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Applying Principles from the Locomotion of Small Animals to the Design and Operation of Robots

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Origins of bio-inspired design

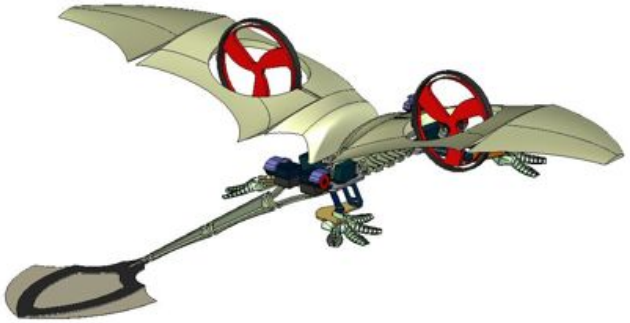
Renaissance discovery:

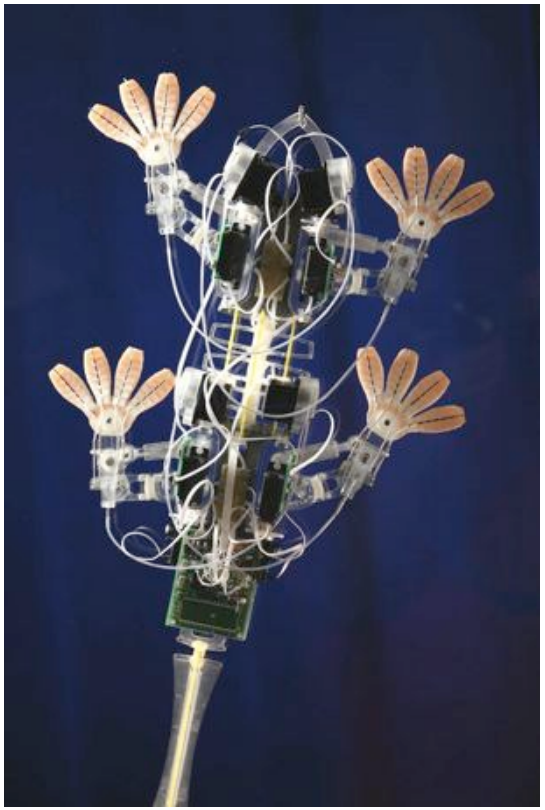
- *Understanding the body as a marvelous machine*
- *Understanding machine elements as examples of limbs, skeletons, muscles and tendons*

Da Vinci notebooks

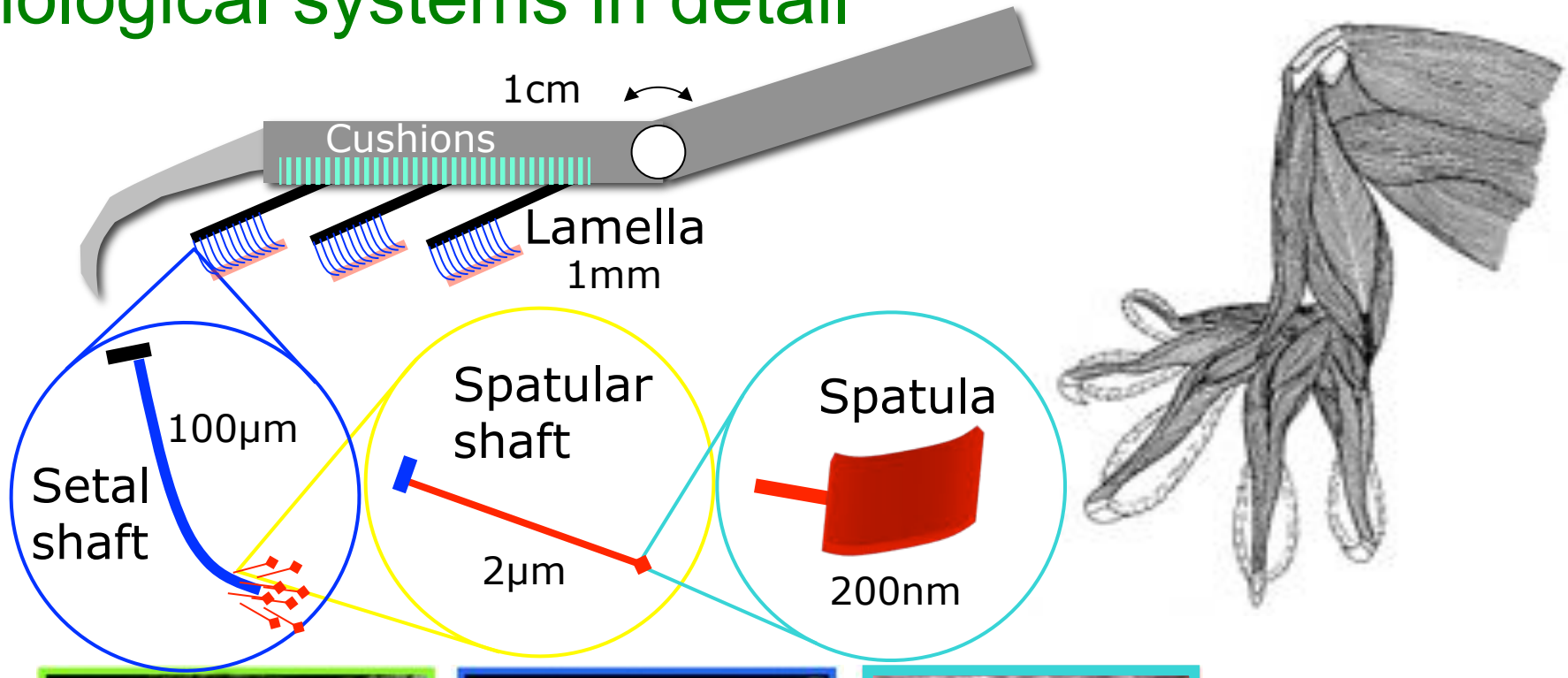
Da Vinci's programmable spring-powered cart

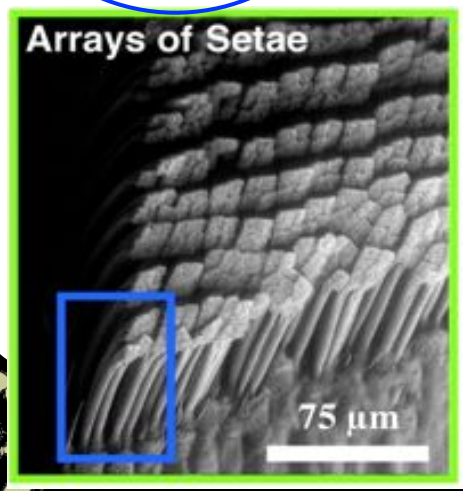
Why the recent proliferation of biomimetic designs?

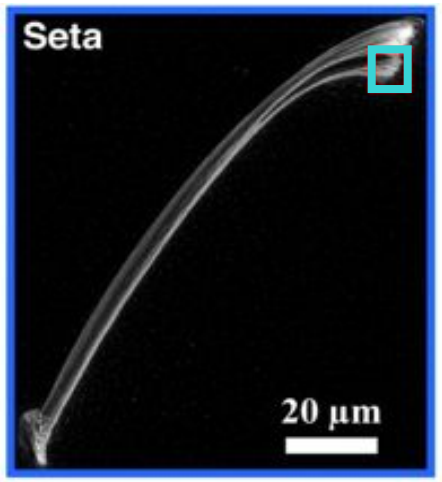


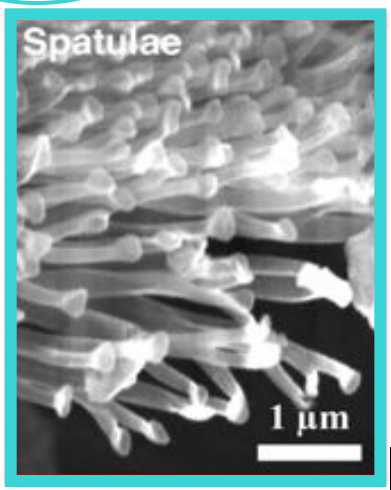


Biology: better tools for understanding biological systems in detail

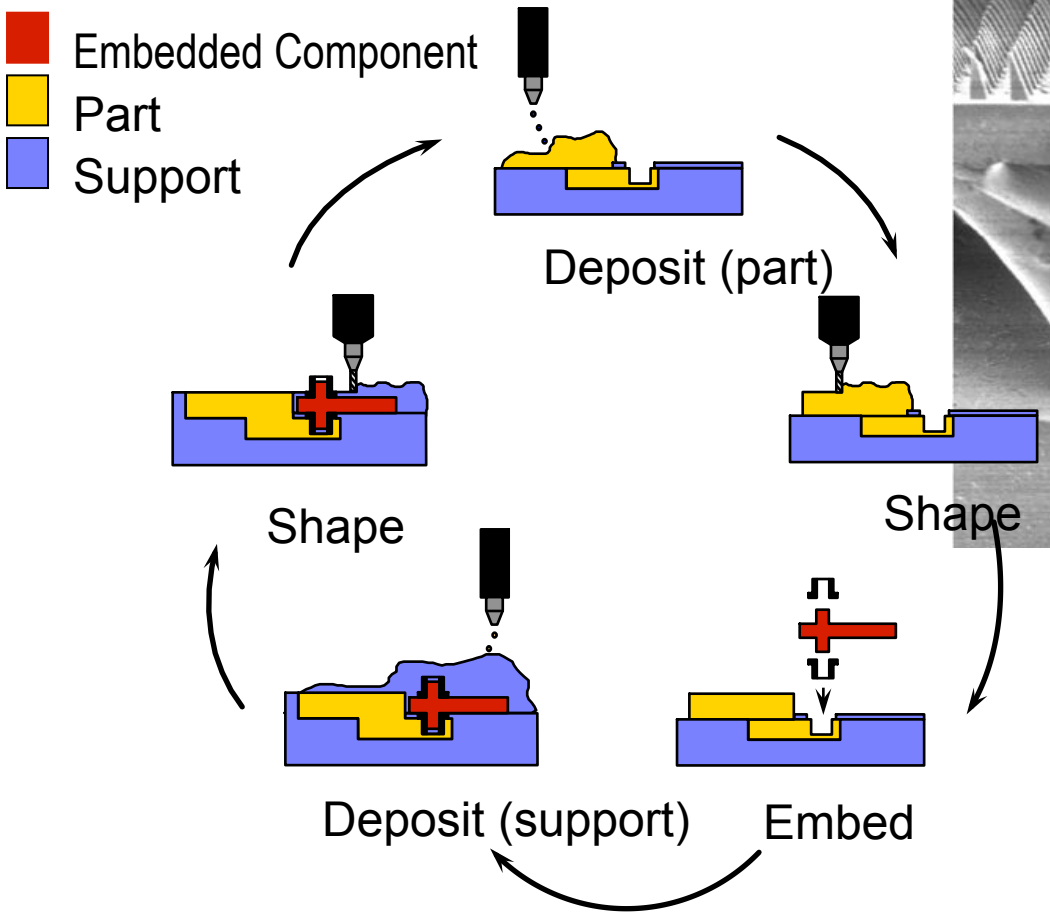




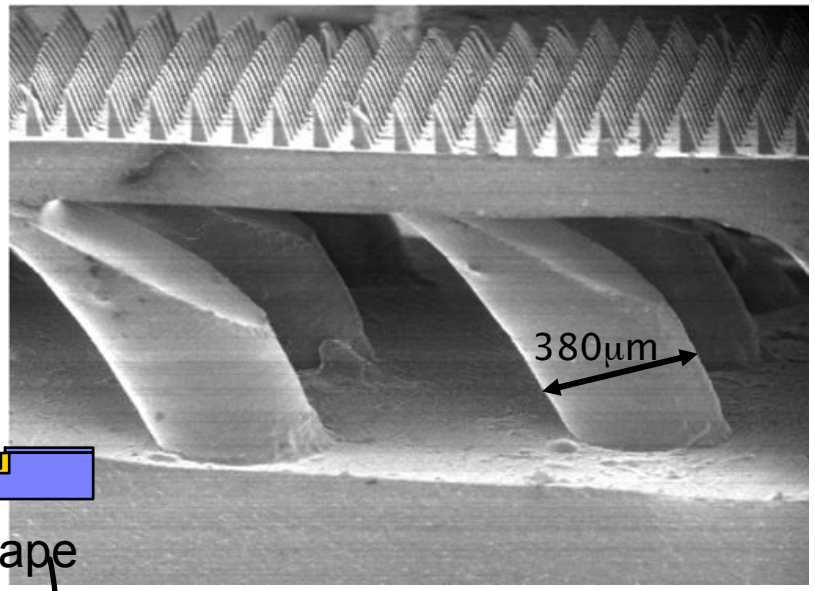




Engineering: better analysis tools, fabrication methods and materials



SDM multi-material fabrication



Synthetic dry adhesive: polymer molds from dual, angled-exposure lithography + micromachining

Behaviors now: discrete, isolated

Biomimetics

Natural Selection is not Engineering

R.J. Full
Dept. of Integrative Biology, UC Berkeley

Evolution - “just good enough”

Lessons from biology for bio-inspired design:

R.J. Full

1. **Reduce Complexity -** Collapse Dimensions
2. **Manage Energy**
3. **Use Multifunctional Materials** - Tuned, Integrated & Robust
4. **Exploit Interaction with Environment**

“Curse of Dimensionality”

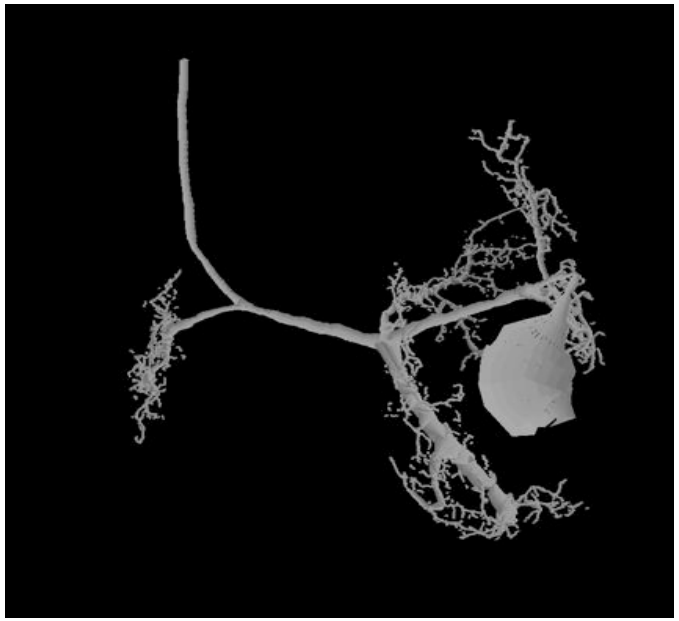
R.J. Full

Designs appear hopelessly complex
No detailed history of design plans

72 DOF

230 Muscles

? Neurons

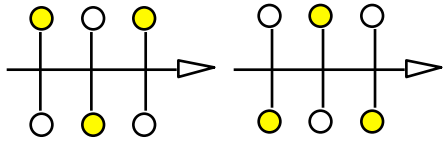


Reducing dimensionality: the sagittal leg spring

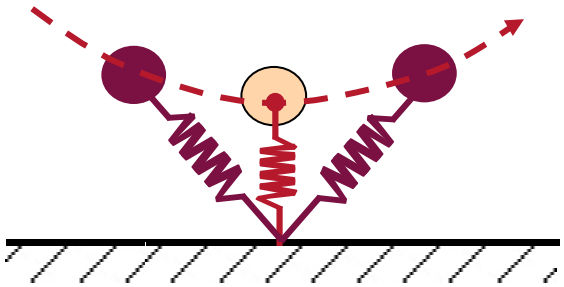
R.J. Full

SIX- Legged

Cockroach

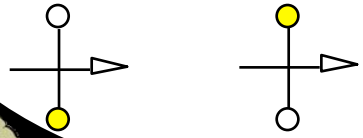


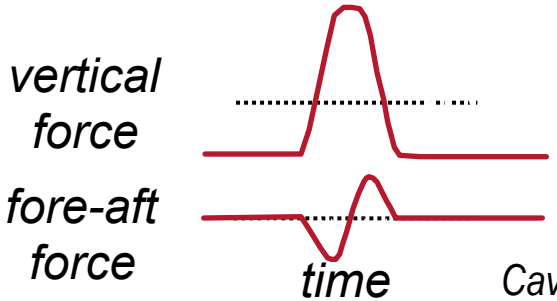
Full and Tu, 1990



TWO- Legged

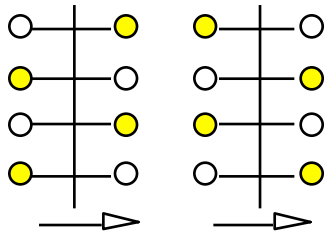
Human





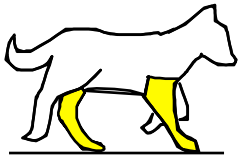
EIGHT- Legged

Crab

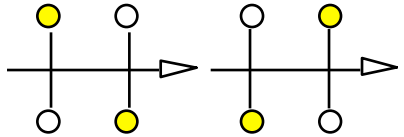


Blickhan and Full, 1987

FOUR- Legged



Dog

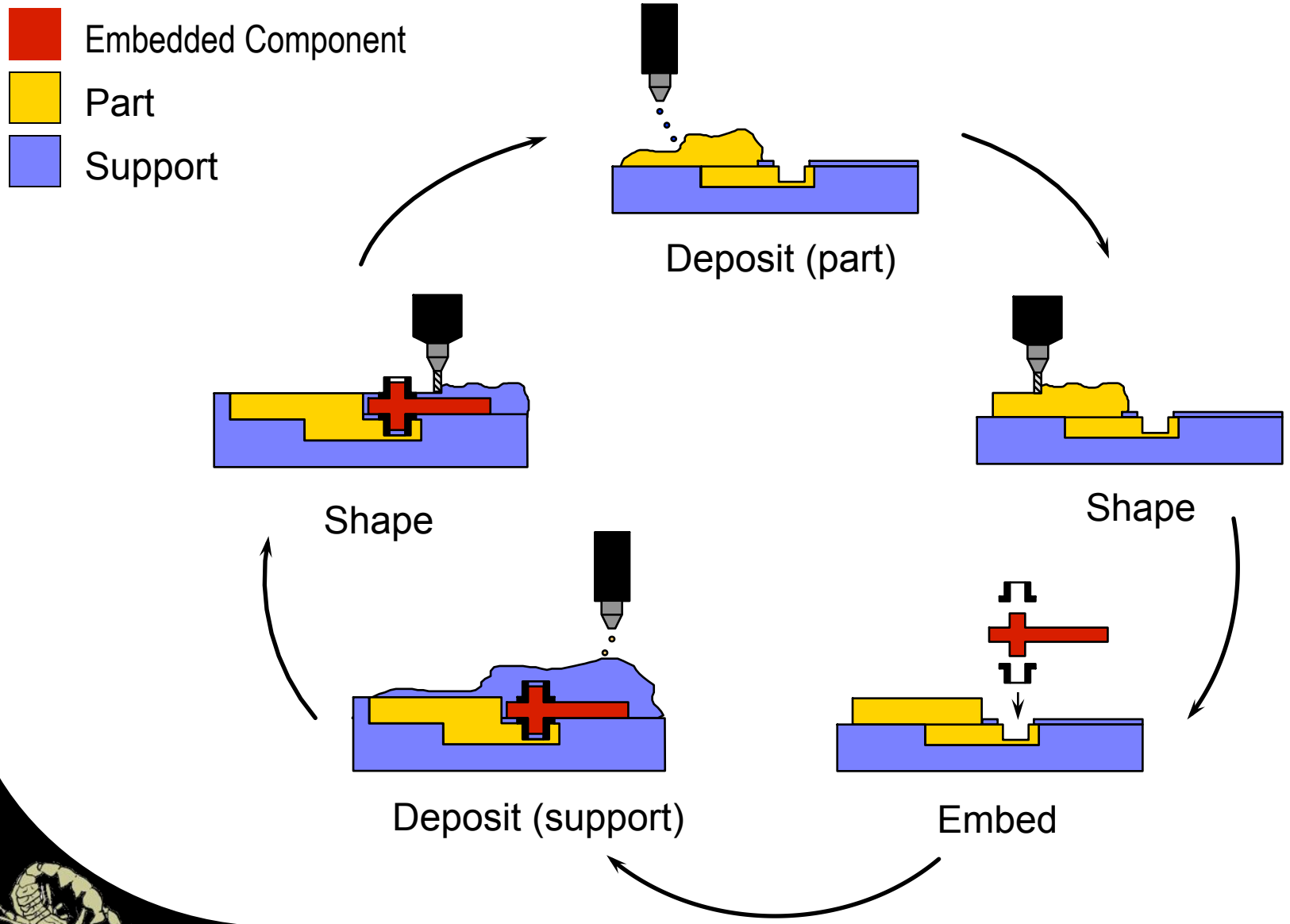


Cavagna et al., 1977

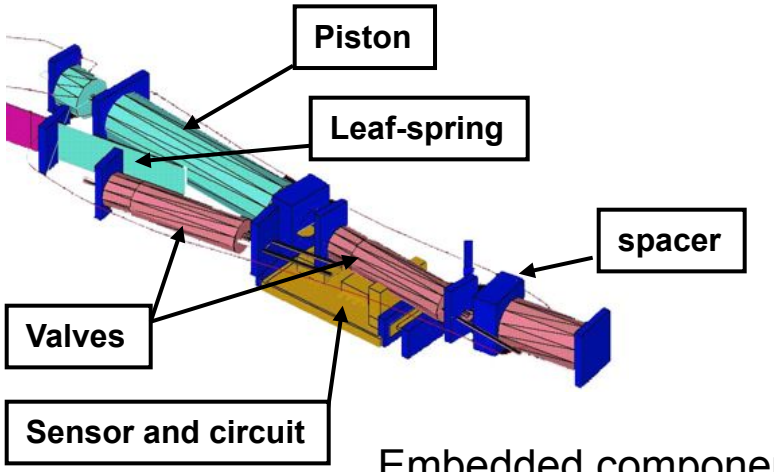
Lessons from Biology

1. **Reduce Complexity - Collapse Dimensions**
2. **Manage Energy**
3. **Use Multifunctional Materials - Tuned, Integrated & Robust**
4. **Effective Interaction with Environment**

Shape Deposition Manufacturing (SU/CMU)

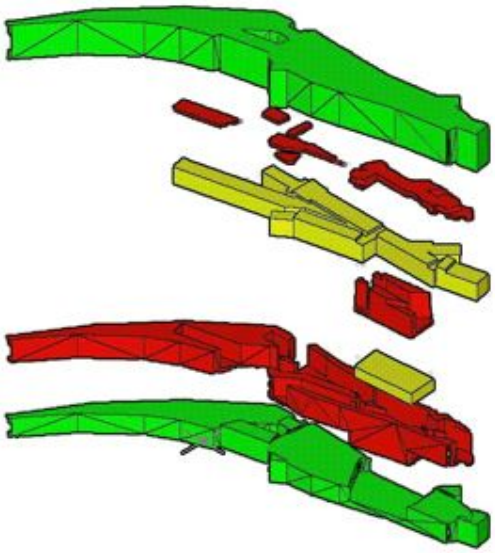


Robot leg with embedded actuator, valves, sensor and circuitry

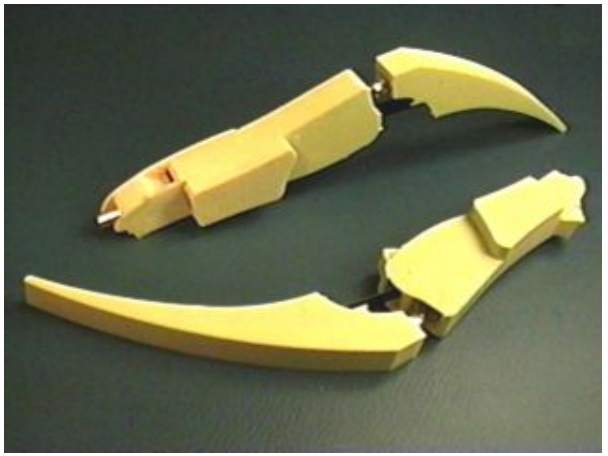


Embedded components

Detail of part just after inserting embedded components



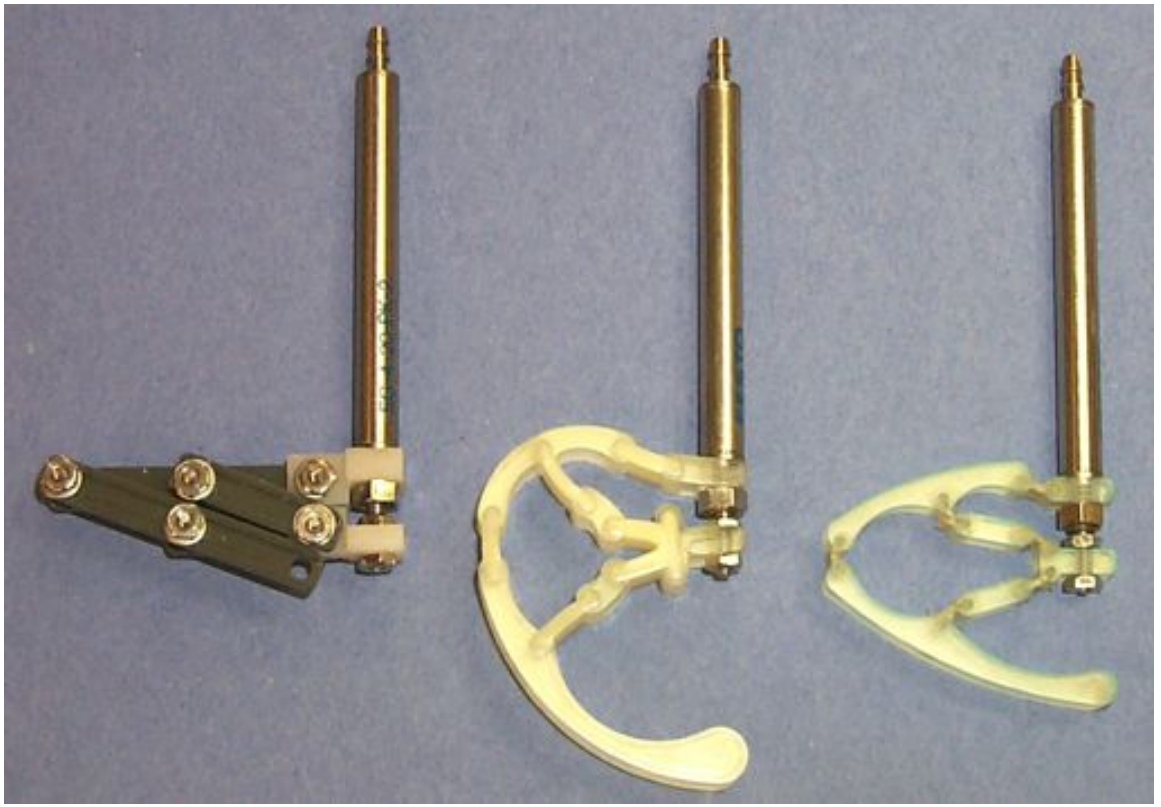
Sequence of geometries for fabrication



Finished parts

[Cham *et al*. 1999]

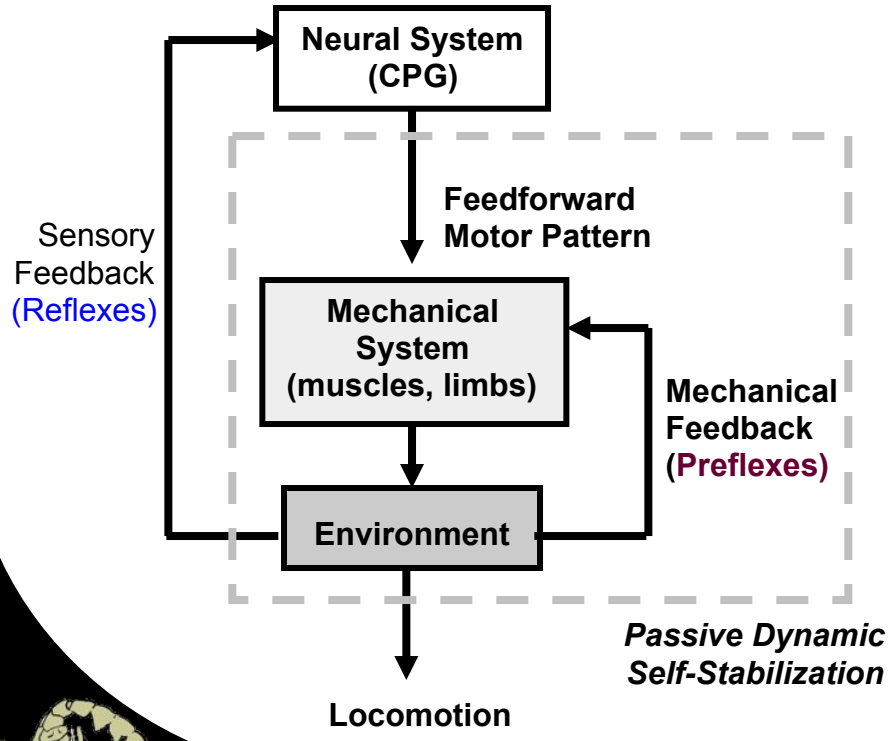
SDM: part number reduction, increased robustness, controlled compliance, damping



Left: Kinematic prototype of linkage with 31 parts
Center: SDM linkage with thick flexures, 1 part
Right: SDM linkage with fabric-reinforced flexures

Biological Inspiration

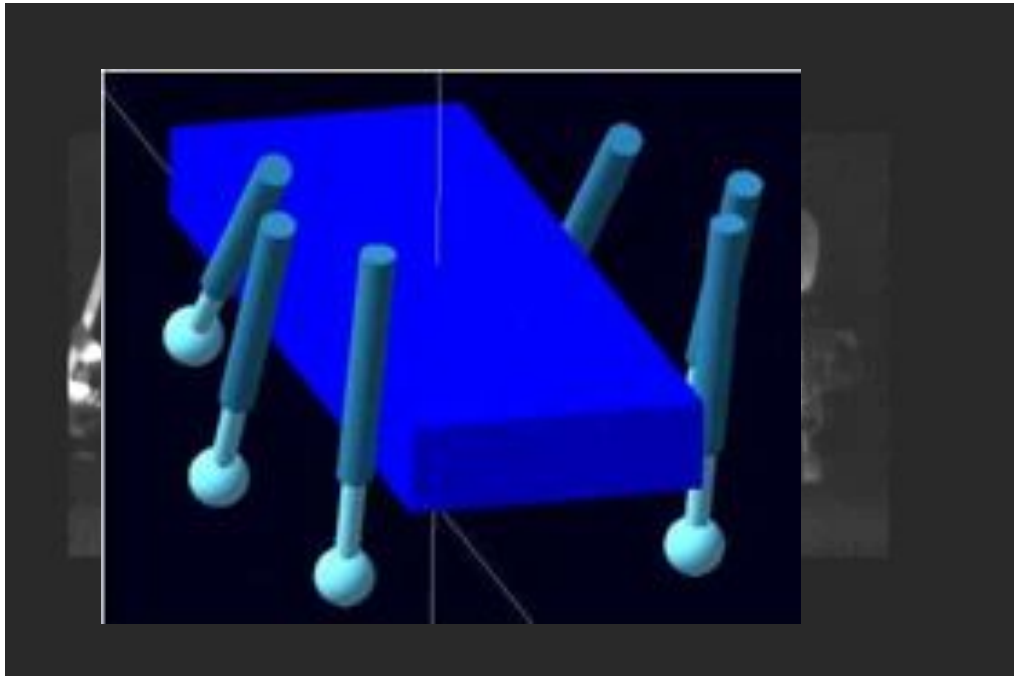
- Control heirarchy
  - Passive component
  - Active component



Mechanical System		Neural System
Feedforward	*Preflex*	*Reflex*
Motor program acting through moment arms	Intrinsic musculo-skeletal properties	Neural feedback loops
Predictive	Rapid acting	Slow acting
Passive Dynamic Self-stabilization		**Active Stabilization**

Full and Koditschek, 1999

Solution Approach: Analyze and "Optimize" Dynamic Model in ADAMS



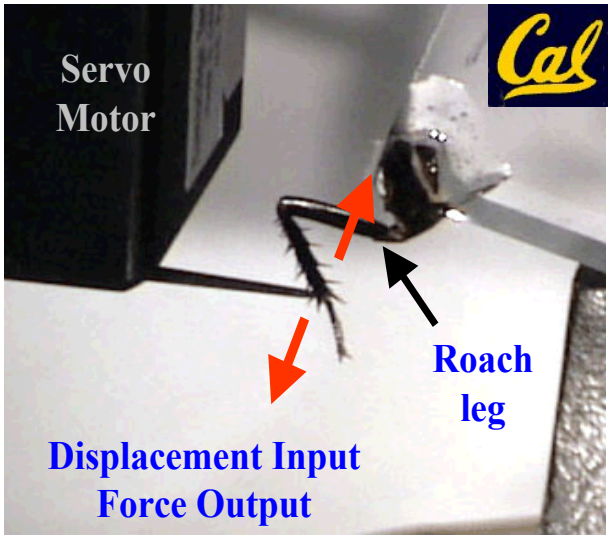
3D model with geometric similarity to robot

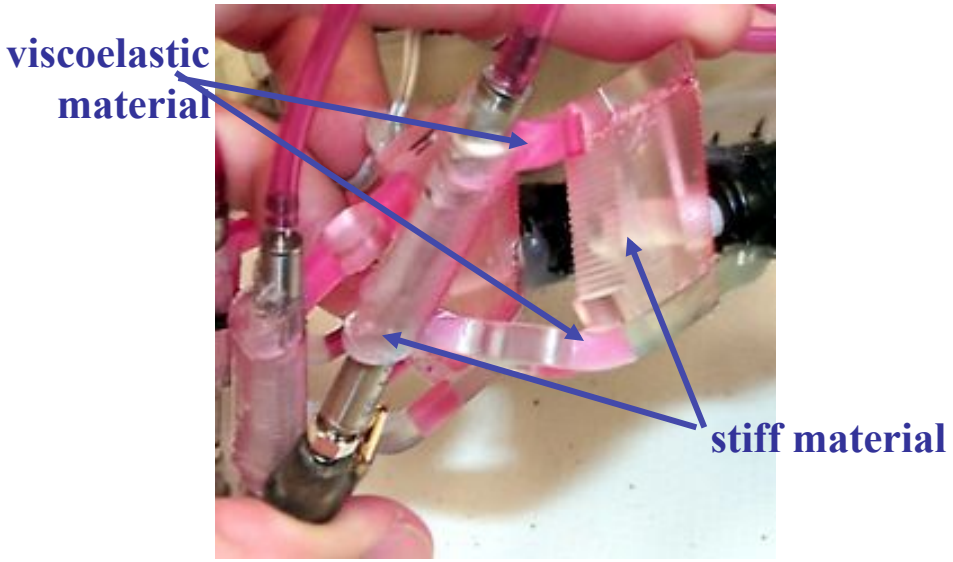
- Rigid body with six legs
- Linear pneumatic actuators (with valve delays)
- Spring-damper rotational joints in sagittal plane
- Friction and ground contact models

Example: mapping from passive mechanical properties of insects to biomimetic robot structures

Study biological materials, components, and their roles in locomotion.

Study Shape Deposition Manufacturing (SDM) materials and components.





Models of material behavior and design rules for creating SDM structures with desired properties

Example: mapping from passive mechanical properties of insects to biomimetic robot structures

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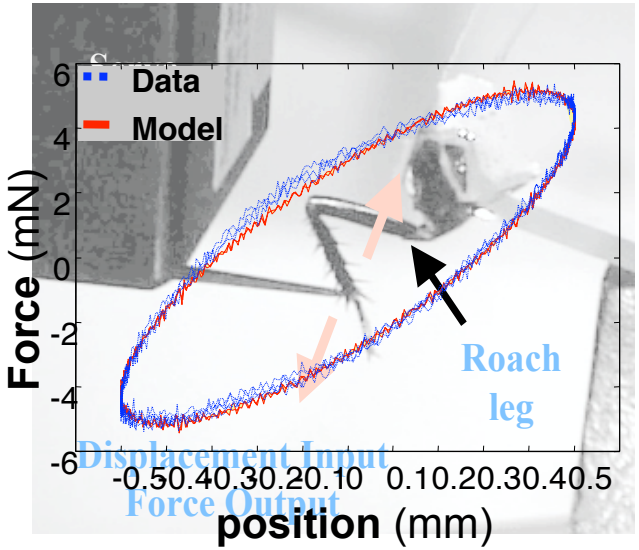
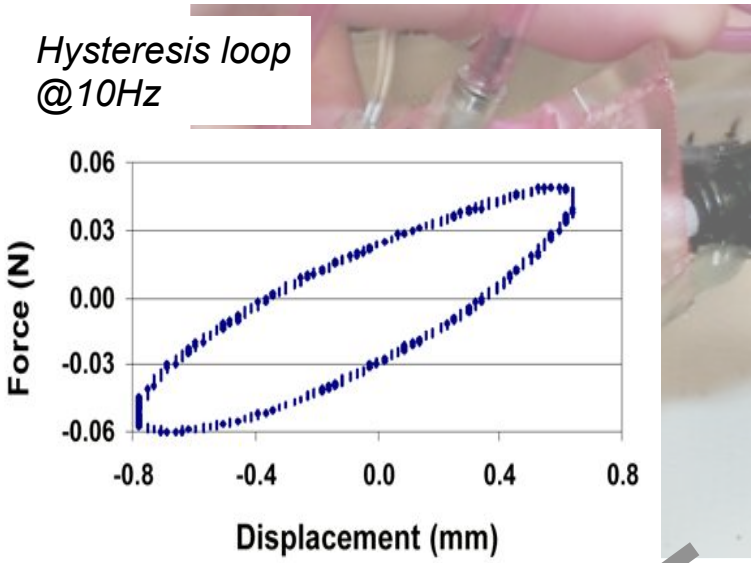
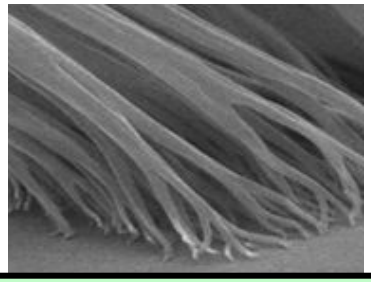
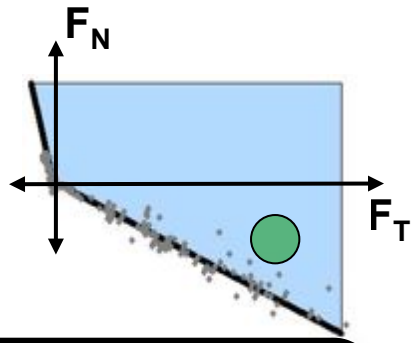




Models of material behavior and design rules for creating SDM structures with desired properties

2. Bioinspiration for **smooth climbing**



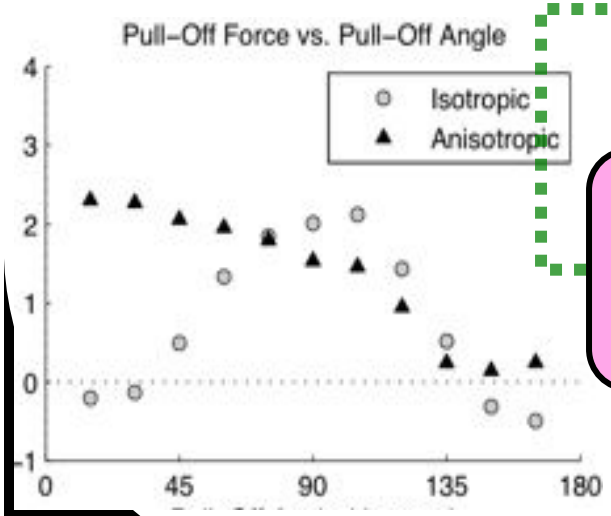


Bioinspiration
how do they do it?

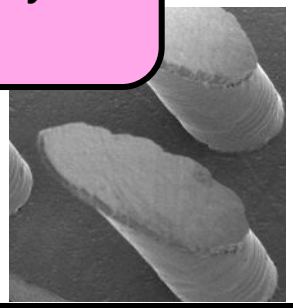
Biology
examine literature, work with biologists

Hypotheses
regarding the principles at work

refinement

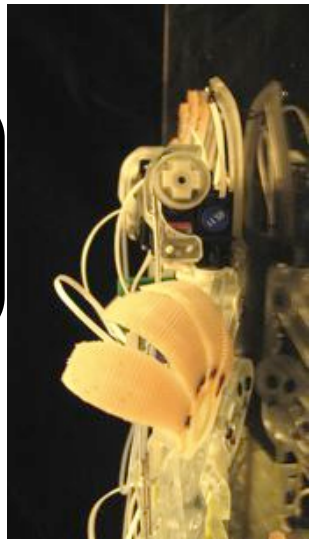


Analysis
test and analyze results



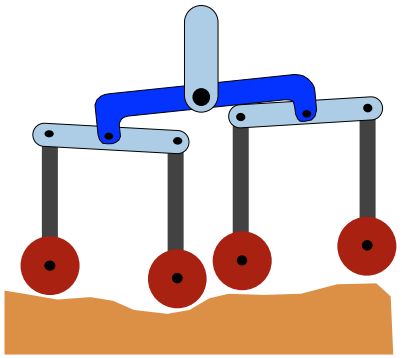
Robotics
implementations of principles

SDM technology

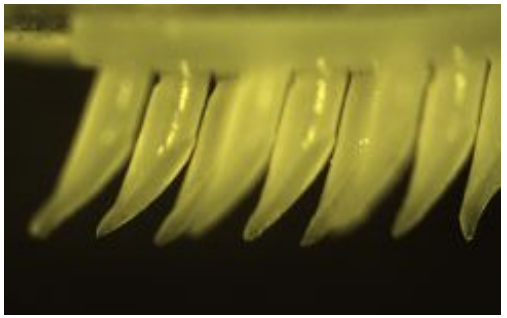


Principles for climbing with dry adhesion

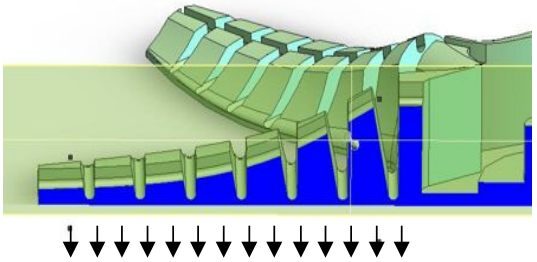
1. Hierarchical compliance



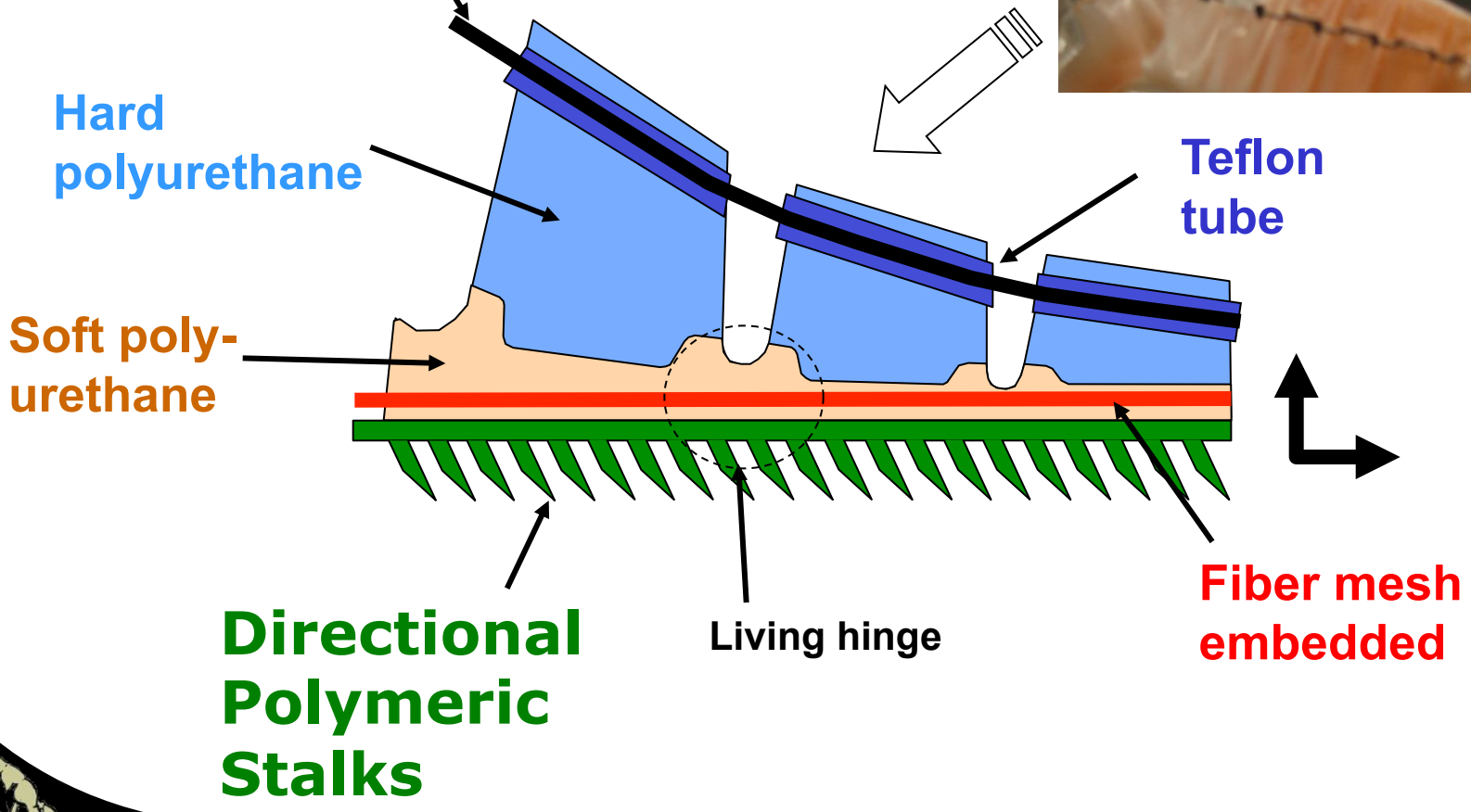
2. Directional adhesives



3. Distributed force control

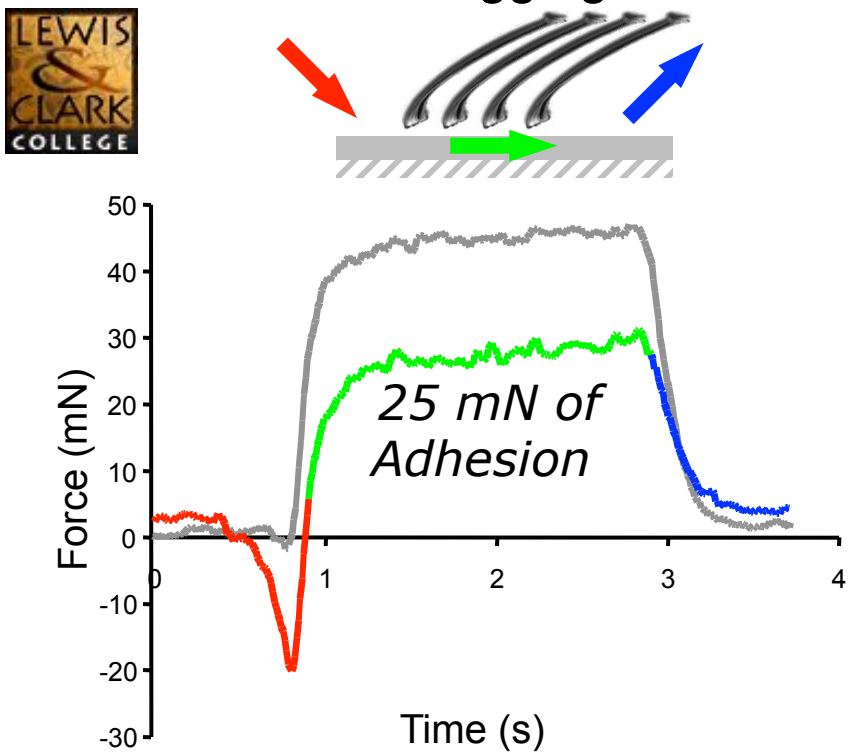


Compliant peeling toe

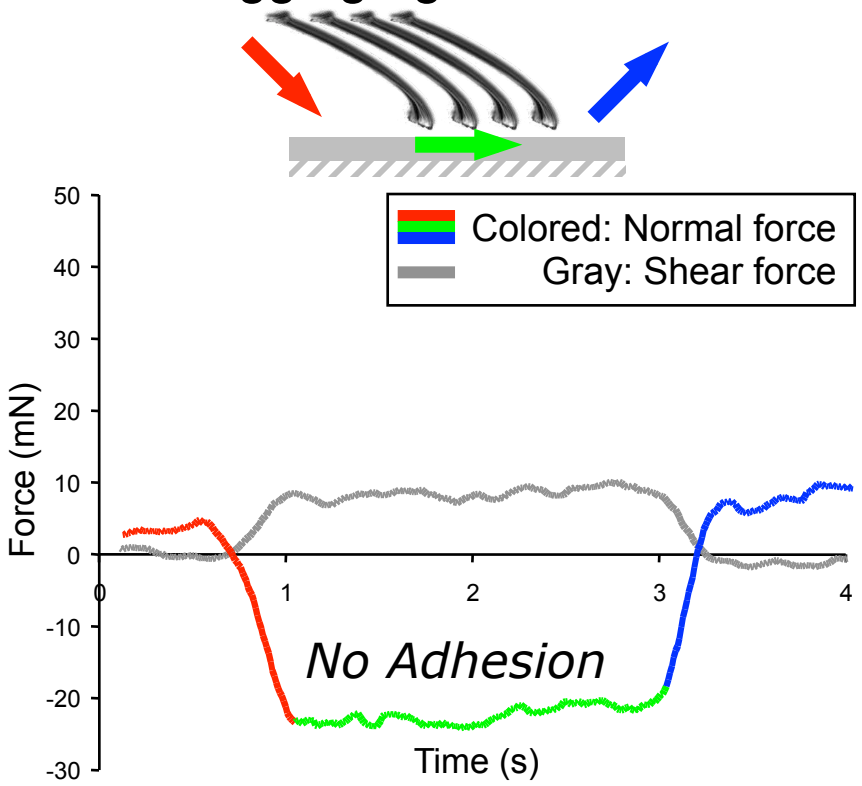


Anisotropic gecko adhesion

Gecko setae dragging with curvature



Dragging against curvature

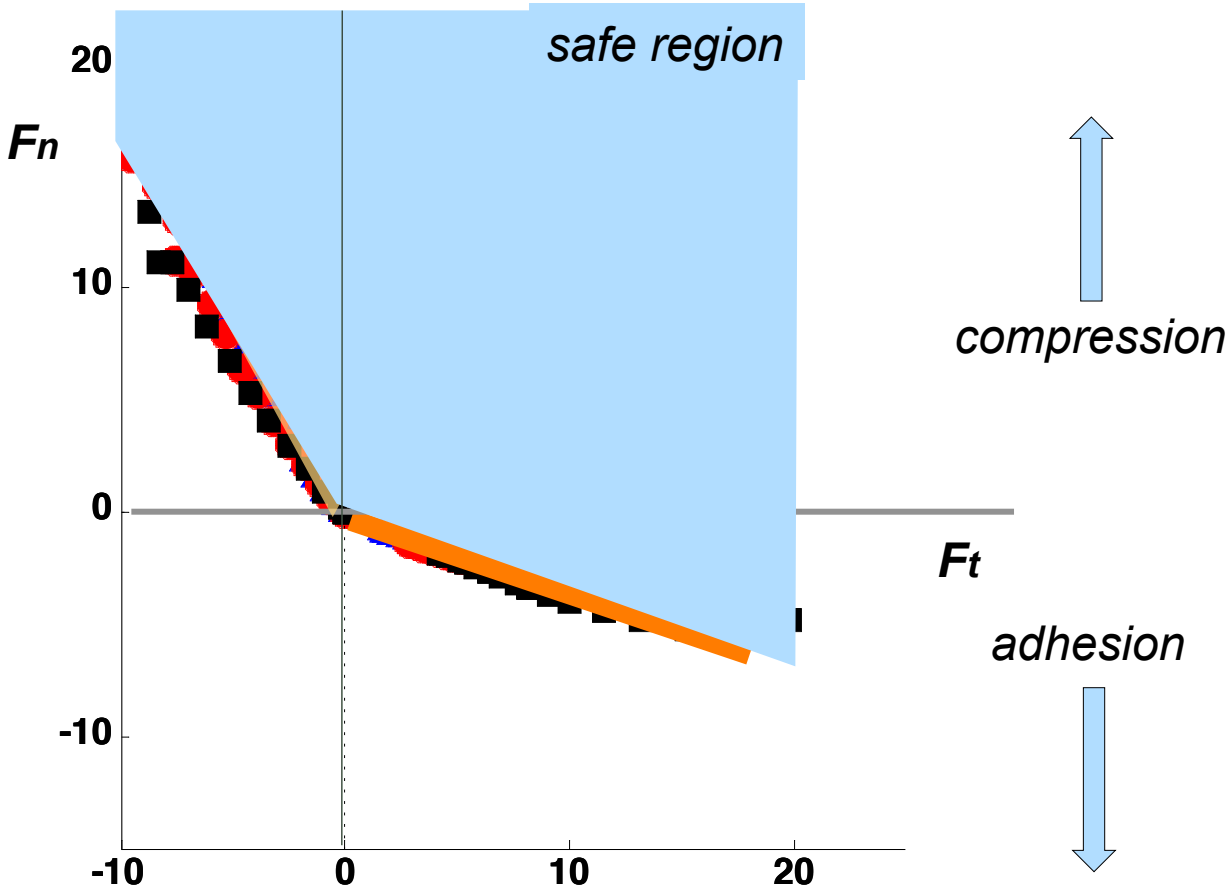


Gecko Force-Space Results

Autumn et al. JEB 2006

loaded *against* stalk angle:
Coulomb friction

Load, then pull off at various angles, and measure force
➔ ***limit curve***

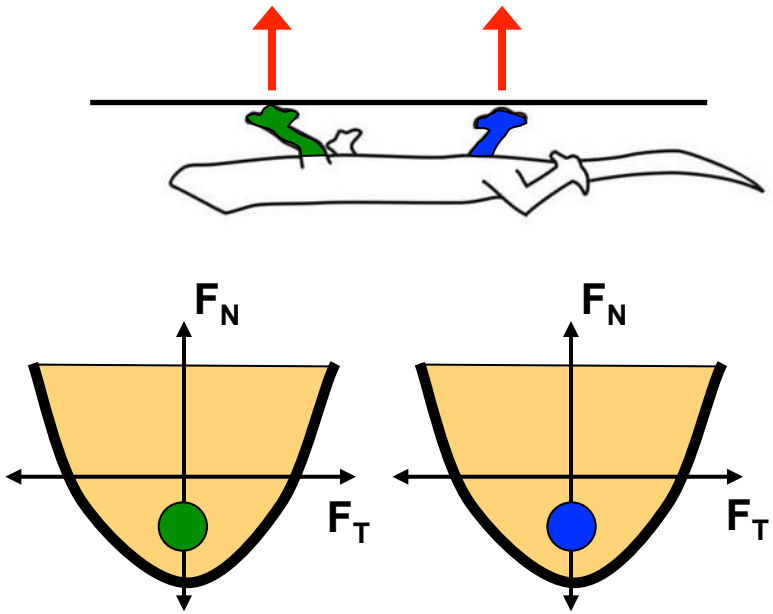


loaded *with* stalk angle:
adhesion ~ tangential stress

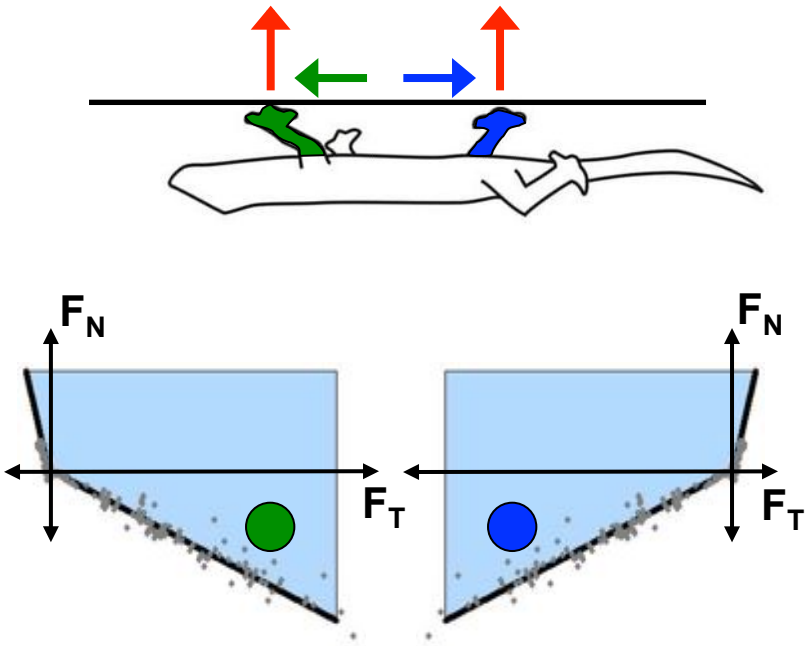
Force Control

optimal strategy for inverted surface

Johnson-Kendall-Roberts



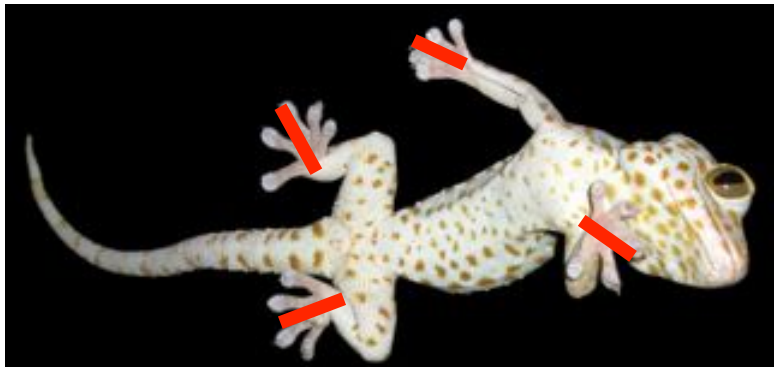
Frictional Adhesion

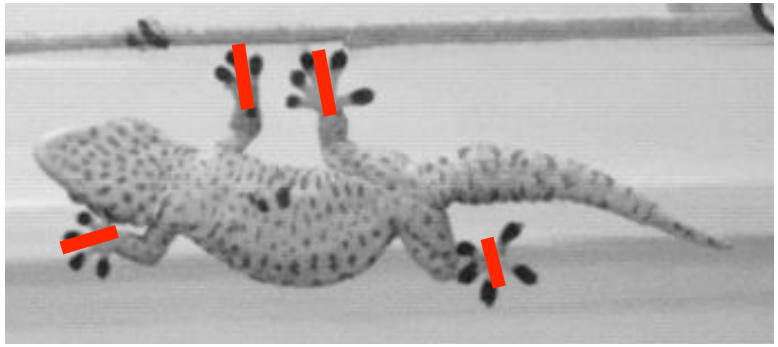


Rear Foot Flipped

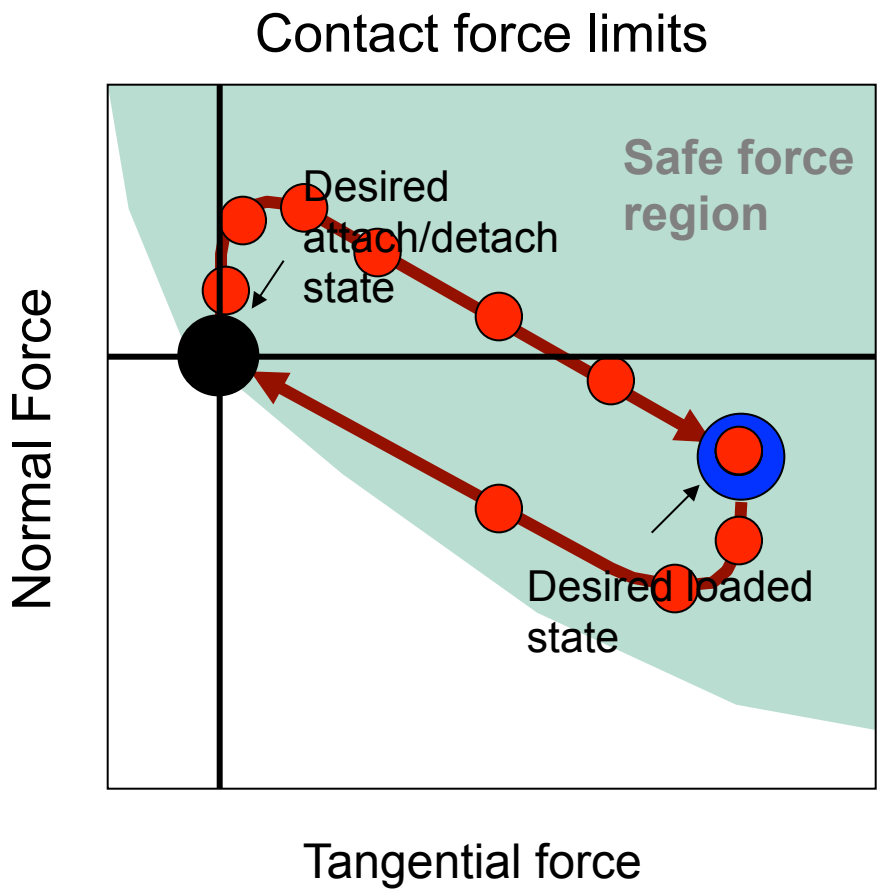
Generalization: Formulate as linear programming problem to control foot orientation & internal forces for arbitrary loading conditions [Santos, JAST09].

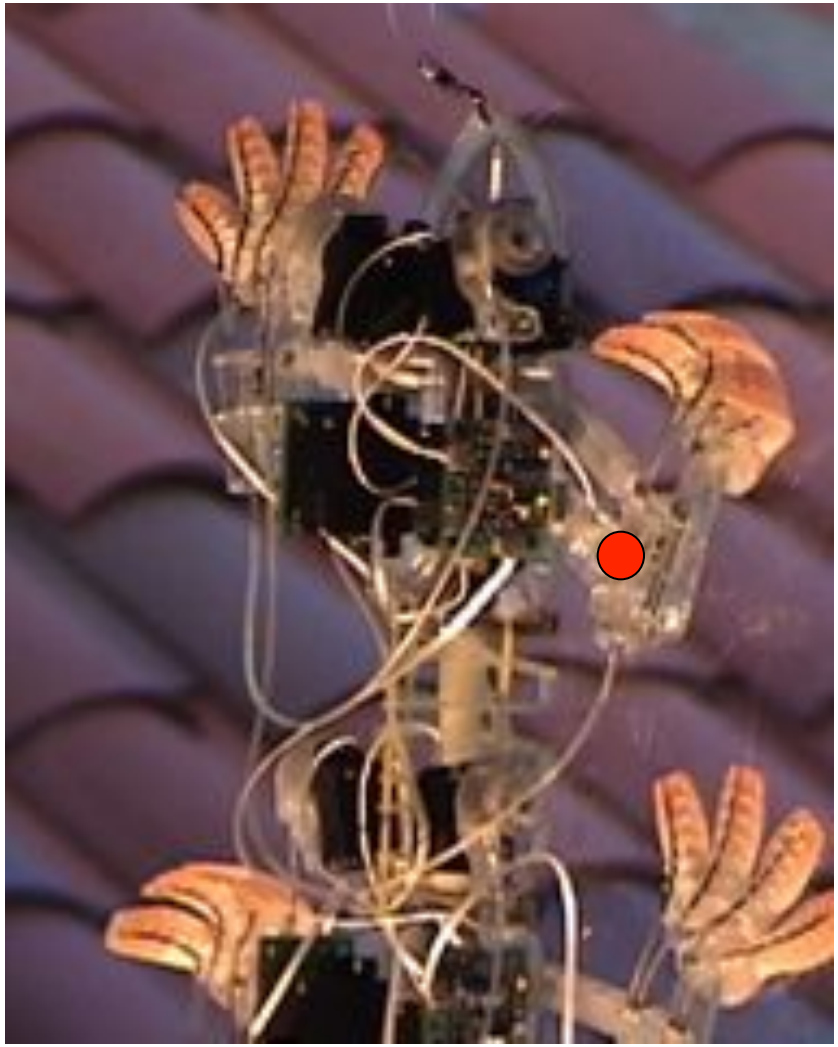
Control foot orientation + internal forces



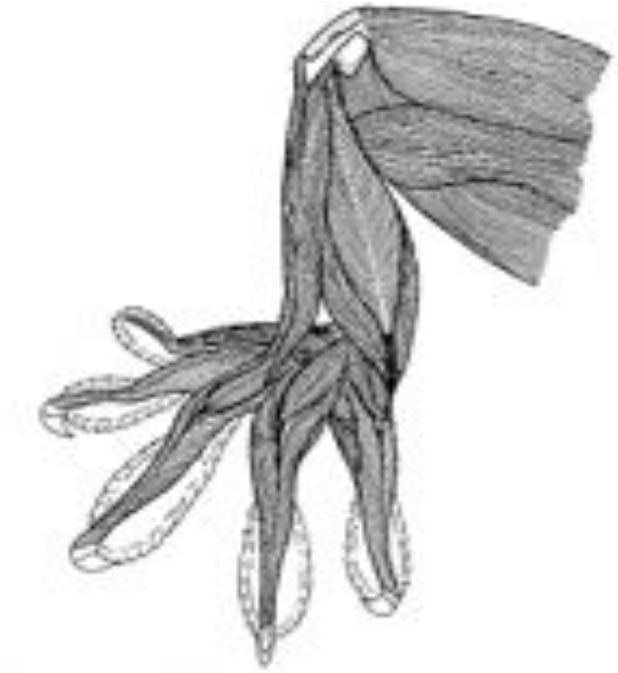


Directional adhesion facilitates control of forces for smooth, efficient locomotion

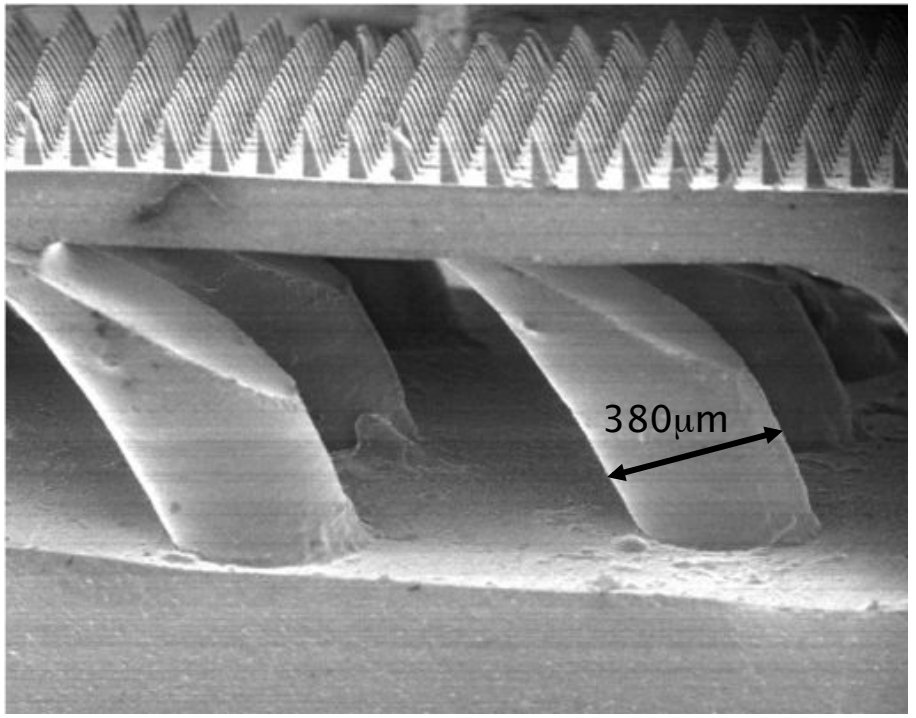




Current work: compliant ***hierarchical*** structures



The gecko's hierarchical adhesive system spans length scales from 1 cm to 100 nm.

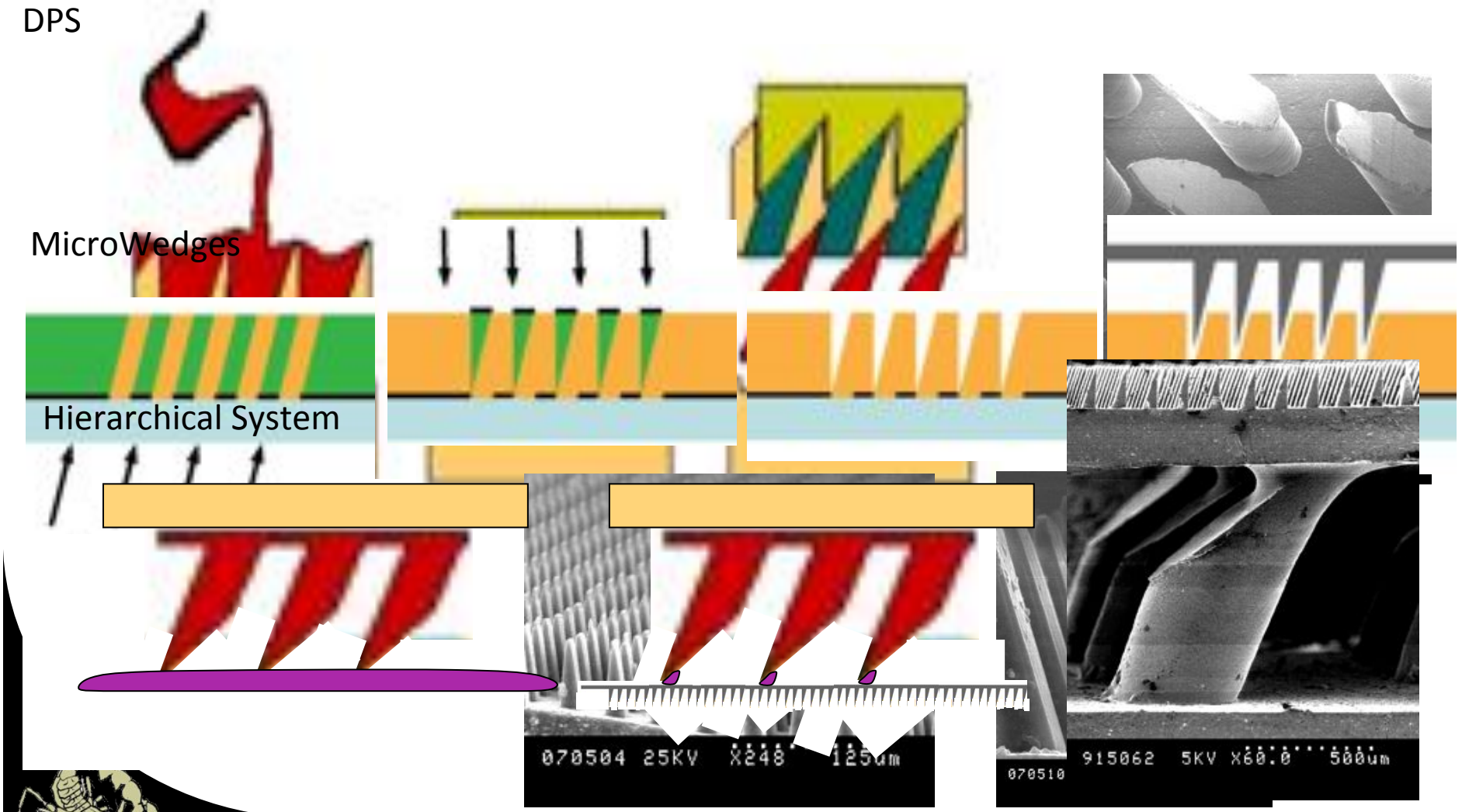


20 μm wedges atop 380 μm directional stalks (SEM photo)

Synthetic adhesives require **hierarchical, directional compliance** to conform to rough surfaces and distribute loads over large areas.

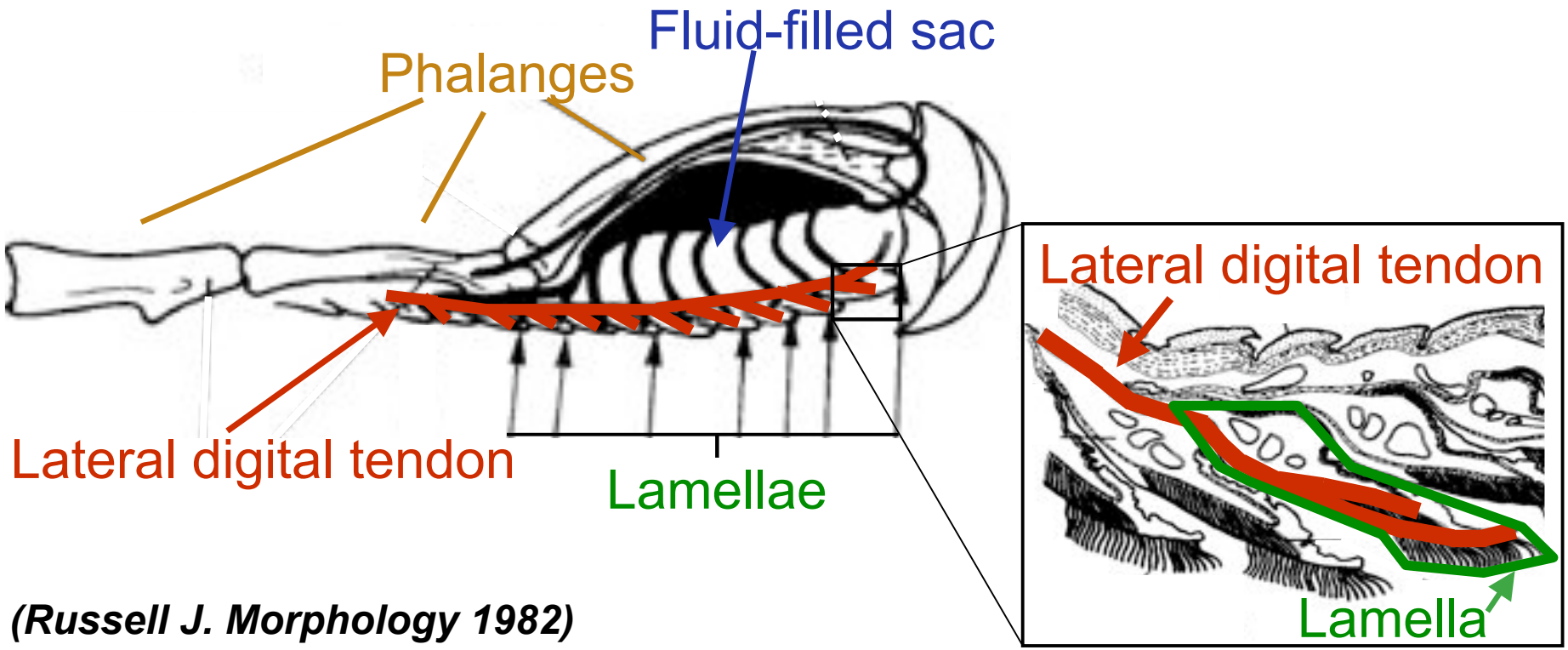
Stanford hierarchical, directional adhesive

Directional Polymer Stalks (DPS)



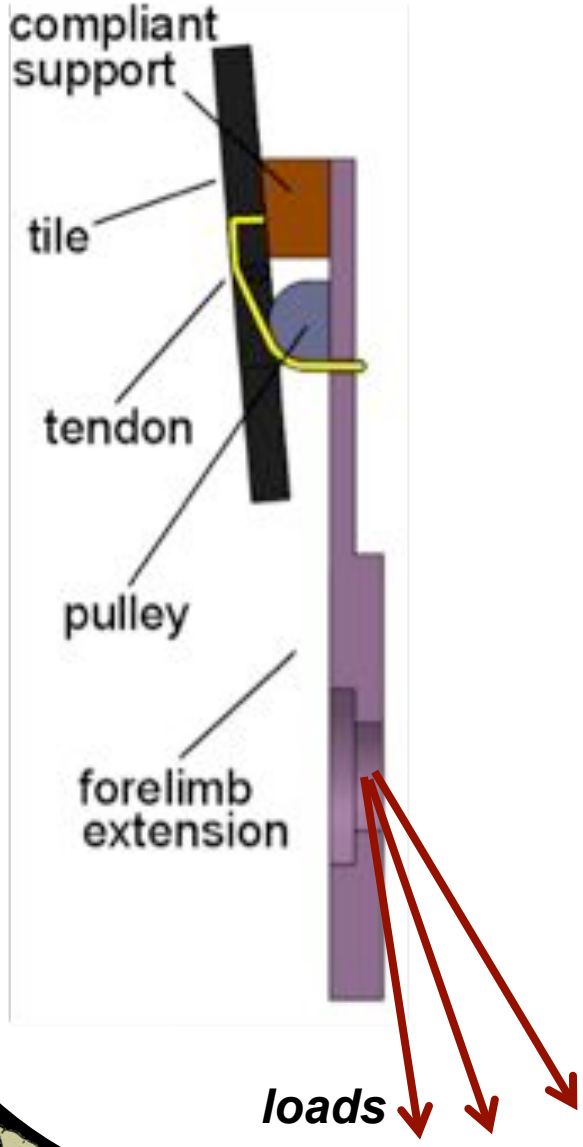
Bio-Inspired?

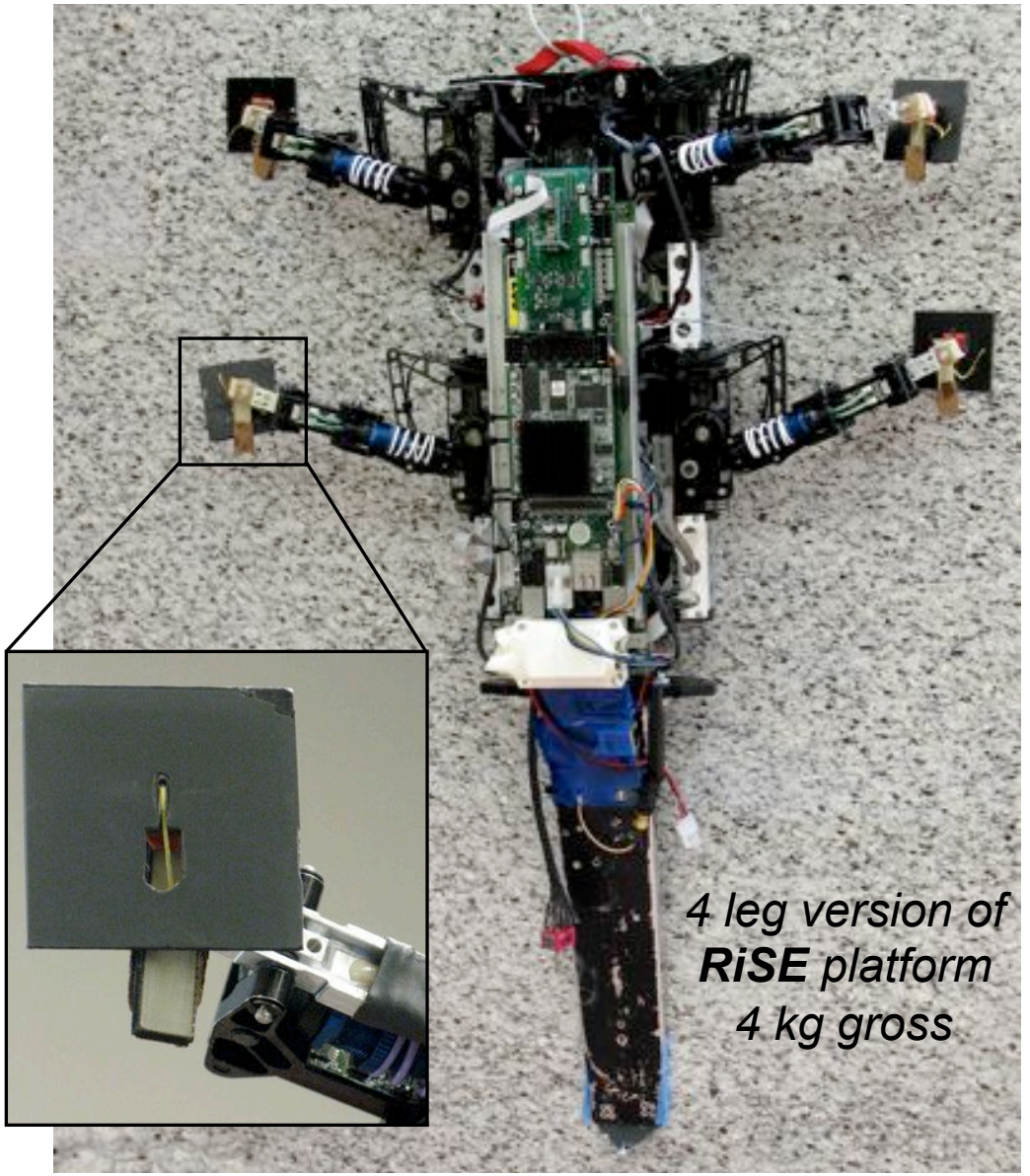
How to get nearly uniform loading over the entire toe, with tolerance to a range of loading angles?



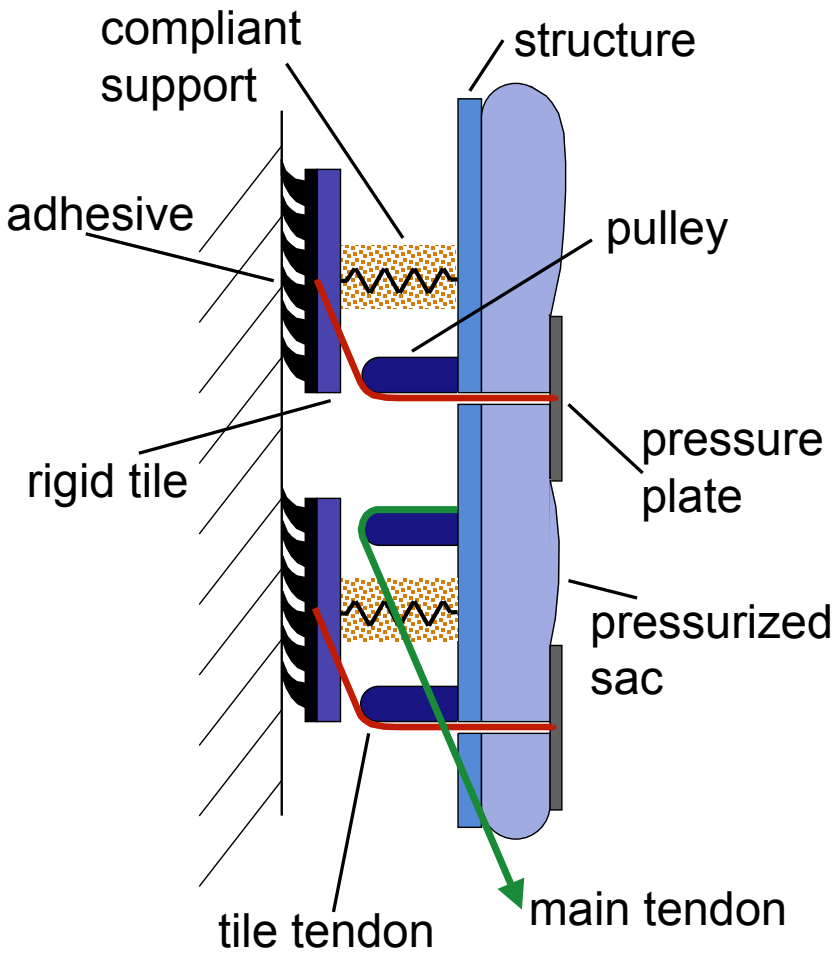
(Russell J. Morphology 1982)

Loading angles: alignment compensation





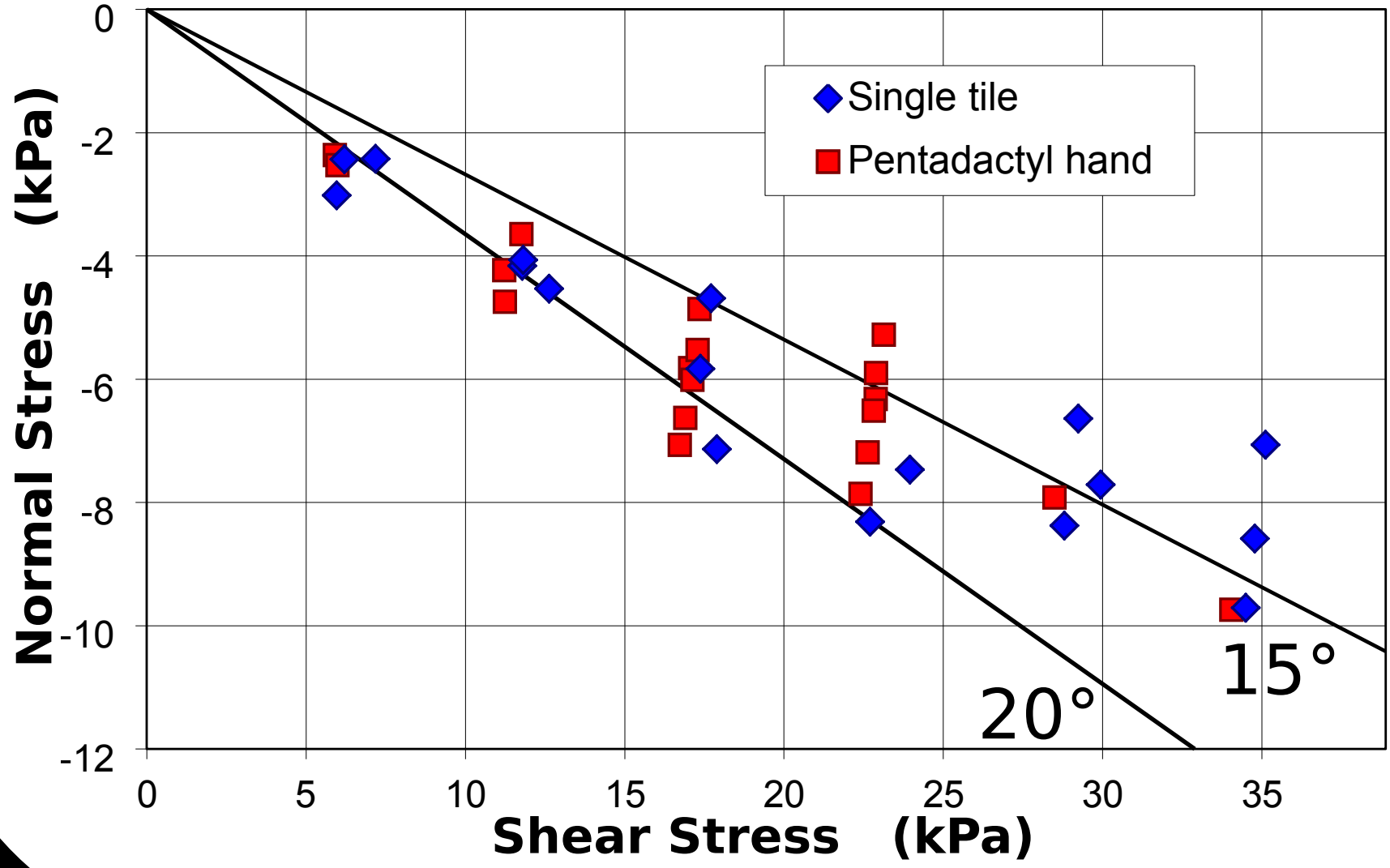
Scaling to larger areas and loads: tiled arrays



Approx. 80cm²

40 kg

Scaling to larger areas and loads: results



Acknowledgements