A flea beetle can stick a perfect landing

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Abstract

When we flip a coin, we expect a 50 percent chance of it landing on heads. But what happens when an insect jumps? In this study, we report the self-righting strategy of the flea beetle, *Altica cirsicola*, which lives in a dense maze of leaves. How can the flea beetle coordinate landing on surfaces of such a range of orientation and position? In this experimental study, we film the take-off, flight, and landing of flea beetles on a configurable angled platform. Dead flea beetles tossed through the air have a 46% chance of landing on their legs, similar to a fair coin. However, live beetles land successfully 85% of the time, suggesting the importance of active self-righting strategies to accommodate the different orientations of the landing platform. We observe that beetles may extend their wings to slow down and reduce impact as well as perform numerous rotations. These behaviors may inspire jumping robots that can land softly.

Introduction

Rapidly escaping from predators has long been a driving force for the evolution of jumping (Gronenberg 1996). As a result, jumping is present in a great variety of insects, including fleas (Krasnov et al. 2004; Sutton and Burrows 2011), locusts (Sutton and Burrows 2008; Cofer et al. 2010), flies (Card and Dickinson 2008; Burrows 2013), moths (Burrows and Dorosenko 2015a), caddis flies (Burrows and Dorosenko 2015b), and many others (Brackenbury and Wang 1995; Burrows and Sutton 2013; Truong et al. 2014). Jumping combined with flapping wings enable insects to travel long distances compared with their body size (Chapman et al. 1998). A jump is completed by landing in a controlled manner to reduce the risk of damage at impact (Ellington 1991; Thomas and Taylor 2001). For the majority of herbivorous insects, landing on the ventral surface is preferred because it improves the chance of clinging to leaves encountered while airborne (Goodman 1960; Ribak et al. 2013). Furthermore, landing on the ventral surface may help the insect take advantage of leg microstructures (hairs, bristles, protrusions etc.) that can be used to improve grip and absorb impact (Goodman 1960). For flea beetles, which have meta-femoral springs in their legs, a leg-first landing enables them to store kinetic energy to be deployed on their second jump (Brackenbury and Wang 1995; Gronenberg 1996; Truong et al. 2014; Reichel et al. 2019; Ruan Y. 2020). In parallel with biological work, many designs of jumping robots inspired by insects (Koh et al. 2015; Ribak 2020; Zhakypov et al. 2019; Chahl JS et al. 2004; Franceschini 2007; Jusufi et al. 2011; Nguyen and Park 2012). In this investigation, we study how the flea beetle *Altica cirsicola* (Fig. 1a and b) achieves a leg-first landing. Just as jumping has inspired many robots, we hope that the process of righting and landing will also provide inspiration for both robotics and biology.

The need to rapidly and effectively orient is often a key feature of a perfect landing (Ribak et al. 2013). Such behaviors are termed adaptive behavioral righting, and they consist of both passive and active strategies. For example, pea aphids passively right themselves by dropping off a plant and rotating themselves using a stereotypic posture that is aerodynamically stable (Ribak et al. 2013). This righting mechanism requires no dynamic control or feedback from the nervous system, and has been found only in pea aphids (*Acyrthosiphon pisum*) (Ribak et al. 2013). In contrast, active aerial righting is generally accomplished using inertial movements of the torso, leg or tail (Jusufi et al. 2011). For instance, experiments with stick insects suggest that aerodynamic torques acting on the limbs and body may play a dominant role in the righting process (Jusufi et al. 2011).

In our work, we will focus on the self-righting of the flea beetle *Altica cirsicola*, which is widely distributed in China. It lives in leaves of its host plants (*Cirsium setosum*) and other vegetation. In a previous study, Brackenbury and Wang (1995) investigated the ballistics and visual targeting in seven species of flea beetles (Alticinae). They showed that flea beetles can jump with or without use of the wings. If wings are closed, the body spins repeatedly, and the beetle rarely lands on its legs. If wings are opened, rotation is halted, facilitating a leg-first landing (Brackenbury and Wang 1995). Because of the technology of the day, involving strobe photography, Brackenbury did not provide videos more of the flight or spinning process. In our work, we use high-speed digital videography to gather a large number of trials to characterize landing success, and then focus on describing a few cases of successful jumps.

Material And Methods

Sample collection

A. cirsicola specimens were collected from Olympic Forest Park in Beijing, China (40.00°N, 116.33°E) and housed in a tank with leaves of *C. setosum*, maintained at a temperature of 25°C and humidity of 50%. No permissions were needed for insect collection at our chosen locations. No endangered or protected species were collected.

Experimental setup and video processing

The experimental setup comprised of an incline made using a pair of rectangular acrylic panels, namely the takeoff platform (165 mm×50 mm) and the landing platform (140 mm×50 mm). The hinge connecting the panels can form angles ranging from 0° to 90° to mimic the orientations of a cluster of leaves on which the flea beetle landed in nature (Fig. 1c). We tested flea beetles by using inclination angles of 30°, 50°, 70° and 90°. We performed tests using 33 flea beetle specimens, recording a total of 124 jumps (an average of 4 jumps per beetle). Between each jump, the beetle was placed on the takeoff platform to rest for 5 mins.

We conducted trials by first using a straw (10 mm in radius) to place a live flea beetle on the horizontal platform. A brush, with a soft hairy tip of diameter of 5–10 mm, was used to provoke the beetle to jump. We completed the jumping experiments within 10 hours of capturing the flea beetle in the wild. The whole jumping process, including takeoff, flight, and landing, was recorded by a high-speed camera (Phantom M110 and VL0910, USA) set at a frame rate of f = 700 fps, and retrofitted with a micro lens (WWL08-110CN, China). The camera was equipped with a 3-DOF positioner that could move with a motion accuracy of 0.01 mm, to adjust for an appropriate focal distance. We observed with our naked eyes whether the flea beetle landed on its legs or not. If the landing was successful, we examined the high-speed video for maneuvering strategies. The video captured by the high-speed camera was processed via the software PCC 2.5 (Phantom, USA). We tracked the trajectories of the flea beetle frame by frame via marking the centroid of the flea beetle and processed using Photoshop CS5 (Adobe, USA) (Fig. 2).

Three-dimensional reconstructions of the flea beetle's leg

Leg specimens of a flea beetle were dehydrated by 100% ethanol and subsequently dried at the critical point (HCP-2, Hitachi Ltd., Japan). Specimens were scanned with an Xradia MicroXCT-400 in the Institute of Zoology, Chinese Academy of Sciences (Xradio Inc., USA). A series of cross section series was used to generate three-dimensional reconstructions. The flea beetle legs were reconstructed with Amira 5.1 (Visage Imaging, USA). The data files were then transferred to Maya 2011 (Autodesk, USA)) to use the smoothing function, specific display, and render options of this software. Final figures were processed by Photoshop CS5 (Adobe, USA) and Illustrator CS5 (Adobe, USA) (Ge et al. 2012).

Definition Of Successful And Unsuccessful Landings

We defined a successful jump in terms of the relative angle β between ground and beetle vector at the moment of impact. We define the ground vector as normal and upwards from the landing platform. The beetle vector was normal to the beetle ventral surface. Vectors in Fig. 3a show the range of possible landing orientations of the beetle. Since the beetle can rotate in mid-air, we must consider two possible orientations, the beetle facing up or down on the landing platform. Traveling clockwise from $\beta = 0°$ on the diagram involves clockwise rotations of the beetle. We define a successful landing if $90° < \beta < 270°$. A perfect landing would involve $\beta = 180°$, as shown by the top image in Fig. 3a. An unsuccessful landing is defined as an under-rotation $\beta < 90°$ or over-rotation, $\beta > 270°$. The worst possible landing is $\beta = 0°$ where it lands completely on its back.

Dropping Experiments With A Dead Flea Beetle

To determine the presence of any passive self-righting abilities, we did drop tests with a dead beetle. We used a scalpel to pick up, handle, and drop the flea beetle randomly without causing them any visible damage. The initial orientation was arbitrary to simulate the beetle jumping from an arbitrary location. The drop height was set to 40 mm according to the average height of real jumps ($n = 124$ jumps). We used the high-speed camera (Phantom M110, USA) to record the landing of the dead flea beetle.

Landing and takeoff kinematics

We calculated the landing velocity at the moment of landing. The jump starts at takeoff and ends at landing, and has a duration T. We defined the centroid coordinates as $P(t) = (x(t), y(t))$, the velocity as $v(t)$, and angular velocity as $\omega(t)$. The landing velocity v_f, as the speed when the flea beetle attaches the platform, can be calculated by $v_i = v(0) = \sqrt{(x(T) - x(T - \Delta t))^2 + (y(T) - y(T - \Delta t))^2} / \Delta t$, in which the time interval is $\Delta t = 1 / f$. The initial velocity v_i, is the speed when the flea beetle detaches from the substrate, may be written $v_i = v(0) = \sqrt{(x(\Delta t) - x(0))^2 + (y(\Delta t) - y(0))^2} / \Delta t$. The takeoff angle, namely the direction of the initial velocity, is defined as the acute angle between the initial velocity and the takeoff platform, which is $\alpha = \arctan[((y(\Delta t) - y(0)) / (x(0) - x(\Delta t))]$ (Fig. 4) (Brackenbury and Hunt 1993; Brackenbury 1992; Nauwelaerts and Aerts 2006; Kral 2010; Libby et al. 2012).

Results

Flea beetles have a body length of 4 mm and are up to 2 mm in width. We filmed the jumping process for *n* = 33 flea beetle specimens, recording a total of 124 jumps. Figure 2a shows the complete trajectory performance of the flea beetle. Here, the flea beetle leaped from the horizontal platform, flew to the left, and landed on the ramp. We defined a successful landing as one in which the beetle landed on its leg. In Fig. 3a, colored arrow lines show the landing orientations and velocities. Each arrow represents a recorded trial. We can see the arrow lines are more densely distributed in the region of successful landing, corresponding to a net rotation of 90° or less. As shown by the first two pie charts in Fig. 3b, the success rates of live flea beetle were 85%, which is far greater than the 46% success rate of a dead beetle flipped through the air. For comparison, the third pie chart shows the 50% chance of the coin landing on head. Although the dead beetle keeps its wings unfurled, the near 50% success rate indicates that aerodynamics of is body alone are insufficient to enable successful landings. Motivated by the higher success rate for the live beetles, we seek to find active re-orientation strategies throughout the entire jumping processes, including takeoff, flight and landing.

In 124 videos captured from 33 flea beetle specimens, we only analyzed the videos in which the flea beetle lands on its legs. We categorized the jumping behavior into the following three modes, which we call wingless, semi-wingless, and winged. In the wingless mode, the flea beetle takes off simply by jumping (Fig. 2a, b). In semi-winged mode, the flea beetle takes off and deploys and flaps is wings in mid-air, conceivably to eliminate spinning, then lands with legs (Fig. 2c, d). In winged mode, the flea beetle takes off with wings assisted and sticks on the ramp (Fig. 2e, f). Rates of successful landing for the wingless, semi-winged and winged modes are 77% (54 out of 77 jumps), 92% (35 out of 38 jumps) and 100% (16 out of 16 jumps) respectively. These numbers are consistent with Brackenbury and Wang (1995), who also found a high correlation of successful landing with the use of wings.

Clearly, wing recruitment is beneficial for a successful landing. The winged takeoff had an initial velocity of 1.25 ± 0.24 m/s (16 samples in winged mode), which was lower than that of the wingless takeoff, namely 1.41 ± 0.28 m/s (108 samples in wingless and semi-winged) because of the air drag. Wingless takeoff generally creates ballistic motion consistent with the speed and angle of takeoff, similar to shooting a ball out of a cannon. The winged takeoff generates substantial lift, enabling the body to gains more than double the height of 78 mm, compared to the height with no wings (30 mm). The mean takeoff velocity in the wingless mode is 10% lower than that of semi-winged mode (1.57 ± 0.29 m/s, 38 samples). We conclude the beetle is more likely to deploy wings later if its initial velocity is higher. This makes sense if wings are used to reduce the speed of impact.

While flapping wings enable the flea beetle to reach greater heights, they also incur tradeoffs because wings increase air drag and require more energy compared with the wingless takeoff. The insect also slows down when it flings wings in midair, which effectively alleviated the impact force while landing. The takeoff time was independent of mode: it took 8 ± 1 ms for the flea beetle to take off (33 insects and 124 entire jumping processes). The takeoff angle for all modes was 45 ± 3°, as expected for maximizing the distance of travel. We now go into further detail about the body posture and behaviors the jump.

For the wingless mode in Fig. 2a, the flea beetle takes off from the horizontal platform, which we define as time t = 0. Nearly instantaneously from takeoff (t = 7 ms) it pitches backwards. Since we cannot see the antennae in the high-speed images, we presume that they are initially folded back during takeoff, as shown in the hand drawing in the figure. It is possible the rotation is too fast to resolve the antenna. At 43 ms, the flea beetle unfolds its antennae at 50 ms (Fig. 2a). Surprisingly that, the insect can rotate along two distinct axes, continuously pitch and roll 2 times until 79 ms (Fig. 2a). The flea beetle shows its right side to us with its body upright at 93 ms. To investigate the dual-axial rotation mechanism, we mapped the pitch and roll angles with respect to duration (Fig. S1, S2). For this trial, the total-accumulated pitch angle is -1494°, which means it turned 4.15 cycles. The accumulated roll angle ranges is -360°, which indicates that the flea beetle rolls one clockwise cycle about its body axis. It continues rotating and successfully lands at 157 ms.

For the wingless mode, (*n* = 77 samples) we found a persistent result that the flea beetle began to roll at $t = 49 \pm 4\ \mathrm{ms}$ after takeoff, and roll around one cycle in either direction, with an average rotation speed of 7.2 deg /ms, which ensures that the flea beetle can accurately roll only one circle during flight (a roll angle magnitude of 353 ± 14°).

We now consider the semi-winged jump in Fig. 2b. The flea beetle begins with a wingless takeoff. It pitches and rolls from t = 0 to 42 ms. At 42 ms, the flea beetle orients almost horizontally with its right side to us. It continues the rotation from 42 ms to 75 ms. The wings unfold at 75 ms, which increases the moment of inertia and instantaneously eliminates the body rotation. The flea beetle flaps its wings and sticks a winged landing at 93 ms. The beetle pitches 2.14 cycles and rolls 360°, which helps it maneuver to a right position before landing. The wings deploy at 70 ms (**Fig. S1**), which stops rolling instantly. After 75 ms, the body only pitches a bit to regulate its position for a successful landing.

Lastly, we consider a winged jump. The flea beetle takes off with wings deployed, and flies directly to the vertical wall. The body does not rotate and then achieves a soft landing by its legs at 93 ms. Observing **Fig. S2**, we can see that the body over-pitches to -114°at 43 ms, and then corrects itself to the correct orientation of 90° to land on the vertical wall.

By zooming into the legs, we can see that takeoff forces are generated by straightening the back and possibly the front legs (Fig. 4a-d) actuated by the meta-femoral spring (Fig. 4f). The hindleg is almost fully extended at take-off, but the tarsus remains in contact with the ground throughout its length. Therefore, the displacement is made by only straightening of the femur-tibia joint (Fig. 4e). The high-speed images indicated that the body displacement during take-off is approximately 1 mm. After taking off, the kinetic energy of the body may be written as $E_{kT}(0) = Mv_i^2/2$ and the rotational energy as $E_{kR}(t) = I\omega(t)^2/2$. Given the peak velocity $v_i = 1.49\ \mathrm{m/s}$ and the peak angular velocity $\omega = 711\ \mathrm{rad/s}$, the average body mass $M = 4.16\ \mathrm{mg}$, and moment of inertia $I = \frac{1}{2}Mr^2 = 9.13 \times 10^{-13}\ \mathrm{kg \cdot m^2}$, which *r* is the half of the body length, we arrived at the rotational energy as $E_{kR}(t) = 162.8\mu J$, occupying only 1.7% of the kinetic energy $E_{kT}(0) = 9.5 \times 10^3 \mu J$. As found by Brackenbury and Wang (1995), we also find that rotational energy is negligibe compared to the kinetic energy. By the law of energy conservation, the work done by the leg is equal to the kinetic energy $F_{\text{take off}} l = E_{kT}(0)$, which *l* = 1 mm is the displacement of the leg during jumping. Thus, we infer the force applied by all the beetle legs is *F* = 9.5 mN, which is 233 times the beetle's body weight.

Discussion

Brackenbury and Wang (1995) performed experiments in which a high-contrast target was placed to lure the beetles. While we did not include such a target, we observed similar behaviors from our species of flea beetle. They also found takeoff angles ranging from 14 to 72 degrees, which encapsulates the 45 degrees found here. Brackenbury and Wang only described two jumping modes, winged and wingless. We here introduce a third jumping mode, the semi-winged where wings are opened just before landing. Brackenbury and Wang's studies showed that wingless landings have only a 10% chance of success, whereas our wingless success rate was much higher at 77%. This difference may be due to the landing target surface; we used a 10-cm scale platform whereas Brackenbury and Wang used an illuminated cross shape of length of 1 cm.

One of our main contributions of this work is resolving the large number of rotations (2–4 rotations in both pitching and rolling direction) made by the body during the jump. One unsolved question is why such large number of rotations are necessary. When cat's land on their feet, they perform a single rotation. It's possible such rotataions can help orient the feet or may be used in visually tracking the targets, which may also give the beetle more opportunities to observe the landing environment. Future experiments will be conducted to examine correlations between driving forces and rotations, such as possible effects of antenna swing on body rolling and pitching.

Conclusion

We investigated the jumping behavior of the flea beetle *A. cirsicola*. We filmed the flea beetle jumping onto ramp angles of 30–90°, finding that the flea beetle can jump in wingless, semi-winged, or winged mode. Modes involving wings involve lower velocities which can reduce the impact of landing. In addition, jumping involved many pitching and rolling rotations. The observed self-righting abilities mechanism may inspire the landing strategies of the jumping robots.

Declarations

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Authors' contributions

Hu and Ge planned the study. Wu, Yang and Shi conduced the experiments. Yang, Ren and Zong drafted the manuscript. All authors reviewed the manuscript.

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Conflict of interest

The authors declare no competing or financial interests.

References

1. Brackenbury J (1992) Insects in flight. Blandford.
2. Brackenbury J, Hunt H (1993) Jumping in springtails- mechanism and dynamics. J Zool 229:217–236. https://doi.org/10.1111/j.1469-7998.1993.tb02632.x
3. Brackenbury J, Wang R (1995) Ballistics and visual targeting in flea-beetles (Alticinae). J Exp Biol 198:1931–1942. https://doi.org/10.1242/jeb.198.9.1931
4. Burrows M (2013) Jumping from the surface of water by the long-legged fly Hydrophorus (Diptera, Dolichopodidae). J Exp Biol 216:1973–1981. https://doi.org/10.1242/jeb.083683
5. Burrows M, Dorosenko M (2015a) Jumping mechanisms and strategies in moths (Lepidoptera). J Exp Biol 218:1655–1666. https://doi.org/10.1242/jeb.120741
6. Burrows M, Dorosenko M (2015b) Jumping mechanisms in adult caddis flies (Insecta, Trichoptera). J Exp Biol 218:2764–2774. https://doi.org/10.1242/jeb.123471
7. Burrows M, Sutton G (2013) Interacting gears synchronize propulsive leg movements in a jumping insect. Science 341:1254–1256. https://doi.org/10.1126/science.1240284
8. Card G, Dickinson MH (2008) Visually mediated motor planning in the escape response of Drosophila. Curr Biol 18:1300–1307. https://doi.org/10.1016/j.cub.2008.07.094
9. Chahl JS, Srinivasan MV, Zhang SW (2004) Landing strategies in honeybees and applications to uninhabited airborne vehicles. Int J Rob Res 23:101–110 https://doi.org/10.1177/0278364904041320
10. Chapman RF (1998) The Insects: Structure and Function. Cambridge University Press. https://doi.org/10.1093/besa/17.4.288

11. Cofer D, Cymbalyuk G, Heitler WJ, Edwards DH (2010) Control of tumbling during the locust jump. J Exp Biol 213:3378–3387. https://doi.org/10.1242/jeb.046367
12. Ellington CP (1991) Aerodynamics and the origin of insect flight. Adv In Insect Phys 23:171–210. https://doi.org/10.1016/s0065-2806(08)60094-6
13. Franceschini N, Ruffier F, Serres J (2007) A bio-inspired flying robot sheds light on insect piloting abilities. Curr Biol 17:329–335. https://doi.org/10.1016/j.cub.2006.12.032
14. Ge SQ, Wipfler B, Pohl H, Hua Y, Slipinski A, Yang XK, Beutel RG (2012) The first complete 3D reconstruction of a spanish fly primary larva (*Lytta vesicatoria*, Meloidae, Coleoptera). PLoS One **7**:e52511. https://doi.org/10.1371/journal.pone.0052511
15. Goodman LJ (1960) The landing responses of insects: I. The landing response of the fly, *Lucilia sericata*, and other Calliphorinae. J Exp Biol 37:854–878.
16. Greenwood, D. T. 2006. Advanced dynamics. Cambridge University Press.
17. Gronenberg W (1996) Fast actions in small animals: Springs and click mechanisms. J Comp Physiol A Neuroethol Sens Neural Behav Physiol 178:727–734.
18. Jusufi A, Zeng Y, Full RJ, Dudley R (2011) Aerial righting reflexes in flightless animals. Integr Comp Biol 51:937–943. https://doi.org/10.1093/icb/icr114
19. Koh, J.-S., Yang, E., Jung, G.-P., Jung, S.-P., Son, J. H., Lee, S.-I., Jablonski, P. G., Wood, R. J., Kim, H.-Y. and Cho, K.-J. (2015). Jumping on water: Surface tension–dominated jumping of water striders and robotic insects. Science 349: 517–521. https://doi.org/10.1126/science.aab1637
20. Kral K (2010) Escape behaviour in blue-winged grasshoppers, *Oedipoda caerulescens*. Physiol Entomol 35:240–248. https://doi.org/10.1111/j.1365-3032.2010.00735.x
21. Krasnov BR, Khokhlova IS, Burdelov SA, Fielden LJ (2004) Metabolic rate and jump performance in seven species of desert fleas. J Insect Physiol 50:149–156. https://doi.org/10.1016/j.jinsphys.2003.11.001
22. Libby T, Moore TY, Chang-Siu E, Li D, Cohen DJ, Jusufi A, Full RJ (2012) Tail-assisted pitch control in lizards, robots and dinosaurs. Nature 481:181–184. https://doi.org/10.1038/nature10710
23. Nauwelaerts S, Aerts P (2006) Take-off and laning forces in jumping frogs. J Exp Biol 209:66–77. https://doi.org/10.1242/jeb.01969
24. Nguyen QV, Park HC (2012) Design and demonstration of a locust-like jumping mechanism for small-scale robots. J Bionic Eng 9:271–281. https://doi.org/10.1016/s1672-6529(11)60121-2
25. Reichel SV, Labisch S, Dirks JH (2019) What goes up must come down: biomechanical impact analysis of falling locusts. J Exp Biol 222:jeb202986. https://doi.org/10.1242/jeb.202986
26. Ribak, G. (2020). Insect-inspired jumping robots: challenges and solutions to jump stability. Curr. Opin. Insect. Sci 42: 32–38. https://doi.org/10.1016/j.cois.2020.09.001
27. Ribak G, Gish M, Weihs D, Inbar M (2013) Adaptive aerial righting during the escape dropping of wingless pea aphids. Curr Biol 23:R102-R103. https://doi.org/10.1016/j.cub.2012.12.010

28. Ruan Y, Konstantinov AS, Shi G et al (2020) The jumping mechanism of flea beetles (Coleoptera, Chrysomelidae, Alticini), its application to bionics and preliminary design for a robotic jumping leg. ZooKeys 915:87.
29. Sutton GP, Burrows M (2008) The mechanics of elevation control in locust jumping. J Comp Physiol A Neuroethol Sens Neural Behav Physiol 194:557–563. https://doi.org/10.1007/s00359-008-0329-z
30. Sutton GP, Burrows M (2011) Biomechanics of jumping in the flea. J Exp Biol 214:836–847. https://doi.org/10.1242/jeb.052399
31. Thomas ALR, Taylor GK (2001) Animal flight dynamics I. Stability in gliding flight. J Theor Biol 212:399–424. https://doi.org/10.1006/jtbi.2001.2387
32. Truong VT, Le QT, Park HC, Yoon KJ, Kim MJ, Byun D (2014). Non-Jumping take off performance in beetle flight (rhinoceros beetle *Trypoxylus dichotomus*). J Bionic Eng 11:61–71. https://doi.org/10.1016/s1672-6529(14)60020-2
33. Zhakypov, Z., Mori, K., Hosoda, K. and Paik, J. (2019). Designing minimal and scalable insect-inspired multi-locomotion millirobots. Nature 571:381–386. https://doi.org/10.1038/s41586-019-1388-8

Figures

Figure 1

The flea beetle *A. cirsicola* and its living environment. a The flea beetle is monophagous and lives in a maze of host plants, *C. setosum*. **b** A pair of flea beetles. **c** Schematic of the experimental setup. The setup included an adjustable landing platform with an inclination angle θ ranging from 0 to 90°.

Figure 2

Midair maneuvering during the leap. Wingless jumping to a 30 degree incline **(a,b)** , semi-winged jumping to a 50 degree incline **(c,d)** and winged jumping to a 90 degree incline **(e,f)**. Left images show a time lapse photo and right images are redrawn trajectories and behaviors. The color bars show the phases of jumping described by the motion of the insect.

Figure 3

Landing orientation and performance of beetles. a Histogram of the landing orientation with respect to the platform and velocities. Each arrow represents one trial, with arrow length indicating the velocity with respect to the scale bar indicating 0.5 m/s. In the insets, the red arrow shows the orientation of the platform and the green arrow the orientation of the ventral surface. **b** Landing success of live beetles, dead beetles, and coins.

Figure 4

Takeoff kinematics. a-d The flea beetle takes off by its hind leg. **a** The femur and tibia are folded with the tarsus attaching the ground. **b** The femur and tibia deploy. **c** The femur and tibia stretch. **d** The flea beetle takes off by the femur and tibia with the tarsus still contacting the takeoff platform. **e** Definition of the initial velocity and takeoff angle. **f** Anatomical structure of the hind leg by the three-dimensional reconstruction. A meta-femoral spring colored in orange stores and releases energy to generate a leap.

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