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Supplementary Information for

Froghoppers jump from smooth plant surfaces by piercing them with sharp spines

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SI Appendix

Plowing friction model for a conical spine in contact with a purely plastic material

The simple theory proposed by Bowden and Tabor (1) considers a rigid conical asperity with half opening angle θ in contact with a smooth surface of a softer, purely plastic material (Fig. 1D and Fig. S1).

Once the pressure at the tip of the spine exceeds the yield stress of the substrate material, the spine sinks in to a depth *h* so that *r* is the radius of the cone at the surface level.

As the cone is dragged across the surface, only its front side is in contact with the material, so that the horizontal projection of the spine contact area is

$$A_H = \frac{1}{2}\pi r^2 \qquad \text{(S1)}$$

As the mean pressure at the tip exceeds the material's yield strength σ_y, the substrate will yield and the normal force F_N will be balanced by σ_y:

$$F_N = A_H\sigma_y = \frac{1}{2}\pi r^2\sigma_y \qquad \text{(S2)}$$

In the shear direction, the cone has a vertical projected contact area $A_V = rh$, and the plowing shear force is again balanced by the material's yield strength σ_y. The total sliding friction consists of this plowing friction and an interfacial shear term:

$$F_S = A_V\sigma_y + A_H\tau \qquad \text{(S3)}$$

where τ is the shear stress of the interface, and A_V and A_H are the vertical and horizontal projections of the contact area. Therefore, the friction coefficient is

$$\mu = \frac{F_S}{F_N} = \frac{\tau}{\sigma_y} + \frac{2h}{\pi r} \qquad \text{(S4)}$$

As the ratio $h/r = \cot\theta$ is given by the half opening angle of the cone, the friction coefficient can be written as

$$\mu = \frac{\tau}{\sigma_y} + \frac{2}{\pi}\cot\theta \qquad \text{(S5)}$$

Hertz estimates for the pressure in the center of spine tips and their contact area

The contact pressure P_0 in the center of an elastic spherical spine tip indenting a smooth substrate can be estimated using the Hertz theory (2) as

$$P_0 = \frac{1}{\pi}\left(\frac{6FE^{*2}}{R^2}\right)^{1/3}, \qquad \text{(S6)}$$

where F is the loading force, R is the spine tip radius, and E^* is the effective elastic modulus ($\frac{1}{E^*} = \frac{1-\upsilon^2}{E_1} + \frac{1-\upsilon^2}{E_2}$, where υ is the Poisson ratio and E_i are the elastic moduli of the spine tip and the surface). Estimating $\upsilon \approx 0.3$ for both materials, $E_1 \approx 20\ GPa$ for stiff cuticle (3), $E_2 \approx 70\ GPa$ for glass, R = 3.6 µm and F ranging from 4.2 to 7.9 mN, a pressure range of 2.6 to 3.3 GPa is obtained.

Using Hertz theory, the contact area A of the spine tip can be calculated as

$$A = \pi \left(\frac{3FR}{4E^*}\right)^{\frac{2}{3}}, \qquad \text{(S7)}$$

which gives a range of 2.4 to 3.6 µm^2 on glass.

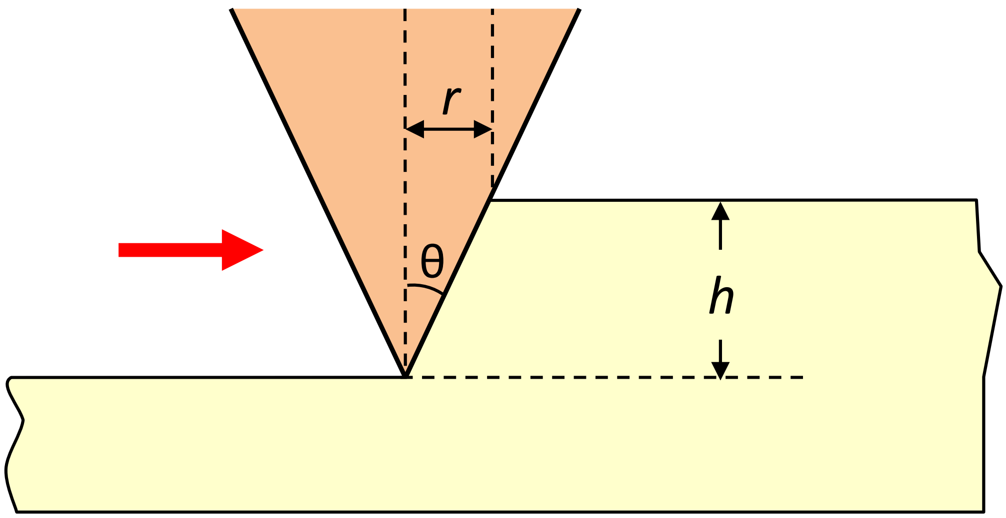

Fig. S1. Schematic of a cone dragged across a purely plastic material. θ: half opening angle, *h*: height of the plastic material in front of the cone, *r*: radius of the cone at the height of the plastic material.

SI Materials and Methods

Scanning electron microscopy (SEM). 11 hind legs, each from a different insect, were studied by SEM. Three of these 11 animals were euthanized with chloroform immediately after capturing them in the field. The hind legs were cut and either freeze-dried, or immediately transferred into fixative (4% glutaraldehyde in 0.1 M PIPES buffer at pH 7.4; Sigma Aldrich, St. Louis, USA) at

4° C for 48 hours. Samples were washed with deionized water, gradually dehydrated in increasing concentrations of ethanol (up to 96%), air-dried or critical point-dried using a Polaron E3100 critical point dryer. After sputter-coating with a 20 nm layer of gold (Emitech K550X , Quorum Technologies Ltd., East Grinstead, UK) samples were examined in a FEI XL30-FEG SEM (FEI, Hillsboro, USA) at 10 kV.

Energy-dispersive X-ray spectroscopy (EDX). EDX analysis was used to test for the presence of metals in tibial and tarsal spines of one hind leg each from seven animals. Hind legs were carbon coated and investigated using an FEI XL30 FEG SEM equipped with an Oxford Instruments EDX spectrometer with a Pentafet X3 Si/Li atmospheric thin window detector. The relative proportions of metals were measured relative to oxygen and chlorine.

Study of tracks left on leaf surfaces. After froghoppers had been filmed jumping from ivy, the leaves from which they had taken off were submerged in a 0.1% solution of methylene blue (Fisher Scientific, Pittsburgh, USA) for 90 minutes and then rinsed briefly with deionized water. We used leaves of variegated ivy (which contain white areas that lack chlorophyll) to enhance image contrast and to facilitate locating the exact takeoff positions on the leaves using the recorded videos. For SEM imaging of the leaf surfaces after the jumps, the section of the leaf from which the froghopper had jumped was cut out and immediately shock-frozen by quenching it in liquid propane cooled down with liquid nitrogen. Samples were freeze-dried at -90° C for 2 hours and gradually warmed up to room temperature over 14 hours in an Emitech K775X (Quorum Technologies Ltd., East Grinstead, UK). The leaf samples were sputter coated with a 10 nm layer of iridium. The froghoppers' foot marks on the epoxy surface were also visualized using scanning electron microscopy after sputter-coating them with 20 nm of gold.

References

1. Bowden FP, Tabor D (1950) The friction and lubrication of solids. (Oxford University Press, Oxford).
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Movie S1.) ***Philaenus spumarius*** **froghopper jumping from glass, viewed from the side, captured at 4700 frames s^{-1} and replayed at 7 frames s^{-1}. Scalebar: 10 mm.**

Movie S2.) ***P. spumarius*** **froghopper jumping from epoxy, viewed from the side, captured at 4700 frames s^{-1} and replayed at 7 frames s^{-1}. Scalebar: 2 mm.**

Movie S3.) ***P. spumarius*** **froghopper jumping from epoxy, captured from below with coaxial illumination at 4700 frames s^{-1} and replayed at 7 frames s^{-1}. Before the jump, only arolium (left) and acutellae (two rows of hairs on the right) are visible in surface contact. At the start of the acceleration, spines on the 2nd tarsal segment start to pierce into the surface and indentations remained visible even after the insect's takeoff. Scalebar: 200 µm. See also Fig.2C.**

Movie S4.) Jump by ***P. spumarius*** **froghopper from variegated ivy leaf, viewed from the side, captured at 4700 frames s^{-1} and replayed at 25 frames s^{-1}. Scalebar: 10 mm. See also Fig.3.**