MOTION & TRANSPORT

Elastic Energy Storage and Release in Biological Mechanisms

How biology creates spring-like energy storage without metal

5	3	3–5	5
convergent strategies	principle clusters	TRL range	featured strategies

PROBLEM FRAMING

Elastic energy storage enables high-power-output mechanisms from low-power inputs — catapult mechanics. Biological springs (flea jump, mantis shrimp strike, click beetle snap) achieve specific energy storage (J/kg) competitive with engineering springs, using biological polymers.

Application domains: robotics, aerospace, medicine

Principle cluster: elasticity, shape memory, gradient materials

Physics & Mechanism

Underlying physics

[DRAFT] Elastic energy density $U = \sigma^2/(2E)$ (J/m^3) — maximised by high stress capacity (σ_max) and low modulus E. Engineering steel springs: E = 200 GPa, σ_max = 1 GPa → U = 2.5 MJ/m^3. Resilin (crosslinked rubberlike protein in insects): E = 0.6–0.9 MPa, σ_max = 3–4 MPa → U = 5–10 kJ/m^3 — low energy density, but with near-perfect elastic recovery (>97% resilience, compared to 90–95% for natural rubber). Flea jump catapult: energy is stored slowly (>100 ms) in compressed thorax resilin pads, released in <1 ms through a mechanical trigger (catch-release mechanism), producing a power amplification of ~100× — decoupling muscle power from output power. Mantis shrimp: spring (saddle-shaped exoskeletal segment, E ≈ 2.5 GPa) stores ~3 mJ, releases in 0.5–2 ms at ~10 m/s velocity → peak force ~1,500 N in a 5 cm appendage. Power output: ~10■ W/kg — 2 orders of magnitude above direct muscle actuation. Engineering leverage: quasi-static loading with rapid release (bistable compliant mechanisms) enables actuator-to-output power amplification for soft robotics. [END DRAFT]

Biological Strategies

Move in/on Solids Golden silk spider · TRL 3/9 · 41 genera

Orb-weaving spiders primarily sense leg vibrations to detect and locate prey caught on their wheel-shaped webs. Biological experiments and computational modeling elucidated the physics of how these spiders use long-timescale web-building behaviors, which occur before prey capture, to modulate vibration sensing of prey by controlling web geometry, materials, and tension distribution. By contrast, t…

Design principle: This is in part due to challenges in biological experiments (e.g., having little control over spider behavior, difficulty measuring the whole spider-web-prey system vibrations) and theoretical/computa

Move in/on Liquids Common octopus · TRL 5/9 · 59 genera ✦ Evidence File

The common octopus propels itself through water by expelling fluid in controlled pulses from its siphon, a funnel-like organ located at the base of its mantle. Muscle tissue in the mantle wall contracts rhythmically to force water through the siphon and generate forward thrust. Each pulse forms a vortex ring that transfers momentum efficiently to the surrounding water. The octopus modulates pulse …

Design principle: Design pulsed-jet propulsion systems that mimic the octopus siphon's muscular control architecture rather than using steady-flow thrusters. Implement variable-velocity profiles with triangular or trap

> What's actually hard: The single deepest unsolved engineering obstacle is achieving low-level 'embodied intelligence' without centralizing computation. Replicating the biological distributed nervous system—where local fluidic circuitry within the arm autonomously couples …

Move in/on Solids Human skin · TRL 3/9 · 41 genera

Appendages such as arms, legs, fins, wings, and tails are peripheral body parts attached to an organism’s main body, playing essential roles in animal locomotion. Tails, found in most vertebrates, are particularly versatile, serving a wide range of functions such as providing stability, maneuverability, and prehension. Inspired by these functions, researchers have been integrating tail-like append…

Design principle: Inspired by this natural locomotion, we present a soft robot capable of navigating complex terrains using a combination of rectilinear motion and asymmetric steering gaits. The robot is made of a pair

Transform Mechanical Energy Fava bean

Forisomes are specialized protein bodies distributed throughout the phloem sieve tubes of legumes. When plant tissue sustains injury, calcium ions flood into the damaged region. Such calcium ions trigger a conformational shift in the forisome proteins, causing the structures to swell radially while contracting lengthwise. That dual motion forces the forisomes to expand and occlude the sieve tube l…

Design principle: This system demonstrates a self-powered damage-response mechanism that converts passive chemical signals into active mechanical sealing without requiring metabolic energy expenditure. Engineers can ap

Disperse Seeds Mexican petunia

This seed capsule consists of two halves joined along a seam. As the capsule desiccates, the outer and inner tissue layers lose water at different rates, creating differential shrinkage between these longitudinally connected layers. That uneven water loss generates internal mechanical stress, similar to the bimetallic strips found in thermostats where two metals with different expansion coefficien…

Design principle: This mechanism demonstrates how material property gradients can be engineered to store and release energy on demand. The design principle involves creating a composite structure with layers that respo

Combination Intelligence

Strategies that address different aspects of the same problem and are not redundant when combined.

Move in/on Solids + Move in/on Solids

Shared principles: elasticity, gradient materials, hierarchical structure

These strategies share 3 underlying principles including elasticity and gradient materials and hierarchical structure. They may not be alternatives — combining them could address different scale regimes of the same problem simultaneously.

EXPLORE THE INTERACTIVE VERSION

This report is a static synthesis. The interactive version includes live strategy cards, the Design Brief generator, Combination Intelligence engine, and filtering by TRL, scale, and principle.

`https://atlasofnature.org/challenge/elastic-energy-storage`

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