So much work, so little time: maximizing elastic energy within the duration of muscle contraction

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Outline

I. Elastic systems in biology

II. Static muscle-spring model

III. Dynamic muscle-spring model

No parallelization

Parallelization

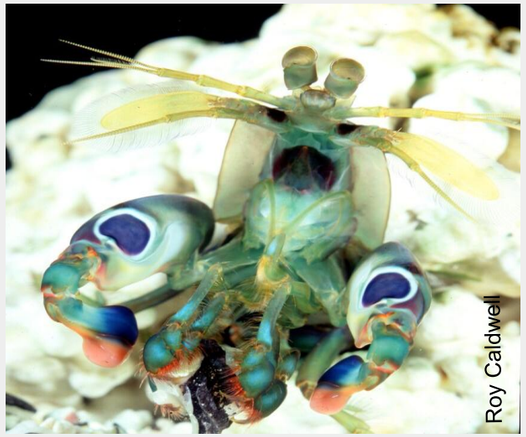
Outline

I. Elastic systems in biology

II. Static muscle-spring model

III. Dynamic muscle-spring model

What do these animals have in common?

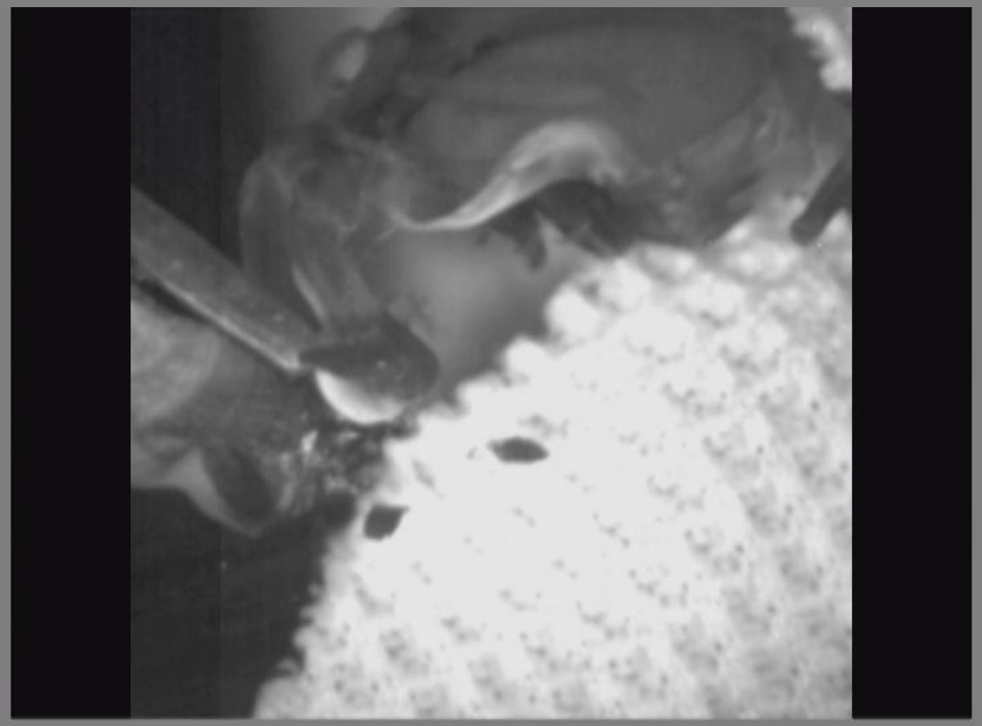


Mantis shrimp

Chameleon

Flea

What do these animals have in common?



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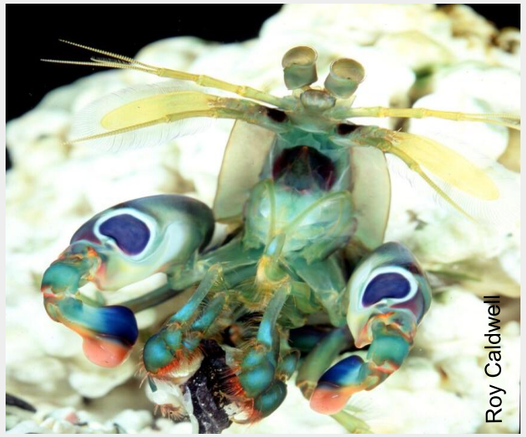

Video courtesy of Stephen Deban

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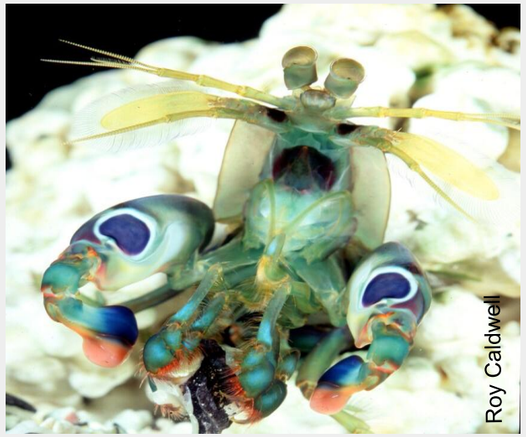

Video courtesy of Gregory Sutton

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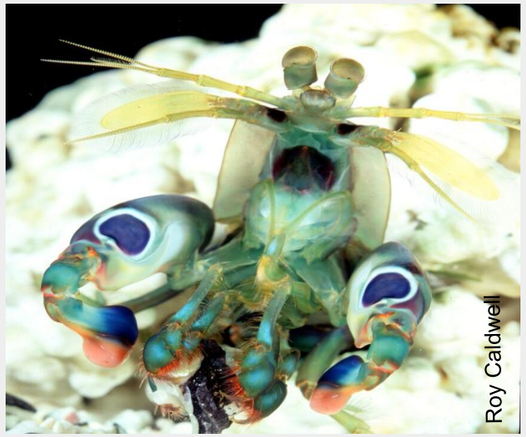
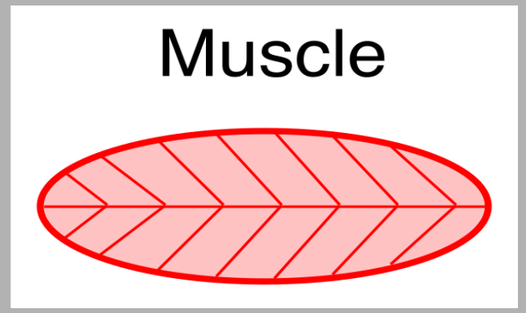


470,000 W/kg

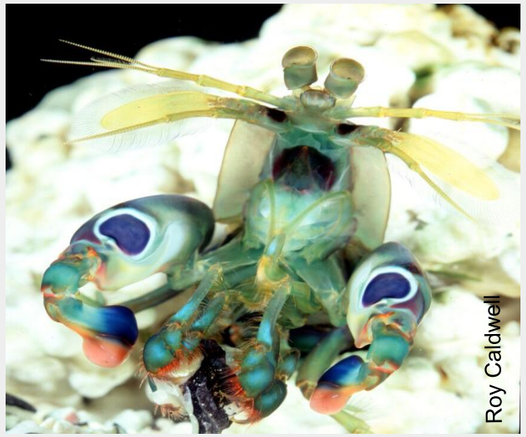
41,000 W/kg

10,000 W/kg



Most powerful muscle:
120 W/kg

What do these animals have in common?



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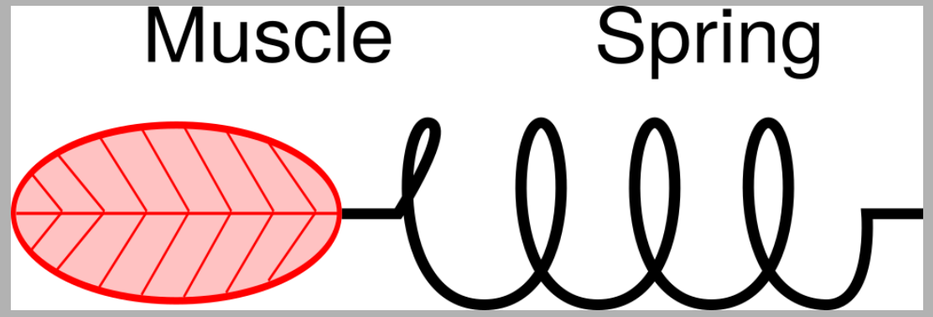
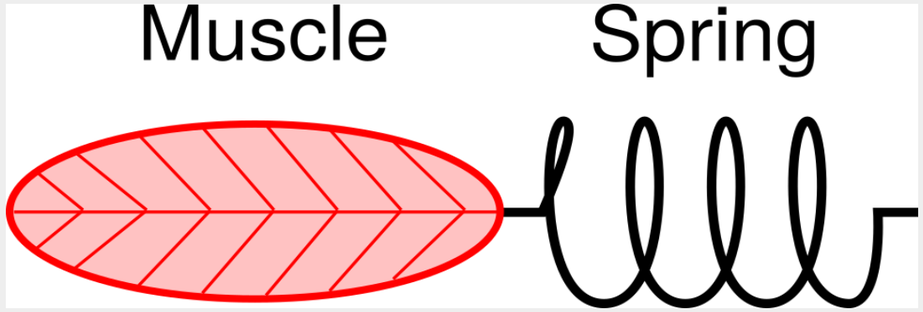
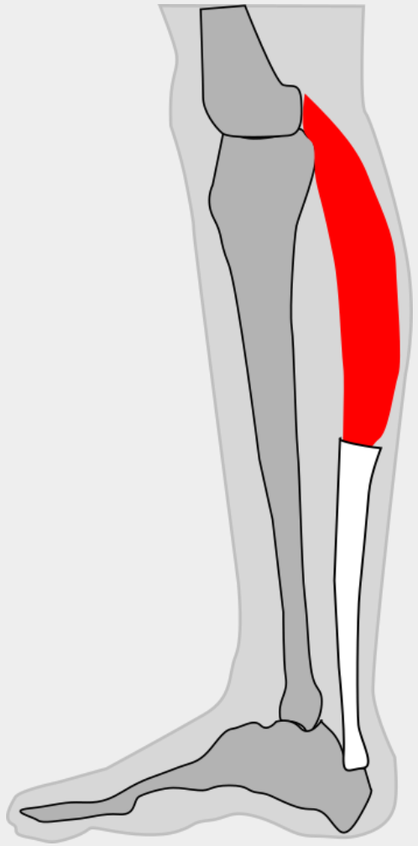


Are springs tuned to muscle to store maximal elastic energy?



Bullfrogs store elastic energy in their hindlimbs before jumping.



Human leg

Outline

I. Elastic systems in biology

II. Static muscle-spring model

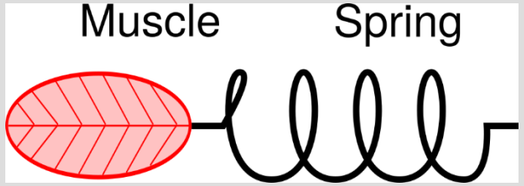
III. Dynamic muscle-spring model

Connecting muscle and springs

$$F_{muscle} = F_{spring}$$

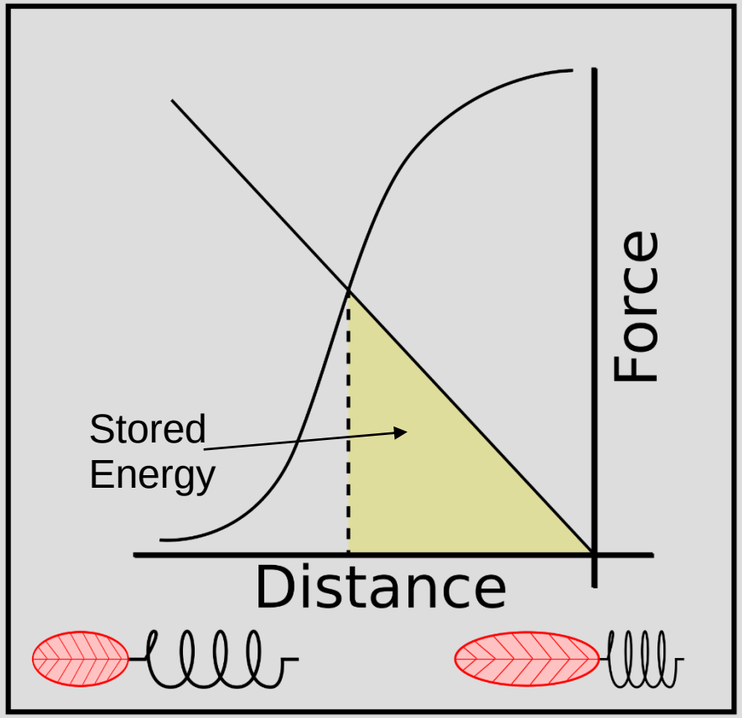
$$F_{activation}(t) \cdot F_{velocity}(v) \cdot F_{length}(x_m) = -kx_s$$

Dynamic factors

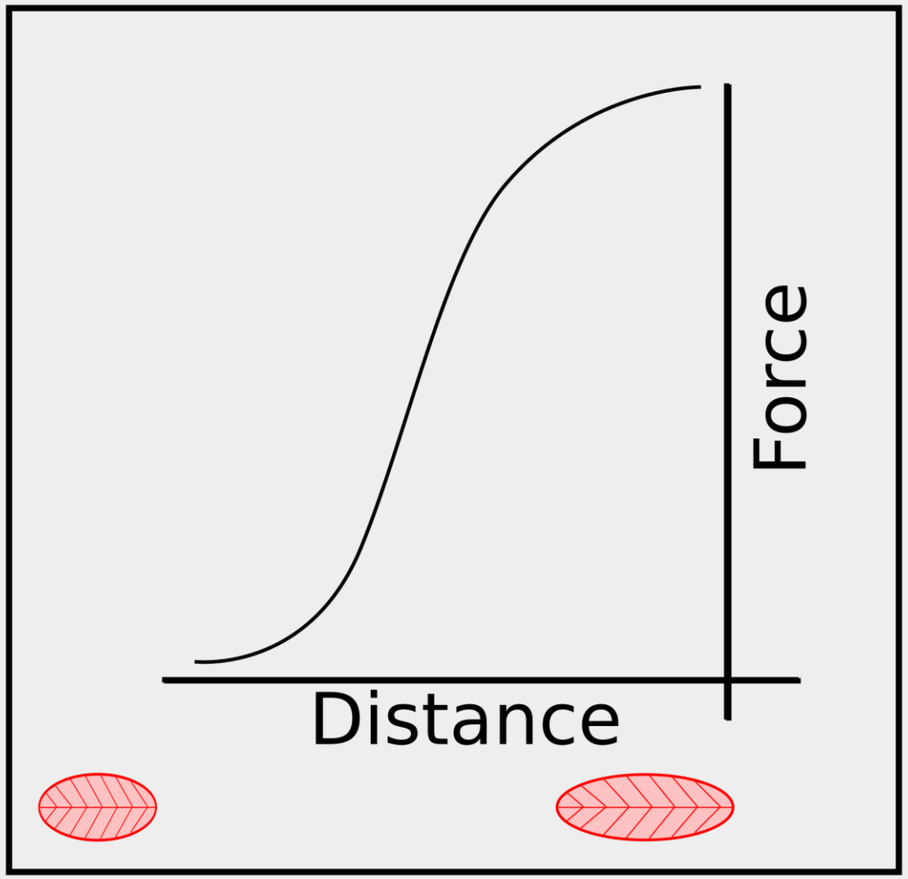


$$x_m = -x_s$$

$$F_{length}(x_m) = kx_m$$



Does the stiffness of Bullfrog tendon maximize energy storage?



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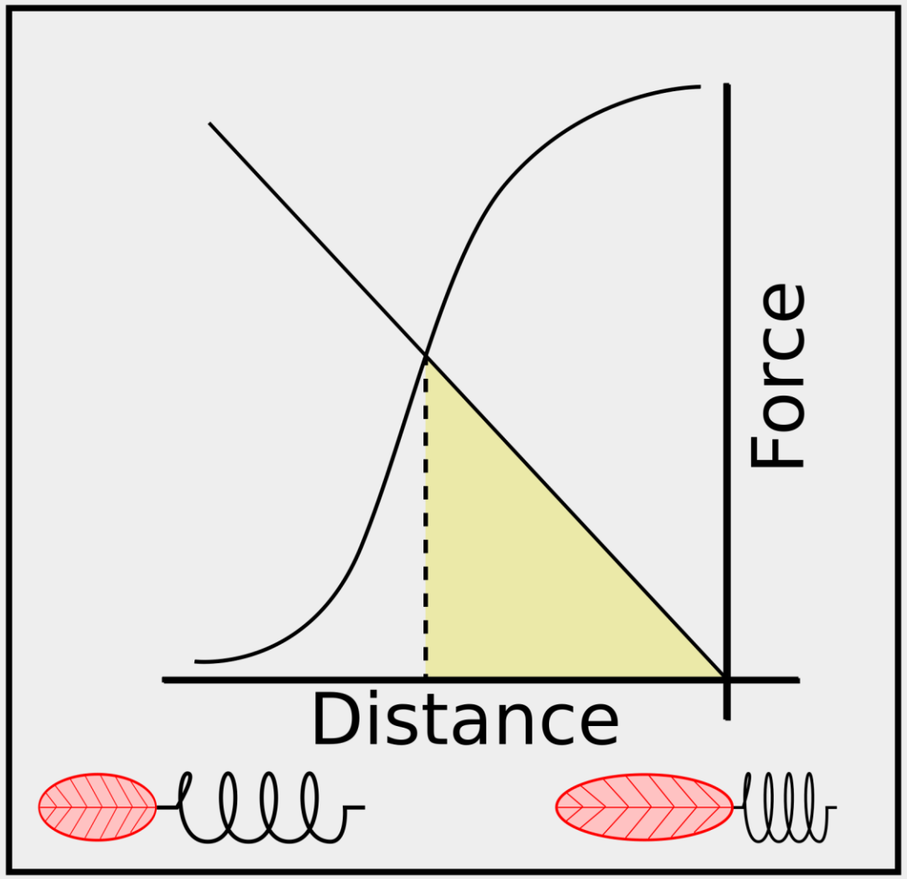

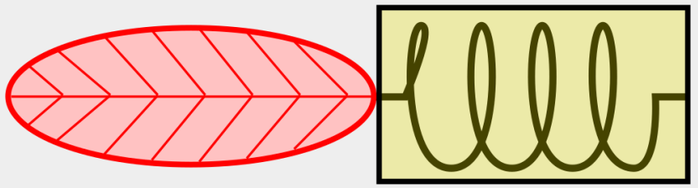

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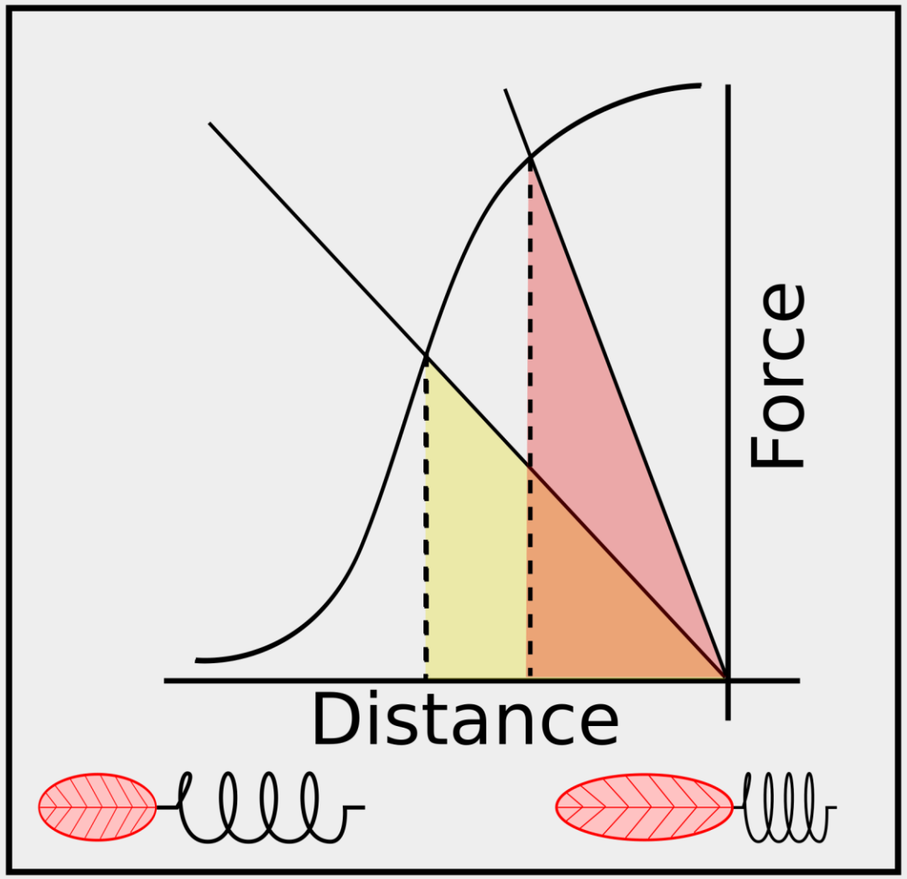

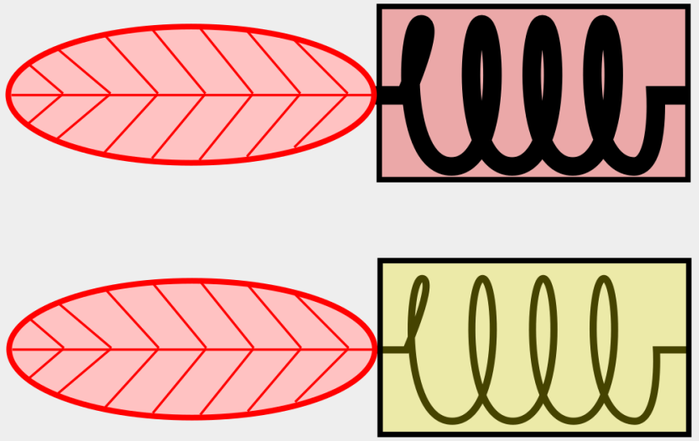

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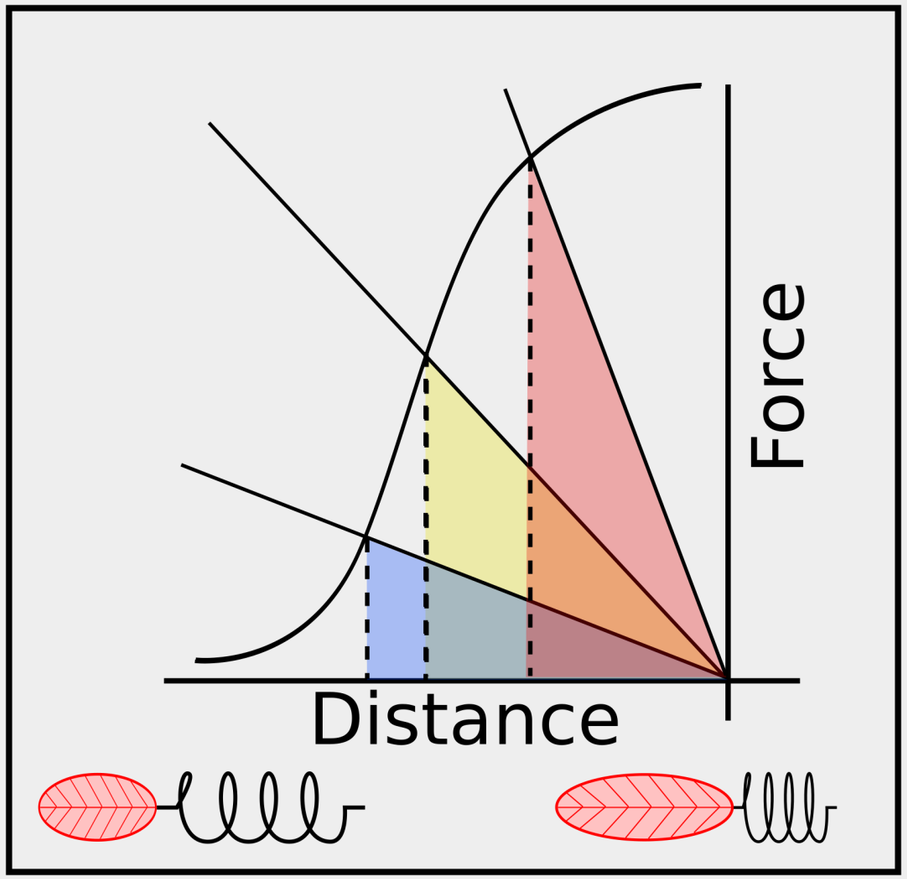

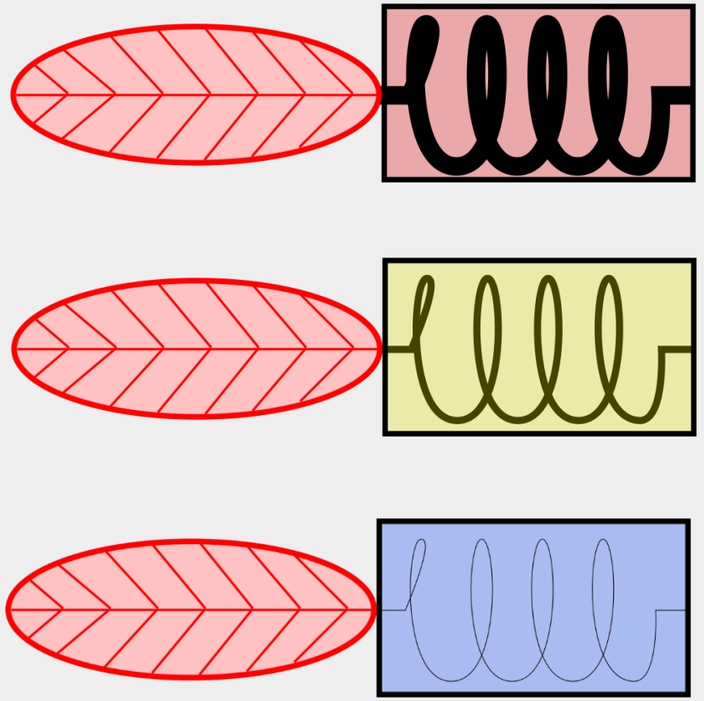

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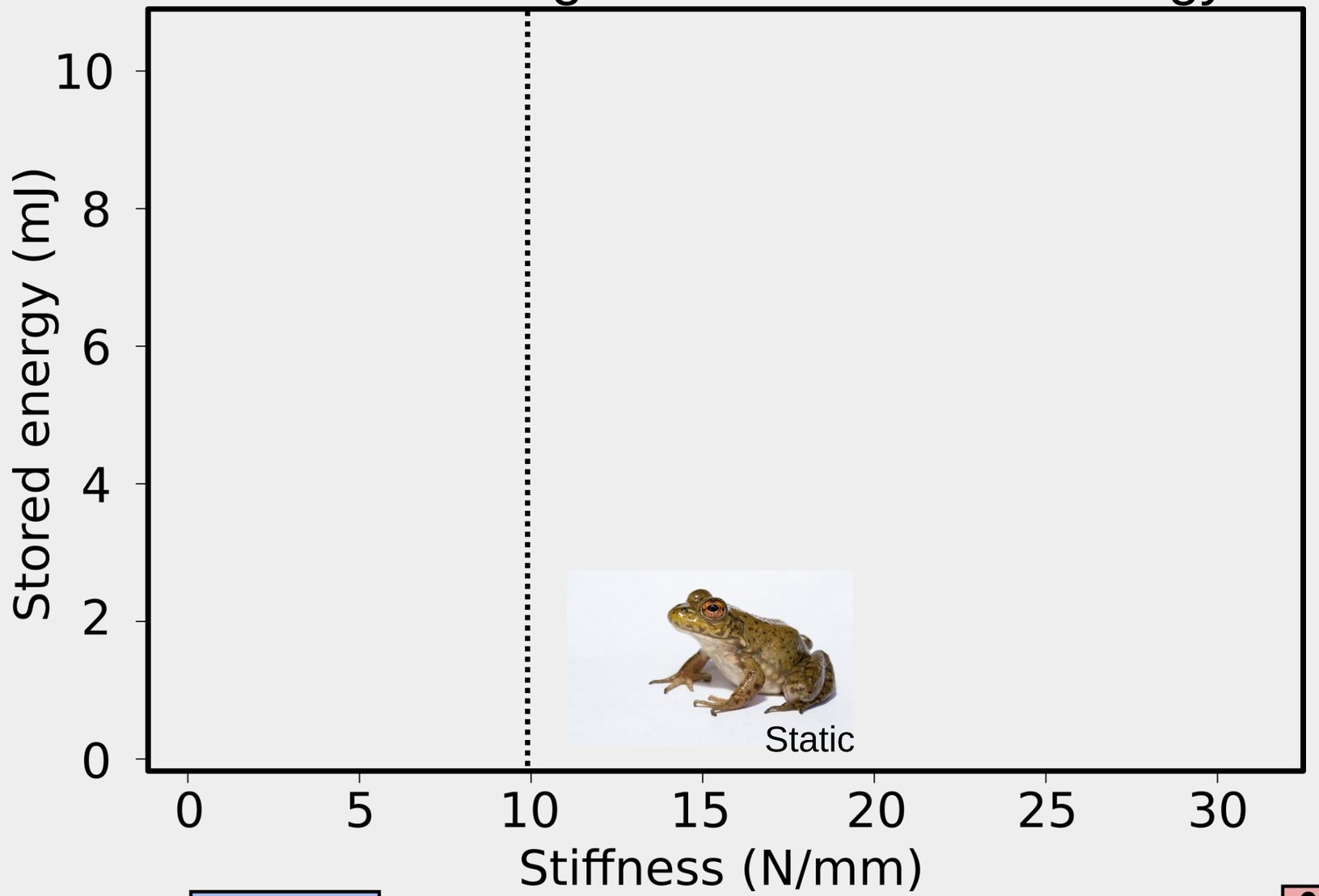

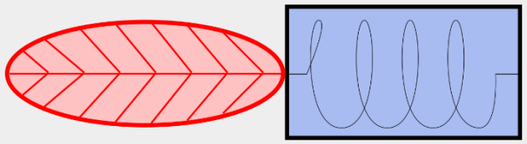

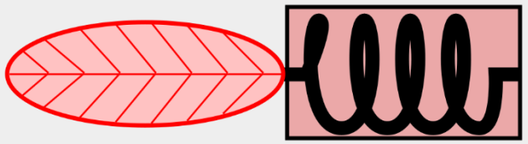

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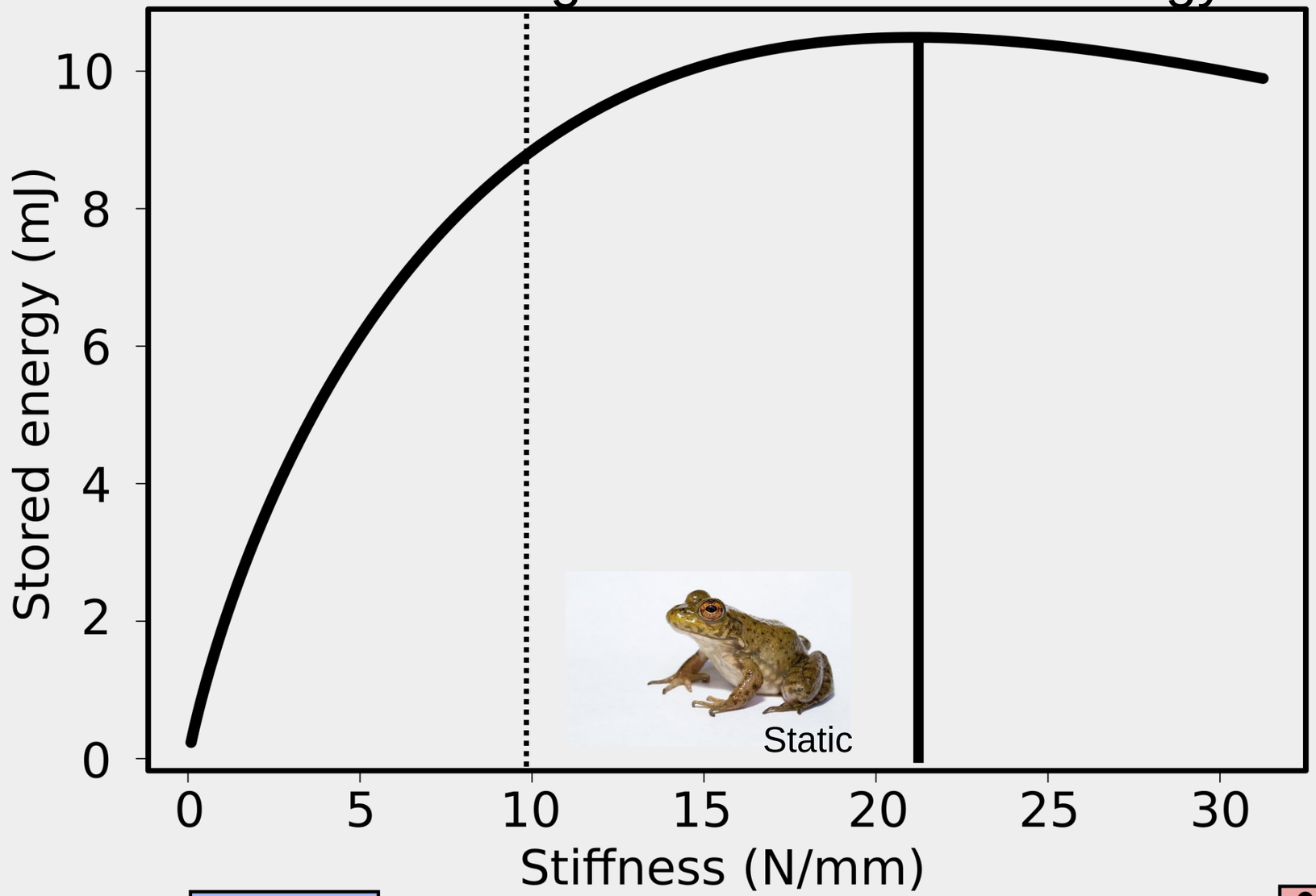
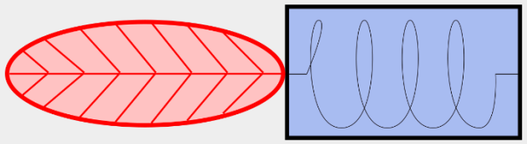
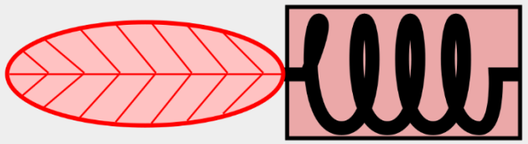
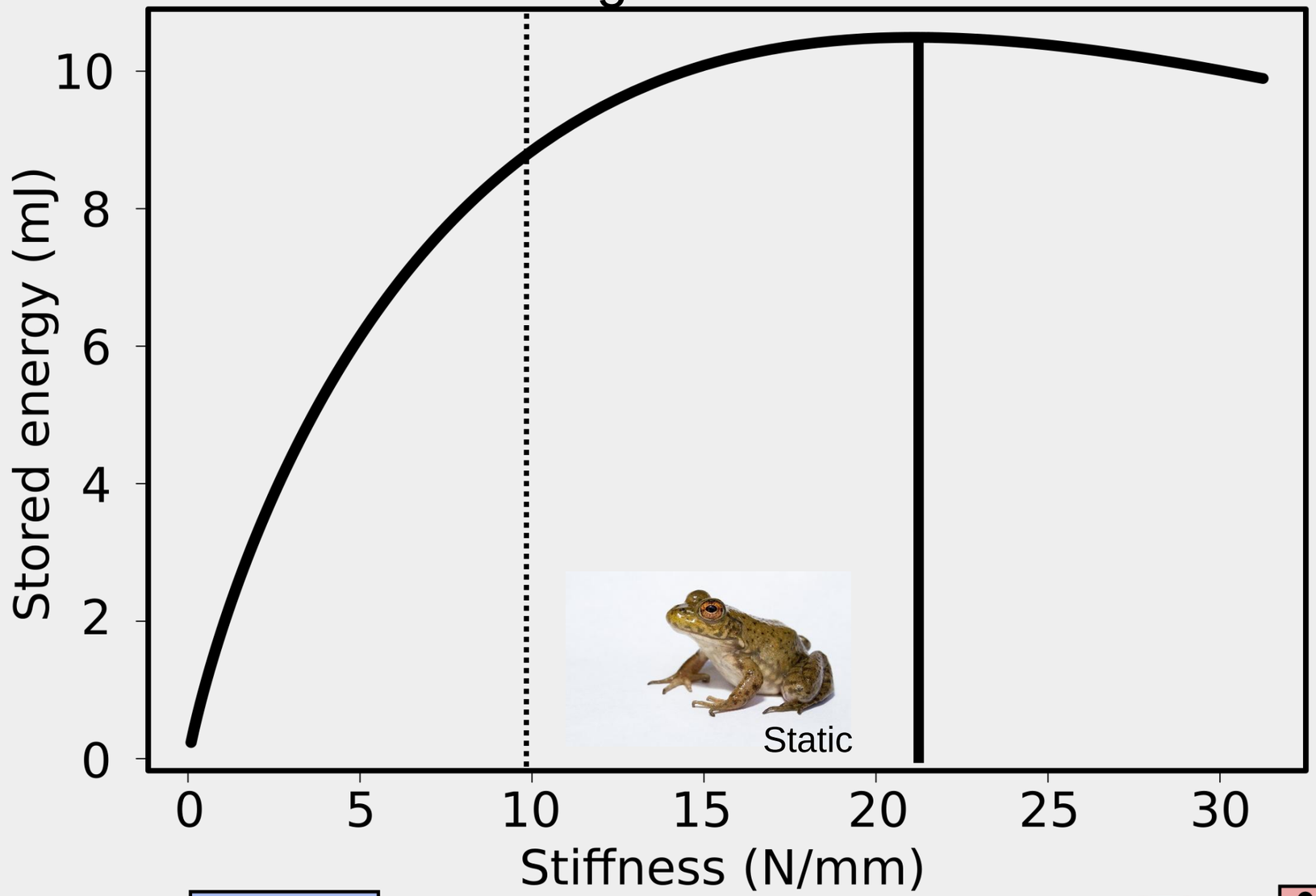
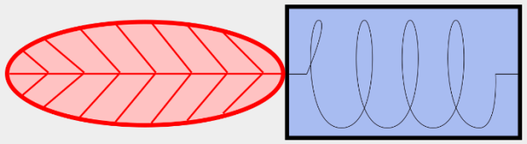


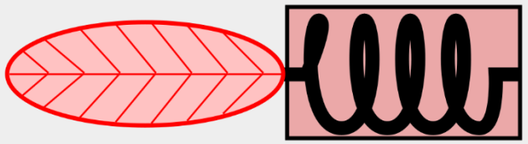




Why doesn't the stiffness of Bullfrog tendon match the model's prediction?







Why doesn't the stiffness of Bullfrog tendon match the model's prediction?

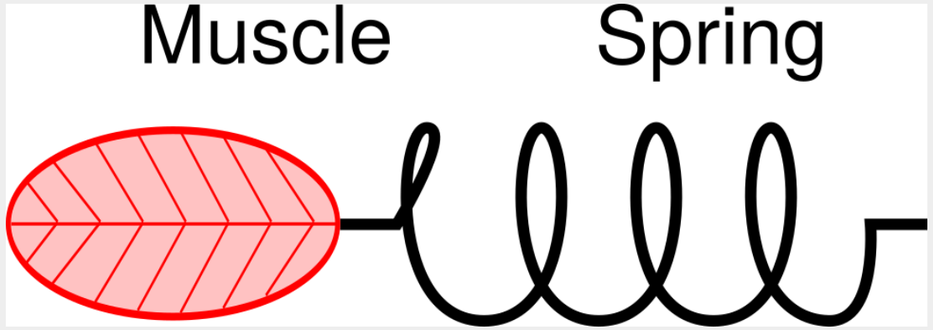
1) Bullfrog muscles and tendons are not tuned to store maximal elastic energy.

2) The mathematical model is incorrect.

Is the model appropriate for our question?

$$F_{muscle} = F_{spring}$$

$$F_{activation}(t) \cdot F_{velocity}(v) \cdot F_{length}(x_m) = kx_m$$



Full contraction

Is the model appropriate for our question?

Full contraction: 100 ms

Model endpoint

Muscle stretches spring: 50 ms

Biological endpoint

Muscle is not fully contracted prior to jump!

Azizi and Roberts (2010)

Outline

I. Elastic systems in biology

II. Simplified muscle-spring model

III. Dynamic muscle-spring model

Investigating the dynamic effects of muscle length

$$F_{muscle} = F_{spring}$$

$$F_{activation}(t) \cdot F_{velocity}(v) \cdot F_{length}(x_m) = kx_m$$

$$F_{activation}(t) \cdot F_{velocity}(\Delta x_m, \Delta t) \cdot F_{length}(x_m) = kx_m$$

Indirect effects

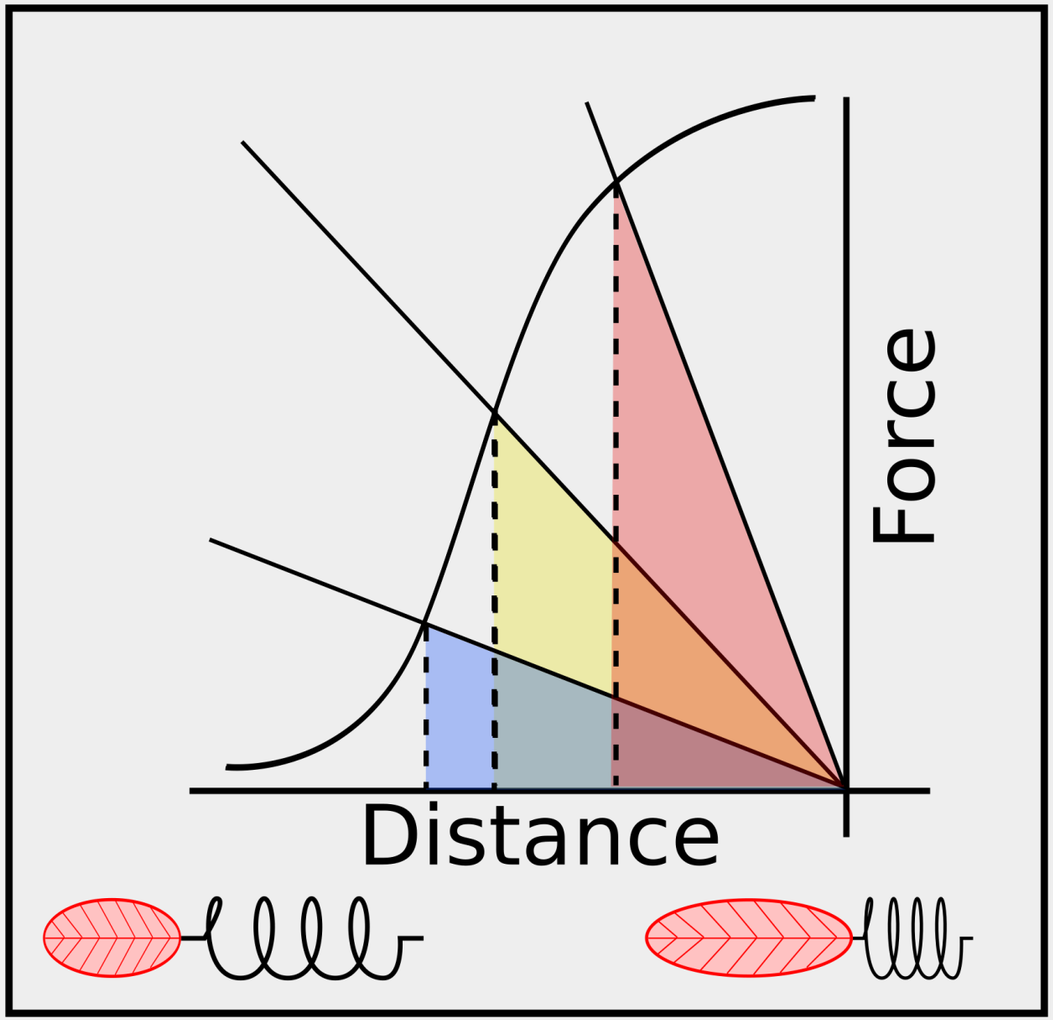
Direct effects

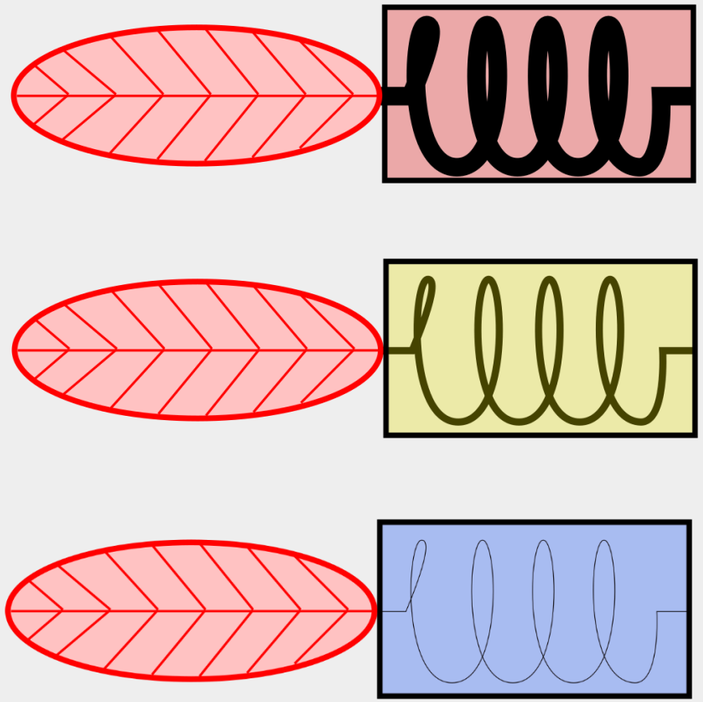
Find the single value of x_m that satisfies the equation.

$$\frac{F_{activation}(t)}{k} = \frac{x_m}{F_{length}(x_m) \cdot F_{velocity}(\Delta x_m, \Delta t)}$$

Does the stiffness of Bullfrog tendon maximize energy storage?

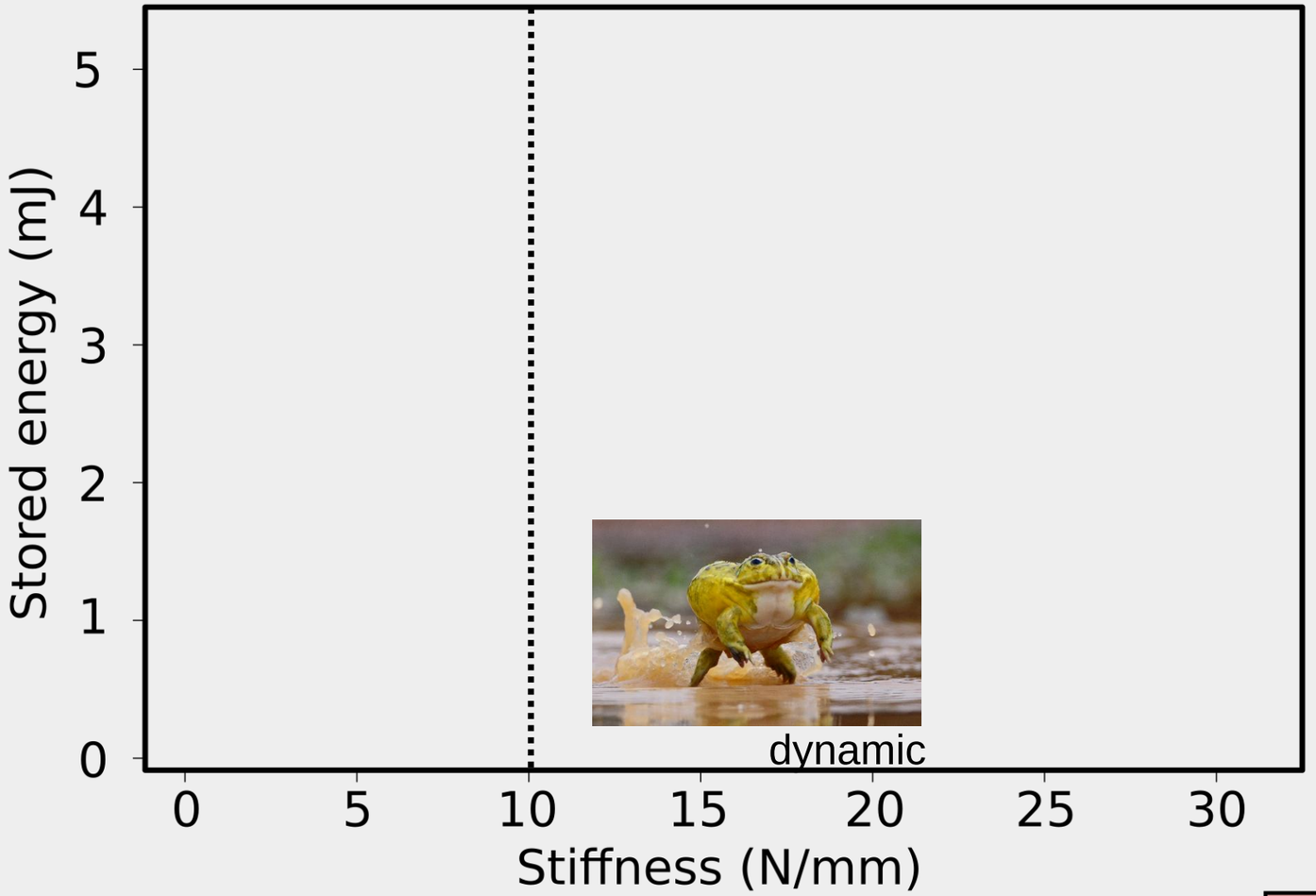
(within 50 ms)

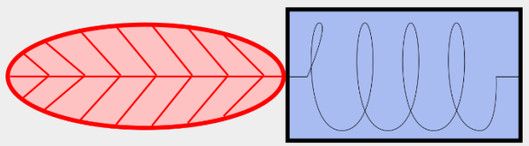


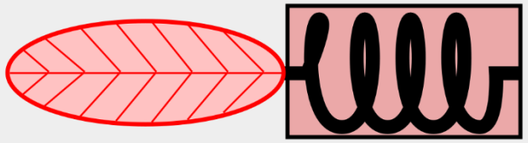


Does the stiffness of Bullfrog tendon maximize energy storage?

(within 50 ms)

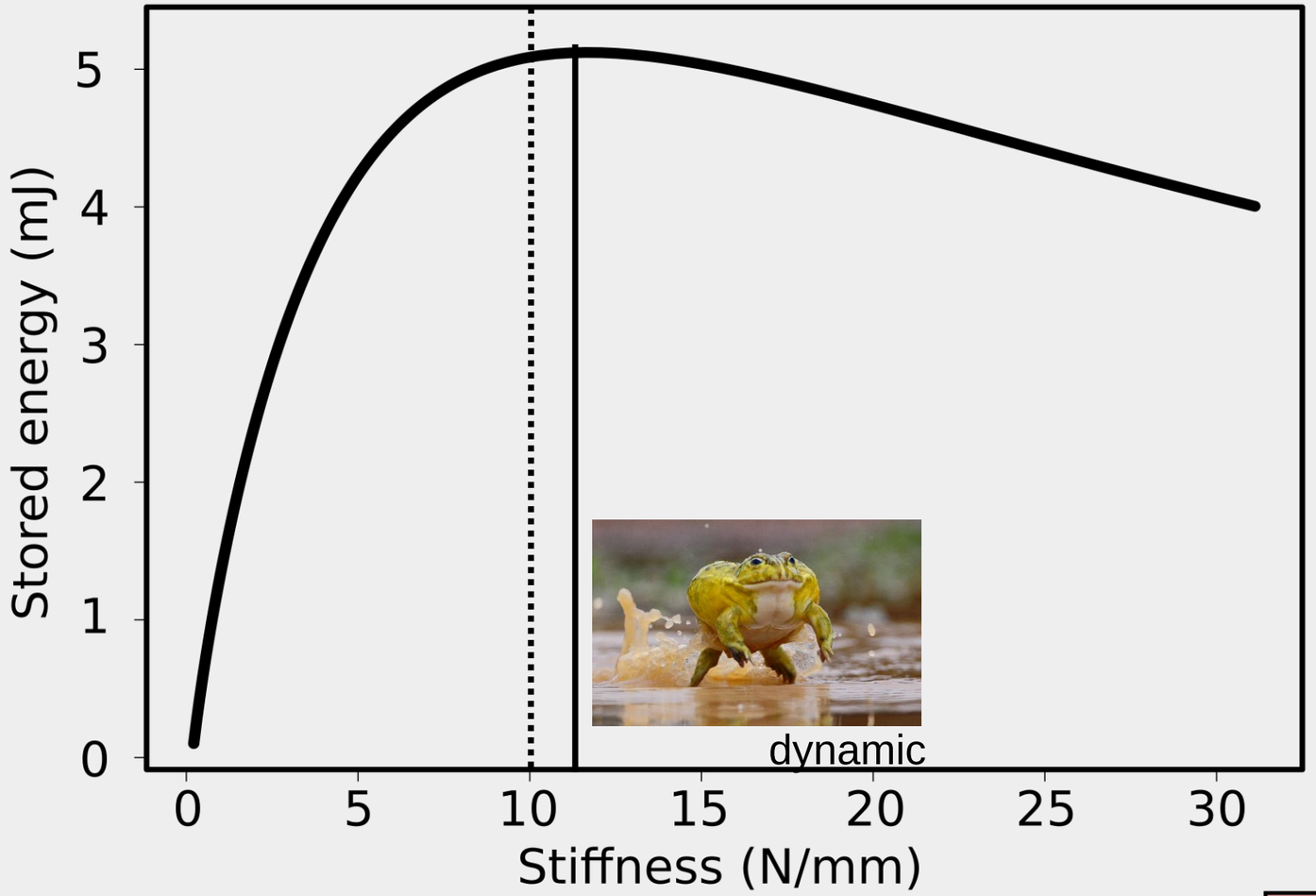


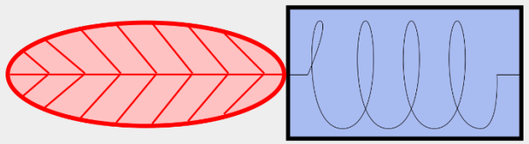


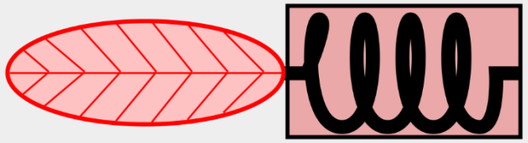


Does the stiffness of Bullfrog tendon maximize energy storage?

(within 50 ms)





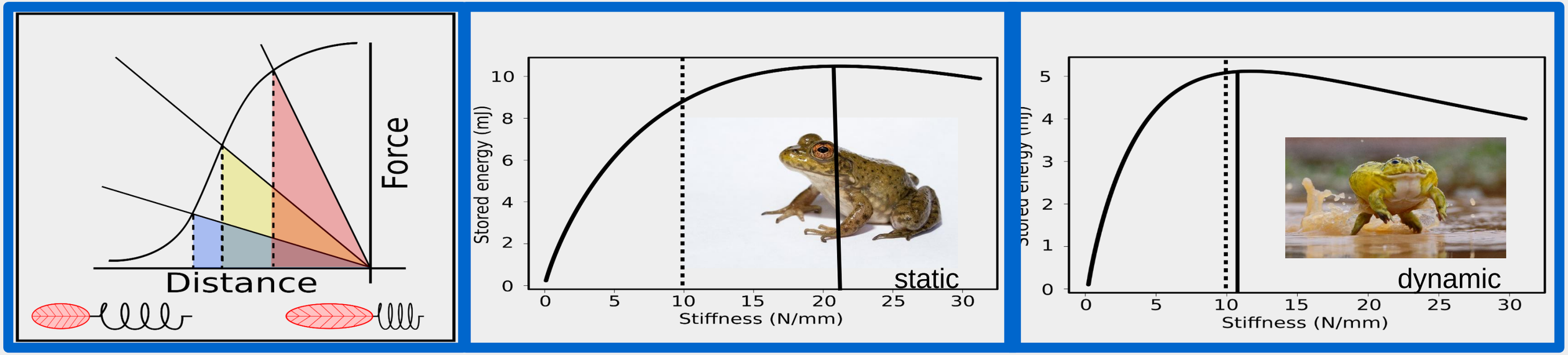


Summary

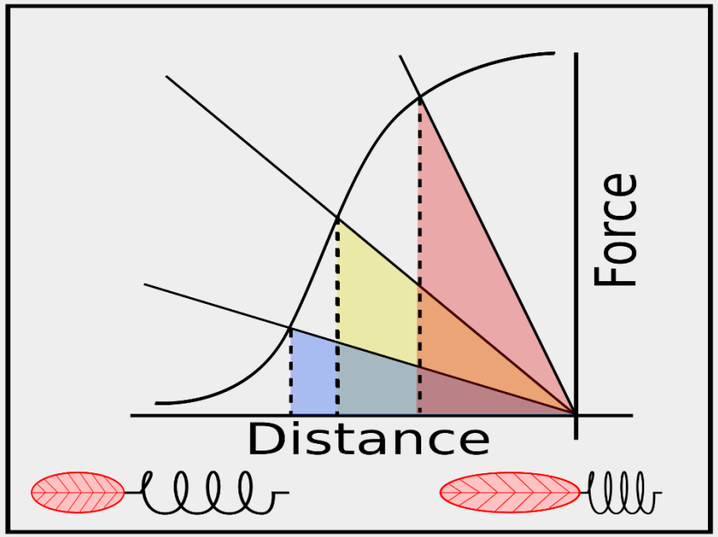
I. Are springs tuned to muscle to store maximal energy?

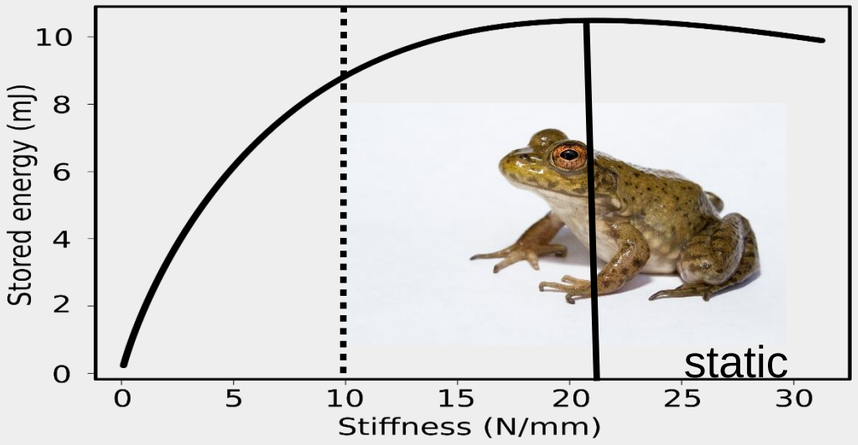
II. Bullfrog tendons don't maximize total elastic energy at full muscle contraction.

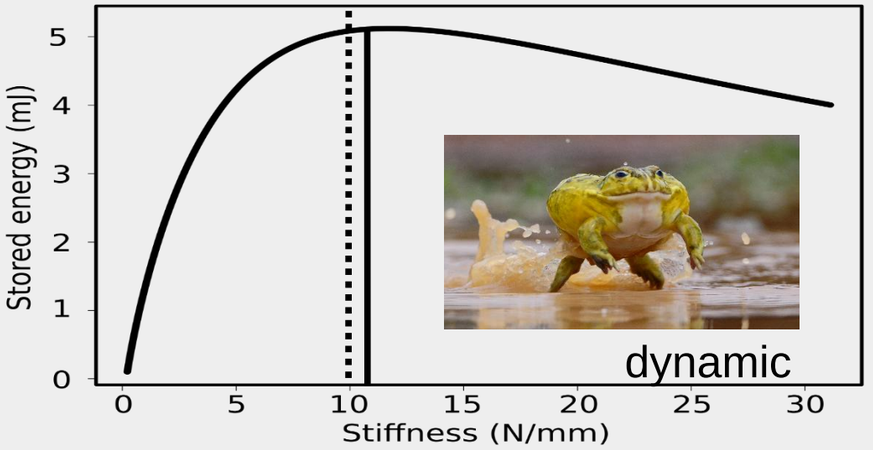
III. Within the duration of a jump, Bullfrog tendons are tuned to store maximal elastic energy.

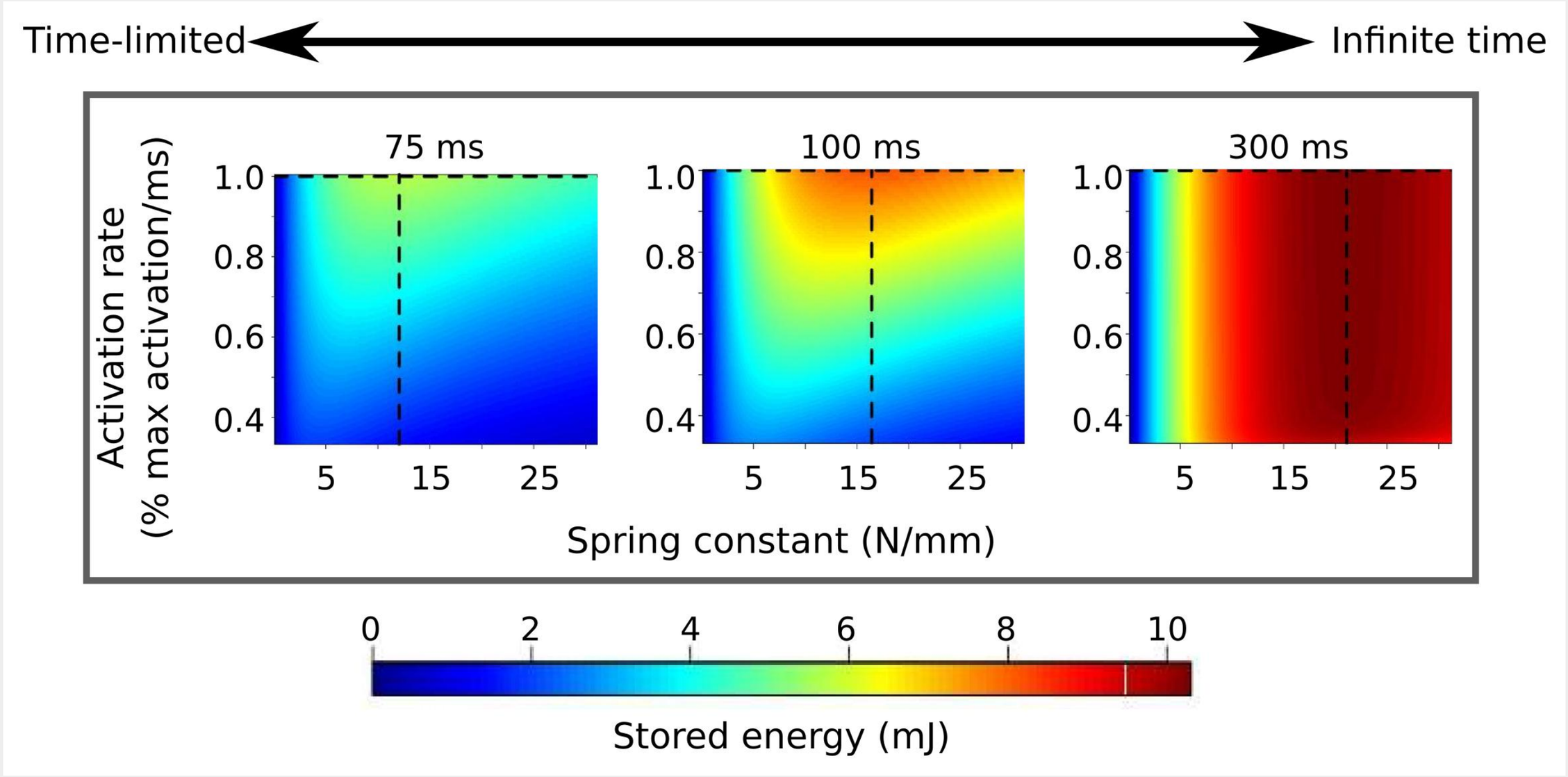


Reflect on the use/role of high performance computing in your research.

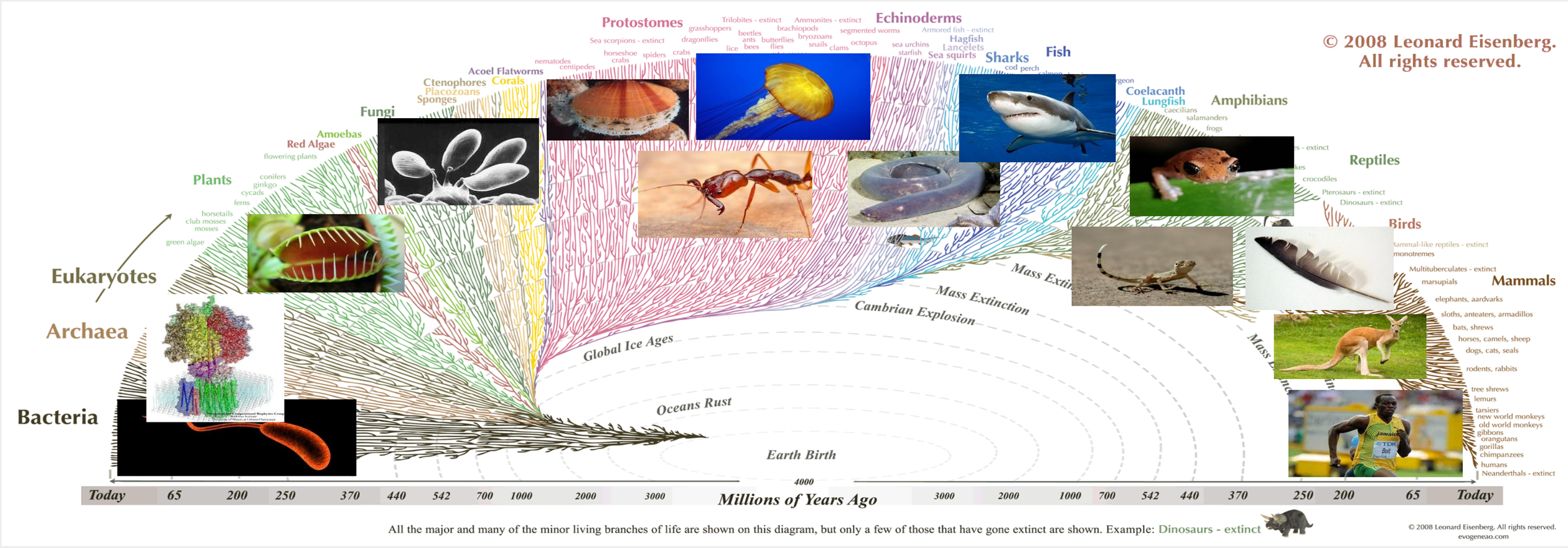







Time-limited
Infinite time
75 ms
100 ms
300 ms
Activation rate
(% max activation/ms)
1.0
0.8
0.6
0.4
5
15
25
Spring constant (N/mm)
0
2
4
6
8
10
Stored energy (mJ)

Elastic systems are ubiquitous in biology.



All the major and many of the minor living branches of life are shown on this diagram, but only a few of those that have gone extinct are shown. Example: Dinosaurs - extinct

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Acknowledgements



Collaborators
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Rachel Crane (Stanford Univ.)

Krell Institute
DOE CSGF

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Thomas Roberts (Brown Univ.)

Questions?