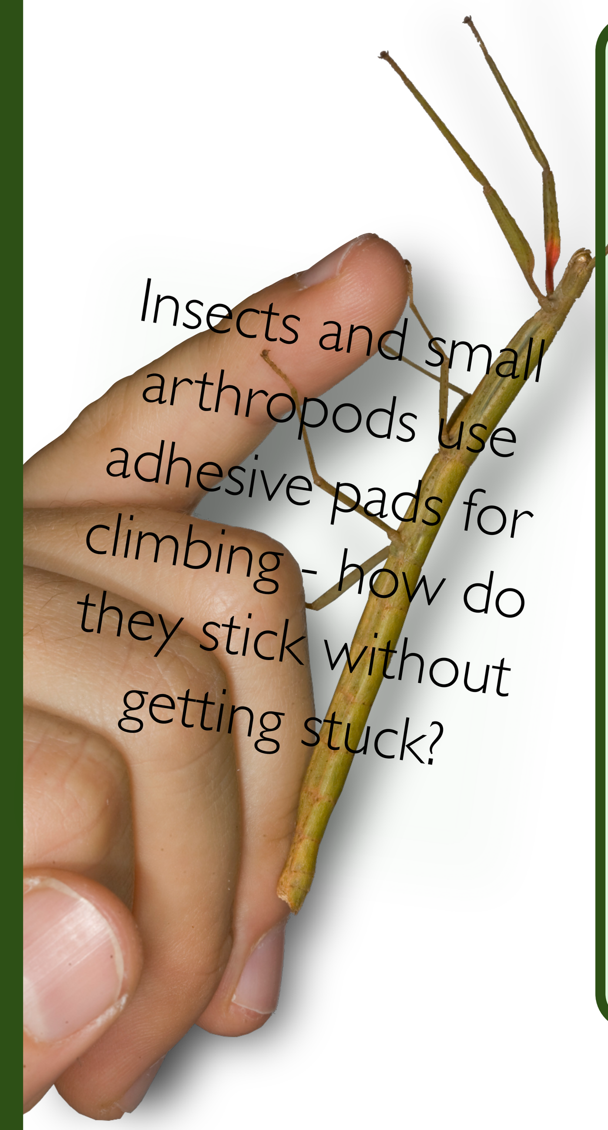
Biomechanics of shear-sensitive adhesion: peeling, pre-tension and sliding-induced changes in interface strength

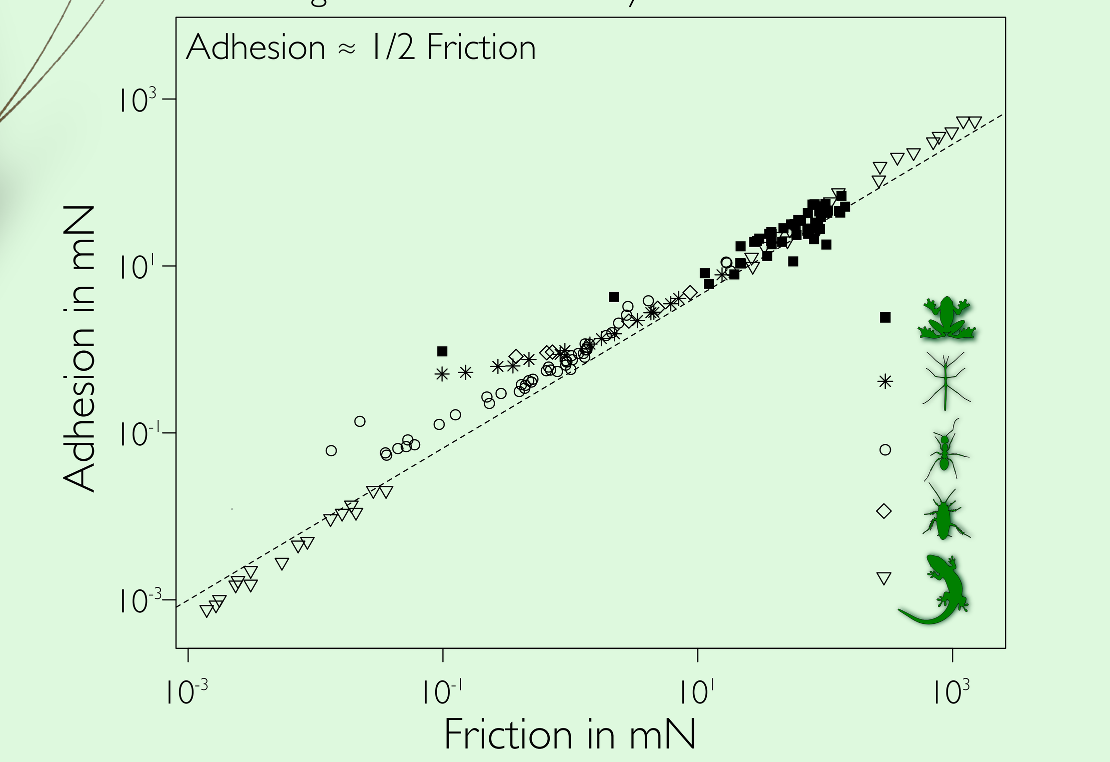
UNIVERSITY OF CAMBRIDGE

David Labonte[1,2] & Walter Federle[2]
[1]Department of Engineering | [2]Department of Zoology
dl416@cam.ac.uk



Insects and small arthropods use adhesive pads for climbing - how do they stick without getting stuck?

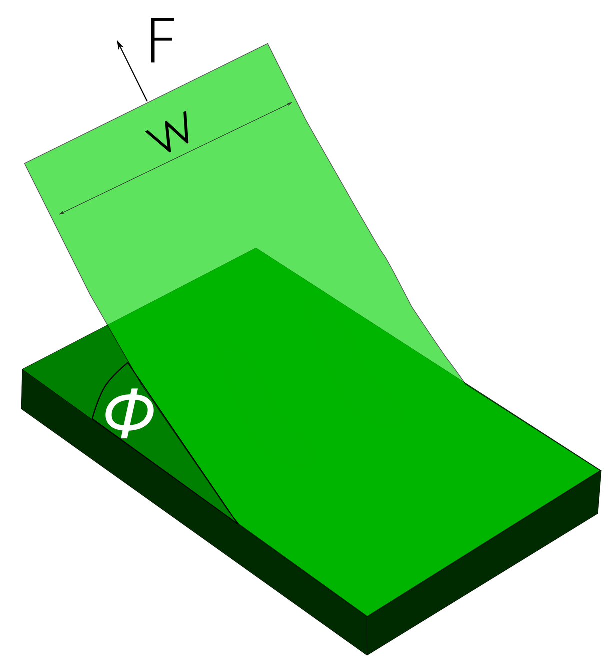
All climbing animals use shear forces to switch between strong attachment and easy detachment at will...



...a control mechanism independent of pad morphology and adhesive mechanism!

Labonte D & Federle W (2015): Phil Trans R Soc B. 370:20140027

What explains shear-sensitive adhesion?



Peeling a unit length of inextensible tape involves work done in creating new surface area, and in moving the point of force appplication. The critical force per unit tape width required for peeling can be found by equating the surface and potential work done:

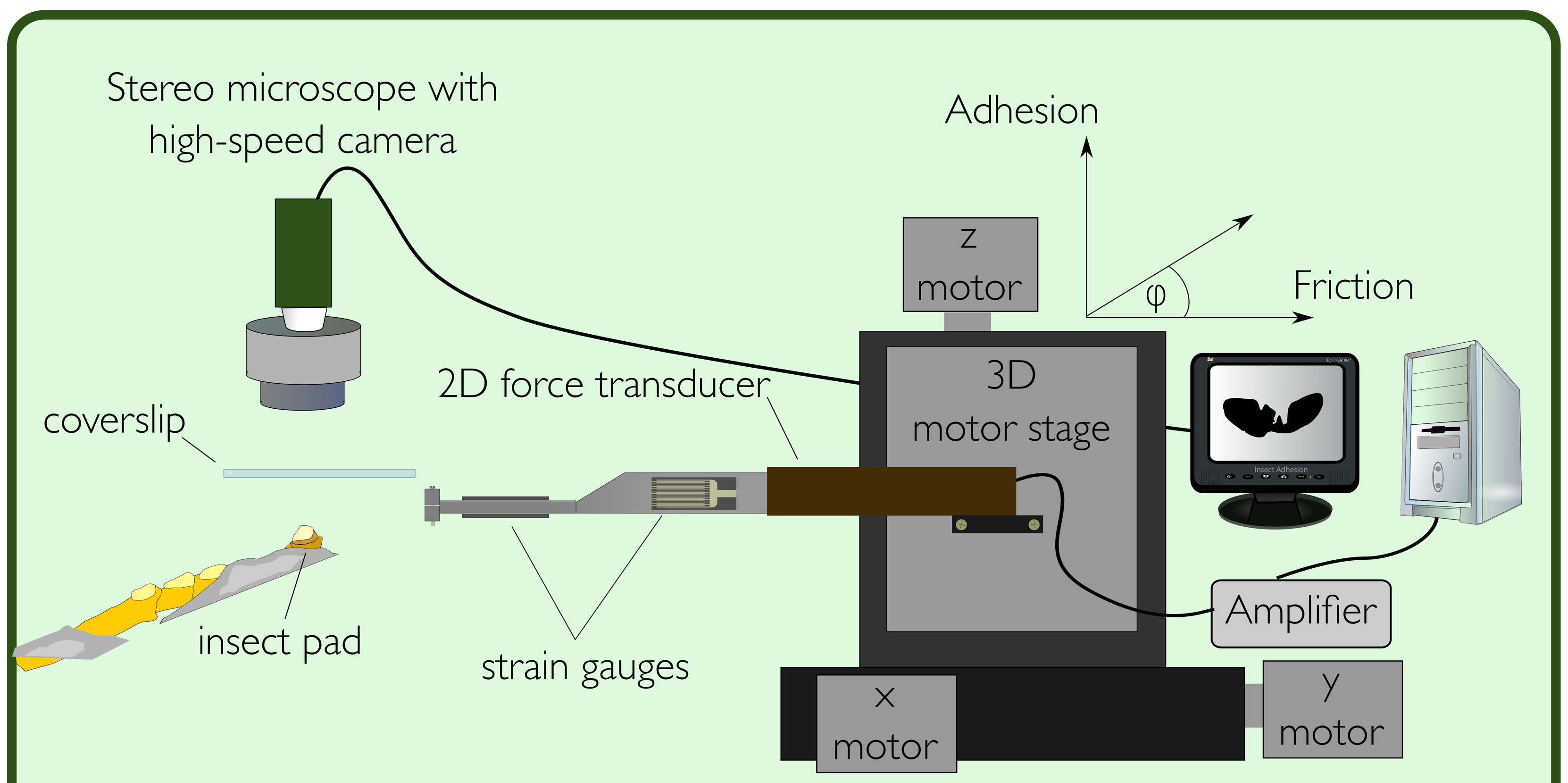
$$P = \frac{G}{[1 - cos(\phi)]}$$

Rivlin R (1944): Paint Technol. 9:215-216

Previous studies have modelled biological attachment pads as thin strips of adhesive tape.

e.g.
Autumn K, Dittmore A, Santos D, Spenko M, & Cutkosky M (2006): J Exp Biol. 209: 3569-3579
Varenberg M, Pugno NM, & Gorb SN (2010): Soft Matter. 6: 3269-3272.
Endlein T, Ji A, Samuel D, Yao N, Wang Z, Barnes WJP, Federle W, Kappl M & Dai Z (2013): J R Soc Interface. 10: 20120838

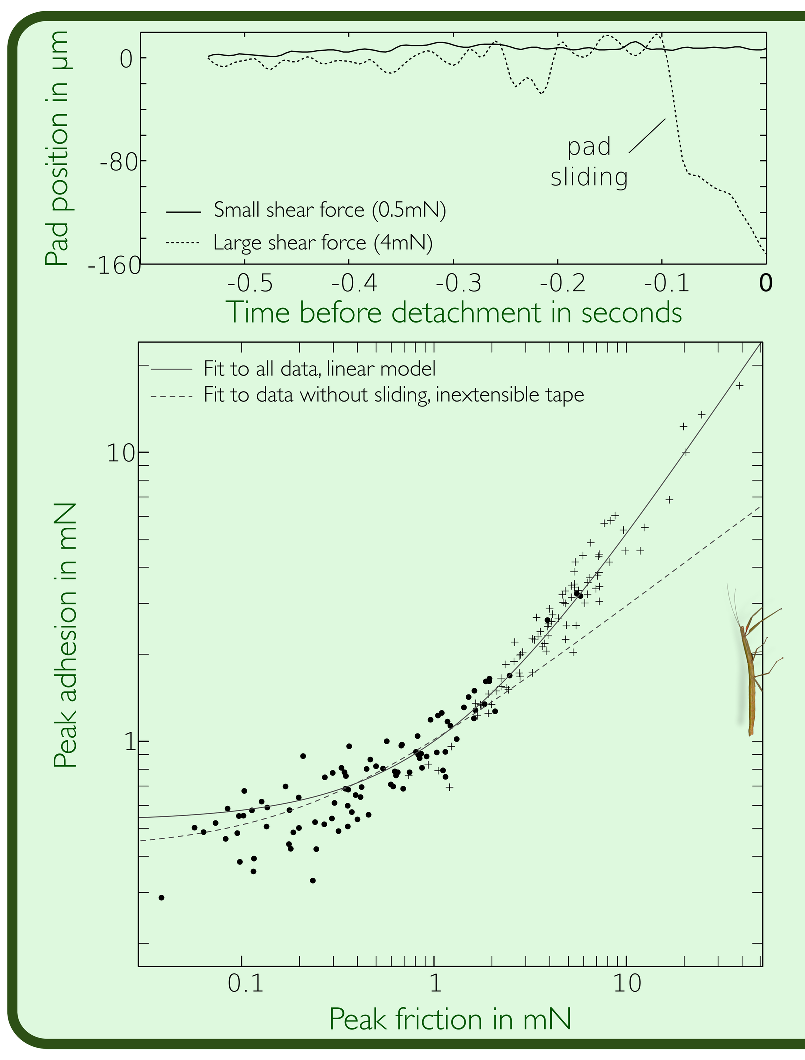
Can peeling theory account for shear-sensitive adhesion?



Details:
A custom-built 2D force transducer was used to measure the force required to detach stick insect pads at different peel angles while simultaneously filming the contact area using reflected light.

Labonte D & Federle W (2016): J R Soc Interface. 13: 20160373

Labonte D & Federle W (2016): J R Soc Interface. 13: 20160373

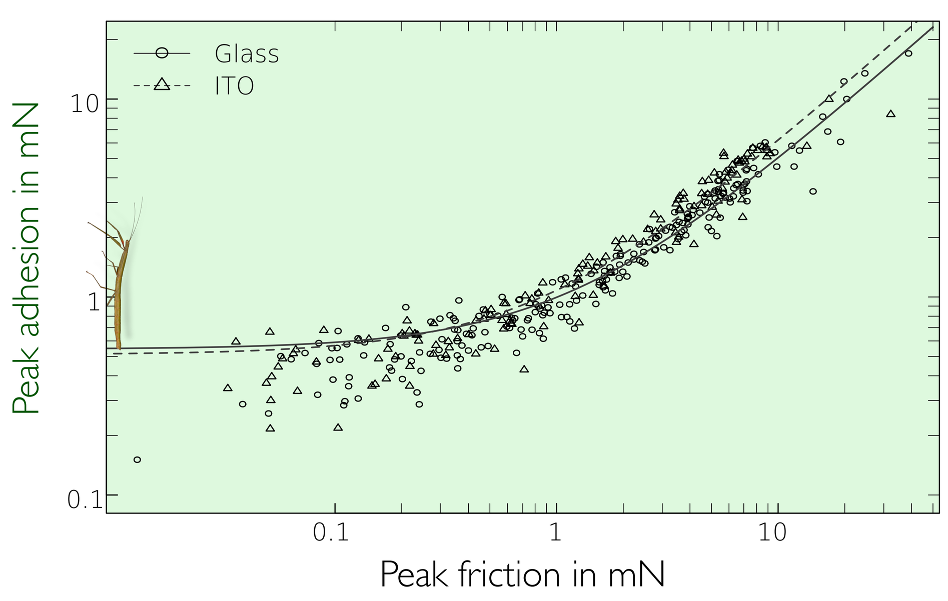


At low shear forces, detachment is static, but pads start to slide at higher shear forces.

An inextensible tape model works well for small shear forces, but the data are in disagreement with theory as soon as pads start to slide!

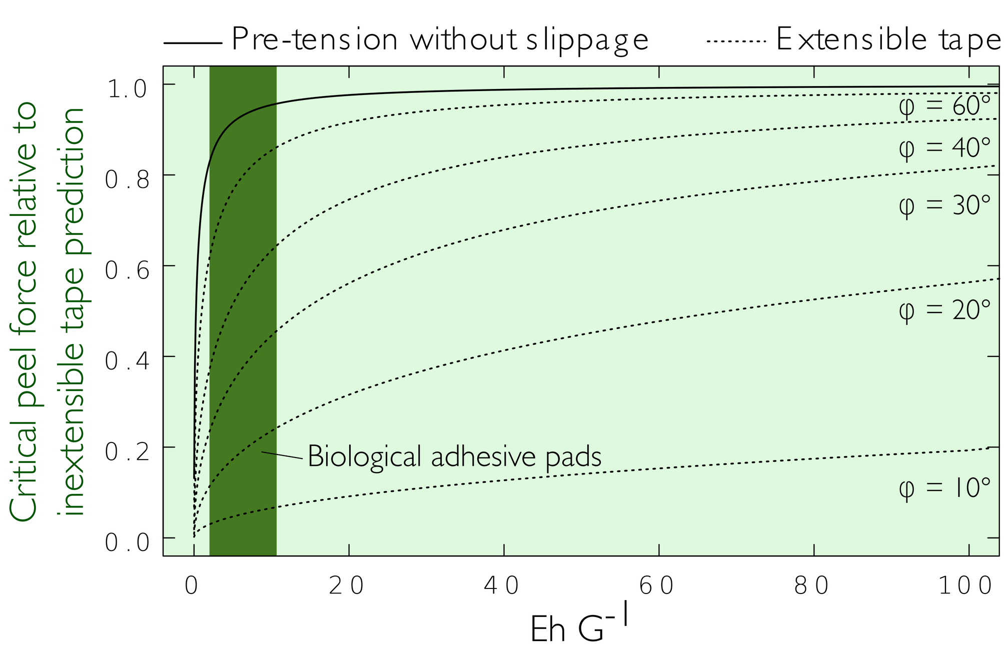
What is the effect of pad sliding?

H_1: Electrostatic charging?



Labonte D & Federle W (2016): J R Soc Interface. 13: 20160373

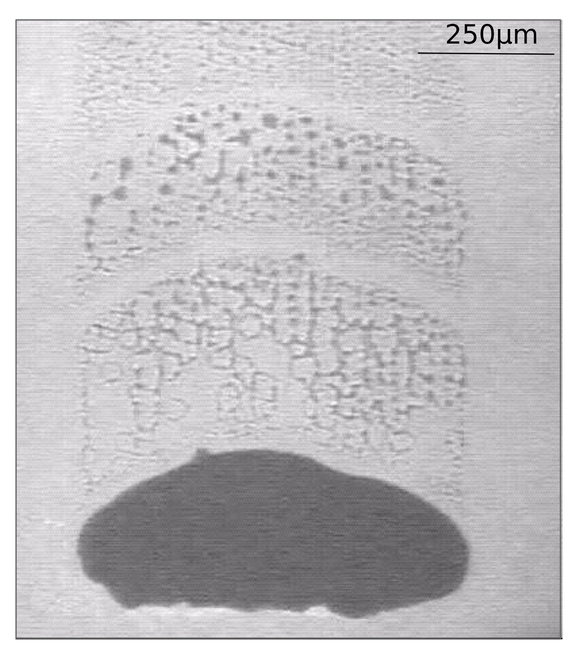
H_2: Frictional dissipation/pad "pre-tension"?



Both frictional dissipation and pad pre-tension increase the critical peel force by reducing the amount of mechanical work done for detachment so that pads behave increasingly like inextensible tape (see detailed leaflet for details).

Chen B, Wu P & Gao H (2009): J R Soc Interface. 6:529-537
Jagota A & Hui C (2011): Mat Sci Eng R. 72:253-292
Begley MR, Collino, R, Israelachvili JN, & McMeeking RM (2013): J Mech Phys Solids,. 61:1265-79
Labonte D & Federle W (2016): J R Soc Interface. 13: 20160373

H3: Liquid depletion?



Labonte D & Federle W (2015): Soft Matter. 11: 8661-8673
Labonte D & Federle W (2016): J R Soc Interface. 13: 20160373

The relationship between friction and adhesion is virtually unchanged when measured on conductive coverslips.

H_1 REJECTED

"Pre-tension" does increase the critical peel force, but the upper bound of this effect is set by the inextensible tape model.

H_2 REJECTED

Depletion of pad secretion may reduce "interfacial" mobility, thereby increasing the work of adhesion.

H_3 ACCEPTED ?

Conclusions

(i) Shear-sensitive adhesion in insects is consistent with classic peeling theory if friction forces are small, but an approximately linear relationship between friction and adhesion occurs when friction forces are large.

(ii) This departure from simple tape models cannot be explained by "pre-tension" or frictional dissipation, and can only be reconciled with peeling theory if the strain energy release rate increases upon sliding.

(iii) At present, the mechanistic basis for shear-sensitive adhesion remains unclear, and requires further investigation.

Supported by the BBSRC (BB/I008667/1), the HFSP (RGP0034/2012), and a Denman Baynes Senior Research Fellowship to D.L.