SOFT ROBOTS

# Chasing biomimetic locomotion speeds: Creating untethered soft robots with shape memory alloy actuators

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**By using compliant lightweight actuators with shape memory alloy, we created untethered soft robots that are capable of dynamic locomotion at biologically relevant speeds.**

By replacing bulky hardware with soft and lightweight materials, soft robotics has the potential for revolutionary impact in autonomous field exploration, human motor assistance, wearable computing, and medicine. Despite impressive progress in recent years, there is still substantial work that remains in creating truly portable or mobile systems that can match the speed, dynamics, and work output of natural organisms or motorized machines. Figure 1A shows that, for the special case of limbed locomotion, untethered soft robots are substantially slower than motor-driven bioinspired robots or natural organisms. For example, the Pneu-Net quadruped (*1*) moves at 0.0077 body lengths per second (blps), which is much slower than biologically relevant walking speeds of ~1 blps. Nonetheless, this early attempt demonstrated that it is possible to engineer an untethered soft robot that is able to maneuver through harsh environments—including snow, water, and fire—while also resisting the high crushing force of a vehicle.

Actuation remains the key bottleneck in creating untethered soft robots that can move at biologically relevant locomotion speeds. For example, pneumatic, fluidic, magnetic, and dielectric elastomer actuators require bulky external hardware, whereas ionic polymer–metal composite actuators require aquatic environments and can only generate limited forces (*2*). To approach the mobility of natural mammalian and reptilian counterparts, we need compliant and lightweight actuators that are capable of generating rapid motions and large forces and can be fully powered and controlled with portable, miniaturized hardware. Rapid motion had previously been shown with a shape memory alloy (SMA) actuator used for a caterpillar-inspired robot called the GoQBot (*3*). Recently, we have introduced soft robot limbs with SMA that enable dynamic actuation and untethered locomotion at biologically relevant speeds. The limbs are composed of a U-shaped SMA wire (Fig. 1B) placed between a prestretched and nonstretched layer of thermally conductive elastomer (2.2 W/m·K). The naturally curled limbs are lightweight (~3 g) and capable of generating rapid motions and forces comparable to natural muscle. The intrinsic curvature introduced by the prestretch allows the actuators to function as load-bearing legs capable of carrying the weight of the robot's electronics, batteries, and frame. The prestretch also introduces an antagonistic force that helps the actuator rapidly transition back from the straightened actuated state to the curled unactuated state, thereby improving the actuation frequency. Last, the thermally conductive tape accelerates the heat dissipation, thereby decreasing the deactivation time and increasing the actuation frequency. The SMA-based compliant actuator can reversibly transition between the compliant unactuated (Fig. 1B, top) and stiff actuated (Fig. 1B, bottom) states with a frequency of ~0.3 Hz and generate a force of 0. 2 N in ~0.15 s. It is powered by a pair of miniature 3.7-V LiPo batteries (4.5 g) that can be incorporated into the body of a soft robot without adding substantial bulk. In this respect, the actuator presented here can be driven by on-board control electronics and power and can provide enough force and actuation frequency for fast locomotion of an untethered, centimeter-scale soft robot.

We demonstrated two untethered soft robotic testbeds that were both composed of flexible printed circuit boards, integrated power and control electronics, and the compliant SMA-embedded limbs. The first implementation was a soft electrically actuated quadruped (SEAQ; Fig. 1C and movies S1 to S6) that was capable of walking on a variety of surfaces, including up inclines, over rocky terrain and poppy seeds, and through geometrically confined spaces. The robot could also climb over a step that was greater than half of its body height. On level ground, the robot could walk continuously at a maximum speed of 0.56 blps (3.2 cm/s) and reach higher peak speeds, although there is a risk for thermal degradation or overheating of the SMA actuators. The second implementation was a multigait caterpillar-inspired robot that was composed of six actuators connected in series (Fig. 1D and movies S7 to S9). It was capable of carrying more than 30 g of payload and could crawl at a maximum speed of ~8 mm/s for over 25 min when carrying six on-board 3.7-V LiPo batteries. The caterpillar robot could also crawl up a 23° incline and over rocky terrains. On level ground, the robot could crawl at a peak speed of 74 mm/s (74 mm per cycle), which is close to 1 blps.

Compared with a pneumatically powered soft robot, the tight integration of materials, control electronics, power, and actuation in these electrically powered soft robots allows for reduced hardware complexity, size, and weight. The material architecture presented here can potentially serve as a template for engineering untethered dynamic soft robots with electrically powered

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CORRECTED 8 JANUARY 2019; SEE FULL TEXT

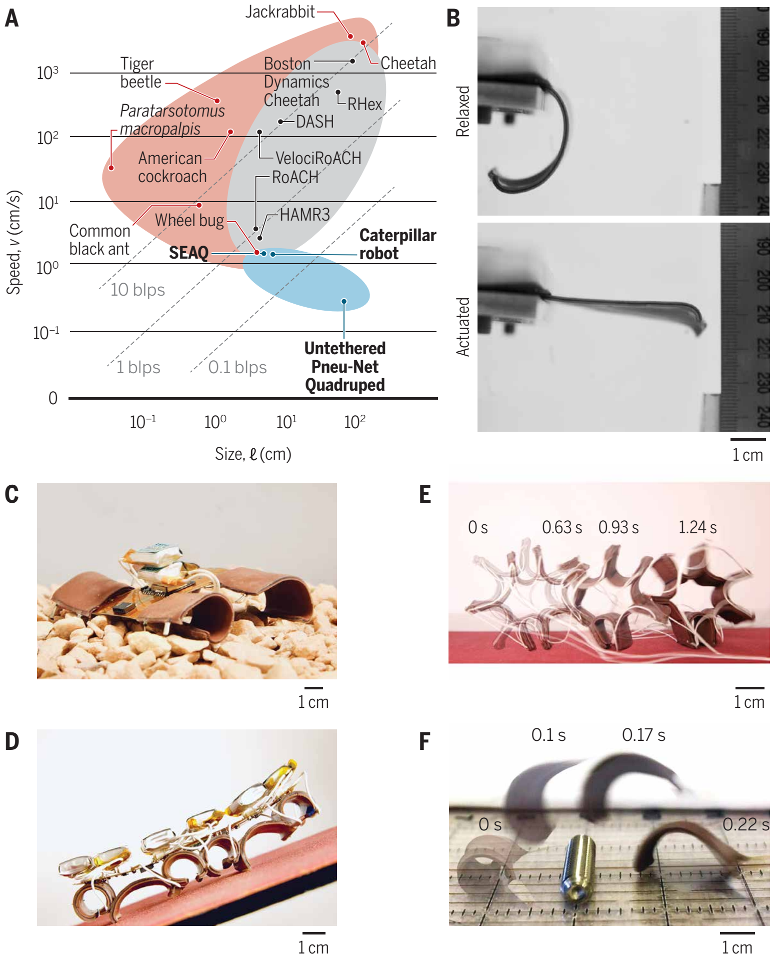

**Fig. 1. Electrically powered soft robots.** (**A**) Walking speeds of natural limbed animals and insects of various sizes (red), rigid and semi-rigid (black), and soft robotic systems (blue). The dashed lines represent blps. SEAQ and an untethered soft caterpillar are located between 0.1 and 1 blps. (**B**) Actuator with embedded SMA wire in a relaxed (top) and activated state (bottom). (**C**) SEAQ walking on a rocky surface. (**D**) Untethered soft caterpillar walking on a 23° incline. (**E**) Composite of video frames showing STAR rolling over 1 blps. (**F**) Composite of video frames showing the SMA-embedded jumper leaping over an obstacle.

limbs. Improved performance can be accomplished by optimizing the actuation and cooling time of each actuation to achieve better heat management using a theoretical heat analysis model and optimizing locomotion gait by implementing novel computational tools such as the discrete elastic rods (DER) (*7*–*9*) computational framework. Already, we have shown that DERs could simulate robot locomotion in real time or faster than real time and produced results that are in good agreement with experiments performed on the untethered caterpillar robot (Fig. 1D) and a tethered soft thermally actuated roller (STAR; Fig. 1E and movie S10).

As next steps, we will further implement DER in simulating and optimizing soft robots with other dynamic locomotion such as jumping (*4*) and swimming (*5*). Preliminary experimental efforts include a single jumper (Fig. 1F and movies S11 and S12) that is capable of continuous jumping at a speed of ~1.5 blps and jumping over an obstacle taller than its body height and an SMA-powered swimming robot (*6*) that is capable of swimming at 0.15 blps. Ultimately, the goal is to create a material, design and computational framework for creating fully untethered soft robots that can match the locomotion dynamics of natural organisms. Such testbeds could be used to better understand natural biomechanics and gait and also serve as platforms for autonomous soft robots that combine actuation and sensing with feedback control, machine intelligence, and communication.

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## SUPPLEMENTARY MATERIALS

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Movie S1. SEAQ—Locomotion in a straight line on a smooth surface at various activation frequencies.
Movie S2. SEAQ—Locomotion in a straight line on inclined surfaces.
Movie S3. SEAQ—Locomotion on a rocky surface (pea pebbles: Vigoro).
Movie S4. SEAQ—Locomotion in a straight line on granular media (poppy seeds).
Movie S5. SEAQ—Maneuverability in a confined space.
Movie S6. SEAQ—Crossing an obstacle over half the height of the body.
Movie S7. Untethered soft caterpillar—Locomotion in a straight line on a smooth surface.
Movie S8. Untethered soft caterpillar—Locomotion in a straight line on an inclined surface.
Movie S9. Untethered soft caterpillar—Locomotion on a rocky surface (pea pebbles: Vigoro).
Movie S10. STAR—Fast locomotion on a smooth surface.
Movie S11. Jumper—Continuous jumping on a smooth surface.
Movie S12. Jumper—Jumping on an obstacle over height of body.

## REFERENCES AND NOTES

1. M. T. Tolley, R. F. Shepherd, B. Mosadegh, K. C. Galloway, M. Wehner, M. Karpelson, R. J. Wood, G. M. Whitesides, A resilient, untethered soft robot. *Soft Robot.* **1**, 213–223 (2014).
2. L. Hines, K. Petersen, G. Z. Lum, M. Sitti, Soft actuators for small-scale robotics. *Adv. Mater.* **29**, 1603483 (2017).
3. H. T. Lin, G. G. Leisk, B. Trimmer, GoQBot: A caterpillar-inspired soft-bodied rolling robot. *Bioinspir. Biomim.* **6**, 026007 (2011).
4. N. W. Bartlett, M. T. Tolley, J. T. B. Overvelde, J. C. Weaver, B. Mosadegh, K. Bertoldi, G. M. Whitesides, R. J. Wood, A 3D-printed, functionally graded soft robot powered by combustion. *Science* **349**, 161–165 (2015).
5. A. D. Marchese, C. D. Onal, D. Rus, Autonomous soft robotic fish capable of escape maneuvers using fluidic elastomer actuators. *Soft Robot.* **1**, 75–87 (2014).
6. M. D. Bartlett, N. Kazem, M. J. Powell-Palm, X. Huang, W. Sun, J. A. Malen, C. Majidi, High thermal conductivity in soft elastomers with elongated liquid metal inclusions. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 2143–2148 (2017).
7. M. Bergou, B. Audoly, E. Vouga, M. Wardetzky, E. Grinspun, Discrete viscous threads. *ACM Trans. Graph.* **29**, 116 (2010).
8. M. Bergou, M. Wardetzky, S. Robinson, B. Audoly, E. Grinspun, Discrete elastic rods. *ACM Trans. Graph.* **27**, 63 (2008).
9. M. K. Jawed, F. Da, J. Joo, E. Grinspun, P. M. Reis, Coiling of elastic rods on rigid substrates. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 14663–14668 (2014).

**Funding:** This work was supported by the Army Research Office (grant no. W911NF-16-1-0148; program manager: S. Stanton) and the National Aeronautics and Space Agency (NASA ECF; grant no. NNX14AO49G; technical contact: B. Bluethmann). **Author contributions:** X.H., K.K., M.K.J., A.M.N., W.S., and C.M. designed the research, analyzed the data, and wrote the paper. X.H. and Z.Y. performed the experimental work. M.K.J. and A.M.N. performed the computational work. **Data and materials availability:** Contact X.H. for materials.

10.1126/scirobotics.aau7557

**Citation:** X. Huang, K. Kumar, M. K. Jawed, A. M. Nasab, Z. Ye, W. Shan, C. Majidi, Chasing biomimetic locomotion speeds: Creating untethered soft robots with shape memory alloy actuators. *Sci. Robot.* **3**, eaau7557 (2018).

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*Sci. Robotics* **3**, eaau7557.
DOI: 10.1126/scirobotics.aau7557