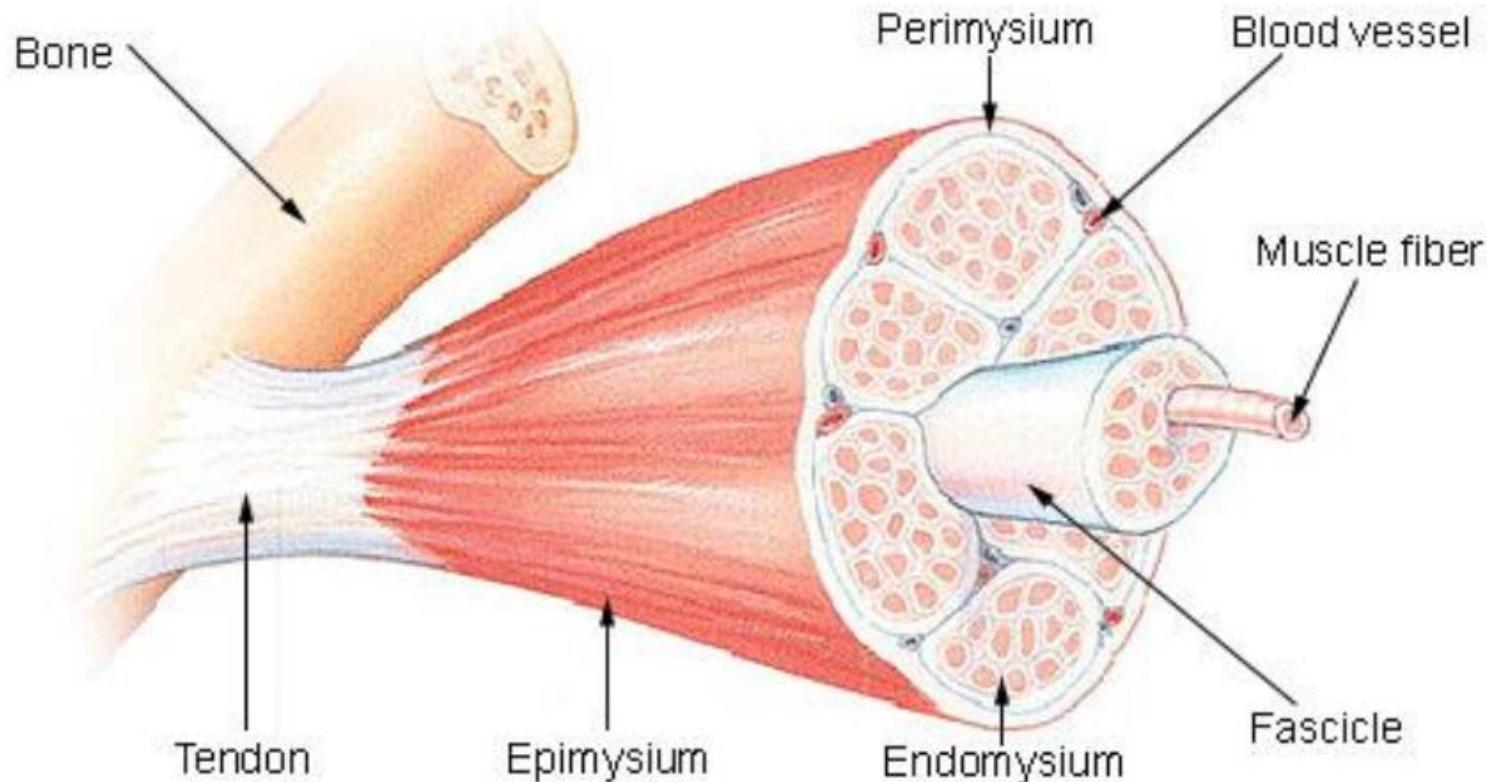


Structure of a Skeletal Muscle



... Where does variable stiffness comes from?

Structure of a Skeletal Muscle



What do we learn?

1. Hierarchical scale
2. Multiple materials
3. Various Stiffness
4. Non-linear?
5. Serial & parallel
6. Mixed boundary conditions
7. Active & passive zones

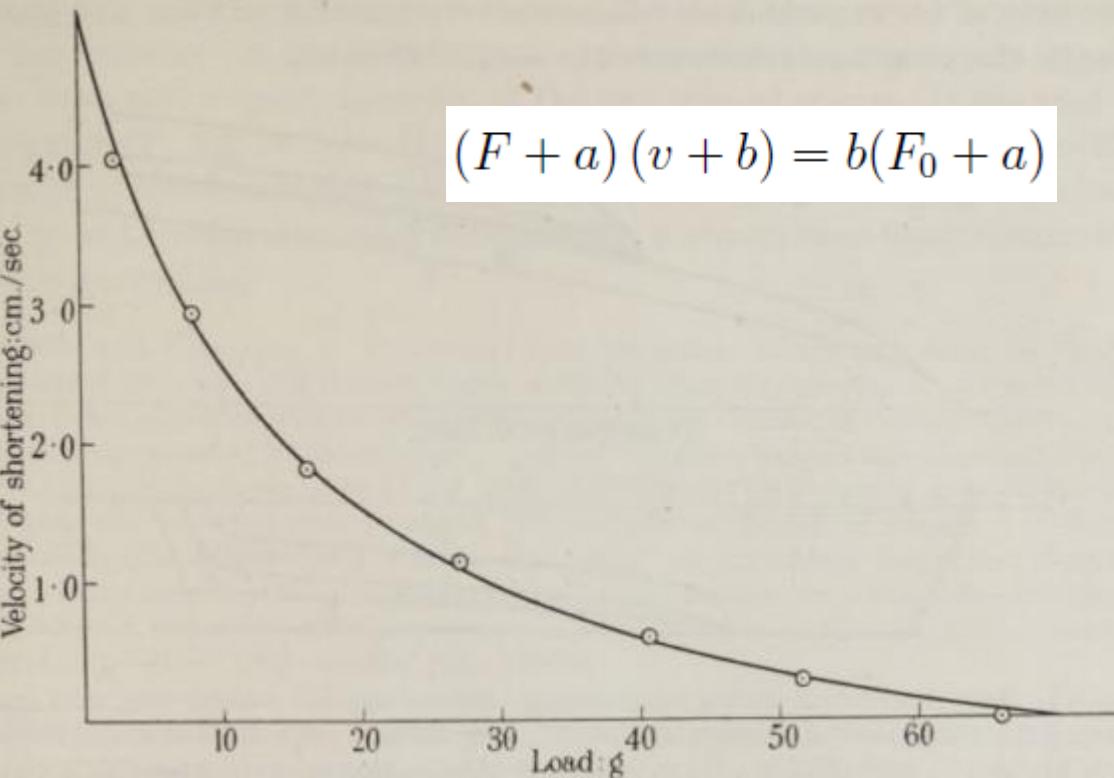
Hill's model

The heat of shortening and the dynamic constants of muscle

By A. V. HILL, SEC. R.S.

*From the Section of Biophysics, Department of Physiology,
University College, London*

(Received 3 August 1938)



$$E = A + H + W$$

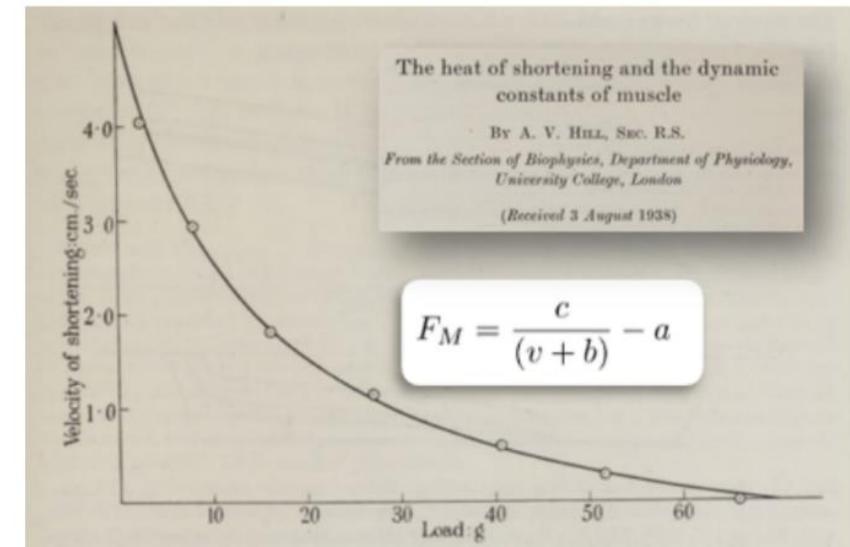
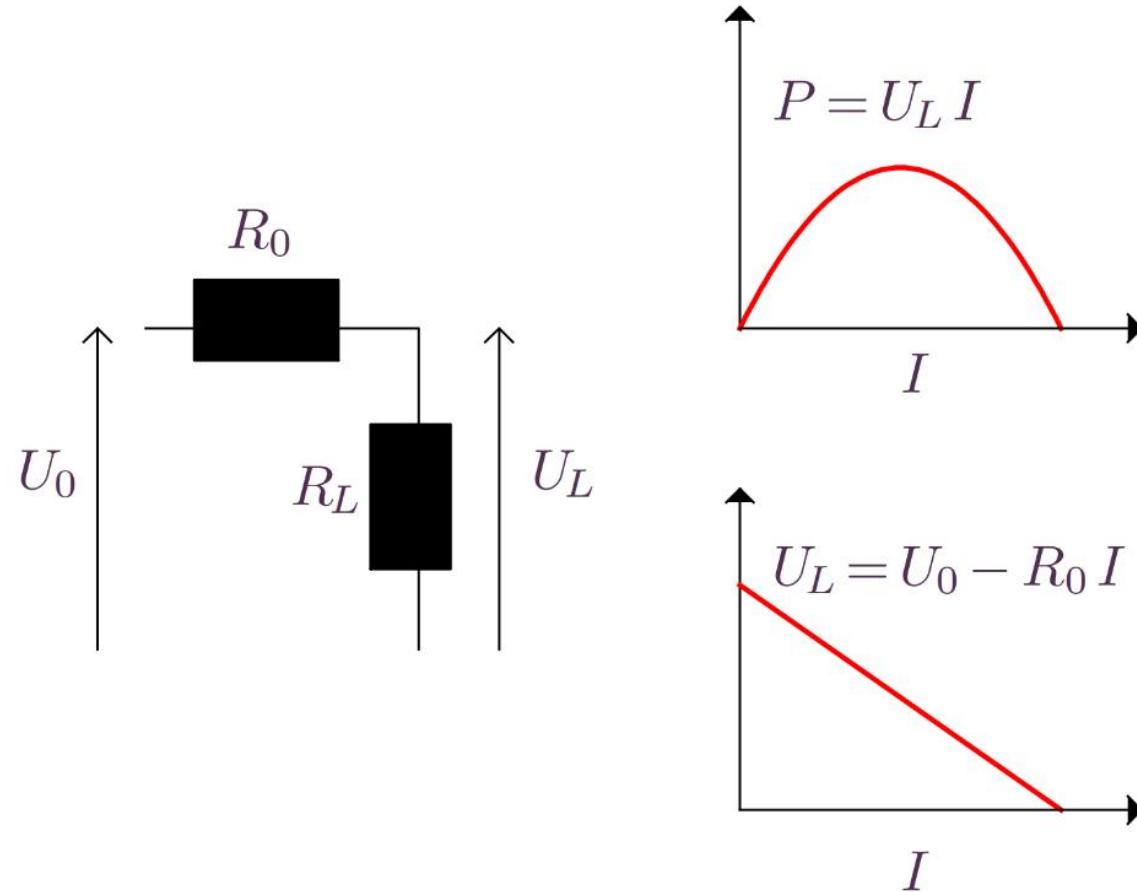
$$W = Fv$$

$$H + W = b(F_0 - F)$$

$$H = av$$

De facto variable impedance

⇒ Power generated $P = UI$ (DC generator) or $P = Fv$ (mechanic)



⇒ Feedback on Effective force U_L , due to the energy conversion process.

Muscle models

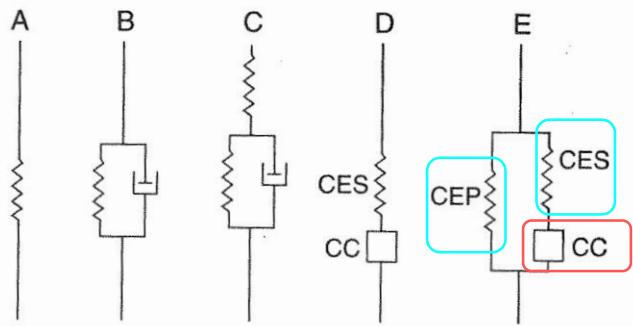


Fig. 2.1. Évolution des modèles de muscles.

(A) Weber, 1846; (B) A.V. Hill, 1922; (C) Levin et Wyman, 1927; (D) A.V. Hill, 1938
(E) A.V. Hill, 1951.

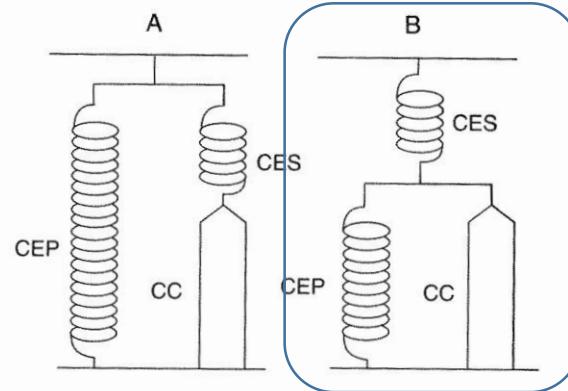
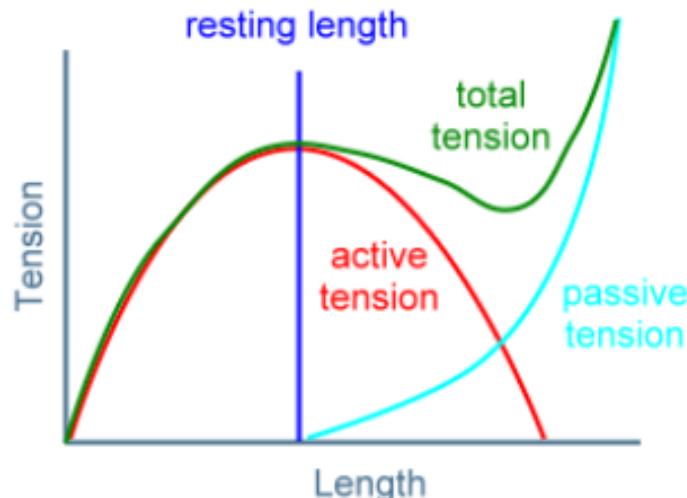


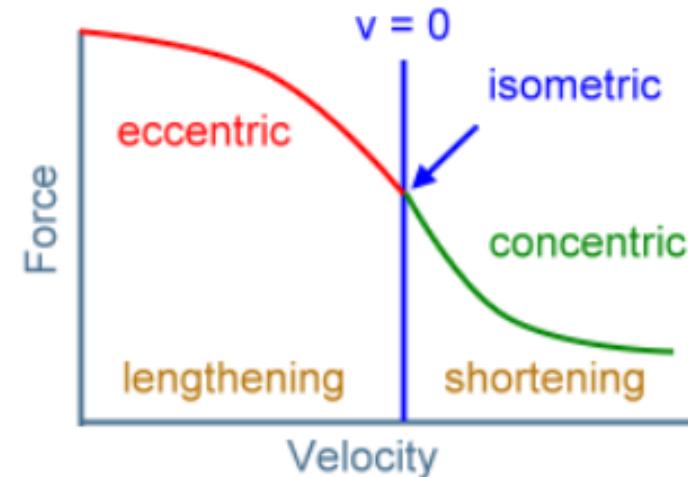
Fig. 2.2. Modèles à trois composantes.

(A) Modèle de A.V. Hill (1951), analogue au modèle rhéologique de Maxwell.
(B) Modèle d'Aubert (1956), analogue au modèle rhéologique de Voigt.

Force-length relationship



Force-velocity relationship



« In the world of hammers anything that is not a hammer is either a nail or an anvil. »

A mathematical analysis of the force-stiffness characteristics of muscles in control of a single joint system *

Reza Shadmehr and Michael A. Arbib

Center for Neural Engineering, University of Southern California, Los Angeles, CA 90089, USA

Received February 15, 1991/Accepted December 9, 1991

$$\frac{d\phi}{dt} = \frac{K_{SE}}{B} \left(K_{PE} \Delta \lambda + B \frac{d\lambda}{dt} - \left(1 + \frac{K_{PE}}{K_{SE}} \right) \phi + P(\lambda, f(t)) \right)$$

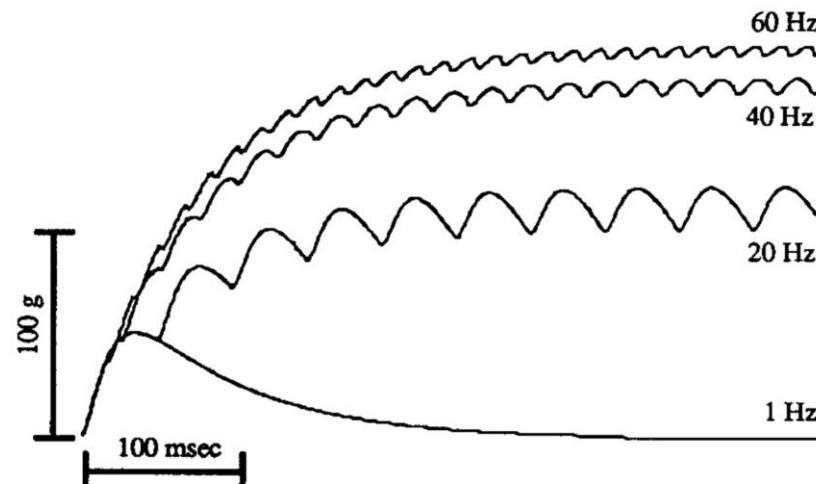


Fig. 9. Force in the active state muscle model of Fig. 8 at resting for a series unit impulses at various frequencies

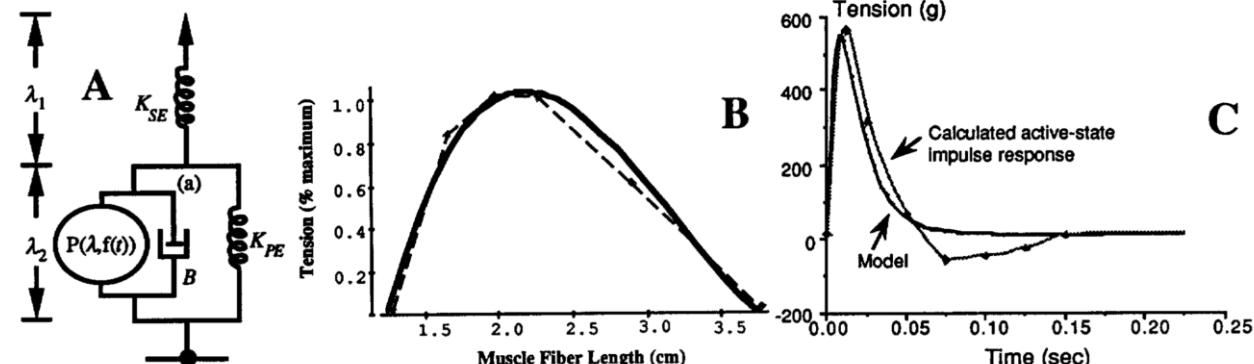


Fig. 8A-C. An active state muscle model. **A** The mechanical model of the muscle: λ_1 and λ_2 are taken as the displacement about the resting length, while $P(\lambda, f(t))$ is the active tension developed by the force generator. **B** Active tension vs. length for a single fiber of frog semitendinosus muscle (dashed line and data points from Gordon et al. 1966). This function was approximated by a third order polynomial: $S(\lambda) = -6.3 + 8.1\lambda - 2.9\lambda^2 + 0.3\lambda^3$. **C** The estimated impulse response of the active state component of the frog gastrocnemius muscle (redrawn from Inbar and Adam 1976), and the model approximation: $h(t) = 1200(\exp(-70t) - \exp(-210t))$

et al. 1966). This function was approximated by a third order polynomial: $S(\lambda) = -6.3 + 8.1\lambda - 2.9\lambda^2 + 0.3\lambda^3$. **C** The estimated impulse response of the active state component of the frog gastrocnemius muscle (redrawn from Inbar and Adam 1976), and the model approximation: $h(t) = 1200(\exp(-70t) - \exp(-210t))$

Distribution of dynamic fibre effects.
...one story among many,
... a multi-scale spatio-temporal problem
...Good luck!

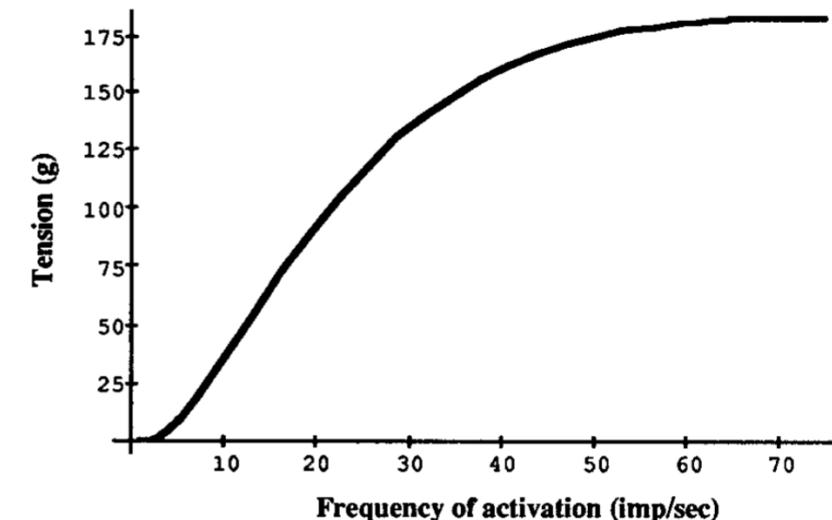
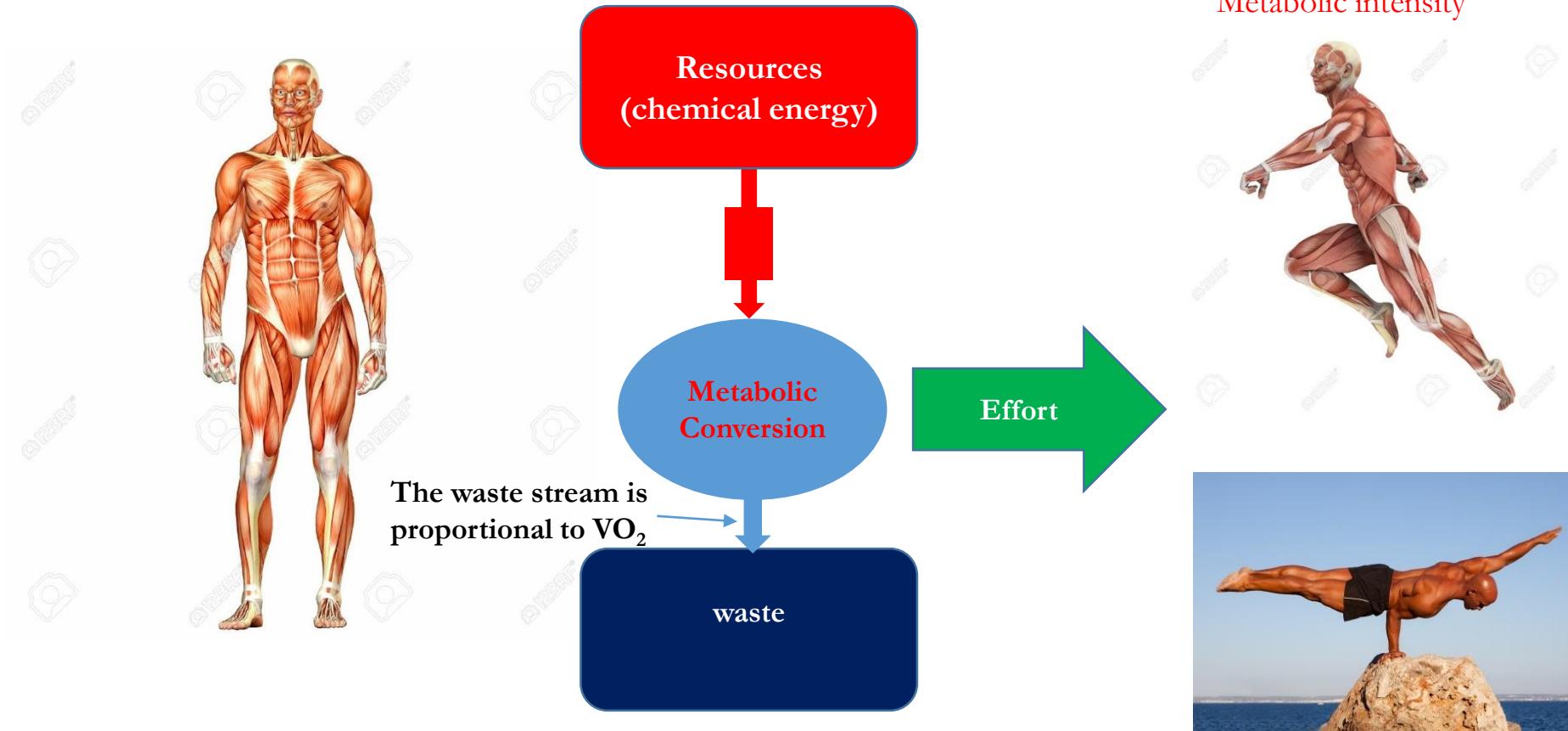


Fig. 10. Steady state tension output of the muscle model at $\lambda = \lambda^*$, i.e., length beyond which passive force develops

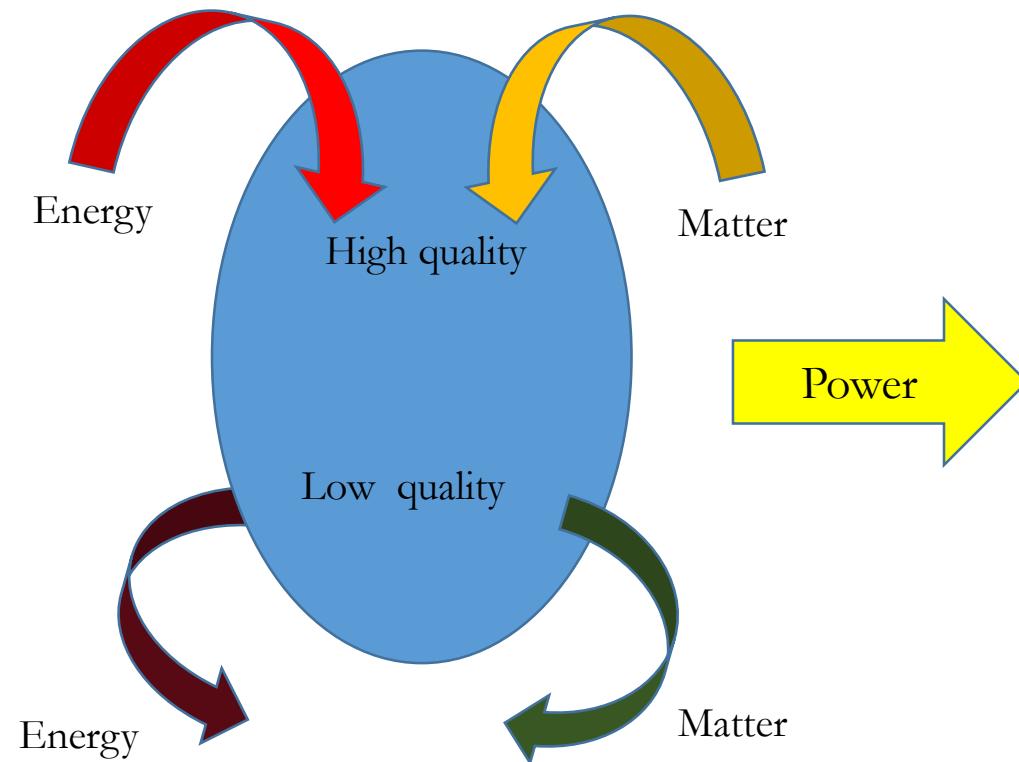
Back to the System: Need for a metabolic model of muscle under various efforts

Caution: effort does not mean
not just movement:
Metabolic intensity



Towards a thermodynamic model of the muscle

Thermodynamic system: Energy-Matter coupling



Conservation of the quantities: First Thermodynamic law (conservation)

Modification of the qualities : Second Thermodynamic law (dispersion)

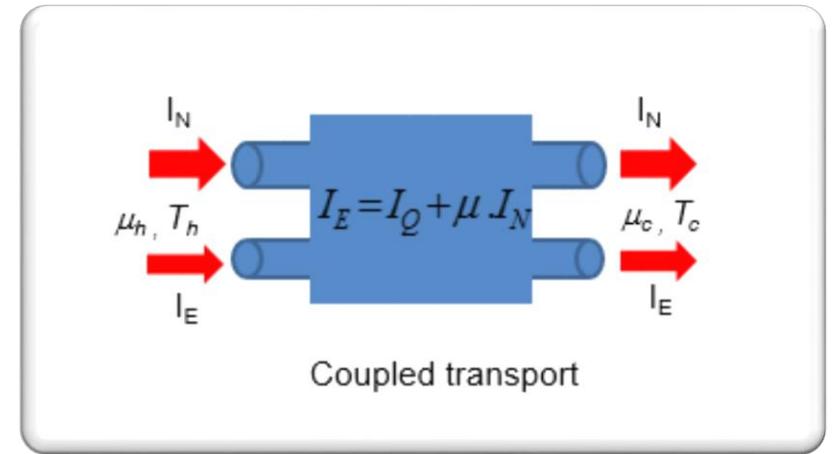
Energy and material flows

Force / Flux metabolism (with $J_{E_m} = \Pi_m J_m$):

$$\begin{pmatrix} J_M \\ J_{E_m} \end{pmatrix} = \begin{pmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{pmatrix} \begin{pmatrix} -\frac{1}{\Pi_m} \nabla \Pi_M \\ \nabla(1/\Pi_m) \end{pmatrix}$$

1. In 1 D,
2. With 2 coupled flows: Onsager reciprocity $L_{12} = L_{21}$ (Lechatelier-Braun)
3. The driving force $F_M = -\nabla \Pi_M$
4. The microscopic potentiel $\Pi_m = \mu$

$$\begin{pmatrix} J_M \\ J_{E_m} \end{pmatrix} = \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix} \begin{pmatrix} \frac{1}{\mu} F_M \\ -\frac{1}{\mu^2} \frac{d\mu}{dx} \end{pmatrix}$$



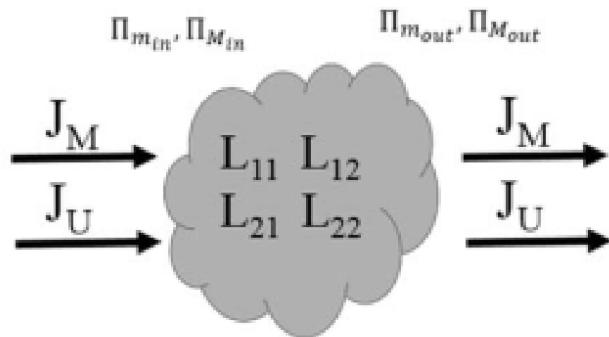
The 3 parameters L_{ij} are related to conductivities and coupling coefficient

coupling coefficient

Onsager description

1. Generalized form of $du = T ds - p dv$:

$$du = \Pi_m dm + \Pi_M dM, \text{ with}$$

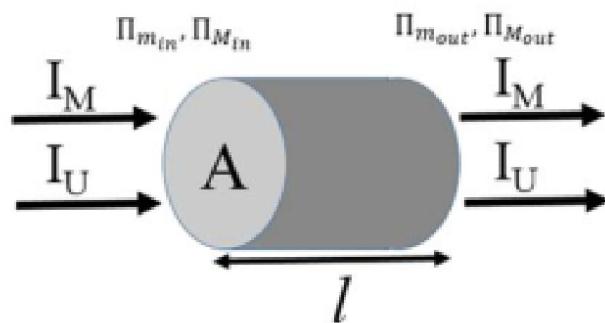


a. Π_m, Π_M the **intensive** variables

b. m, M the **extensive** variables

c. $\Pi_m dm$ generic expression for **diluted** energy

d. $\Pi_M dM$ generic expression for **aggregated** energy



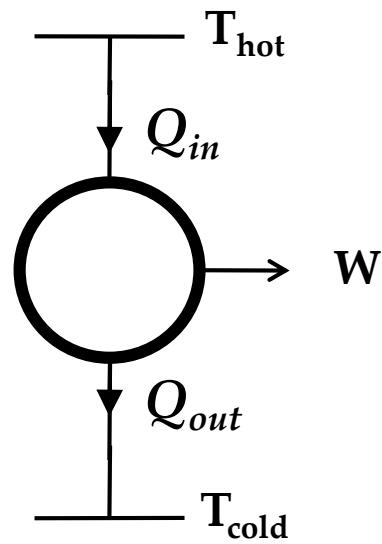
2. Coupling coefficient $\alpha = \left(\frac{\partial \Pi_M}{\partial \Pi_m} \right)_M$

3. Out of equilibrium description: force / flux formalism:

Extension of the Gibbs relation

$$J_U = \Pi_m J_m + \Pi_M J_M$$

How to connect a thermodynamic (or other) system?



$$\eta_C = \frac{W}{Q_{in}} = 1 - \frac{T_{cold}}{T_{hot}}$$

BUT infinite time...



No power

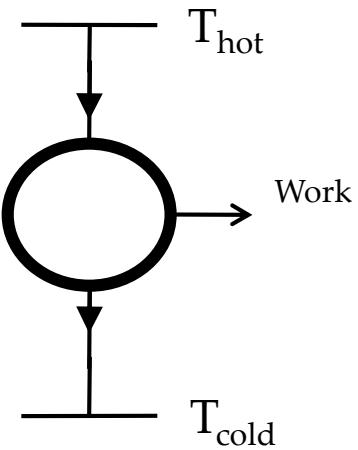
Why ?

Reversible also means acausal. No defined startup conditions!

Solution ?

Modification of the boundary conditions.

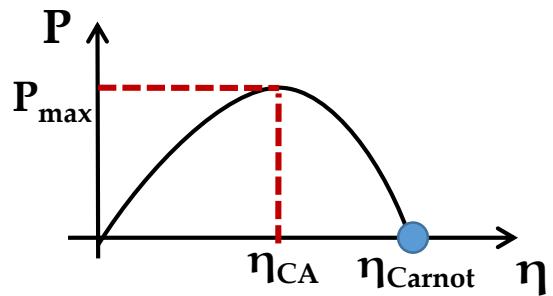
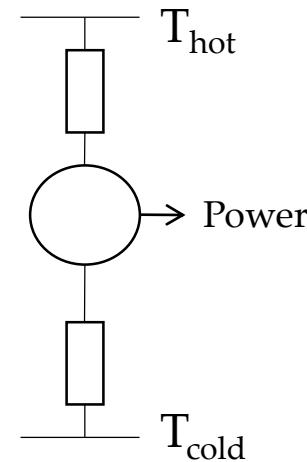
The endoreversible solution



$$\eta_C = \frac{W}{Q_{in}} = 1 - \frac{T_{cold}}{T_{hot}}$$

Finite Time
Thermodynamics
FTT

Endoreversible



$$\eta_{CA} = \frac{\dot{W}}{\dot{Q}_{in}} = 1 - \sqrt{\frac{T_{cold}}{T_{hot}}}$$

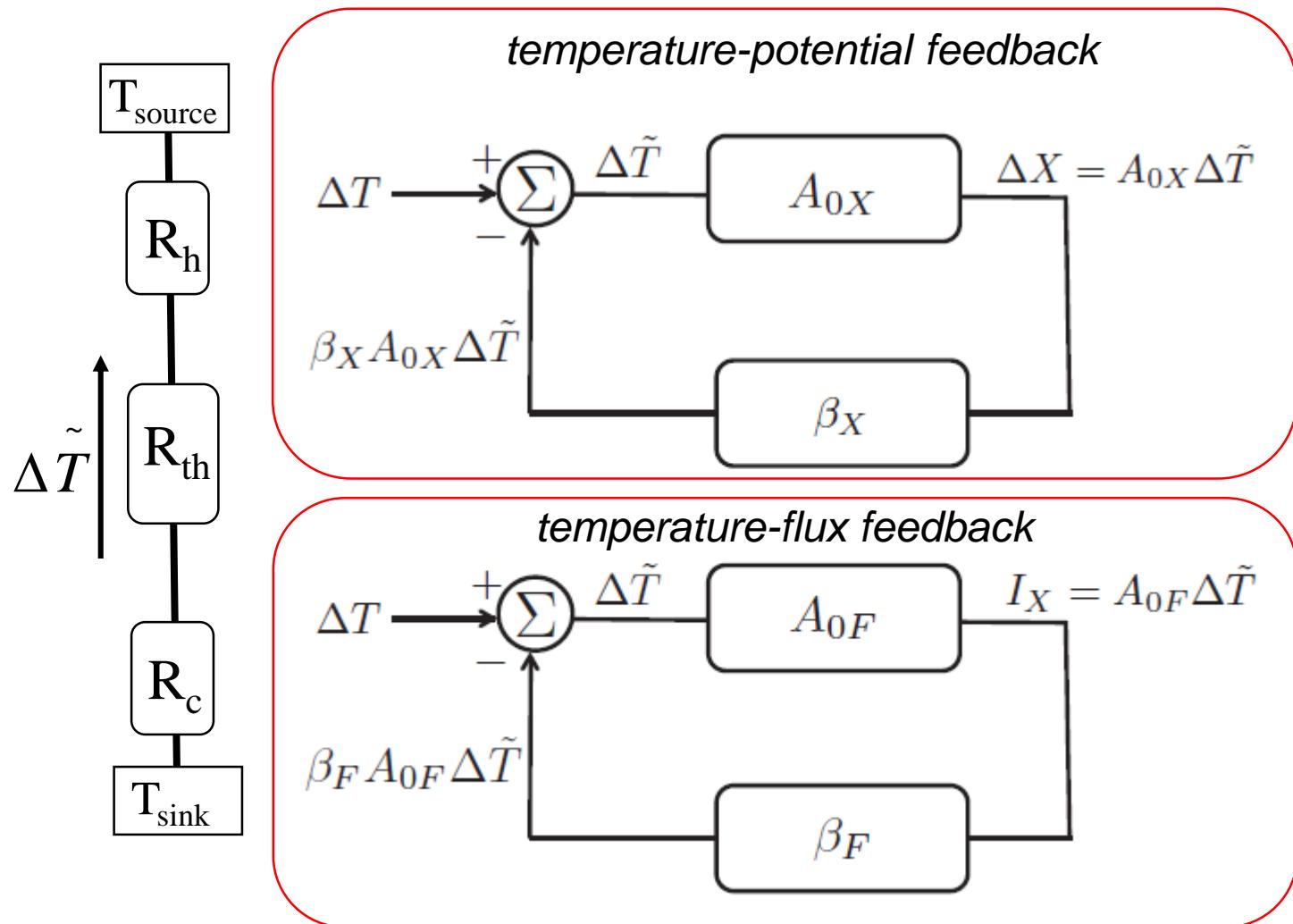


- **J. Yvon**, The saclay Reactor: Two Years of Experience in the Use of a Compressed gas as a Heat Transfer Agent, Proceedings of the International Conference on the Peaceful Uses of Atomic Energy (1955)
- **P. Chambadal** *Les centrales nucléaires*. Armand Colin, Paris, France, 4 1-58, (1957)
- **I.I. Novikov**, Efficiency of an Atomic Power Generation Installation, *Atomic Energy* 3 (1957)
- **F.L. Curzon & B. Ahlborn**, Efficiency of a Carnot Engine at Maximum Power Output, *Am. J. Phys.* 43 (1975)

Closed-loop approach to thermodynamics

C. Goupil, H. Ouerdane, E. Herbert, G. Benenti, Y. D'Angelo, and Ph. Lecoer
 Phys. Rev. E **94**, 032136 – Published 29 September 2016

Mixed boundary conditions and feedback effects



$$A_{0X} = \Delta X / \Delta \tilde{T}.$$

$$A_{0F} = I_X / \Delta \tilde{T}.$$

$$\frac{\Delta \tilde{T}}{\Delta T} = \frac{1}{1 + A_0 \beta}$$

$$A_{CL} = \frac{A_0}{1 + A_0 \beta}$$

$$A_0 \beta = \frac{R_h + R_c}{R_{th}}$$

Working modes

Power  $P = \Delta X I_X = A_{0X} A_{0F} (\Delta \tilde{T})^2 = A_{0X} A_{0F} \left(\frac{\Delta T}{1 + A_0 \beta} \right)^2$

Efficiency  $\eta = \frac{P}{\dot{Q}_{in}} = \frac{A_{0X} A_{0F} \Delta T}{R_{th}} \left(\frac{1}{1 + A_0 \beta} \right)^3$

Conversion, feedback, and gain	A_{0X}	A_{0F}	β_X	β_F	A_{cl}
Zero load	A_{0X}^*	0	$\frac{R_\theta}{\alpha R_{th}}$	∞	$\frac{A_{0X}^*}{1 + \frac{R_\theta}{R_{th}}}$
Blocking load	0	$\frac{\alpha}{\beta_F^*} \frac{R_\theta}{R_{th}}$	∞	β_F^*	0

$$A_{CL} = \frac{A_0}{1 + A_0 \beta}$$



Possible oscillations of the system!

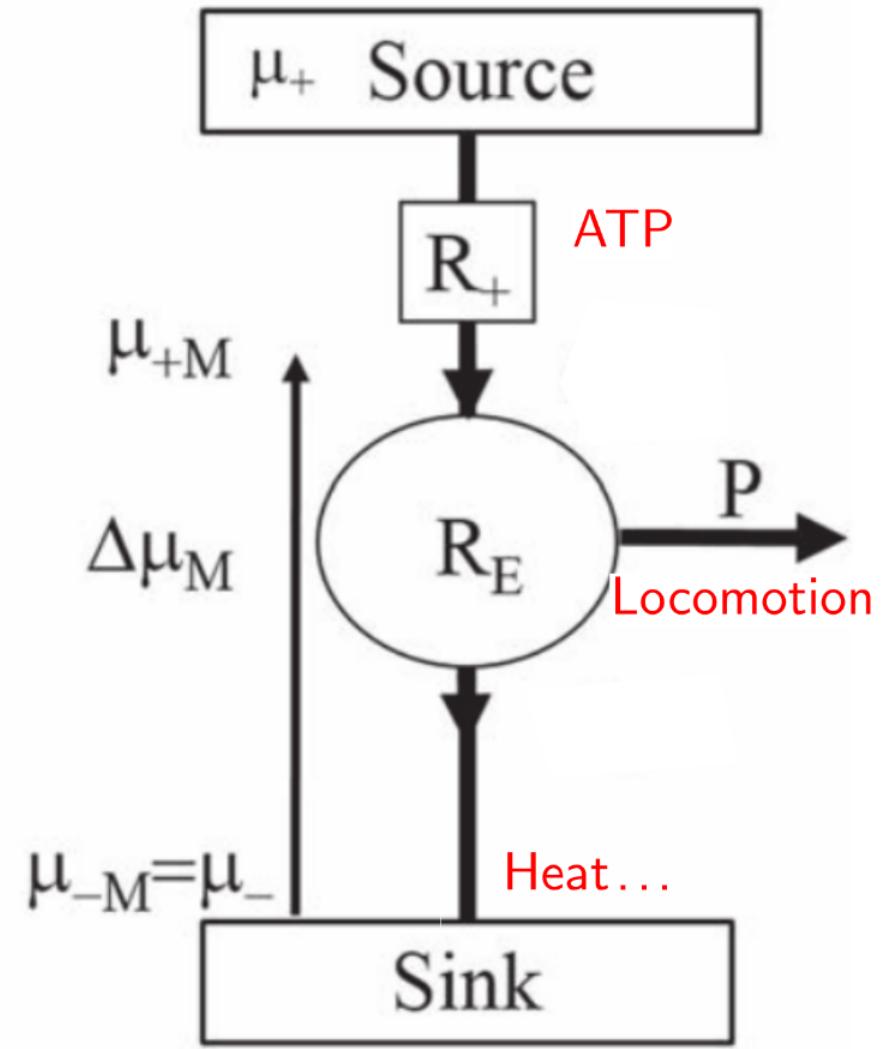
The muscle engine

1. Chemical potential of digested food
⇒ macroscopic energy: muscle work + heat

2. *Dispersed* incident energy flow conversion
⇒ *aggregated* energy flow + *loss* flow

3. Onsager Force / Flux local description:

$$\begin{pmatrix} J_M \\ J_{Em} \end{pmatrix} = \begin{pmatrix} \sigma & \alpha\sigma \\ \alpha\sigma\mu & \kappa_{J_M} \end{pmatrix} \begin{pmatrix} F_M \\ -\frac{d\mu}{dx} \end{pmatrix}$$



Two conductivities & a coupling coefficient

- Force / Flux formalism

$$\begin{pmatrix} J_M \\ J_{Em} \end{pmatrix} = \begin{pmatrix} \sigma & \alpha \sigma \\ \alpha \sigma \mu & \kappa_{J_M} \end{pmatrix} \begin{pmatrix} F_M \\ -\frac{d\mu}{dx} \end{pmatrix}$$

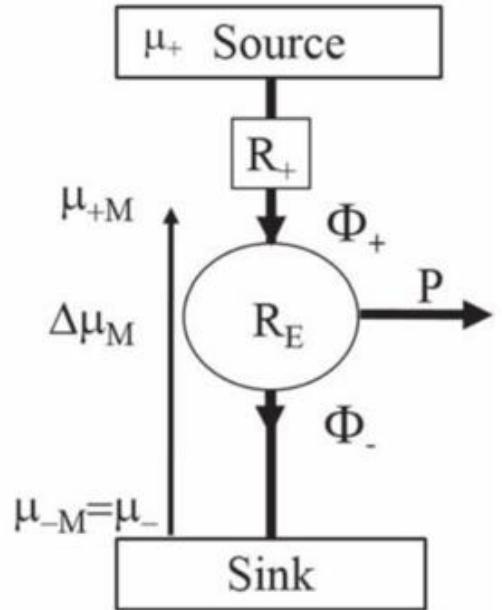
1. $\Pi_M J_M$ aggregated energy flux
 2. $J_{Em} = \Pi_m J_m$ dispersed energy flux
 3. α coupling coefficient
 4. σ isochemical conductivity
 5. μ electrochemical potential
 6. κ_{J_M} basal (zero load) conductivity
 7. $F_M = -\frac{d\Pi_M}{dx}$ driving force
- We assume constant transport parameters and short effort ($R_- = 0$).

- Local energy budget (constant J_U)

$$\kappa_{J_M} \frac{d^2\mu}{dx^2} = -\frac{J_M^2}{\sigma}$$

- The total metabolic energy flux in the volume $A \ell$, $\Phi = A J_{Em}$, with $I_M = A J_M$ can then be expressed after integration

$$\Phi(x) = \alpha \mu(x) I_M + R_M I_M^2 \frac{x}{\ell} + C$$



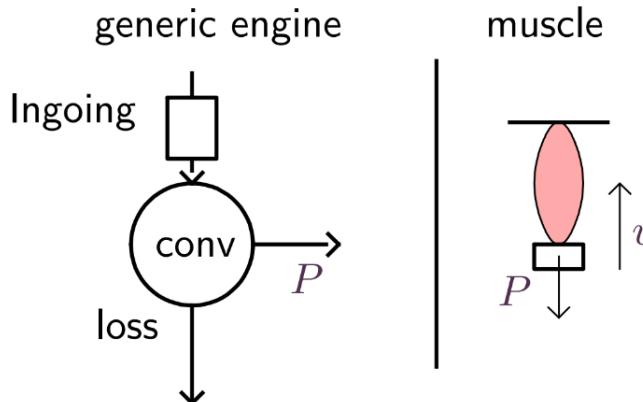
The goal to be achieved

- Hill's phenomenological equation (1938):

$$F_M = \frac{c}{v+b} - a(v)$$

- Linear Onsager Force / Flux description:

$$\begin{pmatrix} J_M \\ J_{Em} \end{pmatrix} = \begin{pmatrix} \sigma & \alpha\sigma \\ \alpha\sigma\mu & \kappa_{\Pi_M} \end{pmatrix} \begin{pmatrix} F_M \\ -\frac{d\mu}{dx} \end{pmatrix}$$



The muscle model

Let extract the power P :

- Extract P from Φ_+ and Φ_- :

$$\begin{aligned} P &= \Phi_+ - \Phi_- \\ &= F_M I_M \end{aligned}$$

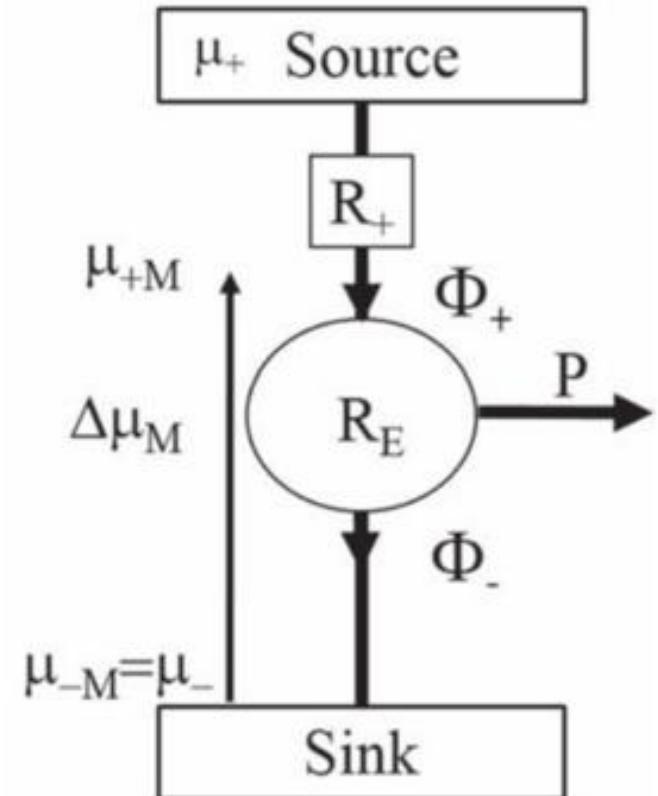
- With

$$\Phi_+ = \alpha \mu_{+M} I_M + \frac{\Delta \mu_M}{R_E}$$

$$\Phi_- = \alpha \mu_{-M} I_M + \frac{\Delta \mu_M}{R_E} + R_M I_M^2$$

- So $P = (F_{iso} - (R_M + R_H)I_M) I_M$

$$\text{and } F_M = F_{iso} - (R_M + R_H)I_M$$



The muscle model and the COT

1. Boundary condition : $\mu_+ - \mu_{+M} = R_+ \Phi_+$

2. Ingoing / outgoing fluxes:

$$\Phi_+ = \alpha \mu_{+M} I_M + \frac{\Delta \mu_M}{R_E}$$

$$\Phi_- = \alpha \mu_{-M} I_M + \frac{\Delta \mu_M}{R_E} + R_M I_M^2$$

3. Aggregated power (locomotion) : $P = \Phi_+ - \Phi_-$

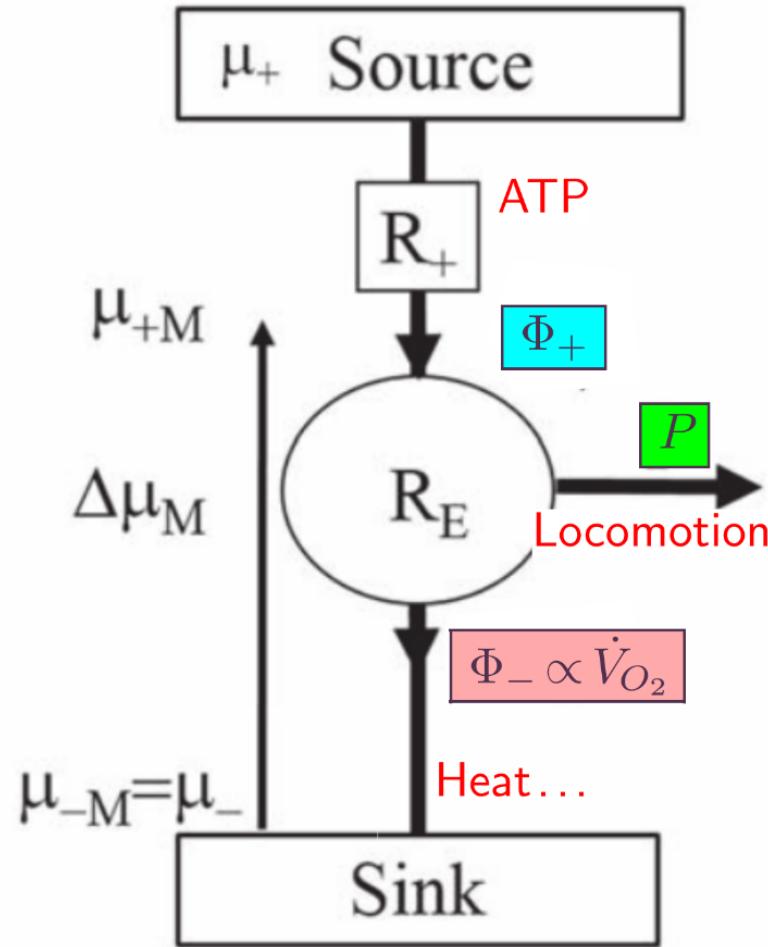
Connexion with experiment :

1. pH: H^+ extraction with O_2

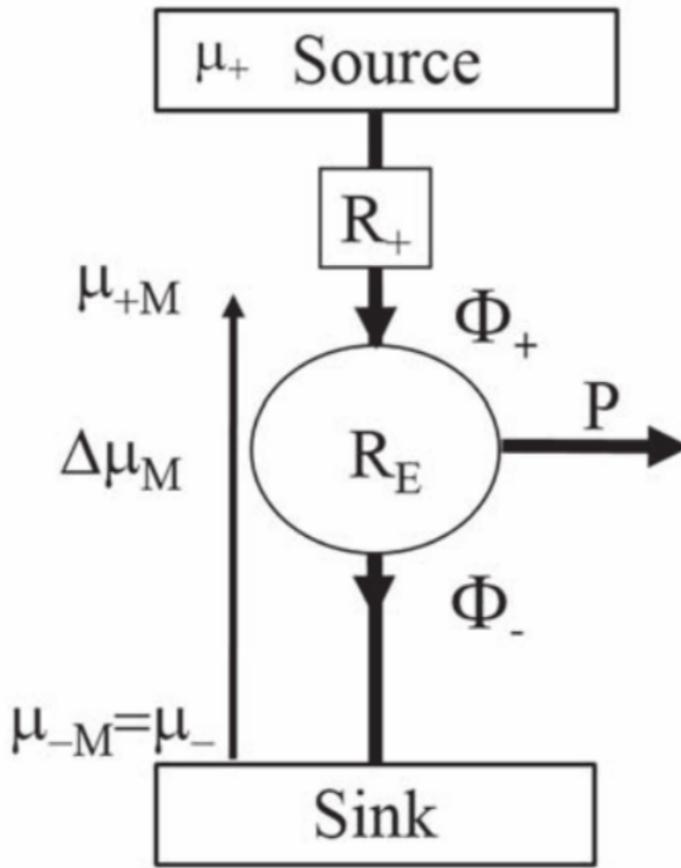
2. O_2 consumption: $\dot{V}_{O_2} \propto \Phi_- \rightarrow$ energy/time

Cost of Oxygen Transport :

$COT = \dot{V}_{O_2}/v \rightarrow$ energy/distance



Aggregated power



$$\begin{aligned} P &= \Phi_+ - \Phi_- \\ &= F_M I_M \\ &= (F_{\text{iso}} - (R_M + \mathbf{R}_H) I_M) I_M \end{aligned}$$

I_M	Macroscopic metabolic intensity
$B = \frac{\Delta\mu}{R_+ + R_E}$	Basal Power ($= \frac{\Delta\mu}{R_E}$)
$I_T = \frac{R_E + R_+}{\alpha R_+ R_E}$	Threshold metabolic intensity ($\rightarrow \infty$)
$R_{\text{fb}} = \frac{\alpha \mu_-}{I_T}$	Feedback resistance ($\rightarrow 0$)
$F_{\text{iso}} = \alpha R_E B$	Isometric force
$R_H = \frac{F_{\text{iso}} + R_{\text{fb}} I_T}{I_T + I_M}$	Hill resistance ($\rightarrow 0$)

The goal

1. Hill's phenomenological equation (1938)

$$F_M = \frac{c}{v + b} - a(v)$$

2. From this model

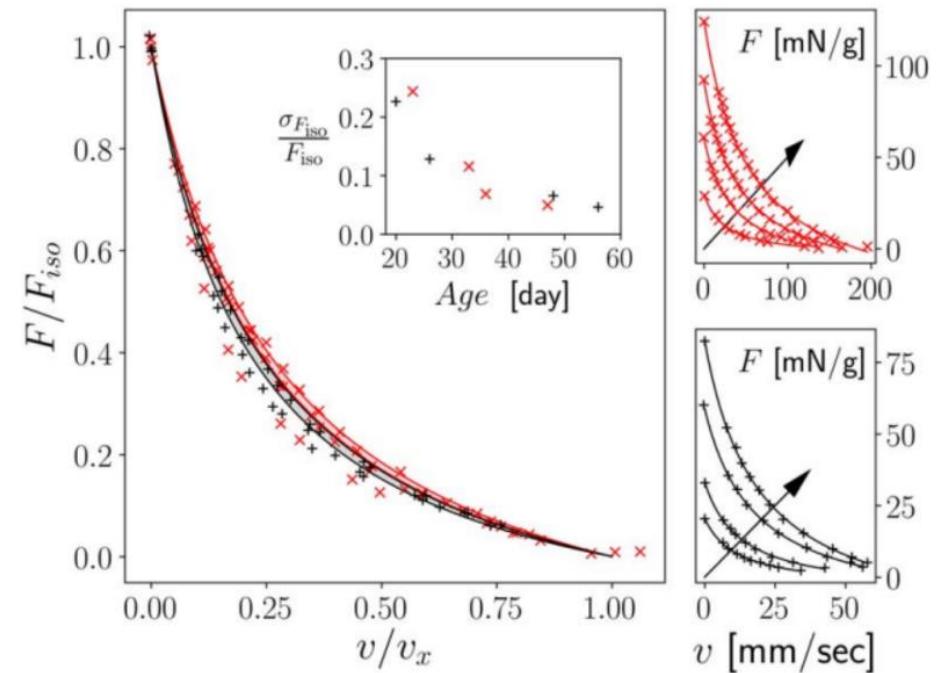
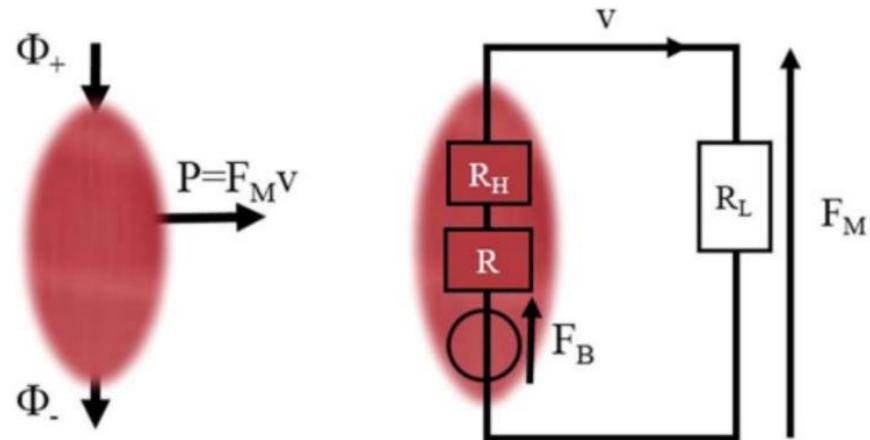
$$F_M = \frac{F_{\text{iso}} + R_{\text{fb}} I_T}{I_M + I_T} I_T - (R_{\text{fb}} I_T + R_M I_M)$$

3. Assuming $I_M \propto v$, we obtain the identity:

$$a(I_M) = R_{\text{fb}} I_T + R_M I_M$$

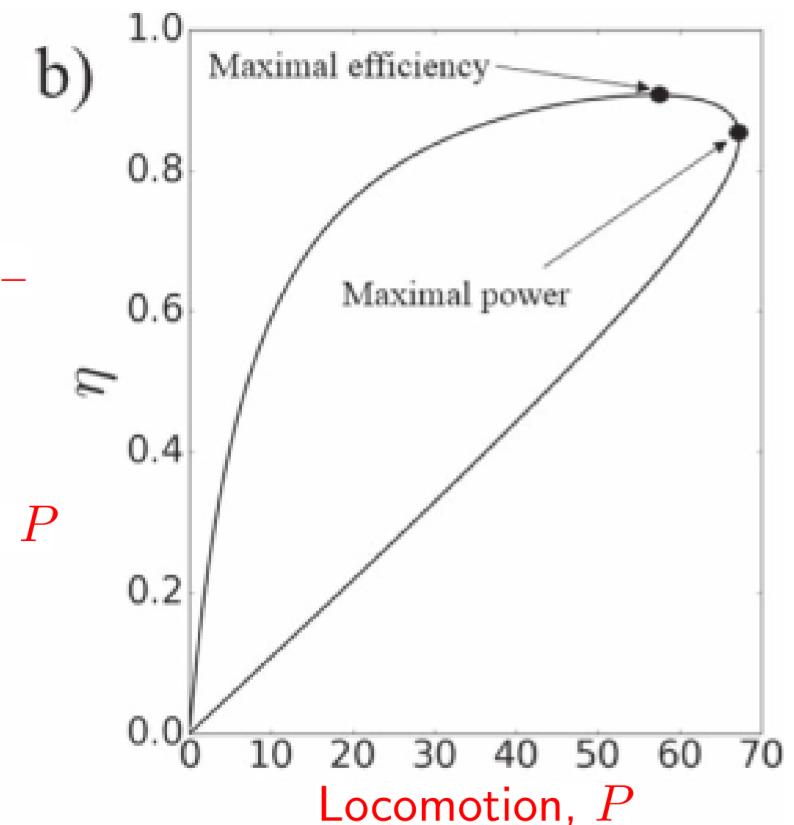
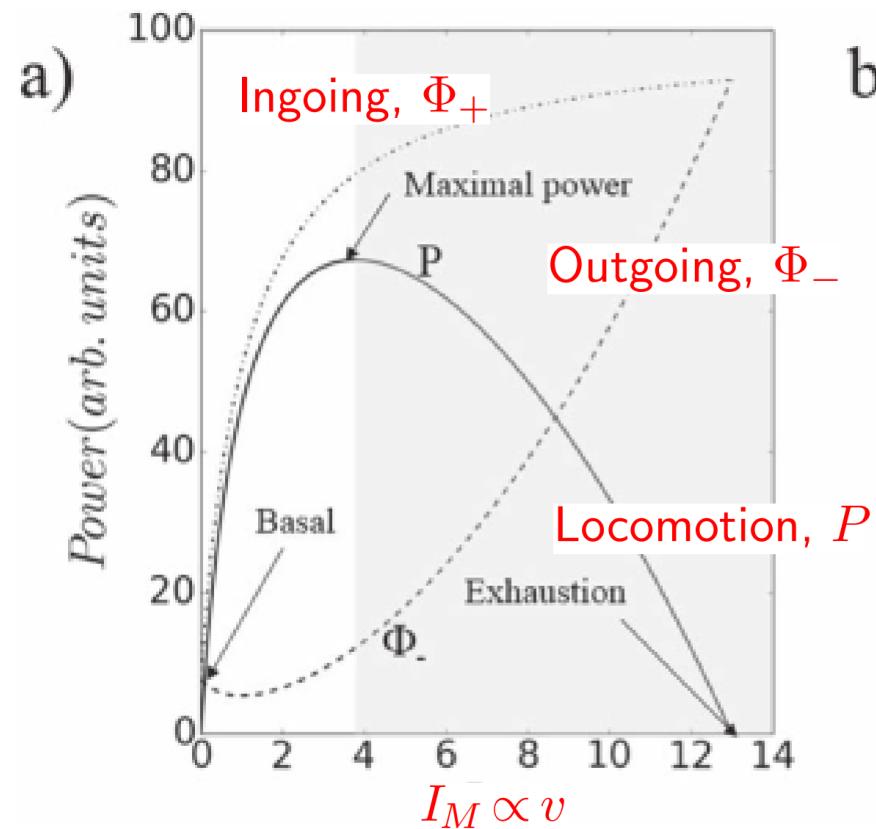
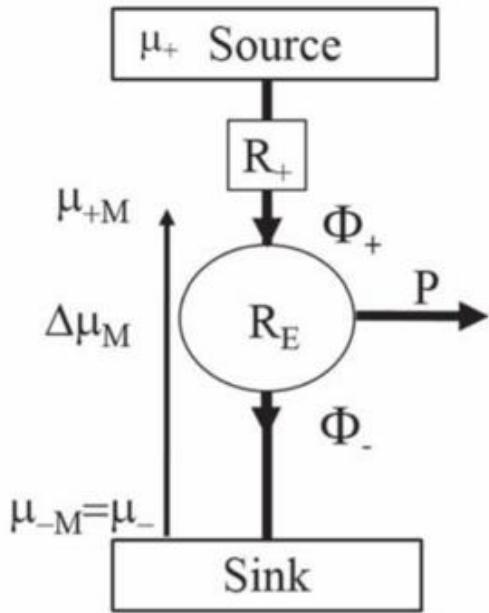
$$b = I_T$$

$$c = (F_{\text{iso}} + R_{\text{fb}} I_T) I_T$$



Working points

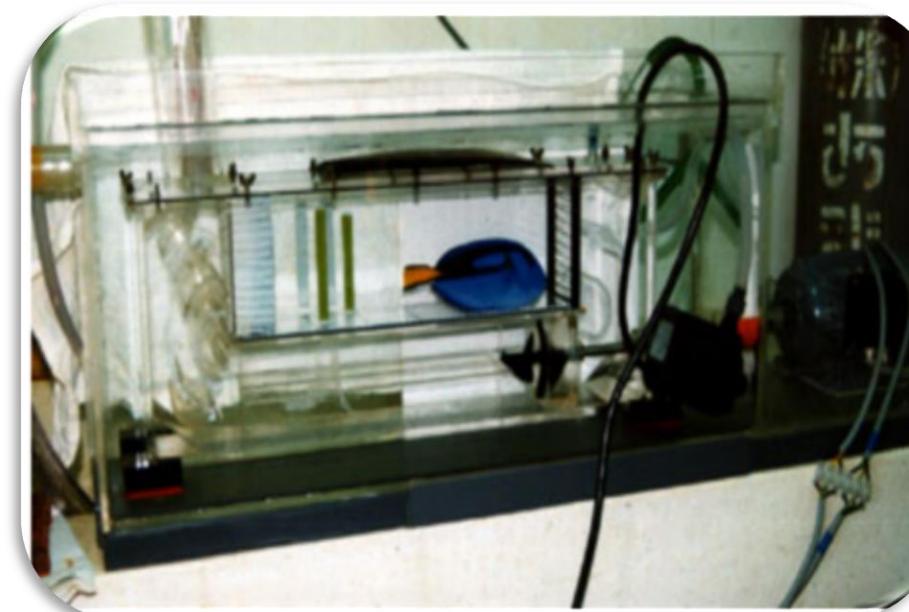
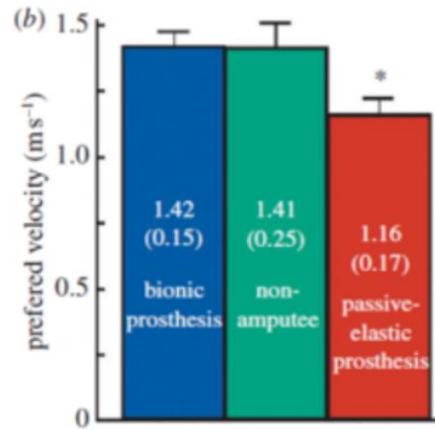
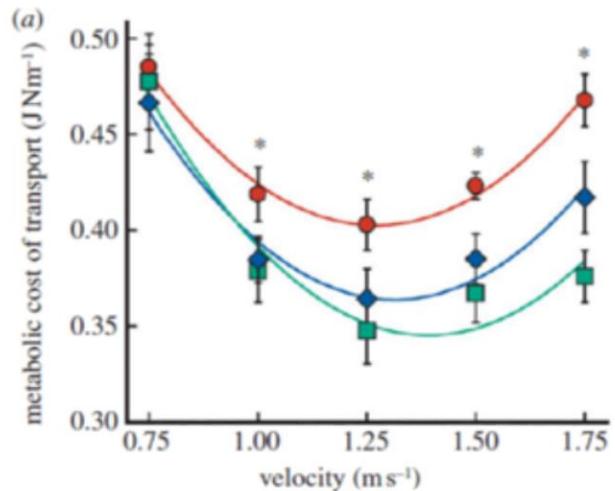
- Maximal power
 - Maximal efficiency
 - Basal power consumption
 - Feedback !
 - $F \neq \text{cste}$
 - different optimal velocities
- \Rightarrow no maximal power principle



Back to the COT

Experimental COT

Bionic leg normalizes walking gait H. M. Herr & A. M. Grabowski 4t



From muscle to COT

1. Starting from Ingoing / Outgoing fluxes of an assembly of N muscle units

$$\begin{aligned}\Phi_+ &= N\varphi_+ \\ \Phi_- &= N\varphi_-\end{aligned}$$

2. O_2 consumption: $\dot{V}_{O_2} \propto \Phi_-$

3. We define Cost Of Energy

$$COE_- = \Phi_- / I_M$$

4. Or $COT = V_{O_2}/v$: energy per unit distance

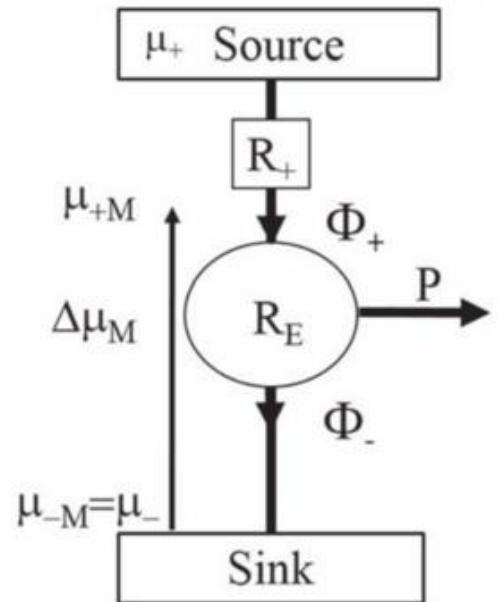
$$\begin{aligned}COT &= \frac{N}{N_H} \left(a_0 k + r_M k^2 v + \frac{b}{v} \right) \\ &= k \frac{N}{N_H} COE_-\end{aligned}$$

with $I_M = N k v$ and $a_0 = a(I_M = 0)$, N_H the maximum number of fiber

For a single organism with different gaits, the following predictions can be made:

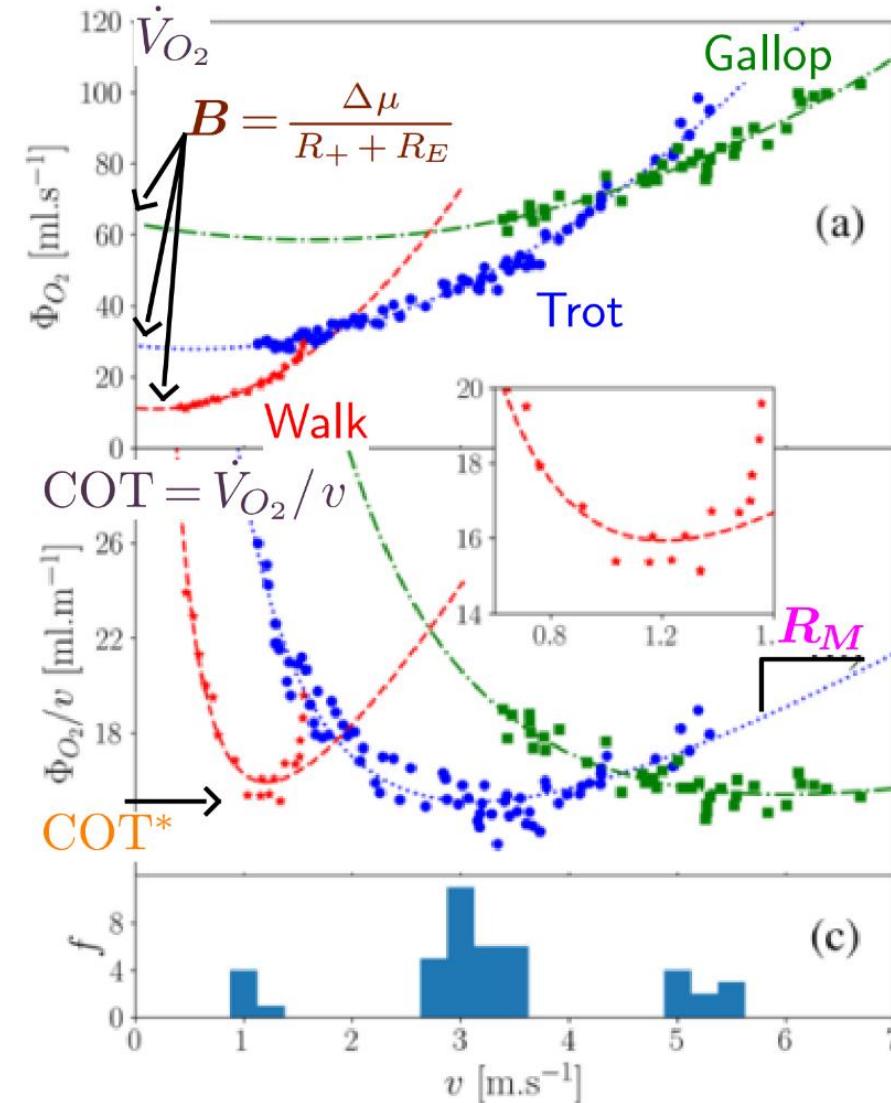
1. Basal consumption $B = N b$
2. Metabolic resistivity $R_M = r_M / N$
3. Global intensity $I_M = N i_M$
4. COT min (COT^*) does not depend on N

$$\begin{aligned}COT^* &= a_0 k + 2 k \sqrt{r_M b} \\ &= a_0 k + 2 k \sqrt{R_M B}\end{aligned}$$



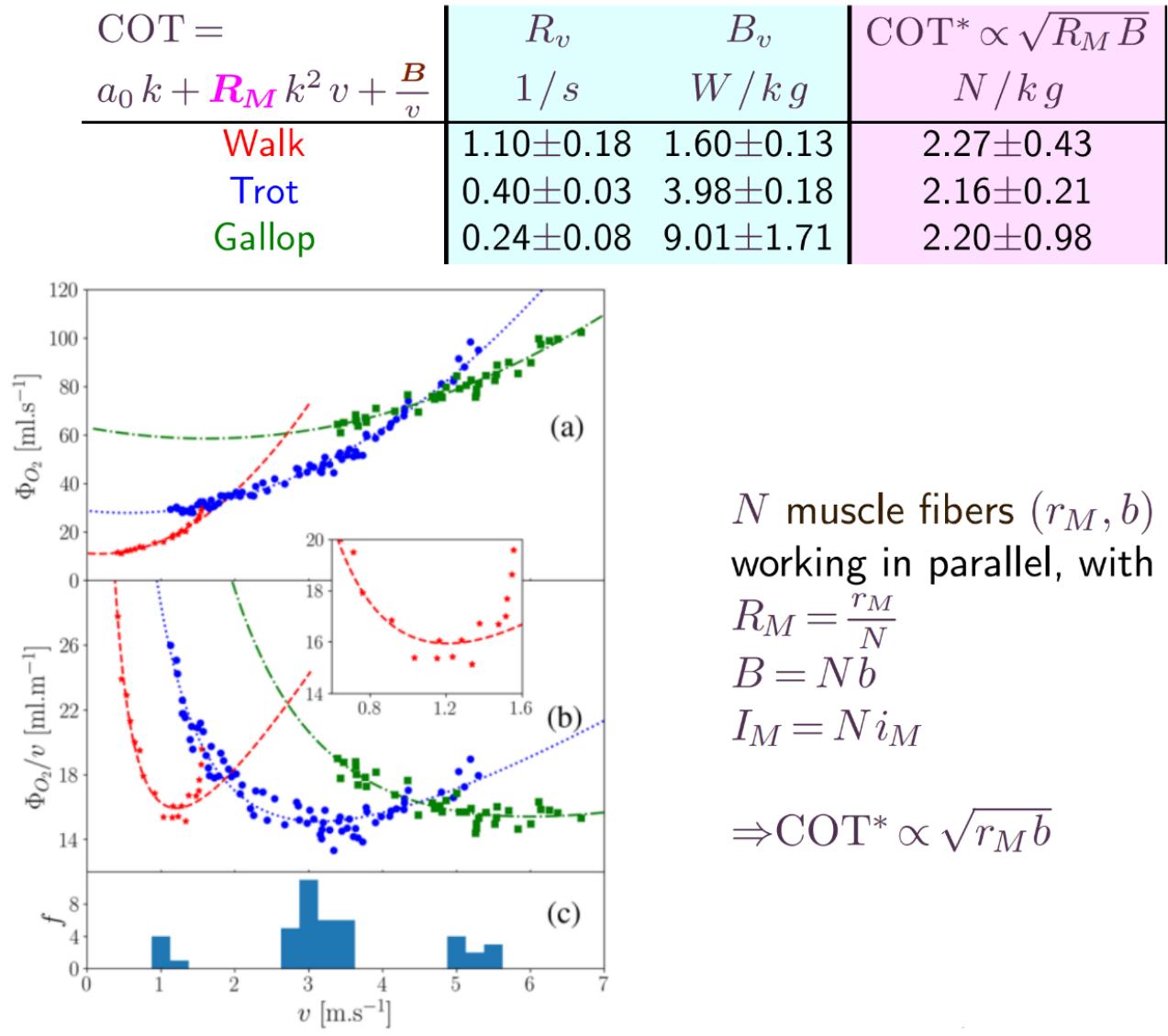
Horse measurements

- Velocity $I_M = k v$, driving parameter
- $\text{COT} = \frac{\Phi_-}{v} = \frac{\dot{V}_{O_2}}{v}$
 $\Rightarrow \text{COT} \propto a_0 k + R_M k^2 v + \frac{B}{v}$
- Min COT
 $\Rightarrow \text{COT}^* = a_0 k + 2 k \sqrt{R_M B}$
- Horse on a treadmill:



Adapted from Hoyt et al., Nature 1981

Horse results



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Thermodynamics of Animal Locomotion

E. Herbert, H. Ouerdane, Ph. Lecoer, V. Bels, and Ch. Goupil
Phys. Rev. Lett. **125**, 228102 – Published 23 November 2020

N muscle fibers (r_M, b) working in parallel, with

$$R_M = \frac{r_M}{N}$$

$$B = N b$$

$$I_M = N i_M$$

$$\Rightarrow \text{COT}^* \propto \sqrt{r_M b}$$

Gaits of the horse: how to activate variable populations of nearly similar muscles

$COT = \frac{N}{N_H} (a_0 k + r_M k^2 v + \frac{b}{v})$	$COT^* \propto \sqrt{r_M b}$	N Muscle Fibers
	N / kg	
Walk	2.27 ± 0.43	1
Trot	2.16 ± 0.21	2.5
Gallop	2.20 ± 0.98	5.6

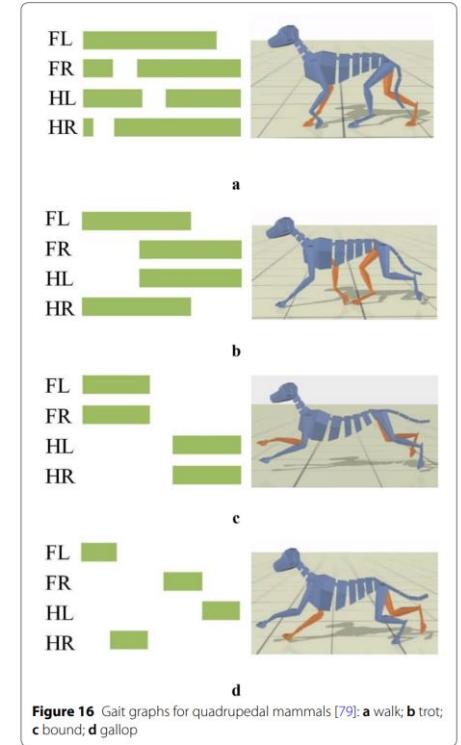
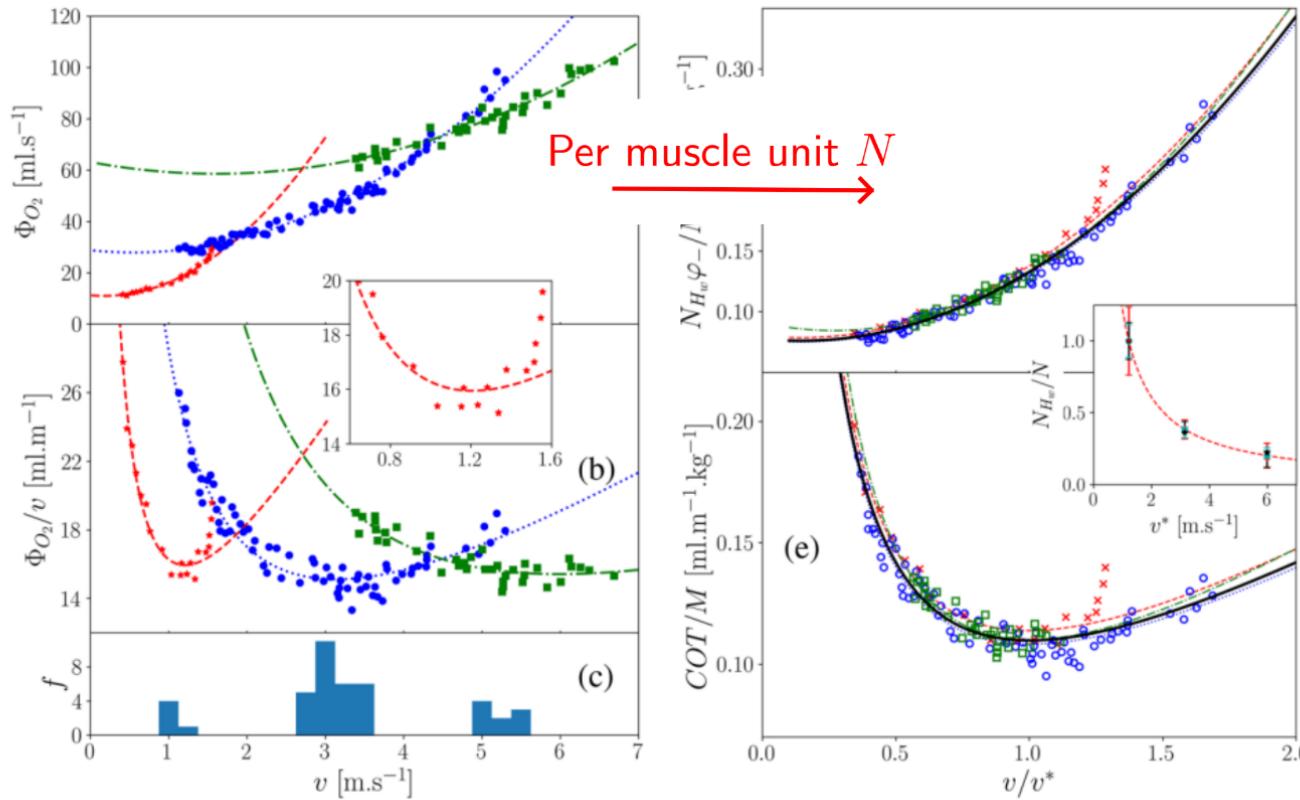
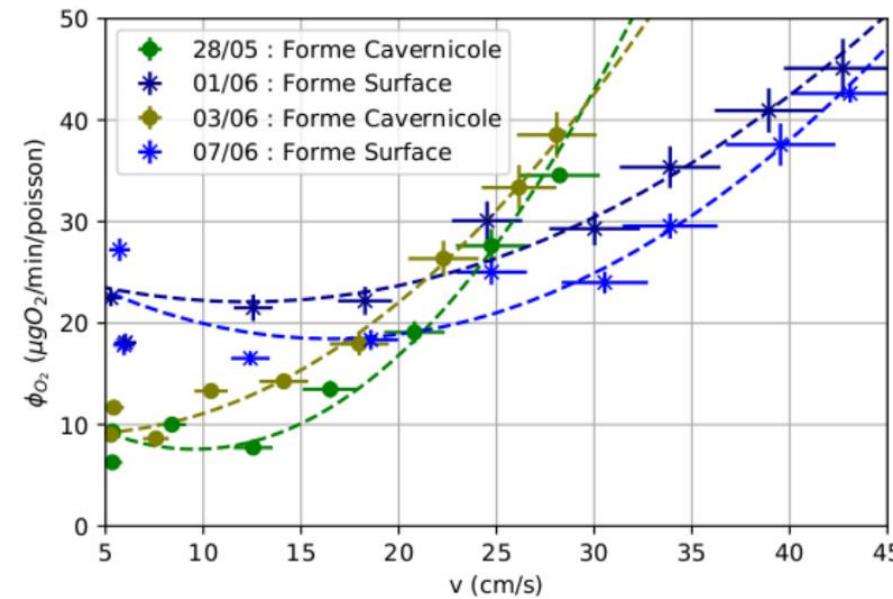


Figure 16 Gait graphs for quadrupedal mammals [79]: **a** walk; **b** trot; **c** bound; **d** gallop

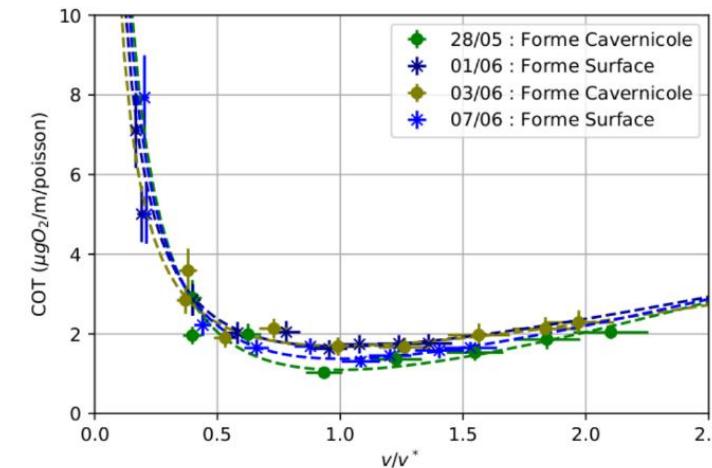
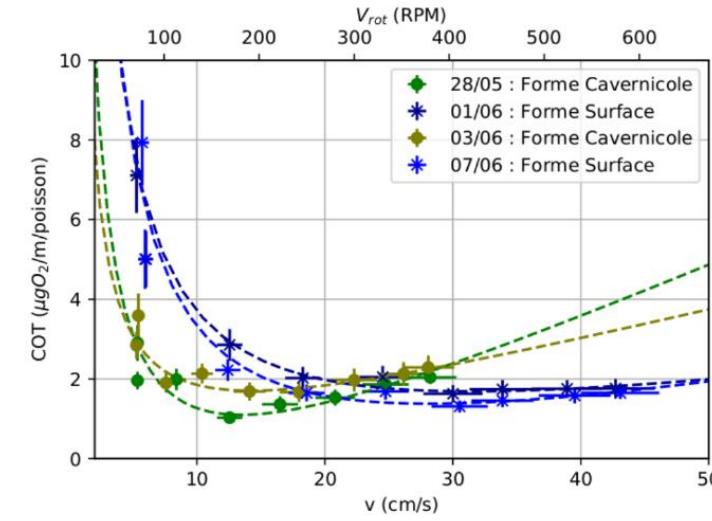
What about fishes? (*Astyanax Mexicanus*)

Two morphotypes of a single species



Fish that differ in the number of motor units

Evolution of effort production mechanisms: An adaptive transition model



Conclusion

1. Chemical to Mechanical energy conversion under muscle load, from the derivation of thermoelastic and transport coefficient
2. Feedback resistance as an active parameter
3. Building on COT
 - a. A single muscle unit
 - b. Horses adapt to a particular gait by mobilizing a nearly constant number of muscle units minimizing waste production per unit distance covered
4. The mechanical function of the animal is determined
 - a. By its own thermodynamic characteristics, $R_M B = r_M b$
 - b. By the metabolic operating point of the locomotor system.
5. Maximum power principle should not be considered as a fundamental / extremal principle

Thank you

<https://dyco.lied.univ-paris-diderot.fr/recherche/>

Thermodynamics of metabolic energy conversion under muscle load

Christophe Goupil, Henni Ouerdane, Eric Herbert, Clémence Goupil and Yves D'Angelo

<https://iopscience.iop.org/article/10.1088/1367-2630/ab0223/meta>

Adapted or Adaptable: How to Manage Entropy Production?

Christophe Goupil and Eric Herbert

<https://www.mdpi.com/1099-4300/22/1/29>

Thermodynamics of Animal Locomotion

E. Herbert, H. Ouerdane, Ph. Lecoeur, V. Bels, and Ch. Goupil

<https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.125.228102>

Closed-loop approach to thermodynamics

C. Goupil, H. Ouerdane, E. Herbert, G. Benenti, Y. D'Angelo, and Ph. Lecoeur

<https://journals.aps.org/pre/abstract/10.1103/PhysRevE.94.032136>

Résumé:

La question de la réponse musculaire n'est pas nouvelle et sa modélisation couvrent plusieurs champs de la physique, depuis la mécanique jusqu'à la thermodynamique. En 1938 Archibald Hill propose un modèle de la réponse force-vitesse du muscle, formalisée par une équation impliquant trois constantes. Ce modèle rend très bien compte de la réponse force -vitesse mais le sens physique des trois constantes est longtemps resté obscur.

En repartant des premier et second principes de la thermodynamique notre équipe a pu reconstruire la forme analytique de Hill en attribuant un sens thermodynamique précis à chacun des trois termes.

Dans ce cadre de description le muscle se comporte comme une machine thermodynamique placée sous une différence de potentiel chimique.

Cette modélisation a mis en lumière le fait que le muscle se comporte comme une machine thermodynamique placée en conditions aux limites mixtes avec ses réservoirs. Il en résulte que le muscle est un système rétroagit, avec toutes les propriétés qui découlent des systèmes bouclés.

Nous avons par ailleurs montré que la mesure de consommation en oxygène d'un organisme sous effort aérobie permet de remonter aux principaux paramètres de Hill.

Il s'en suit que le point de fonctionnement d'un muscle peut parfaitement se décrire en terme de Cost Of Transport, (COT).

Compte-tenu de l'usage du concept de COT dans le cadre de l'optimisation énergétique des actionneurs en robotiques, il devient donc possible d'envisager une approche réellement bio-inspirée des muscles synthétiques et des actionneurs.