Traversing Highly-varied Terrain: Enhanced Contacts for Human-scale Robot Locomotion

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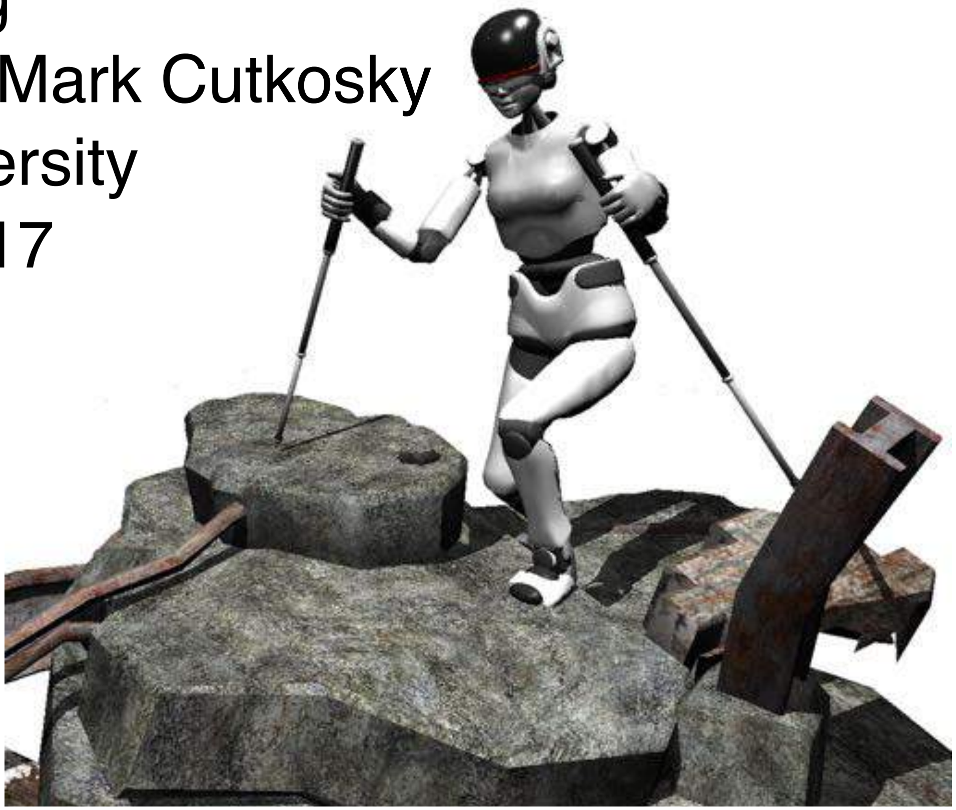
Stanford University
June 14th, 2017



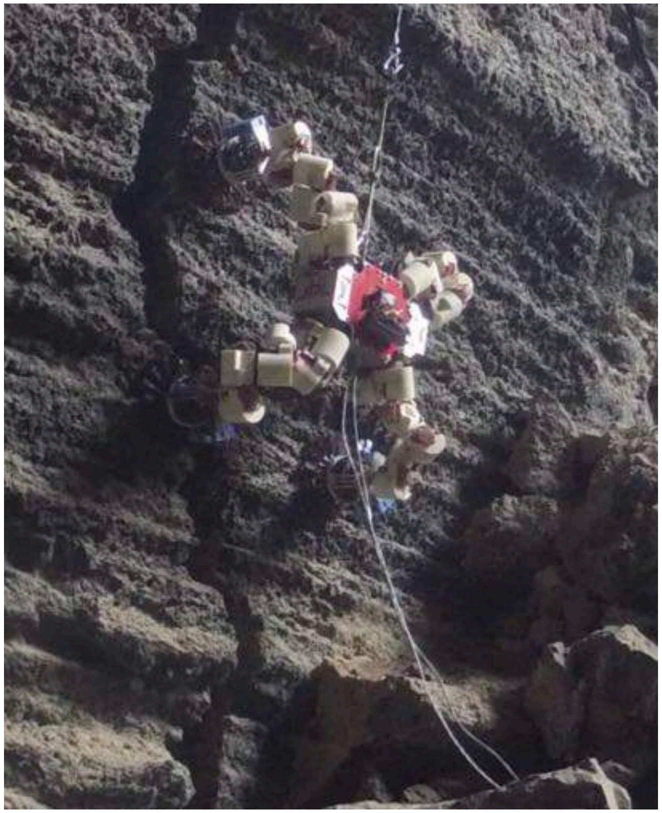
Stanford ENGINEERING
Mechanical Engineering

Biomimetics & Dexterous
Manipulation Laboratory

Traversing complicated environment

- Rescue, exploration, construction and other activities in the field

http://www.deccanchronicle.com/150101/technology-science-and-trends/article/nasa-designs-ape-robot-robosimian-disaster-relief



http://www.dailymail.co.uk/sciencetech/article-3222992/Nasa-reveals-bizarre-hedgehog-robot-roll-fall-alien-planets.html

Rocky terrains

https://www.pinterest.com/pin/495114552764154649/

http://www.summitpost.org/start-of-rocky-terrain/781777

https://www.reddit.com/r/SketchDaily/comments/2icdmr/
october_5th_rocky_terrain/

Attempts on rough terrain locomotion


RHex


Athlete


LemurII


Spinybot


Little Dog


ANYmal


Big Dog


AtlasII


Petman

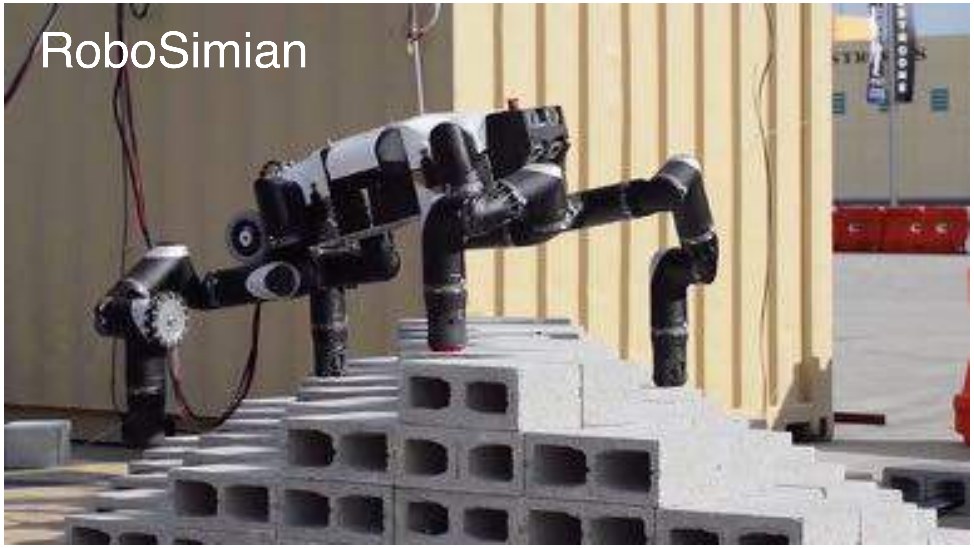
Tradeoff on robot scales

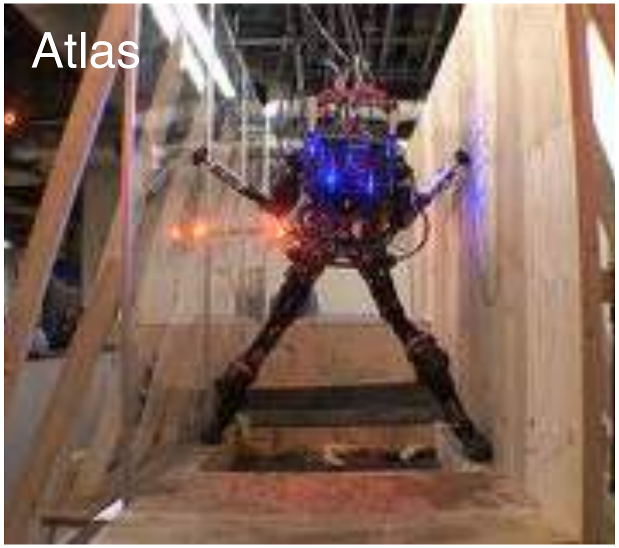
Small


Rise


RHex

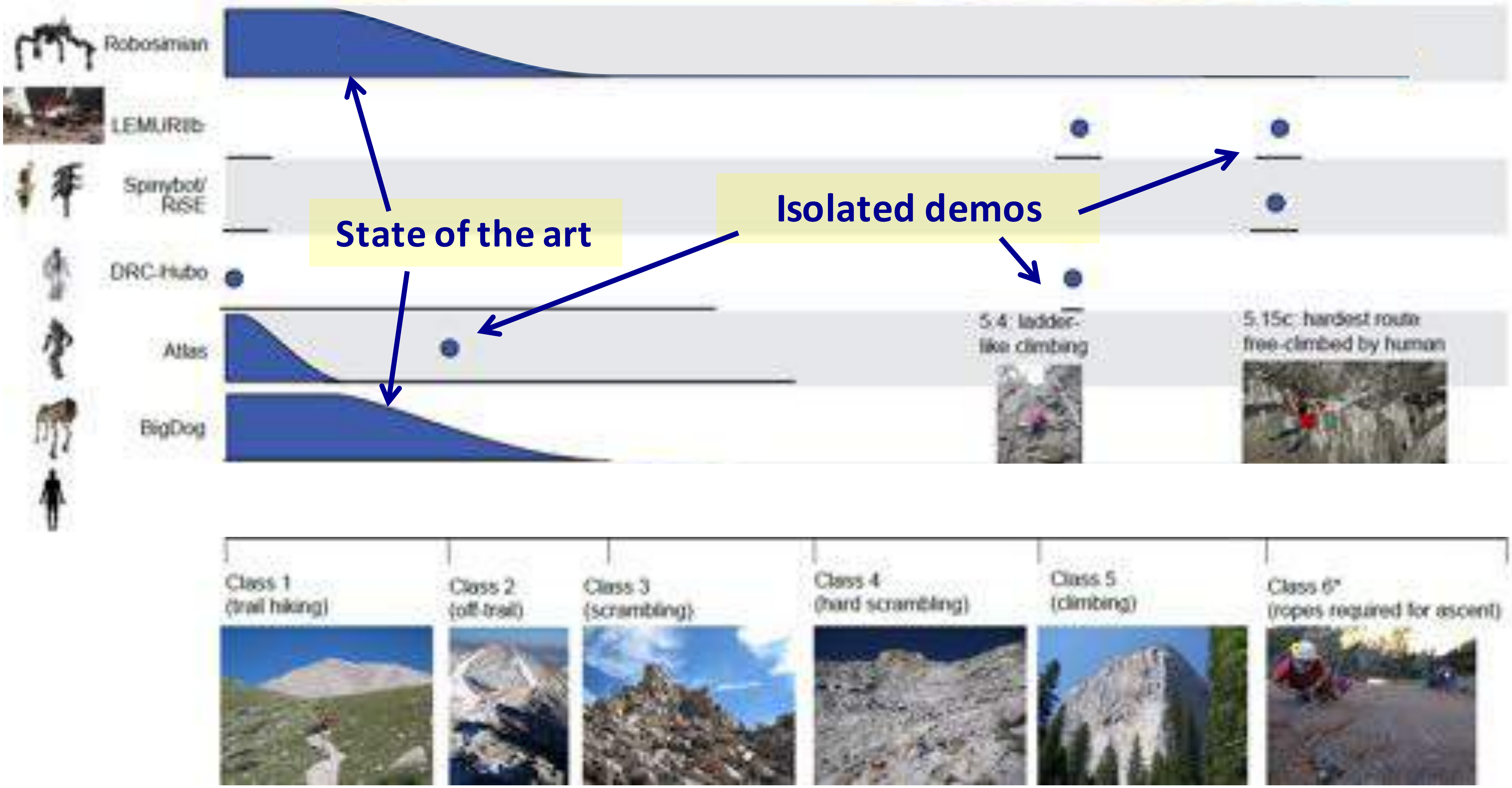
Large


RoboSimian


Atlas

Limited robot-accessible terrain types

- Still much narrower than human



State of the art

Isolated demos

Adapted from Duke-Stanford-UCSB NSF Proposal

Limiting factor: contact

- Locomotion: transform the robot posture through a sequence of contacts that guarantee static and dynamic stability.

https://www.youtube.com/watch?v=WYKgHa8hH1k

https://www.inverse.com/article/24487-atlas-partial-foothold-algorithm

http://www.switchbacktravel.com/best-trail-running-shoes

How do humans improve contacts?

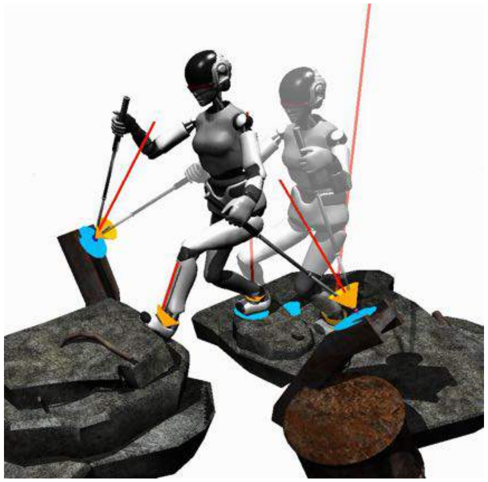
Hiking pole

http://www.trailspace.com/articles/trekking-poles-fit-maintain.html

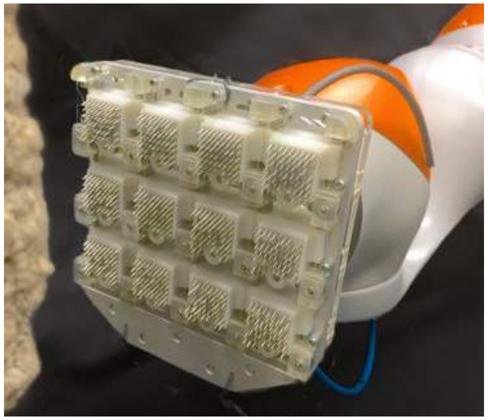
Surface Grasping

http://avantgardica.blogspot.com/2014/02/winter-vacation-climbing-in-getu.html

Contributions



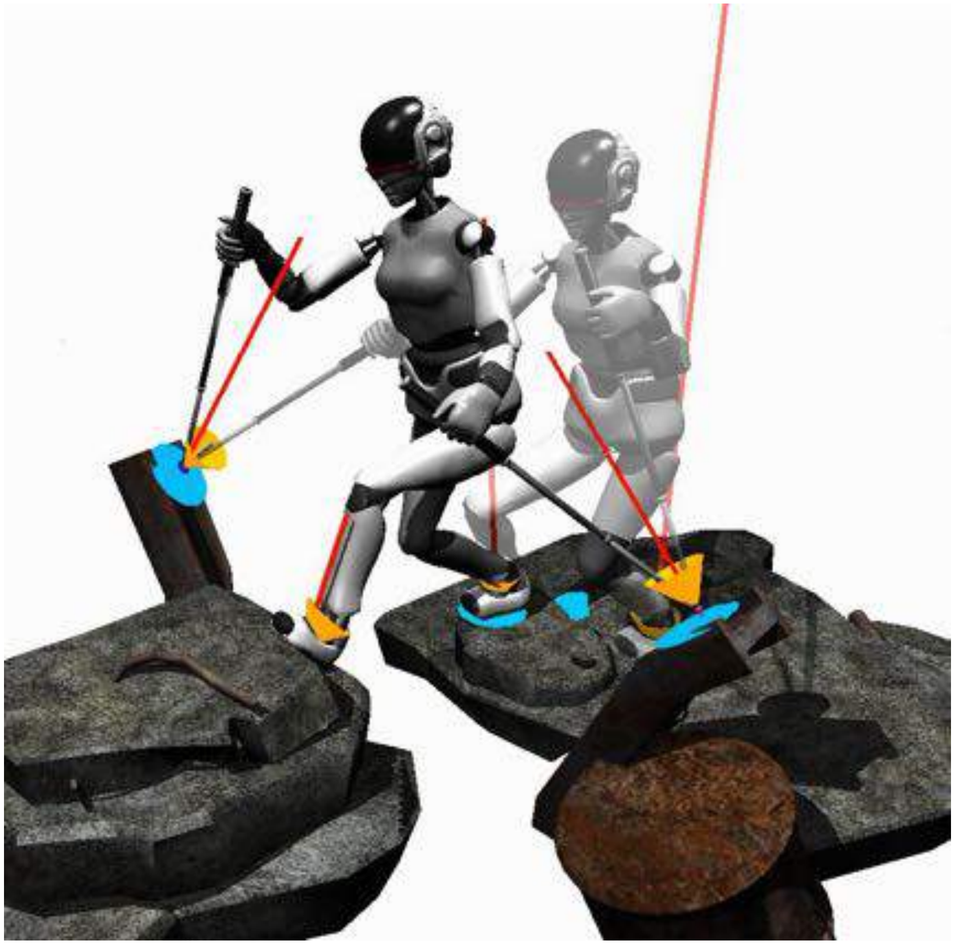
- SupraPed: point contact
  - Design solutions of the smart staff
  - Sensing methods for terrain information



- SpinyPalm: contact patch
  - New spine design for higher adhesion density
  - Spine contact model
  - Scaled-up contact patch (palm)

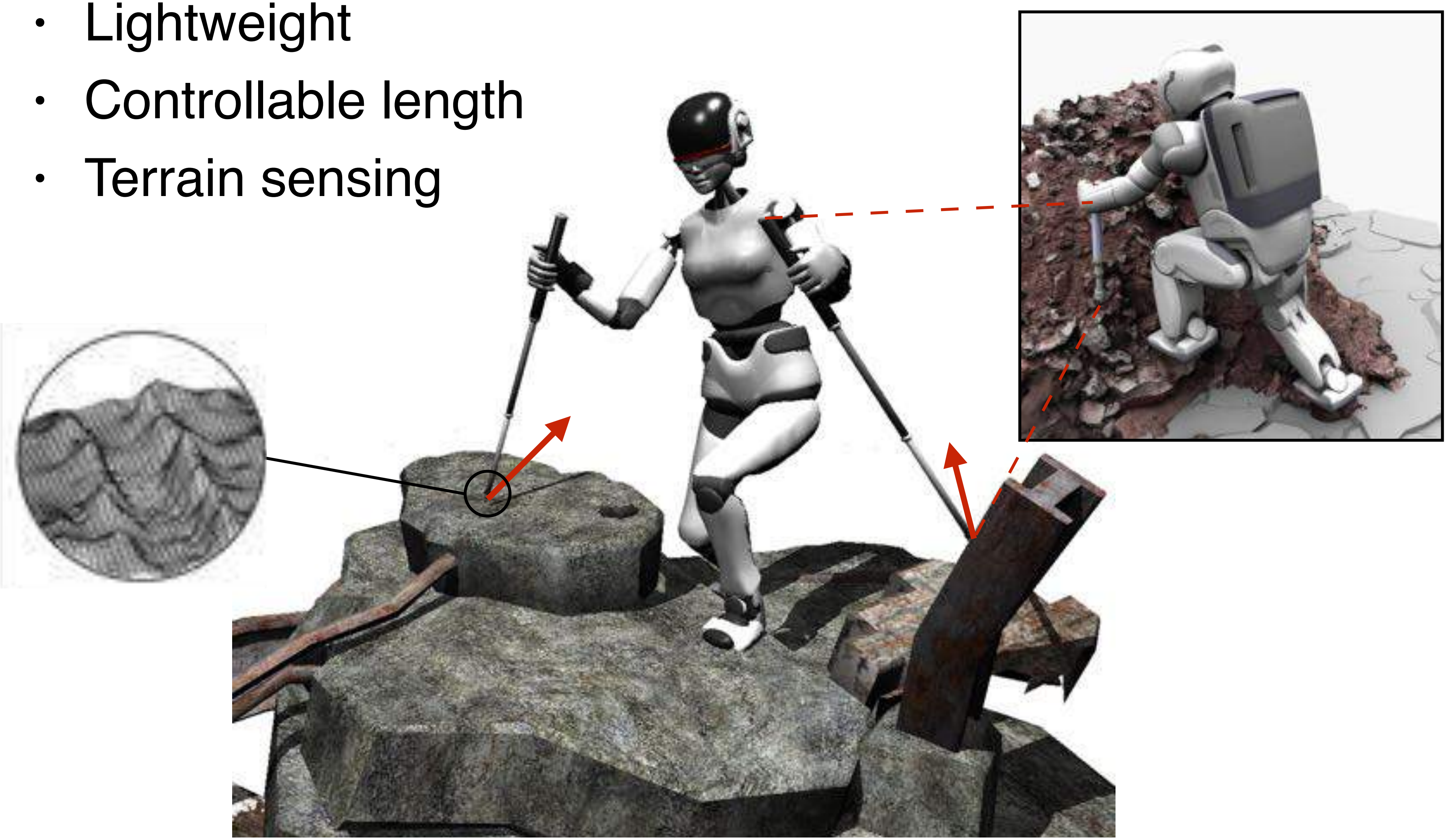
- SpinyHand: hierarchical contact patches
  - Hand design
  - Grasp model with spine contact (non-convex)
  - SimGrasp: a convenient hand/grasping simulator

SupraPed:
Extend the reach of a point contact



Design requirements (smart staff)

- Lightweight
- Controllable length
- Terrain sensing



Smart staff design

- 3 segments
- Single actuator with tendon
- Spring design
- SMA active brake

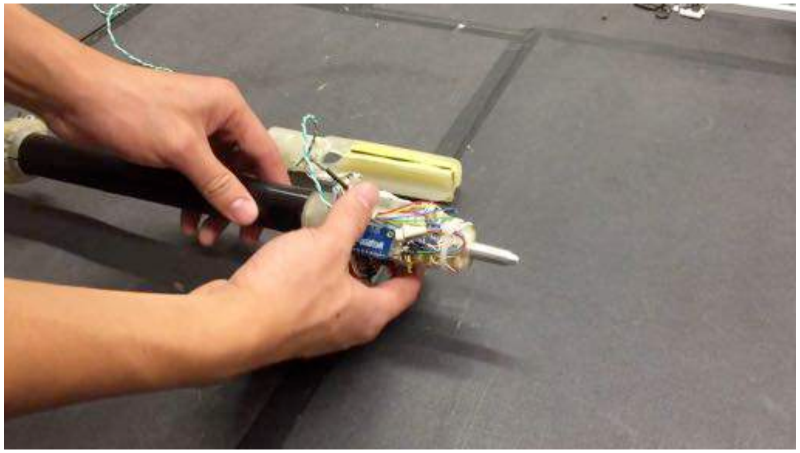
Smart staff design

- 3 segments
- Single actuator with tendon
- Spring design
- Active brake

⇩

- Range of length: 0.4 ~ 1.0m
- Weight: 350 g
- Interchangeable end-effector

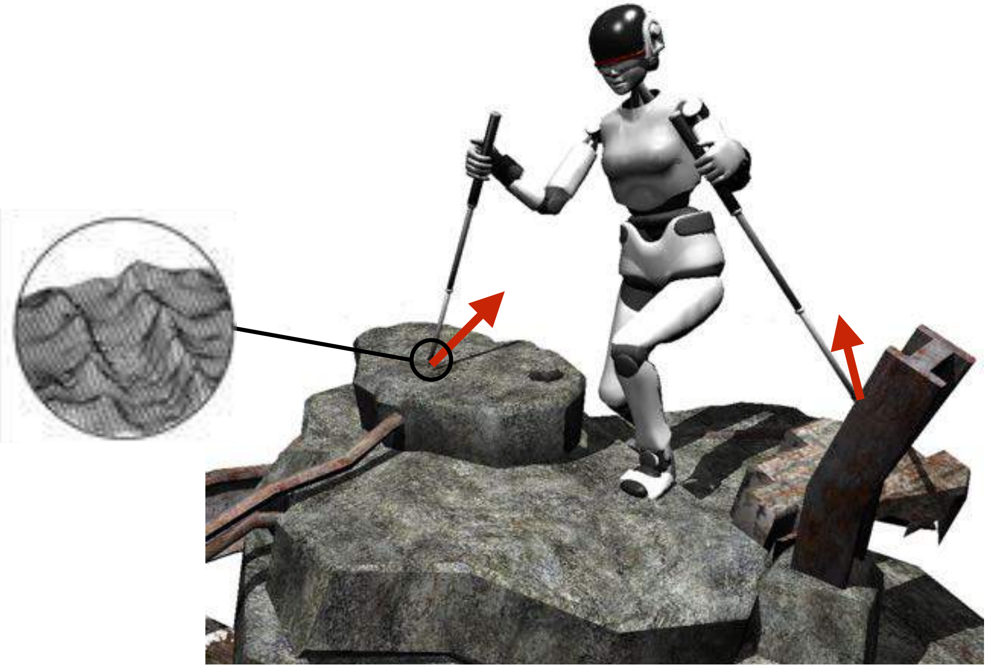
Extending to grasp

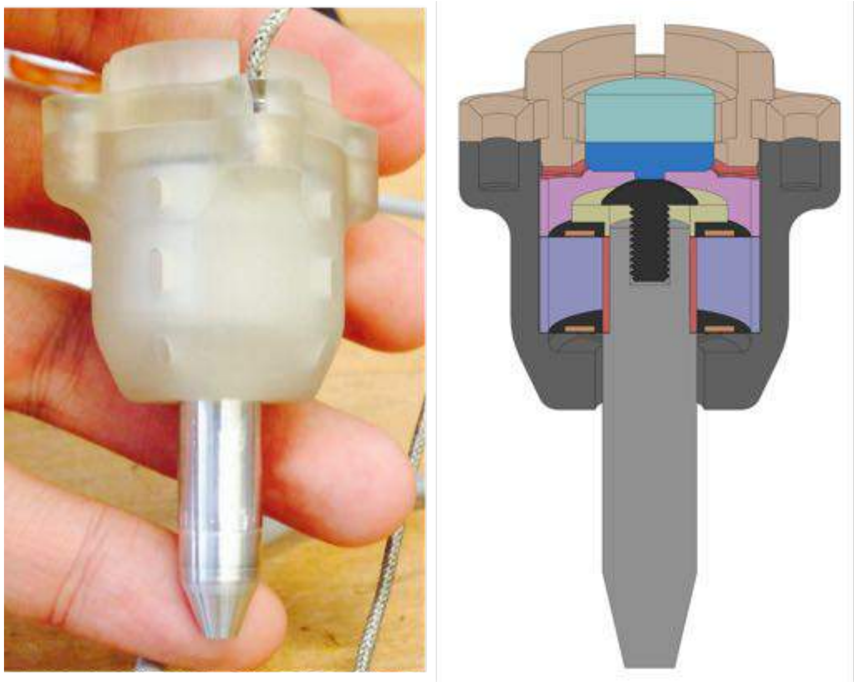


Changing the tool tip

Sensor design

- Ground reaction force
  - 500N axial and 50N lateral
- Robust, compact, and low inertia



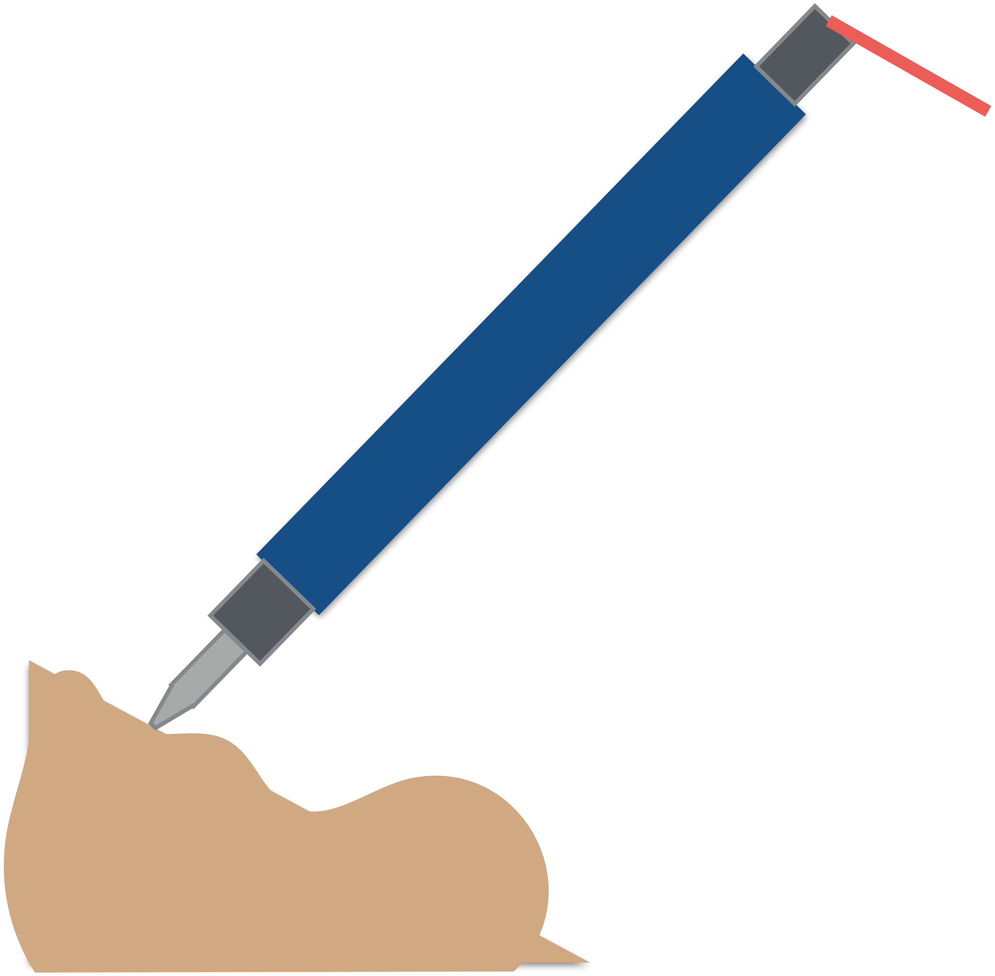


5-DOF Force and Torque Sensor
(Patent Pending)

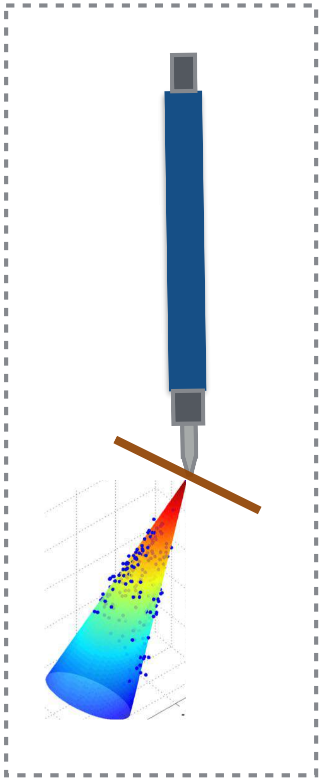
Terrain sensing methods

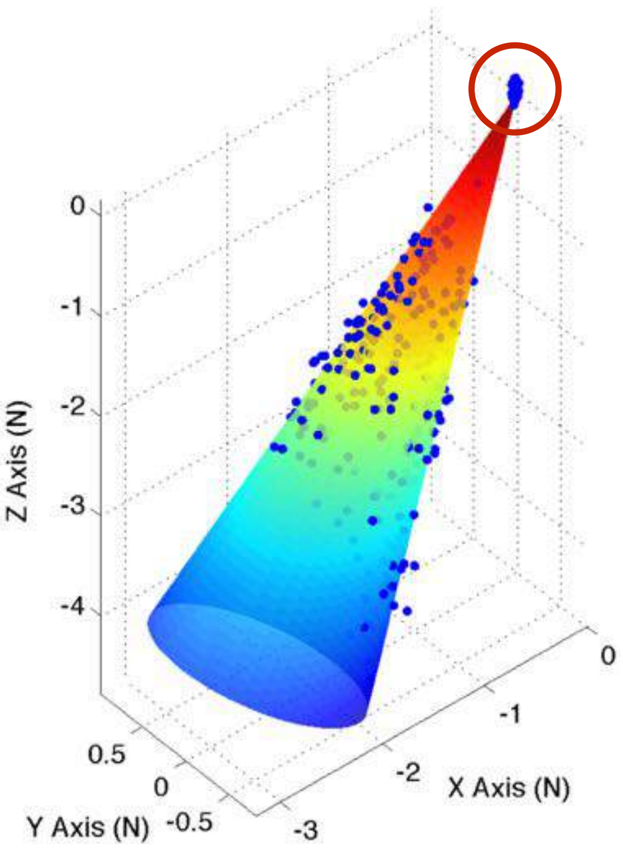
1) Surface normal   2) Coefficient of friction

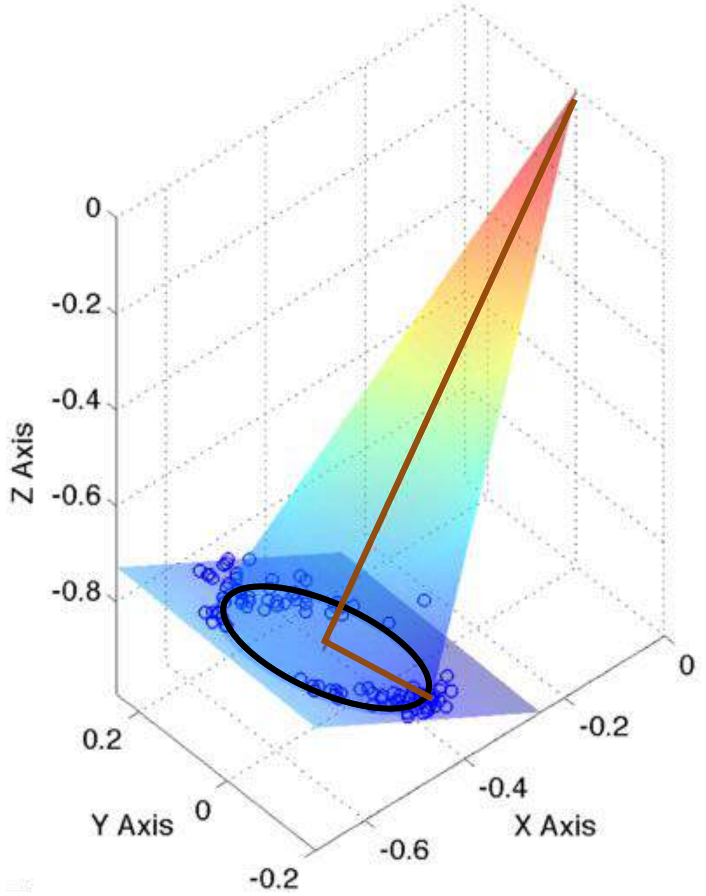
- **Vision**
  - Complexity
  - Occlusion
- **Contact position based**
  - Poor accuracy
  - Non-flexible
- **Contact force based**
  - Low control effort
  - Short tip travel (few mm)
  - Fast (few seconds)



Terrain sensing procedures







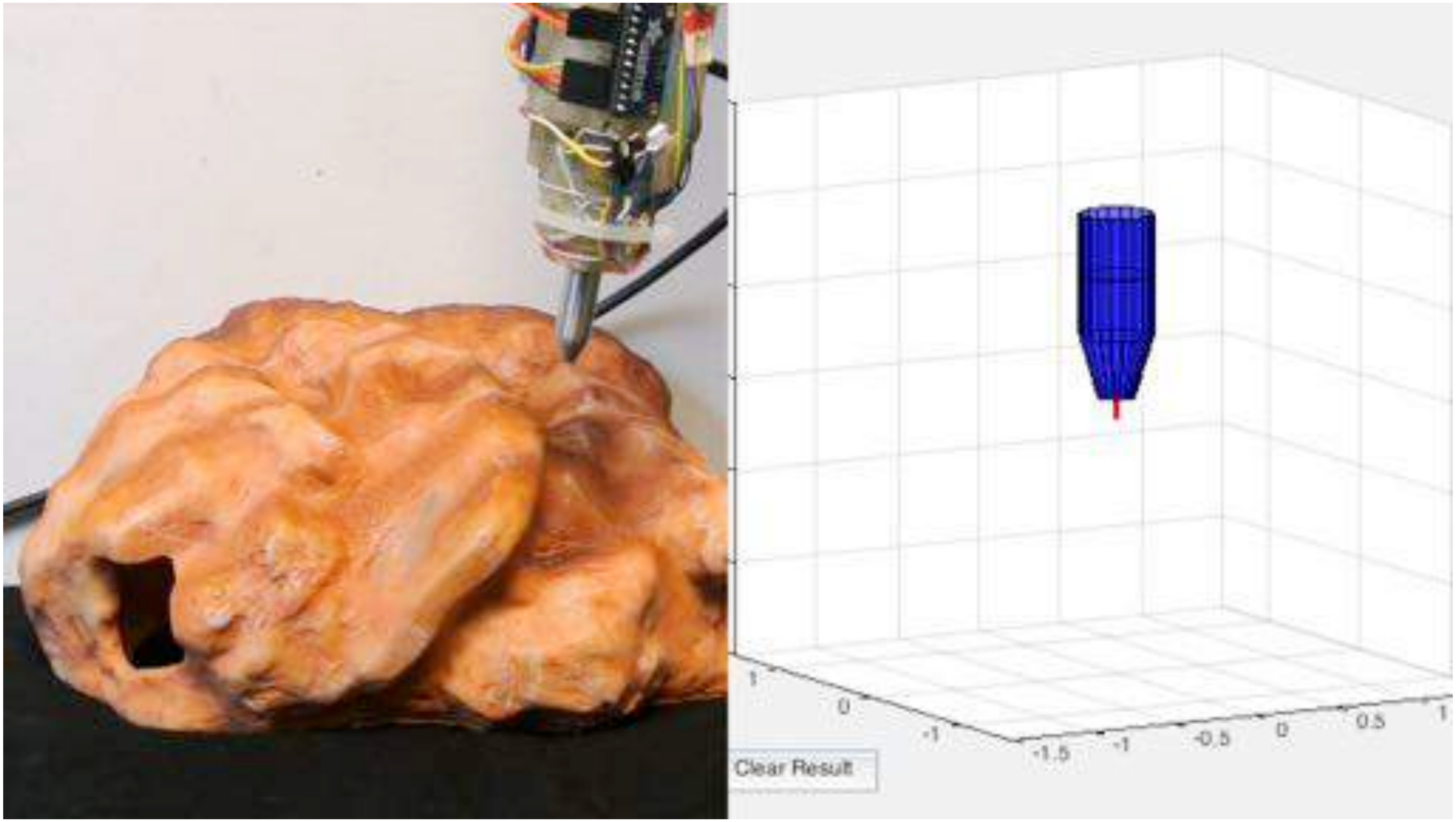
Surface
Scratching

Data
Seperation

Cone Fit

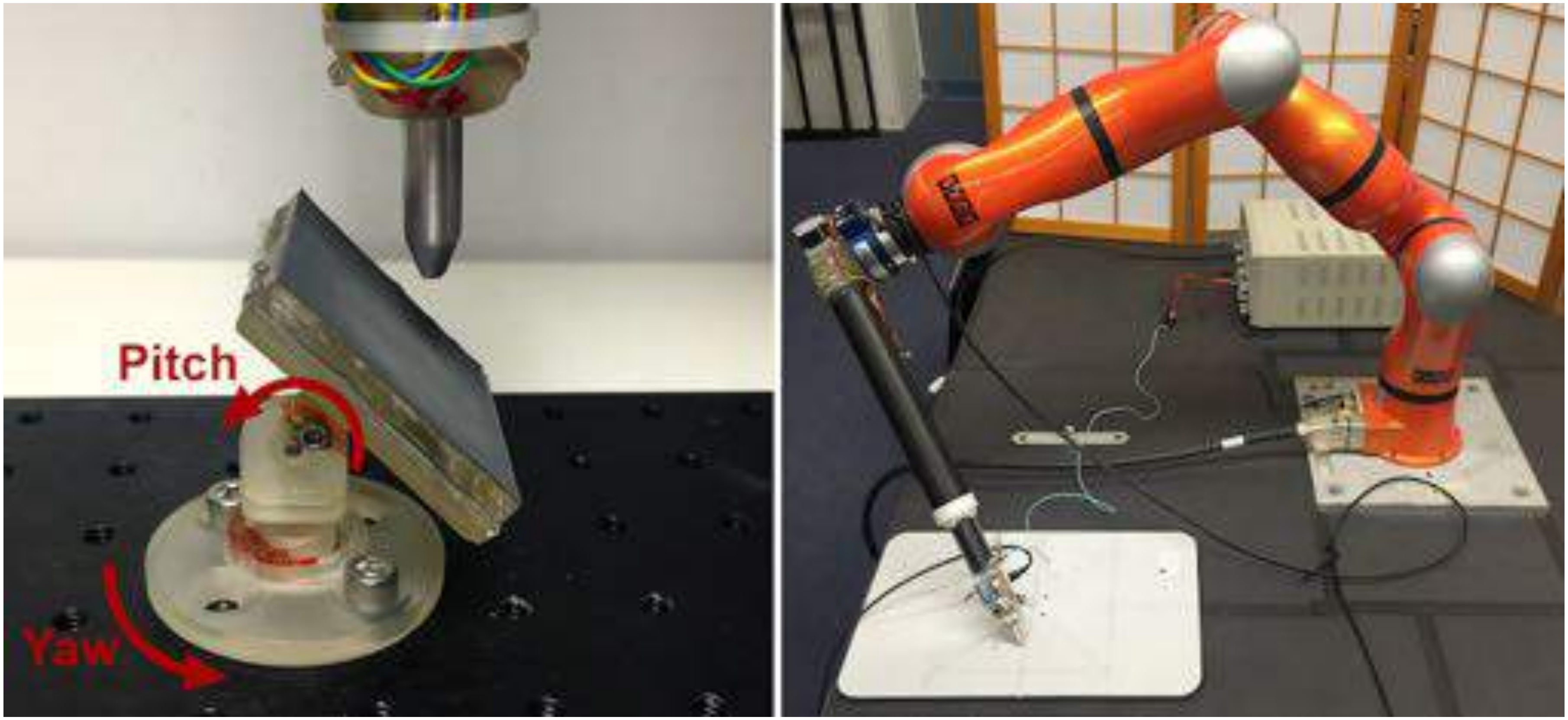
WANG, et al. IROS2015

Active sensing primitive



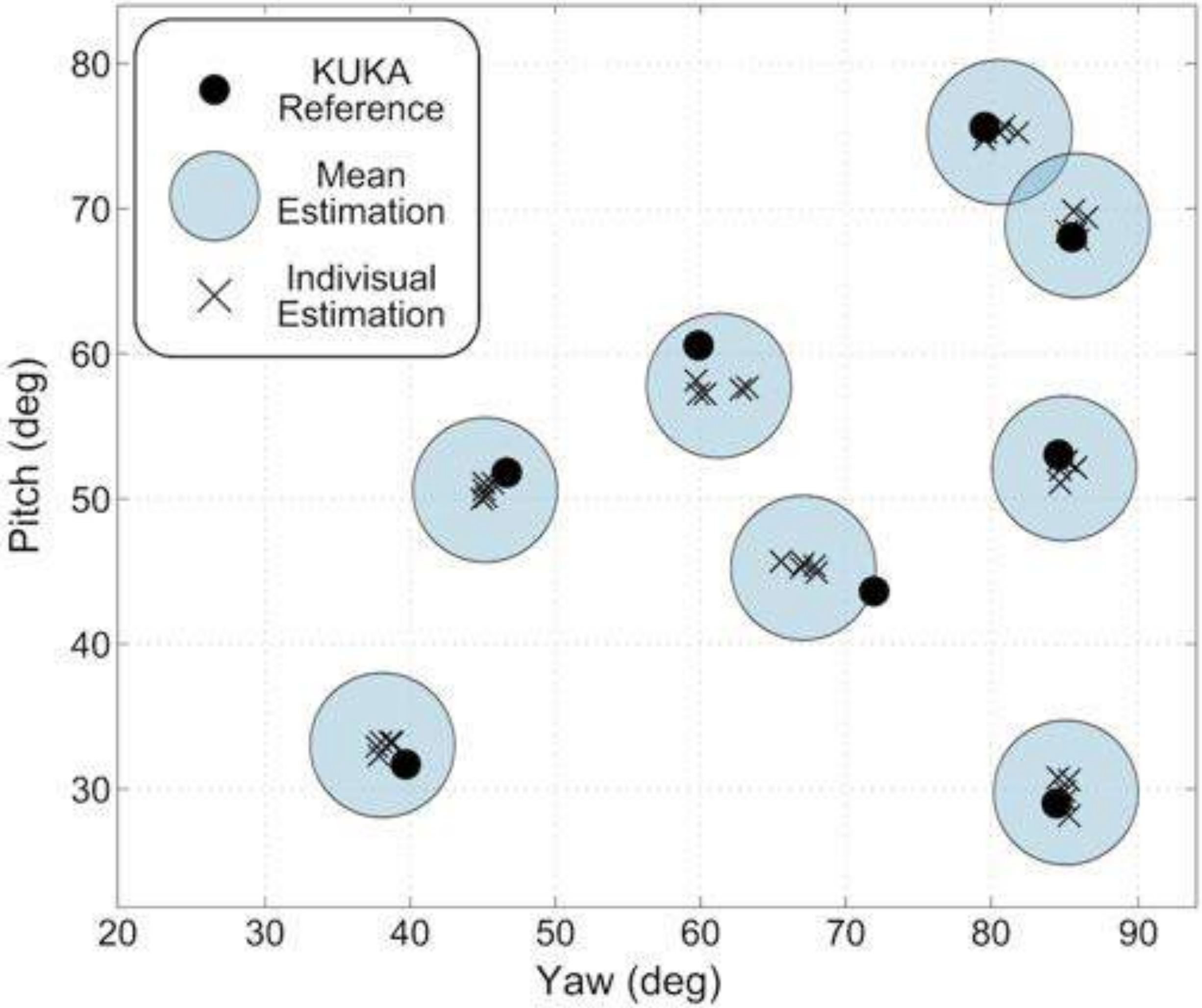
Terrain sensing verification

- Probing manually
- KUKA arm



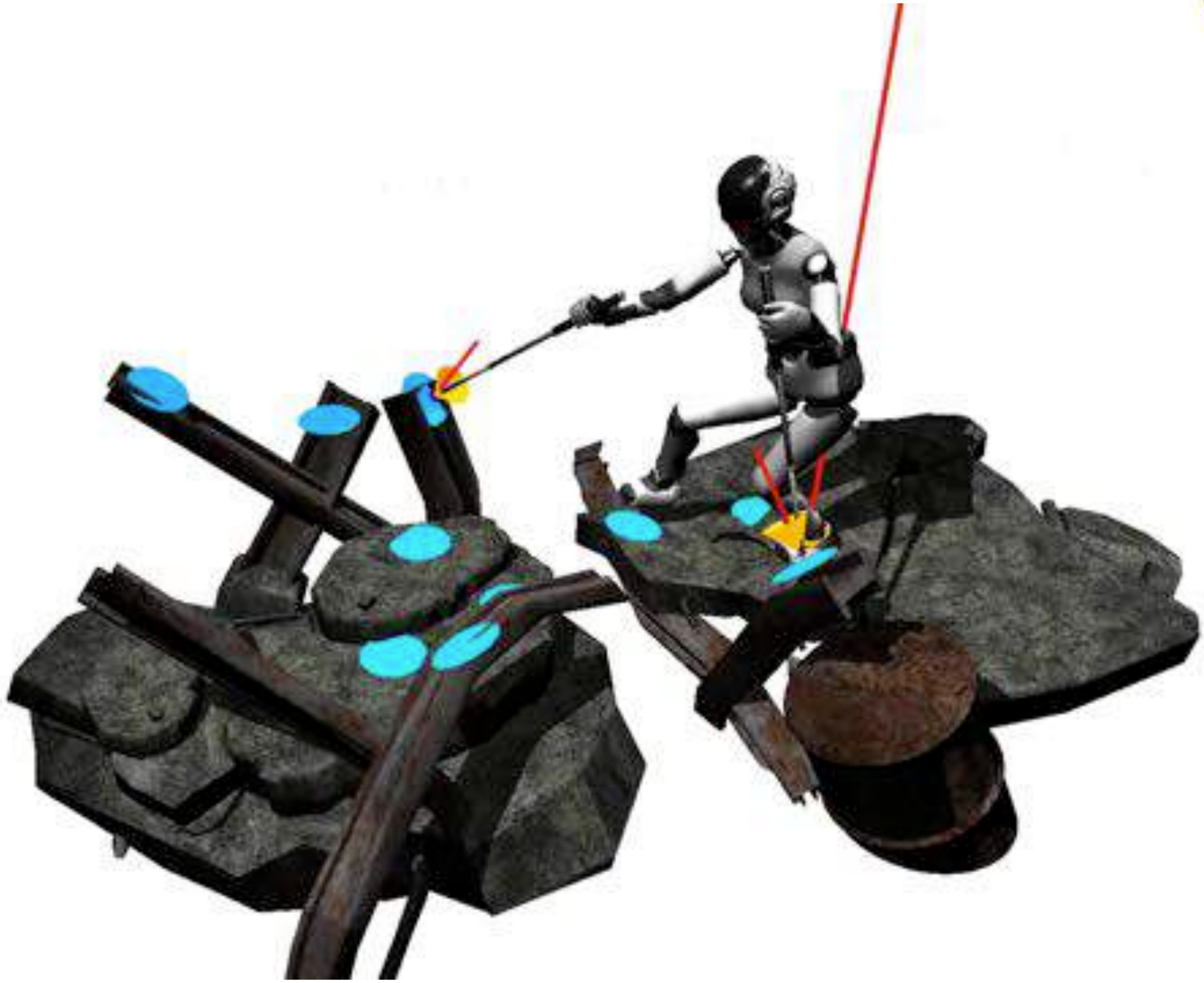
Results

- 2 deg average error (both experiments)



SupraPed contact limitation

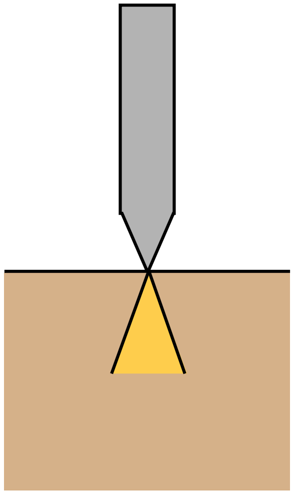
- Constrained by friction cone



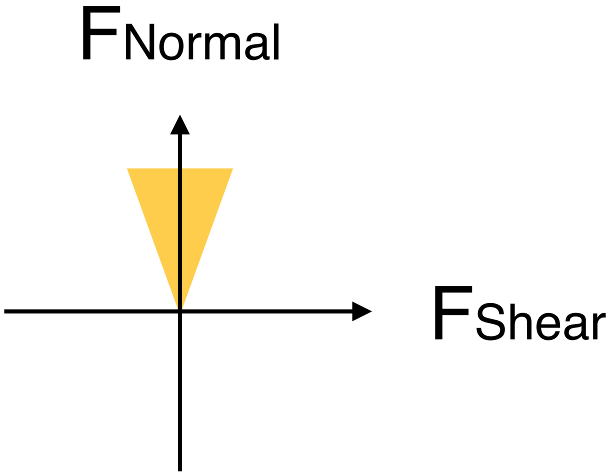
O. Khatib and S. Chung 2014

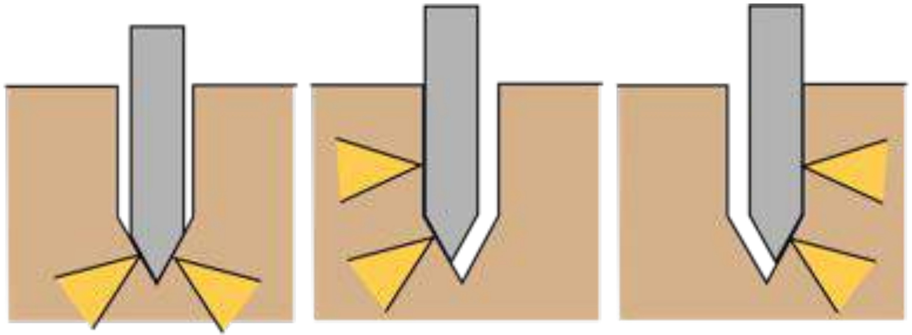
Improve the contact

- Admissible force volume

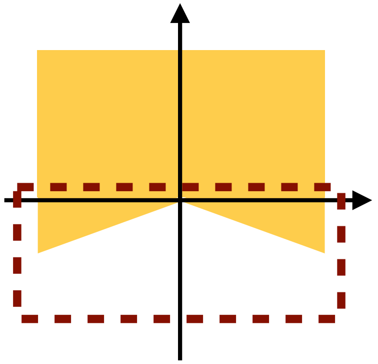


Point contact



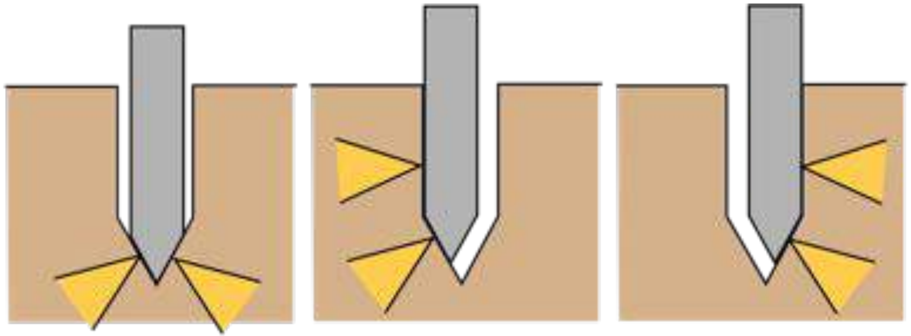


Anchored contact

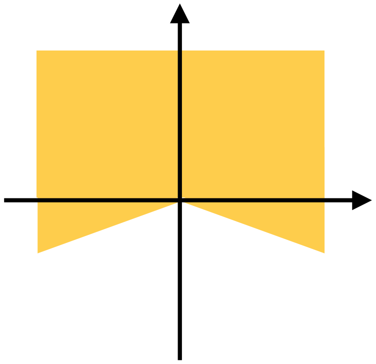


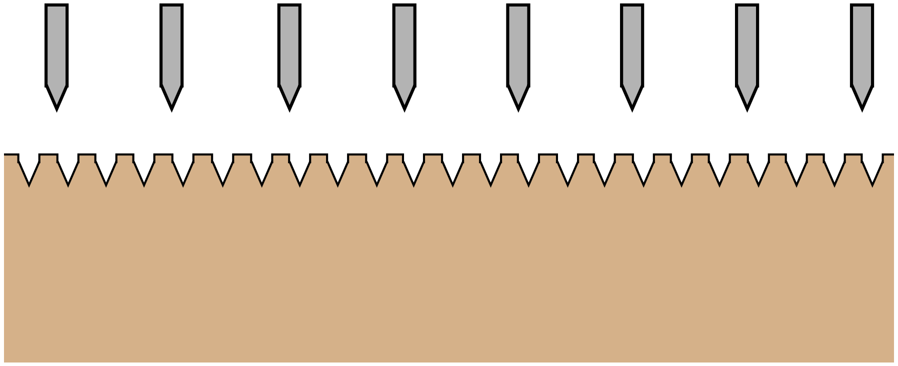
Adhesion

Improve the contact

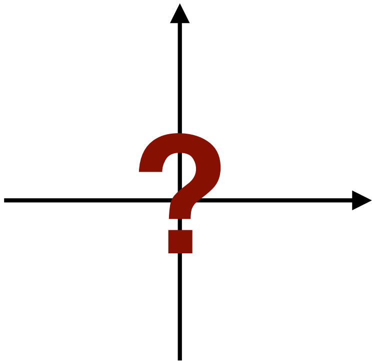


Anchored contact

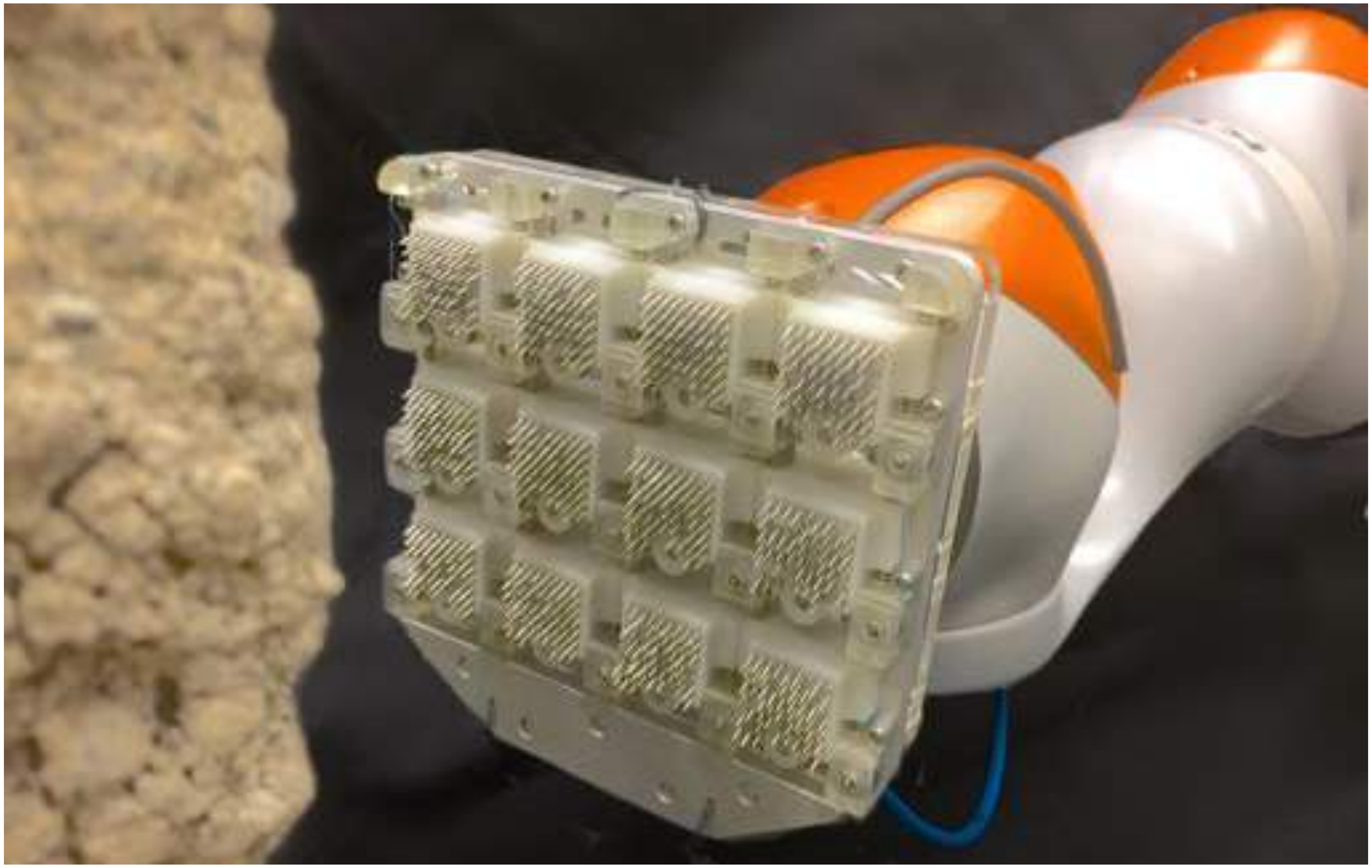




Miniatured anchored contact array

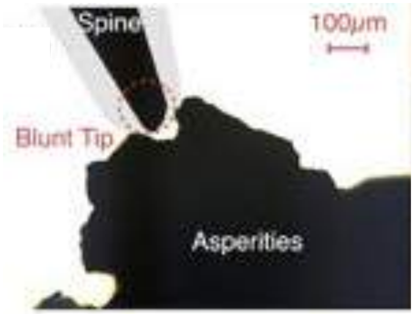


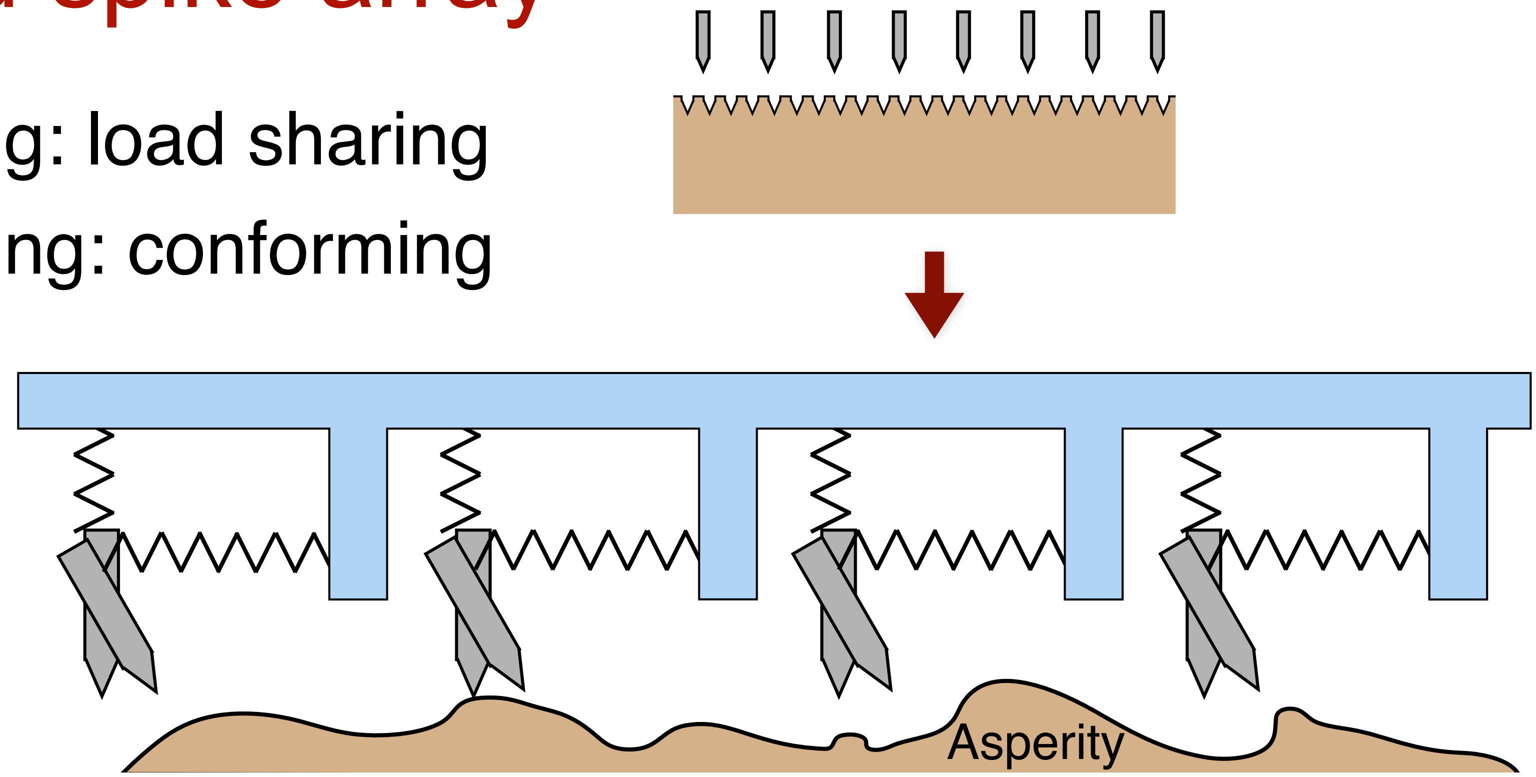
SpinyPalm:
Enhance the admissible force volume of a contact patch

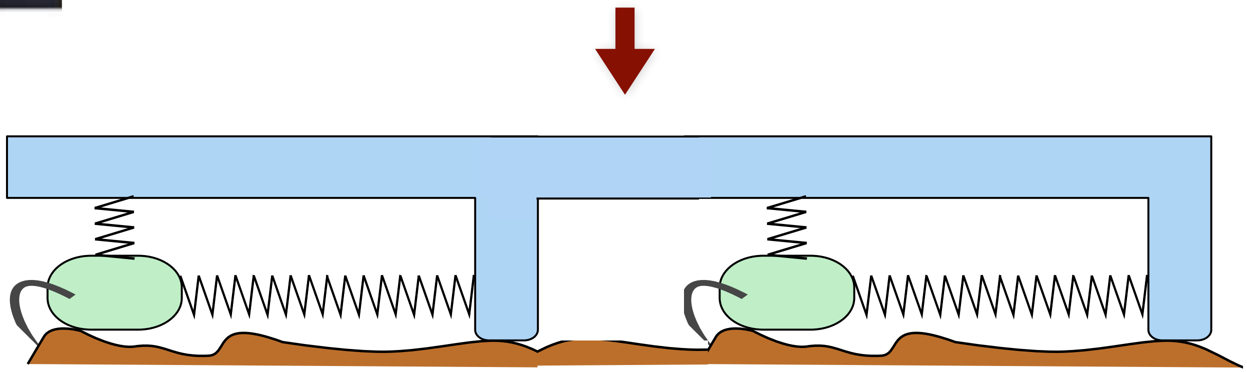


Miniatured spike array

- Shear spring: load sharing
- Normal spring: conforming







Compliantly-supported Micro-spines

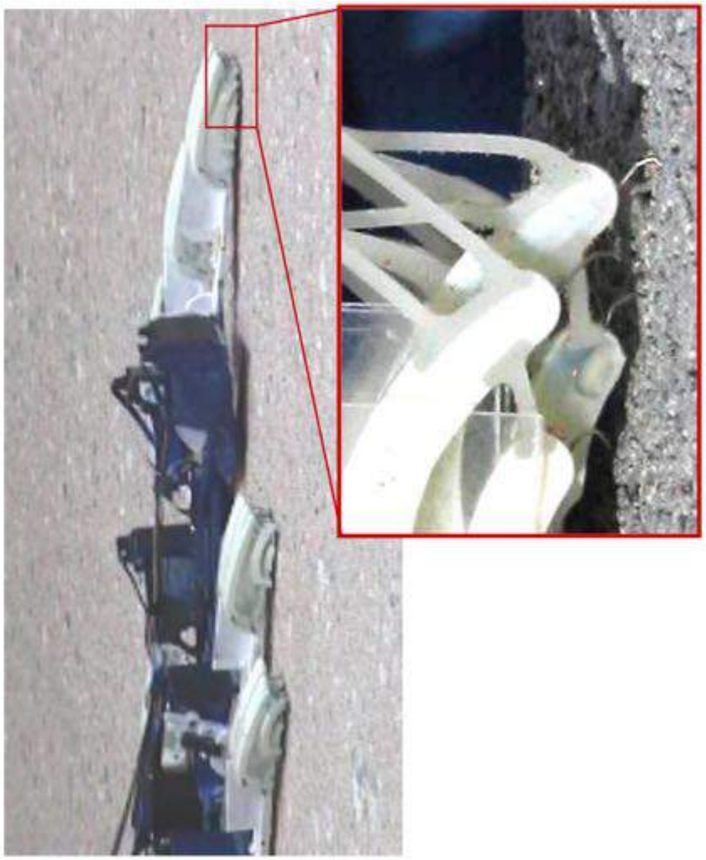
Asbeck, et al. IJRR2006

Compliantly-support micro-spines

Micro-spine

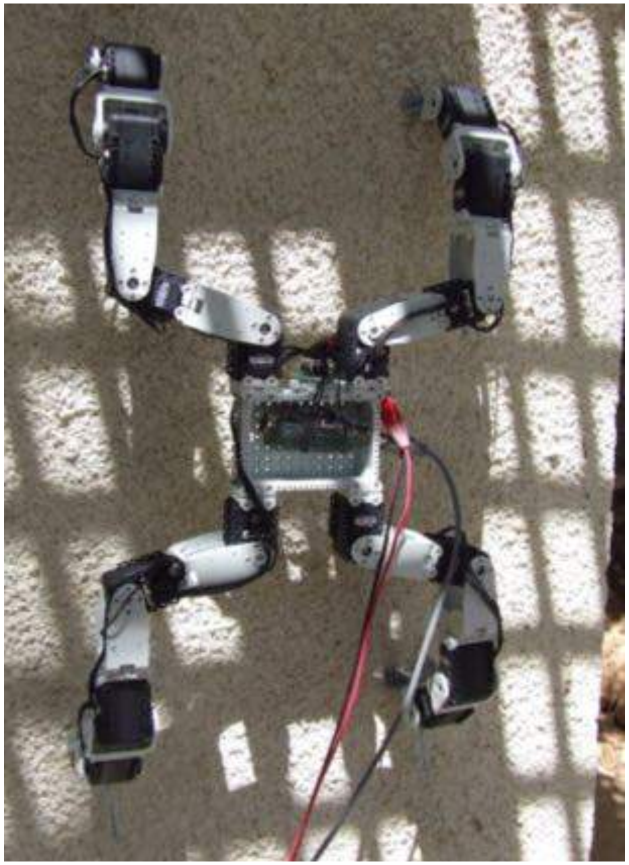
Dai and Gorb, JEB2002

Prior work (micro-spine)



SpinyBotII

S. Kim 2005

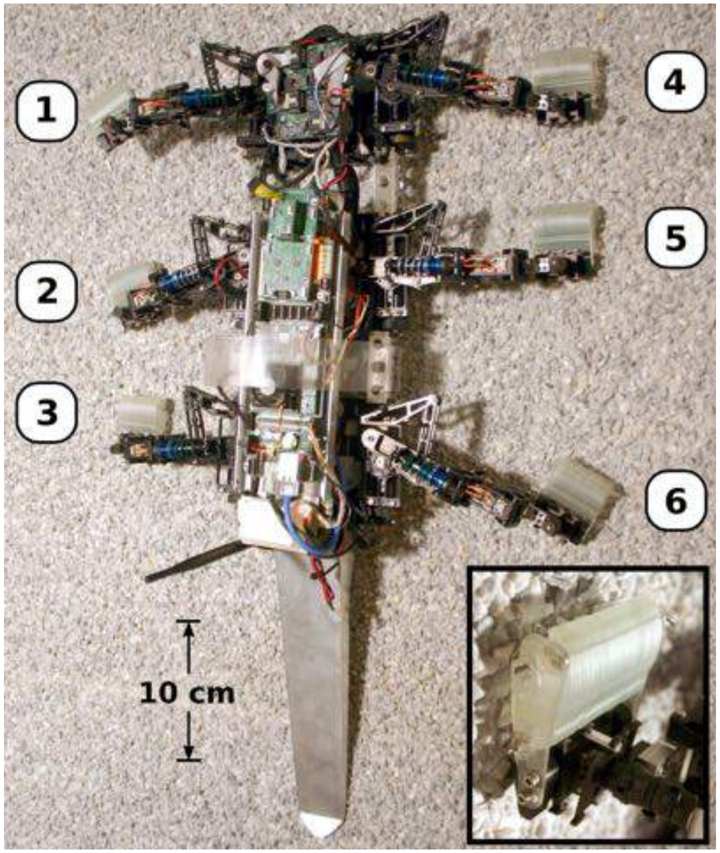


CLIBO

A. Sintov 2011

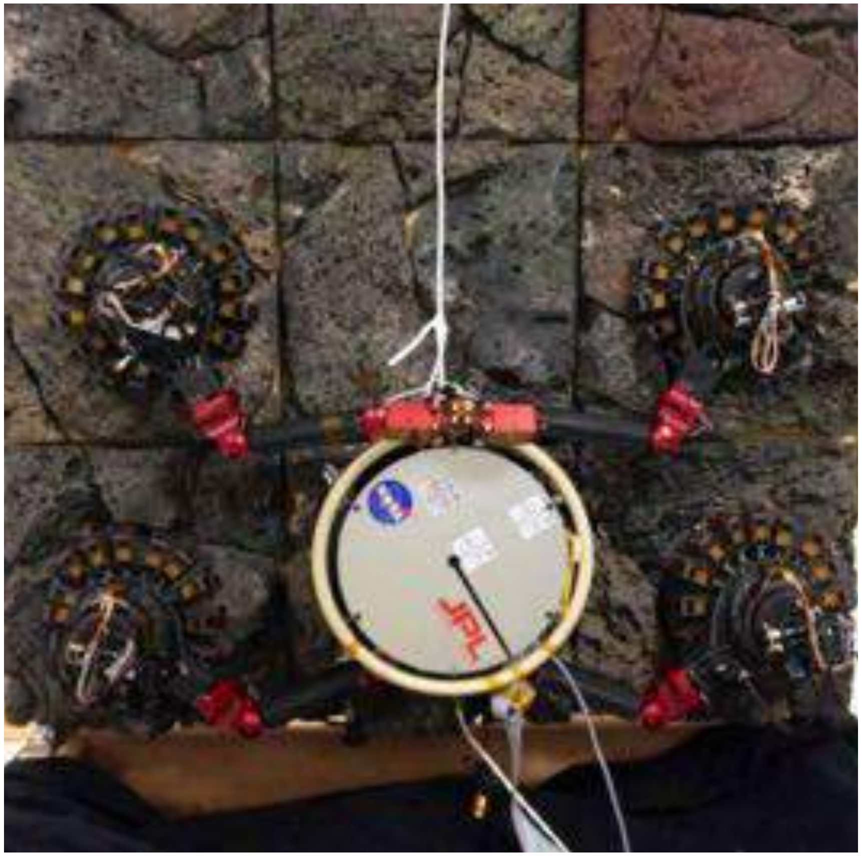
0.4kg **2kg**

Prior work (micro-spine)



RiSE

M. J. Spenko 2008



LEMUR IIB

A. Parness 2013

4kg → **8kg**

Our goal: human-scale application

JPL LEMUR
8kg

>10X

JPL RoboSimian
100kg

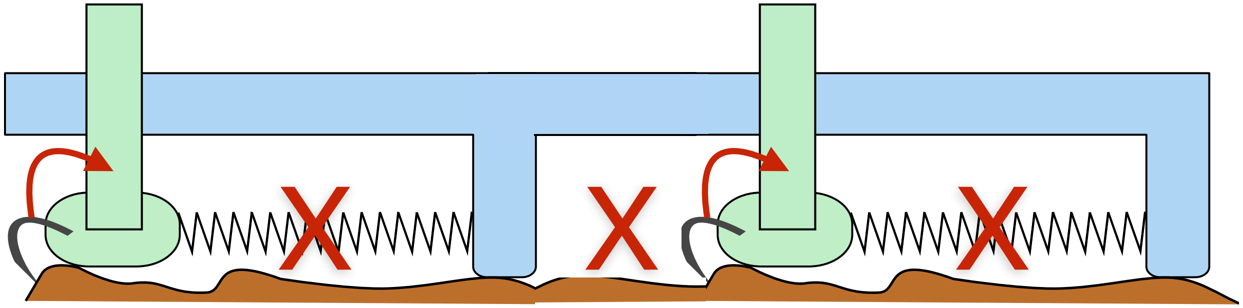
Further scaling up

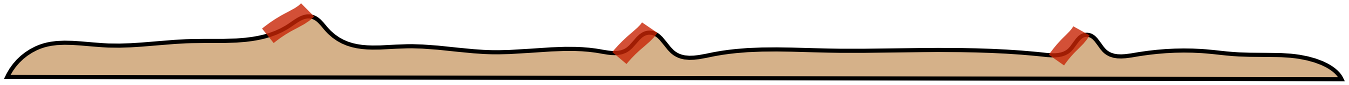
Need to improve the adhesion density!

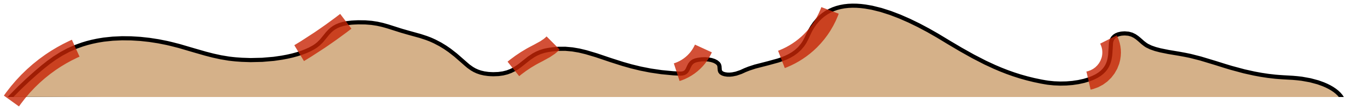
http://northdesignlabs.com/cockroach-mimetic-climbing-paddles/

Spine design with smaller footprint?

- Number of immediately engaged spines is proportional to spine density



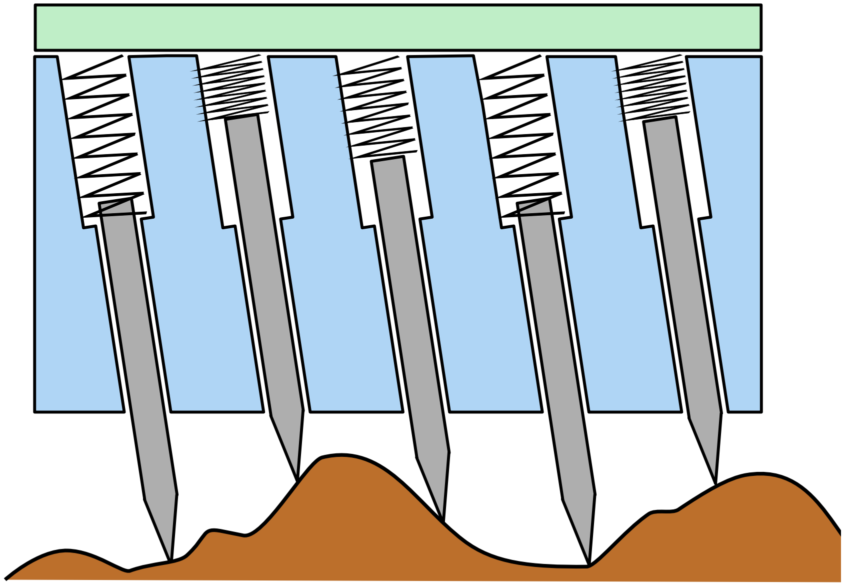




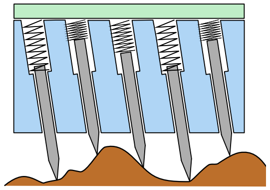
20-40 % immediately engaged surface

New spine design: linearly constrained

- Longer normal travel: conformability
- Low shear contact compliance



Linearly-constrained spine array

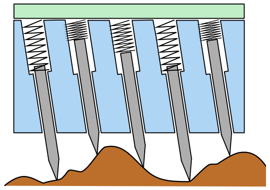


How to optimize the spine design?

How well the adhesion scale up with spine density?

What is the admissible force volume?

Linearly-constrained spine array



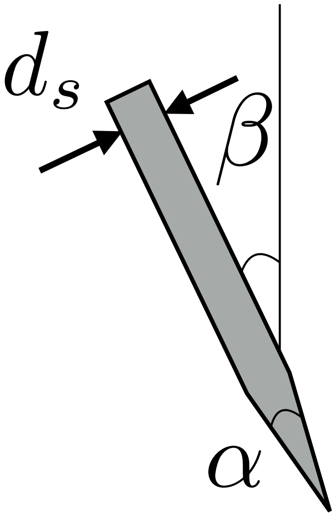
How to optimize the spine design?

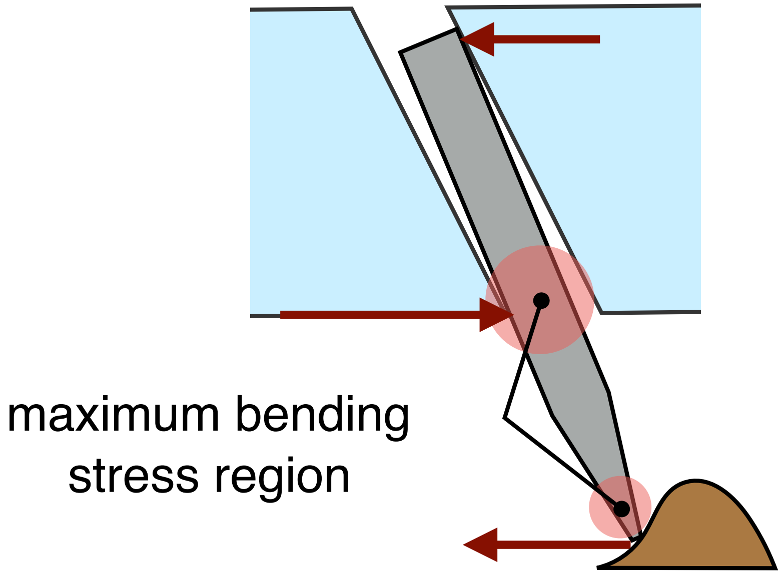
How well the adhesion scale up with spine density?

What is the admissible force volume?

Design parameters

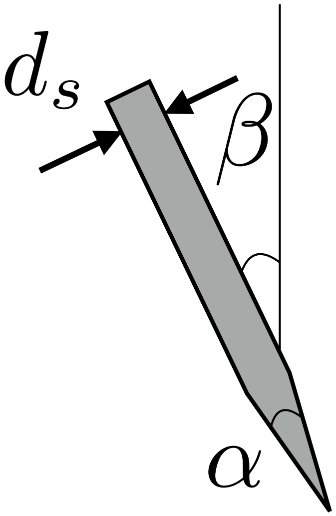
- Spine diameter d_s

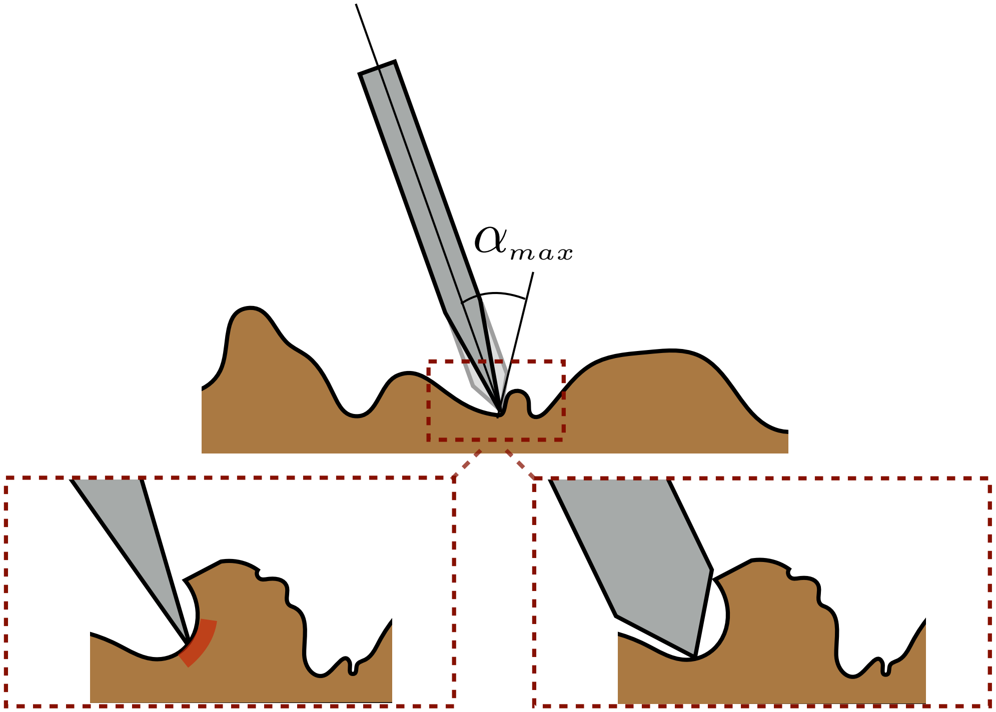




Design parameters

- Spine diameter d_s
- Tip angle α





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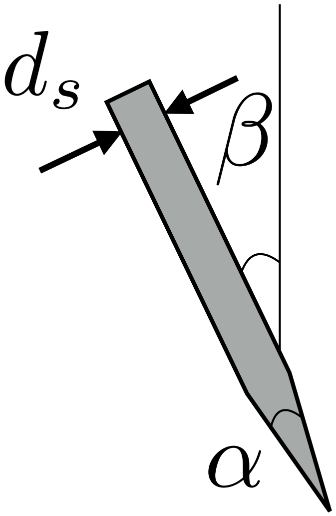
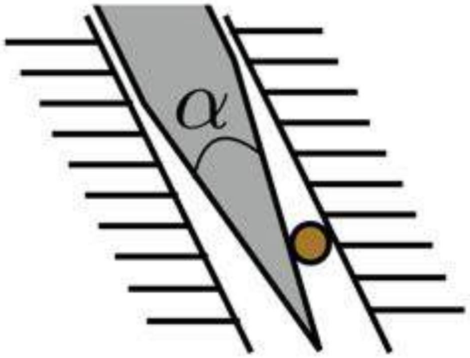
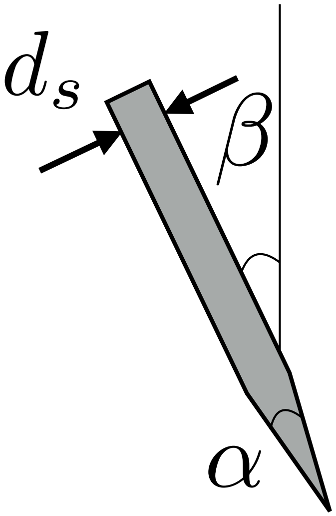
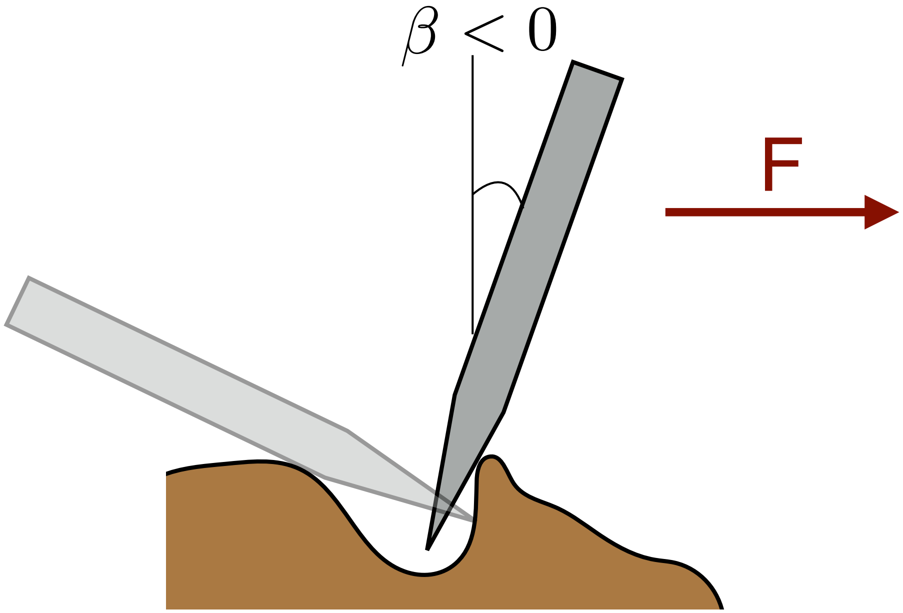




Design parameters

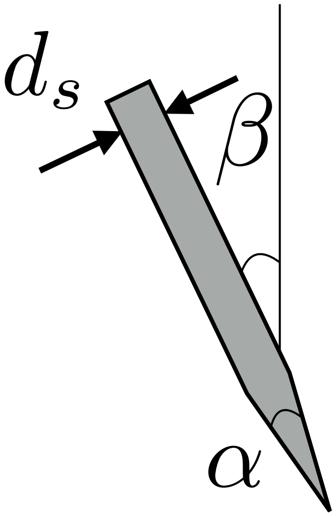
- Spine diameter d_s
- Tip angle α
- Inclination angle β



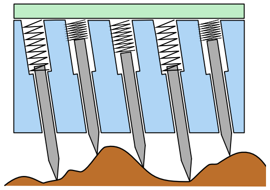


Design parameters

- Spine diameter d_s = 1 mm
- Tip angle α = 15 deg
- Inclination angle β = 15 deg



Linearly-constrained spine array



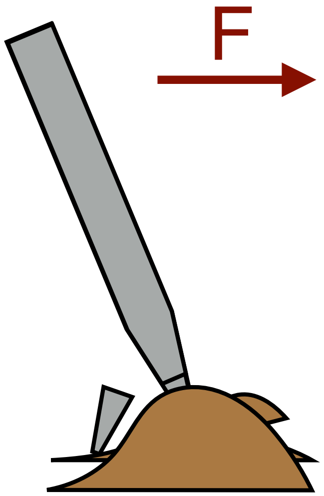
How to optimize the spine design?

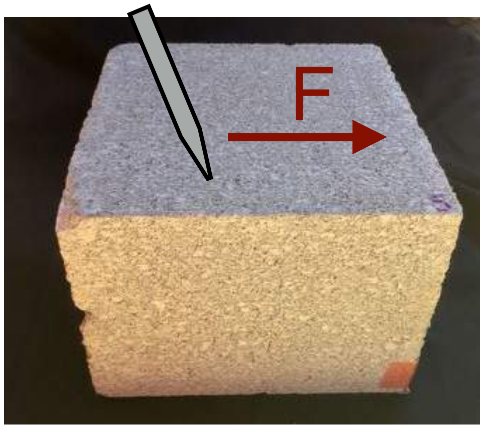
How well the adhesion scale up with spine density?

What is the admissible force volume?

1D single spine empirical model

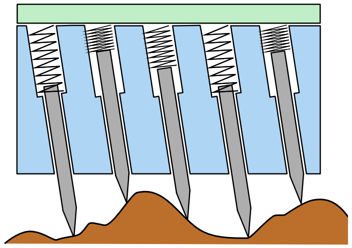
- Slip failure: fixed probability 🟩
- Asperity failure: truncate Gaussian 🟨
- Spine failure: Gaussian 🟥

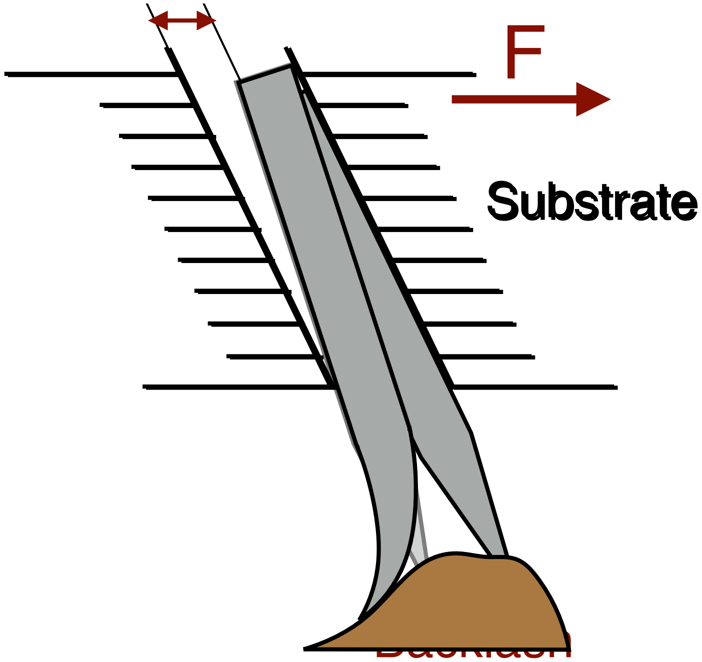




1D spine array probability model

- Backlash
  - 0.1 ~ 1 mm
  - Uniform distribution
- Engaged spine bending
  - 17.5 N/mm





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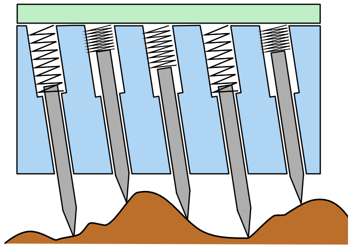

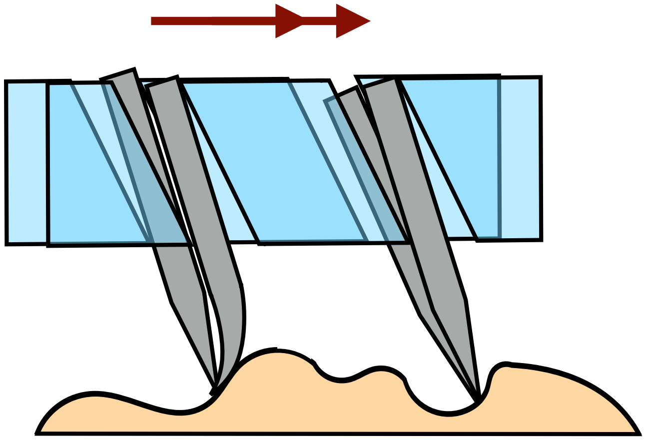

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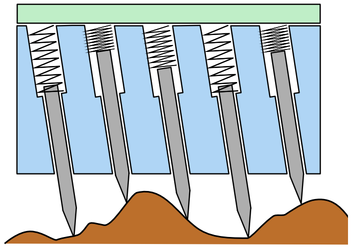
  - 17.5 N/mm



$$E[F] = \boxed{\sum_{i=1}^{n}} \iiint \boxed{F_i} \boxed{f_{\Phi_{Mi}} f_{Si} f_{M_i}} dM_i dS_i d\Phi_{Mi}$$

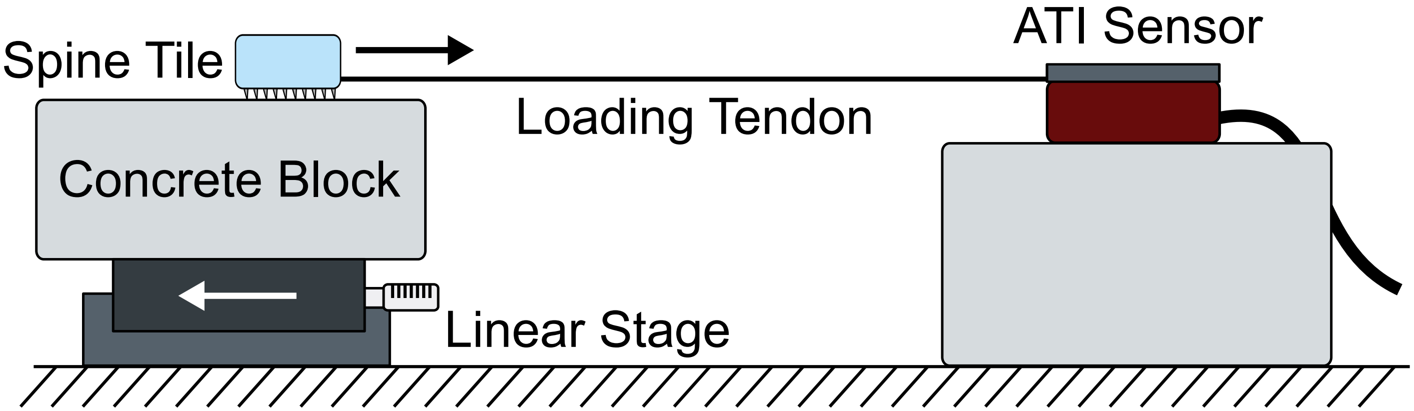
Spine Force

- Failure Force
- Failure Type
- Backlash

- Mean spine array adhesion
  - Non close-form solution
  - Monte Carlo

Experimental verification

- Loading test with different spine density (fixed contact area)




Fine Concrete


Coarse Concrete

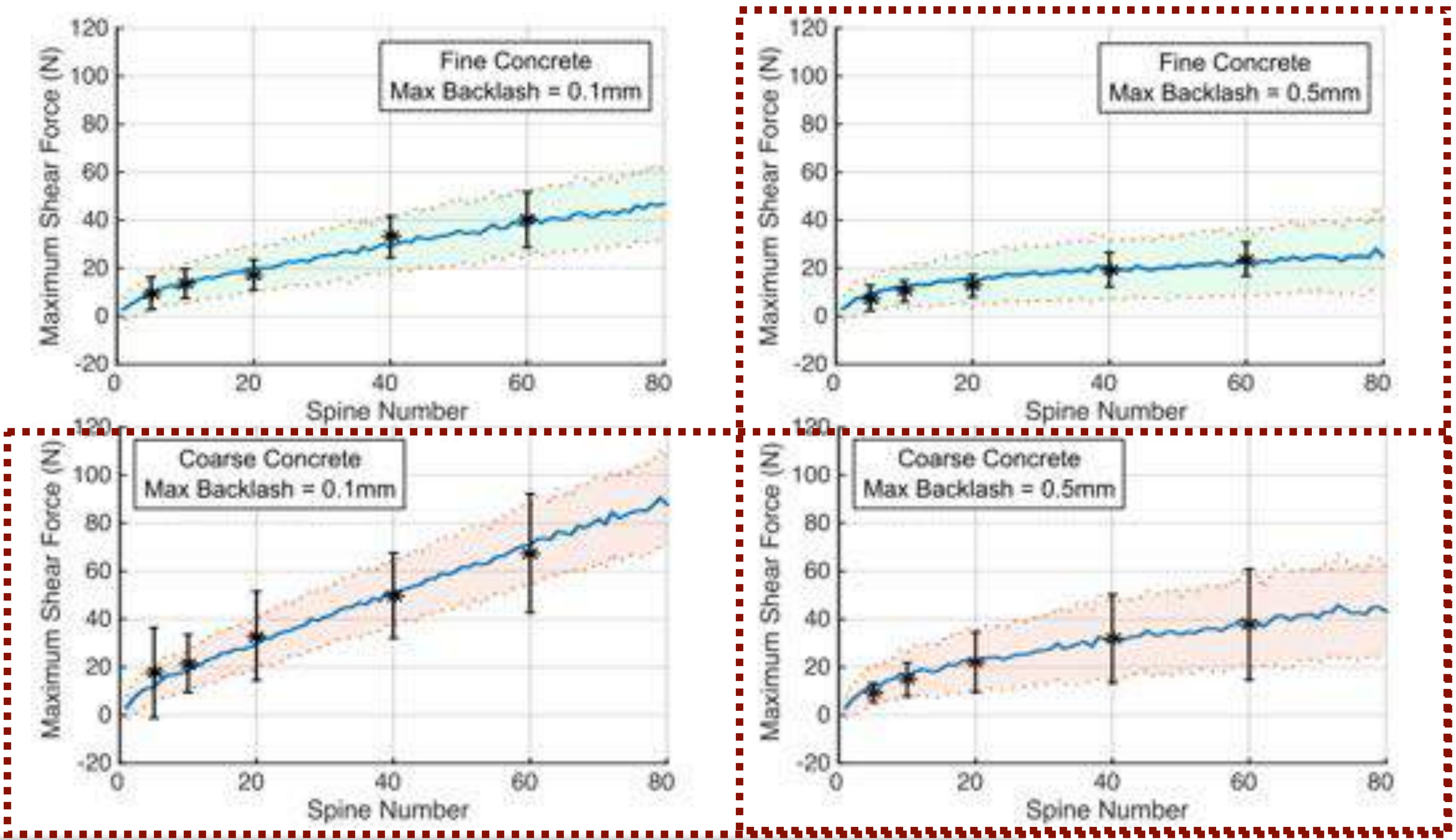
Results: density scalability

- Highly stochastic
- Backlash causes scaling plateau

Model Mean

Model STD

Experiments

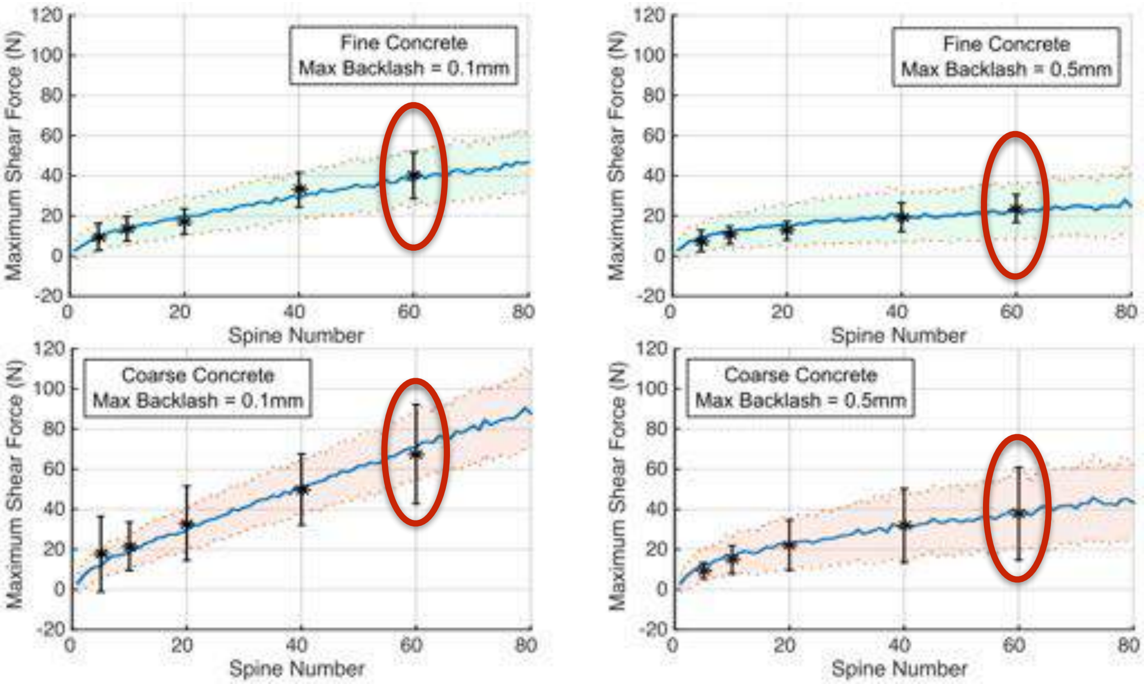


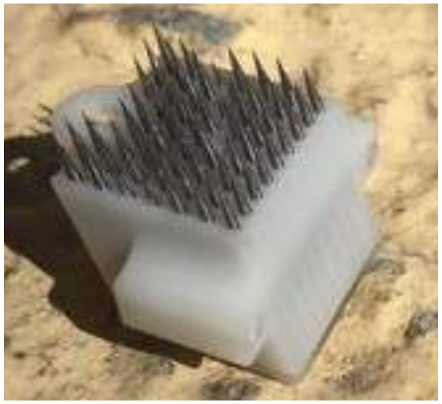
Larger Backlash

Rougher Surface

Adhesion density scalability

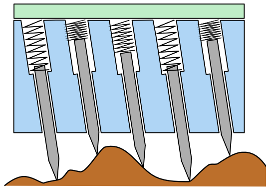
- Implementation
    - 60 spines
    - 18 x 18 mm area
- Performance
    - 42 - 67 N
    - 3 - 4 x adhesion





Spine Tile

Linearly-constrained spine array



How to optimize the spine design?

How well the adhesion scale up with spine density?

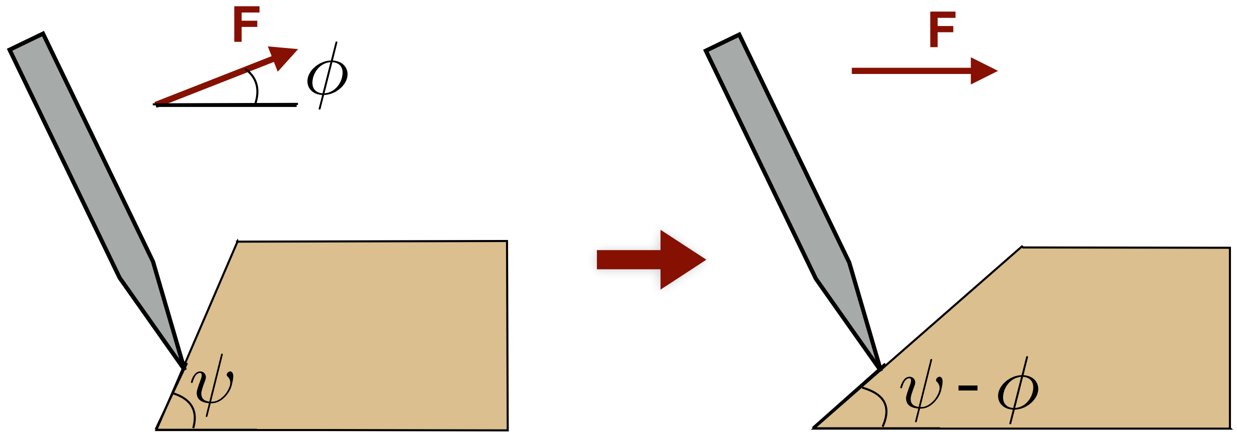
What is the admissible force volume?

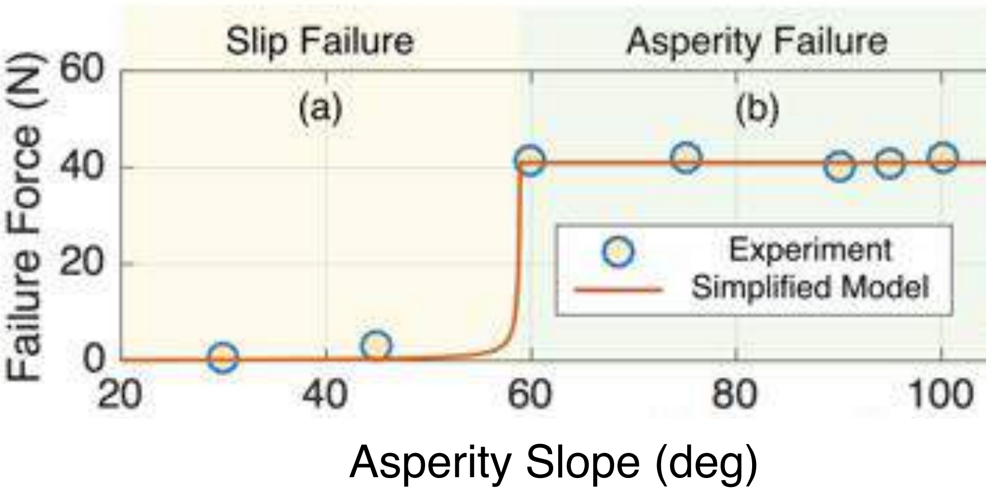
3D spine array model

- 1D adhesion model
  - Single spine empirical $\xrightarrow{\text{Probability Model}}$ spine array prediction
  - Not feasible for 2 & 3D

3D spine array model

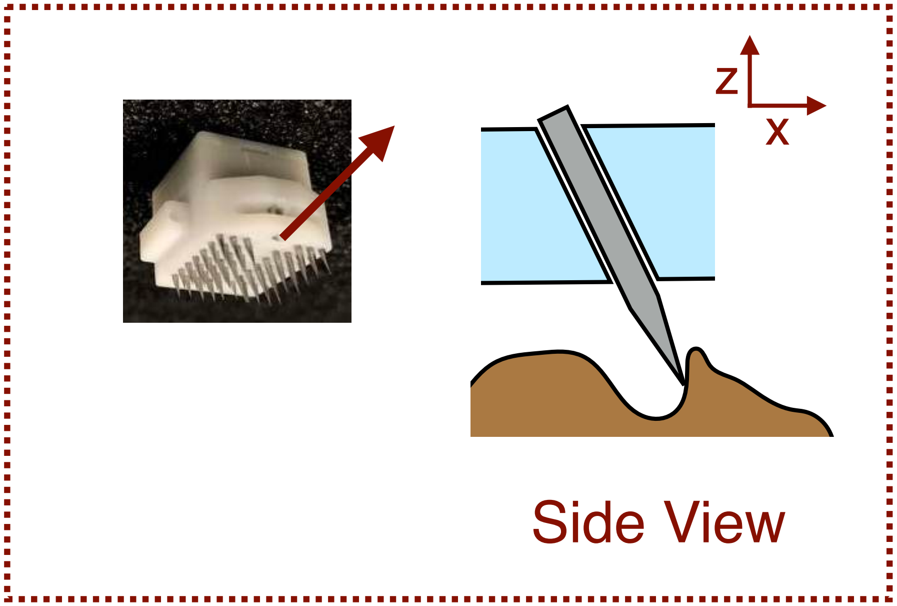
- 2D adhesion model $F(\phi)$
  - Equivalent asperity slope -> failure force





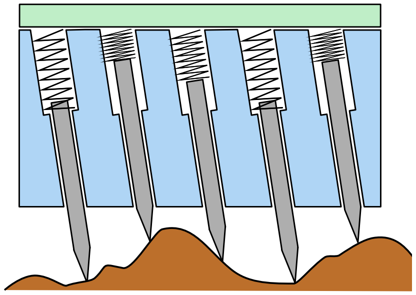
3D spine array model

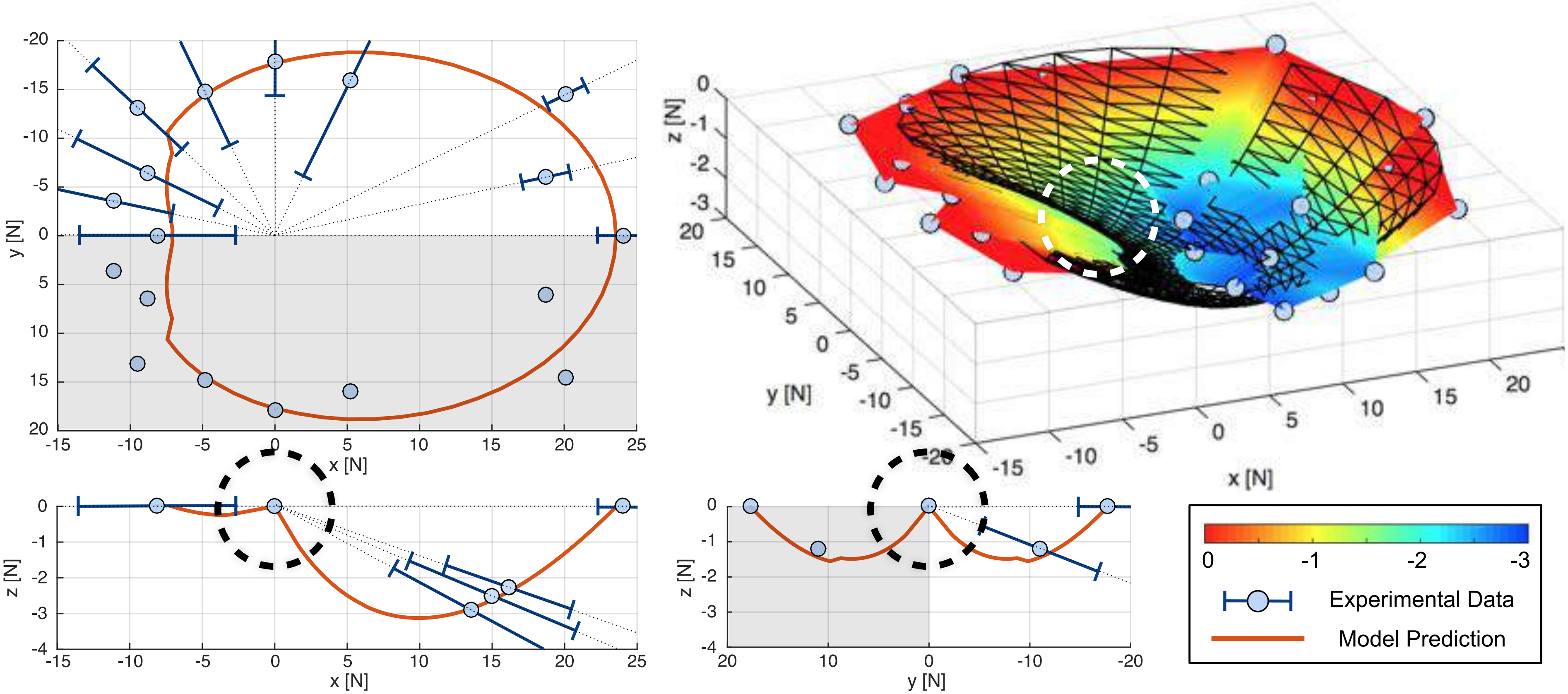
- 3D adhesion model $F(\phi, \theta)$
  - Smaller equivalent inclination angle $\beta'(\theta) = \arcsin(\sin\beta\cos\theta)$
  - Shaft contact -> weaker asperity



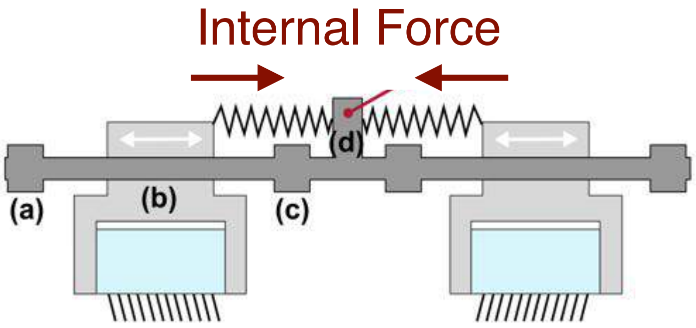
Spine model verification

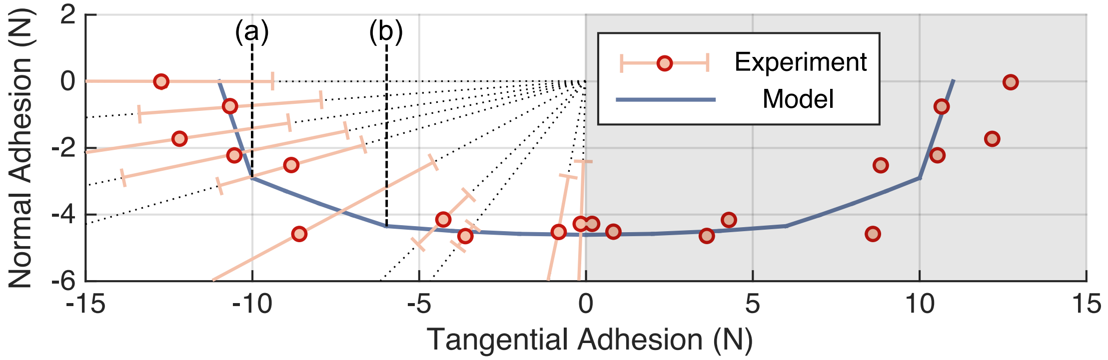
- Non-convex boat shape

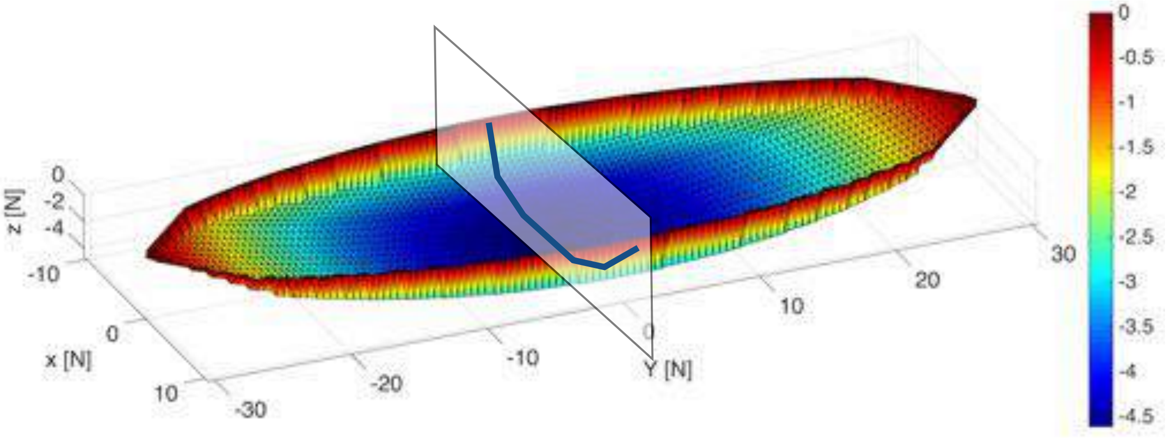




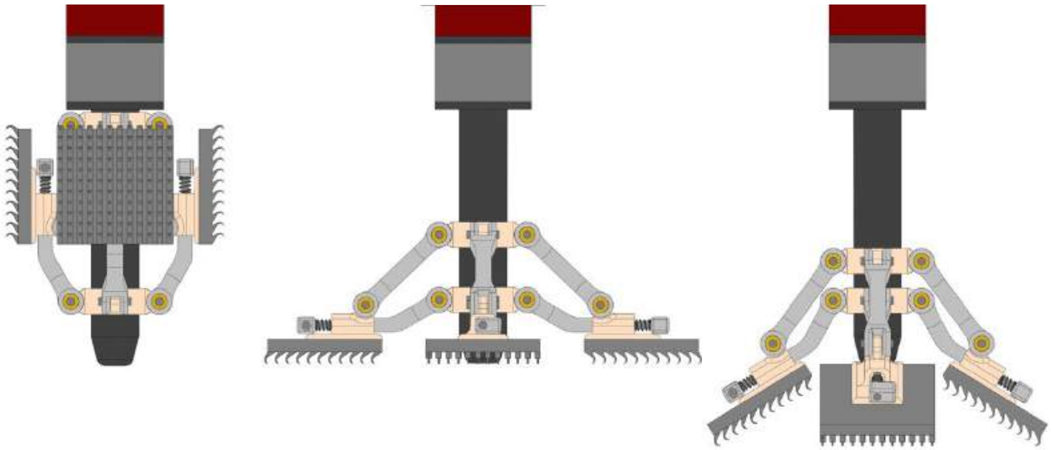
Opposed spine contact patch

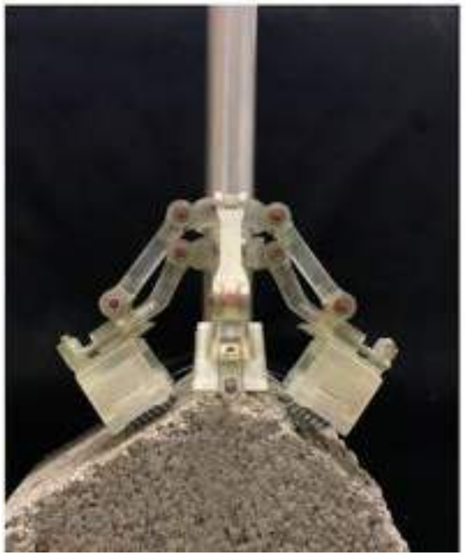






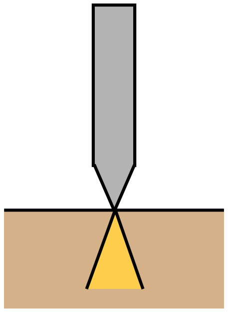
SupraPed with enhanced contact



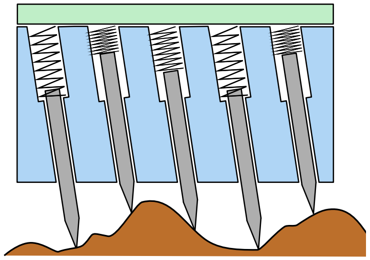


Scaling up spine contact patch

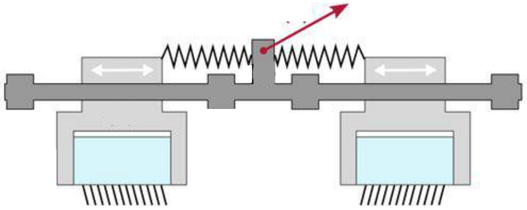
Pole

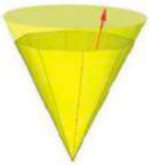


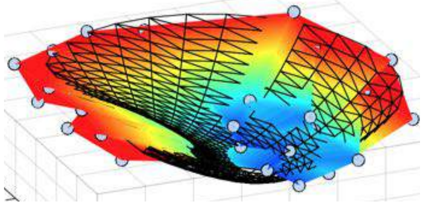
Spine Tile

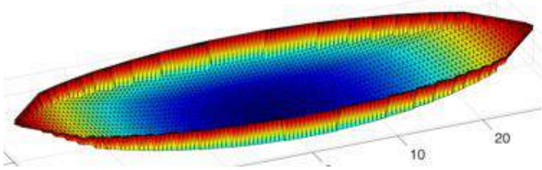


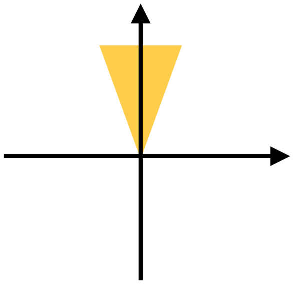
Opposed Spine Tiles

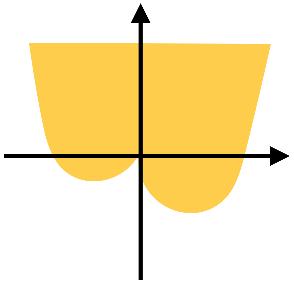




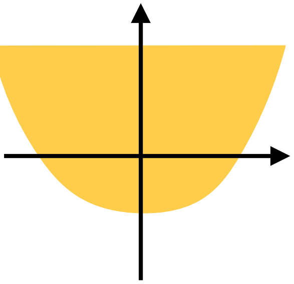








<100N



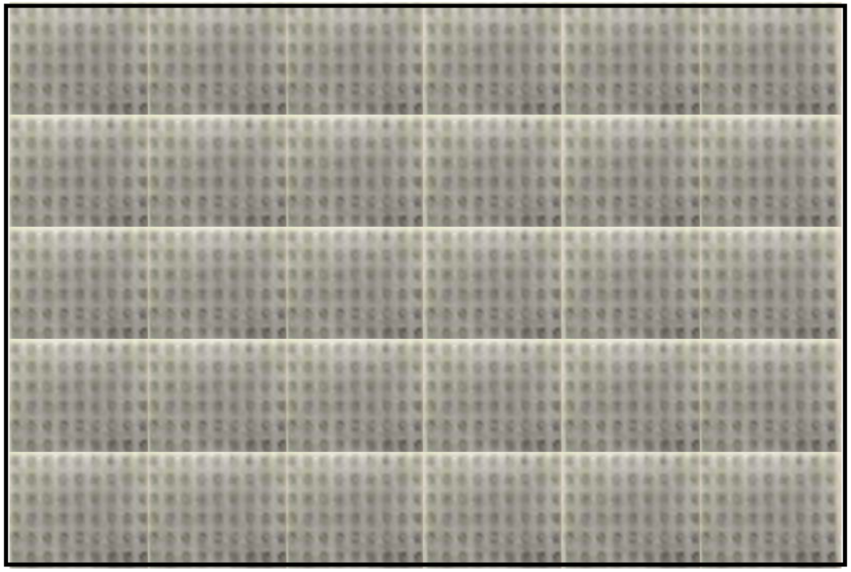
Point Contact

Spine Contact Patch

Opposed Spine Contact Patch

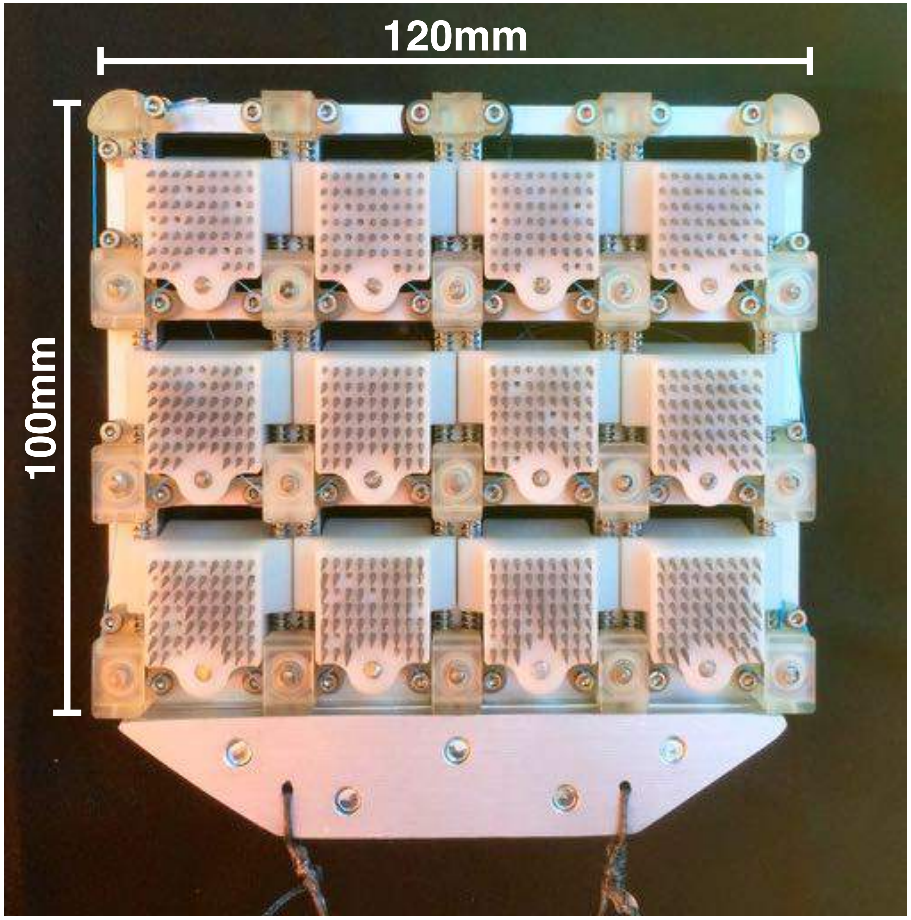
Scaling up spine contact patch: SpinyPalm

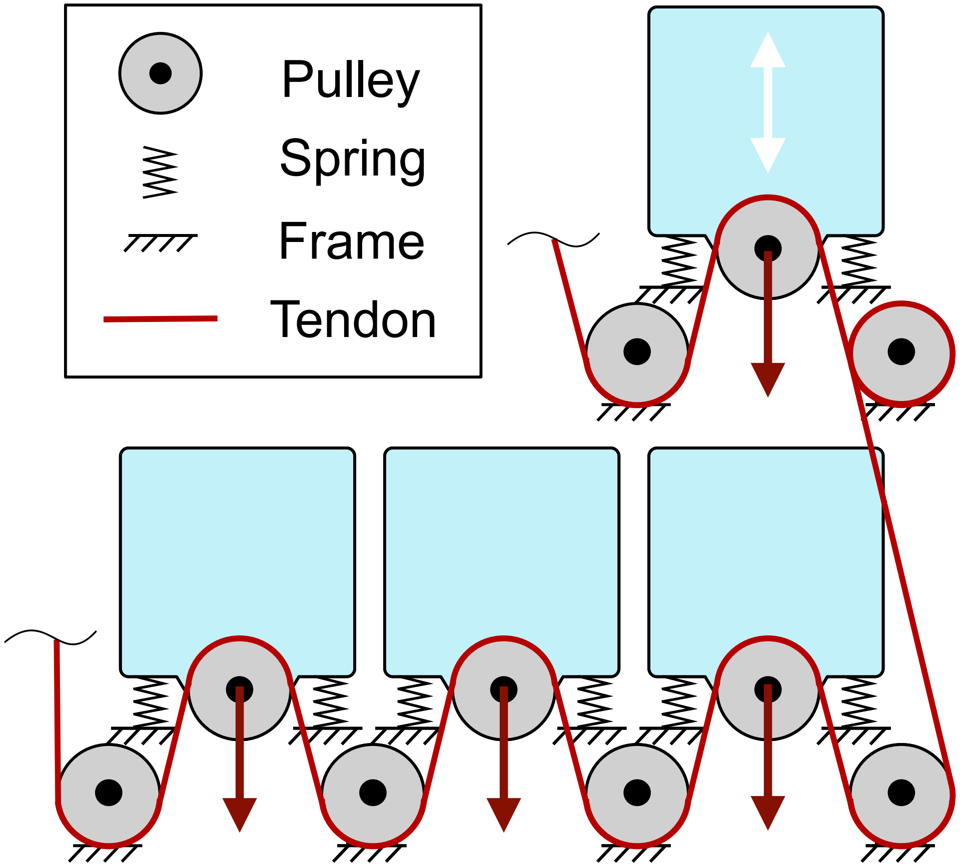
- Giant spine tile
  - Scaling up plateau due to backlash
  - Limited by local poor contact



Scaling up spine contact patch: SpinyPalm

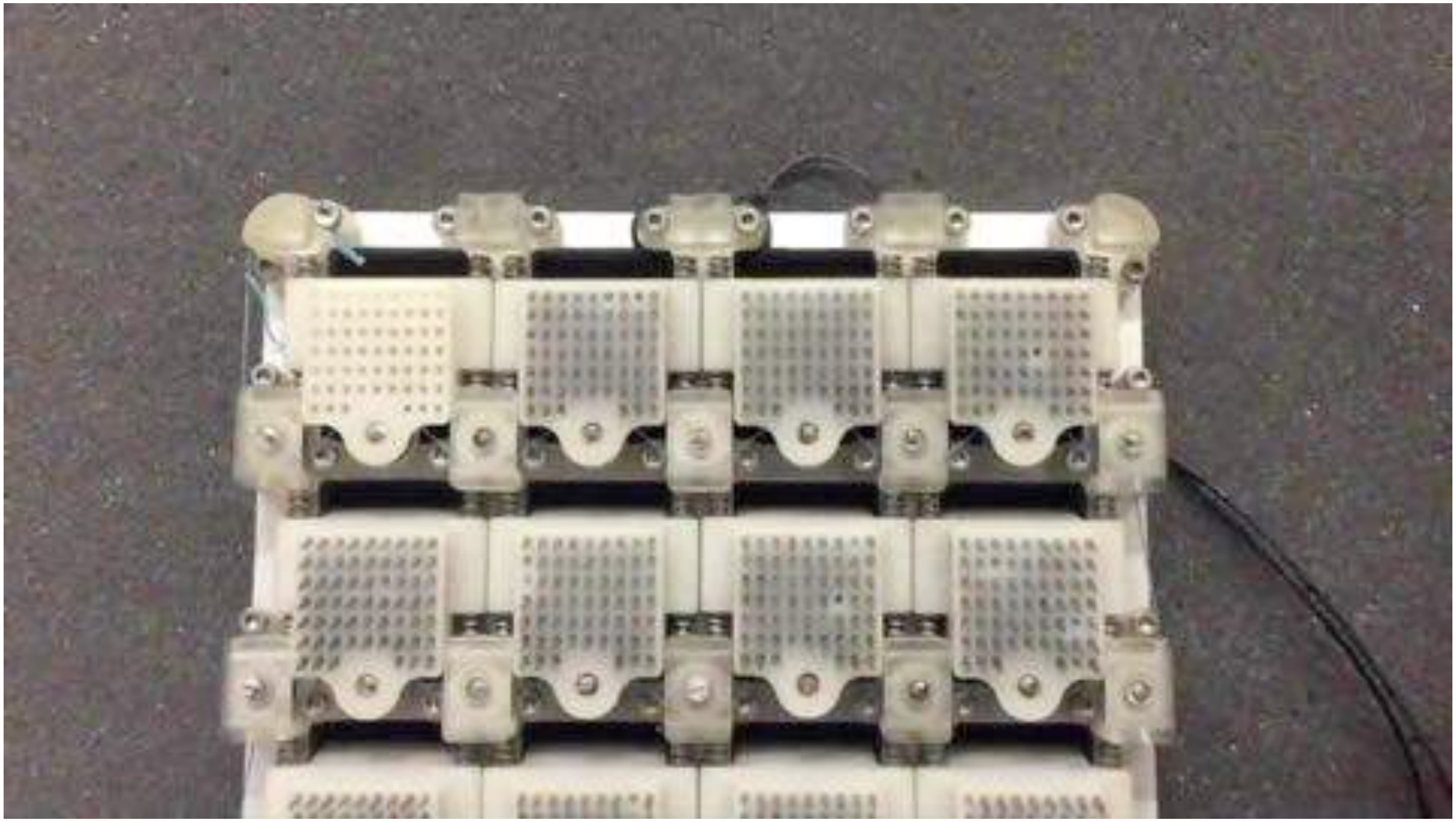
- Pulley system: 1) load sharing; 2) free travel; 3) outliner





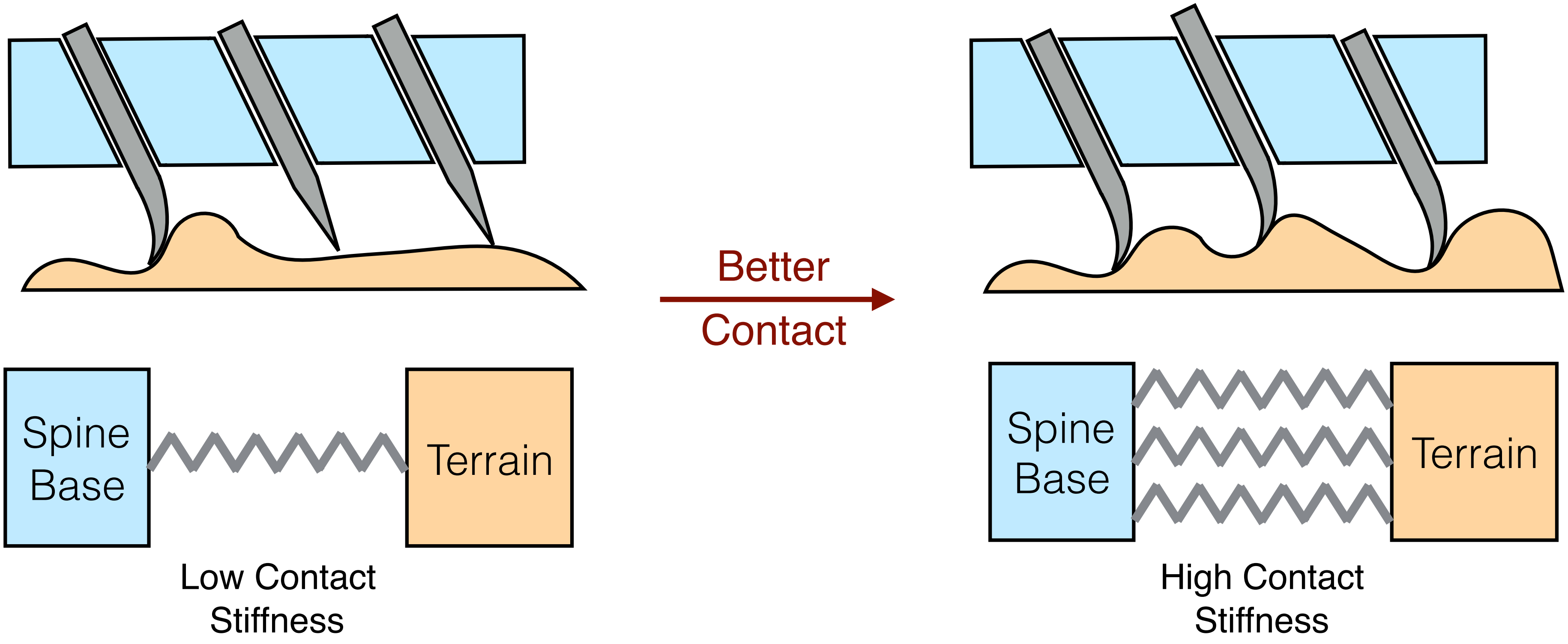
Scaling up spine contact patch: SpinyPalm

- Pulley system: 1) load sharing; 2) free travel



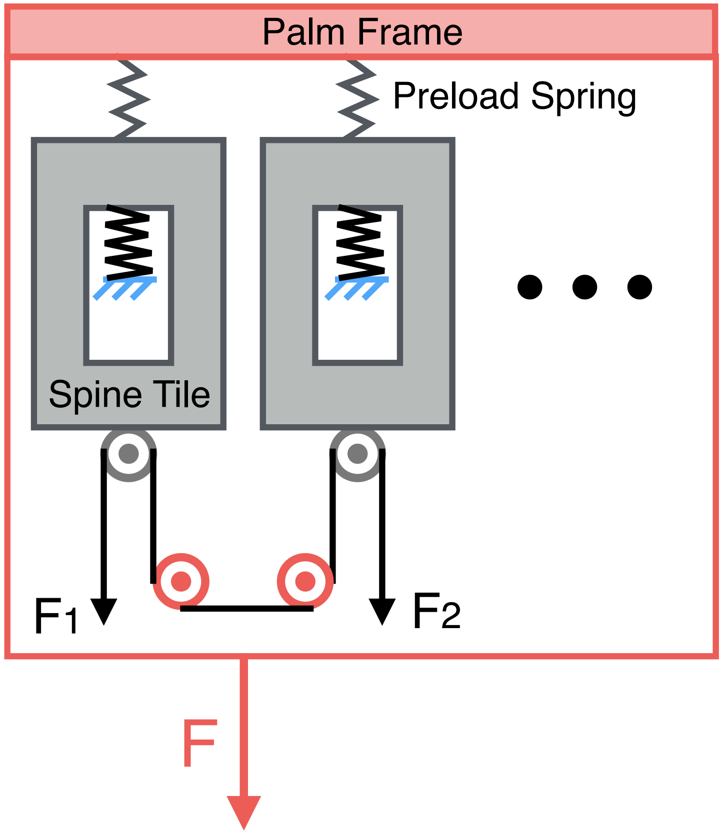
Spine contact patch load sharing

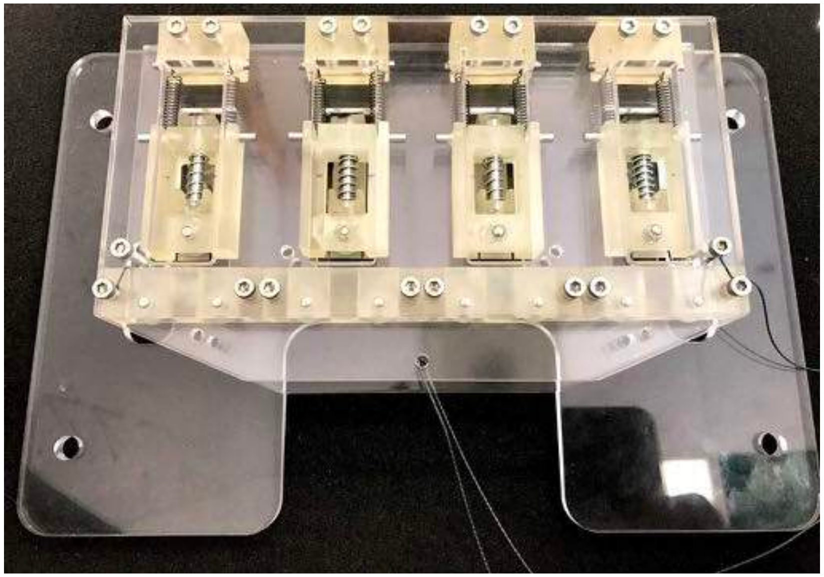
- Better load sharing
  - Allow better contact patch to take more load
- Spine tile contact stiffness
  - Reflects the contact quality



Spine contact patch load sharing model

- Friction prevents identical load sharing
- Contact stiffness distributes more load on better tile
- Moderate friction improves palm performance

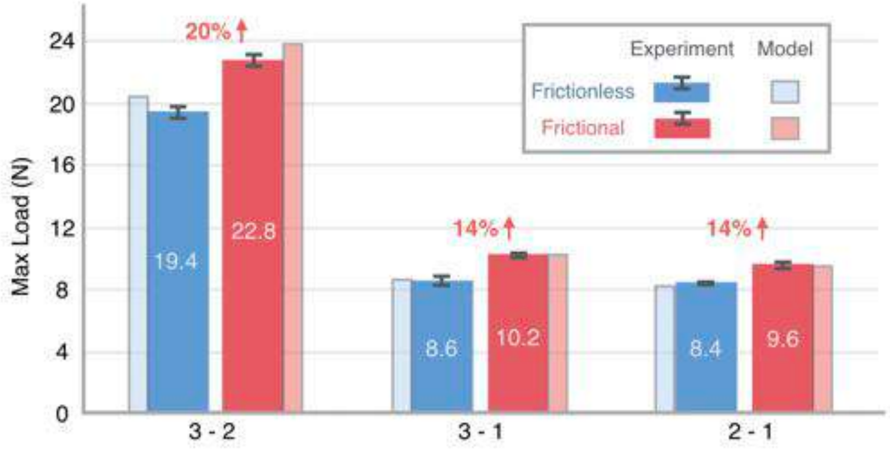




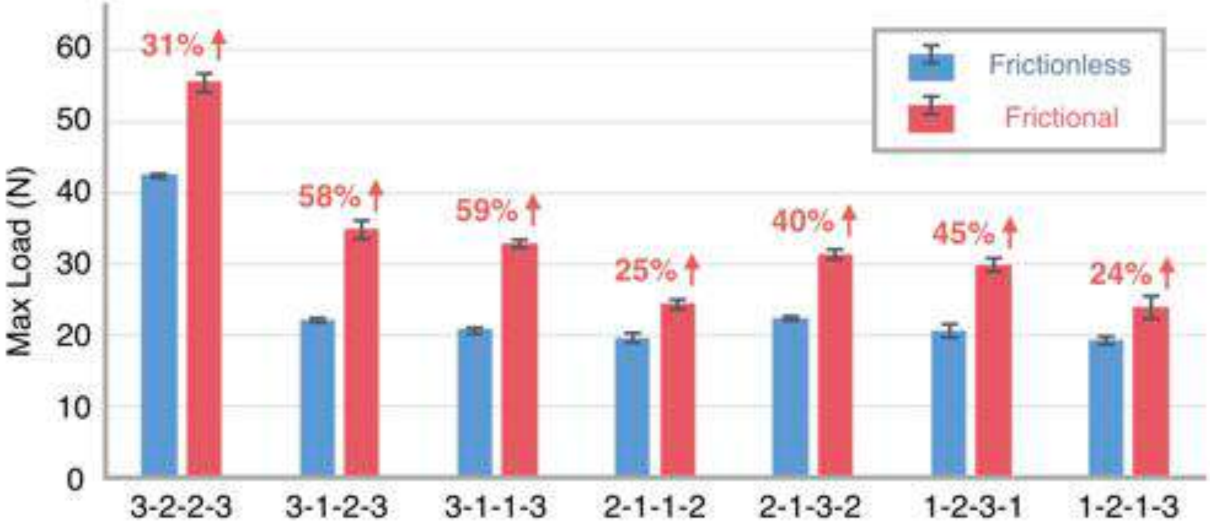
Equivalent palm system for experiments

Improve SpinyPalm with friction

- Overall adhesion is improved by 20~60 %
- Bearing support pulley is replaced with fixed rod
  - Less complexity
  - Higher spine tile density

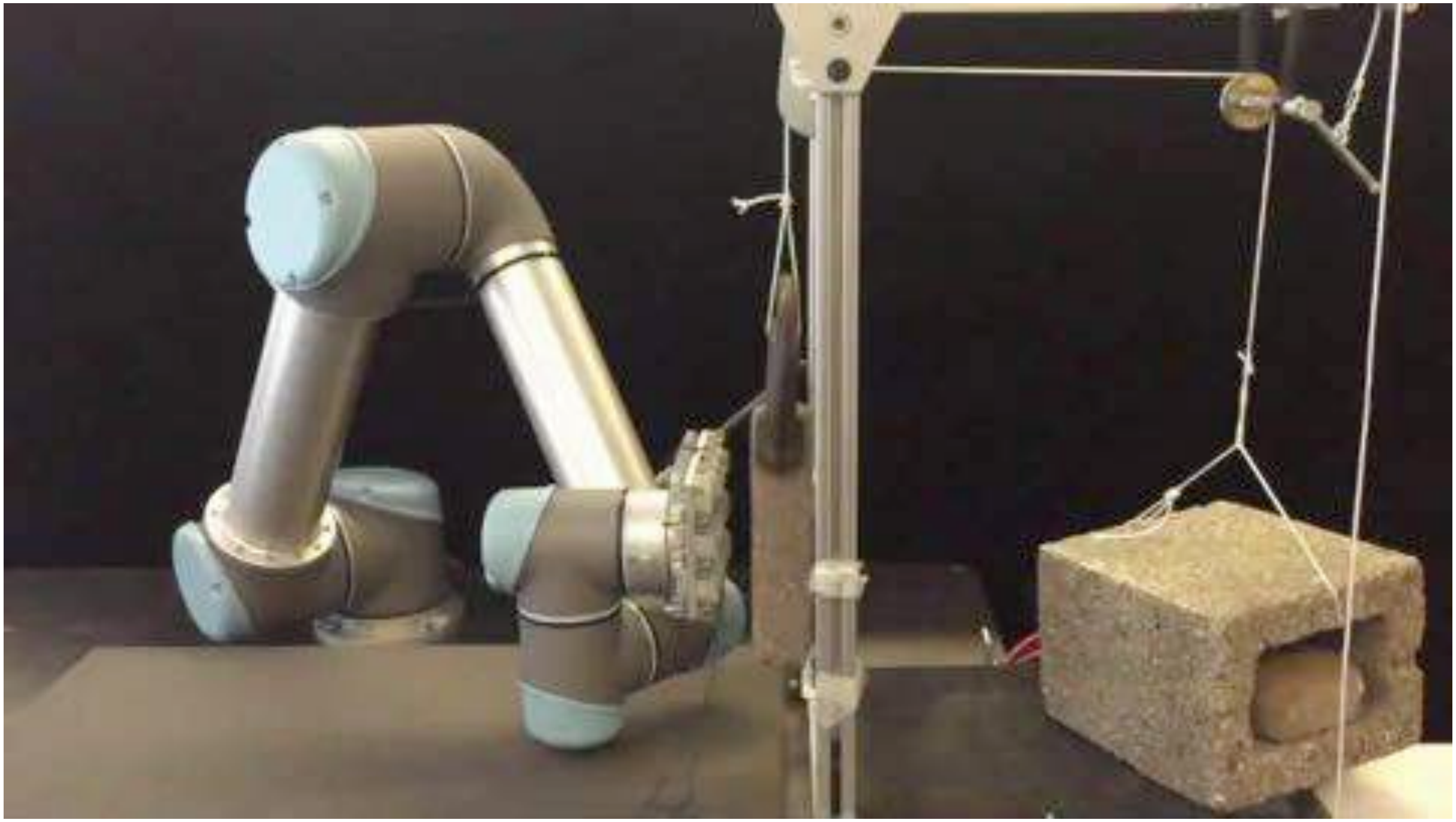


2-tile model & experiments



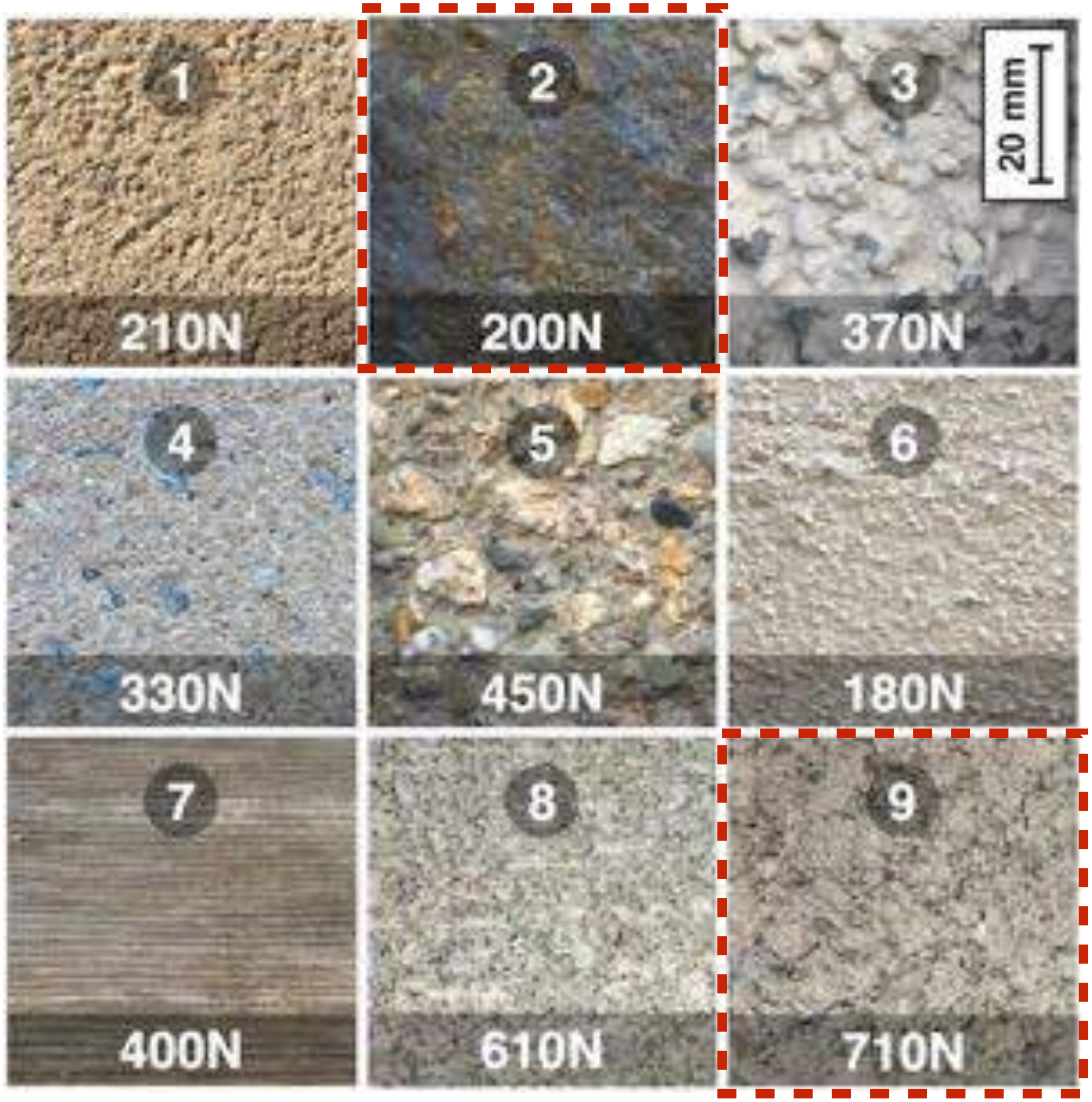
4-tile model empirical verification

SpinyPalm test with robot (5kg in shear)



SpinyPalm test with human (55kg in shear)

SpinyPalm test on different surfaces



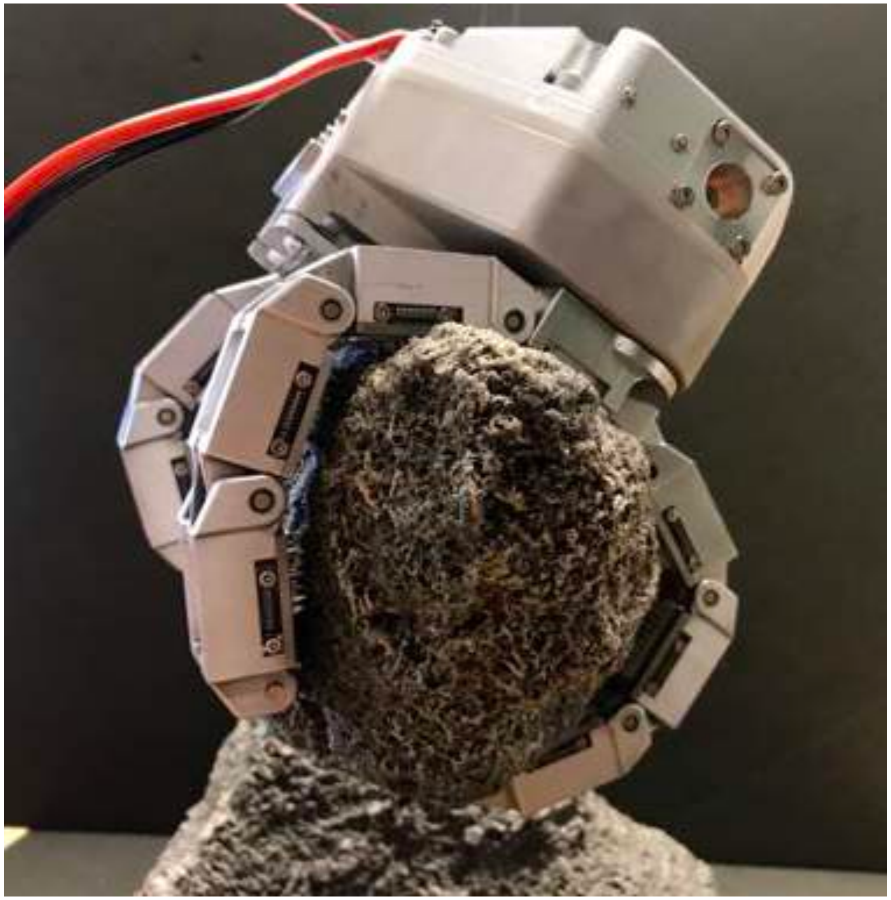
Surface types are:

1) paving stone;
2) natural rock;
3) coarse stucco;
4) sand stone;
5) pebble wall;
6) fine stucco;
7) bark texture wood;
8) fine concrete;
9) coarse concrete.

SpinyPalm limitation

- Poor performance on large surface variation

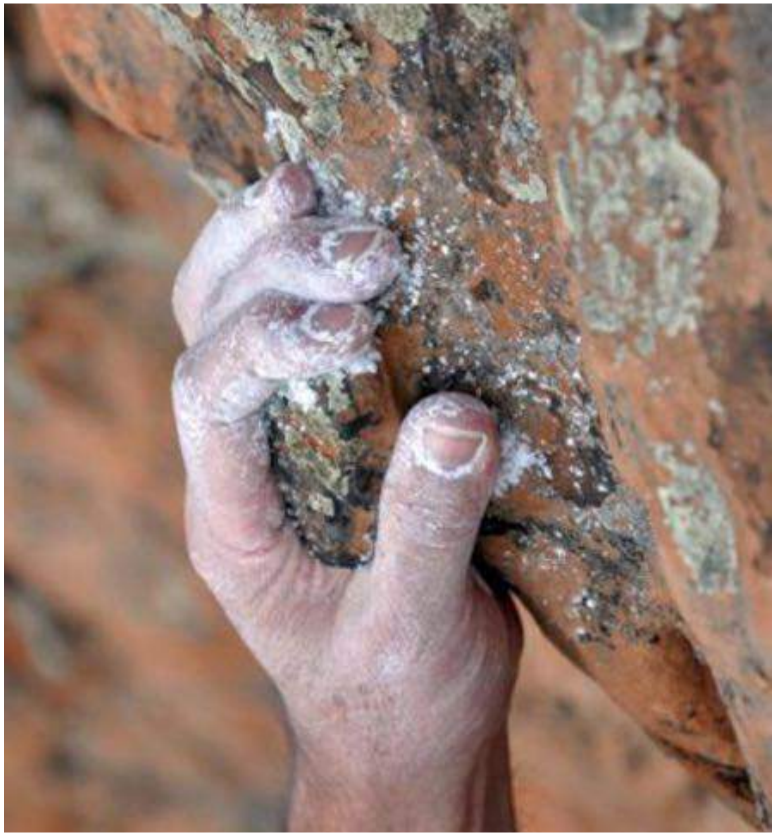
SpinyHand: Hierarchical Contact Patches



Rock Climbing

- Surface grasping

Rock climbing griping technique

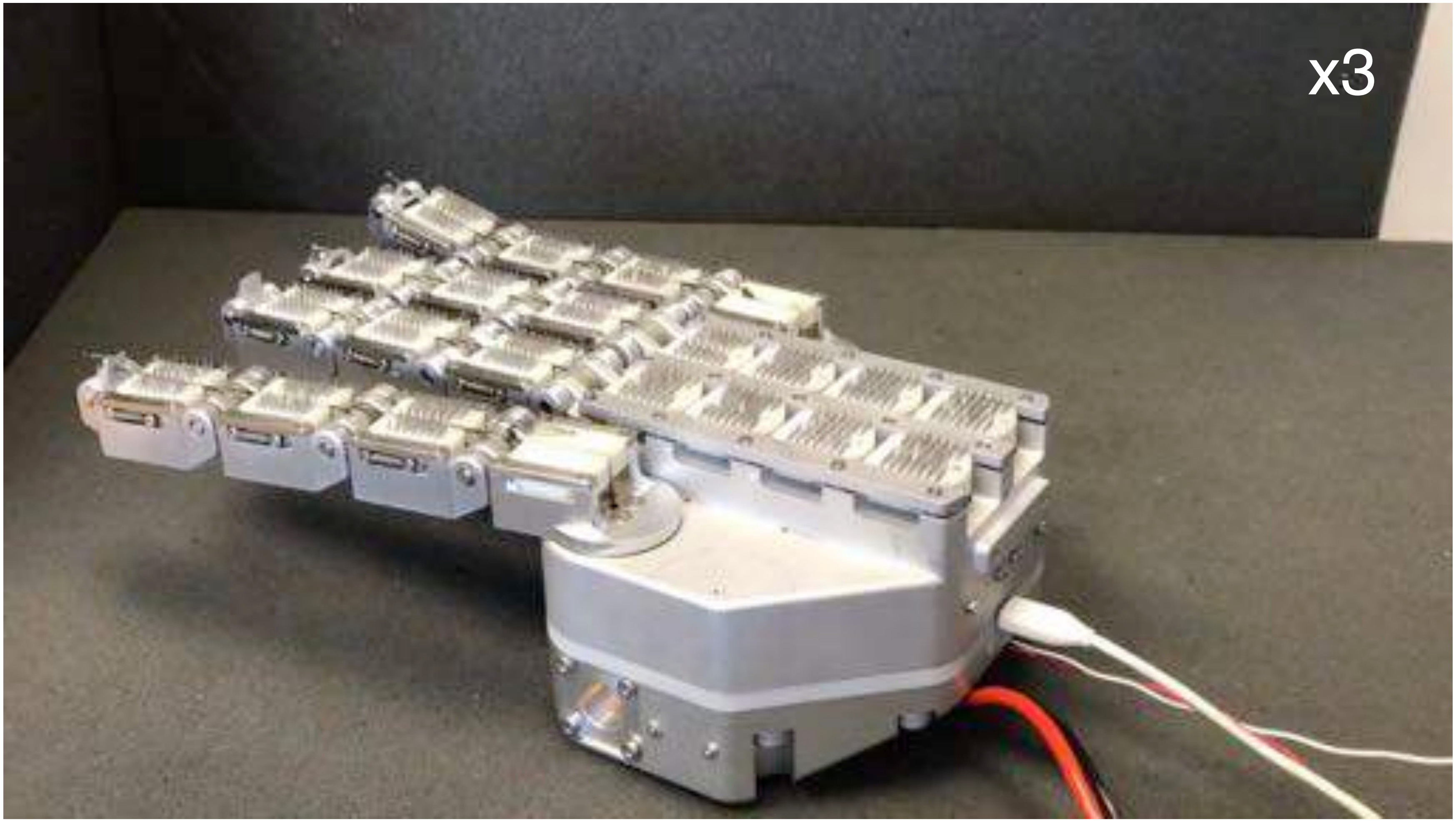


Pinch

Crimp

Sloper

SpinyHand design



SpinyHand grasping types

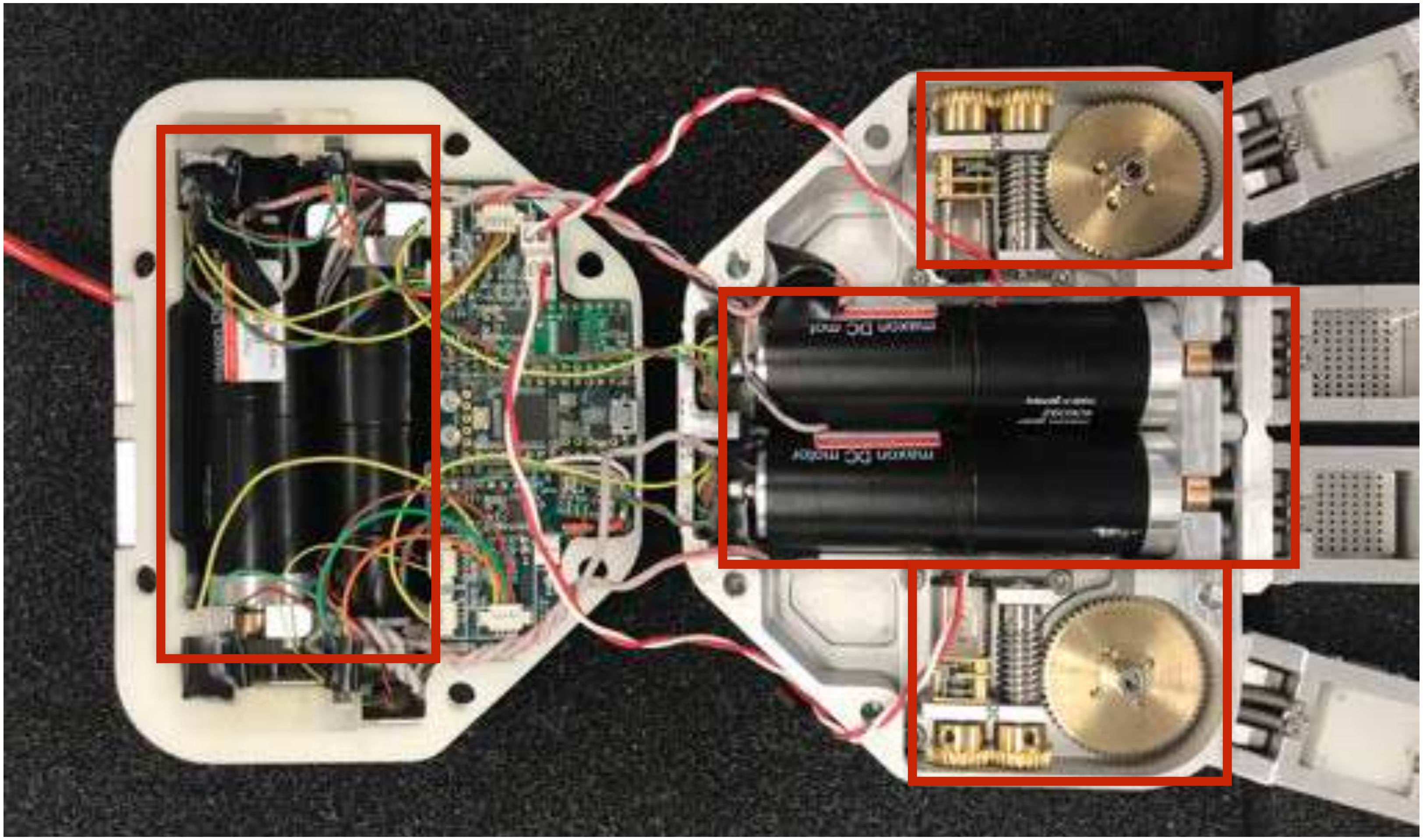
Pinch

Crimp

Sloper

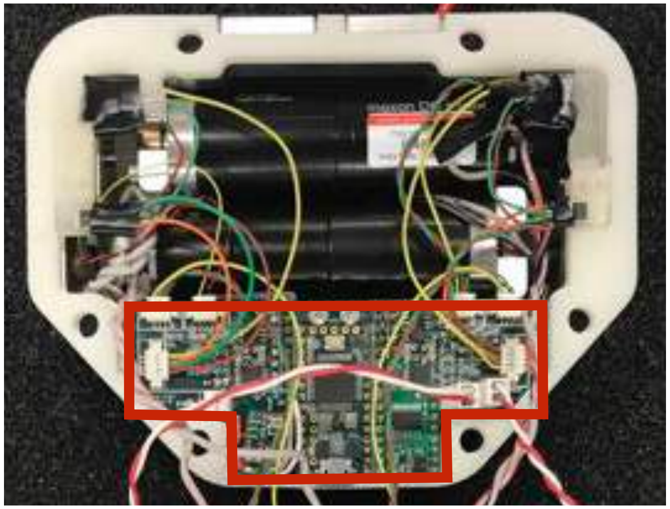
SpinyHand implementation

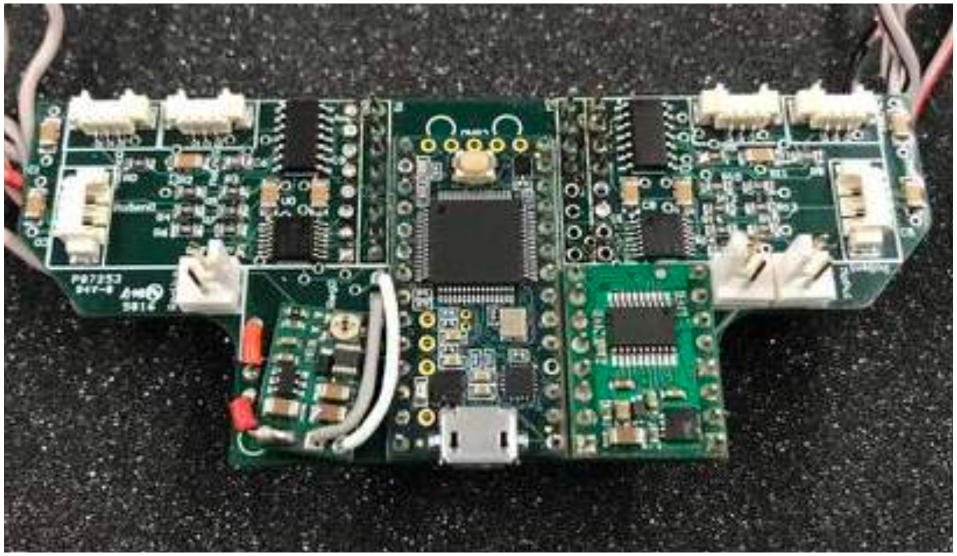
- (Motor + double support pulley) x 4
- (Motor + worm drive) x 2

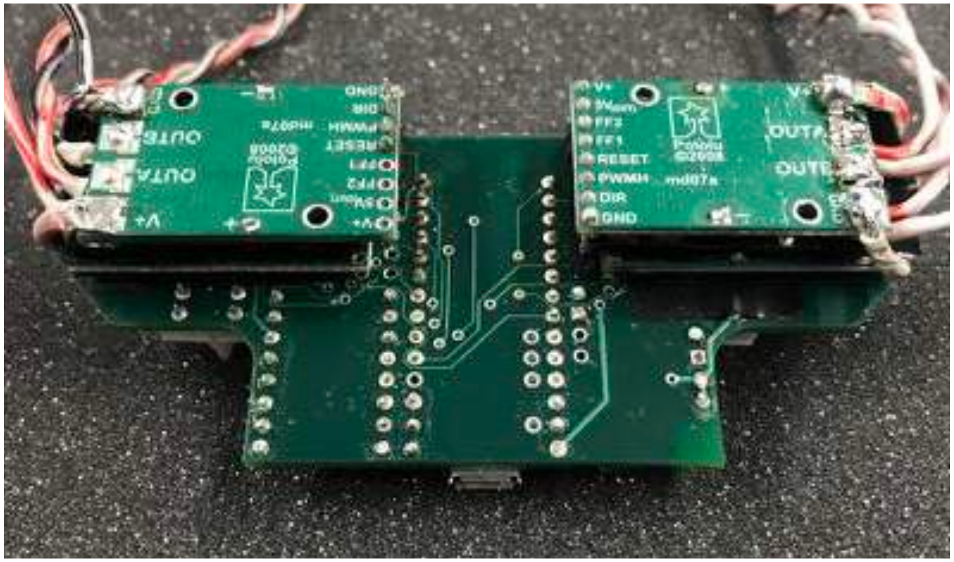


SpinyHand implementation

- 4-layer PCB
  - Motor drivers
  - Signal conditioning
- Sensors
  - Tendon position sensor x 4
  - Rotary finger position / moment x 4







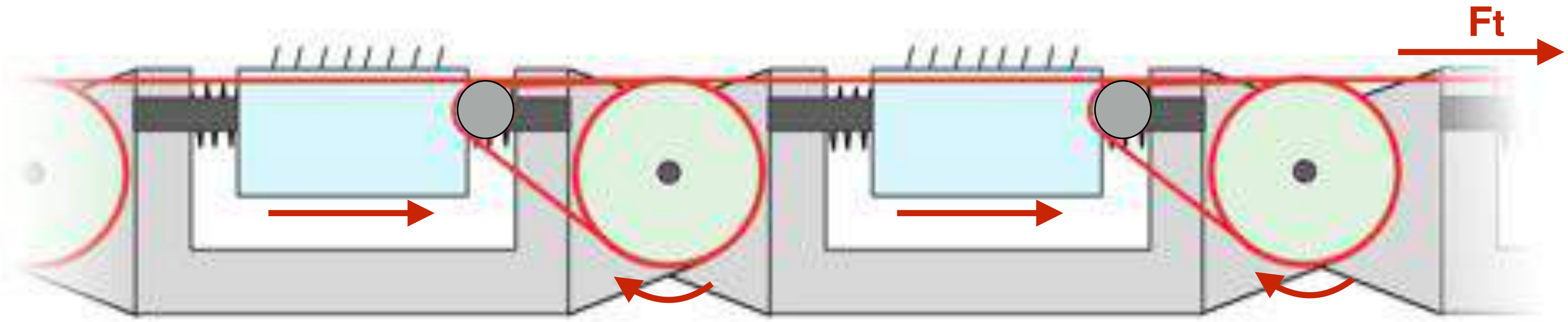
How to apply grasping force?

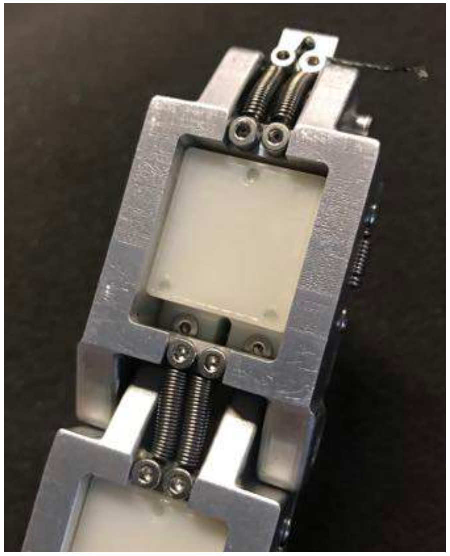
https://lockerdome.com/stackmedia/6881873678971668

How to apply grasping force?

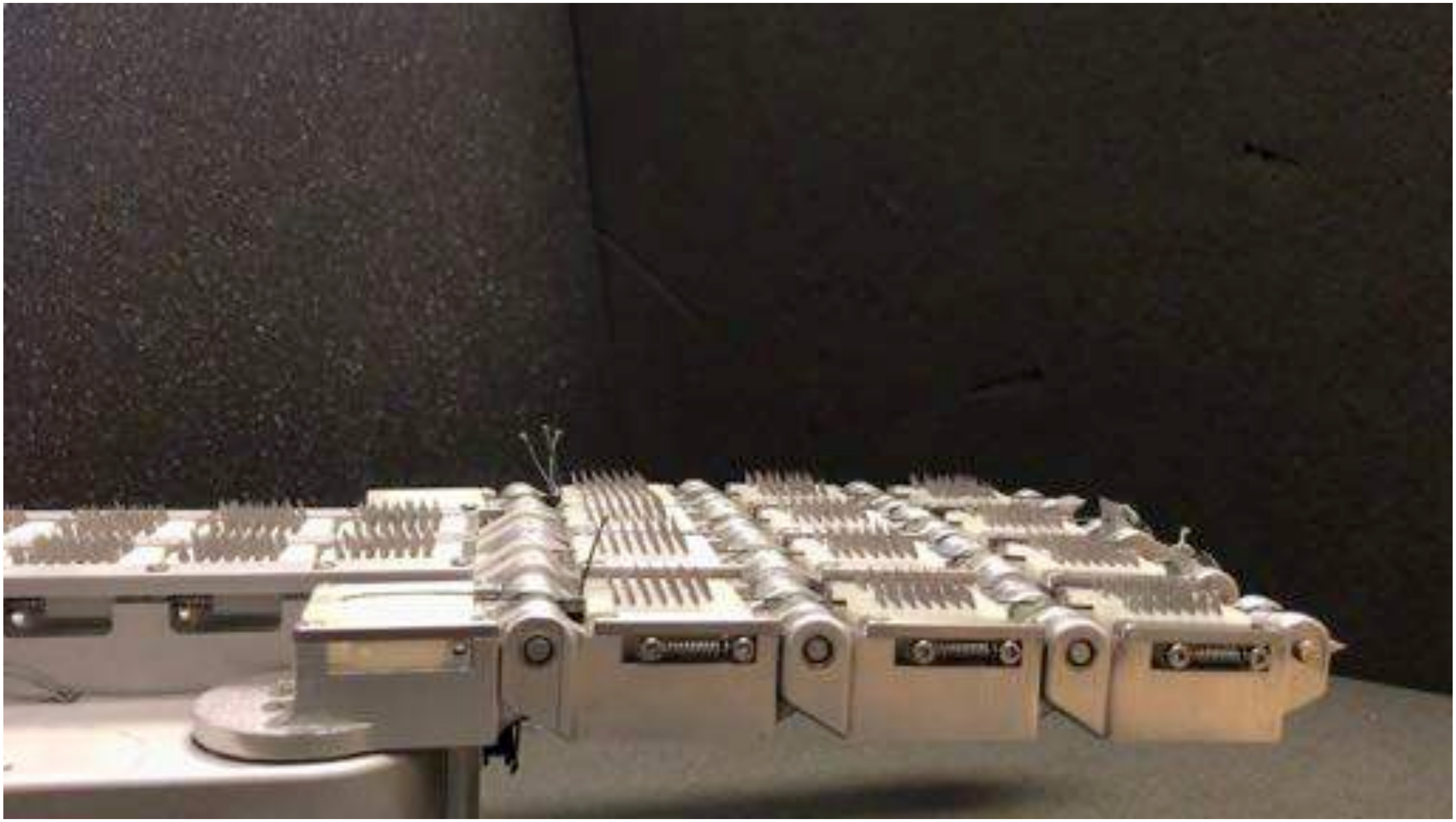
Finger design: prismatic phalanx

- Shear contact force
- Strong phalanx spring: travel after contact is formed



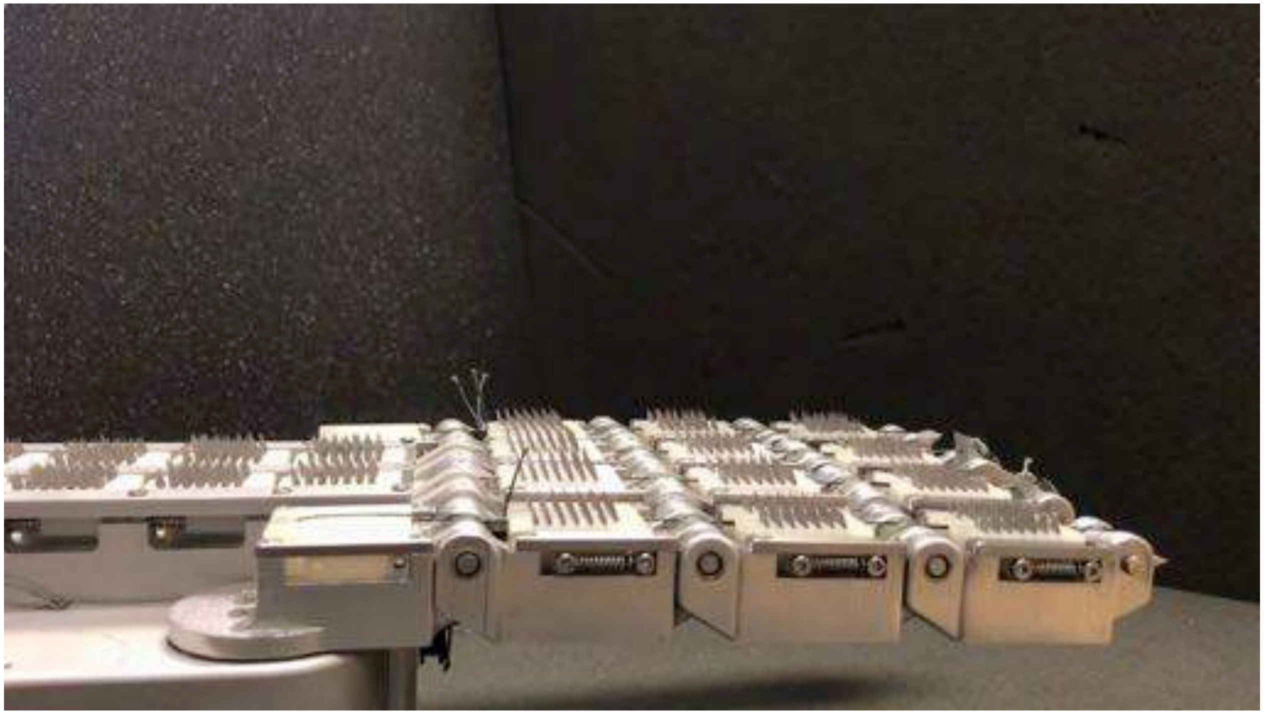


Finger design: prismatic phalanx



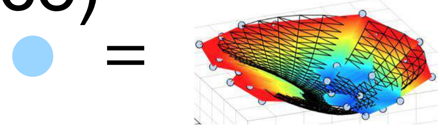
Finger design: fingernail

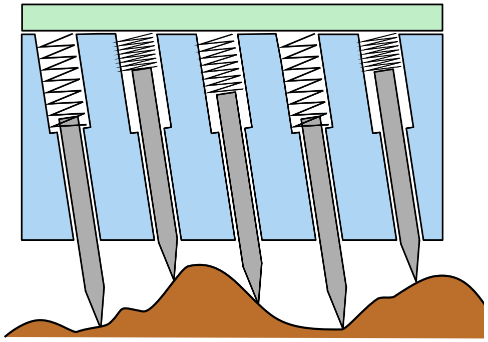
- 600N force on fingernail
- Motion sequence:
  - fingernail -> hard stop -> the rest of finger joints

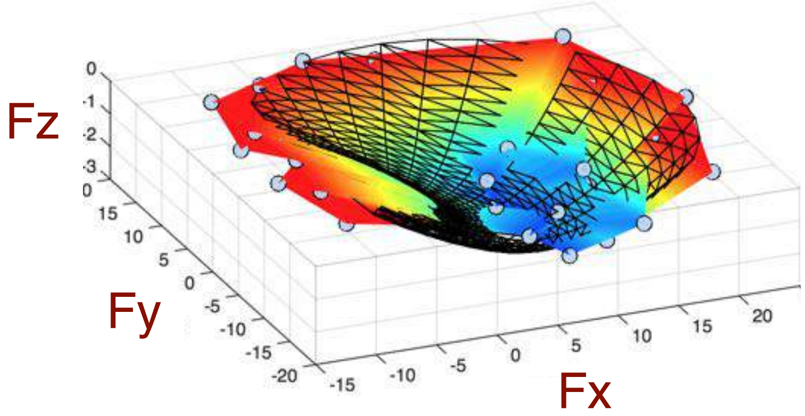


Grasp performance

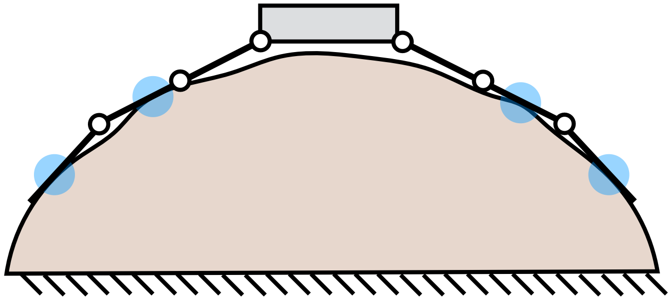
- 3D force -> 6D force and torque (wrench space)

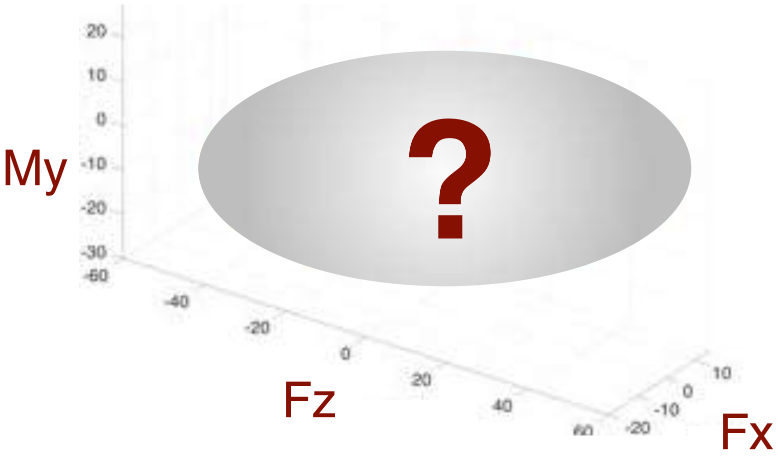






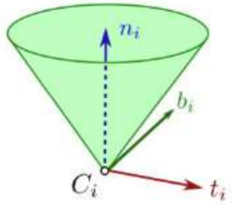
$$f_{ext} \in \mathbb{R}^3$$



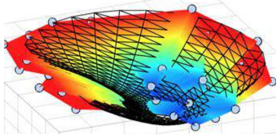


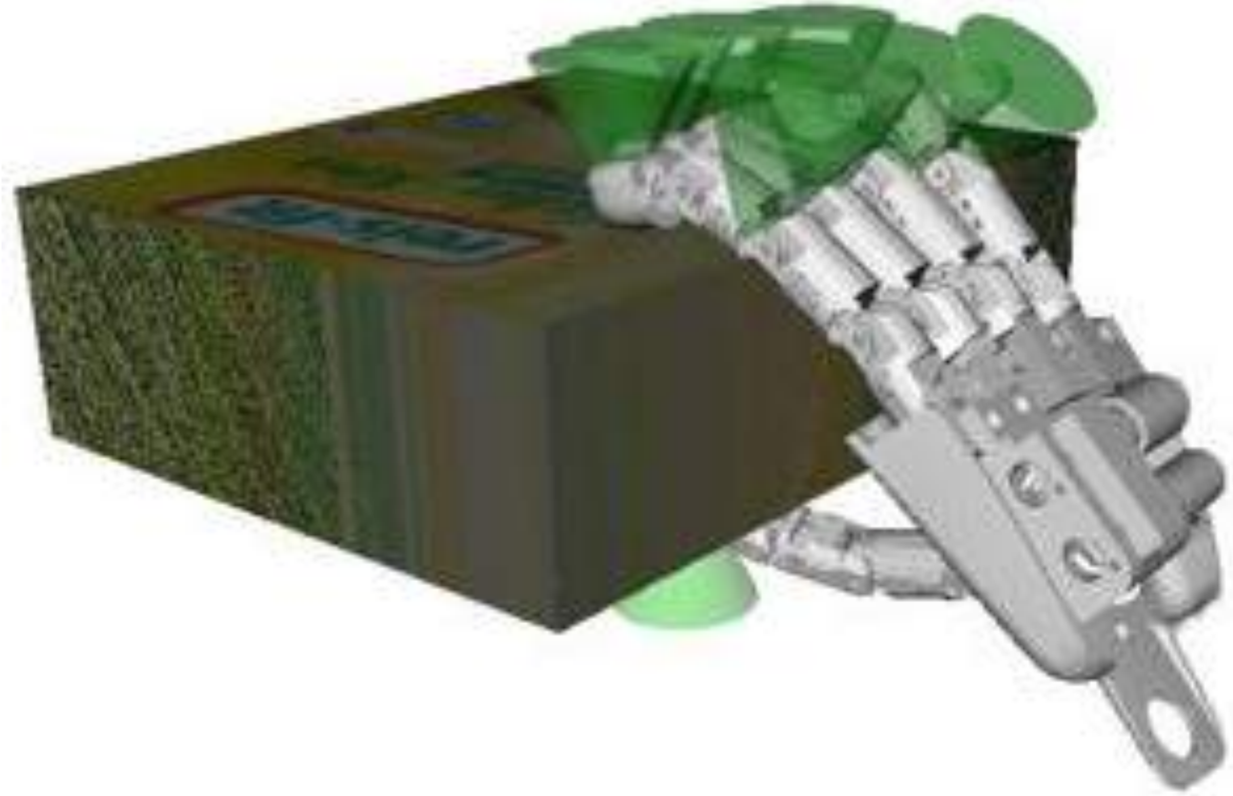
$$w_{ext} \equiv (f_{ext}, t_{ext}) \in \mathbb{R}^6$$

Grasp modeling challenge



- Optimization problem given contact constraints
  - Convex admissible volume (Coulomb friction cone)
- Non-convex spine contact

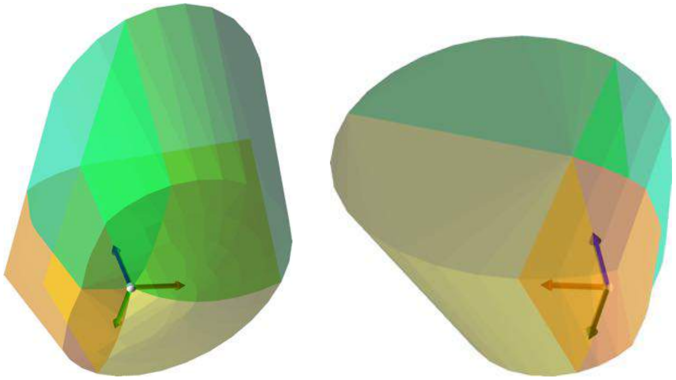


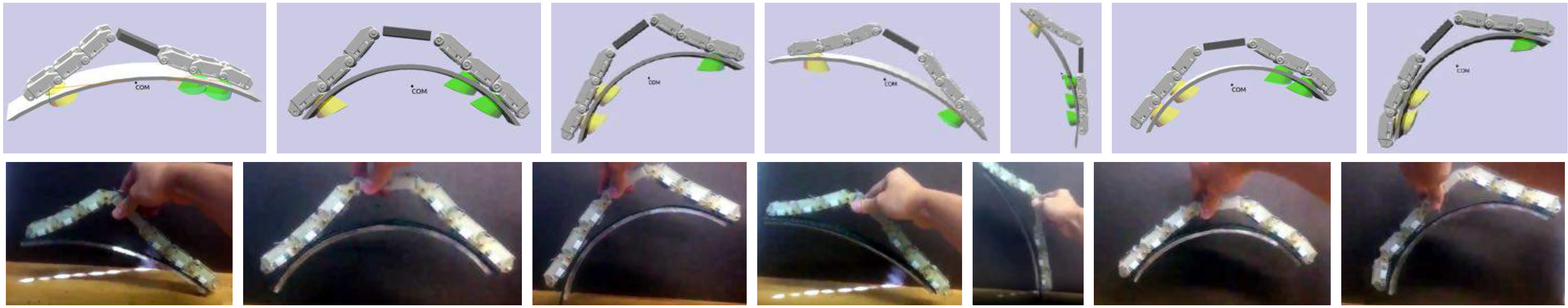


https://sourceforge.net/p/simox/wiki/GraspStudio/

Grasp model with non-convex adhesion

- Hierarchical convex decomposition
- Branch-and-bound (BnB) with heuristic
- Mixed-integer linear programming (MILP)
- Performance (2 x 3-phalanx finger)
  - 5 ~10 x efficiency
  - Equilibrium test: avg. 185 ms
  - Wrench limit: avg. 12 s

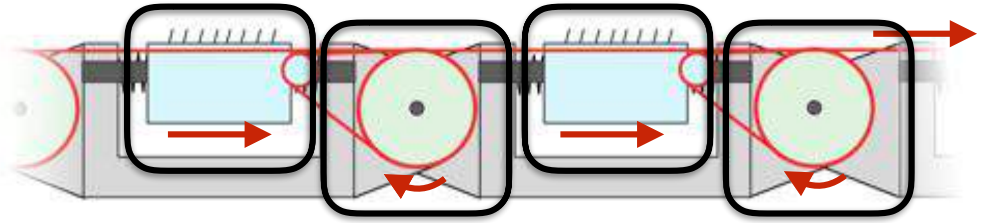


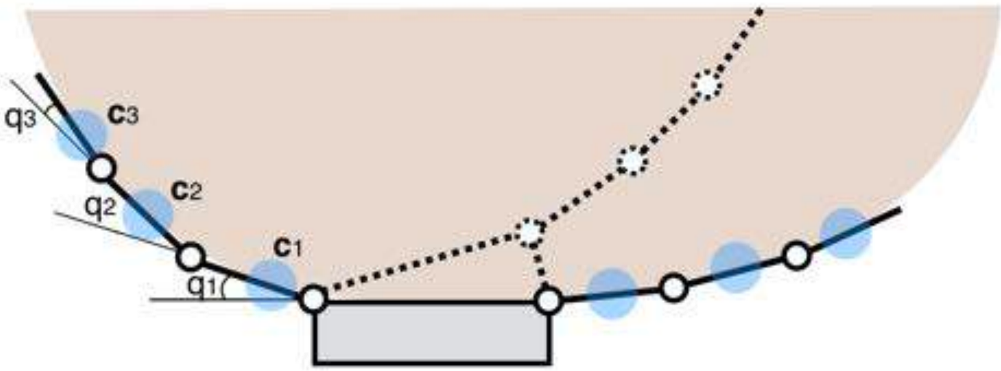


Stability test under different configuration

SpinyHand grasp model: contact forces

- Finger states: 1) joint angles; 2) contact positions
- Finger contact force





Joint Torque Balance

$$\boxed{J(\boldsymbol{q},\boldsymbol{c})^T\boldsymbol{f}_c} + \boxed{f_t\boldsymbol{r}} - \boxed{K_r\boldsymbol{q}-\boldsymbol{p}_r} = \boldsymbol{0}$$

Contact Tendon Joint Spring

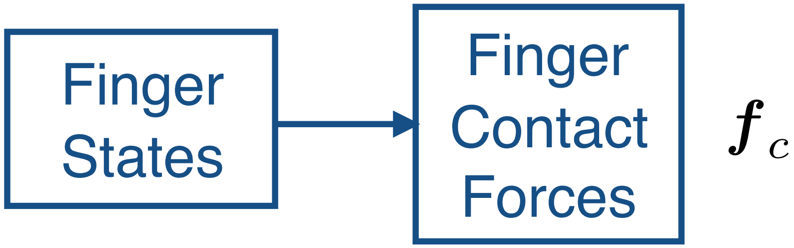
Phalanx Force Balance

$$\boxed{P_x\boldsymbol{f}_c} + \boxed{\boldsymbol{f}_p(\boldsymbol{c}, f_t)} - \boxed{K_p\boldsymbol{d}-\boldsymbol{p}_p} = \boldsymbol{0}$$

Contact Tendon Phalanx Spring

SpinyHand grasp model: contact forces

- Closed form solution
- Inverting square matrix A
- Modifying b to consider frictions



Finger States

Finger Contact Forces

$\boldsymbol{f}_c$

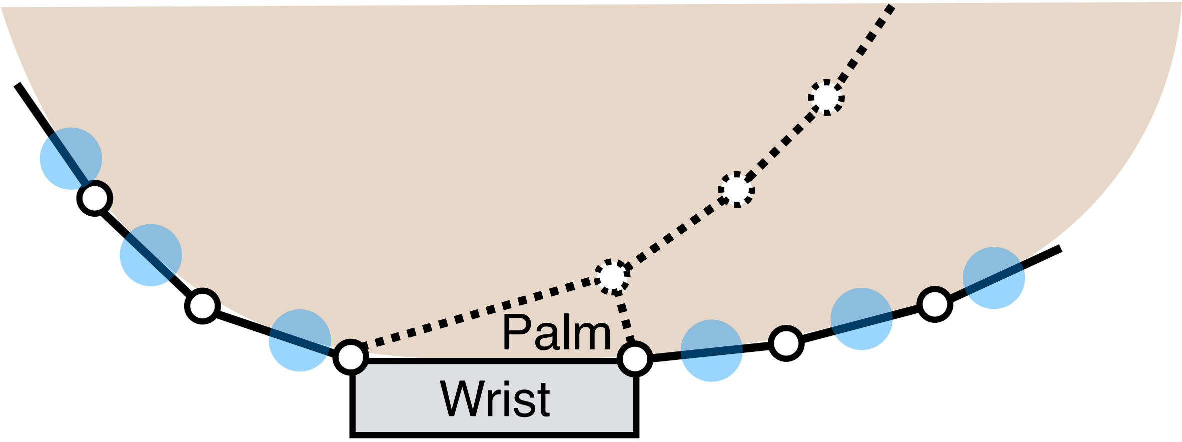
$$\boxed{A\boldsymbol{f}_c = \boldsymbol{b}}$$

where

$$A = \begin{bmatrix} J^T \\ P_x \end{bmatrix} \quad and \quad \boldsymbol{b} = \begin{bmatrix} K_r\boldsymbol{q} + \boldsymbol{p}_r - f_t\boldsymbol{r} \\ K_p\boldsymbol{d} + \boldsymbol{p}_p - \boldsymbol{f}_p(\boldsymbol{c}, f_t) \end{bmatrix}$$

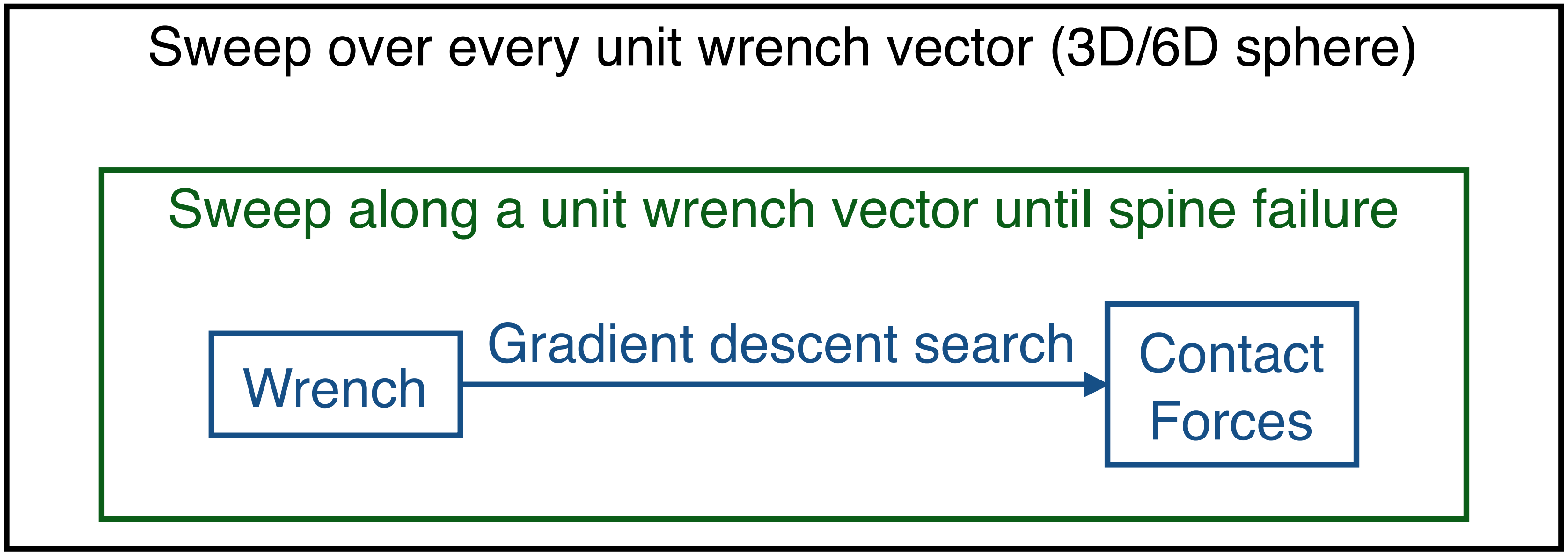
SpinyHand grasp model: wrench space

- Fixed-wrist failure
  - Finger tendon force control
  - Polyhedral spanned by n finger wrench vectors
- Floating-wrist failure
  - Wrist F/T control
  - Fixed finger tendon
  - Loading at the wrist



SpinyHand grasp model: wrench space

- Inefficiency: gradient descent search
- Instability (sensitive to step size): ill-conditioned A



Sweep over every unit wrench vector (3D/6D sphere)

Sweep along a unit wrench vector until spine failure

Wrench

Gradient descent search

Contact Forces

SpinyHand grasp model: wrench space

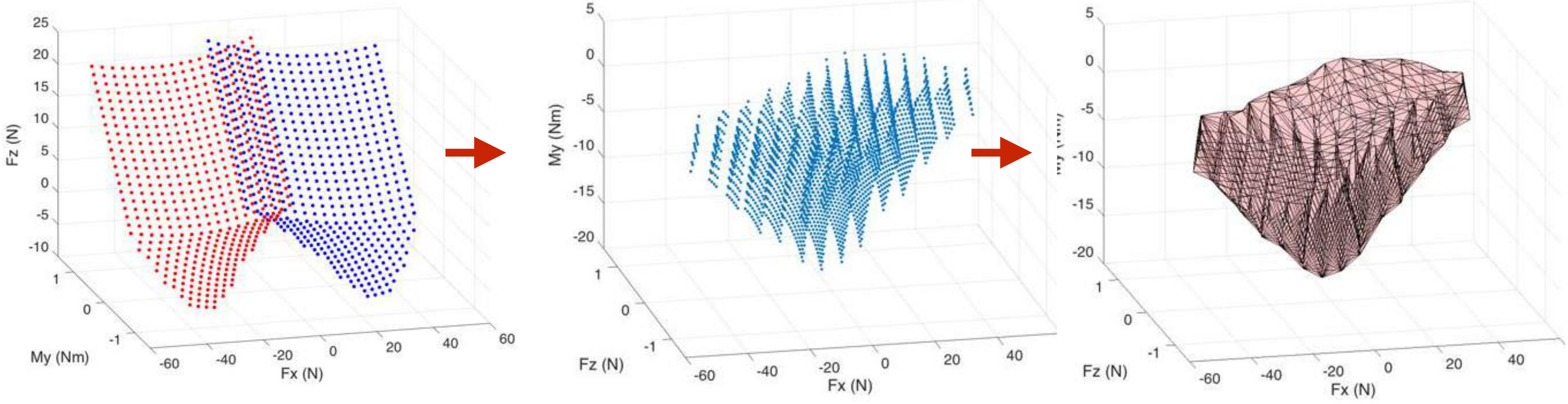
1) Finger wrench spaces (points cloud x n)

2) Finger position search space (6n) -> wrist position search space (6), search for valid sets

3) Compute grasp wrench space point cloud based on valid sets

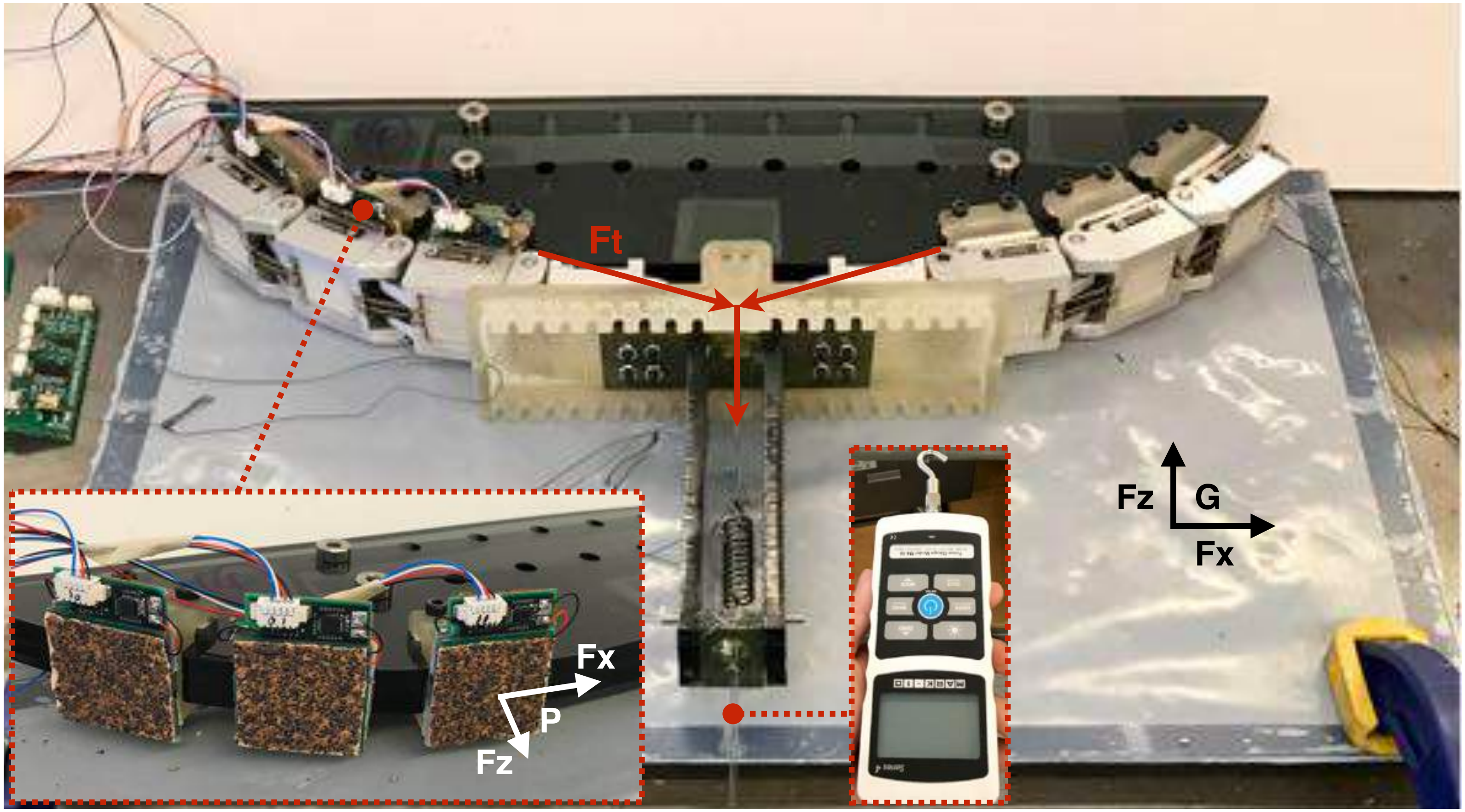
4) Find the boundary

2-3 orders improvement: 12s / wrench limit (4200s / wrench space) -> 6s / wrench space



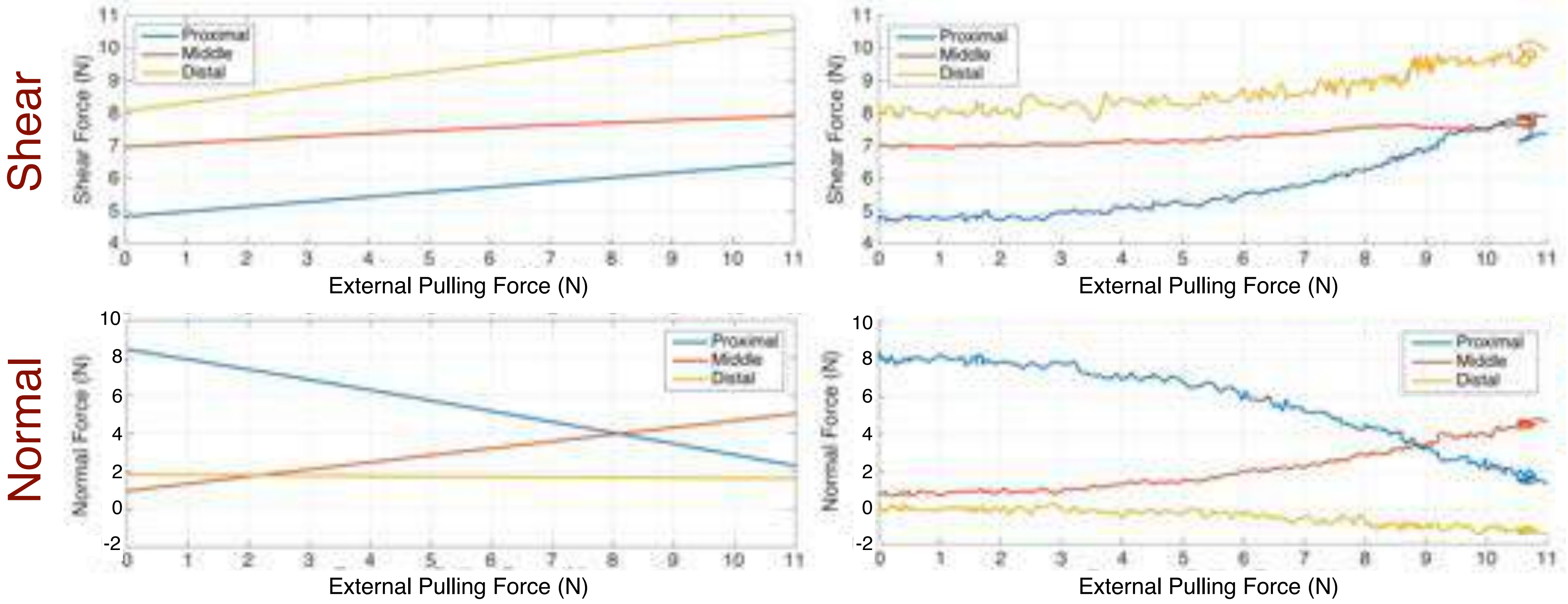
Experimental validation: setup

- Adjustable spring for finger tendon actuation
- Contact force sensing: capacitive tactile sensor
- External loading force (sync)



Experiment results: loading process

- Similar trend
- Non-linearity

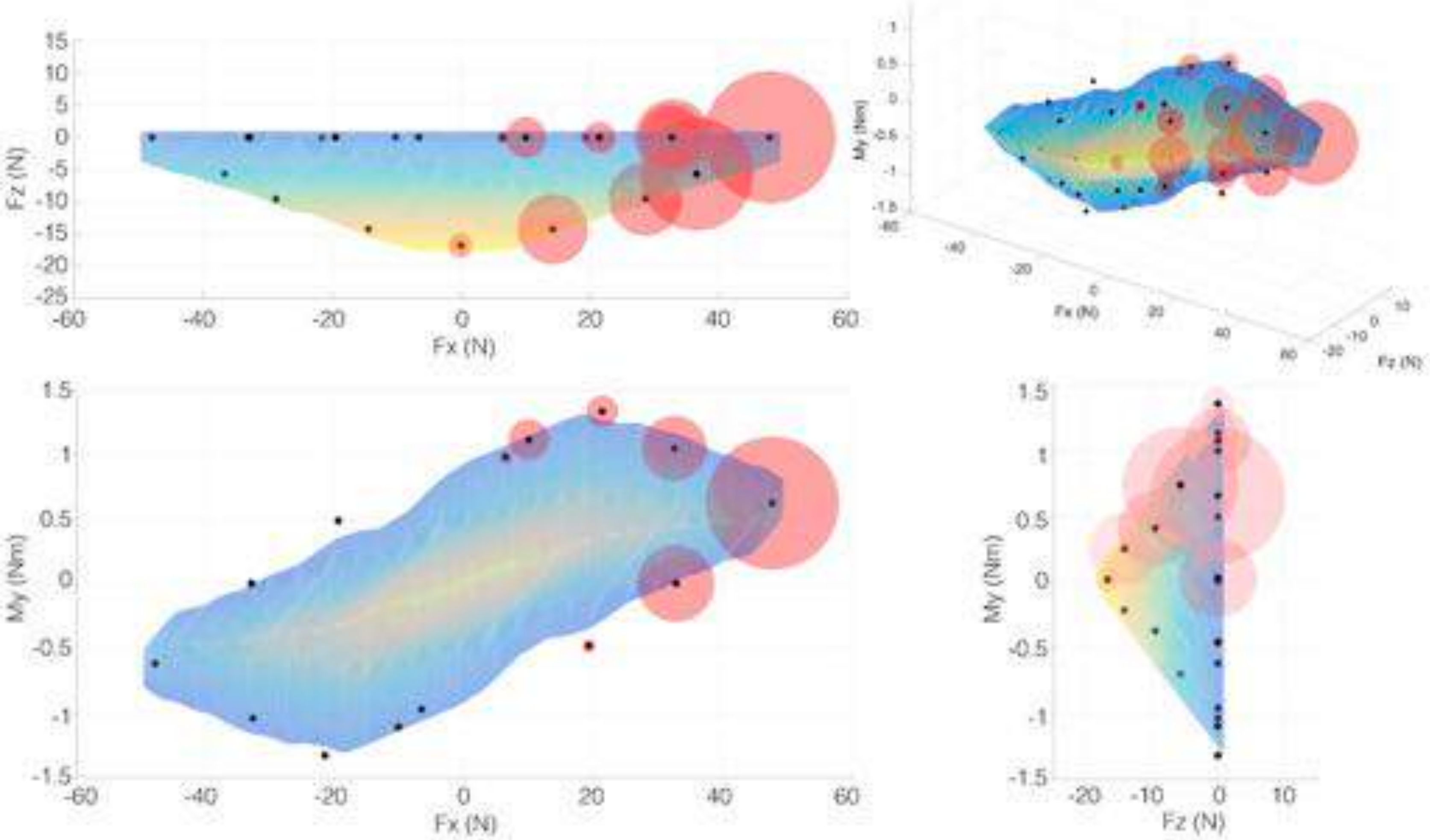


Model

Experiment

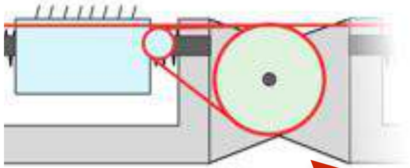
Experiment results: wrench space

- Mountain shape symmetric about Fz
- avg. 12% error (2 surfaces & 2 grasping forces)

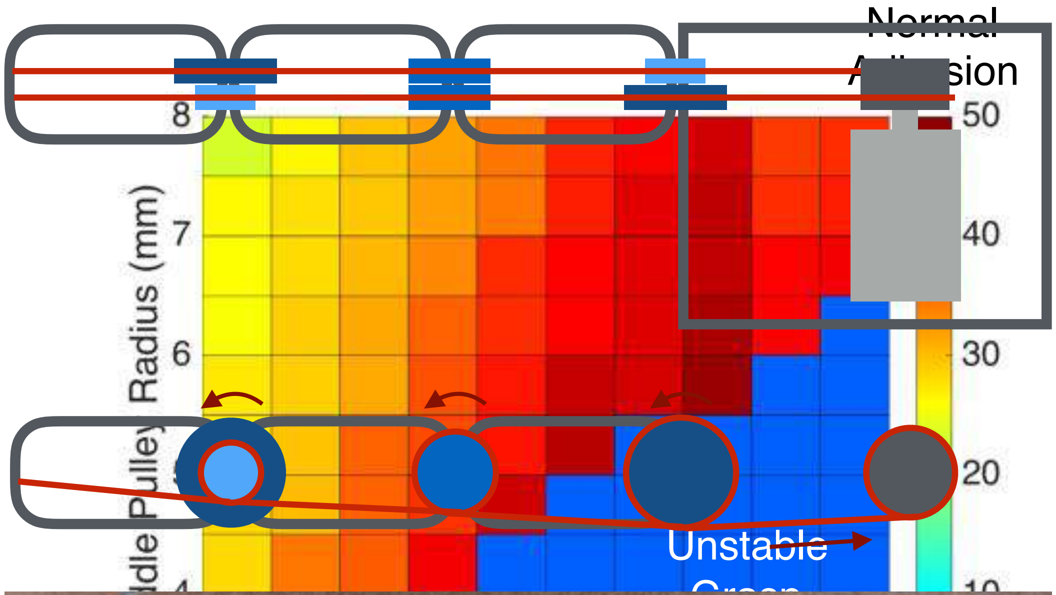


Model discussion

- Key design parameters: joint pulley radius
- Design guidelines
- Dual pulley chain
  - Pulleys with different radii
  - Select with motor direction

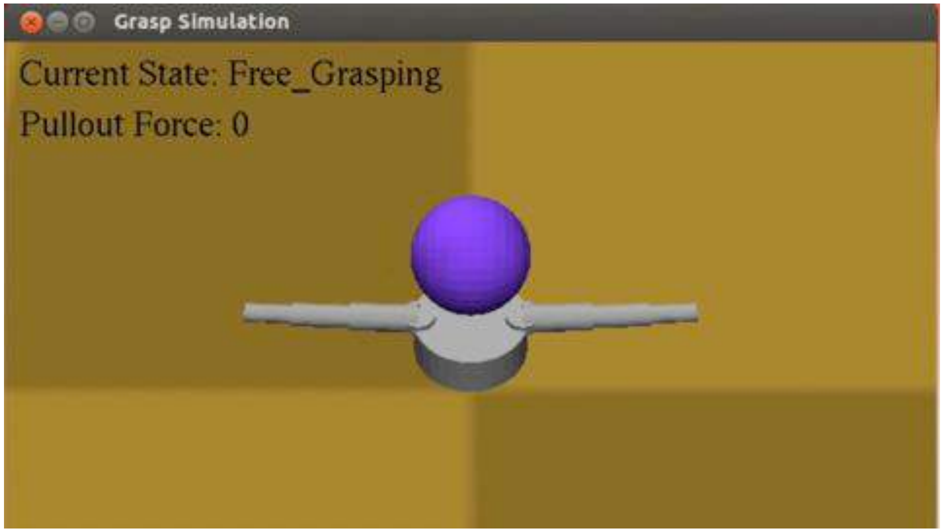


$$\boldsymbol{f}_c = A^{-1}\begin{bmatrix} K_r\boldsymbol{q} + \boldsymbol{p}_r \\ K_p\boldsymbol{d} + \boldsymbol{p}_p \end{bmatrix} - f_t A^{-1}\begin{bmatrix} \boldsymbol{r} \\ \boldsymbol{f}_p \end{bmatrix}$$



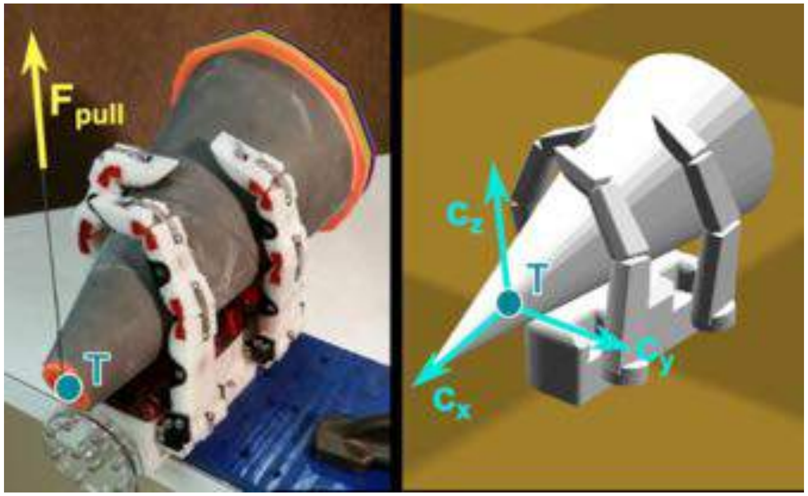
Simulation platform

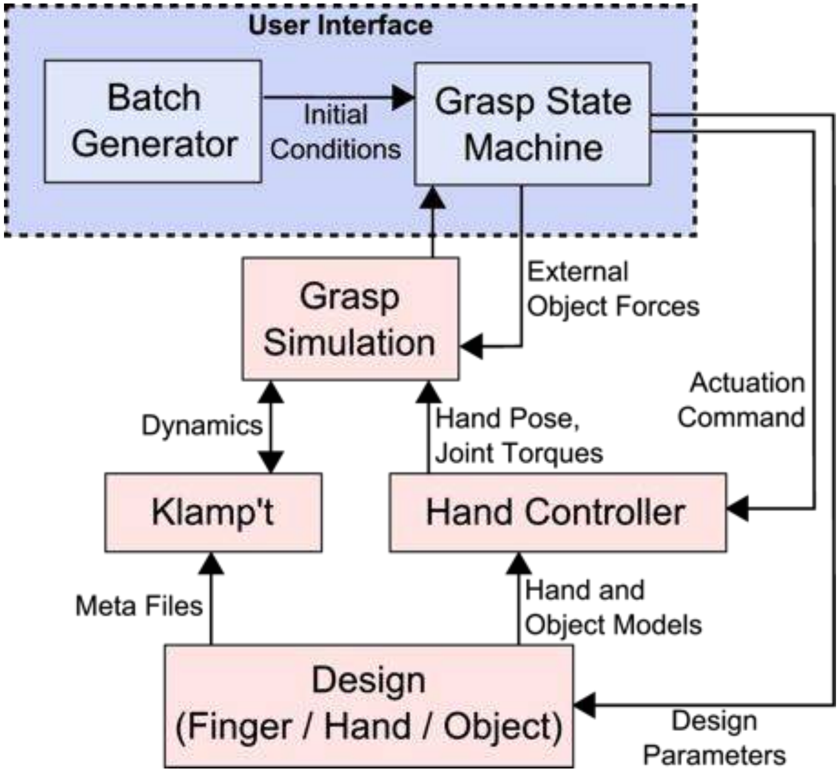
- SimGrasp
  - https://bitbucket.org/shiquan/sim-grasp/overview
  - Built upon dynamic engine Klamp’t
  - Grasp simulator for generic hand design (in batch)



Current State: Free_Grasping

Pullout Force: 0





User Interface

Batch Generator → Initial Conditions → Grasp State Machine

Grasp Simulation → Grasp State Machine

Grasp State Machine → External Object Forces → Grasp Simulation

Grasp State Machine → Actuation Command → Hand Controller

Grasp State Machine → Design Parameters → Design (Finger / Hand / Object)

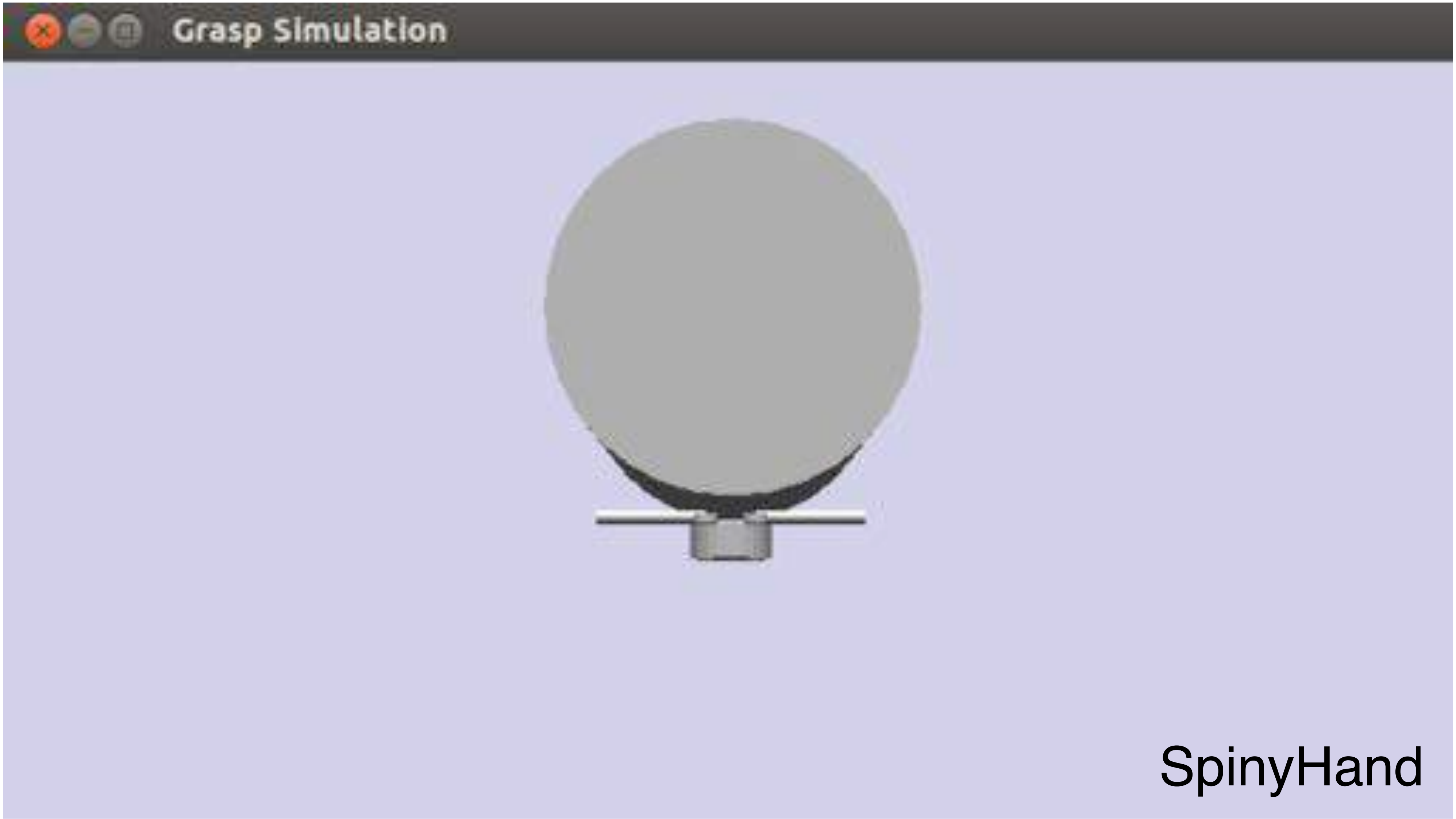
Grasp Simulation ↔ Dynamics ↔ Klamp't

Hand Controller → Hand Pose, Joint Torques → Grasp Simulation

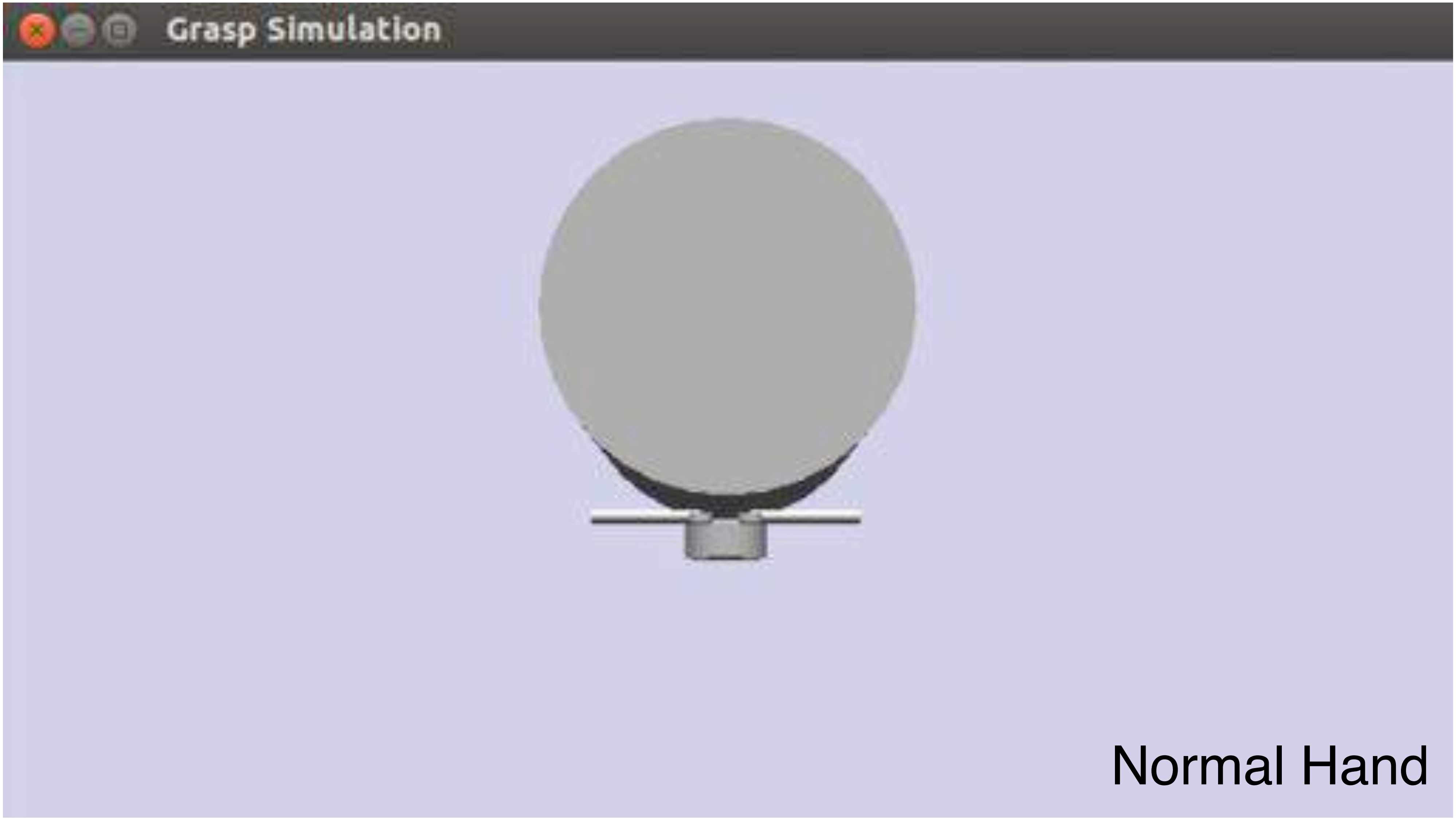
Design (Finger / Hand / Object) → Meta Files → Klamp't

Design (Finger / Hand / Object) → Hand and Object Models → Hand Controller

SimGrasp for SpinyHand



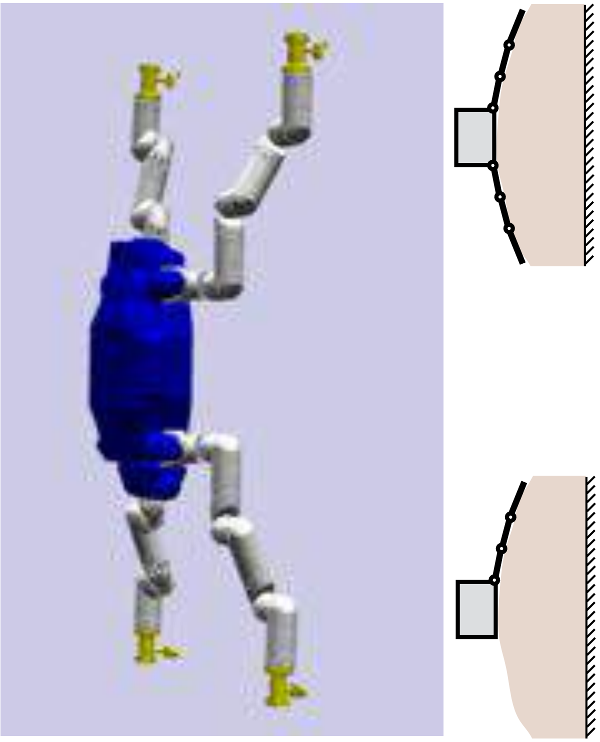
SimGrasp for SpinyHand

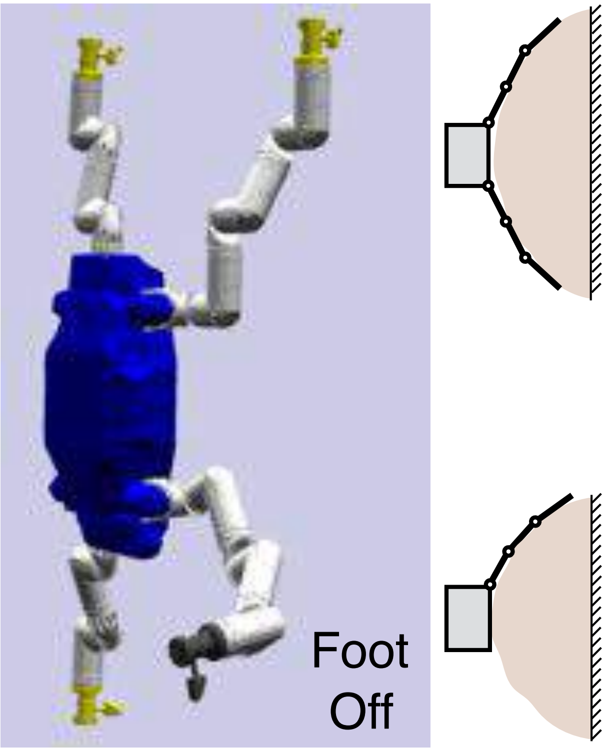


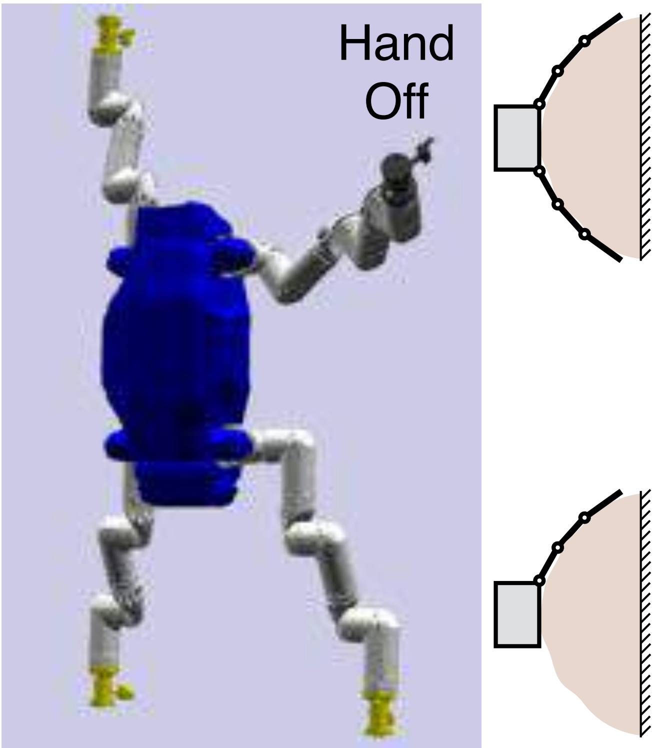
Rock climbing analysis

- RoboSimian: 108kg

[Shear(N) Moment(Nm) Normal(N)]







Upper	[273 -9 -42]	[353 7 -62]	[368 -14 -96]
Lower	[286 -15 47]	[593 28 54]	[367 -9 100]

Future work

- Test SpinyHand in the field!
- Compliant-base spine tile and spine retraction
- Grasping strategy
- SpinyHand II

Contributions

- SupraPed: point contact
  - Design solutions of the smart staff
  - Sensing methods for terrain information
- SpinyPalm: contact patch
  - New spine design for higher adhesion density
  - Spine contact model
  - Scaled-up contact patch (70 kg)
- SpinyHand: hierarchical contact patches
  - Hand design (108kg Robosimian)
  - Grasp model with spine contact (non-convex)
  - SimGrasp: a convenient hand/grasping simulator