

"Mouvement Animal et Humain, Biomécanique, Biorobotique"

## Bio-inspiration et énergie: Un hymne à la vertu

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# Comparaison bio-inspirée

# La nature a la solution?

- 1. La nature n'utilise que l'énergie dont elle a besoin.**
- 2. La nature recycle tous les matériaux.**
- 3. La nature résiste aux perturbations.**
- 4. La nature a tendance à optimiser plutôt qu'à maximiser.**
- 5. La nature offre des avantages mutuels.**
- 6. La nature fonctionne à l'information.**
- 7. La nature utilise une chimie sans danger pour les êtres vivants.**
- 8. La nature construit en utilisant des ressources abondantes.**
- 9. La nature est localement à l'écoute et réactive.**
- 10. La nature utilise la forme pour déterminer la fonctionnalité.**

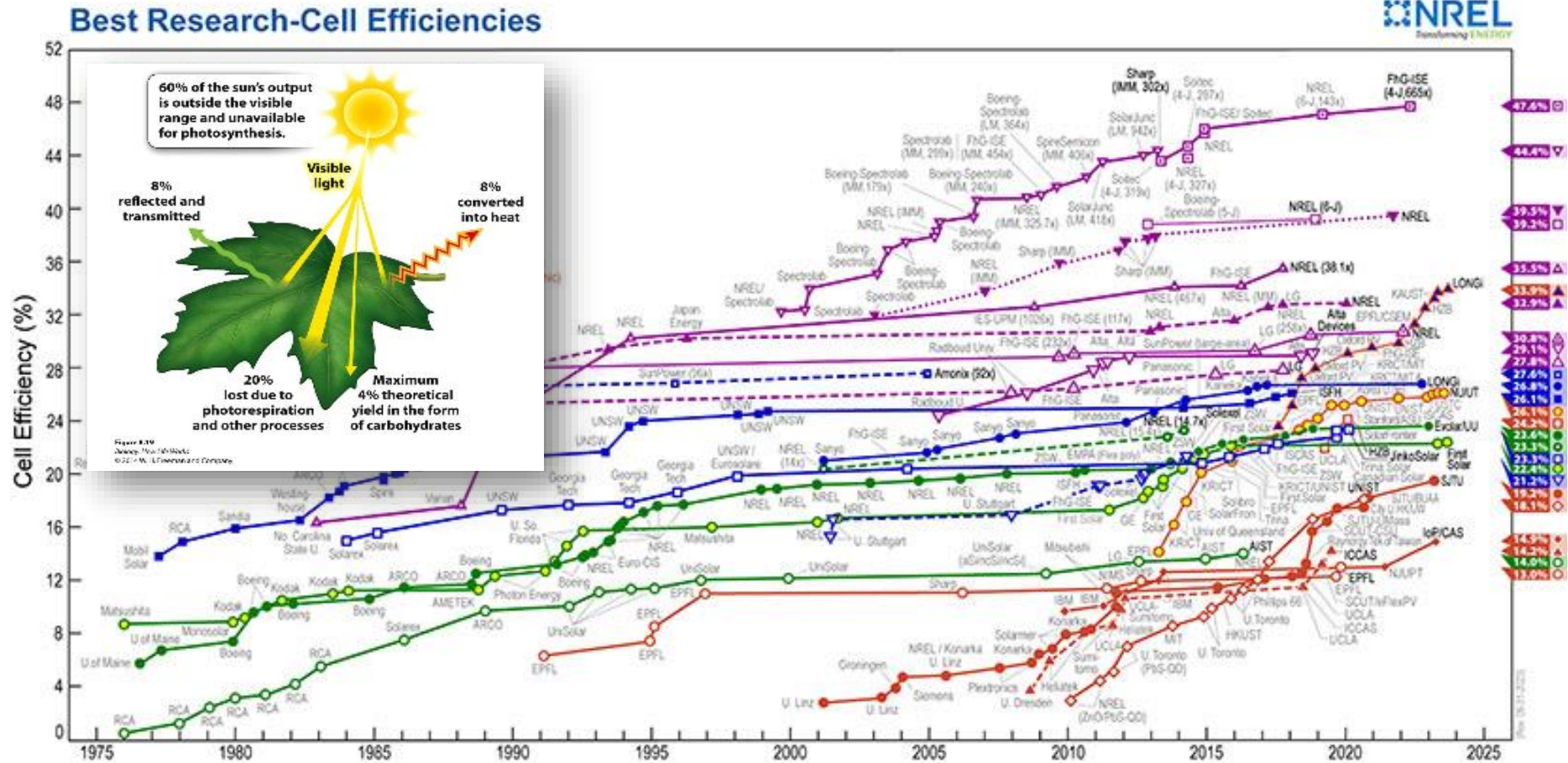
D'après <https://toolbox.biomimicry.org/core-concepts/natures-unifying-patterns/>

La nature est vertueuse, elle optimise..?





# La nature est une incapable?



# Périmètre des contraintes et espace des possibles

**1 Contraintes Physiques:** cf Darcy Thomson « On growth and form »

**2 Contraintes historique:** Dépendance au chemin.

**3 Contraintes d'évolution:** cf les équilibres ponctués de Stephen Jay-Gould

**4 Contraintes des conditions aux limites:** cf accès à la ressource

**5 Contraintes de système: adaptable ou adapté ?** Ex: mammifère et sudation

# Des contraintes différentes

**6 Contraintes de ressources: CHNOPS..**

**7 Contraintes de puissance: < 50kW**

**8 Absence de contraintes de temps:** temporalité biologique/ industrielle

**9 Absence de contraintes économique et géopolitique**

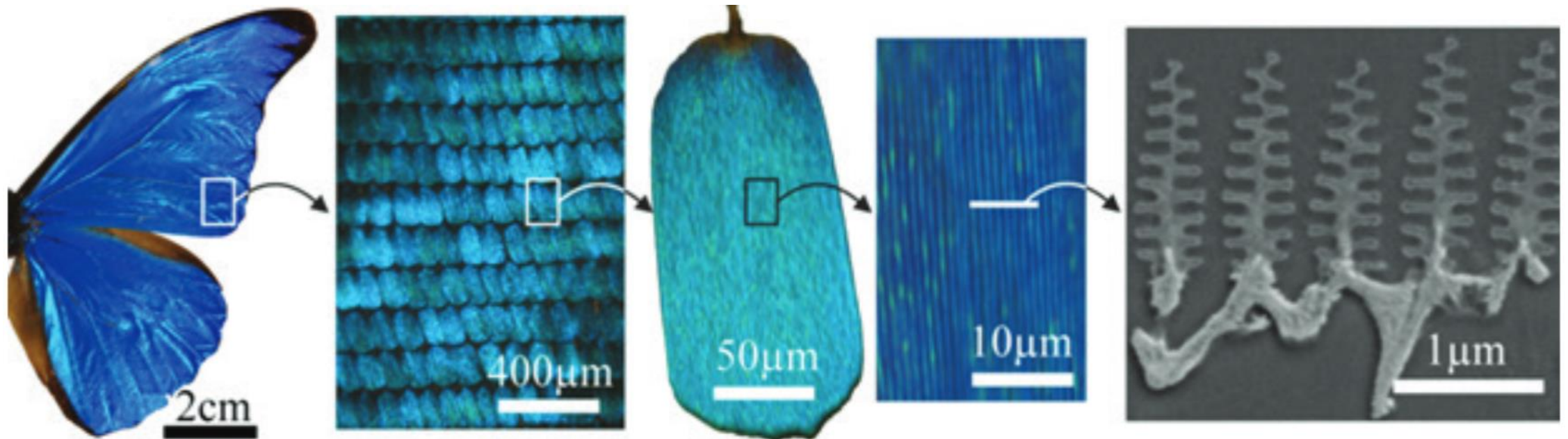


Adapté ou adaptable: il faut choisir...





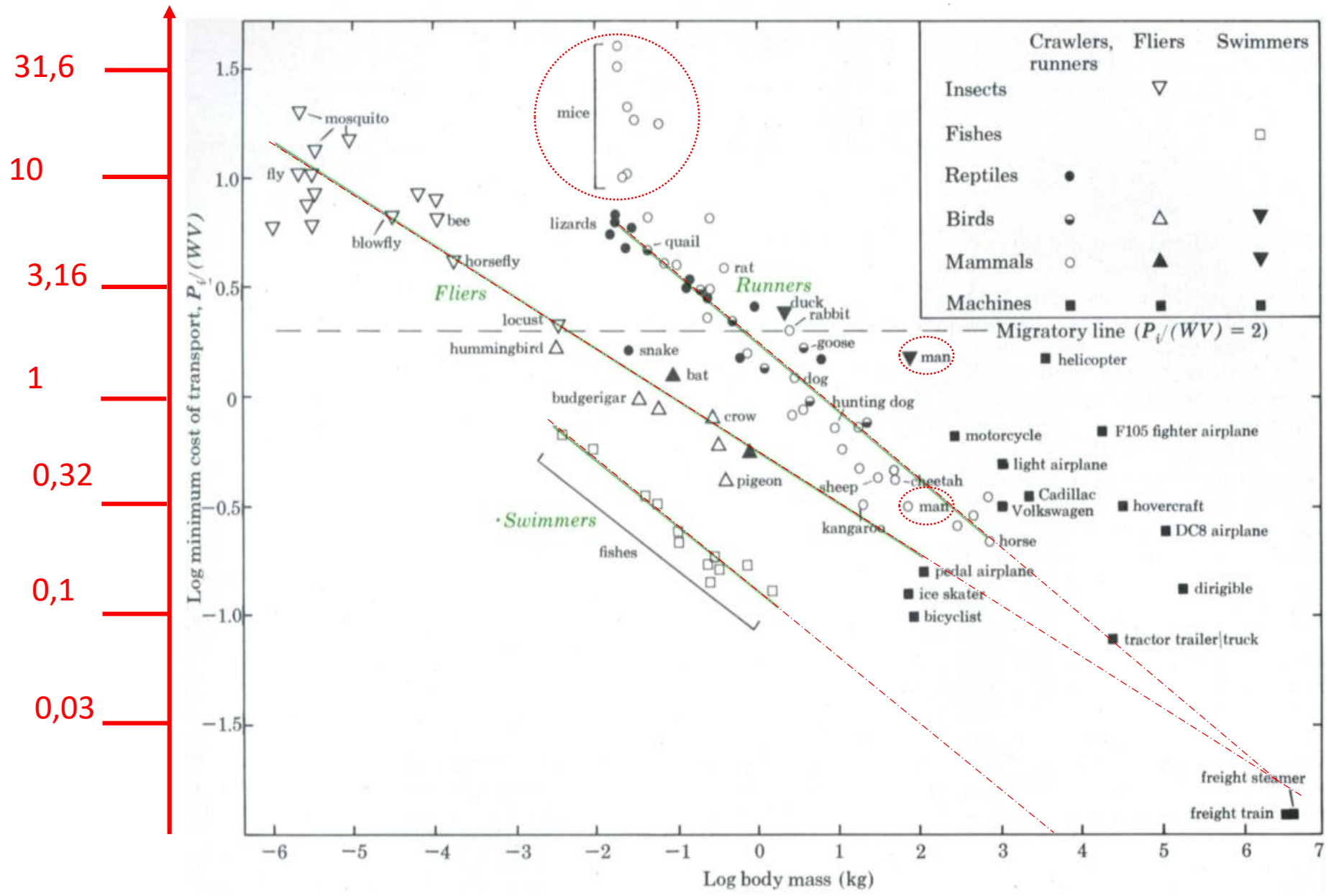
# ... et hybrider les solutions



Robotique et  
comparaison avec le vivant

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

# COT



V. A. Tucker

## Energetic Cost of Moving About

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

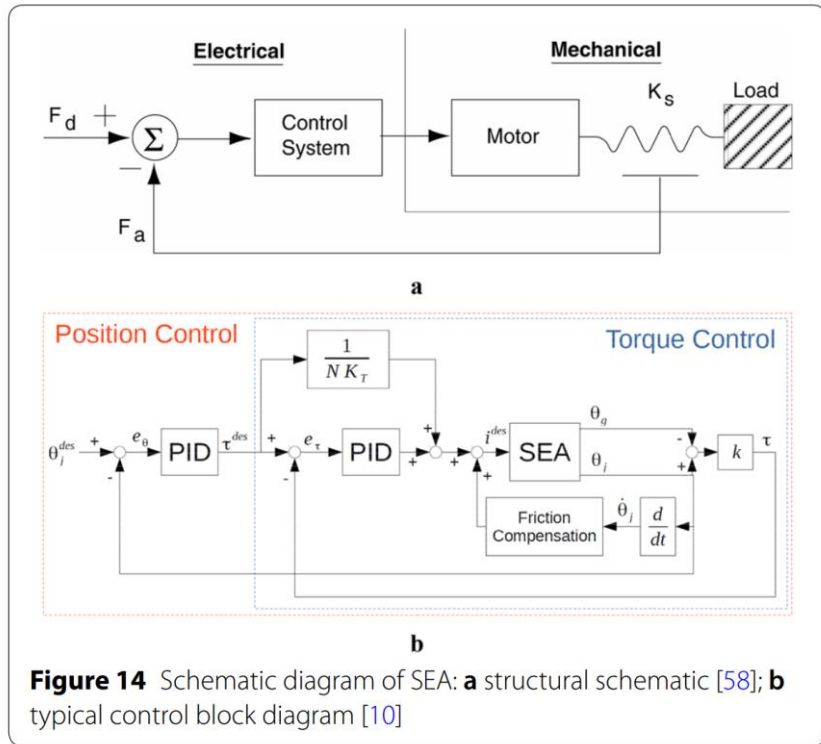
REVIEW

Open Access

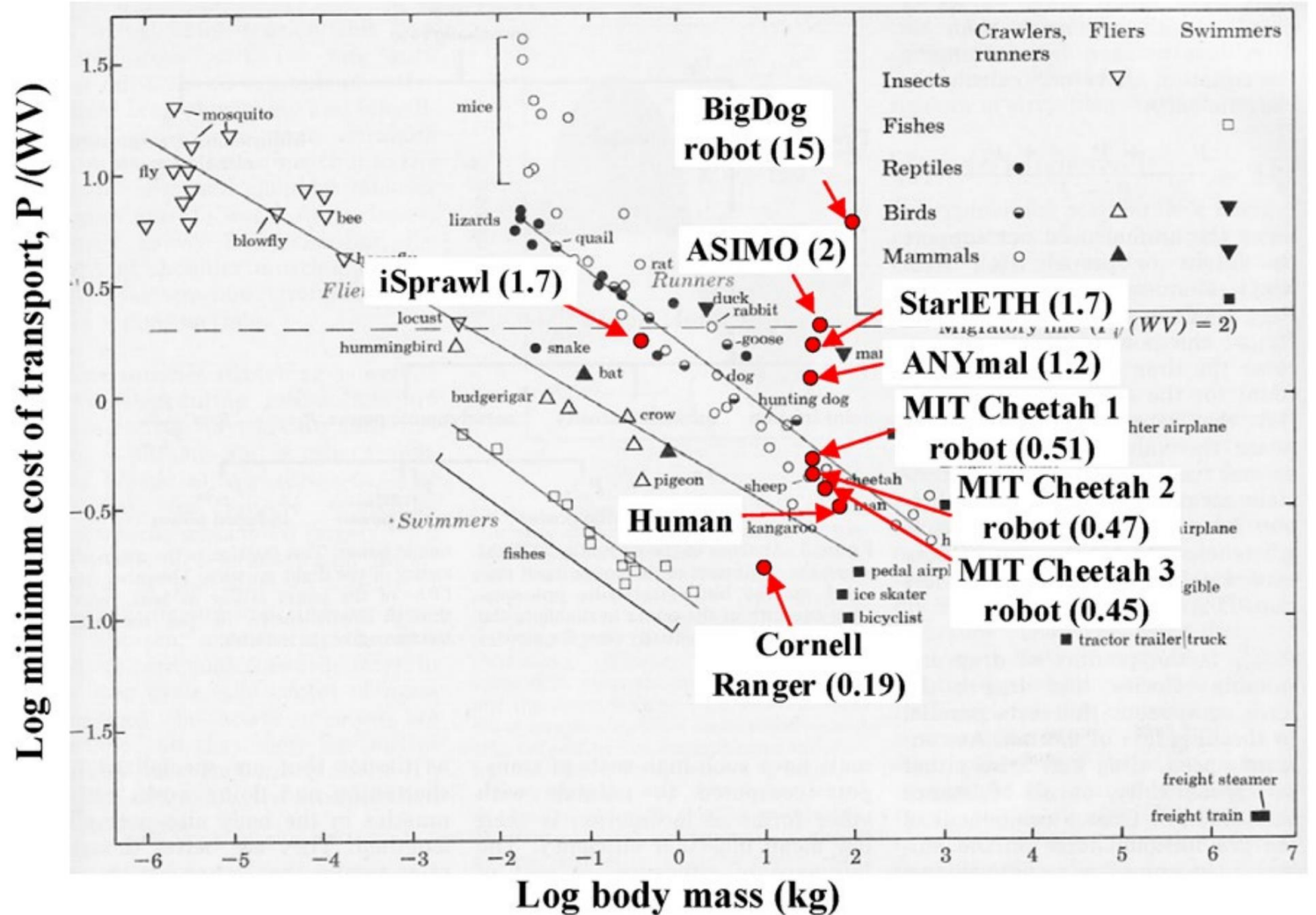


# Mechanism, Actuation, Perception, and Control of Highly Dynamic Multilegged Robots: A Review

Jun He and Feng Gao\*



## Serial elastic actuation (SEA)





### Stabilization System of a Bipedal non-anthropomorphic Robot AnyWalker

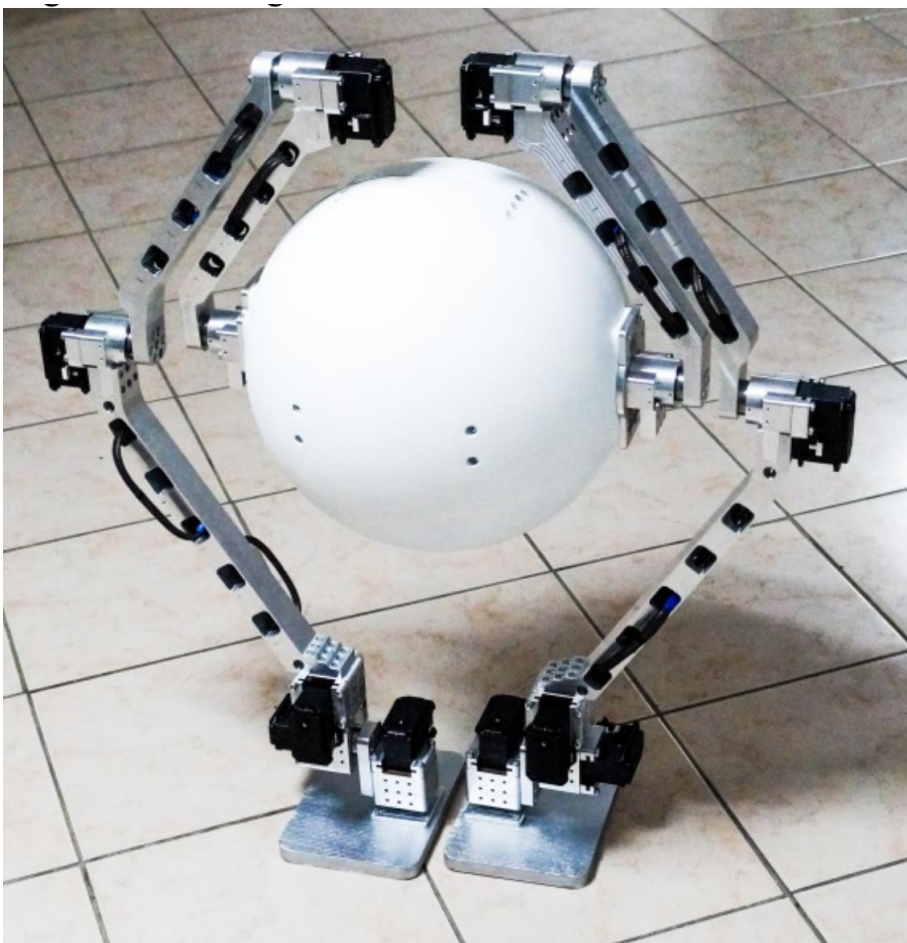
I. Ryadchikov<sup>1</sup>, S. Sechenov<sup>1</sup>, M. Drobotenko<sup>1</sup>, A. Svidlov<sup>1</sup>, P. Volkodav<sup>1</sup>, R. Vishnykov<sup>1</sup>, D. Sokolov<sup>2</sup>  
and E. Nikulchev<sup>3,\*</sup>

<sup>1</sup>Kuban State University, Krasnodar, Russia

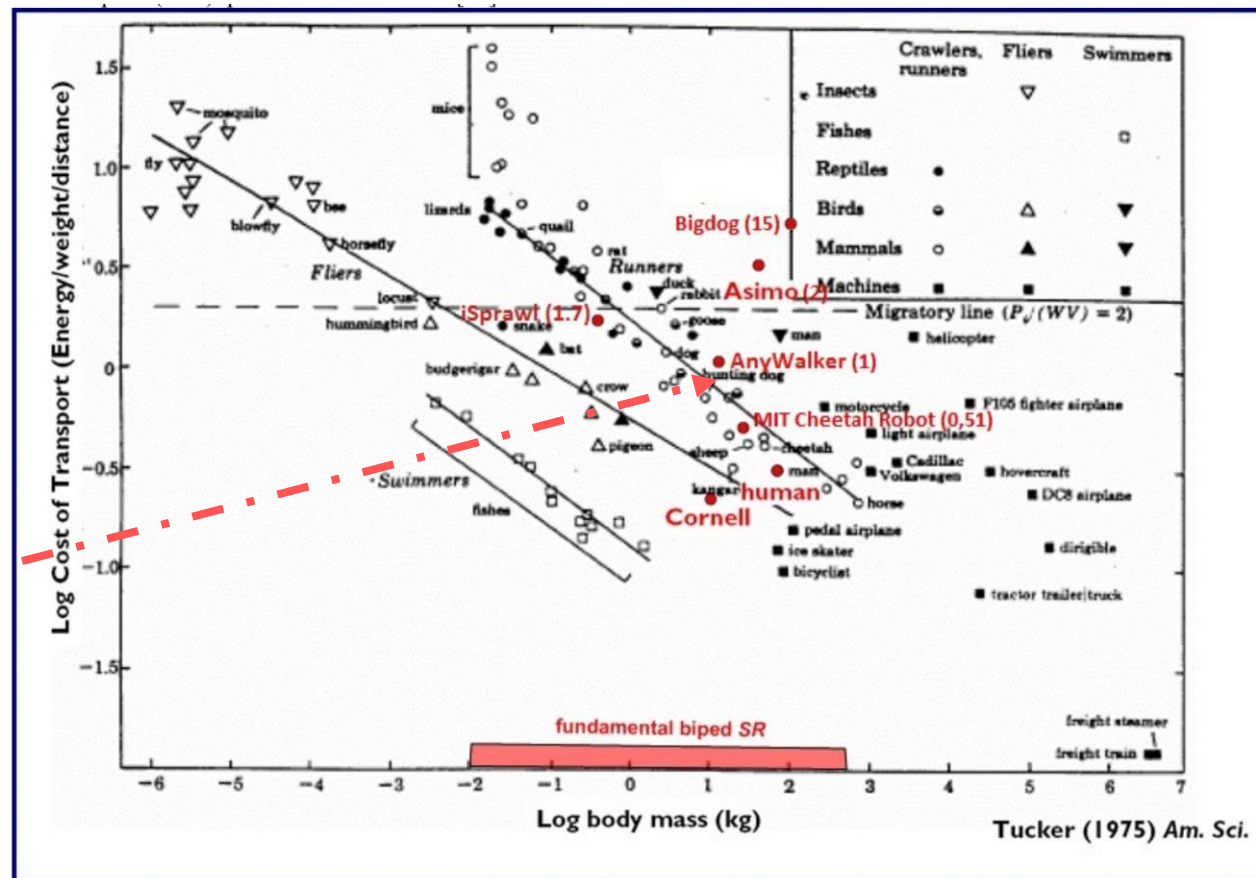
<sup>2</sup>University of Lorraine, Nancy, France

<sup>3</sup>MIREA – Russian Technological University, Moscow, Russia

Received 20 November 2017; Accepted 22 November 2018



# Marcher



# Courir

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

Sangok Seok<sup>1</sup>, Albert Wang<sup>1</sup>, Meng Yee (Michael) Chuah<sup>1</sup>, Dong Jin Hyun<sup>1</sup>, Jongwoo Lee<sup>1</sup>, David Otten<sup>2</sup>, Jeffrey Lang<sup>2</sup>, and Sangbae Kim<sup>1</sup>

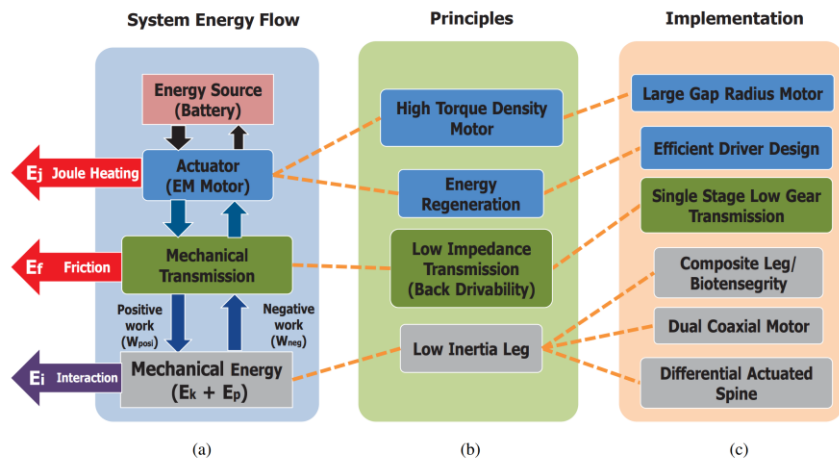
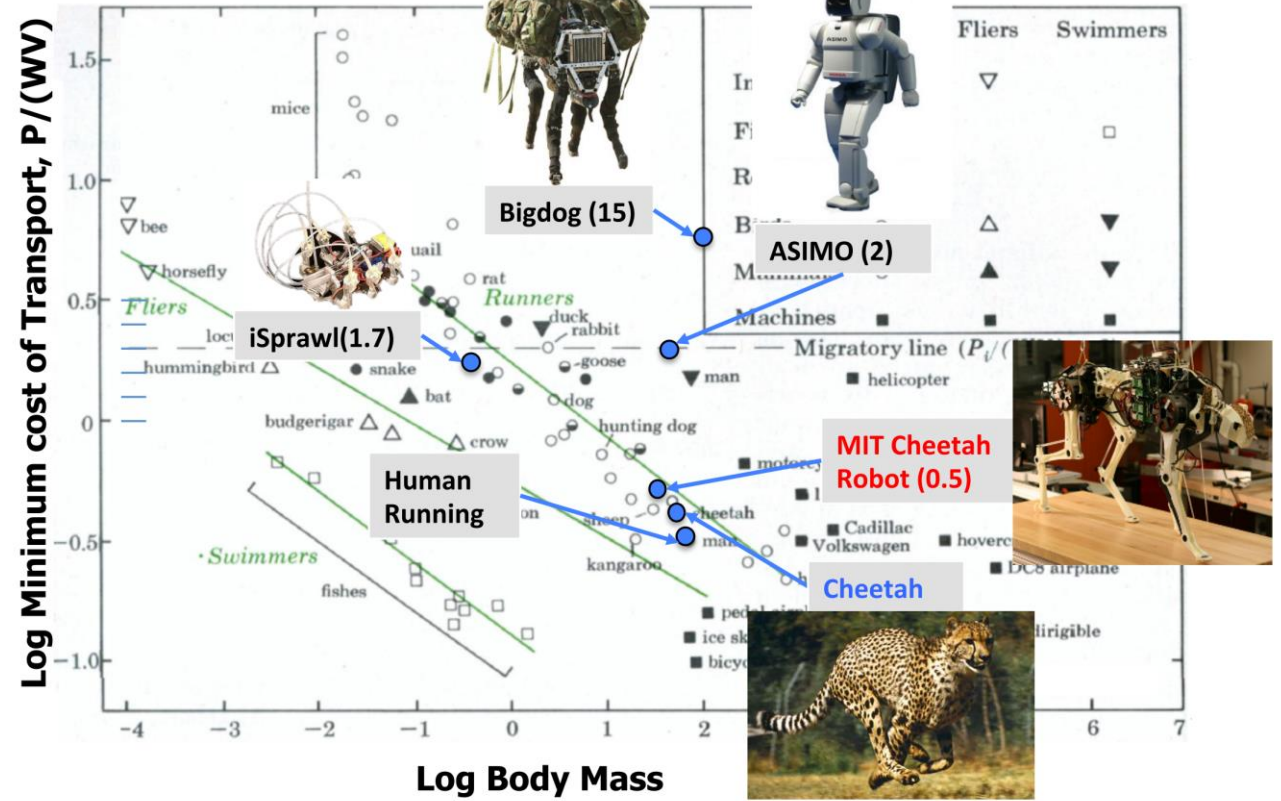
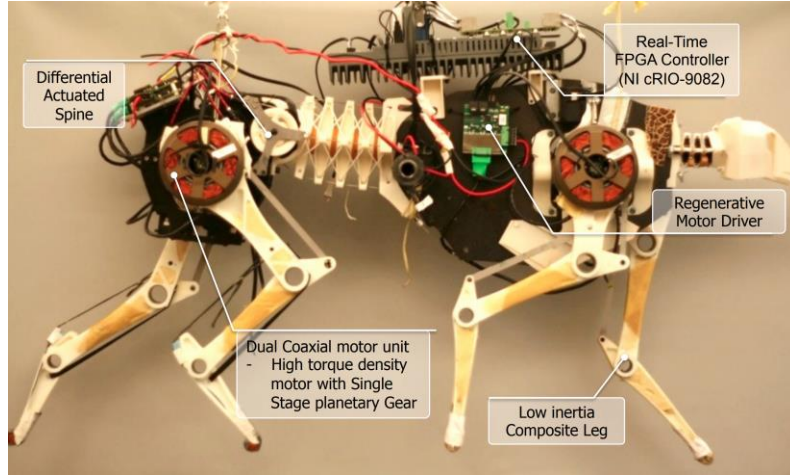


Fig. 2: (a) Energy flow diagram of the robot showing energy flows between the source and mechanical energy. Joule heating loss occurs at the motor, friction loss occurs in the mechanical transmission and interaction loss reduces the total mechanical energy. (b) Design principles to improve efficiency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

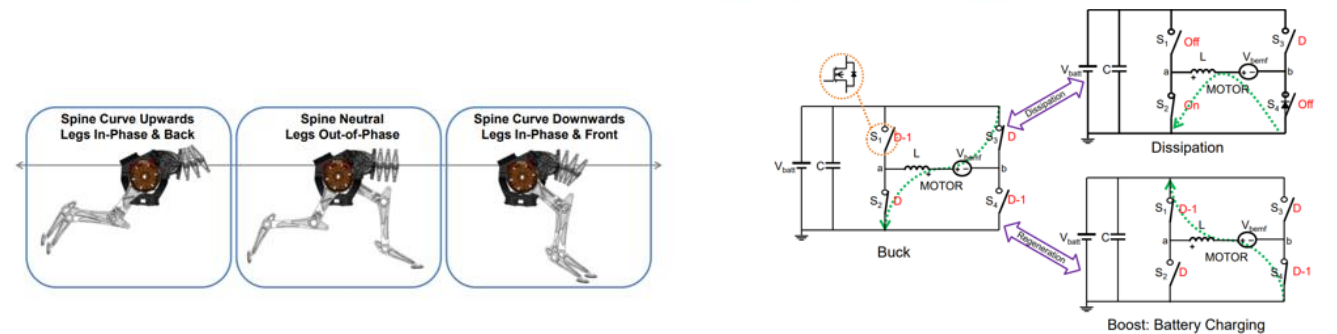
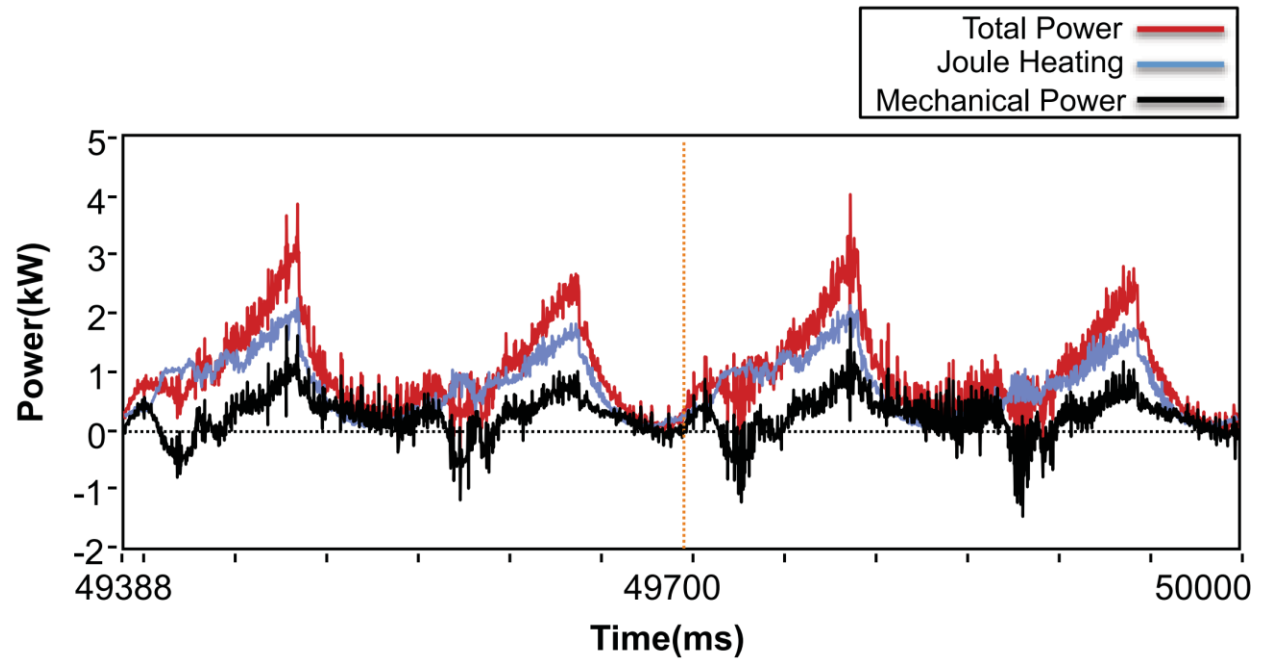
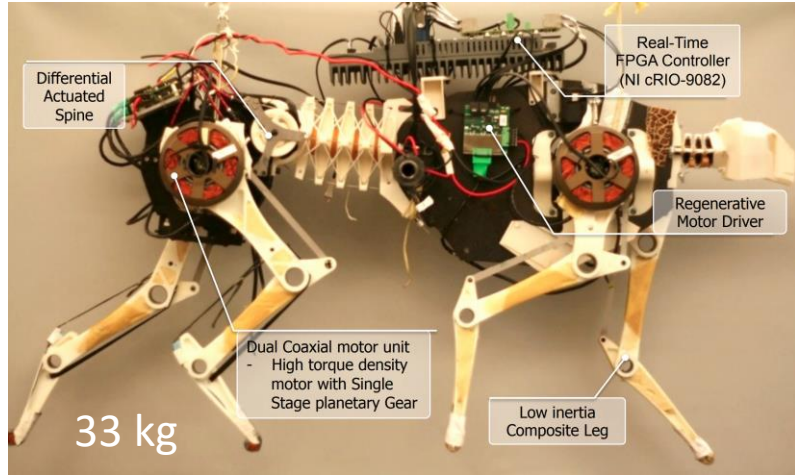


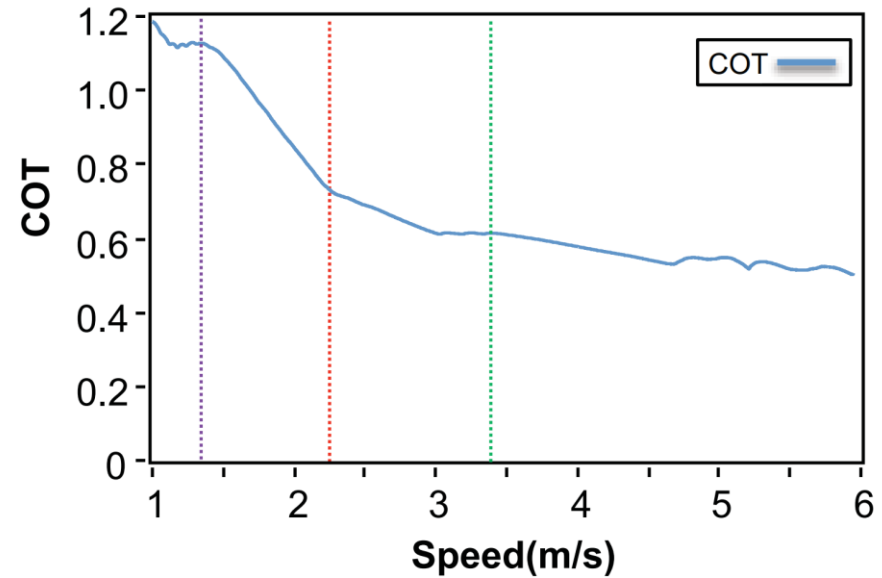
Fig. 6: Energy flow in a Bidirectional Buck Boost Converter.



# Etude du COT



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



# COT minimal... gamme d'usage minimale

## 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*

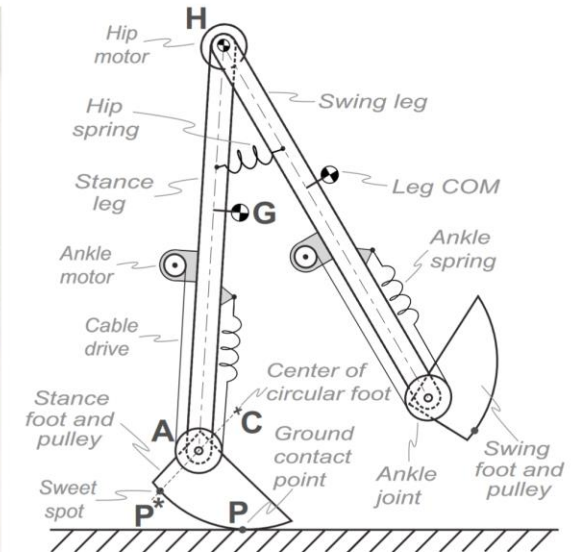
*E-mail: pab47@disneyresearch.com, jbc2@cornell.edu, ruina@cornell.edu*

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



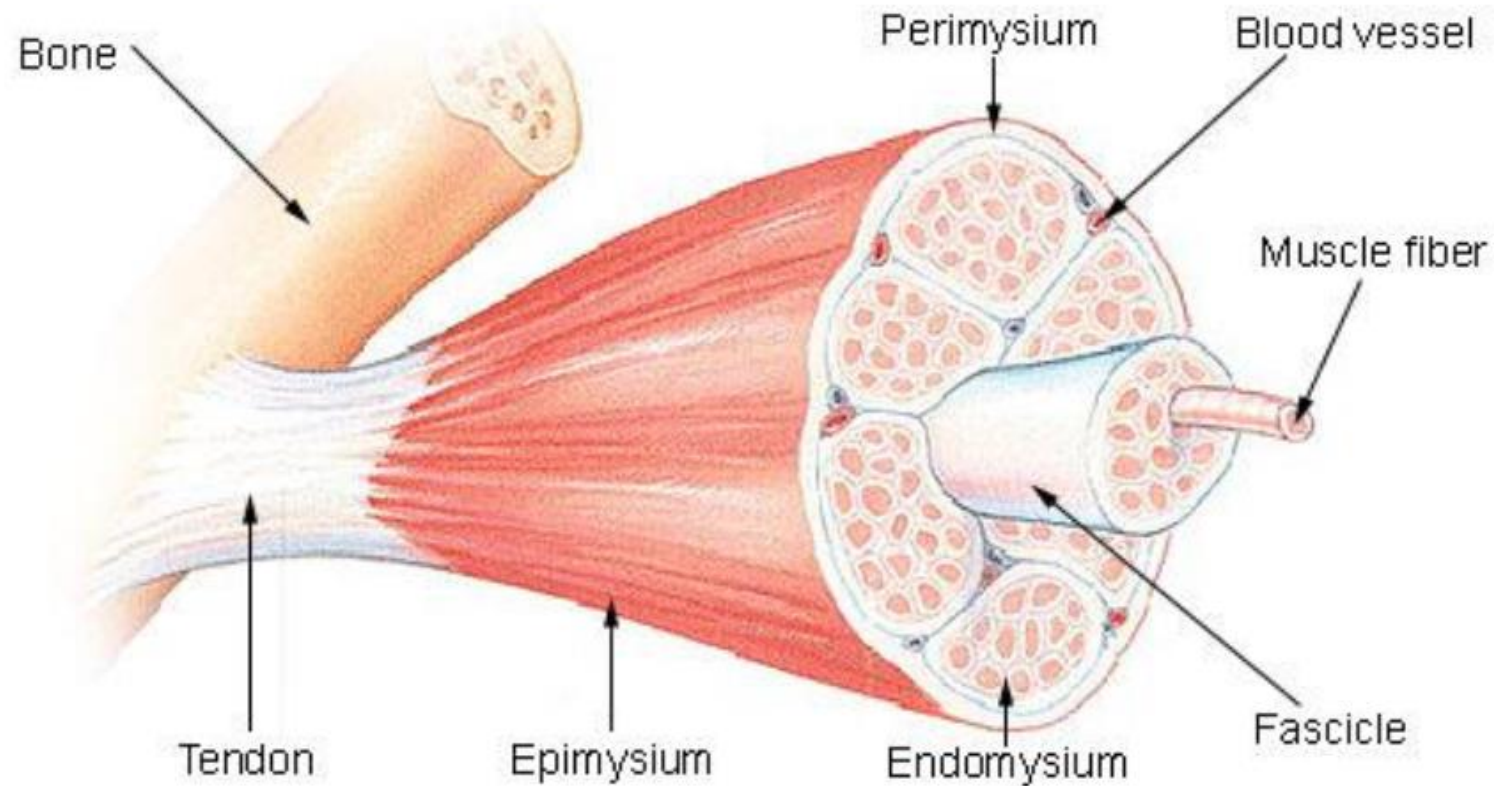
Gait Parameter	Fine-grid	Coarse-grid	Experiment
Total COT	0.167	0.180	0.190
Motor COT	0.087	0.100	0.110
Overhead COT	0.083	0.080	0.080
Hip COT	0.019	0.018	0.030
Ankle COT (push-off)	0.029	0.052	0.046
Ankle COT (foot-flip)	0.039	0.029	0.034
Step Length	0.38	0.39	0.38
Step Velocity	0.64	0.66	0.62
Step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

Bio-robotique

Comment décrire un muscle?

## ... D'où vient la rigidité variable ? (impédance variable)

### Structure of a Skeletal Muscle



### Quelles leçons ?

1. Hiérarchie et échelles
2. Matériaux multiples
3. Différentes rigidités
4. Non linéarités ?
5. Série et parallèle
6. Conditions aux limites
7. Hybridation active-passive



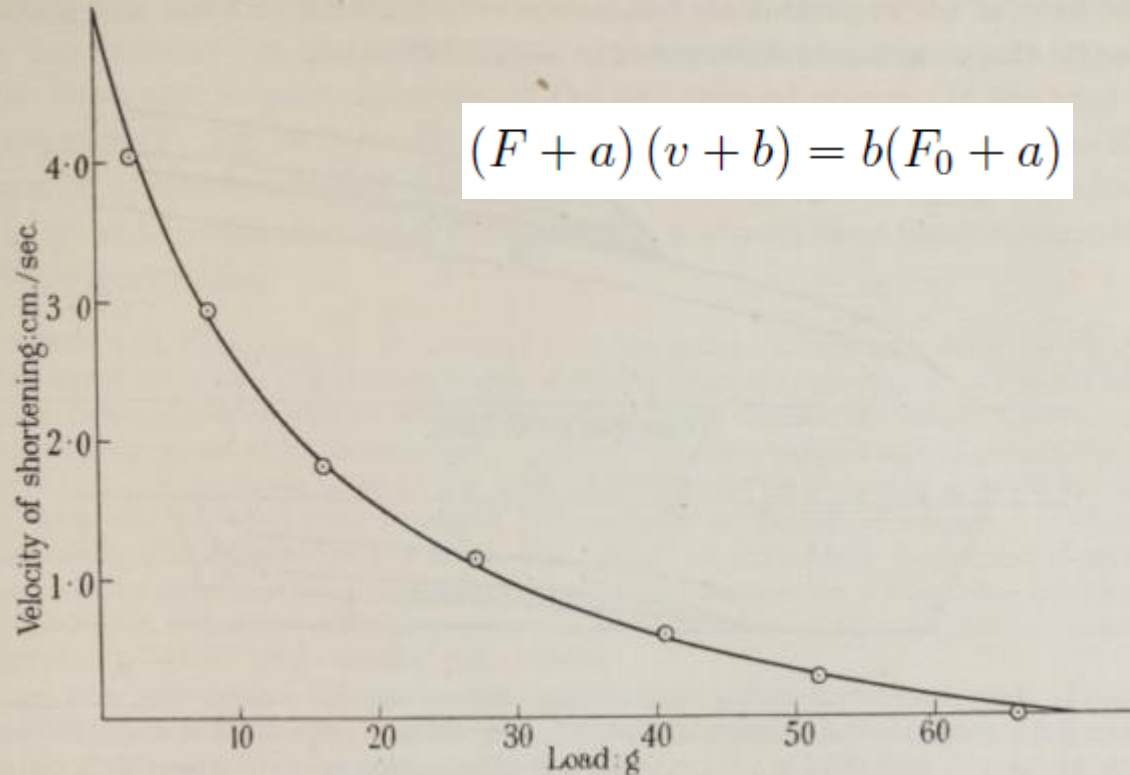
# Modèle de Hill

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)*



$$E = A + H + W$$

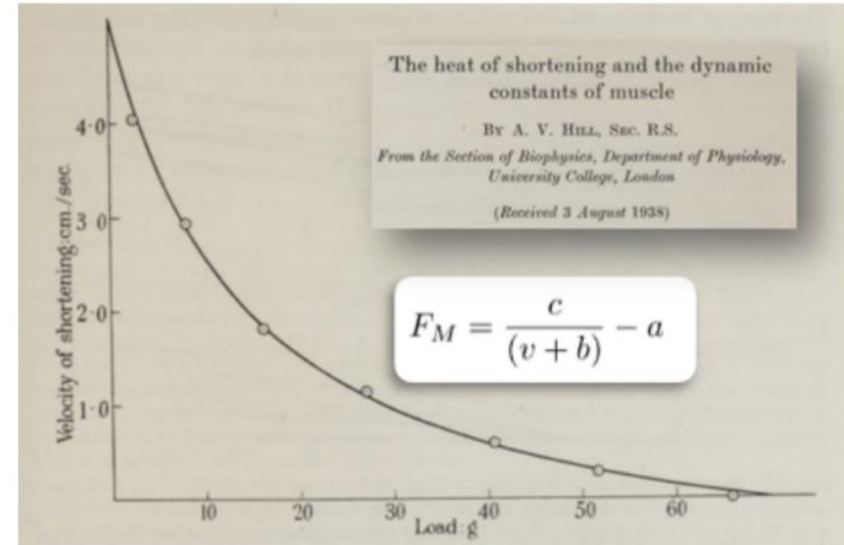
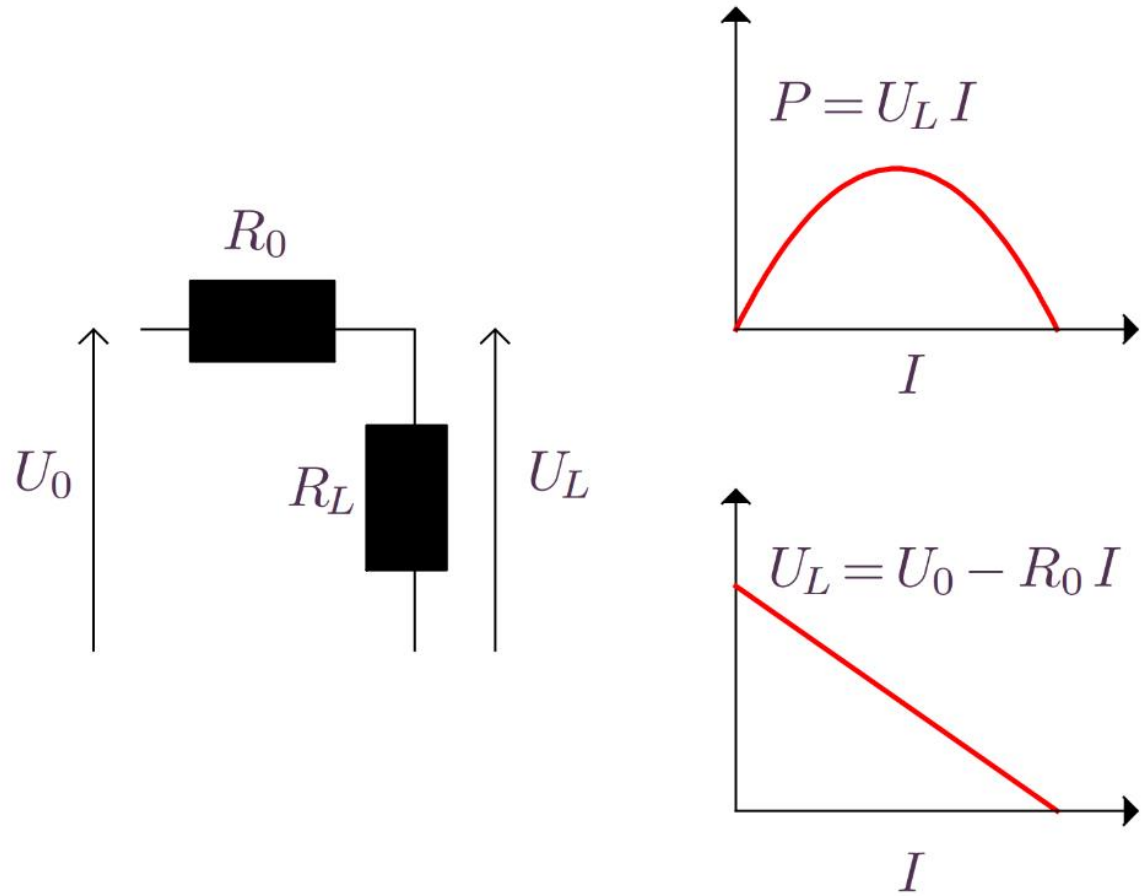
$$W = Fv$$

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

$$H = av$$

# Impédance mécanique variable

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

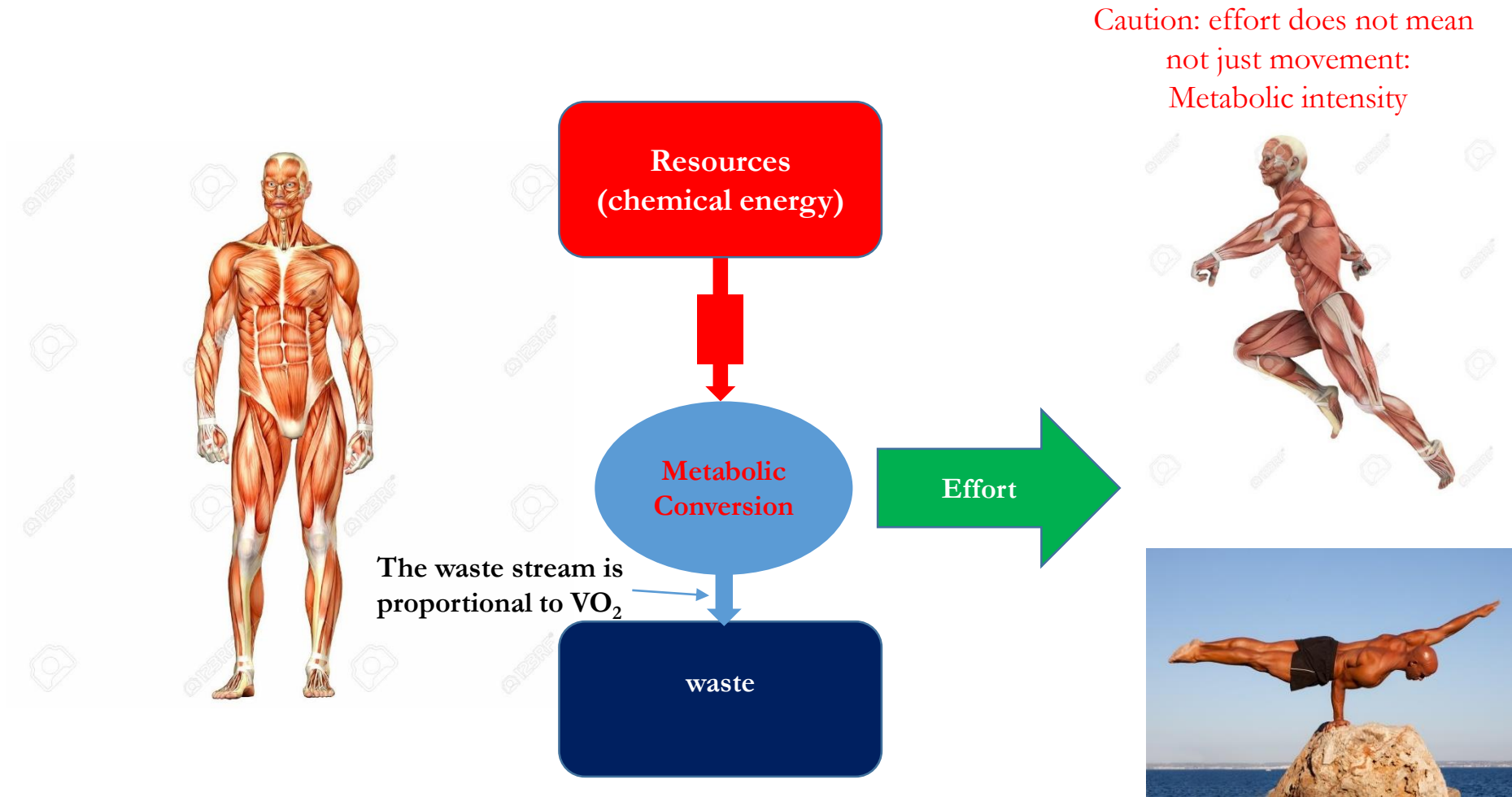


⇒ Feedback on Effective force  $U_L$ , due to the energy conversion process.

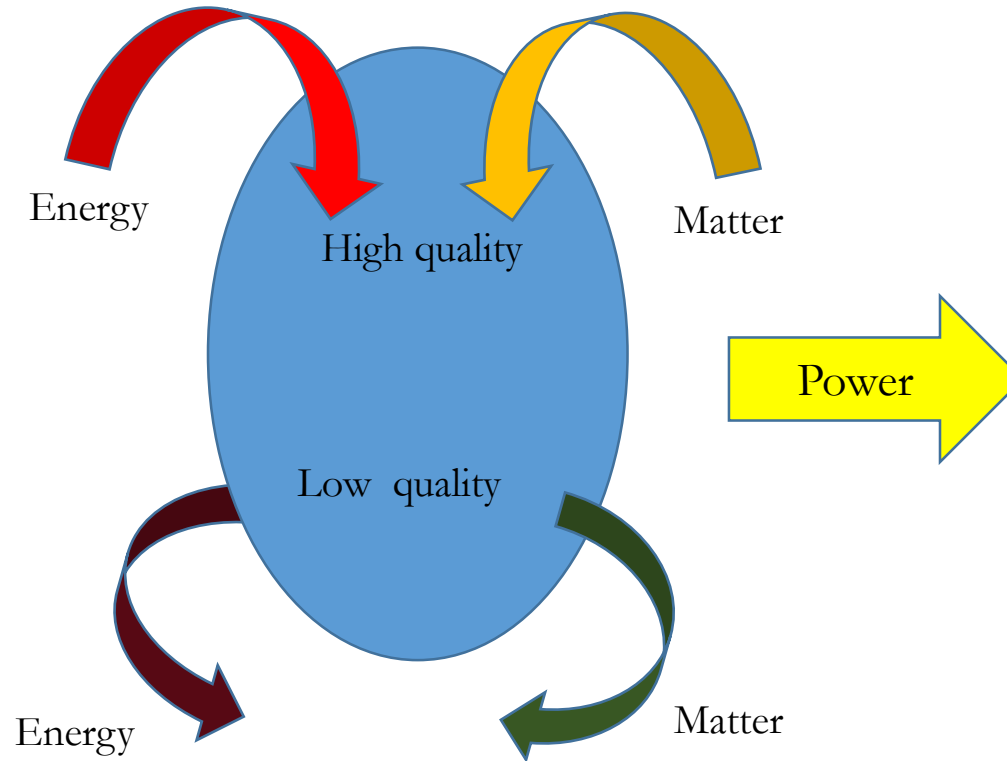


Vers un modèle thermodynamique du muscle

# Vers un modèle métabolique du muscle sous différents efforts



# Systeme thermodynamique: couplage energie-matiere

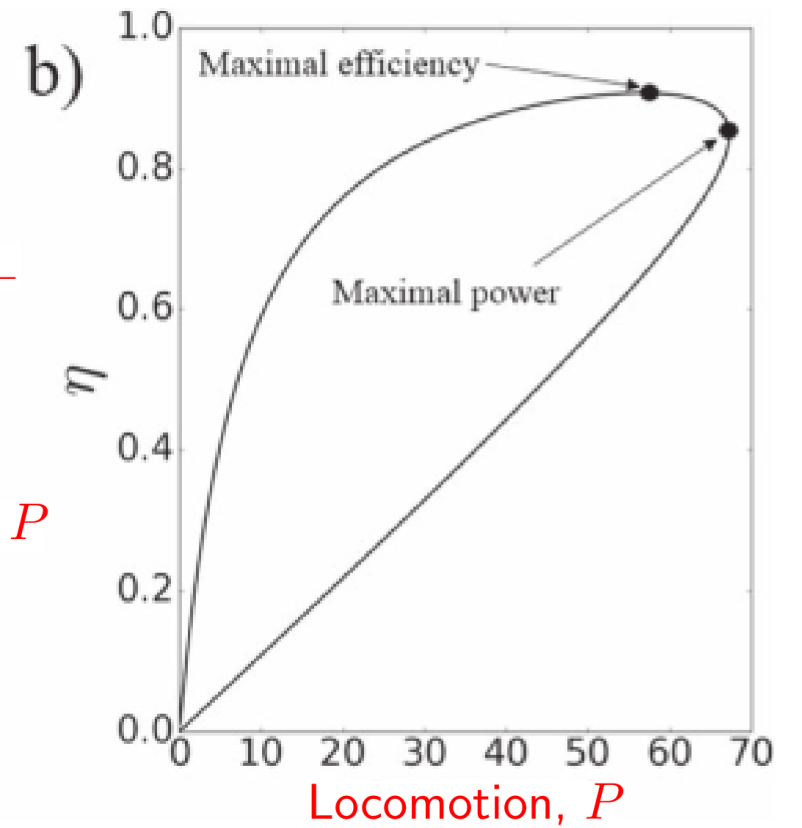
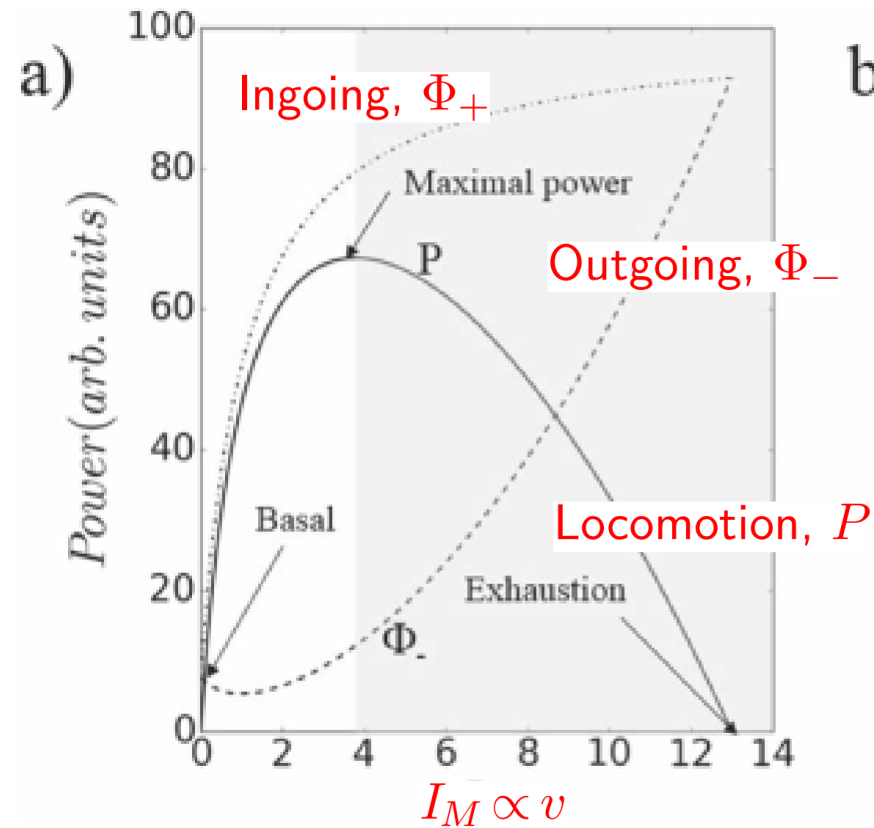
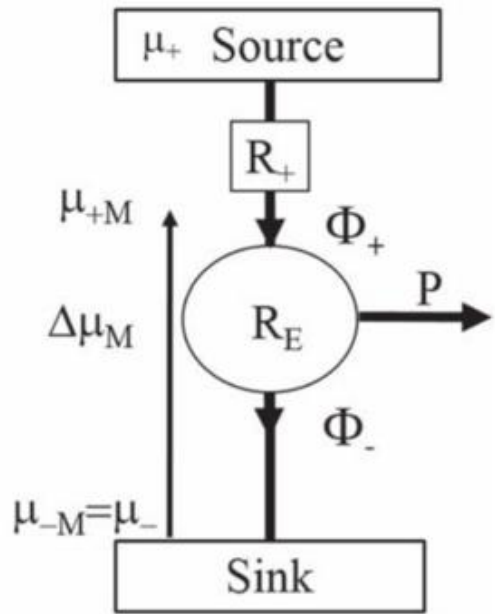


**Conservation des quantités : Première loi thermodynamique (conservation)**

**Modification des qualités : Deuxième loi thermodynamique (dispersion)**

# Working points

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



# Metabolic figure of merit

$$Z = \frac{R_{fb} F_B I_T}{R_M B}$$

- $I_T$  : Maximal intensity: the chemistry conversion
- $R_{fb} I_T = \text{cte}$  : Minimal viscosity: the chemistry conversion
- $F_B / B = \text{cte}$  : Available power and dissipation trade-off

# The goal

1. Hill's phenomenological equation (1938)

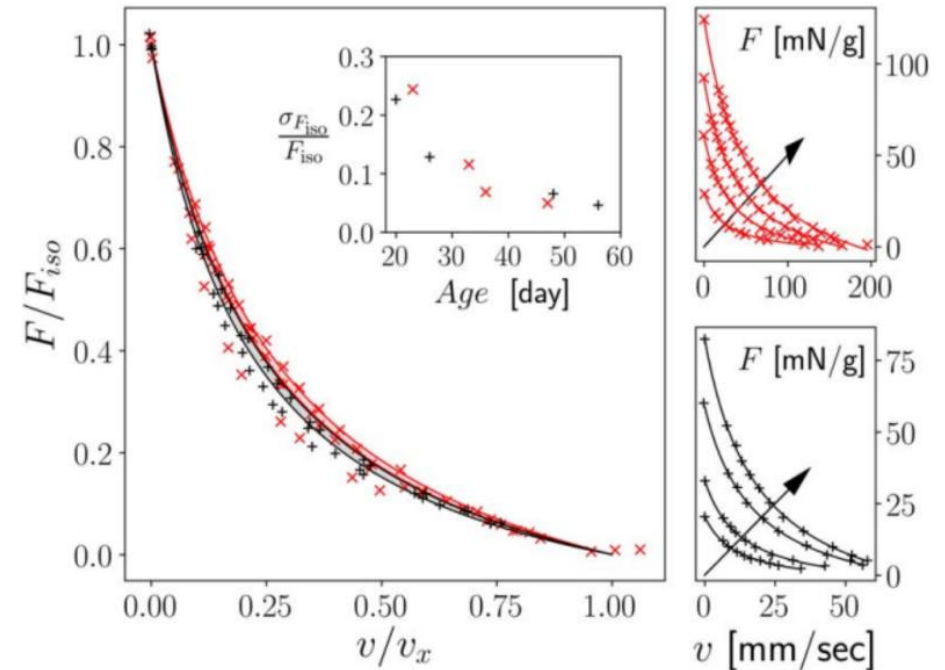
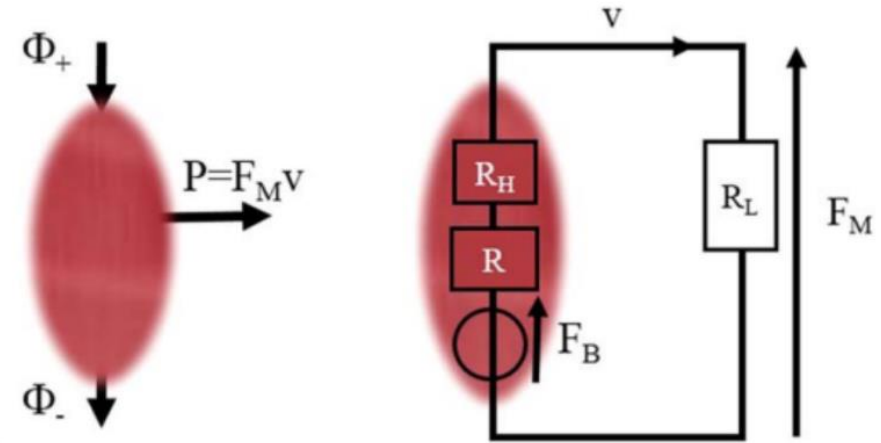
$$F_M = \frac{c}{v+b} - a(v)$$

2. From this model

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

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

$$\begin{aligned} a(I_M) &= R_{fb} I_T + R_M I_M \\ b &= I_T \\ c &= (F_{iso} + R_{fb} I_T) I_T \end{aligned}$$

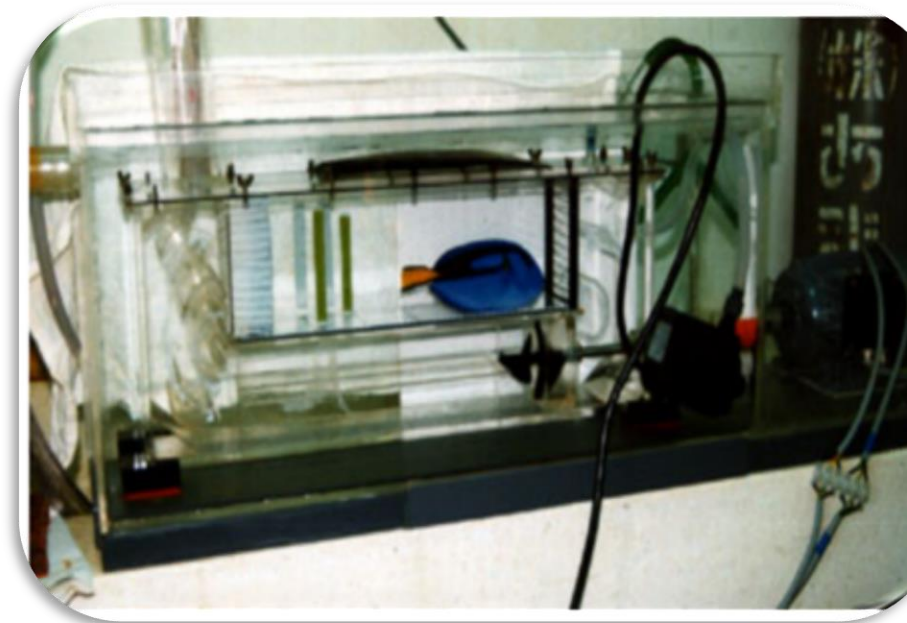
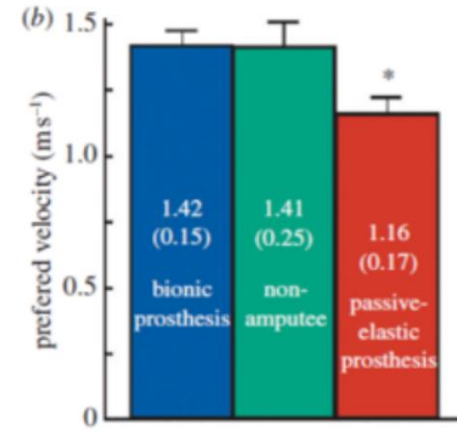
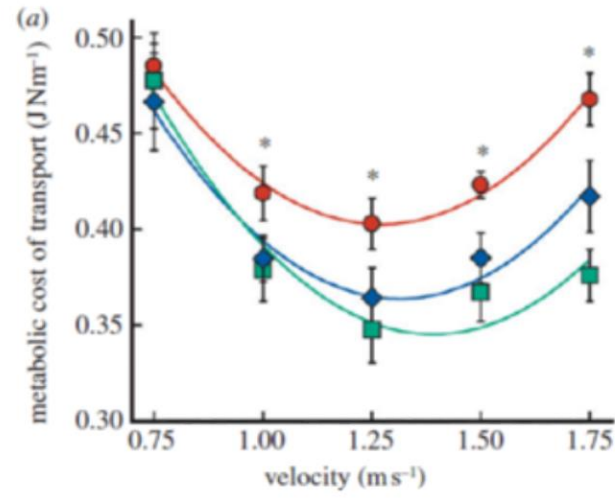




Back to the COT

# Experimental COT

Bionic leg normalizes walking gait H. M. Herr & A. M. Grabowski 46



# A propos du point de fonctionnement

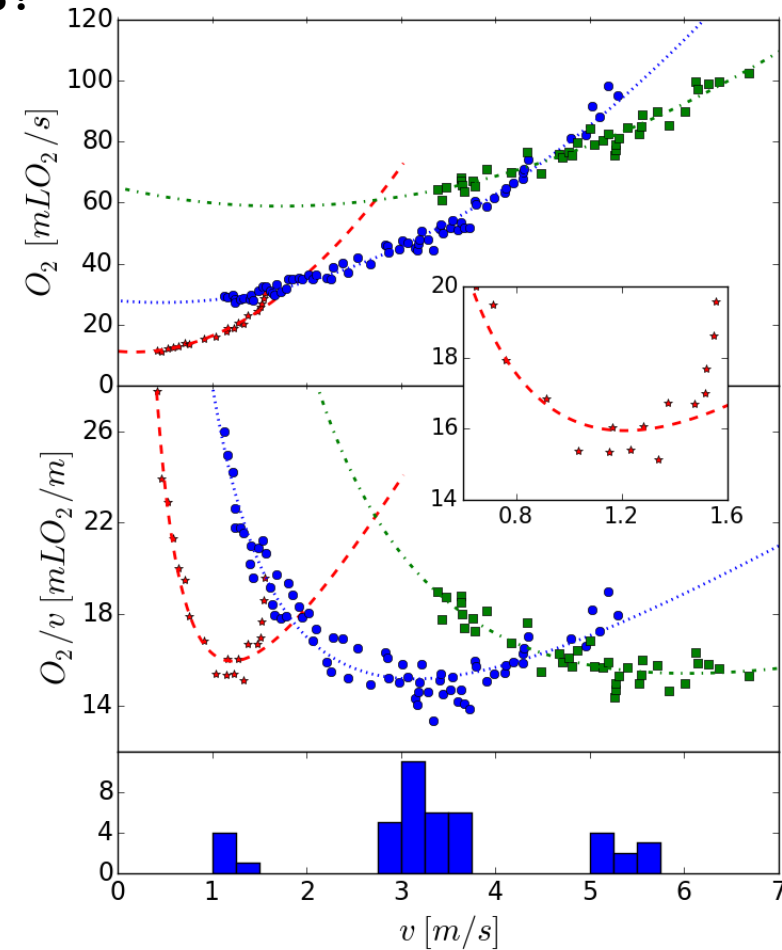
Maximiser la vitesse des échanges?  
Maximiser le rendement dans les échanges?  
Minimiser la production des déchets?



En fonction de son allure, le cheval minimise sa production de déchet.

Thermodynamics of Animal Locomotion

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

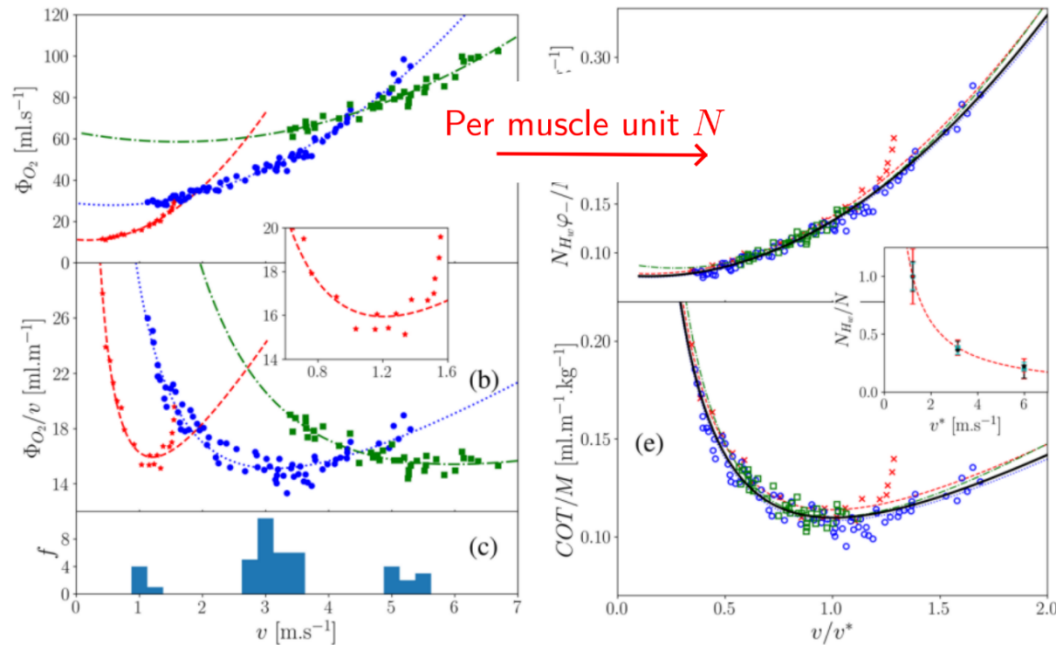


En fonction du point de fonctionnement de nos sociétés...

# Horse results

$COT = a_0 k + R_M k^2 v + \frac{B}{v}$	$R_v$ 1/s	$B_v$ W/kg	$COT^* \propto \sqrt{R_M B}$ N/kg
Walk	$1.10 \pm 0.18$	$1.60 \pm 0.13$	$2.27 \pm 0.43$
Trot	$0.40 \pm 0.03$	$3.98 \pm 0.18$	$2.16 \pm 0.21$
Gallop	$0.24 \pm 0.08$	$9.01 \pm 1.71$	$2.20 \pm 0.98$

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



## PHYSICAL REVIEW LETTERS

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### Thermodynamics of Animal Locomotion

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

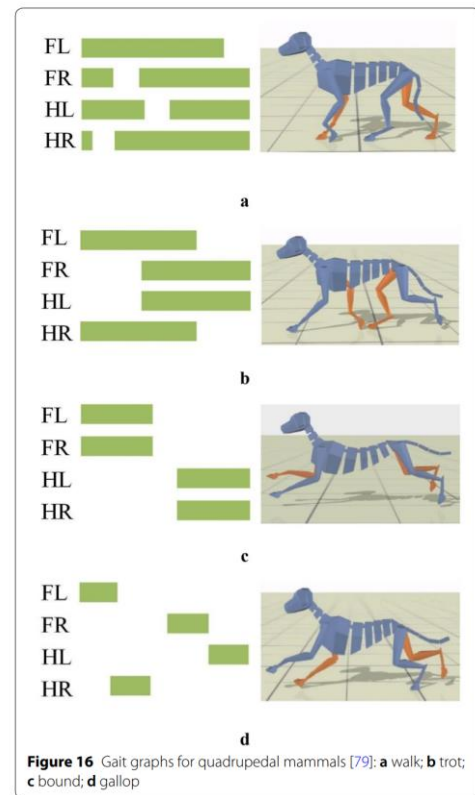


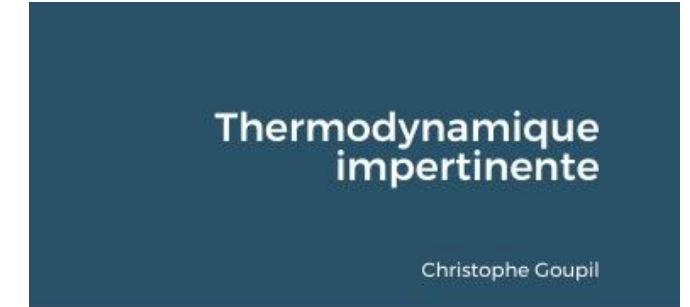
Figure 16 Gait graphs for quadrupedal mammals [79]: a walk; b trot; c bound; d gallop

# Merci!

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

[christophe.goupil@u-paris.fr](mailto:christophe.goupil@u-paris.fr)



Goupil, *et al.* « Thermodynamics of Metabolic Energy Conversion under Muscle Load ». *New Journal of Physics*, 2019. <https://doi.org/10.1088/1367-2630/ab0223>.

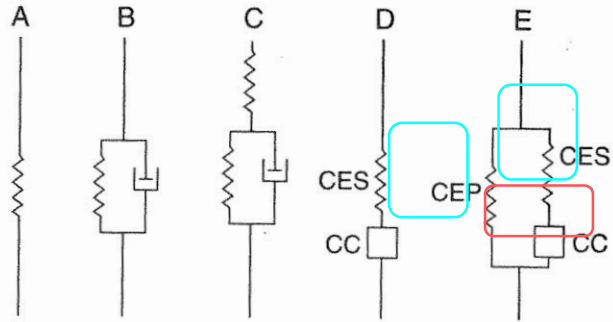
Goupil and Herbert « Adapted or Adaptable: How to Manage Entropy Production? » *Entropy* 2020. <https://doi.org/10.3390/e22010029>.

Herbert, *et al.* « Thermodynamics of Animal Locomotion ». *Physical Review Letters*, 2020. <https://doi.org/10.1103/PhysRevLett.125.228102>.



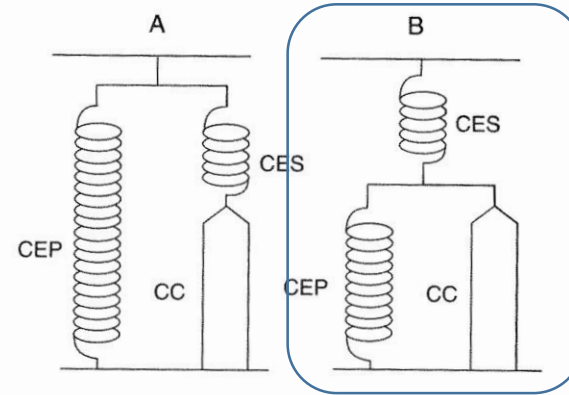


# Un muscle et des modèles



**Fig. 2.1.** Évolution des modèles de muscles.

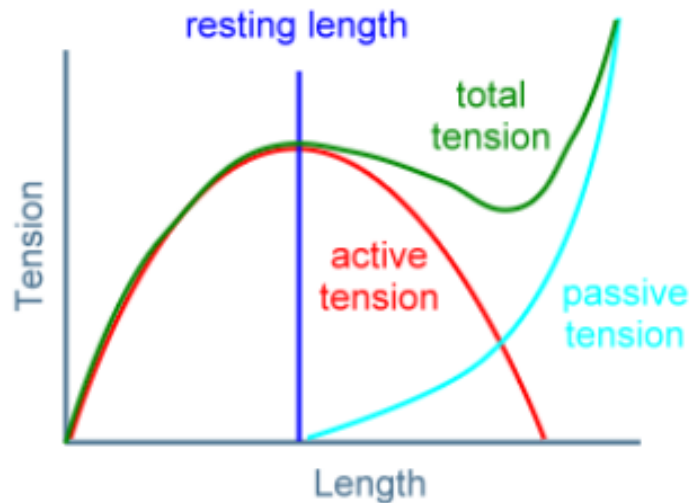
(A) Weber, 1846; (B) A.V. Hill, 1922; (C) Levin et Wyman, 1927; (D) A.V. Hill, 1938  
(E) A.V. Hill, 1951.



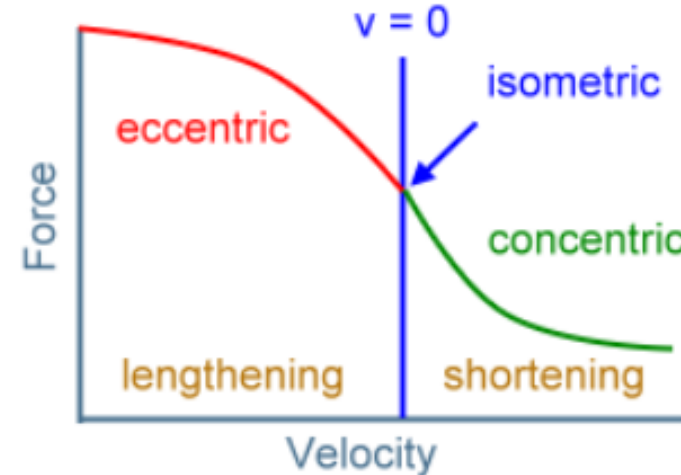
**Fig. 2.2.** Modèles à trois composantes.

(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

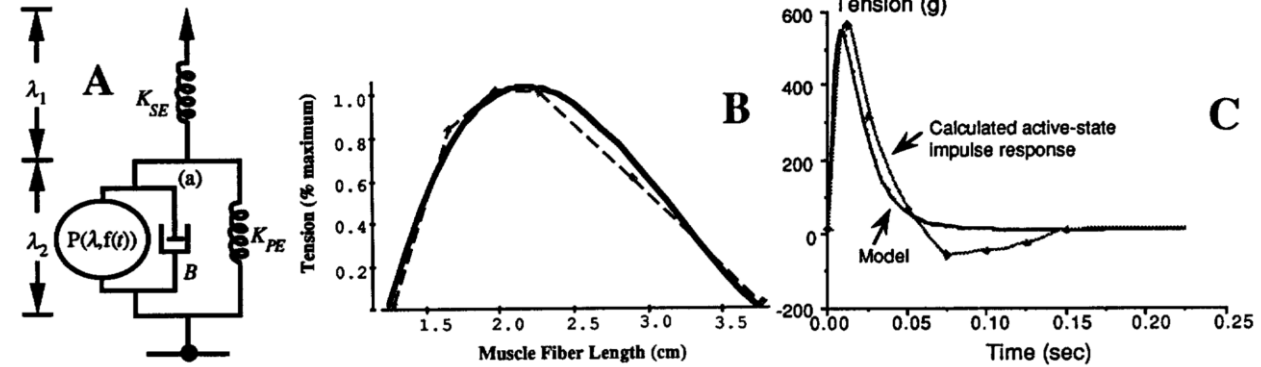


Fig. 8A–C. An active state muscle model. A The mechanical model of the muscle:  $\lambda_1$  and  $\lambda_2$  are taken as the displacement about the resting length, while  $P(\lambda, f(t))$  is the active tension developed by the force generator. B Active tension vs. length for a single fiber of frog 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:  $h(t) = 1200(\exp(-70t) - \exp(-210t))$

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

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

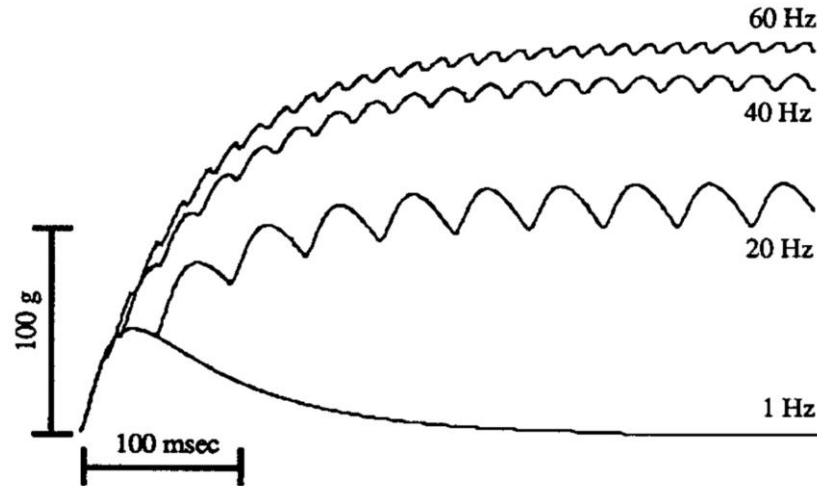


Fig. 9. Force in the active state muscle model of Fig. 8 at resting for a series unit impulses at various frequencies

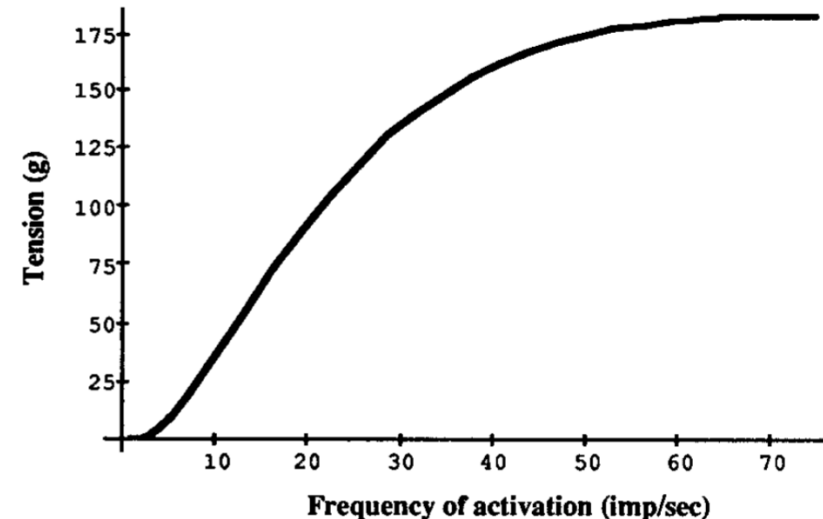


Fig. 10. Steady state tension output of the muscle model at  $\lambda = \lambda^*$ , i.e., length beyond which passive force develops