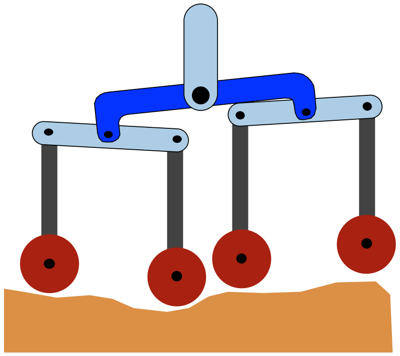
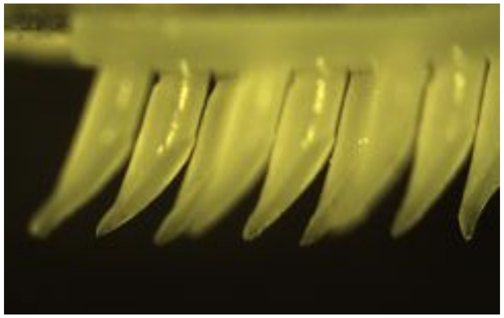
Principles for climbing with dry adhesion

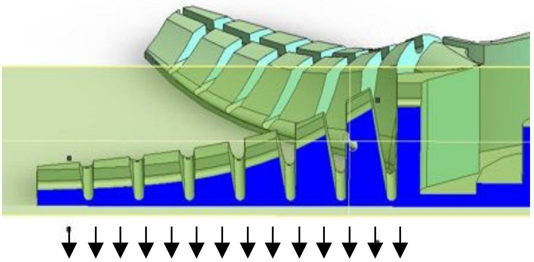
1. Hierarchical compliance



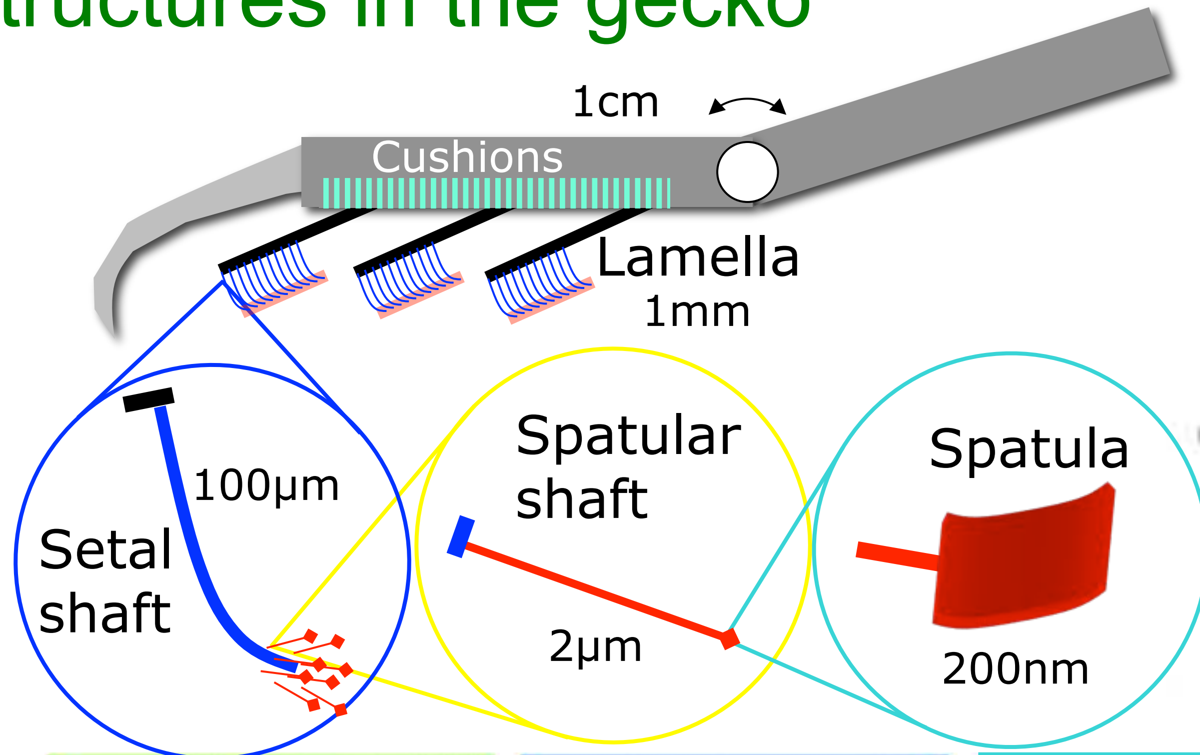
2. Directional adhesives

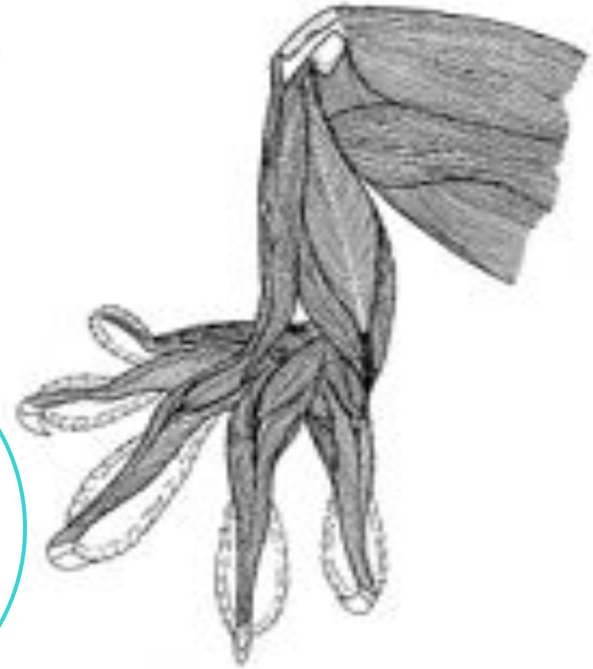


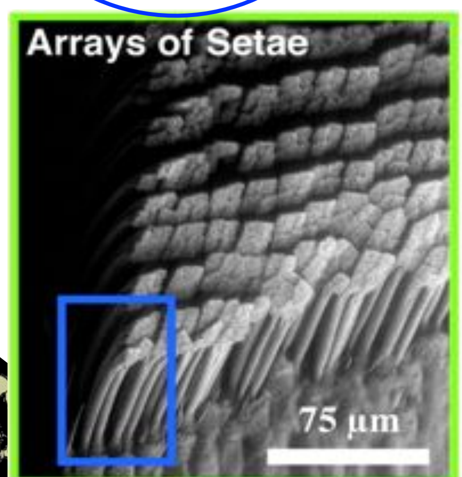
3. Distributed force control

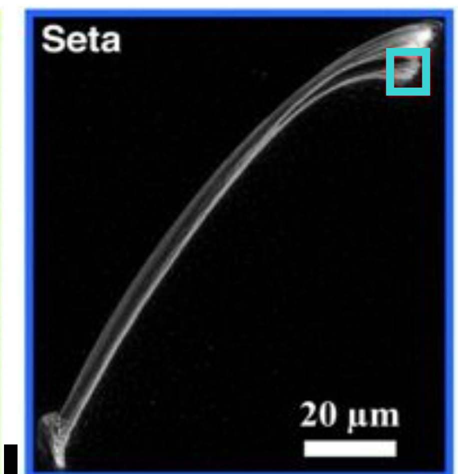


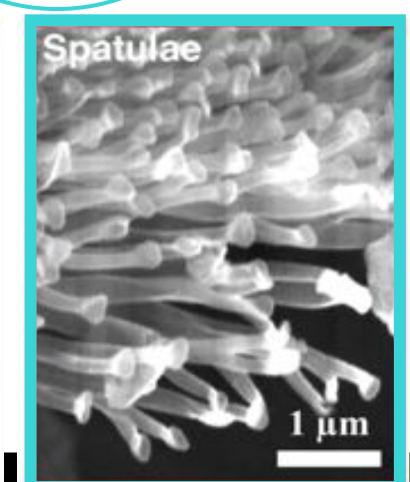
Conforming to surfaces: hierarchy of compliant structures in the gecko





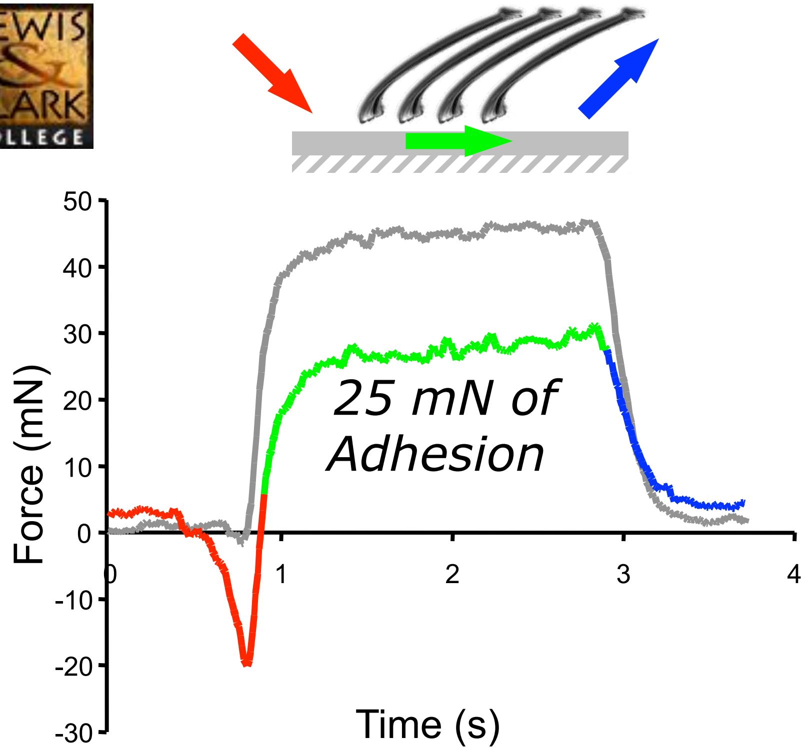




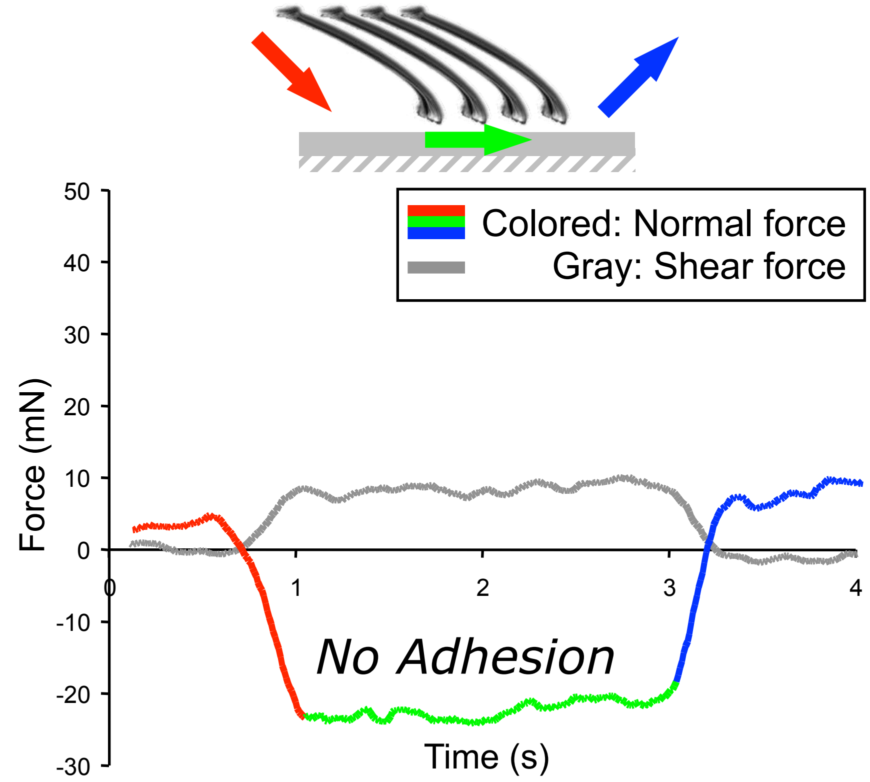


Directional gecko adhesion

Gecko setae dragging with curvature



Dragging against curvature

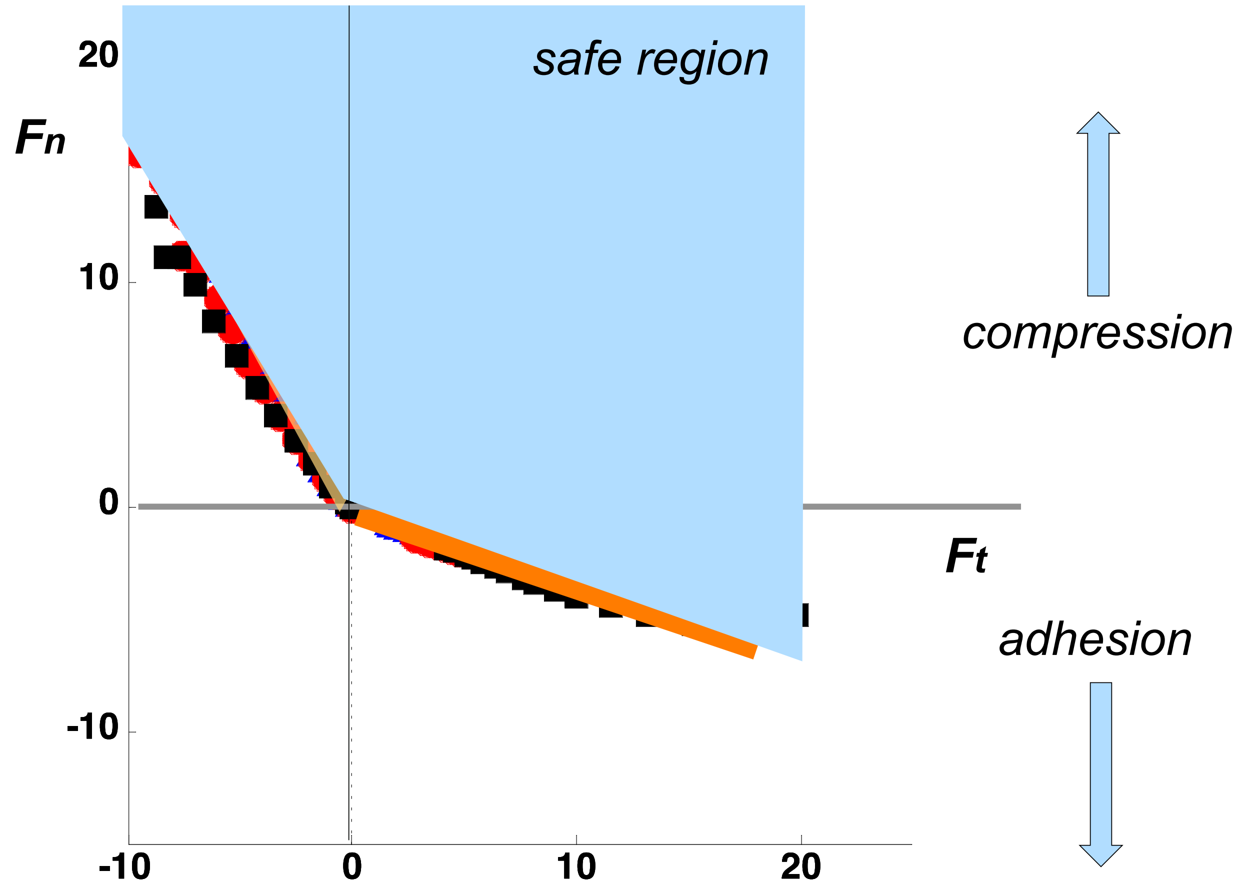


Gecko Force-Space Results

Autumn et al. JEB 2006

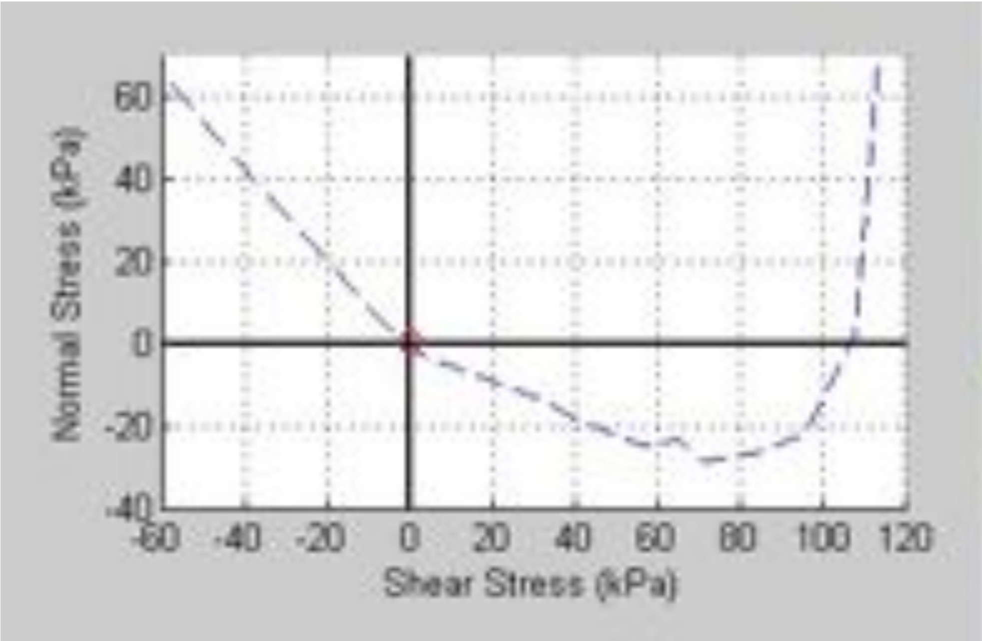
loaded *against* stalk angle:
Coulomb friction

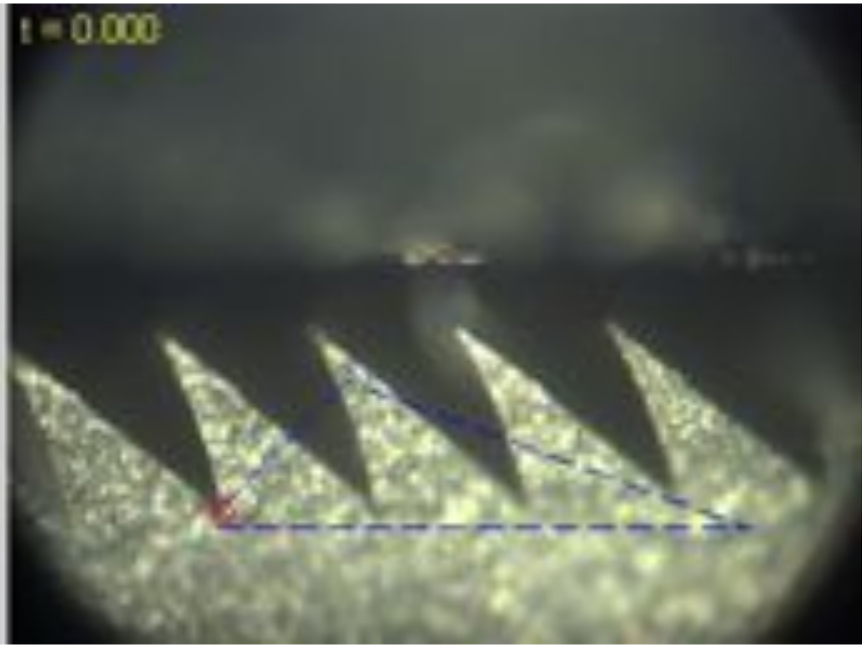
Load, then pull off at various angles, and measure force



loaded *with* stalk angle:
adhesion ~ tangential stress

Directional adhesion: loading cycle determines adhesion

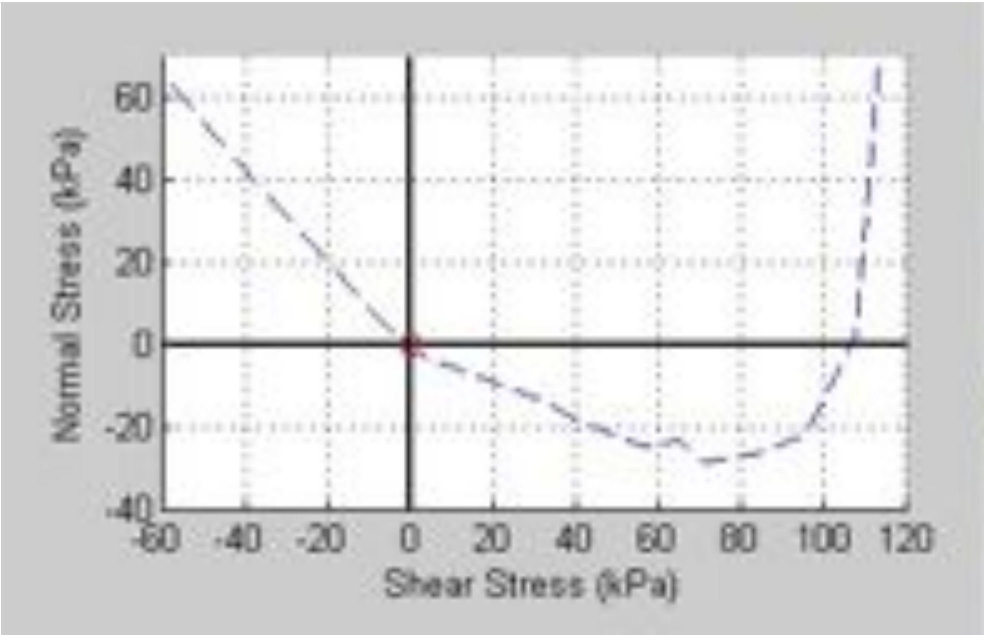


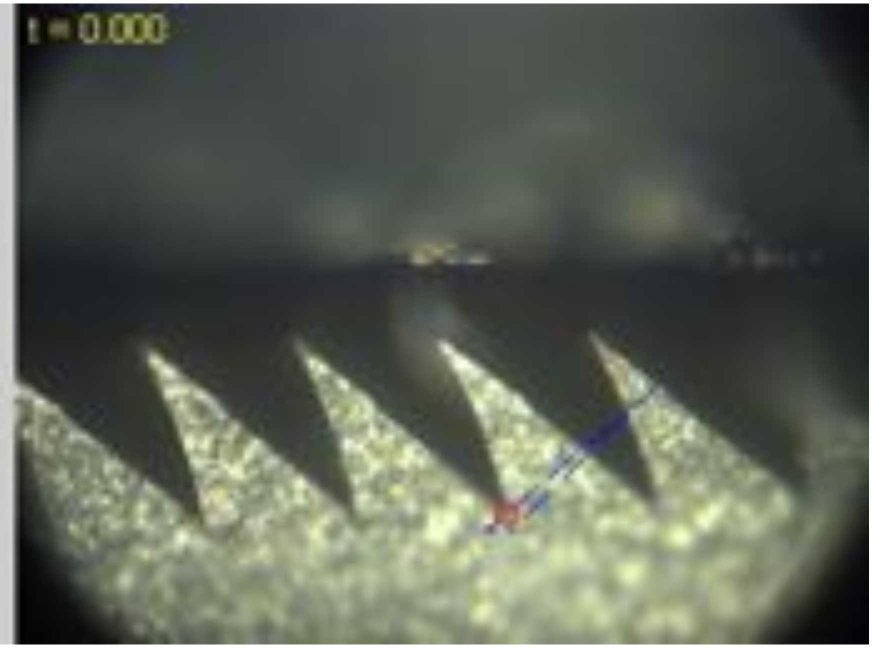


normal and shear stress trajectory versus limit curve

microscope video, side view with trajectory shown

Directional adhesion: loading cycle determines adhesion

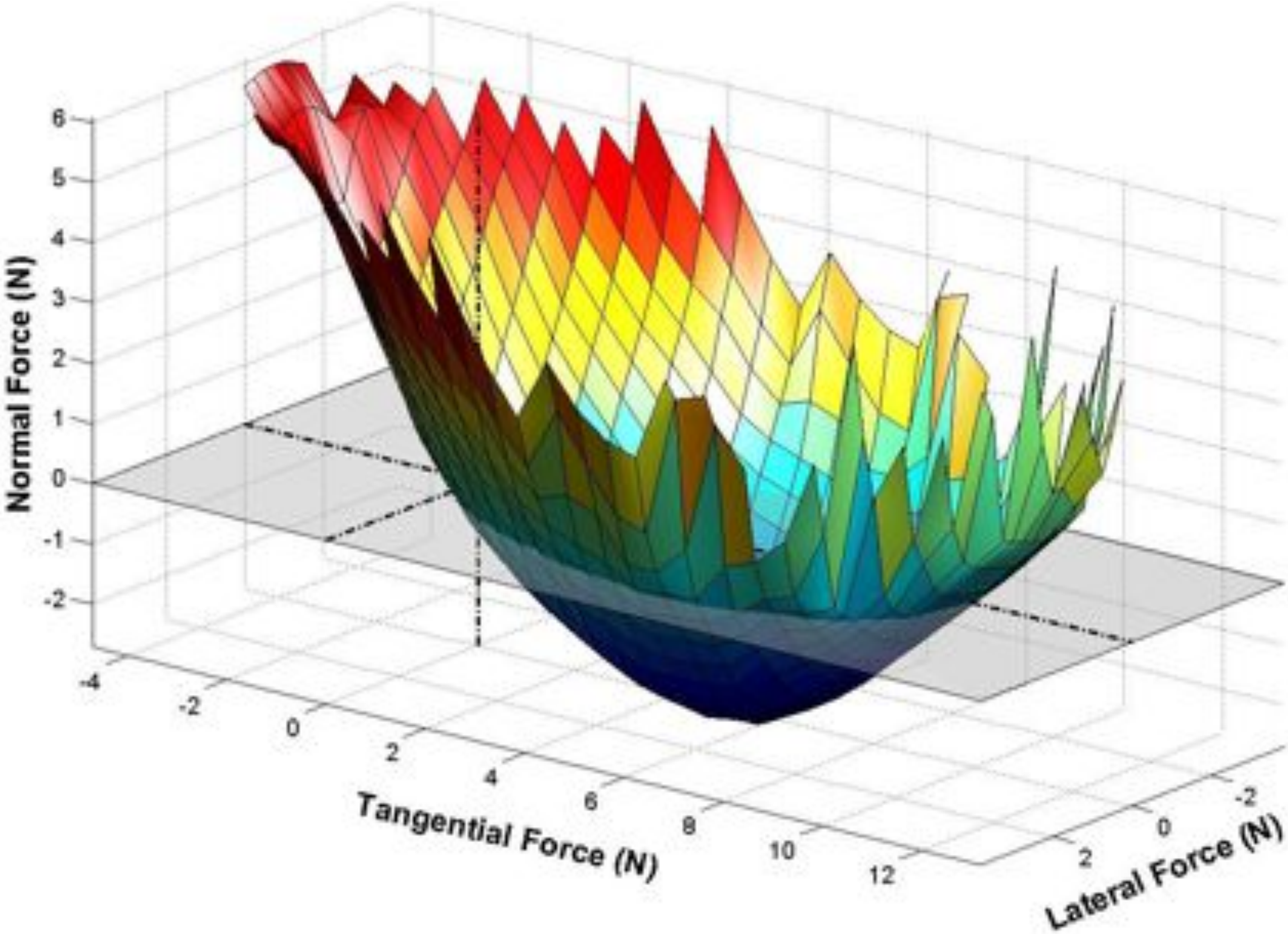




normal and shear stress trajectory versus limit curve

microscope video, side view with trajectory shown

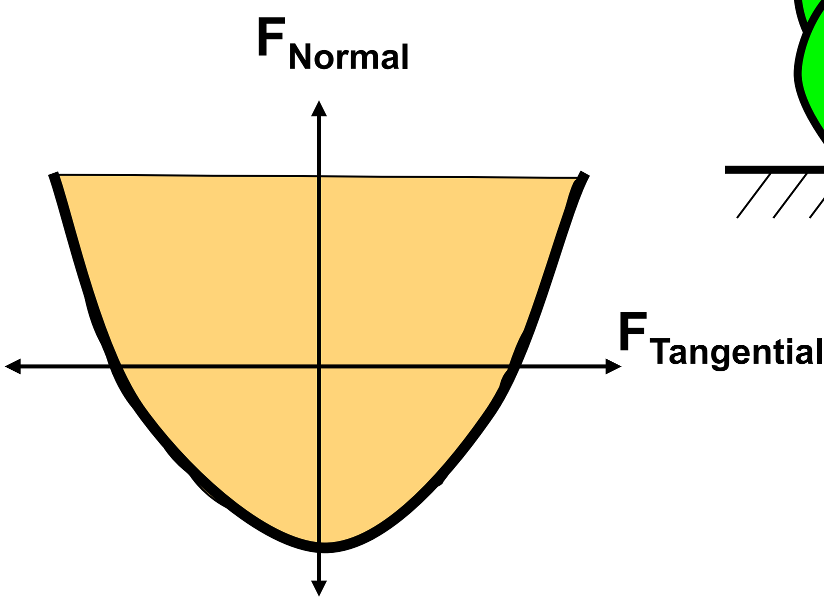
Stickybot foot adhesion limit surface



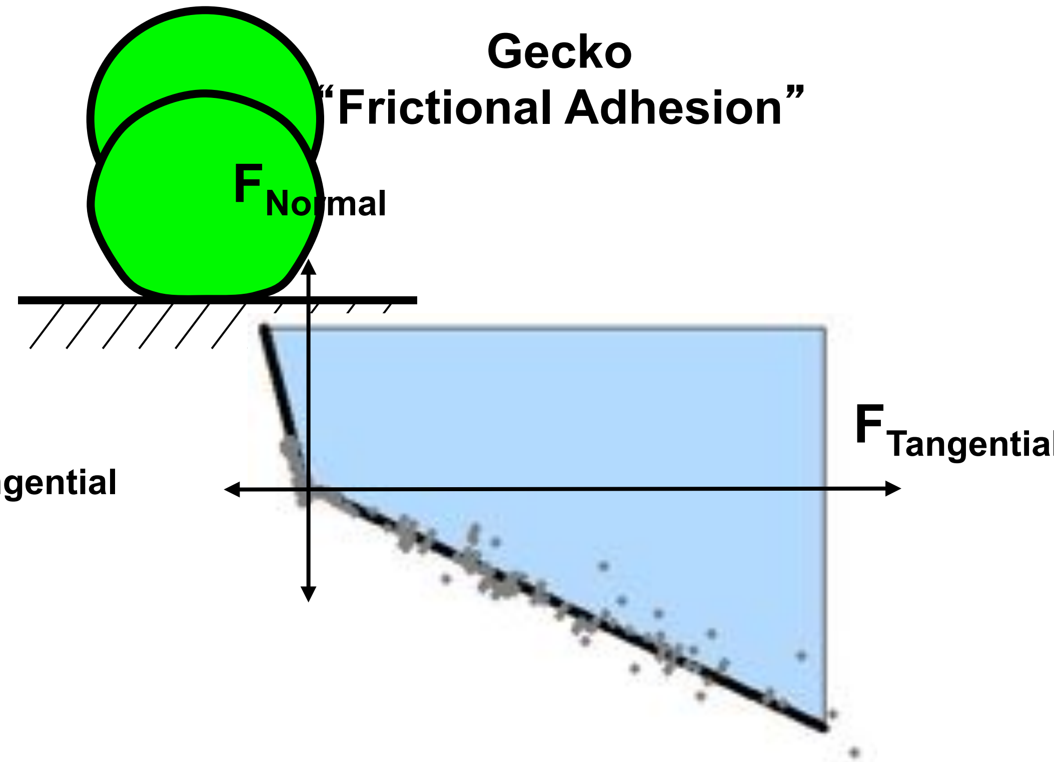
D. Santos, et al.Gecko-Inspired Climbing Behaviors on Vertical and Overhanging Surfaces, IEEE ICRA 2008.

Adhesion limit surface implications

Johnson-Kendall-Roberts



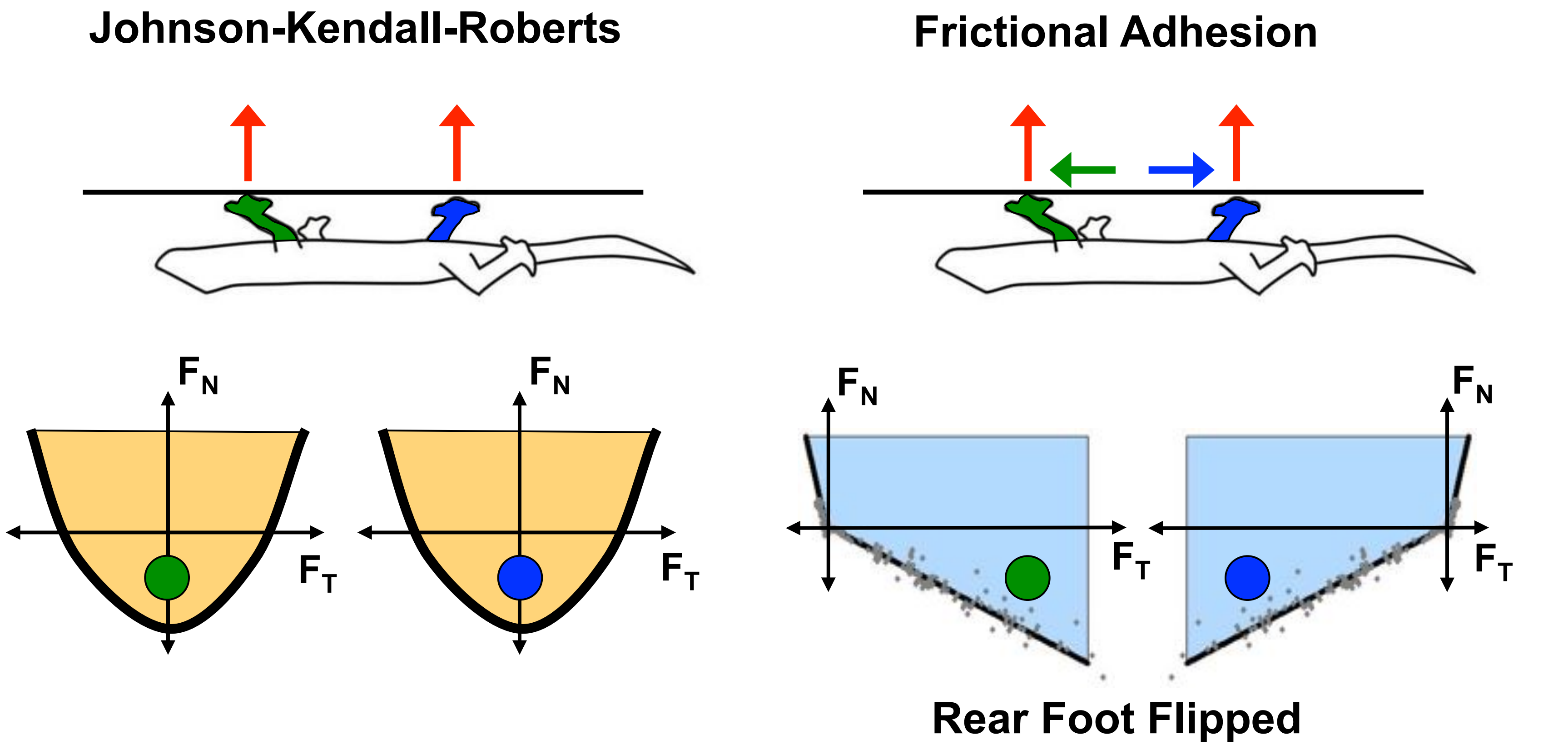
Gecko
"Frictional Adhesion"



Autumn, et al.; Journal of Experimental Biology; Volume 209, 2006

Force Control

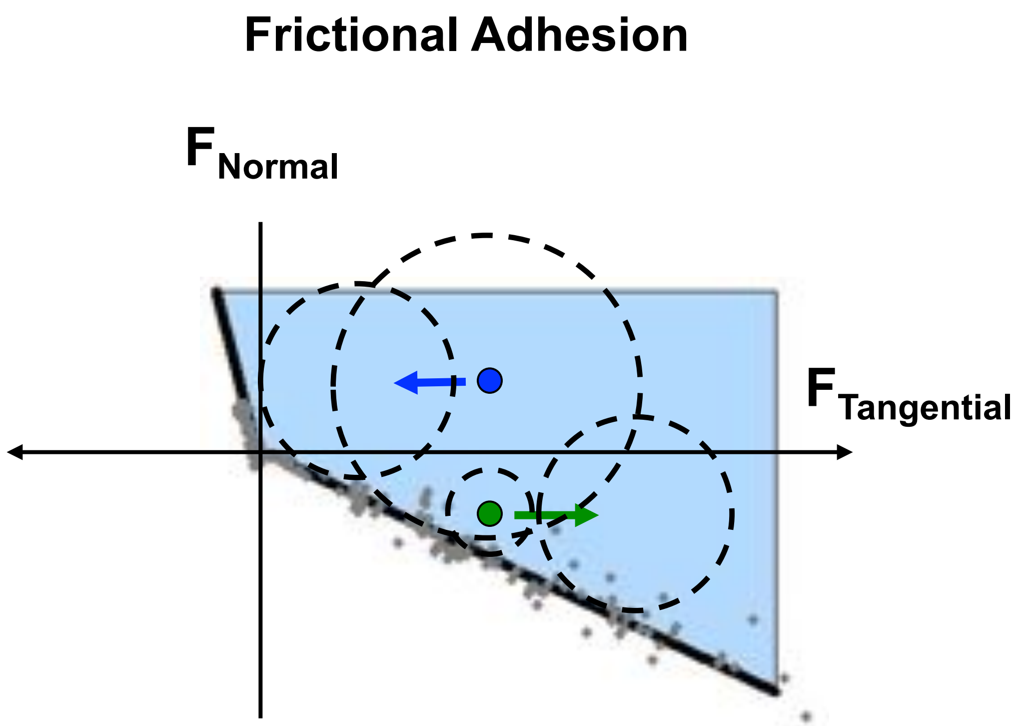
optimal strategy for inverted surface

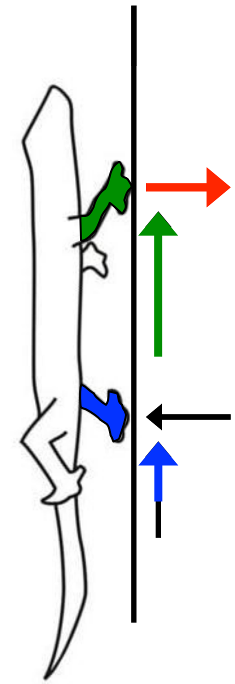


Generalization: Formulate as linear programming problem to control foot orientation & internal forces for arbitrary loading conditions [Santos, JAST09].

Force Control: vertical surfaces

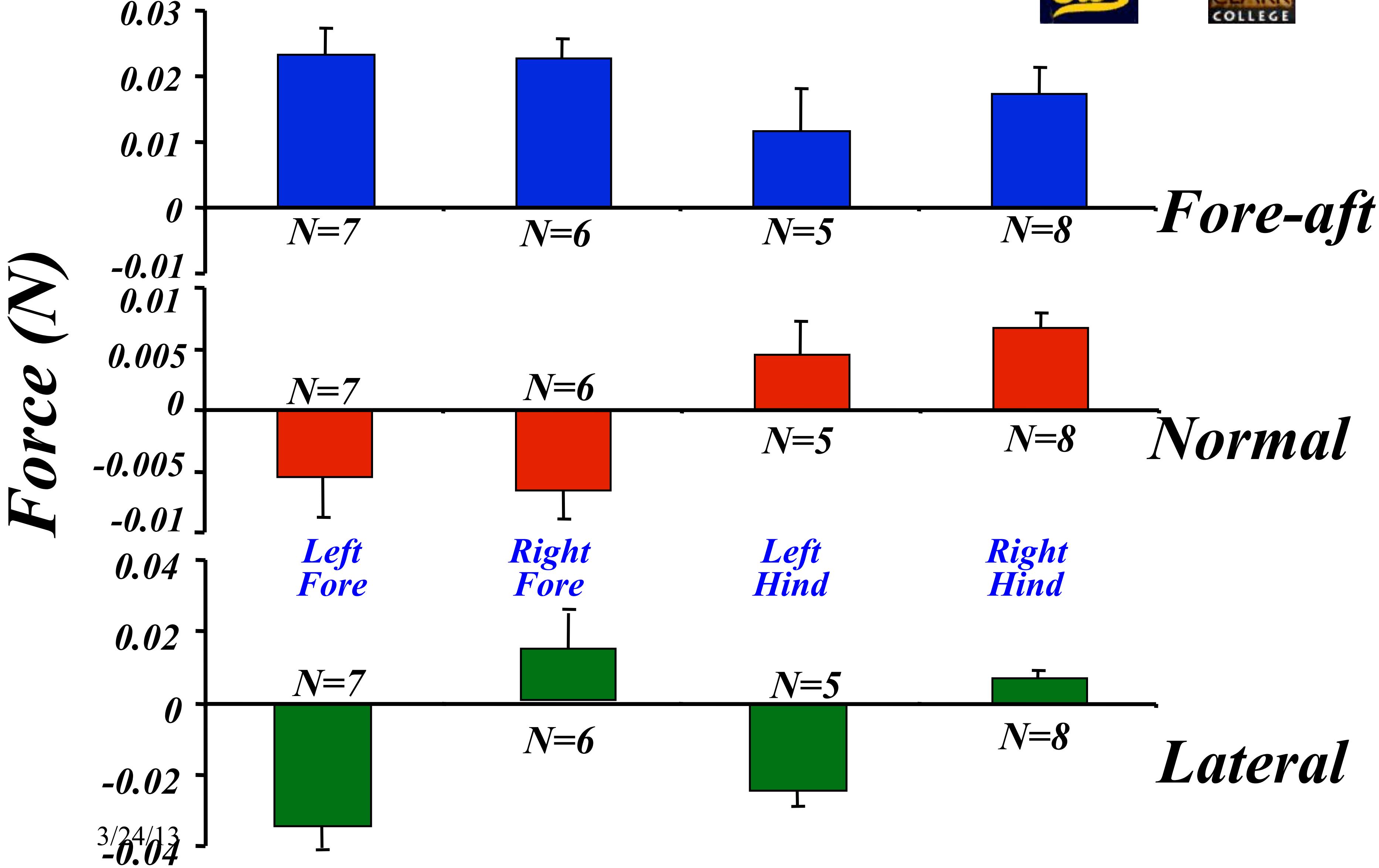
consequences of adhesion model



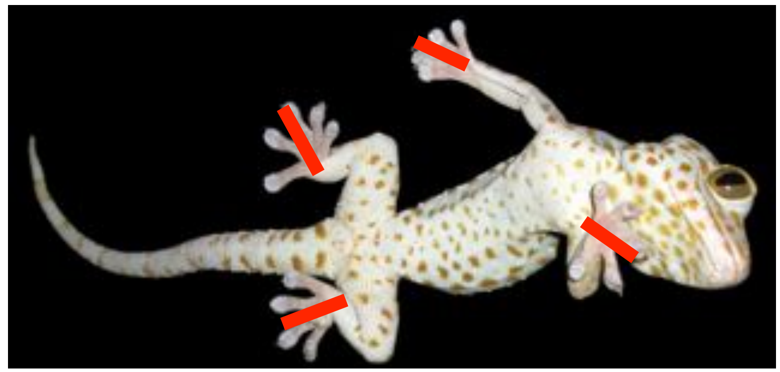


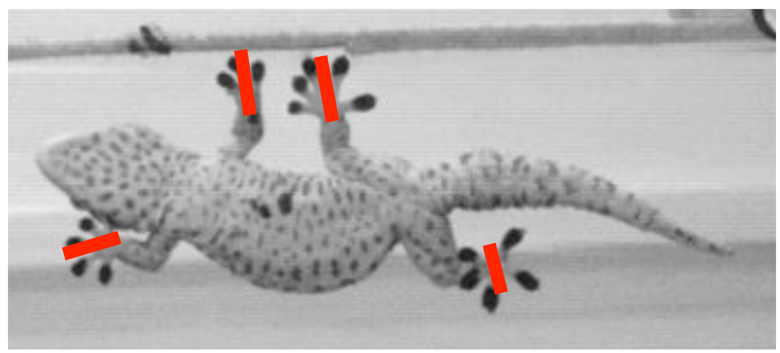
Gecko wall reaction forces

R.J. Full K. Autumn

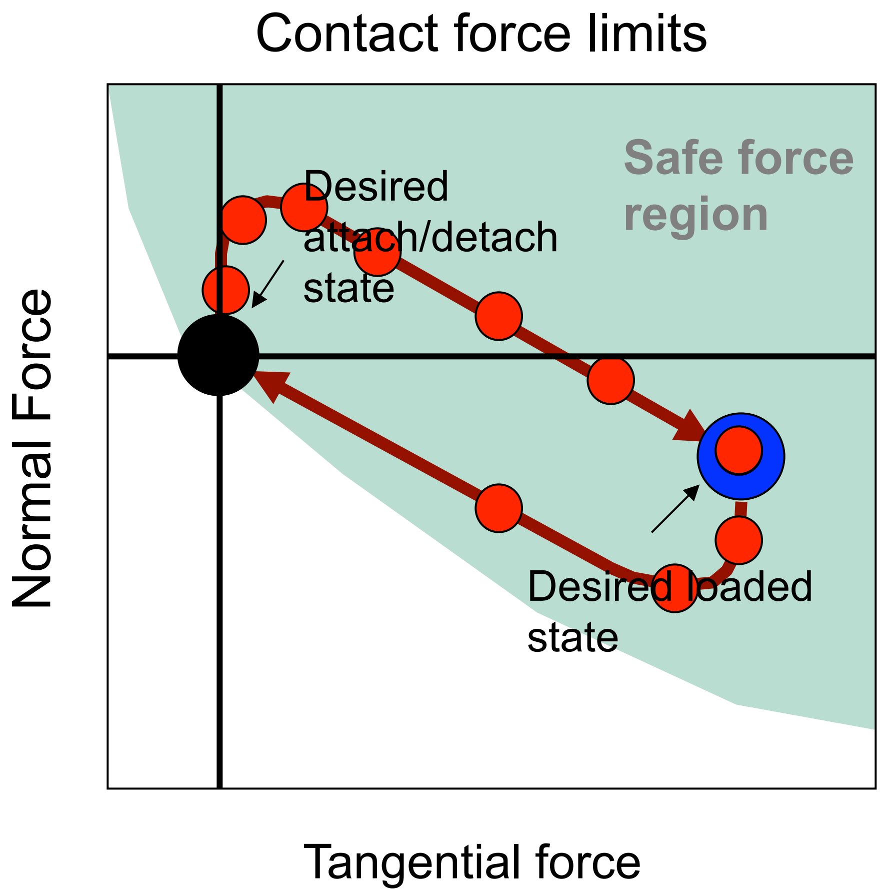


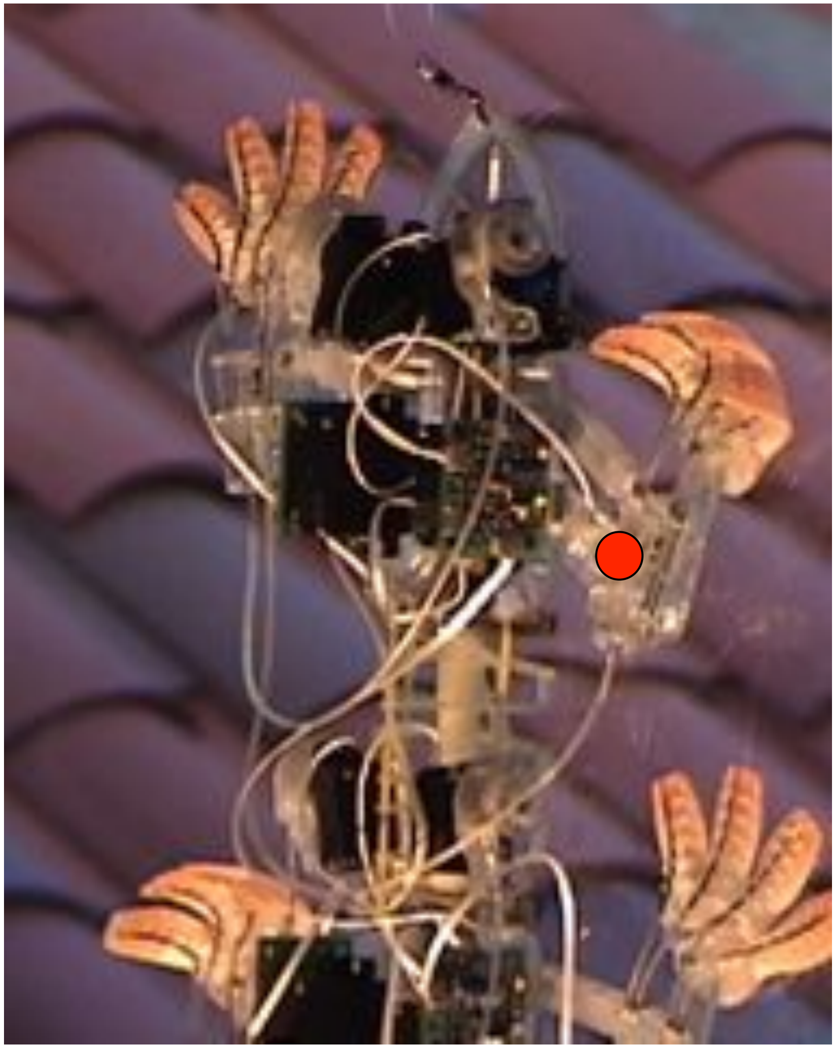
Control foot orientation + internal forces





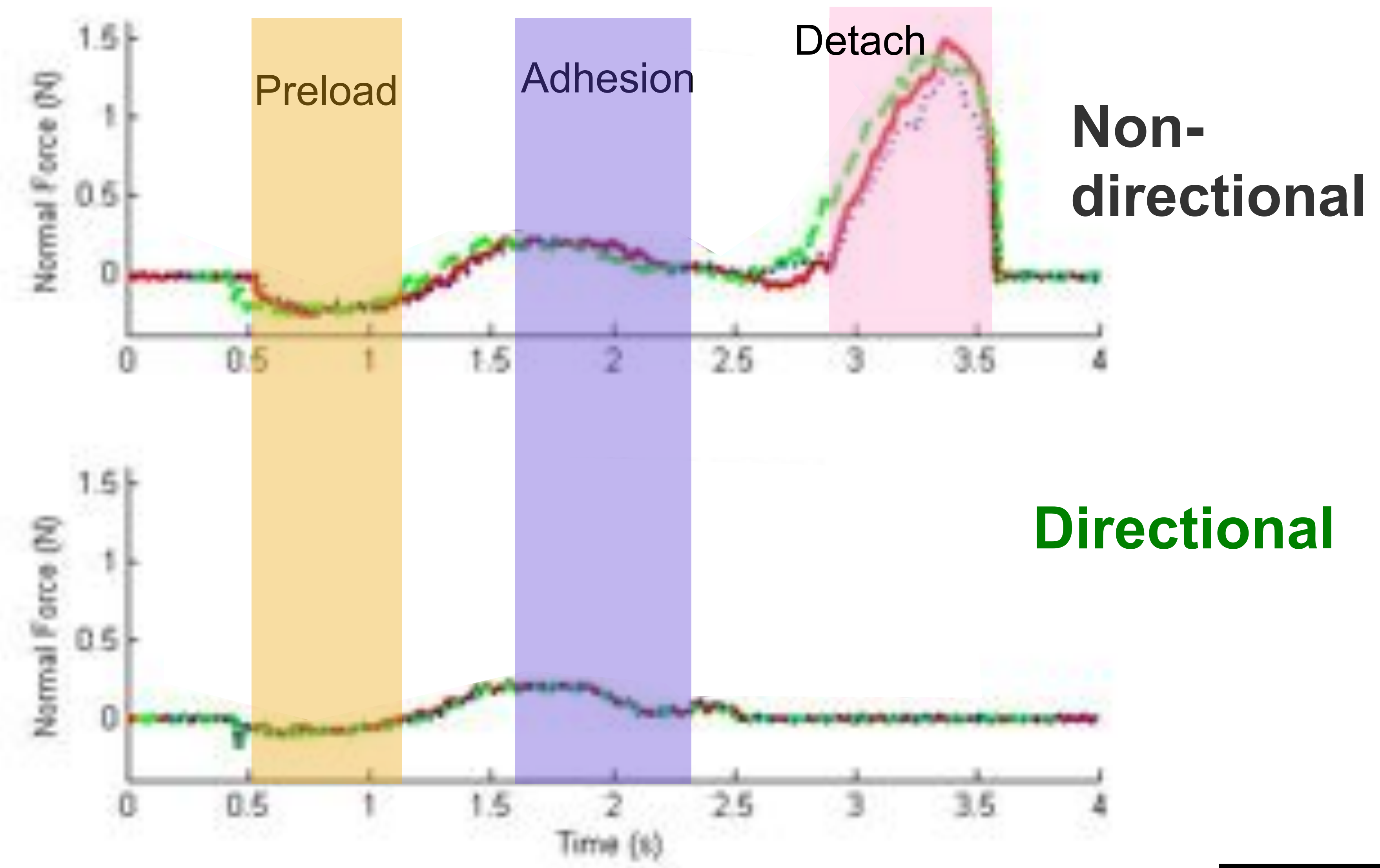
Directional adhesion facilitates control of forces for smooth, efficient locomotion





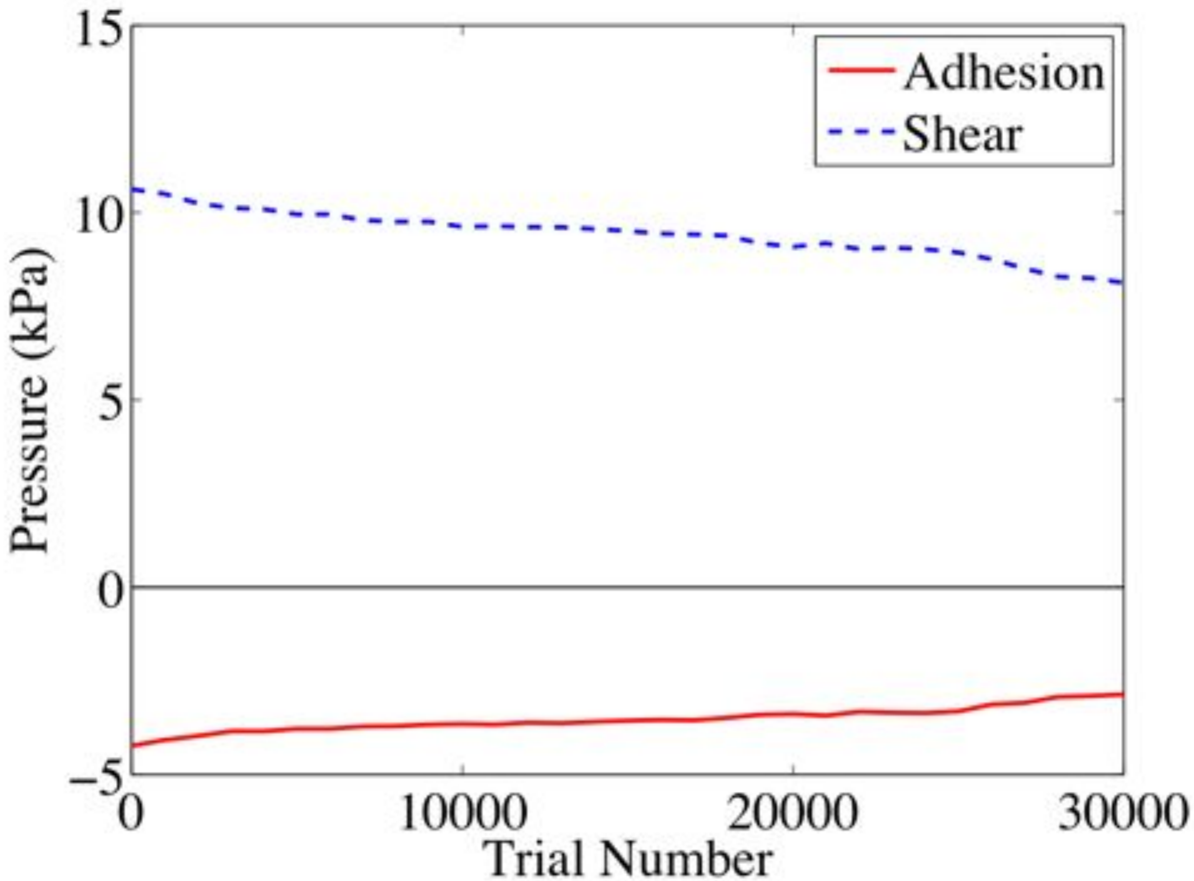
Directional vs. non-directional

One front leg cycled with three feet attached (tripedal crawl). 3 successive steps shown



Dynamic Directional Adhesion

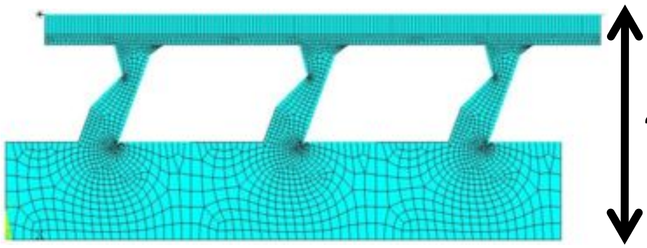
- Directional behavior similar to gecko and larger Stickybot stalks
- Adhesion maintained, while sliding.
- Provides *non-catastrophic* failure mechanism.



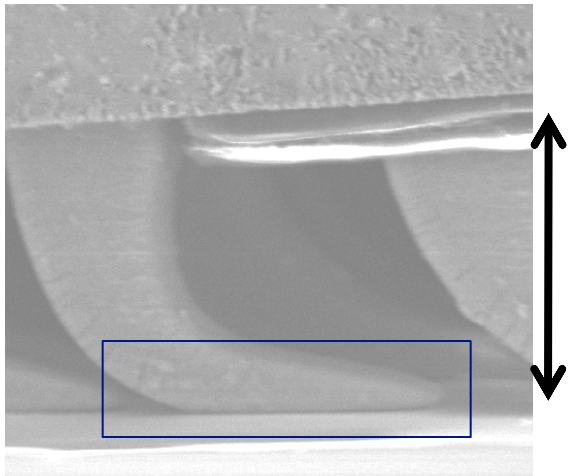
Hypothesis: directional adhesion ➡ gentle loading + lift-off ➡ long life

Adhesive structure analysis for optimization of performance

- Behavior occurs at multiple scales
  - Suspension scale (mm)
    - Commercial software is viable
      - Preload path only
  - Terminal features scale (µm)
    - Custom FE code
    - Semi-analytic models



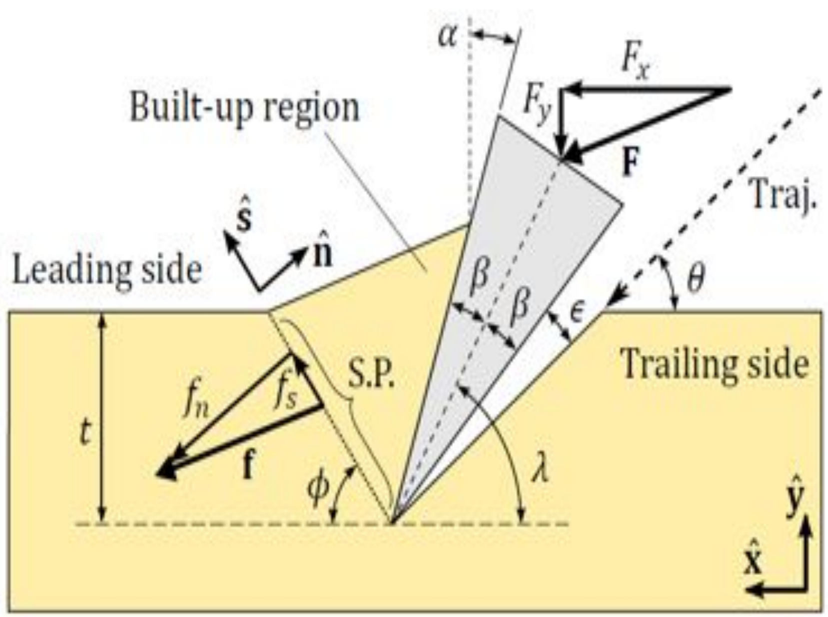
~2mm

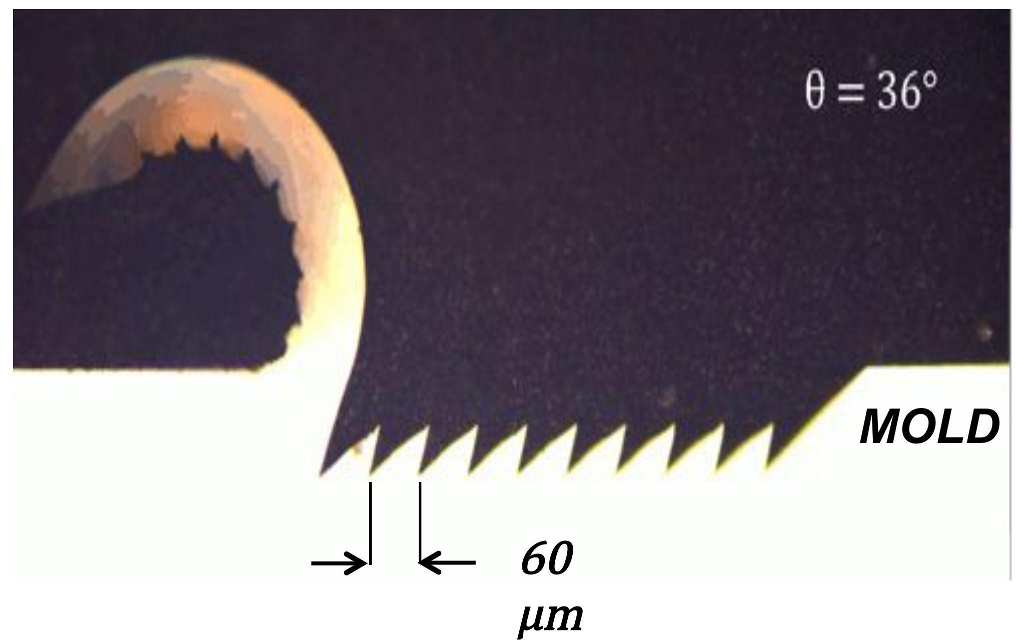


~40µm

Machining Process Overview

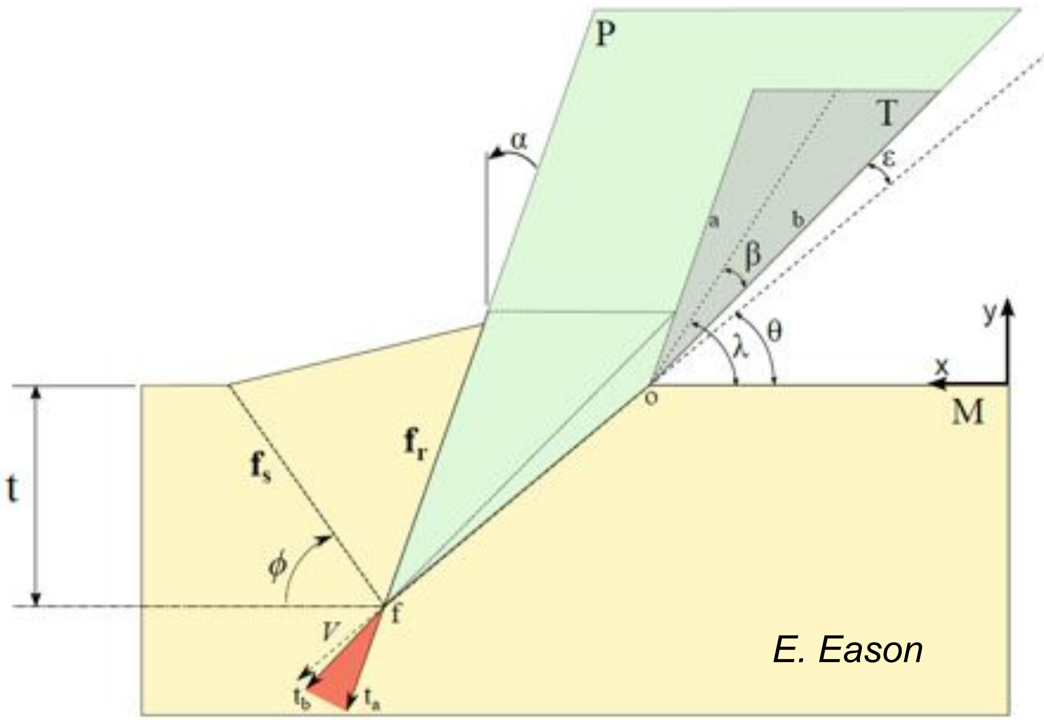
Control blade trajectory to get desired shape and dense packing of features

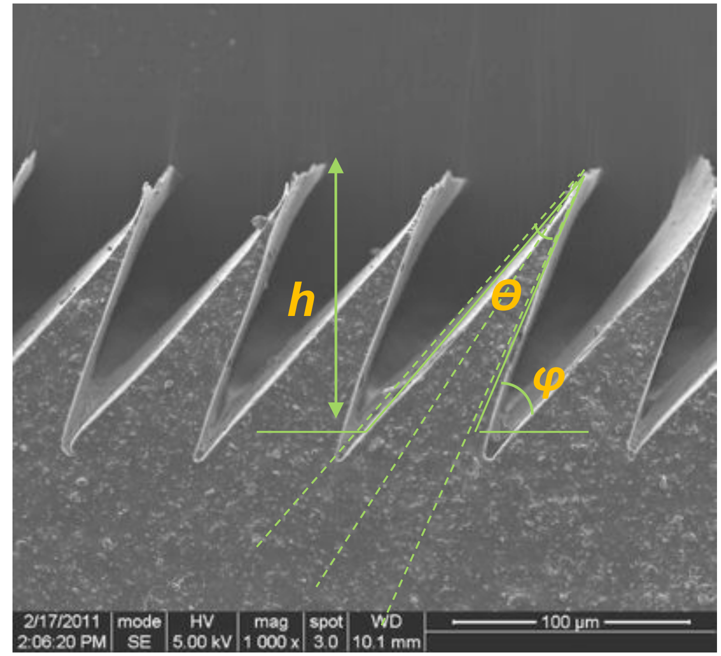




E. Eason et al., "Micro-Wedge Machining for the Manufacture of Directional Dry Adhesives," ASME Journal of Micro and Nano-Manufacturing, 2013 (in press)

Angle control: micromachining process

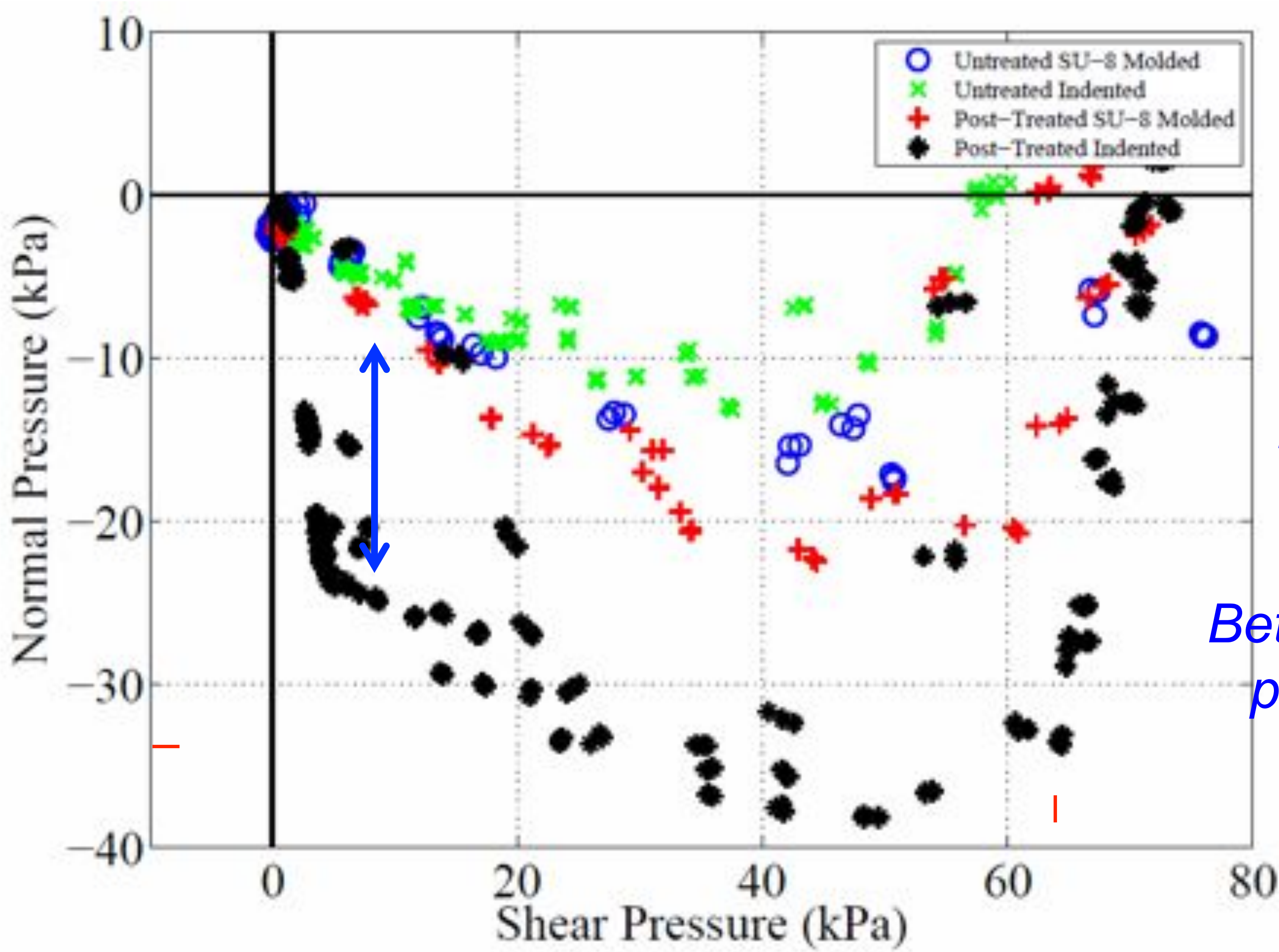




Key Design Parameters

- ϕ: angle of fiber
- ϴ: interior fiber angle
- h: fiber height
- s: fiber spacing
- E: material Young's Modulus

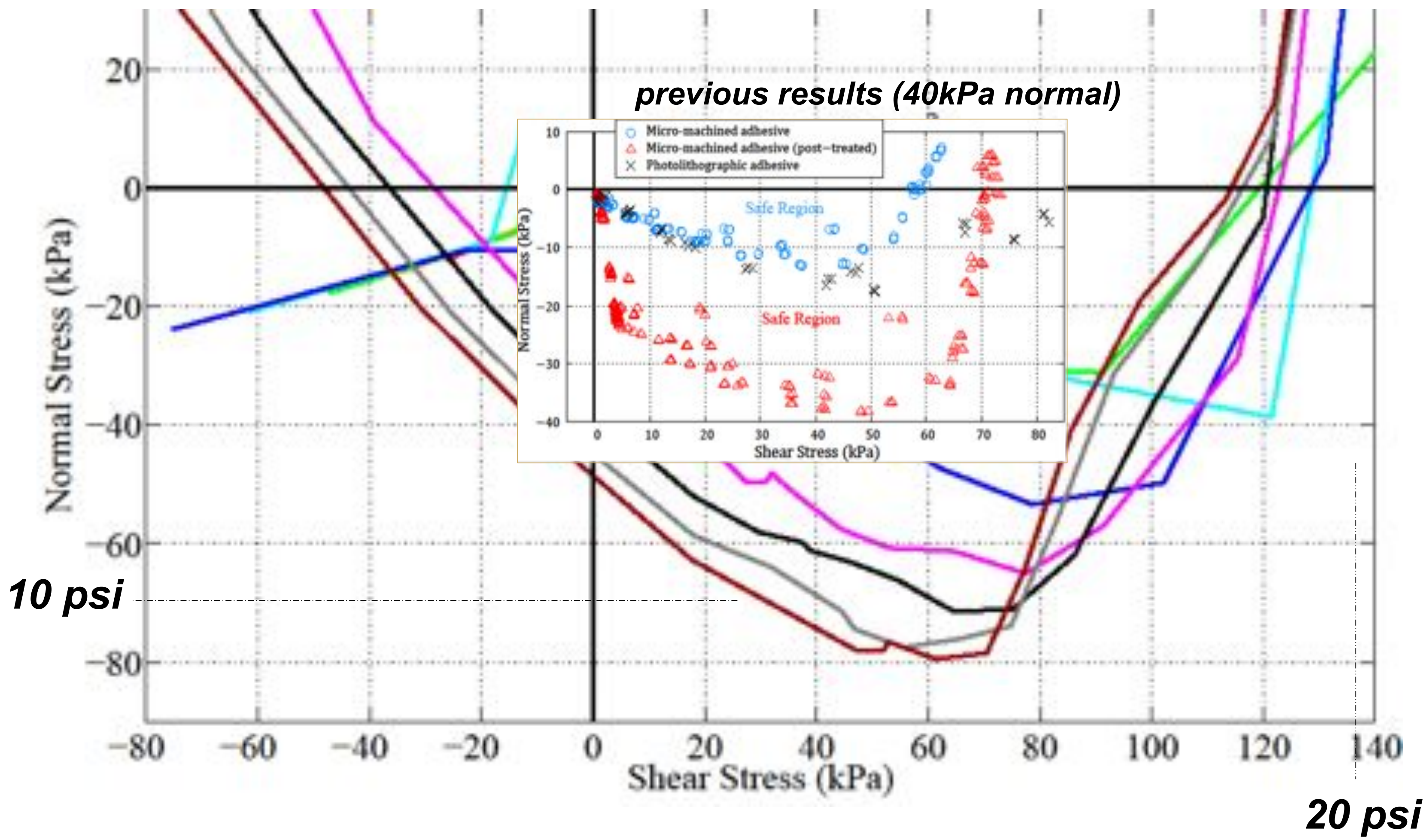
Machined *vs* lithographic microwedge performance



Increased adhesion

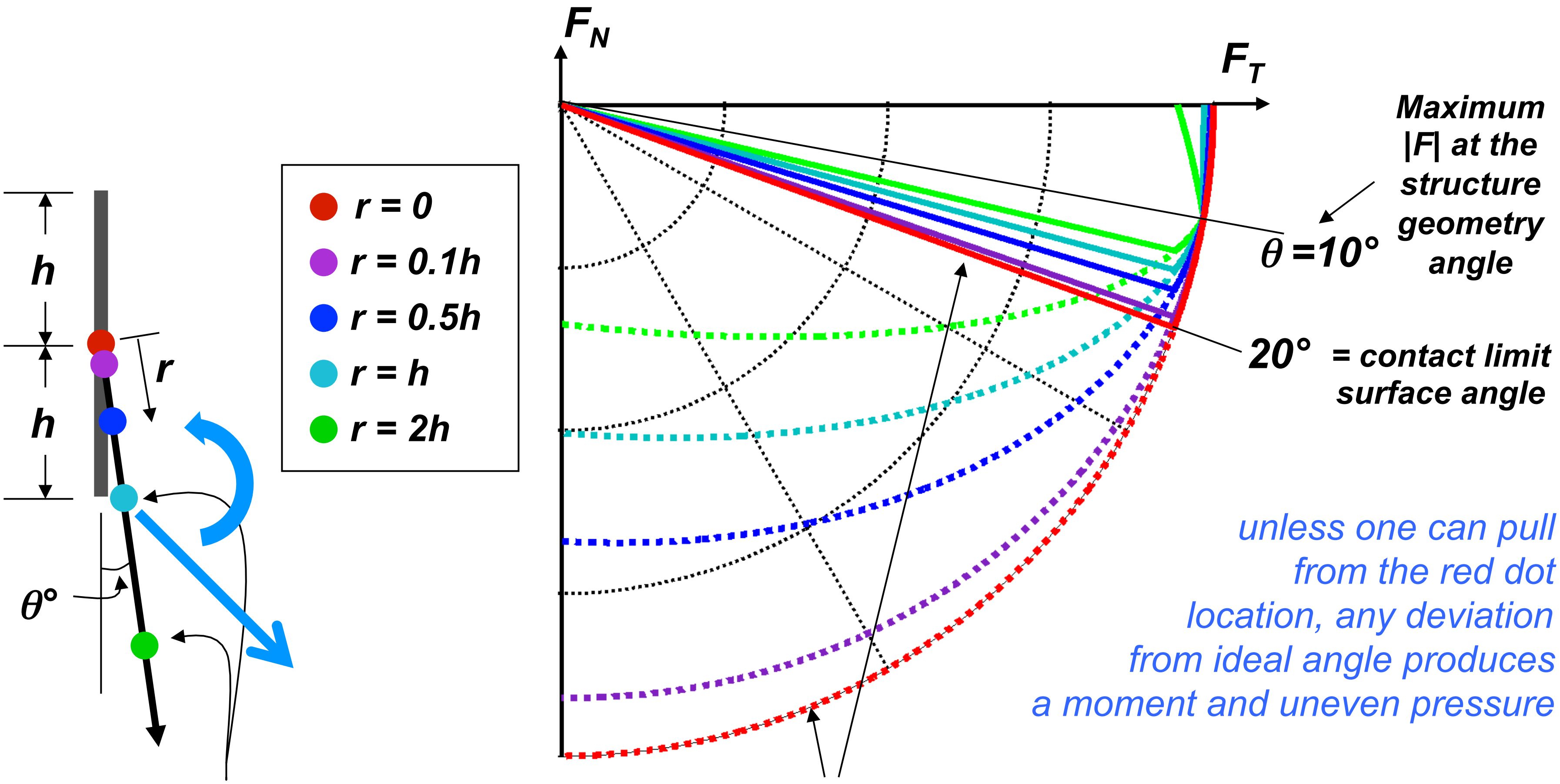
Better low-shear performance

Test results with unfilled PDMS



Large scale results: 17 psi in pure shear over 1x1 in

Loading on the wall is different from benchtop tests; geometry affects limit surface

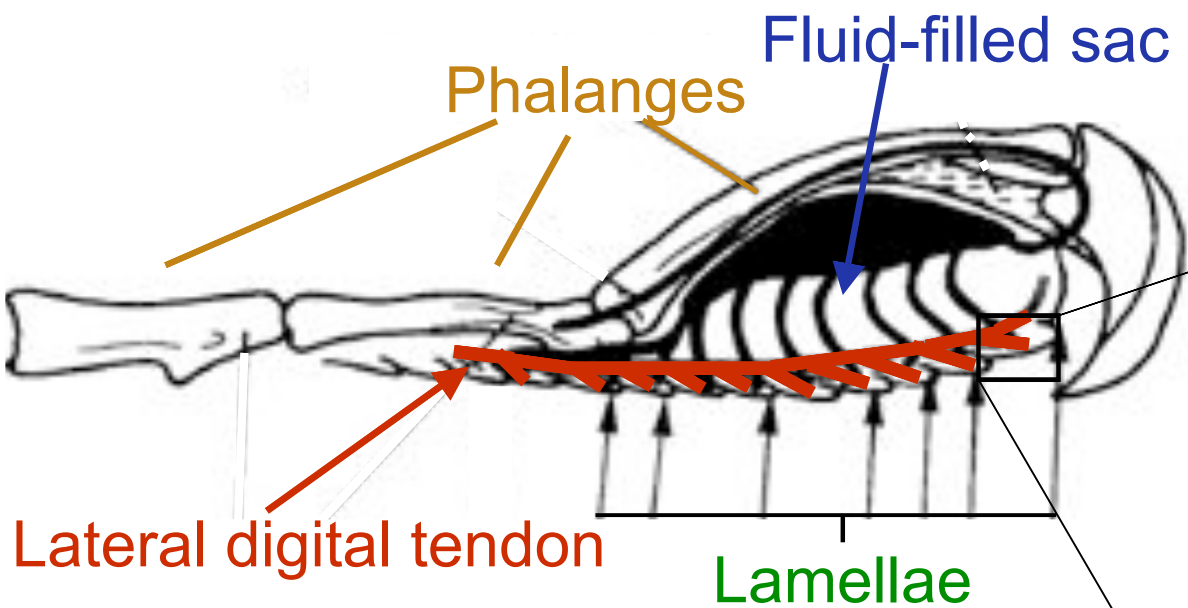


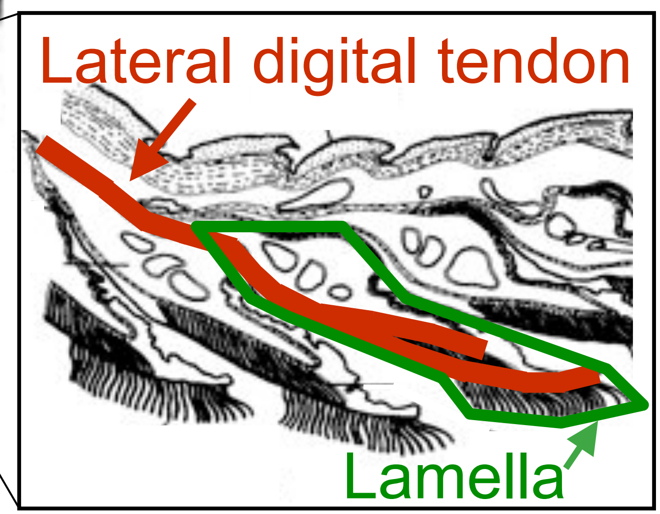
unless one can pull from the red dot location, any deviation from ideal angle produces a moment and uneven pressure

Different pull locations (structure is rigid between pull location and contact points)

Red r=0 lines match the original contact limit surfaces

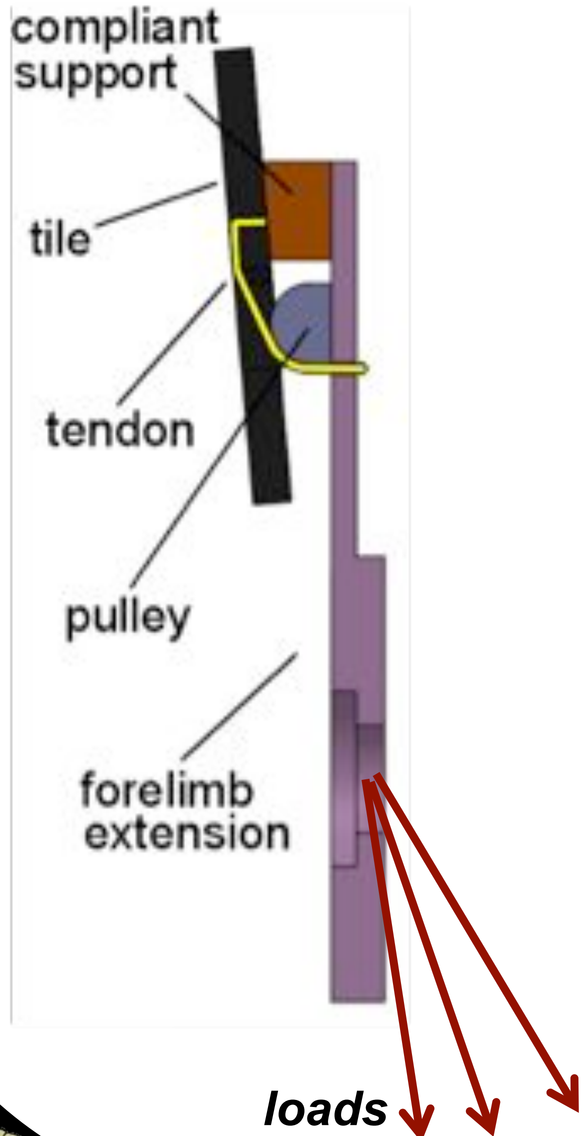
How to get nearly uniform loading over the entire toe, with tolerance to a range of loading angles?

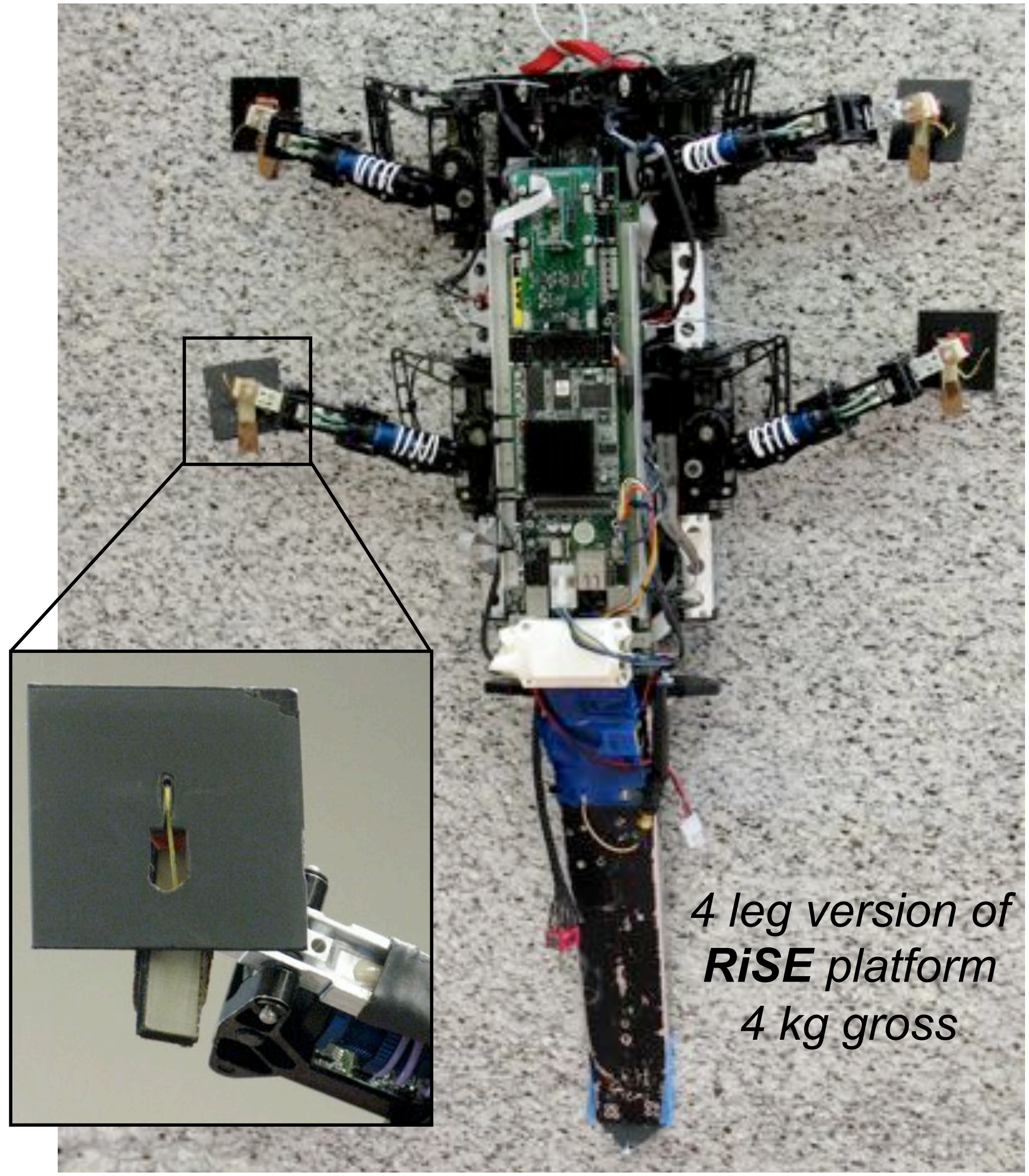




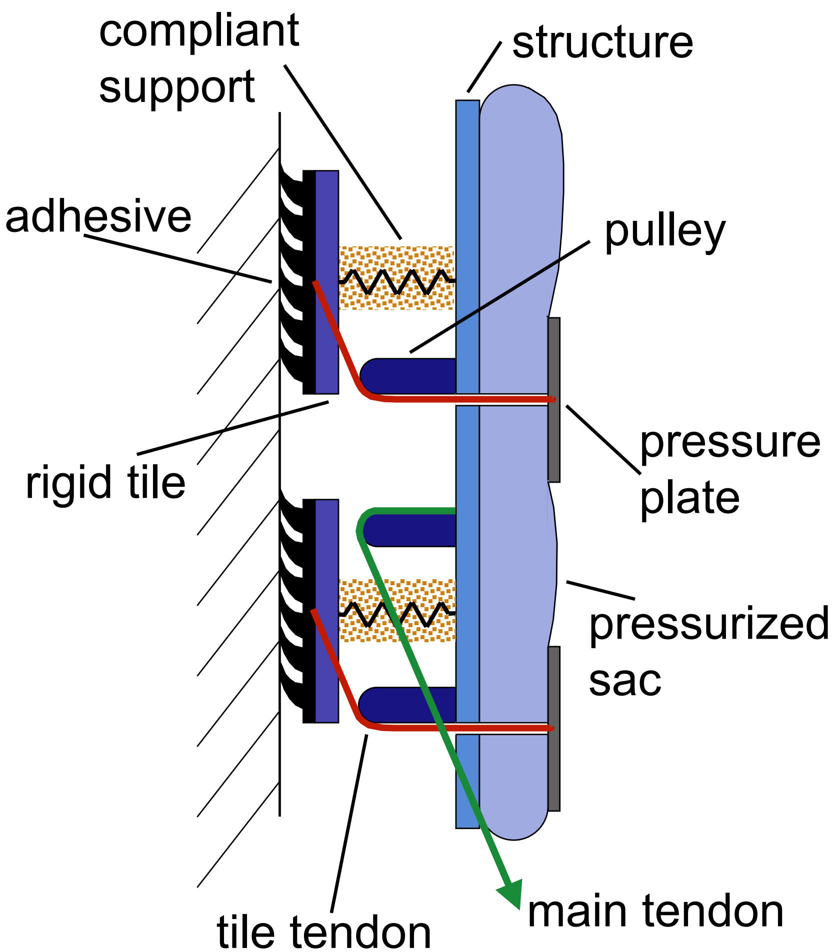
(Russell J. Morphology 1982)

Loading angles: alignment compensation





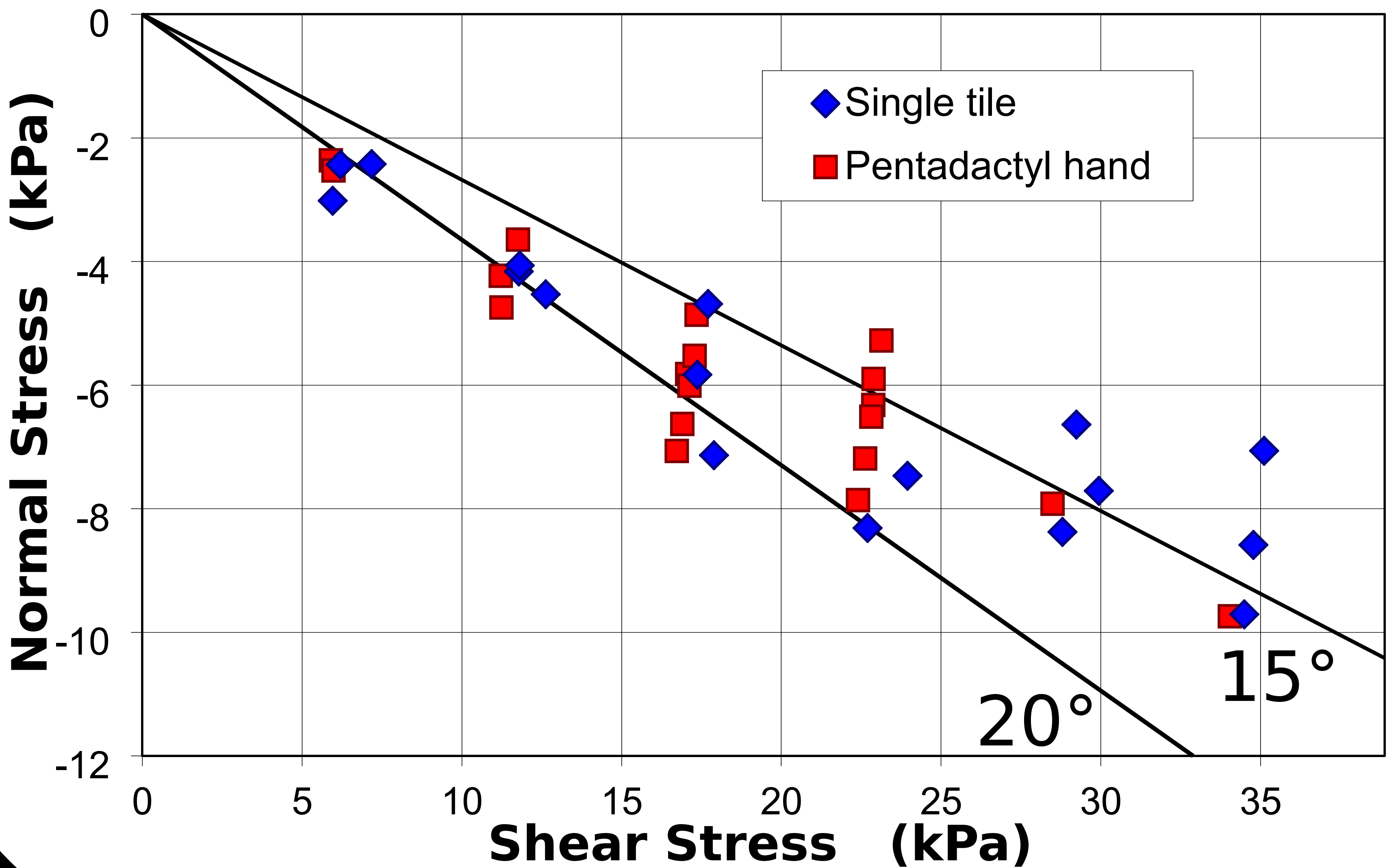
Scaling to larger areas and loads: tiled arrays



Approx. 80cm²

40 kg

Scaling to larger areas and loads: results



Manufacturing Adhesives

Problem: wax mold is not durable

- No surface treatment: reuse 1-2 times
- Repel Silane treatment: reuse 5-8 times (Draper)

This is an **expensive** problem

- Replacing mold takes 4 hr (**$300** at $75/hr)

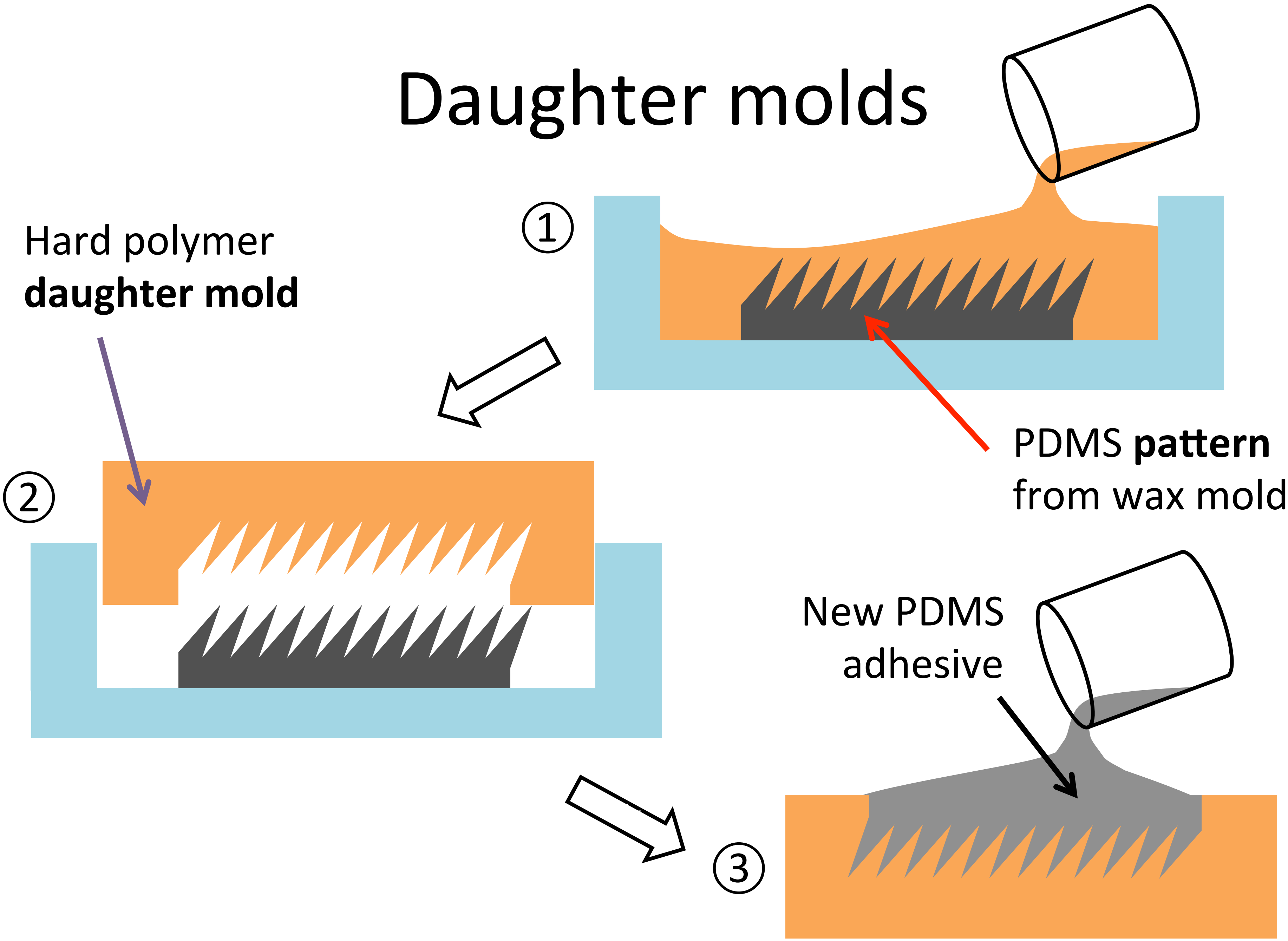
We want to reuse molds >100 times

- Mold cost per use: 2.4 min (**$3**)

Attempts at more durable molds

1. Use harder material in micromachining
   Attempted by Stanford (Pb-Sn) and Draper
   Forces are too high: indenting tool deflects and dulls
2. Lost-wax casting to replicate mold in metal
   Concerns about surface finish & grain size
3. Nickel metallization on wax mold (Draper)
   Poor surface finish and fidelity so far
4. Daughter molds made from adhesives
   Promising

Daughter molds

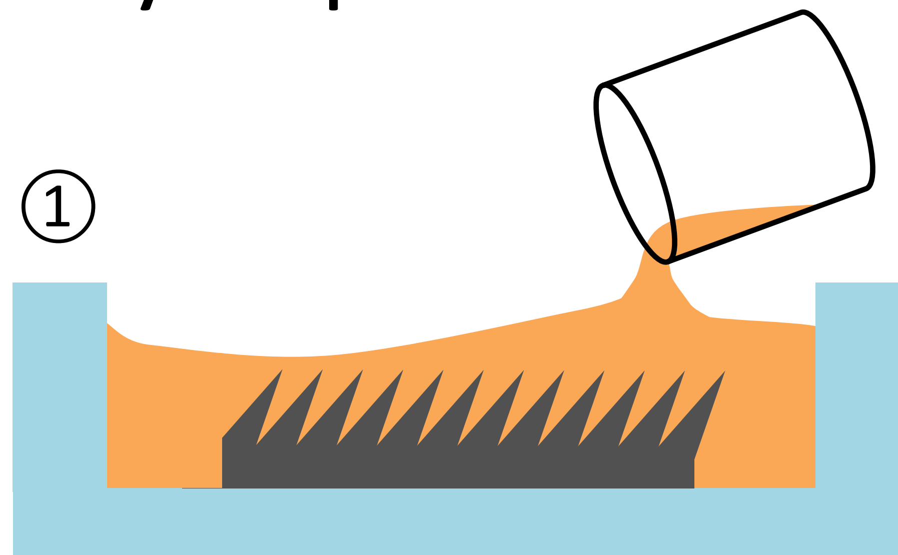


Materials compatibility requirements

Daughter mold material

- Cures on PDMS
- **No bond** to PDMS
- No distortion during cure

①



Step 2 is problematic

- PDMS pattern gets torn leaving debris in mold
- Cannot be **removed**
- **Destroys** feature tips

②

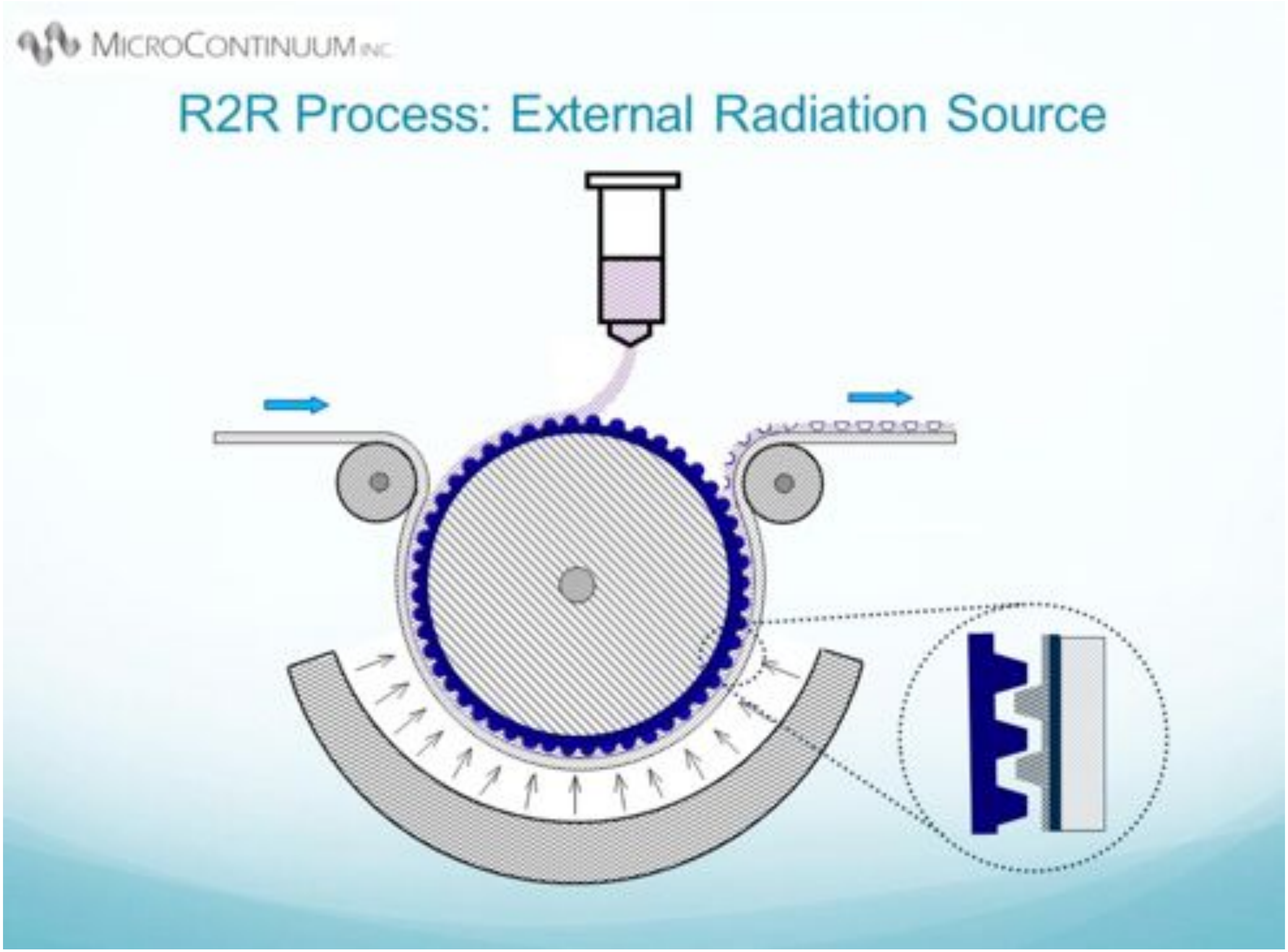
Daughter Mold compatibility trials

Tested 7 epoxies, 3 urethanes, 2 mold releases

- Epoxies bonded strongly to pattern, causing **tearing**
- Mold releases caused loss of fidelity and missing features
- Best results with **urethanes** and **no mold release**.

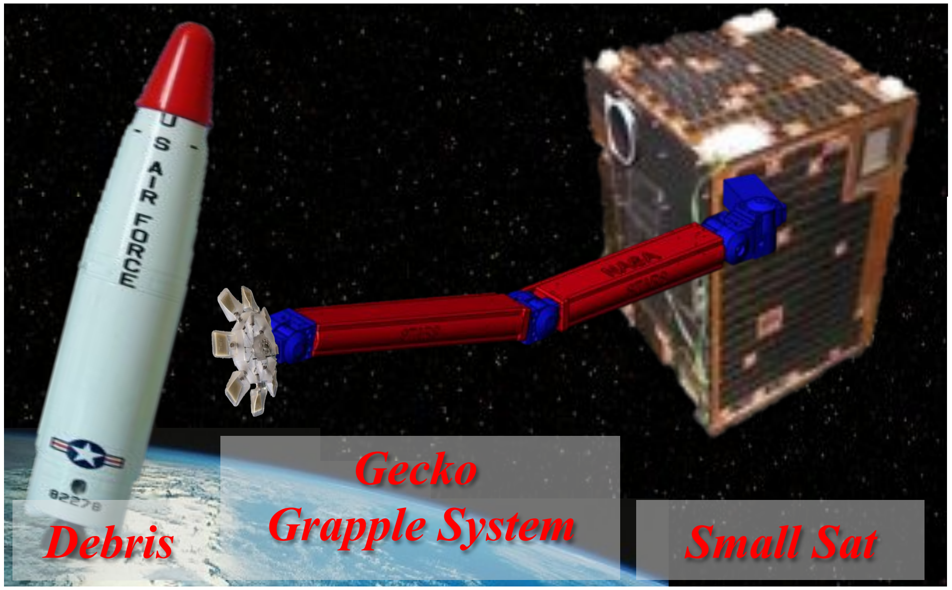
	No mold release	Repel Silane	Ease Release 200
EpoxAcast 690	full cure high bond	full cure bond	full cure mild bond
EpoxAcast 670 HT	full cure high bond	partial cure no bond	partial cure no bond
E-Z Lam 60	no cure no bond	no cure no bond	no cure mild bond
Devcon 2 Ton	full cure mild bond	full cure bond	full cure no bond
Z-Poxy 30	full cure mild bond	full cure mild bond	full cure no bond
Great Planes 45	full cure high bond	full cure bond	full cure no bond
MAS Slow/Low Visc	full cure high bond	full cure high bond	full cure no bond
Innothane IE-20AH	full cure no bond	full cure no bond	full cure no bond
Innothane IE-70A	full cure no bond	full cure no bond	partial cure no bond
Innothane IE-90A	full cure no bond	full cure no bond	full cure no bond

Looking ahead



Inspired partly by new Zman spin-off:

Gecko-Inspired ON-OFF Adhesives For Orbital Debris Mitigation



Task Objectives:

1. Develop full capture head using current gecko adhesive and leveraging small-scale two pad gripper prototypes

2. Mock up compliant robotic arm and integrate with capture head for floating object capture demonstration on RoboDome testbed

Infusion Path:

option A: Small Sat Demo (partner with Qinetiq and Aerospace Corp)

option B: ISS experiment or inspection (partner with JSC)

Technical Approach / Expected Accomplishment:

Develop Robotic Capture Head

Mock up compliant robotic arm

Demo floating object capture

Role	Team Members	Section
PI	**Aaron Parness**	347
Co-I	**Mark Cutkosky**	Stanford
Co-I	**George Studor**	JSC
Co-I	**Victor White**	389
Co-I	**Carl Seubert**	344

Critical Milestones	Date
Demo of capture head on stiff mount	**Apr 2013**
Completion of mock-up compliant arm	**Jun 2013**
Demo of floating object capture	**Sep 2013**

Primary Technical Hurdles:

- *Scaling 2-pad prototypes to full capture head*
- *Correctly sizing compliance in robotic arm*
- *Integrating elements for demo*

other groups' adhesives

http://robotics.eecs.berkeley.edu/~ronf/Gecko/gecko-biblio.html

- CMU (Sitti)
- UC Berkeley (Fearing)
- Max Planck Inst. (Arzt)
- UCSB (Turner)
- Case Western (Dai)
- Seoul (Suh)
- . . .

Most of these require more normal force to stick, but also provide more adhesion once attached. They are less optimized for climbing and very low energy attachment/ detachment. Still, they are quite interesting too!

Your group’s task:

- Find a reasonable “usage case” – assume technology will continue to improve, cost will come down.
- Find a **User** and think about what she or he needs
- Present your idea on Thursday (1-2 slides)

Acknowledgements