Understanding the Elastic Efficiency of Biological Springs

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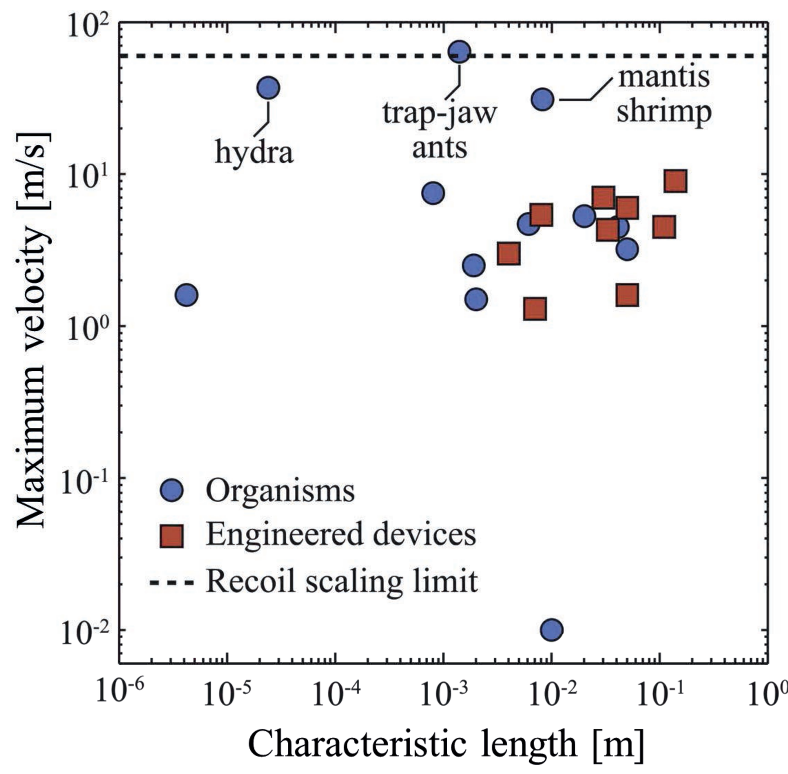
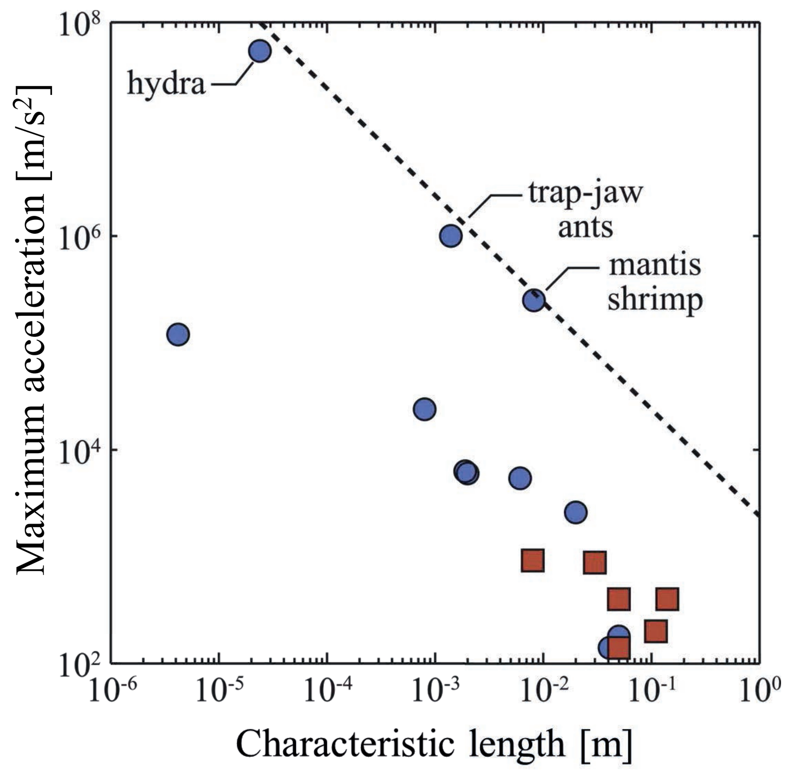
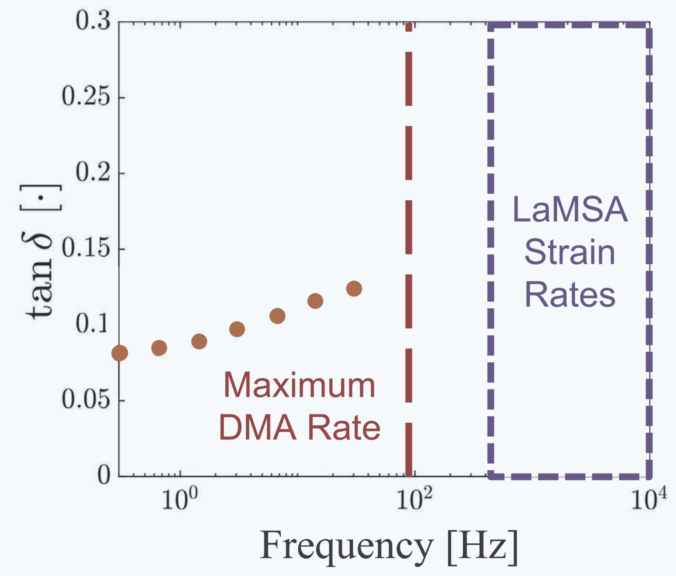
Introduction

Latch-mediated spring actuated (LaMSA) systems store and rapidly release energy to drive motion[1,2]. Example organisms include hydra, trap-jaw ants, and mantis shrimp, which have impressive kinematics compared to engineered micro-robotic devices of the same characteristic size. Performance in these systems depends on size and the material properties of components such as the elastic/spring[3].



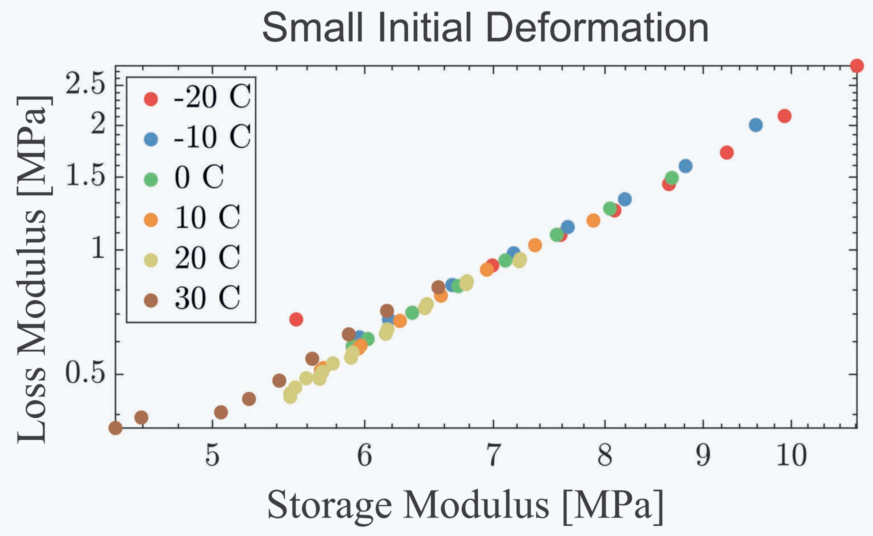


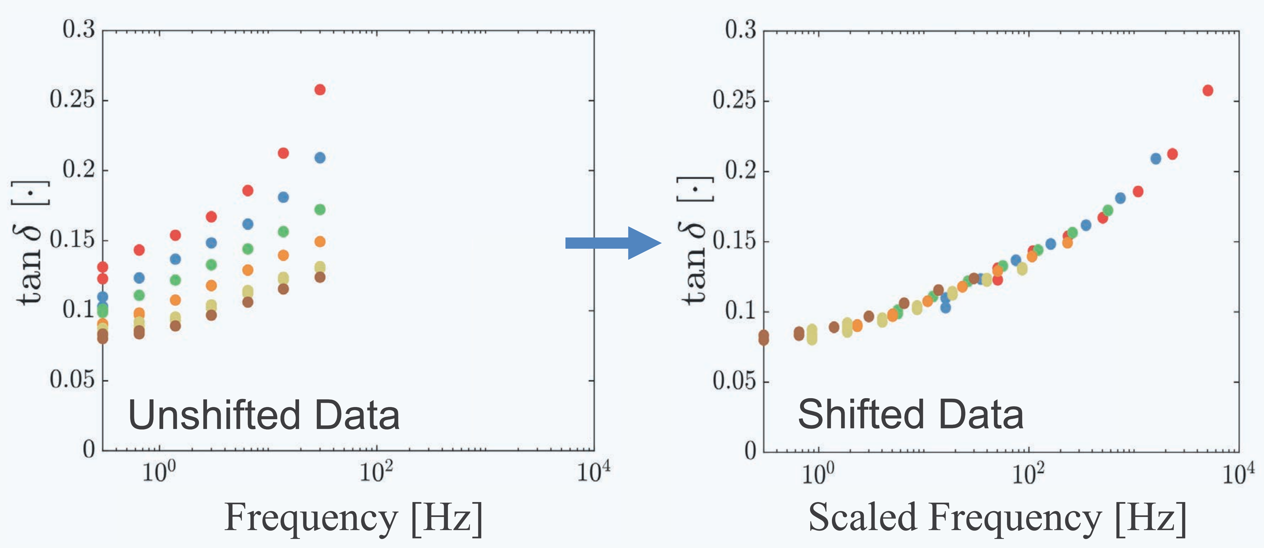
Using tan(δ) to Predict Efficiency of Spring Material Recoil



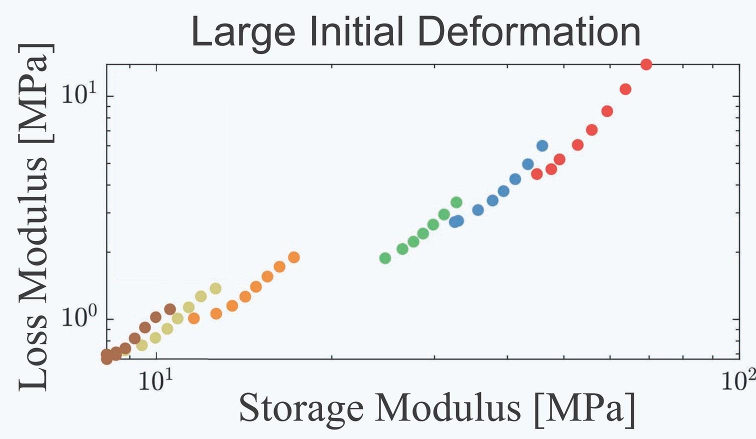
To understand behavior at kilohertz rates relevant to studying LaMSA systems, we use the principle of **time-temperature superposition**.

At small amplitude deformations, testing materials at **lower temperatures** is analogous to testing materials at **higher rates**.





At large amplitude deformations, testing materials at **lower temperatures** is **not** analogous to testing materials at **higher rates**.

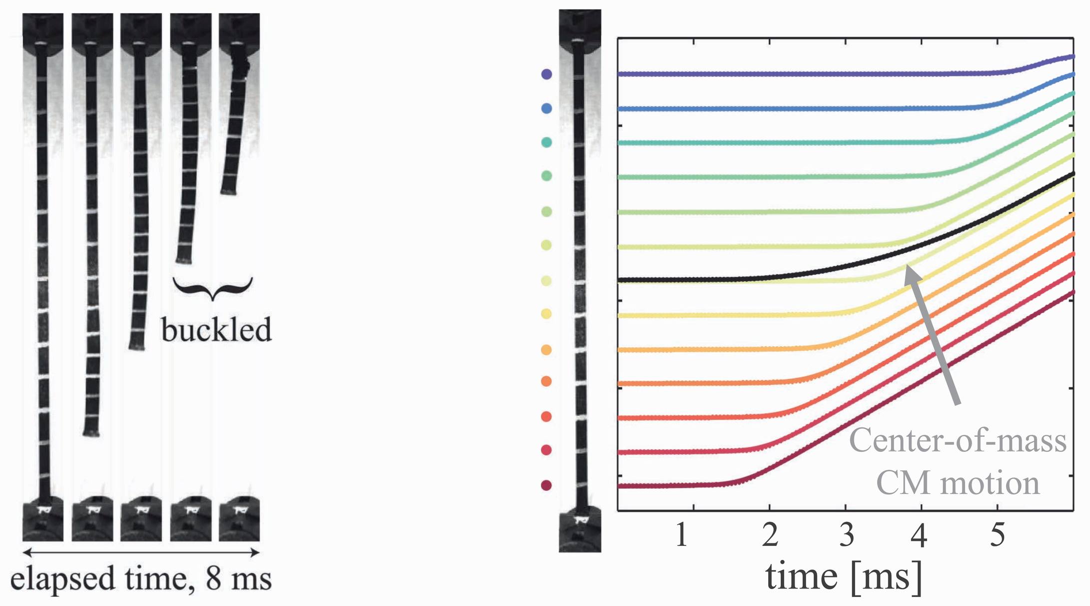


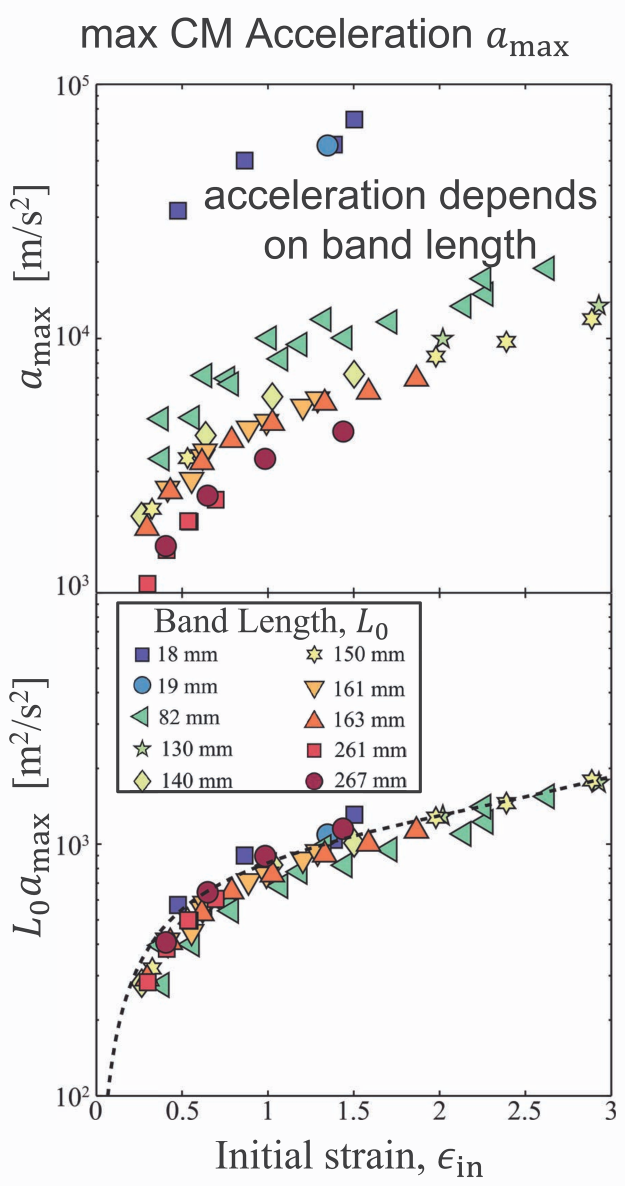
Future Work

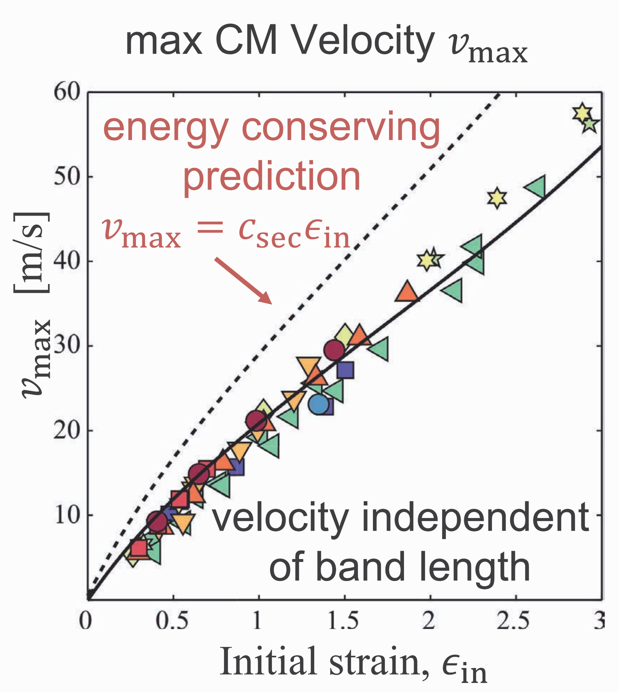
- Non-linear viscoelasticity and recoil
- DMA testing with biological samples

Size-scaling of Elastic Energy Release

Previous work
"The effect of size-scale on the kinematics of elastic energy release"
Ilton, Cox, Egelmeers, Sutton, Patek, Crosby, *Soft Matter*, **15**, 9579 (2019).







max CM Velocity limited by material properties

$$v_{max} = \sqrt{r_{eff}}\, c_{sec}\, \epsilon_{in}$$

effective resilience — wave-speed

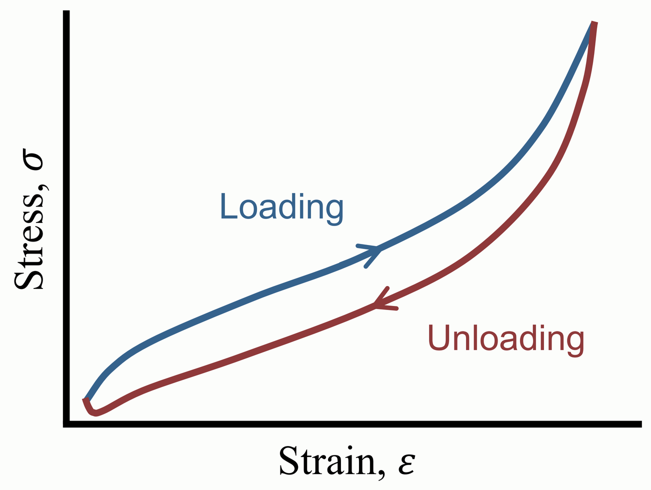
Size-scaling of elastomer recoil consistent with size-scaling observed in nature

	Recoil	Organisms	Devices
Velocity	$\sim L_c^{0}$	$\sim L_c^{-0.1}$	$\sim L_c^{0.2}$
Acceleration	$\sim L_c^{-1}$	$\sim L_c^{-0.9}$	$\sim L_c^{-0.5}$

Measuring Elastic Efficiency of Materials

1. Quasi-static Loading and Unloading

(large amplitude deformation, low rate)

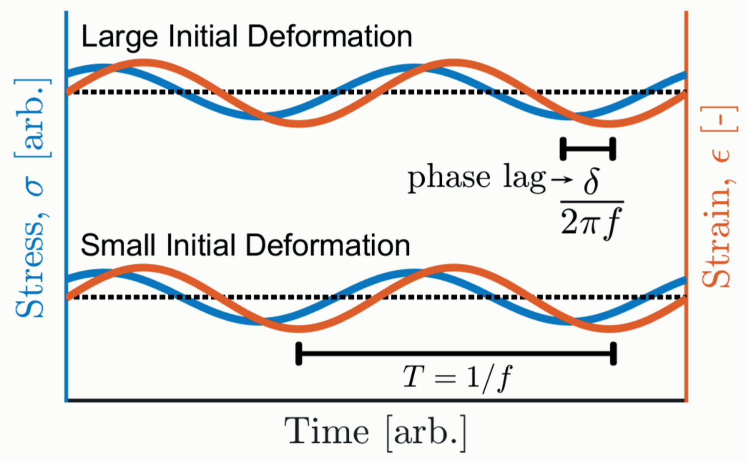


Elastic Efficiency Metric

$$\text{resilience} = \frac{\text{Energy Released}}{\text{Energy Stored}}$$

2. Dynamic Mechanical Analysis (DMA) Frequency Sweep

(small amplitude deformation, high rate)

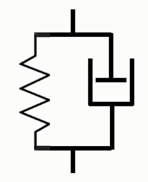


Elastic Efficiency Metric

$$\tan(\delta) = \frac{\text{Loss Modulus}}{\text{Storage Modulus}}$$

How are resilience and tan(δ) related?

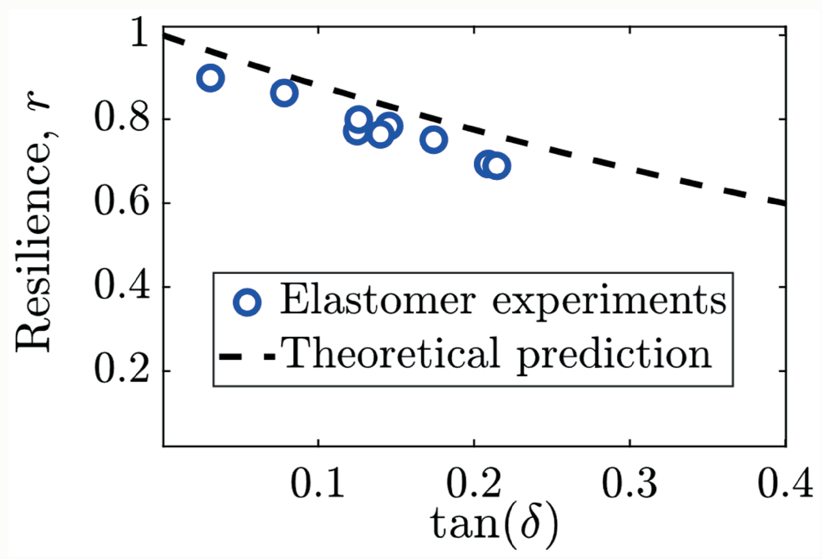
Assuming Kelvin-Voigt material model



Theoretical Prediction

$$\text{Resilience} = \frac{\left(1 - \frac{\tan(\delta)}{\pi}\right)^2}{\left(1 + \frac{\tan(\delta)}{\pi}\right)^2}$$

Elastomer Samples



Qualitative agreement between experiment and theory for small initial deformation and small amplitude limit

References

[1] Ilton, Bhamla, Ma, Cox, Fitchett, Kim, Koh, Krishnamurthy, Kuo, Temel, Crosby, Prakash, Sutton, Wood, Azizi, Bergbreiter, Patek
"The principles of cascading power limits in small, fast biological and engineered systems"
Science 360, eaao1082(2018).

[2] Longo, Cox, Azizi, Ilton, Olberding, St. Pierre, Patek
"Beyond power amplification: latch-mediated spring actuation is an emerging framework for the study of diverse elastic systems"
The Journal of Experimental Biology 222 (15), jeb197889 (2019).

[3] Ilton, Cox, Egelmeers, Sutton, Patek, Crosby
"The effect of size-scale on the kinematics of elastic energy release"
Soft Matter 15 (46), 9579 (2019).