

# Co-opting wings and legs to self-right on ground

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## I. INTRODUCTION

Ground self-righting is critical for ensuring survival of animals and continuous operation of robots in complex 3-D terrain. To self-right, animals and robots in principle can change their body posture arbitrarily. However, a recent study [1] discovered that when discoid cockroaches self-right on ground, although their body and appendage motion is highly variable, it is also stereotyped (Fig. 1A). When flipped over, the animal opens its wings in its attempt to self-right, but is trapped in a metastable mode (Fig. 1B). It can then self-right by either continuing to pitch, or by rolling sideways. However, this is strenuous and the animal often succeeds only after multiple failed attempts, during which the body repeatedly pitched up and down, showing stereotypy (Fig. 1A, C). In successful attempts the animal almost always self-rights by rolling sideways, which is also stereotyped (Fig. 1A, C). Curiously, the animal often flails its legs vigorously during its attempts (Fig. 1B). Here, we study the principles of how co-opting wing opening and leg flailing facilitates strenuous self-righting on ground and test the hypothesis that the stereotyped self-righting body motion reflect physical constraint from the environment [2].

## II. ROBOTIC PHYSICAL MODELLING

Because the animal's body and appendage motion are highly variable and cannot be controlled, we used a robotic physical model with a head, two wings, and a leg (Fig. 1D). We controlled the robot's wing and leg actuation to emulate the animals' strenuous behavior. When the robot opened its wings to self-right, it first pitched forward, but was trapped in a metastable mode. It eventually escaped after multiple failed attempts and always did so by rolling sideways. Co-opting wings and legs facilitated the robot's self-righting. As both wing opening and leg oscillation amplitudes increased, robot's self-righting was more probable and required fewer attempts. Similar to the animal, the change in robot's body pitch, body roll, and center of mass height were stereotyped during both successful and failed attempts, but with trial-to-trial variations (Figs. 1C, E).

## III. POTENTIAL ENERGY LANDSCAPE MODELLING

We modelled the robot's self-righting as a barrier-crossing transition on a potential energy landscape (Fig. 1E). When flipped over, the robot's system state was trapped in an upside-down basin on the landscape. As the robot opened its wings and its body shape changed, the upside-down basin evolved into a metastable basin, which strongly attracted and trapped the system state over multiple failed wing opening attempts. When an attempt eventually succeeded, the system state escaped by overcoming an energy barrier (Fig. 1E) and was attracted towards the roll-upright basin. We then measured the potential energy barriers for escaping metastable basin and compared them to the robot's kinetic

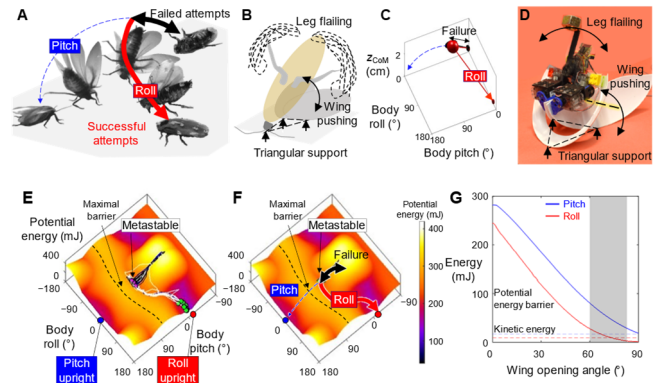
energy fluctuation (Fig. 1G). As wings opened more, the escape barrier decreased for both roll and pitch modes but was always higher for pitch mode. Without leg flailing, the pitch kinetic energy generated by wings pushing was insufficient to overcome the high barrier to pitch and somersault (Fig. 1G). However, when used together, wing opening further lowered the roll barrier and enabled the roll kinetic energy fluctuation from leg perturbation to probabilistically induce barrier-crossing and self-right.

## IV. DISCUSSION

The stereotypy of system state trajectories emerged from strong attraction of the system state to landscape basins. Given this constraint, inherent and added randomness produces variation in wing opening and leg flailing, and as a result, the robot's motion, leading to stochastic outcomes. This is beneficial when locomotor behavior is separated into distinct modes as it can induce stochastic transition between modes. Our landscape modeling revealed that co-opting propelling (wings) and perturbing (legs) appendages facilitated ground self-righting. The animal's self-righting also involves other complex body and appendage motion, such as abdomen flexion and twisting, passive wing deformation under load, and occasional leg pushing against the ground. We expect that these can further facilitate self-righting.

## REFERENCES

- [1] C. Li, T. Wöhrle, 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.
- [2] R. Othayoth, Q. Xuan, and C. Li, "Co-opting propelling and perturbing appendages facilitates strenuous ground self-righting," *bioRxiv*, no. 2021.04.06.438657, 2021.



**Fig. 1. Self-righting is a barrier-crossing transition on potential energy landscape.** (A) Snapshots of animal's self-righting by pitch and roll modes. (B) Animal stuck in metastable mode. (C) Stereotyped body motion trajectories of the animal. Ellipsoids show the standard deviation along the three axes. (D) Robot shown in metastable mode. (E) Robot's stochastic yet stereotyped state trajectories for failed (black curve with pink dots) and successful (white curve with green dots) self-righting attempts on the potential energy landscape over its body pitch-roll space. (F) Illustrative trajectories of possible locomotor modes and transitions. (G) Potential energy barrier to self-right by pitch (blue) and roll (red) modes as a function of wing opening angle. Blue and red dashed lines show pitch and roll kinetic energy fluctuation, respectively. Gray band shows range of wing opening tested.