PRESSURE SENSITIVE TAPE COUNCIL

A bond you can trust.

SHEAR-SENSITIVE ADHESIVES: BIOMECHANICS OF DYNAMIC ATTACHMENT IN INSECTS

David Labonte. B.Sc.
PhD Student
University of Cambridge
Cambridge, UK

Scholarship recipient of Bayer-Research Fellow, Cusanuswerk undergraduate scholarship, winner best talk Biomechanics.

I used experimental techniques such as SEM, AFM, photolithograpy, so. imprinting, interference reaction microscopy, surface treatment techniques (silanisation and plasma treatment), static and dynamic contact angle measurements, strain-gauge force transducer measurements, high-speed video recordings, and techniques to quantify hardness, stillness, impact strength as well as interface strength in technical and biological materials.

SHEAR-SENSITIVE ADHESIVES: BIOMECHANICS OF DYNAMIC ATTACHMENT IN INSECTS

David Labonte & Walter Federle, University of Cambridge, Cambridge, United Kingdom

Introduction

Many insects are fast runners and skilful climbers. In order for climbing insects to forage efficiently and to escape rapidly from predators, contradictory demands must be met: attachment forces must be strong and reliable, but voluntary detachment should be fast and effortless. Indeed, some insects can withstand detachment forces of over 100 times their own body weight while also being able to run upside down on a smooth surface [1]. This highly dynamic control of attachment forces is achieved by a number of adaptations at different hierarchical levels, ranging from whole body kinematics to the ultra-structure of the adhesive pads [2-5].

Controllability of attachment is partly caused by a fast change of the contact area of the adhesive pads in response to mechanical loading [2; 6-10]. The pad contact area increases when the legs are pulled towards the body, but the pads easily detach when pushed away from it, providing a simple and effective mechanism for controlling adhesion [7; 8]. However, this direction-dependent change of contact area is not sufficient to ensure safe attachment, as even with the whole pad in surface contact, adhesion can be small. Adhesive pads are inherently „non-sticky“, and adhesion only becomes appreciable if significant shear forces are acting on the pad [11]. Hence, insects can not only increase the contact area but also the adhesive stress of their pads by pulling the legs towards the body. This simple, reversible and fast mechanical control-system makes use of forces that may arise passively during climbing [11]. A similar “shear-sensitivity” of adhesive structures has also been reported to control adhesion in geckos and tree frogs [12; 13], suggesting convergent evolution of the same control mechanism, independent of the morphology and the type of adhesive structure (fibrillar vs. smooth, wet vs. dry). What explains the shear-sensitivity of adhesive stress in animal footpads?

Results and Discussion

We used a custom-made 2D strain gauge force transducer to perform “peel” (low-angle pull-off) experiments with isolated adhesive pads of living insects. Peeling at low angles resulted in an increase in shear-forces during detachment. Measured adhesion was consistent with simple steady-state peeling models for inextensible tapes [14; 15], but only for peel-angles larger than approximately 30-40°. For smaller peel-angles, the measured adhesion significantly exceeded predictions from the inextensible tape model. In this case, pad detachment was preceded by sliding (see Fig. 1A). The effect of sliding was also visible in a significant decrease of crack propagation speed (measured as reduction in contact area divided by perimeter, see Fig. 1B).Sometimes sliding resulted in a complete temporary crack arrest and/or re-attachment of already detached parts of the pad. Thus, sliding effectively increased the force required to drive detachment, “toughening” the adhesive interface (see [16; 17], for similar observations on technical adhesives). This effect led to a more than five-fold increase of the effective work of adhesion for detachment at small peel angles, against the predictions of classic peeling theory where work of adhesion is assumed to be constant.

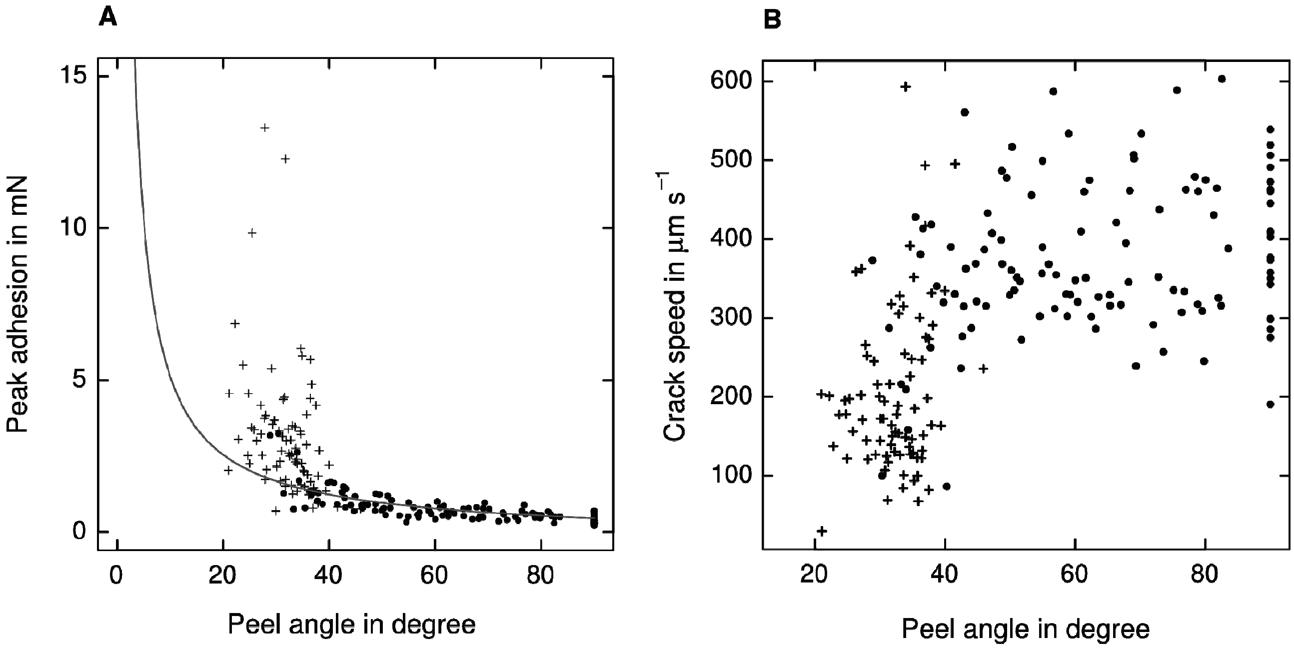

Fig. 1: Adhesion and crack propagation speed measured for different peel (pull-off) angles. In both figures, crosses indicate detachments involving significant sliding, while circles denote detachments without sliding. Sliding almost exclusively occurred for peel angles <40°. (A) Peak adhesive force against the peel angle. The grey solid line is a non-linear least square fit of the data with the inextensible tape model (fit restricted to quasi-static peeling data). (B) Crack propagation speed against the peel angle.

Analogous to technical pressure-sensitive adhesives, insect pads show a strong adhesion hysteresis. The underlying energy dissipation via sliding is mainly "external", (i.e. at the interface rather than within the adhesive), allowing insects to re-use adhesive pads repeatedly without any visible decrease in performance (see also [18]). This is in contrast to the "internal" energy dissipation that generates a significant part of the interface strength in pressure-sensitive adhesives [19]]. A more detailed understanding of this and other functional properties of insect adhesive pads may help to improve current technical adhesives in terms of their reversibility and reusability.

References

[1]Federle, W.; Riehle, M.; Curtis, A. S. & Full, R. (**2002**). *An Integrative Study of Insect Adhesion: Mechanics and Wet Adhesion of Pretarsal Pads in Ants*, Integr Comp Biol 42: 1100-1106.
[2]Gorb, S. & Scherge, M. (**2000**). *Biological microtribology: anisotropy in frictional forces of orthopteran attachment pads reflects the ultrastructure of a highly deformable material*, Proc R Soc Lond 267: 1239-1244.
[3]Niederegger, S. & Gorb, S. (**2003**). *Tarsal movements in flies during leg attachment and detachment on a smooth substrate*, J Insect Physiol 49: 611-620.
[4]Goldman, D. I.; Chen, T. S.; Dudek, D. M. & Full, R. J. (**2006**). *Dynamics of rapid vertical climbing in cockroaches reveals a template*, J Exp Biol 209: 2990-3000.
[5]Goodwyn, P.; Peressadko, A.; Schwarz, H.; Kastner, V. & Gorb, S. (**2006**). *Material structure,*

*stiffness, and adhesion: why attachment pads of the grasshopper (*Tettigonia viridissima*) adhere more strongly than those of the locust (*Locusta migratoria*) (Insecta: Orthoptera)*, J Comp Physiol 192: 1233-1243.
[6]Federle, W.; Brainerd, E. L.; McMahon, T. A. & Hölldobler, B. (**2001**). *Biomechanics of the movable pretarsal adhesive organ in ants and bees*, Proc Natl Acad Sci U S A 98: 6215 - 6220.
[7]Bullock, J. M. R.; Drechsler, P. & Federle, W. (**2008**). *Comparison of smooth and hairy attachment pads in insects: friction, adhesion and mechanisms for direction-dependence*, J Exp Biol 211: 3333-3343.
[8]Clemente, C. J. & Federle, W. (**2008**). *Pushing versus pulling: division of labour between tarsal attachement pads in cockroaches.*, Proc R Soc B 275: 1329-1336.
[9]Dirks, J.; Li, M.; Kabla, A. & Federle, W. (**2012**). In vivo *dynamics of the internal fibrous structure in smooth adhesive pads of insects*, Acta Biomater 8: 2730-2736.
[10]Endlein, T. & Federle, W. (**2013**). *Rapid preflexes in smooth adhesive pads of insects prevent sudden detachment*, Proc R Soc B 280: 20122868.
[11]Labonte, D. & Federle, W. (**2013**). *Functionally different pads on the same foot allow control of attachment: stick insects have load-sensitive "heel" pads for friction and shear-sensitive "toe" pads for adhesion*, PLoS ONE 8: e81943.
[12]Autumn, K.; Dittmore, A.; Santos, D.; Spenko, M. & Cutkosky, M. (**2006**). *Frictional adhesion: a new angle on gecko attachment*, J Exp Biol 209: 3569-3579.
[13]Endlein, T.; Ji, A.; Samuel, D.; Yao, N.; Wang, Z.; Barnes, W. J. P.; Federle, W.; Kappl, M. & Dai, Z. (**2013**). *Sticking like sticky tape: tree frogs use friction forces to enhance attachment on overhanging surfaces*, J R Soc Interface 10: 20120838.
[14]Rivlin, R. (**1944**). *The effective work of adhesion*, Paint Technol. 9: 215-216.
[15]Kendall, K. (**1975**). *Thin-film peeling -- the elastic term*, J Phys D: Appl Phys 8: 1449-1452.
[16]Newby, B. & Chaudhury, M. (**1998**). *Friction in adhesion*, Langmuir 14: 4865-4872.
[17]Newby, B.; Chaudhury, M. & Brown, H. (**1995**). *Macroscopic evidence of the effect of interfacial slippage on adhesion*, Science 269: 1407-1409.
[18]Gravish, N.; Wilkinson, M. & Autumn, K. (**2008**). *Frictional and elastic energy in gecko adhesive detachment*, J R Soc Interface 5: 339-348.
[19]Creton, C. (**2003**). *Pressure-sensitive adhesives: an introductory course*, MRS bulletin 28: 434-439.