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Vacuum-Driven Artificial Muscles Exploiting Snap-Through Instability for Fast and Efficient Linear Actuation

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Vacuum-driven artificial muscles are promising candidates for lightweight and compliant robotic systems; however, achieving fast, efficient, and load-retaining actuation at relatively low pressure remains challenging. In this work, we present a vacuum-driven linear artificial muscle that exploits geometrically programmed snap-through instability to enhance actuation speed and energy efficiency. The actuator consists of a one-dimensional 3D-printed metamaterial skeleton enclosed within a sealed nylon membrane. Two material systems were investigated: FDM-printed PLA with different infill densities and SLA-printed Flexible 80A resin. A combined experimental and finite element approach was used to characterize the snap-through response, bistability, internal energy evolution, and actuator performance under quasi-static and dynamic loading conditions.

The results show that the snap-through transition is primarily governed by the unit-cell geometry, while material stiffness controls the energy landscape and the ability to retain a secondary stable configuration. PLA-based actuators exhibited true bistability and load-dependent self-locking after vacuum removal, whereas Flexible 80A actuators showed reversible snap-through actuation without self-locking due to their lower stiffness and reduced energy barrier. Among the investigated configurations, the PLA actuator with 75% infill provided the best overall performance, achieving a peak mechanical efficiency of approximately 50% while lifting a 0.5 kg load under a vacuum pressure of −65 kPa. The highest actuation speed, approximately 325.4 mm/s, was obtained with the PLA 100% infill actuator under a 0.1 kg load. Flexible 80A actuators demonstrated smooth and repeatable reversible actuation, with enhanced cyclic durability but lower efficiency and no load-retaining capability.

Overall, the proposed design demonstrates that snap-through instability combined with tailored structural stiffness can enable fast, efficient, and self-locking vacuum-driven artificial muscles. This approach offers a promising route toward compact, lightweight, and energy-efficient actuators for soft robotics, wearable devices, and human-interactive systems.

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