# Kinetic energy fluctuation helps animals and robots self-right on the ground

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## I. Introduction

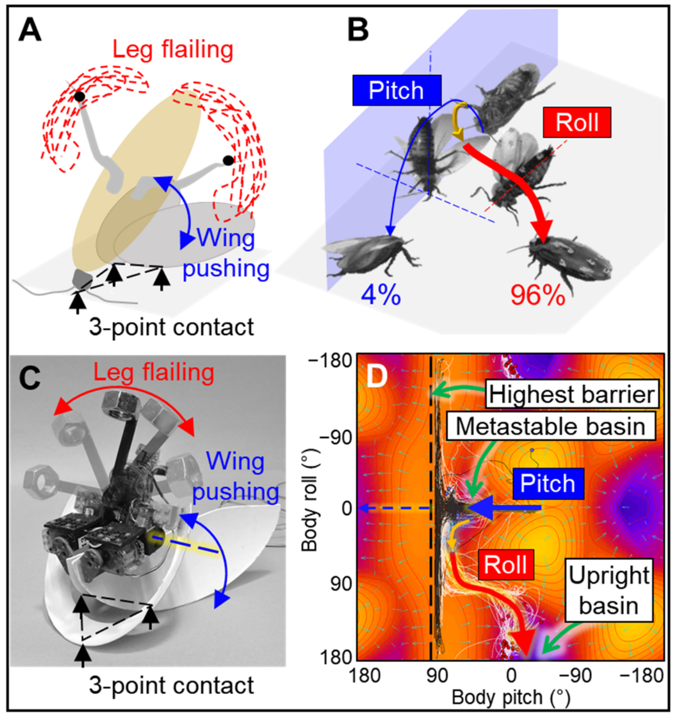
Robots moving in complex terrain are susceptible to perturbations from terrain interaction, which can lead to loss of foothold and flipping over [1], and this poses challenges for critical applications like search and rescue in earthquake rubble. Many robots either adopt a body shape that is unstable when upside-down to self-right passively or add extra appendages that push against the ground to self-right quasi-statically. By contrast, many animals co-opt appendages primarily meant for other functions to self-right dynamically. Understanding the physical principles of these strategies can help create robots with higher self-righting performance.

A recent study [2] observed a strategy used by the discoid cockroach which co-opts legs and wings to self-right dynamically (Fig. 1A). In this leg-assisted, winged self-righting mode, the animal opens and pushes its wings against the ground in an attempt to do a somersault (Fig. 1B, blue arrows). However, it rarely completes a somersault (4% probability). As the animal continually attempts to do so, it often transitions to rolling (96% probability, Fig. 1B, red arrow) and self-rights. Curiously, the animal desperately flails their legs during self-righting maneuver (Fig. 1A, red trajectories). Here, we hypothesize that kinetic energy fluctuation from leg flailing can help animals and robots escape from being stuck in the stable state to self-right.

## II. Methods & Results

To test this hypothesis, we directly modified hind legs of the discoid cockroach to vary kinetic energy fluctuation during leg flailing. In addition, to discover general principles, we designed a cockroach-inspired self-righting robot (Fig. 1C) as a physical model for systematic parameter variation. The robot's leg is a pendulum that swings laterally to generate kinetic energy fluctuation. We also recorded the robot's motor control signals to reconstruct its wing and leg actuation and used an onboard IMU to measure its body orientation during self-righting. These measurements allowed us to reconstruct a potential energy landscape and how the system state behaved on it (Fig. 1D).

In both animal and robot experiments, we discovered that self-righting was more likely and faster as kinetic energy fluctuation increased. System state trajectories on the potential energy landscape over body pitch-roll space revealed that, as wings opened and the system was stuck in a stable configuration with 3-point ground contact, its state was stuck in a metastable local minimum basin on a landscape (Fig. 1D, thick blue arrow, black trajectories), unable to cross the highest barrier (black dashed line) that occurs during a somersault (pitching forward by 180°; Fig. 1D, dashed blue arrow). Kinetic energy fluctuation helped the system stochastically escape this basin (Fig. 1D, red arrow, white trajectories) and transition to roll basin by overcoming lower barriers.




## III. Discussions

Our study demonstrated that seemingly desperate and wasteful leg flailing is actually useful for self-righting, and it suggests new strategies for robots to co-opt existing appendages (legs, tails, etc.) for dynamic self-righting. Our findings are analogous to thermal noise-assisted escape of microscopic particles from a metastable potential well. We envision this as an initial step towards a statistical physical understanding of how locomotor transitions emerge from physical interaction with the terrain.

## References

[1] E. Guizzo and E. Ackerman, "The hard lessons of DARPA's robotics challenge," *IEEE Spectr.*, vol. 52, no. 8, pp. 11–13, 2015.

[2] C. Li, T. Wöhrl, H. K. Lam, and R. J. Full, "Cockroaches use diverse strategies to self-right on the ground," *J. Exp. Biol.*, vol. 222, no. 15, p. jeb186080, 2019.

This work is supported by an ARO YIP, a BWF CASI, a Beckman Young Investigator award, and JHU WSE startup funds to C.L.