Machine Touch for Dexterous Robotic and Prosthetic Hands

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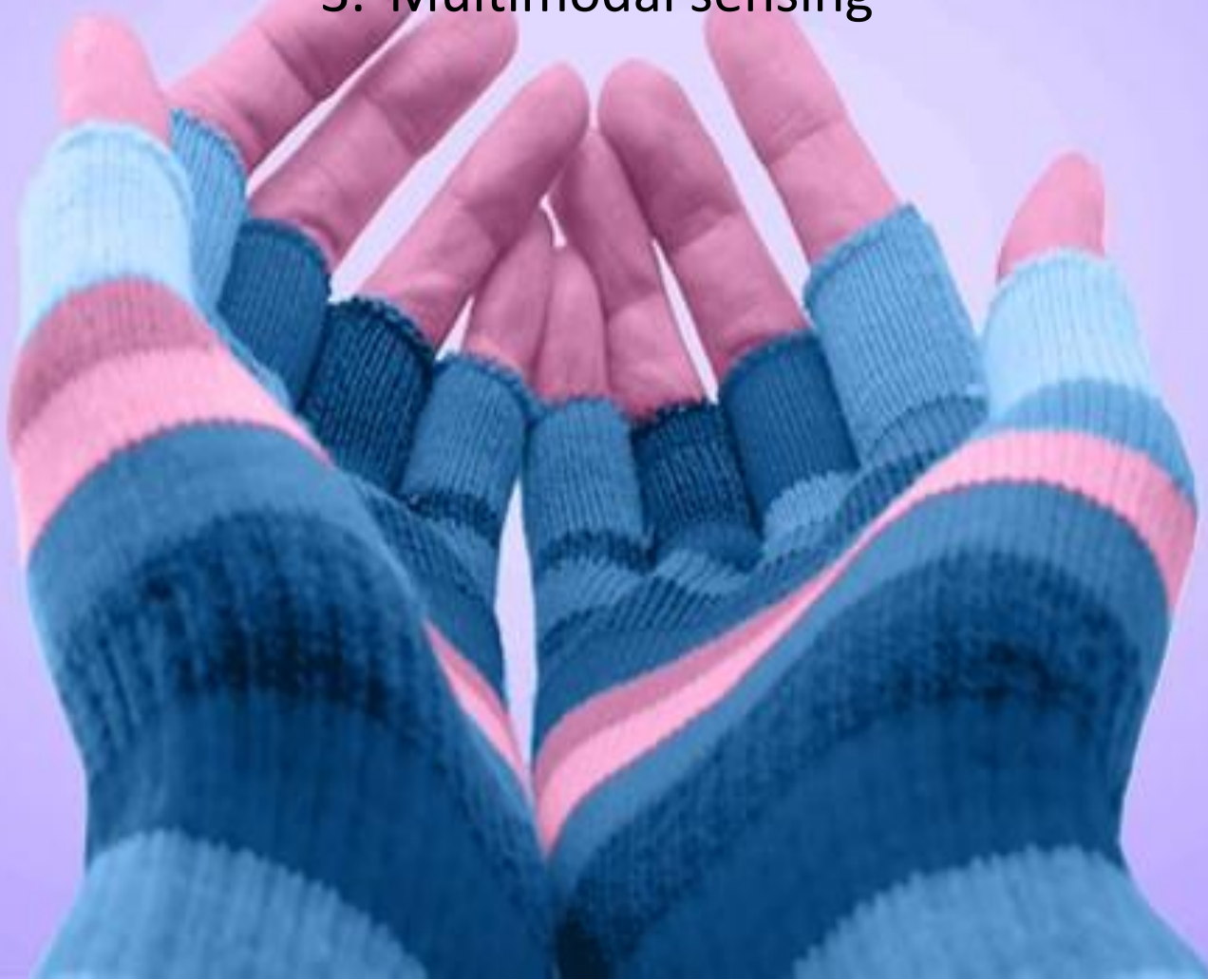
syntouch

Tactile feedback is essential for dexterity.

Humanlike tactile sensing is NOT about force sensors:

1. Exploratory movements
2. Mechanical properties
3. Multimodal sensing

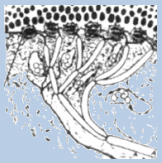


Biological Transducers

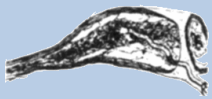
Cutaneous Touch

Force & Deformation

Merkel Disc



Ruffini Ending



Tree Nerve Ending

Thermal

Meissner Corpuscle

Vibrations

Pacinian Corpuscle

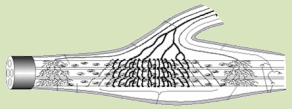
Enabled by Exploratory Movements…

Proprioceptive Touch

Actuator Force

Golgi Tendon Organ

Muscle Spindle



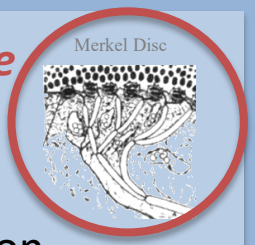
Position & Velocity

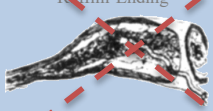
Engineered Transducers

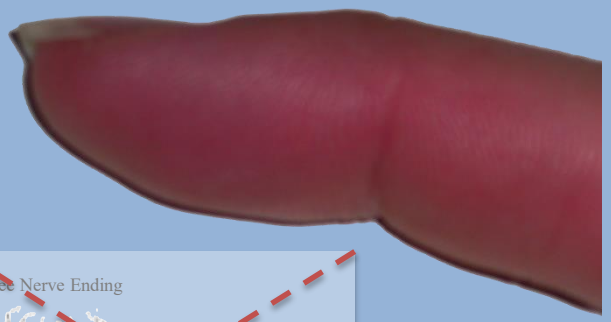
Cutaneous Touch

"Taxel"
Normal Force Arrays

Force & Deformation

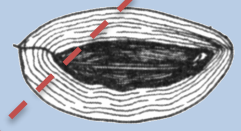






Thermal

Vibrations



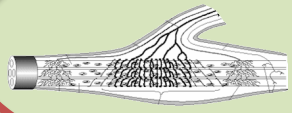
Enabled by Exploratory Movements…

Proprioceptive Touch

Actuator Force

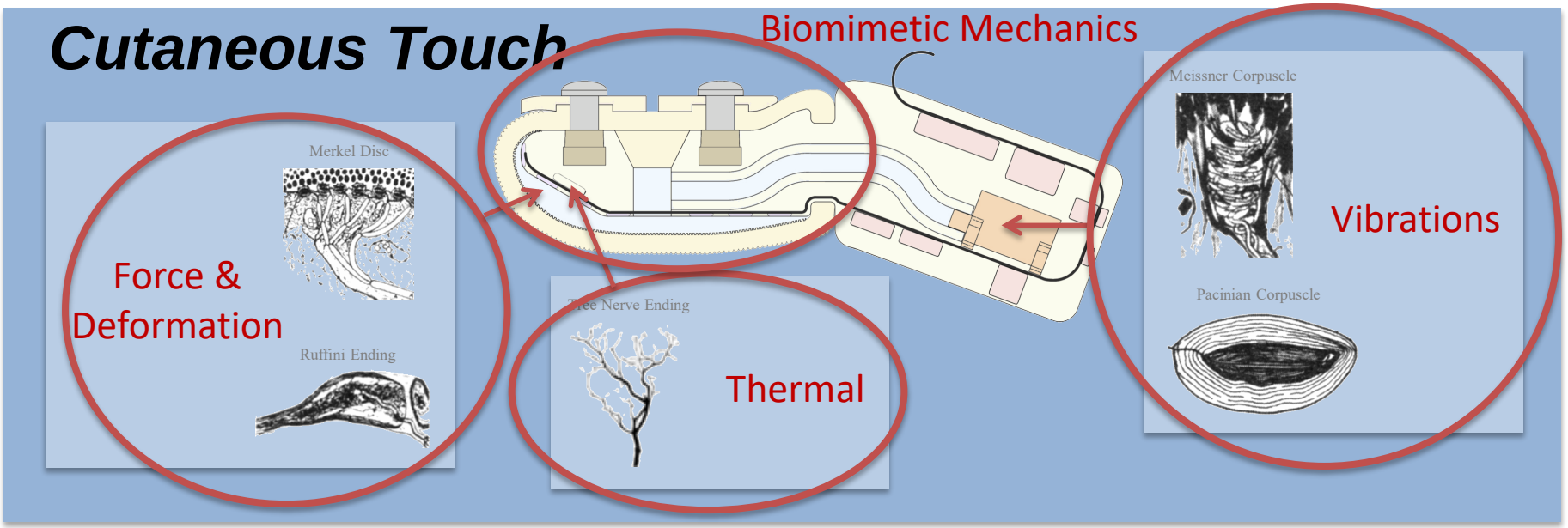
Strain Gages

Position Encoders



Position & Velocity

The BioTac Design Approach



BioTac developers and SynTouch founders

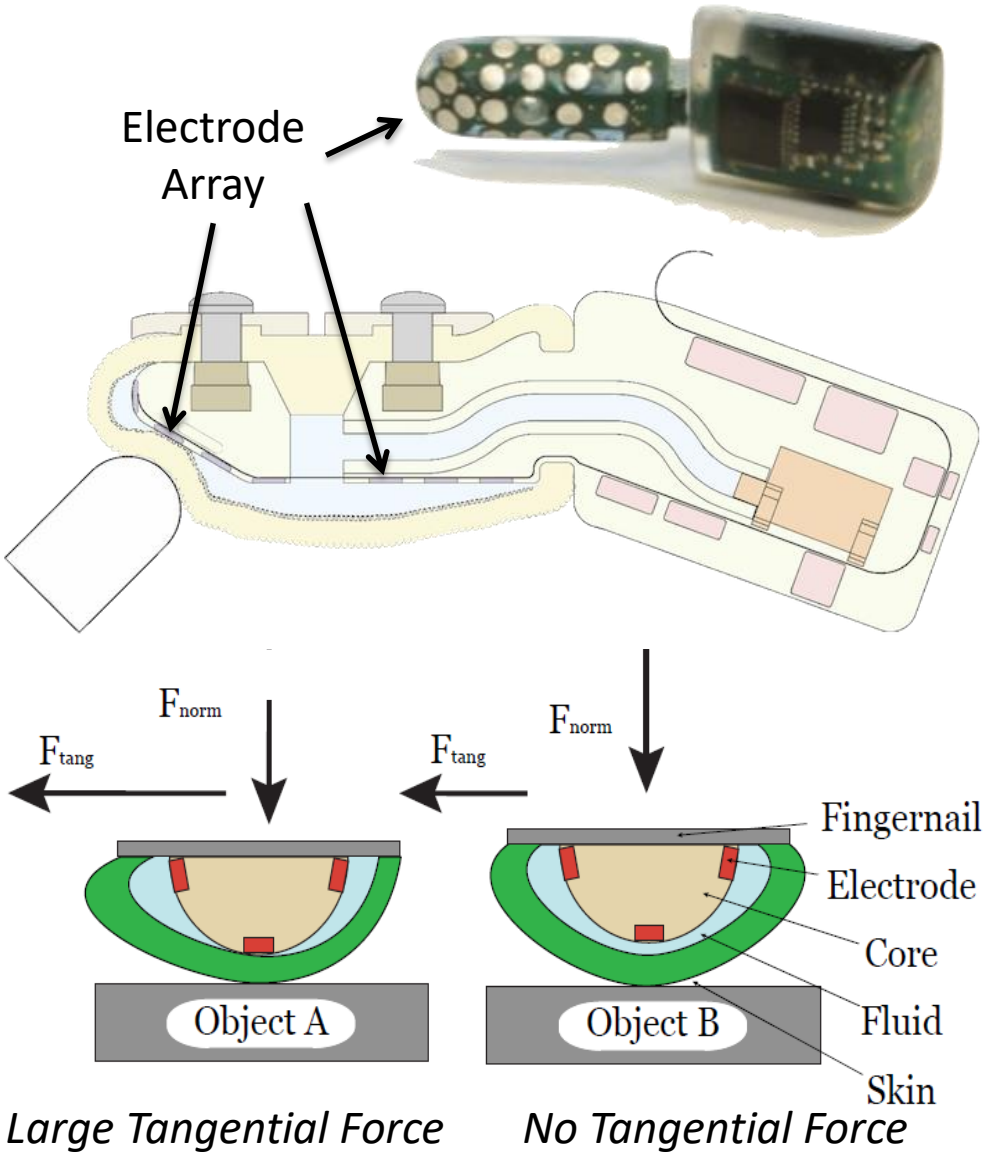
Jeremy Fishel, Nick Wettels, Gary Lin, Ray Peck, Matt Borzage

Contributing researchers

Roland Johansson, Veronica Santos, Dipayon Roy, Blaine Matulevich, Vikram Pandit, Danfei Xu, Zhe Su, Lorenzo Smith, Todd Erickson, Morelle Arian, Alex Blaine, Meghan Jimenez, Rahman Davoodi, Kelsey Muller, Alexandra Llic

Deformation Sensing

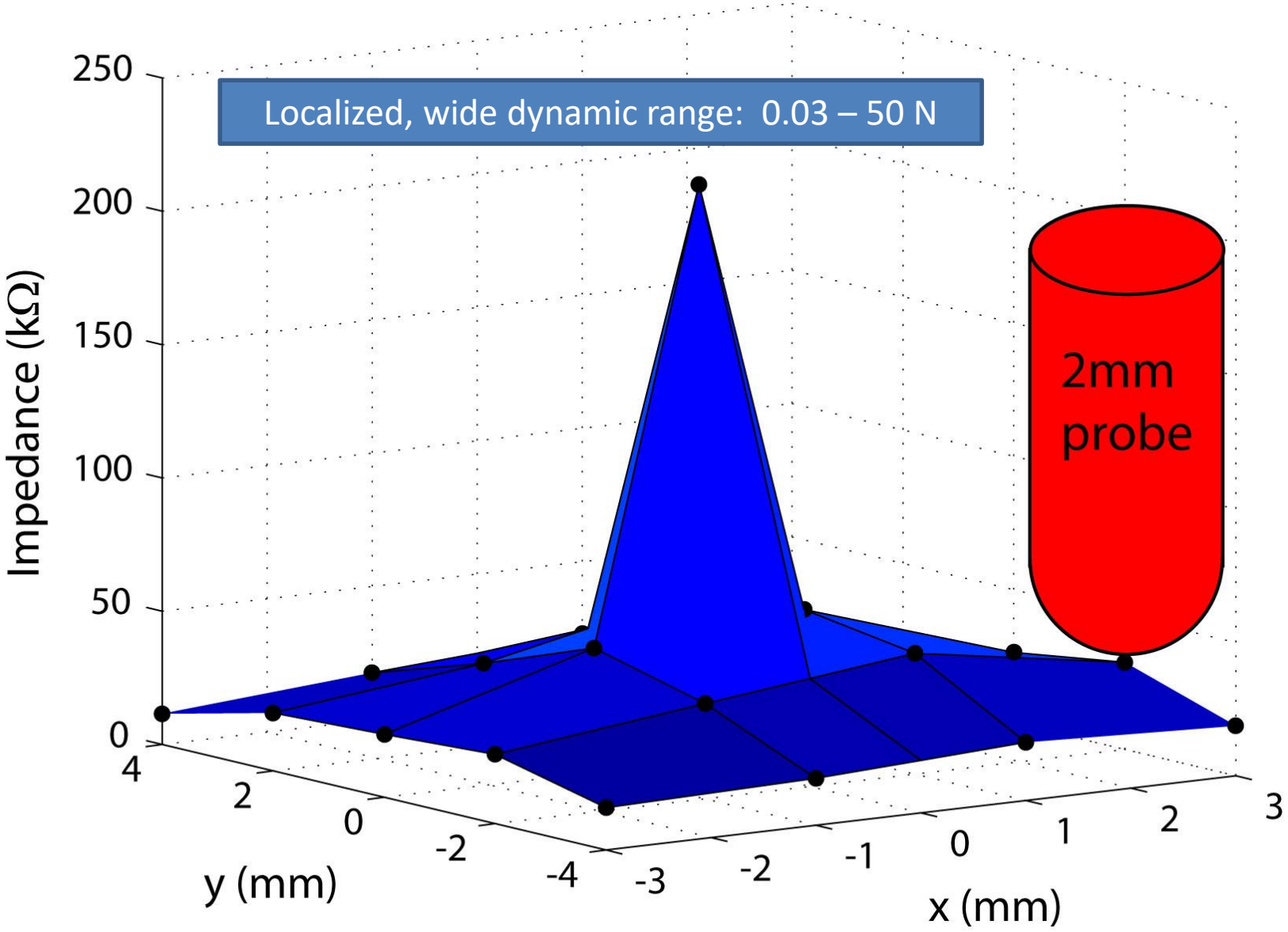
- Forces deform skin and fluid
- Impedance changes are sensed by electrodes
- Raw data can be used with machine learning techniques to extract features:
  - Tri-Axial Force
  - Point of Contact
  - Radius of Curvature
  - …



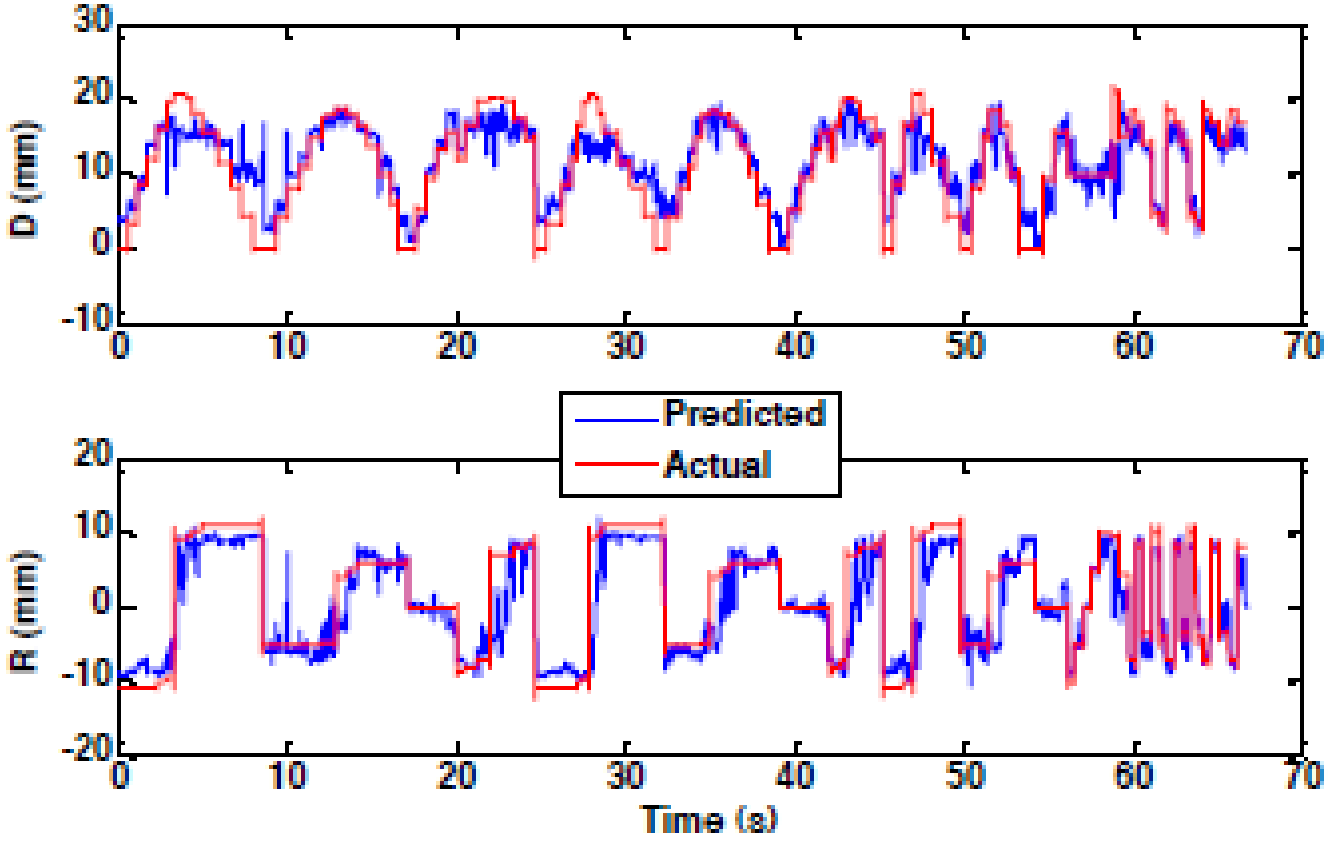
Wettels, Popovic, Santos, Johansson, Loeb. *Advanced Robotics* (2008)

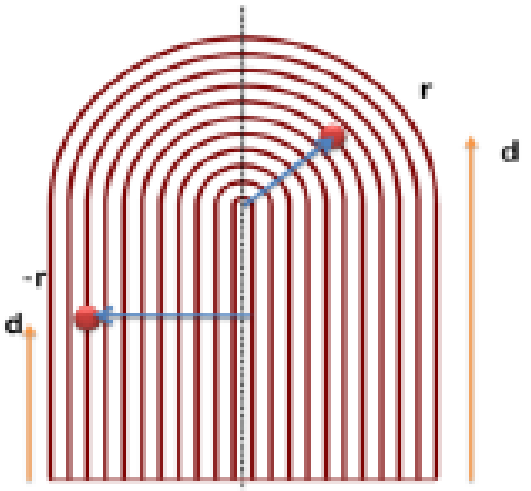
Wettels, Smith, Santos, Loeb. *IEEE Intl Conf Biomed Robotics and Biomechatronics* (2008)

Impedance: Probing about an Electrode

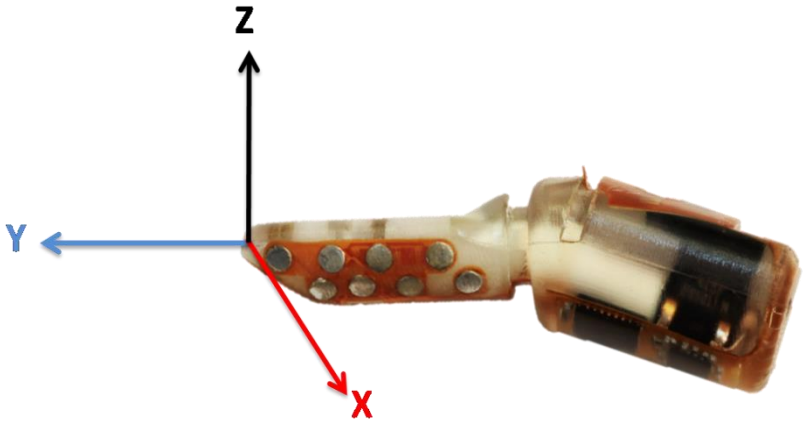


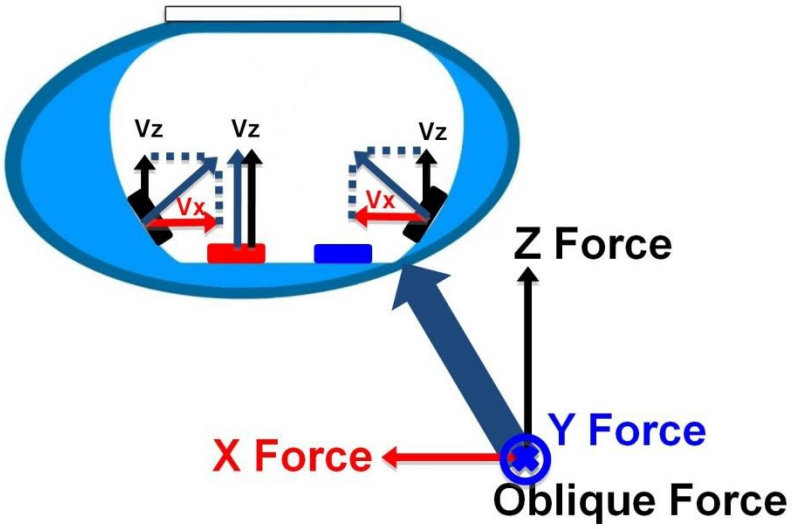
Point of Application Computation
(post Lowess Filtering)





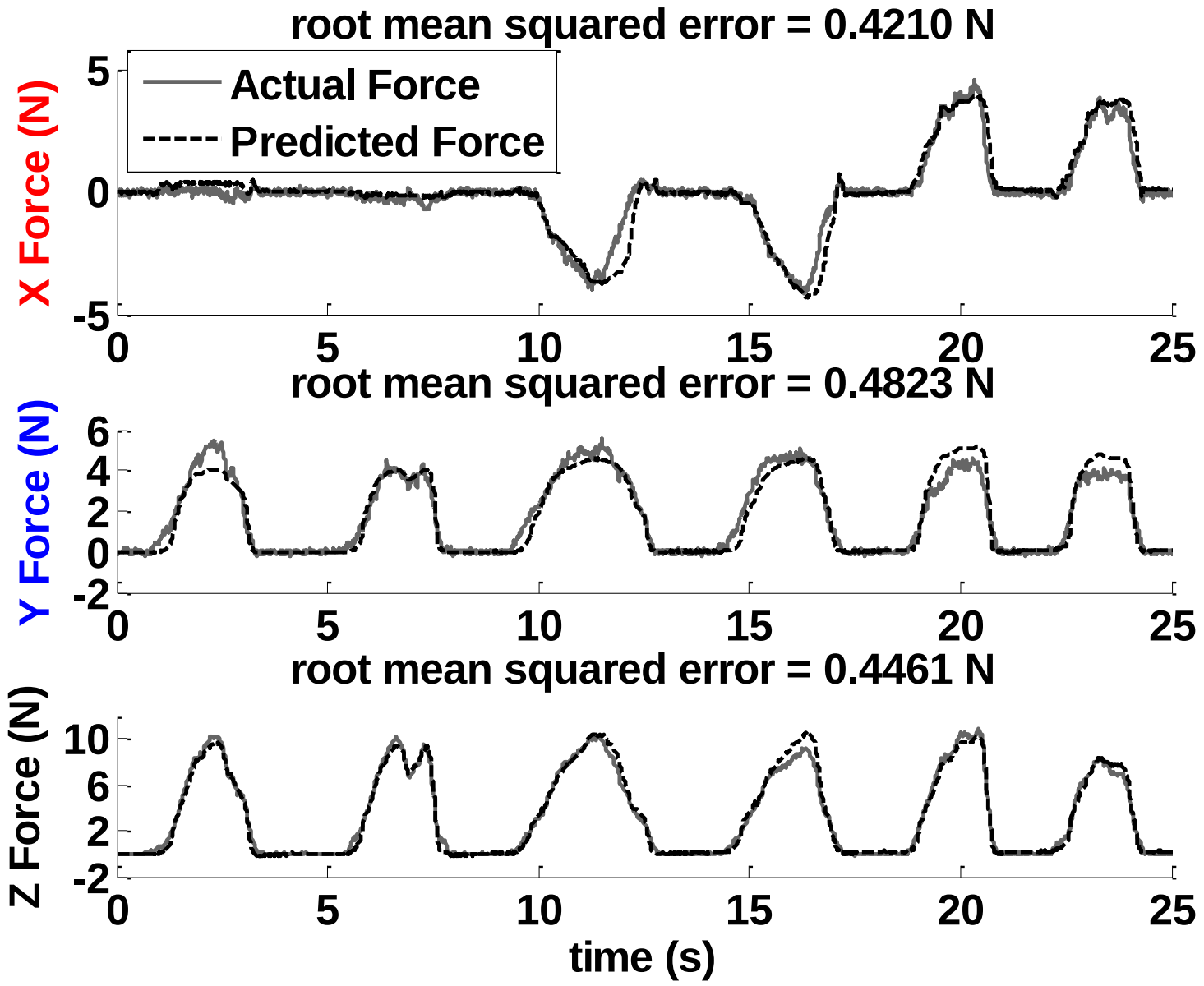
Tri-axial force vectors extraction on BioTac



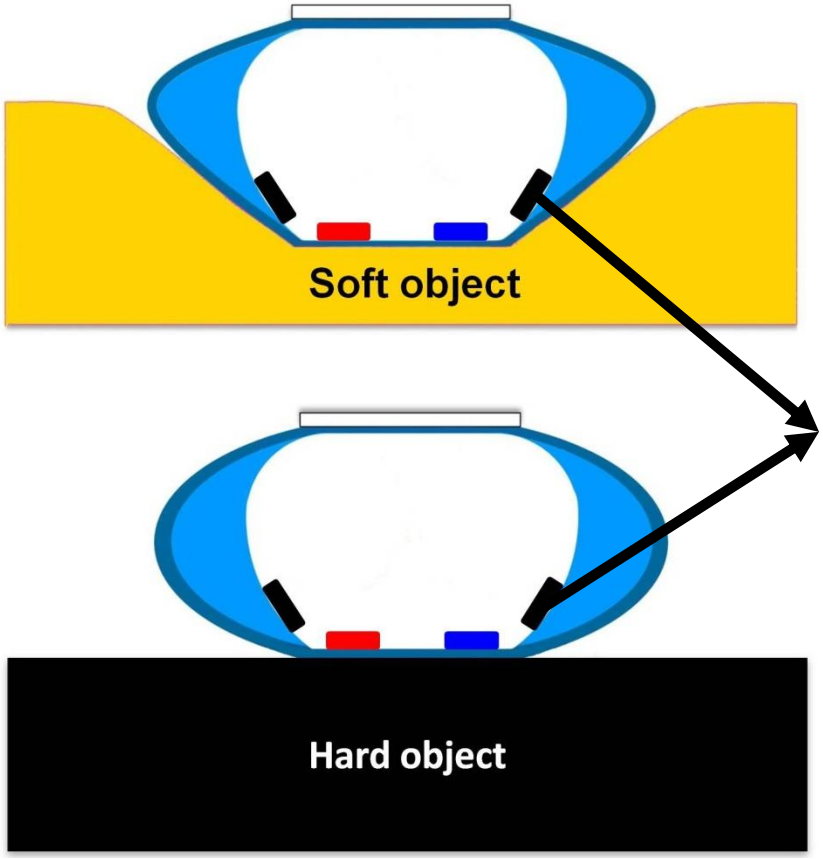


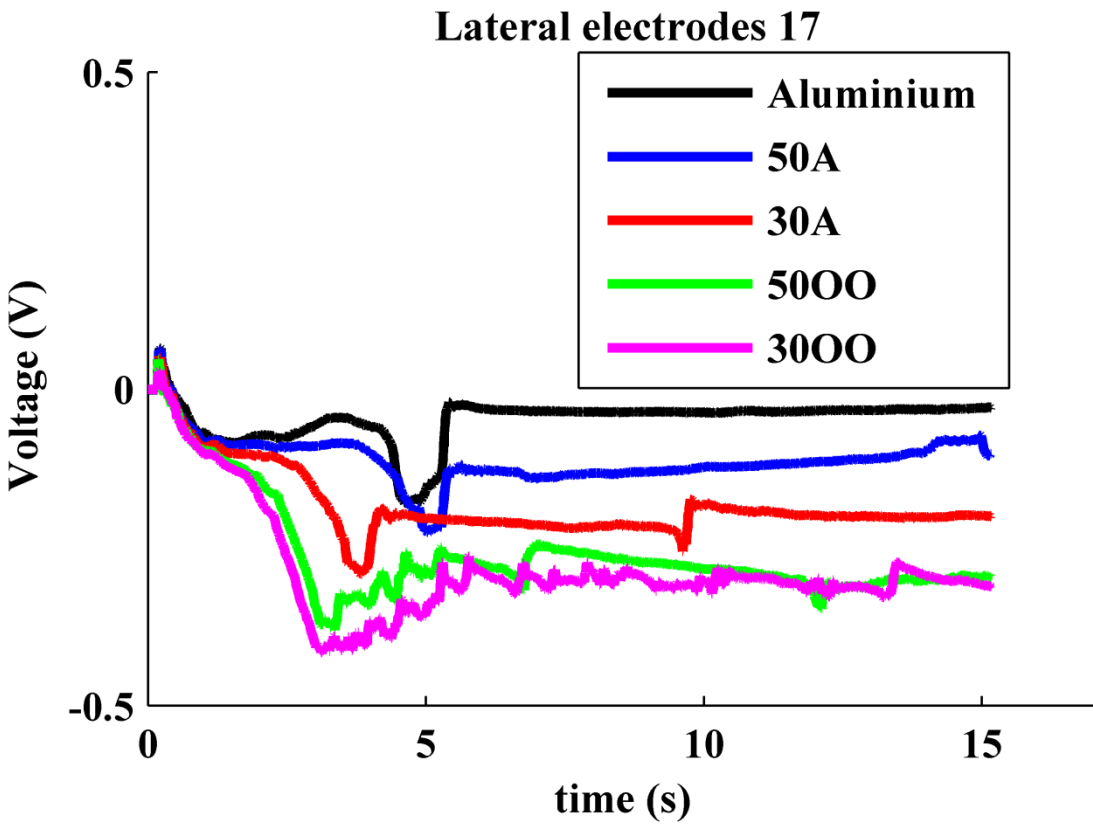
$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} S_x & 0 & 0 \\ 0 & S_y & 0 \\ 0 & 0 & S_z \end{bmatrix} \times \begin{bmatrix} N_{1,x} & \cdots & N_{19,x} \\ N_{1,y} & \cdots & N_{19,y} \\ N_{1,z} & \cdots & N_{19,z} \end{bmatrix} \times \left(\begin{bmatrix} E_1 \\ \cdots \\ E_{19} \end{bmatrix} - \begin{bmatrix} E_{1,rest} \\ \cdots \\ E_{19,rest} \end{bmatrix} \right)$$

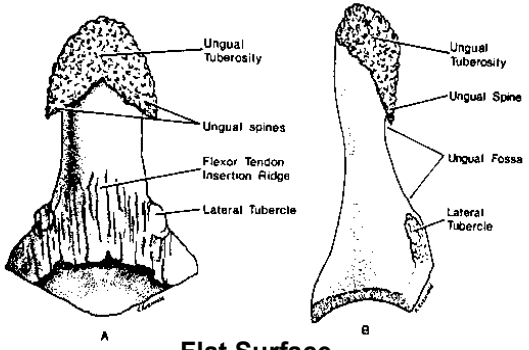
Force vector extraction and control

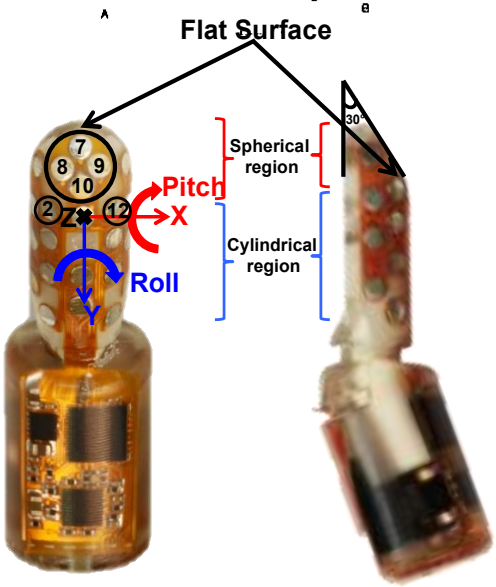


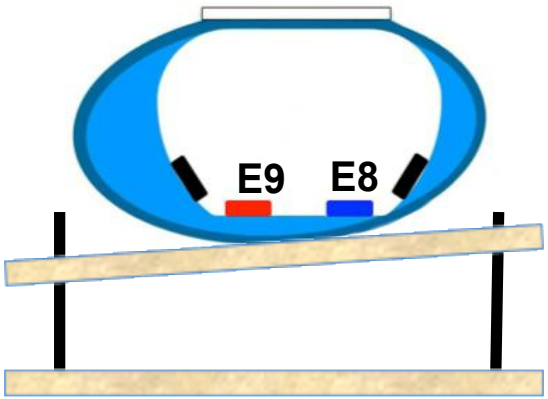
The skin enveloping lateral impedance electrodes provides compliance and radius-of-curvature discrimination.





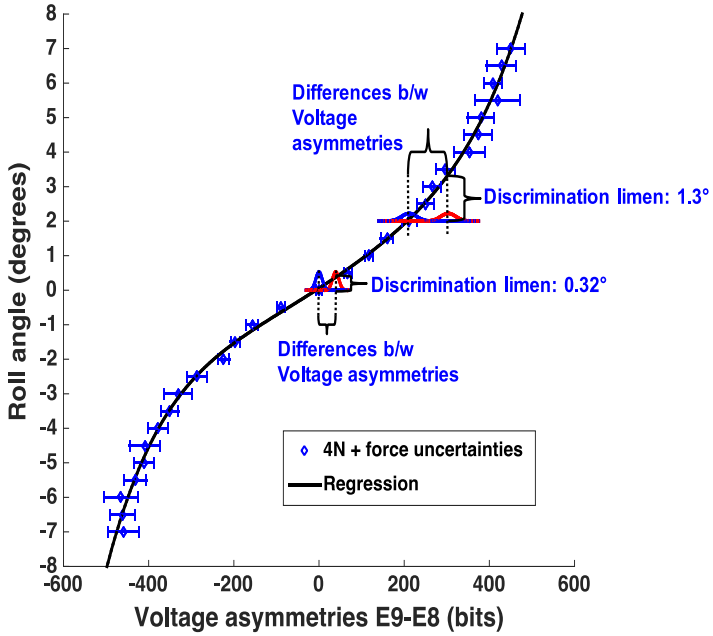


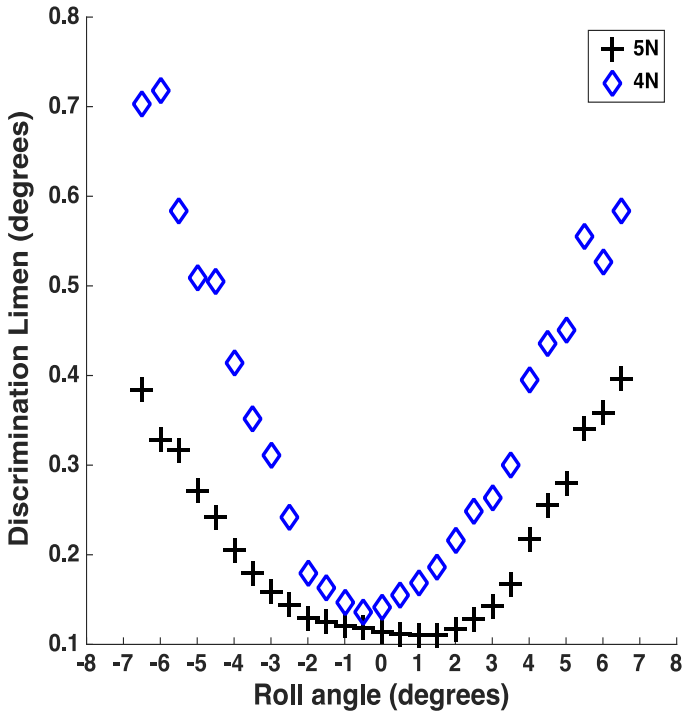




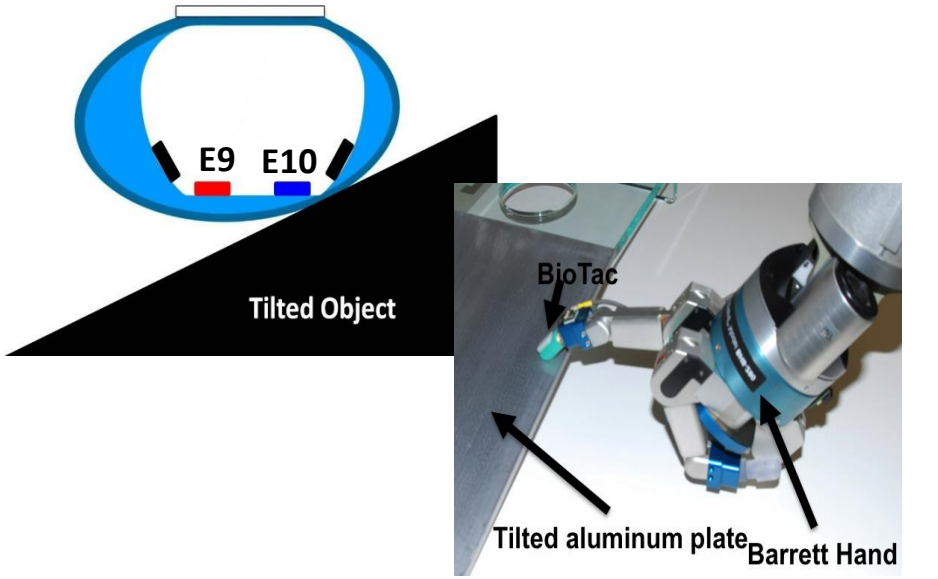
Apical Tuft as a Vernier Tilt Sensor

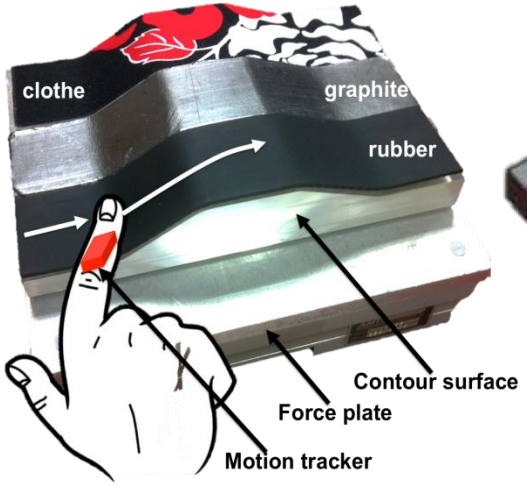
Su, Z., Schaal, S. and Loeb, G.E.
Surface tilt perception with a biomimetic tactile sensor
BioRob 2016, Singapore

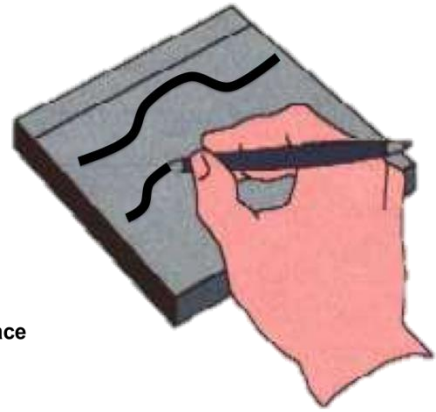


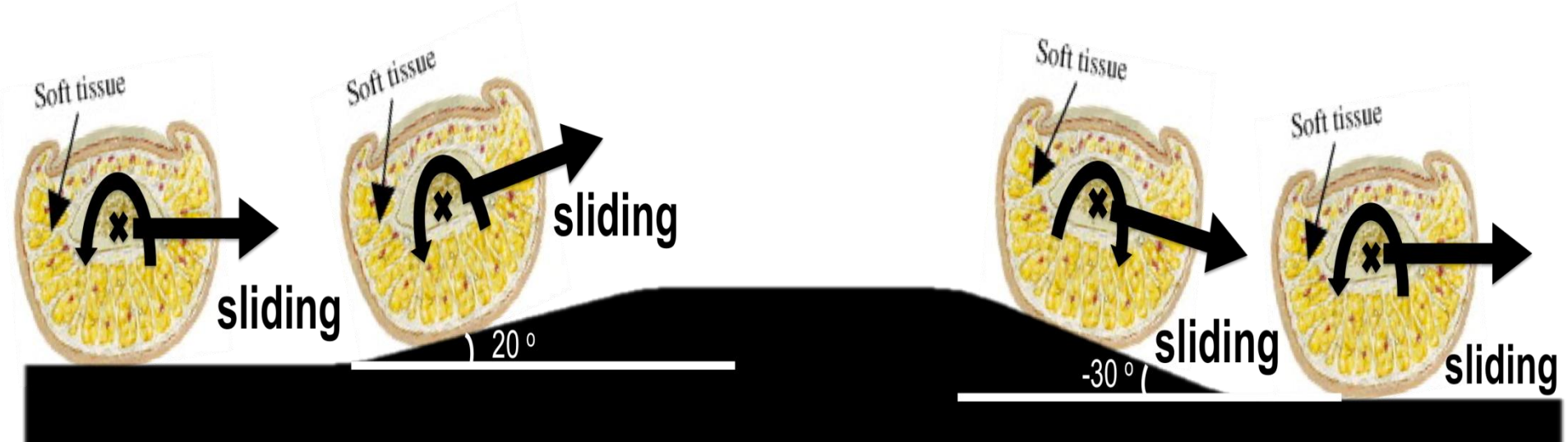


Exploring Complex Shapes: Deconvolving Contour and Friction





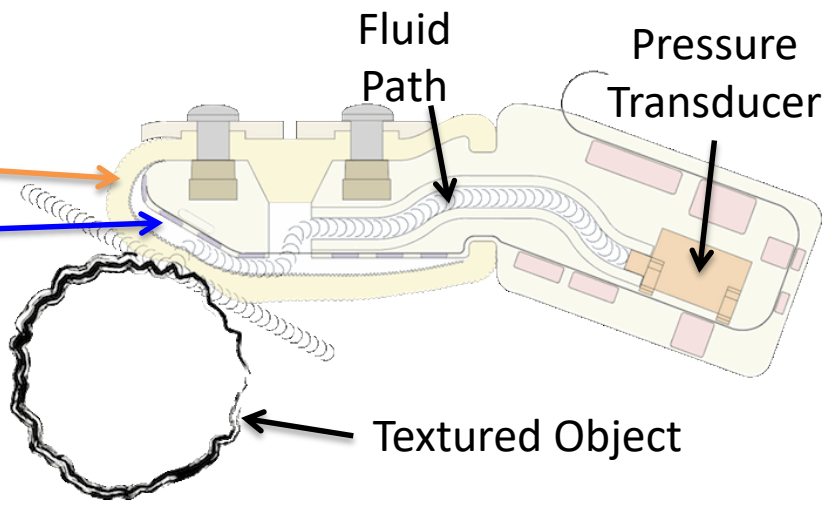




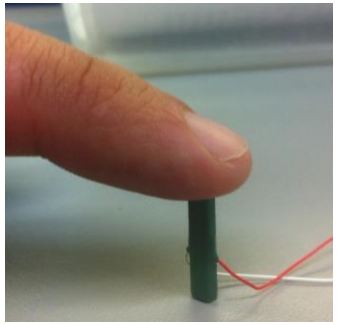
Vibration Sensitivity

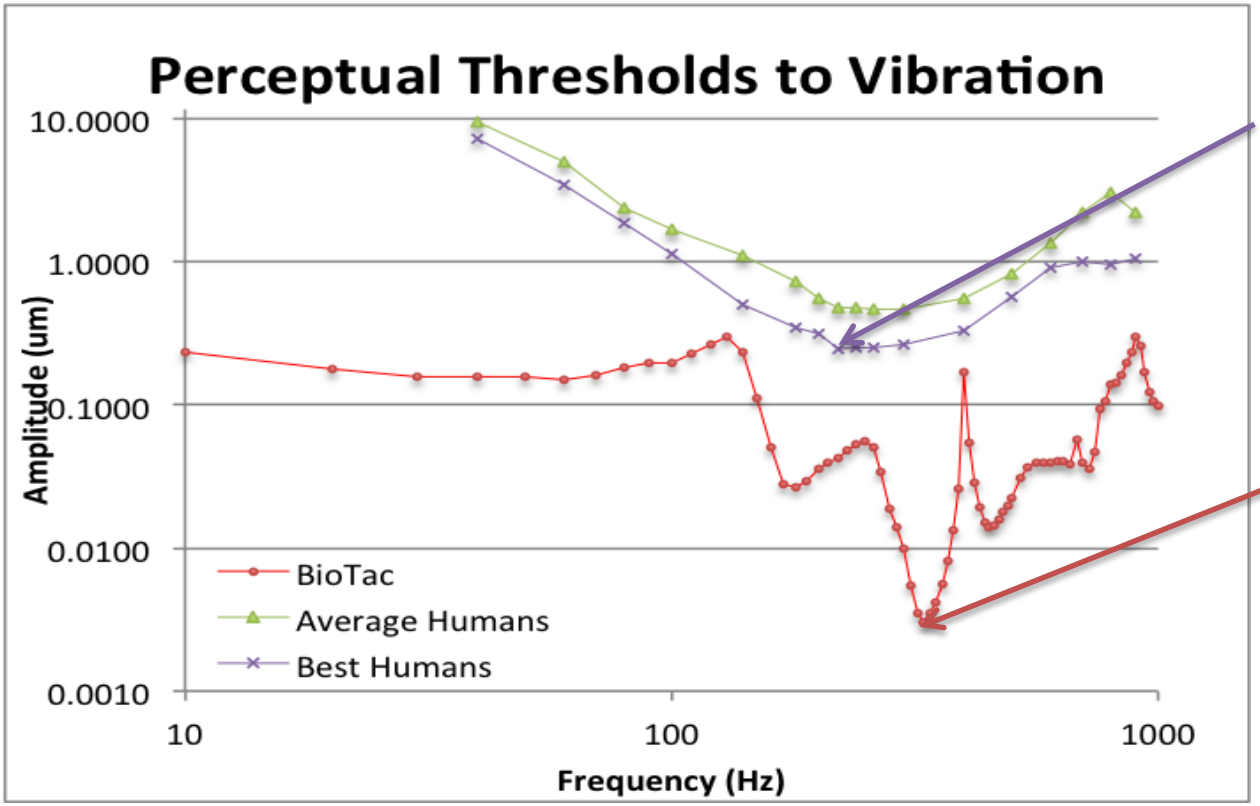
Similar size, shape and structure as the human fingertip

Flexible skin over liquid "pulp"



Similar mechanical properties and dynamic response as the human finger

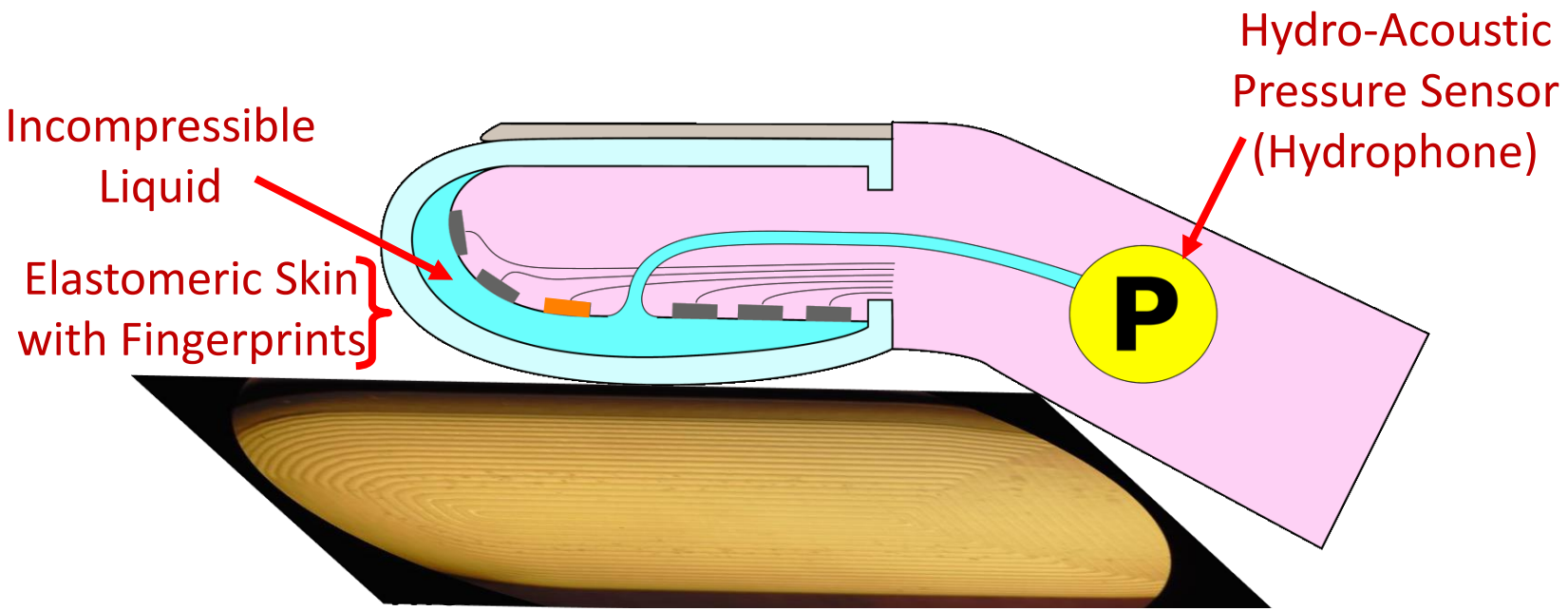


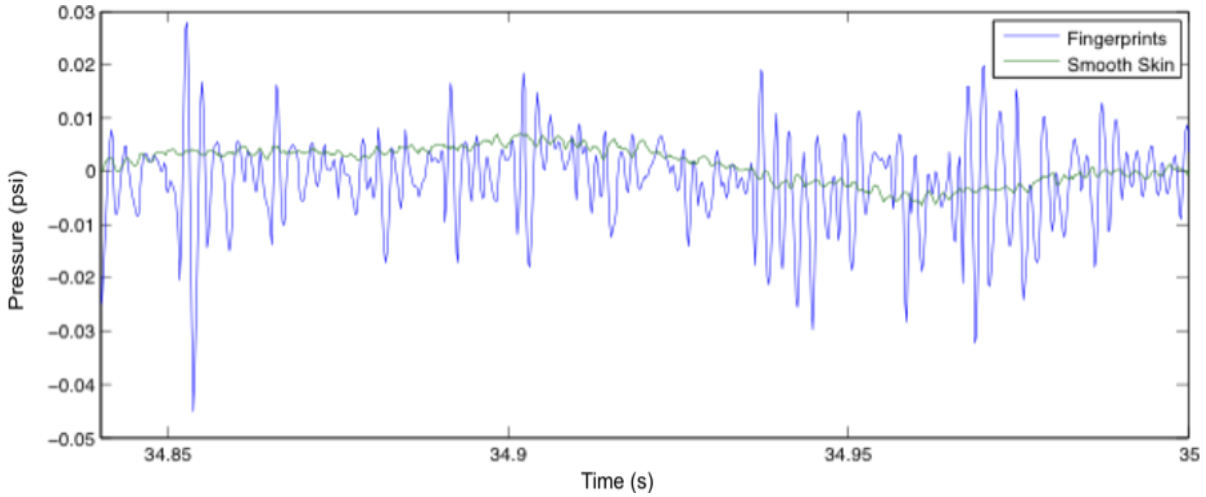


Humans
200 nm

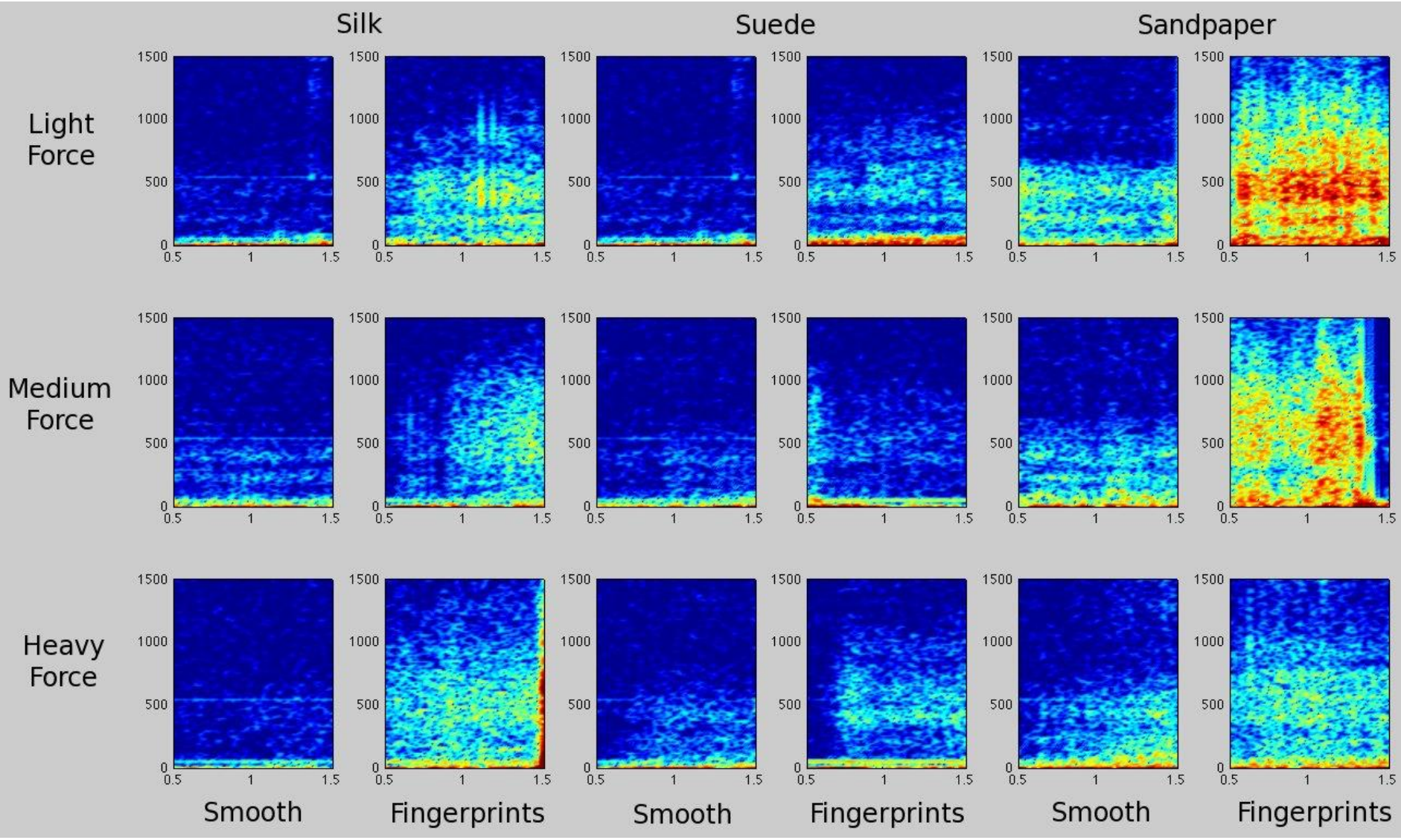
BioTac
3 nm

Fingerprints Greatly Enhance Sliding Vibration Amplitude





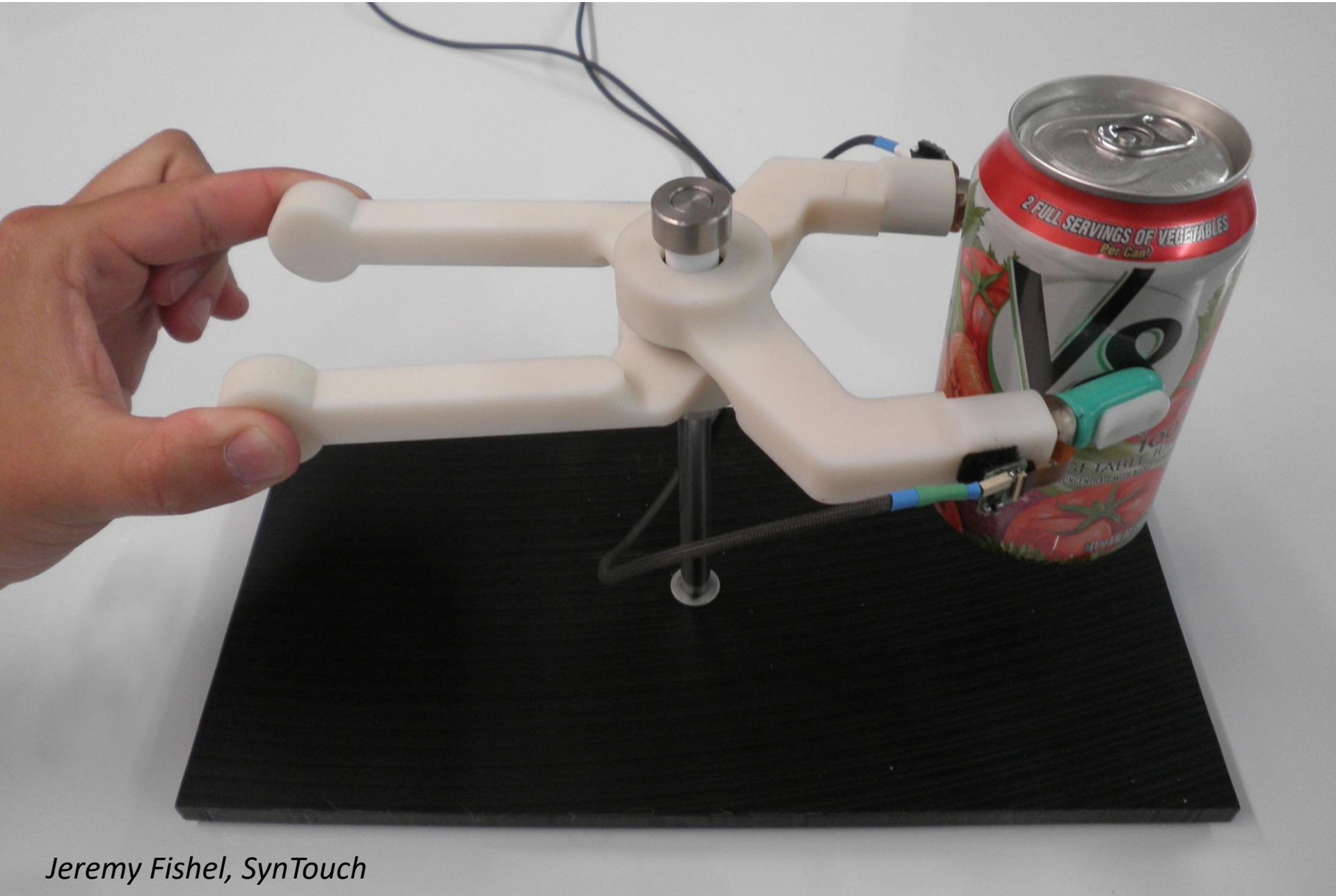
Fingerprints Enhance Vibration Spectra



When is Tactile Sensing Necessary?

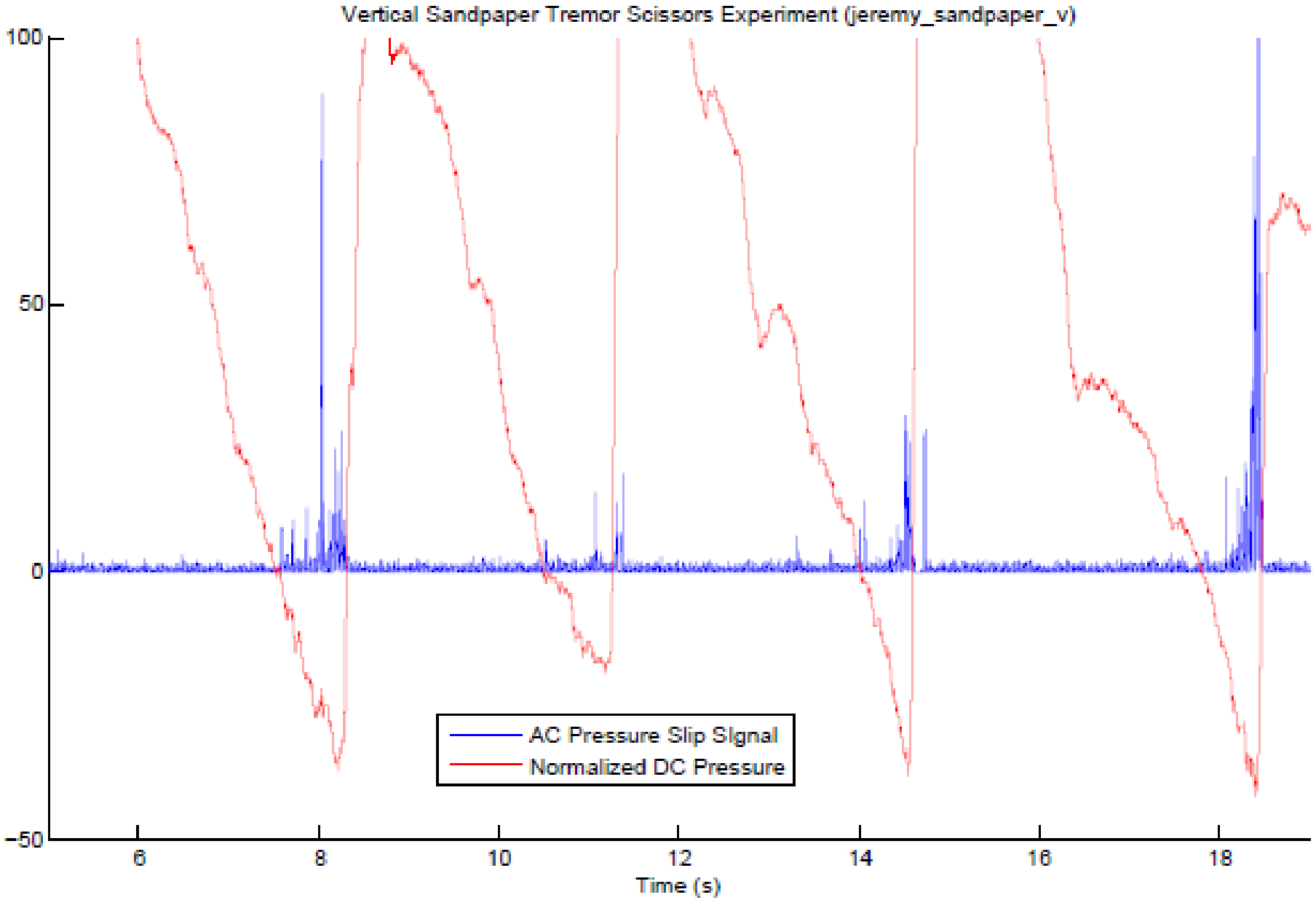
- Dexterous Manipulation = *"Perception for Action"*
  - Contact timing
  - Grip adjustment
  - Slip detection
- Object Characterization = *"Action for Perception"*
  - Identify without vision
  - Anticipate handling properties
- Utility of related objects = *"Affordances"*

Incipient Slip and Grip Adjustment

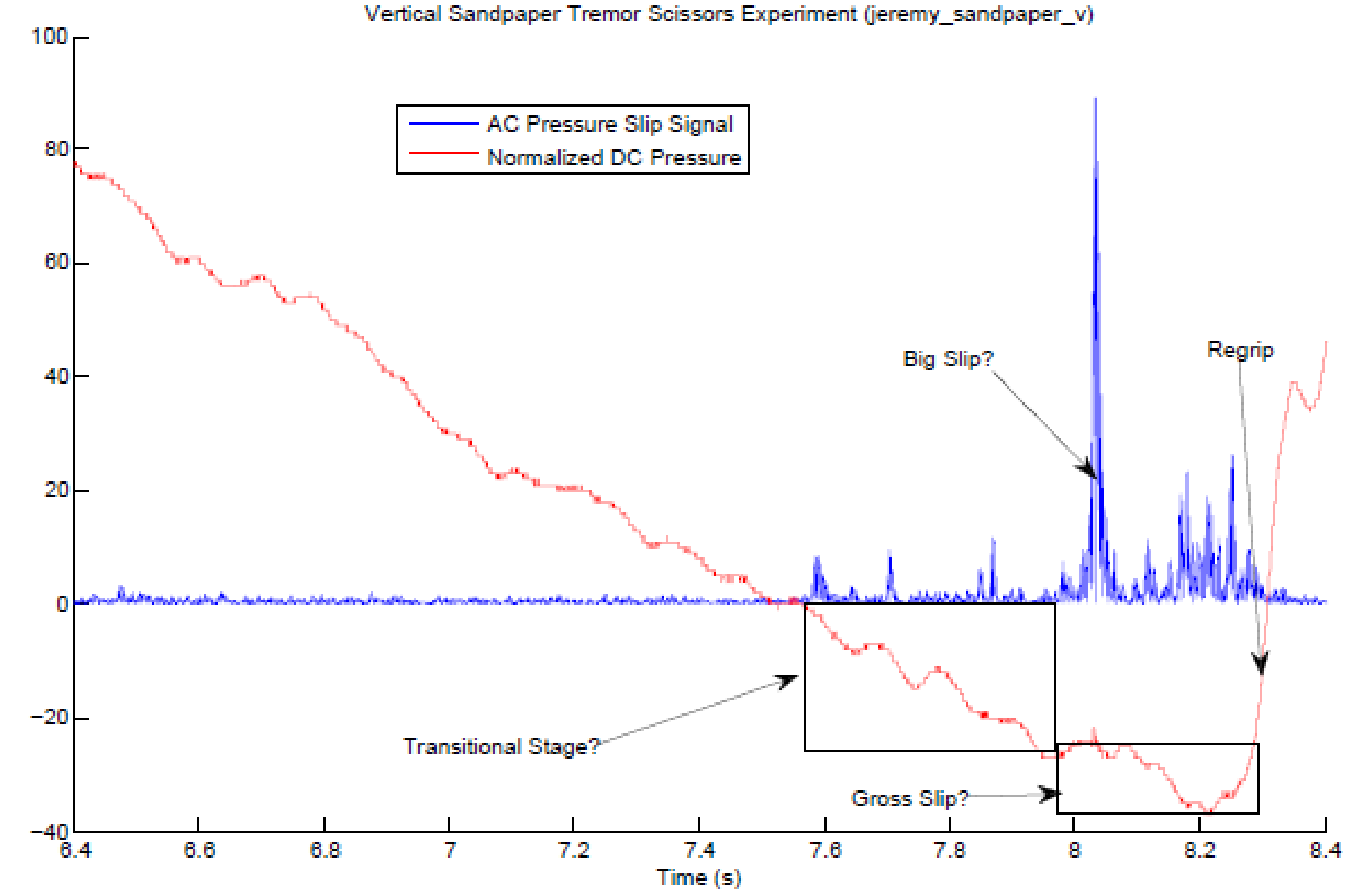


Jeremy Fishel, SynTouch

Incipient Slip Detection During Tremor-Grip



Incipient Slip Detection During Tremor-Grip

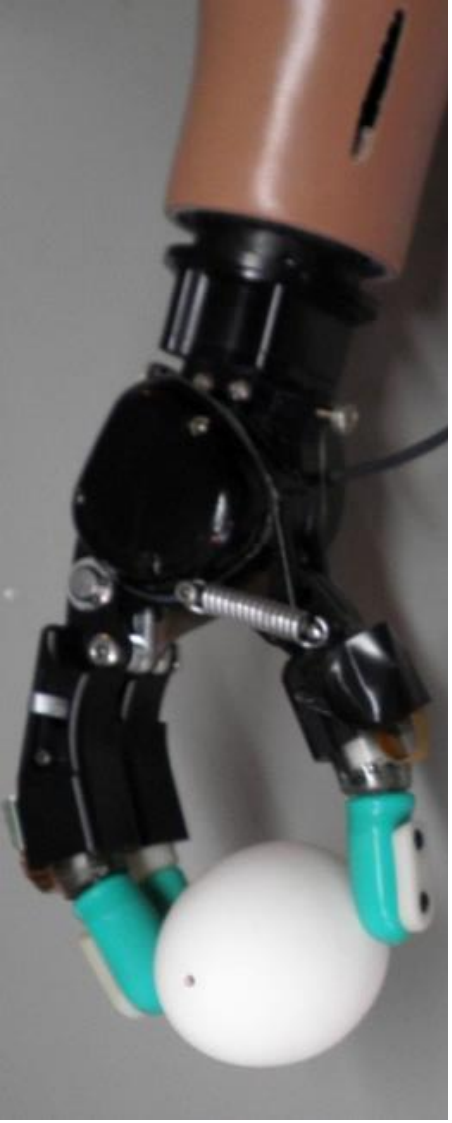


Perception for Action: Fragile Grasp

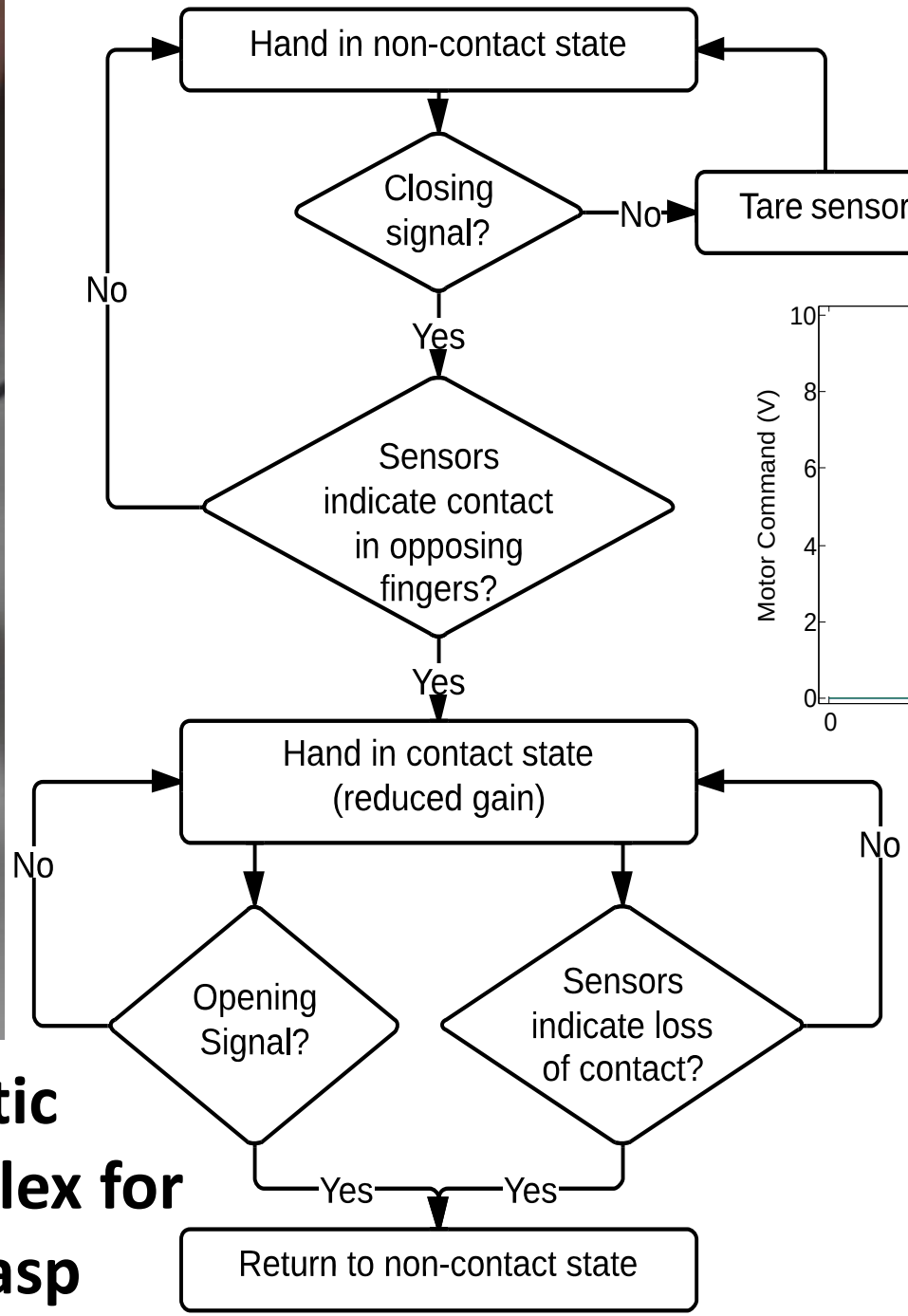
OttoBock Health Care

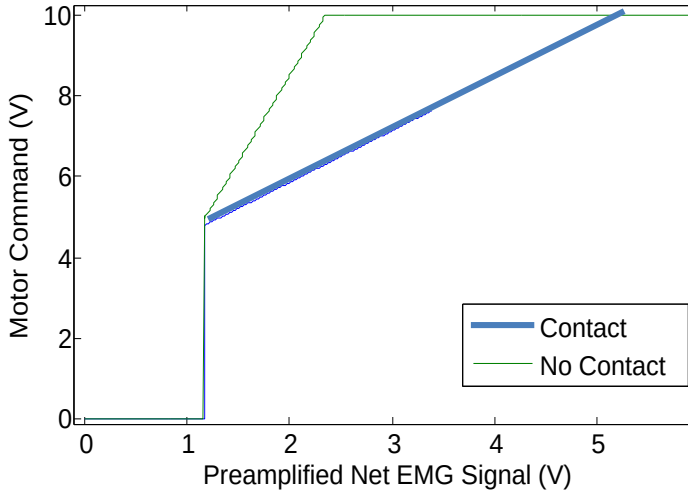
Prosthetic hands typically operate with the motors stalling on objects with high forces (up to 100N).

It is very difficult to grasp fragile objects without intense visual feedback to control finger position.



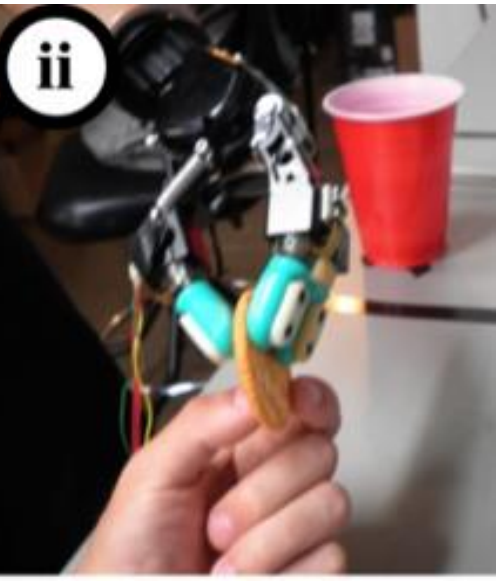
Biomimetic Inhibitory Reflex for Fragile Grasp

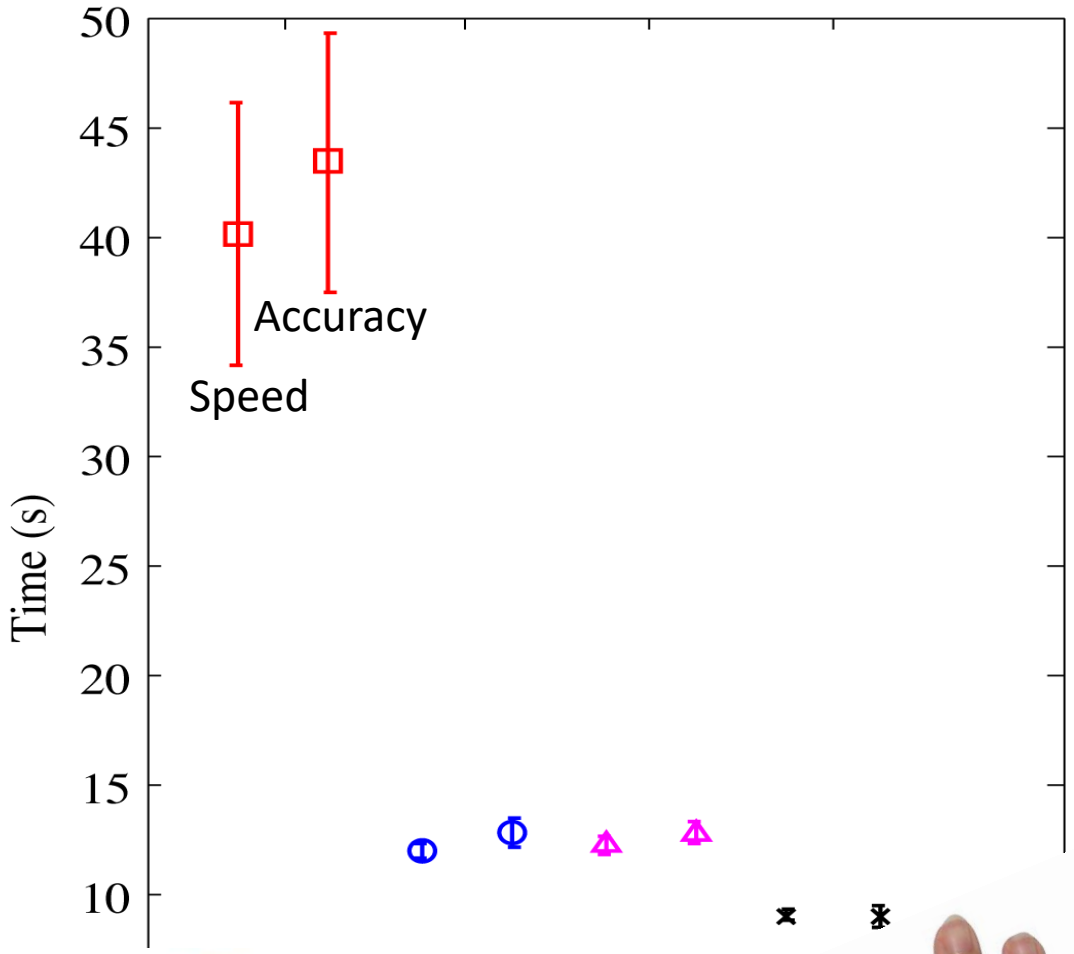




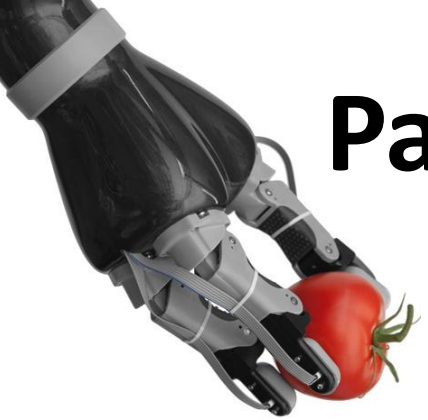
Blaine Matulevich,
Vikram Pandit,
Jeremy Fishel

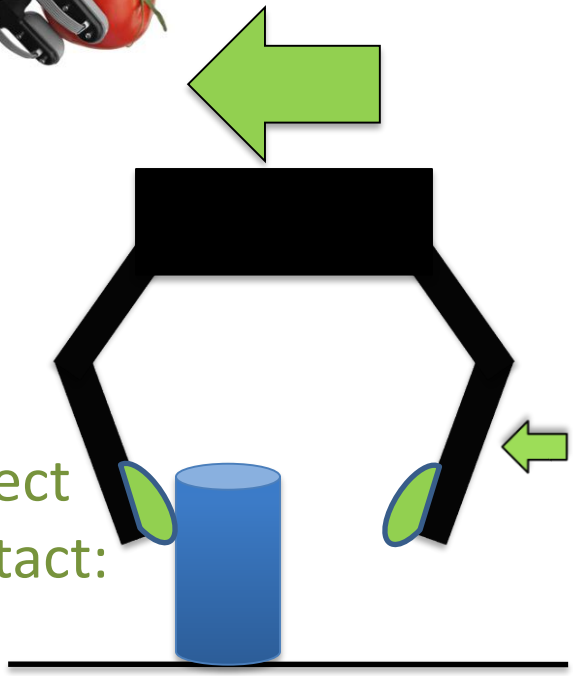
Performance on cracker task





Part Misalignment Mitigation

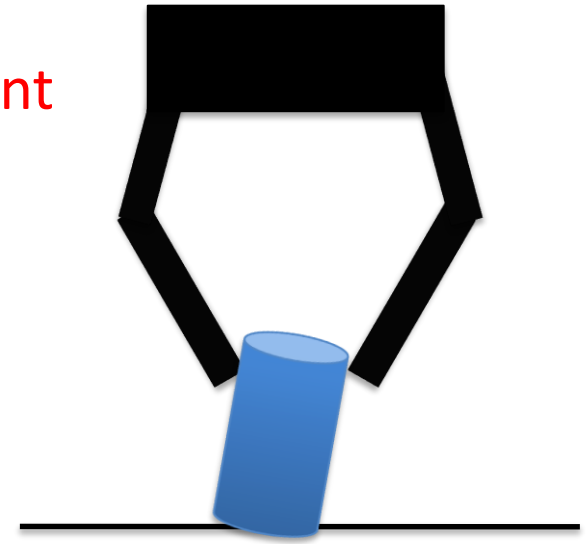




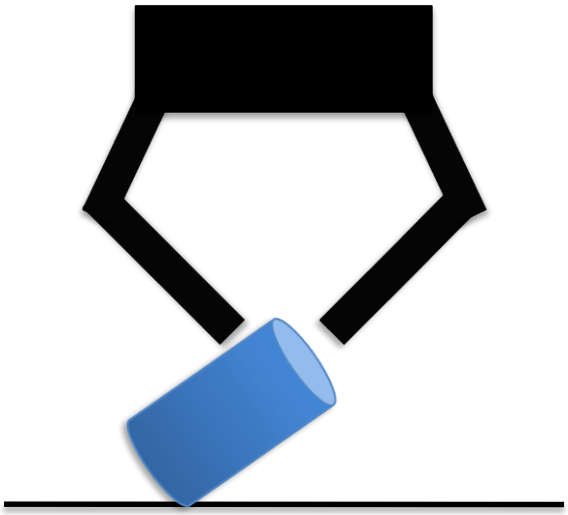
Detect contact:

Translate wrist or adjust finger to avoid:

Displacement

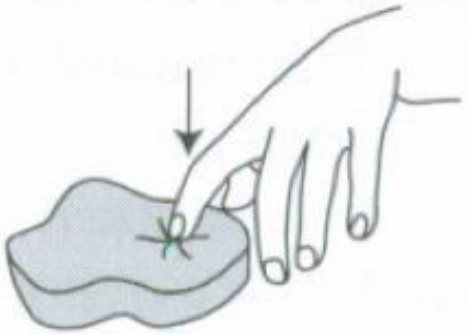
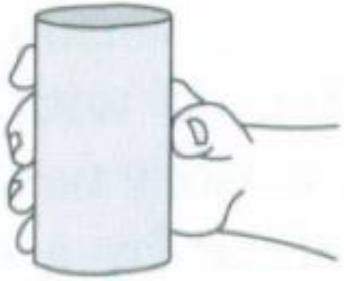


Ejection



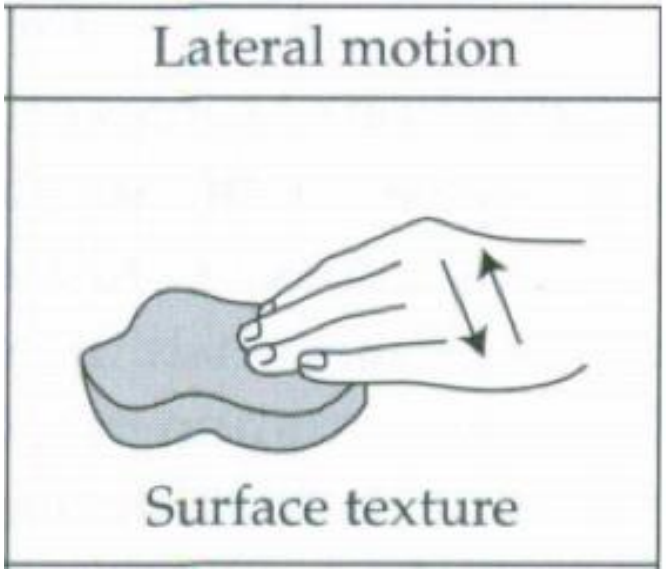
Actions for Perception
Identifying Objects by Touch

:

Static contact	Pressure	Lateral motion
 Temperature	 Hardness	 Surface texture
Contour following	**Enclosure**	**Unsupported holding**
 Global shape, exact shape	 Global shape, volume	 Weight

Source: S. Najarian, et al. (2009) “Artificial Tactile Sensing in Biomedical Engineering”.

Test: Artificial Texture Discrimination

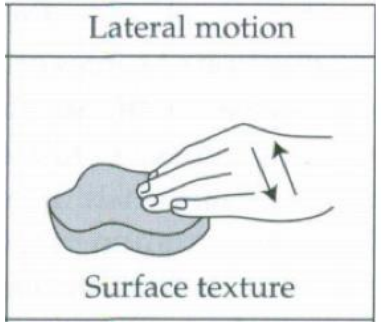


Exploratory Movements
Which Ones?

Texture Discrimination
How?

Fishel, J.A. and Loeb, G.E. Bayesian exploration for intelligent identification of textures. *Frontiers in Neurorobotics,* 2012

Artificial Texture Discrimination Requirements: *Biomimicry*



- **<u>Tactile Vibration Sensitivity:</u>**

  near human performance ✓

- **<u>Texture Exploratory Movements:</u>**

  inspired from human behavior

- **<u>Relevant Texture Properties:</u>**

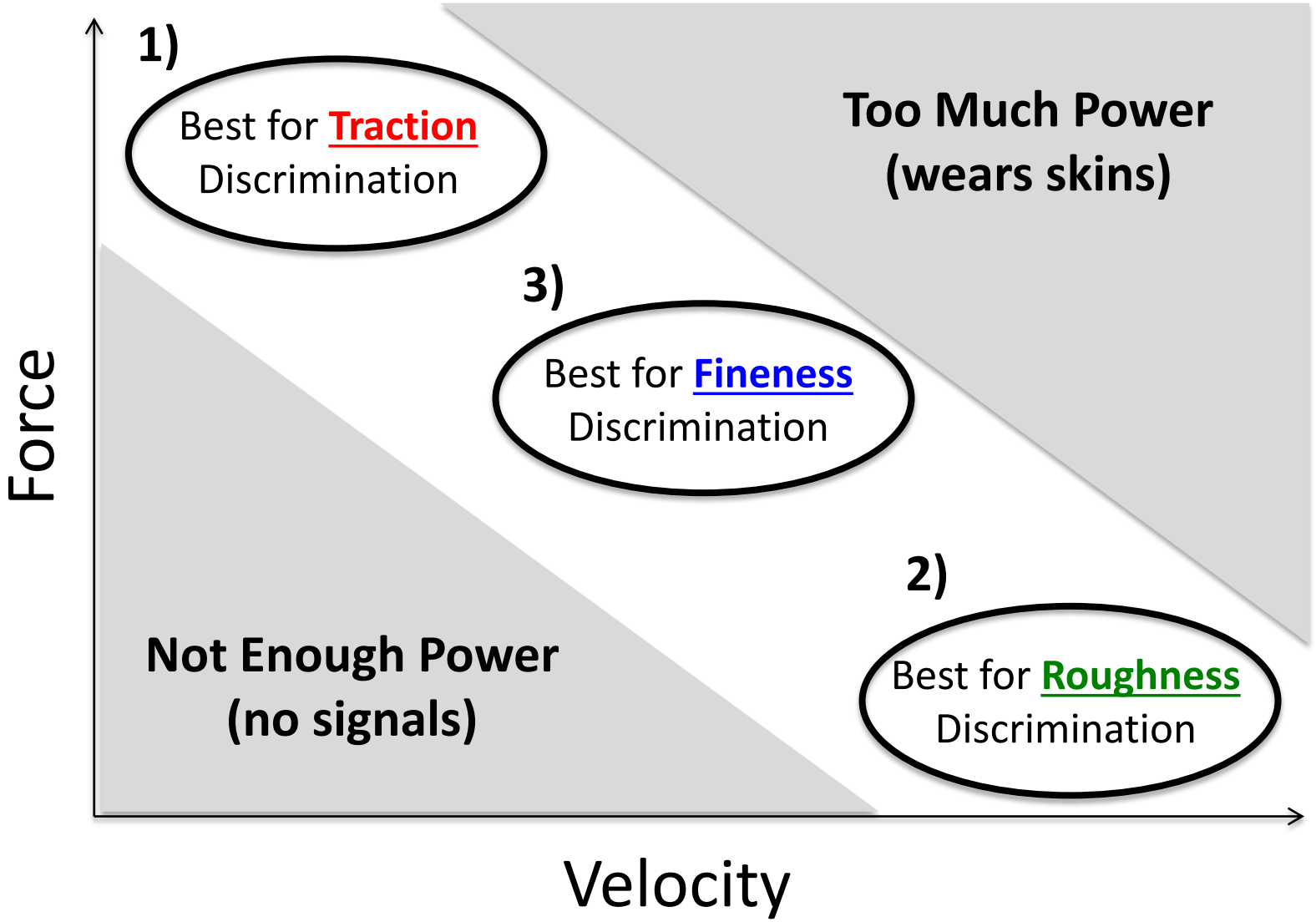
  from language humans use

- **<u>Intelligent Exploratory Strategies</u>**

  inspired by theories of biological behavior

Pilot Study – Which Movements are Best?

$$Power \mu Force' velocity$$

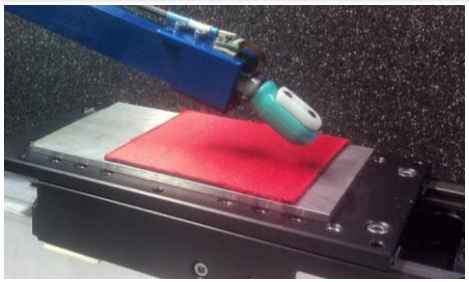


Texture Properties (from Language)

Inspired from psychophysical literature on texture discrimination

- Traction: *sticky / slippery*

  Thrust (from motor)

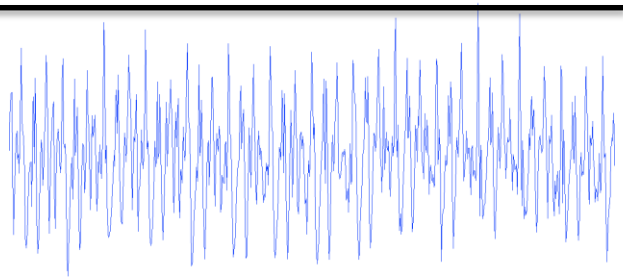


- Roughness: *rough / smooth*

  Vibration Power

Vibration:

Rough:

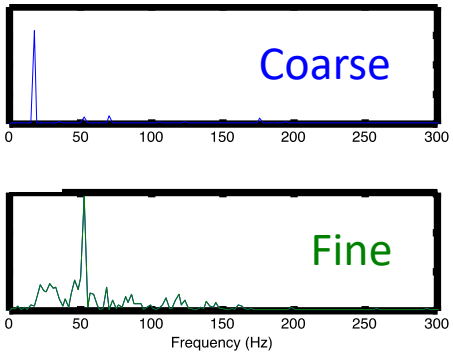


Smooth:

- Fineness: *coarse / fine*

  Center Frequency

FFTs:



Bayesian Inference

$$P(A \mid B) = \frac{P(B \mid A)P(A)}{P(B)}$$

Bayes' Theorem

Used to update probabilities of textures **<u>after</u>** a movement and observation is made…

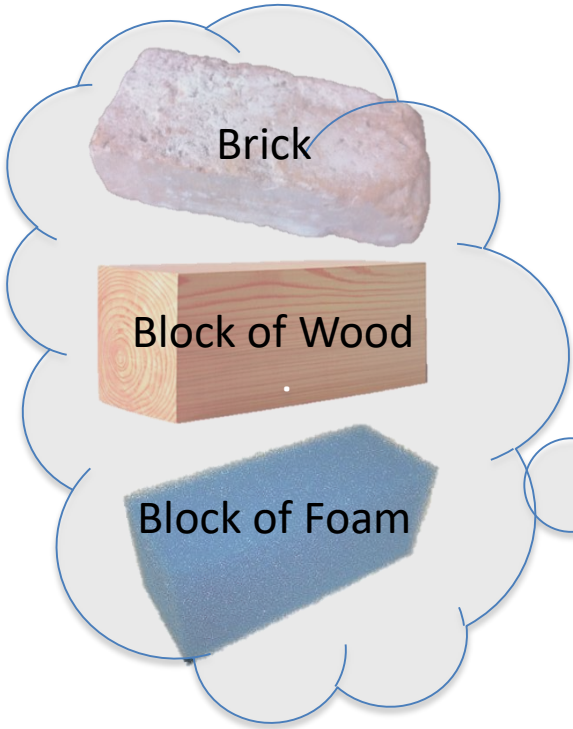
How do people decide which movements to make when exploring textures?

Theory: Bayesian Exploration

Unknown Object:

1) Grasp: Figure out shape/size

➔ Rectangular, Large

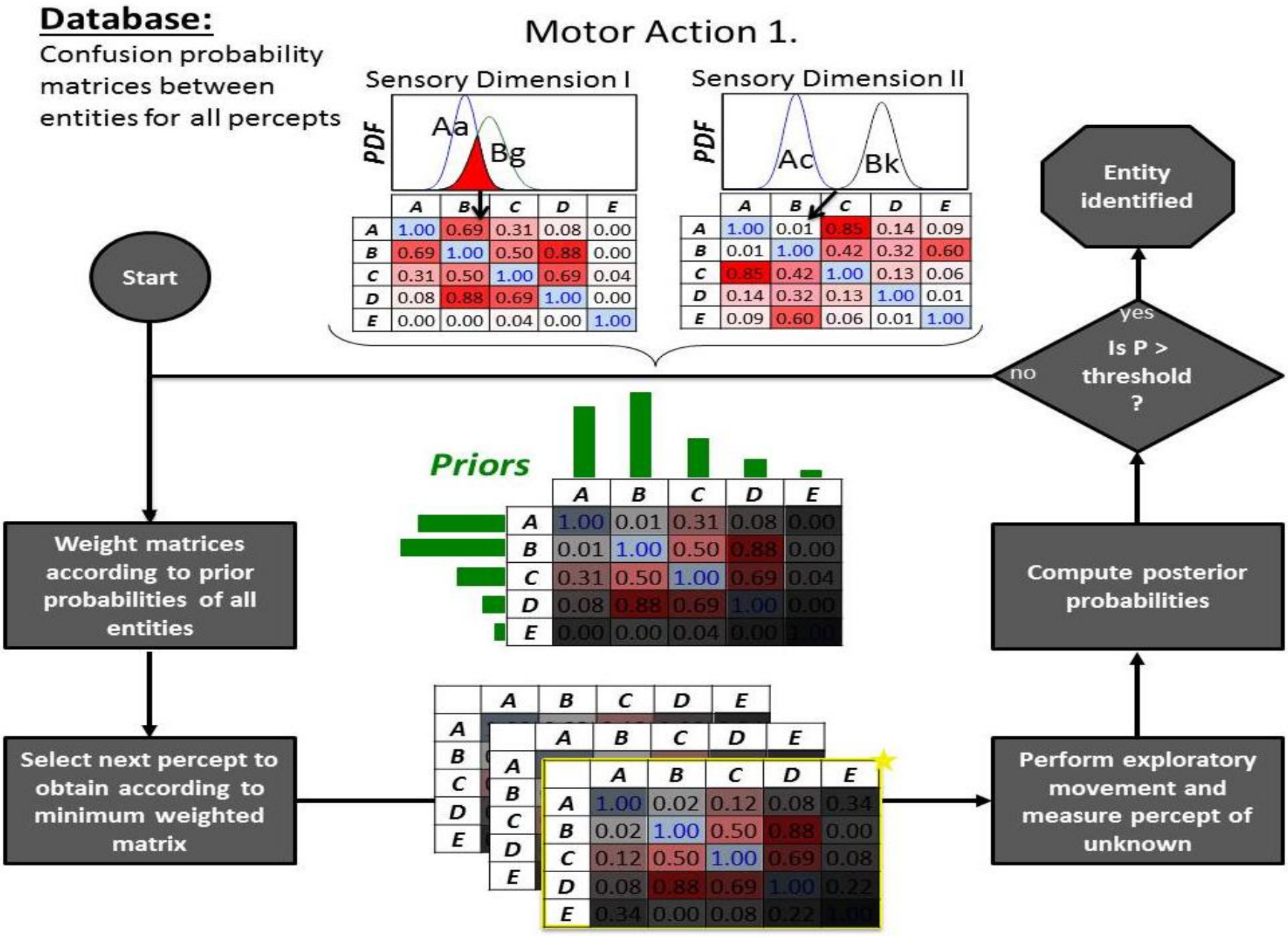


2) Pick Up: Is it Heavy?

➔ Heavy

It's a Brick!

Bayesian Exploration



117 Textures!

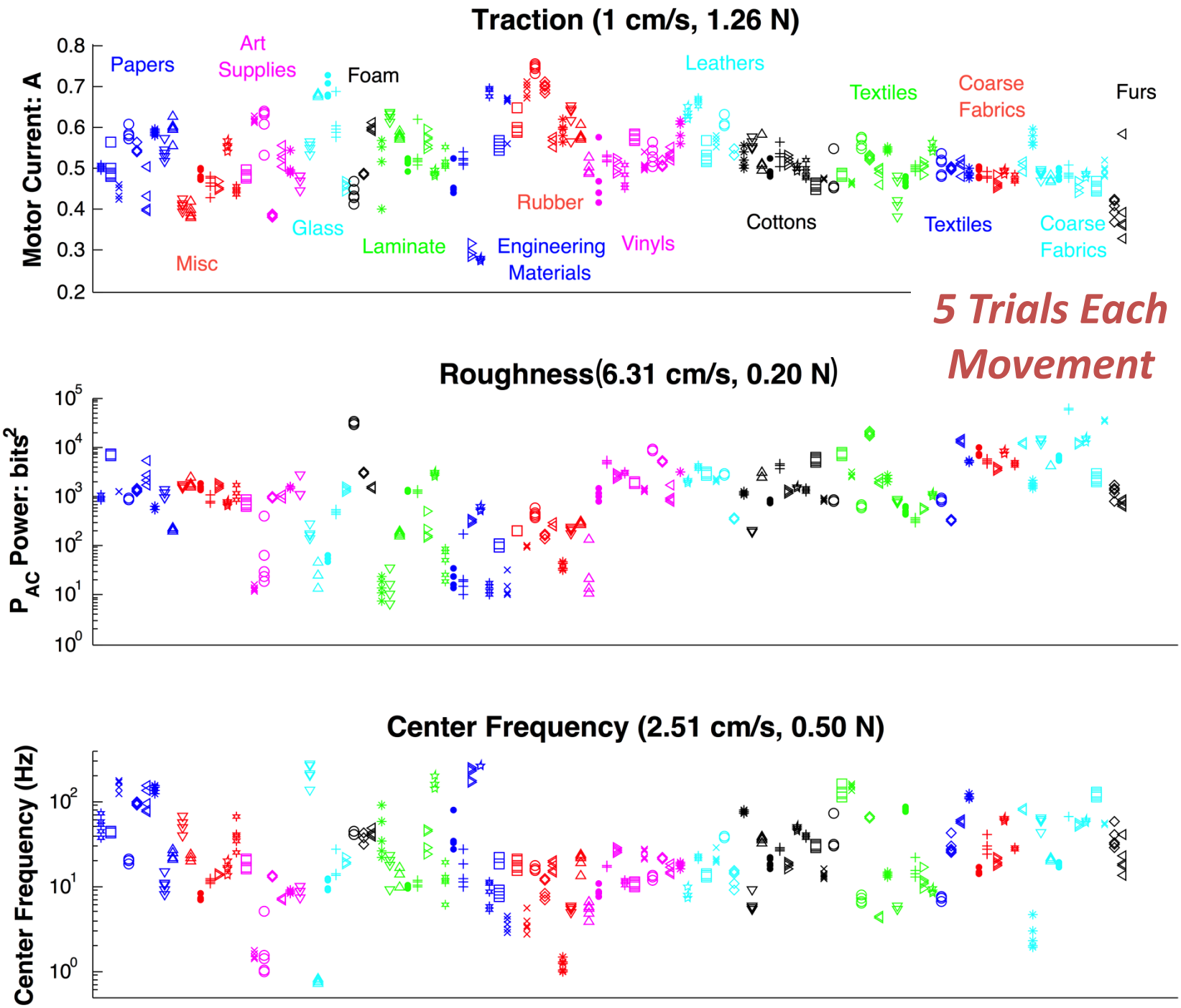
5 Trials Each Movement

Glasses Foams Rubbers Leathers Cloths Weaves

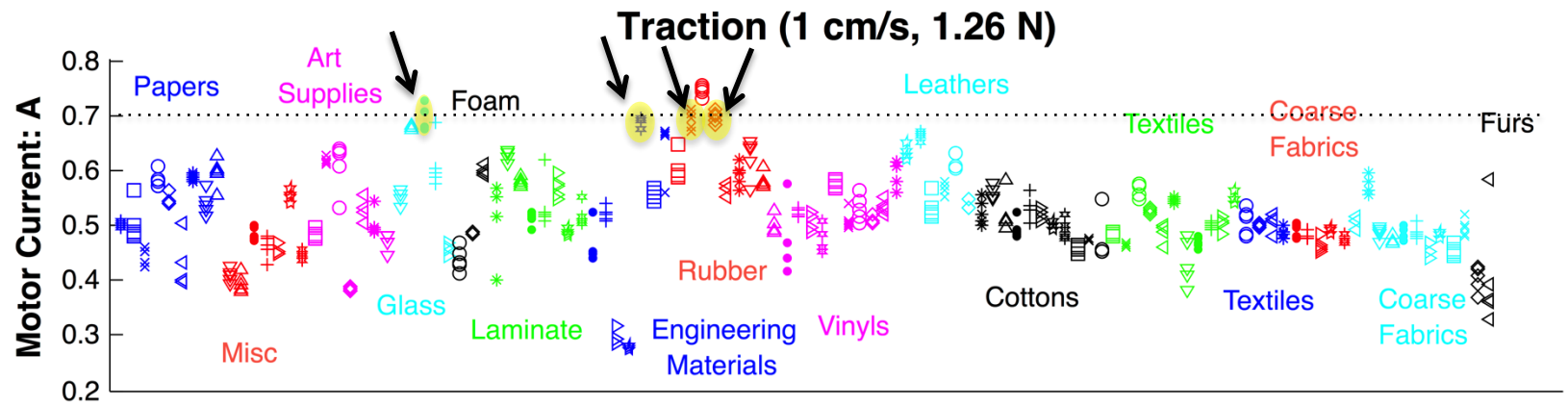
Papers

Furs

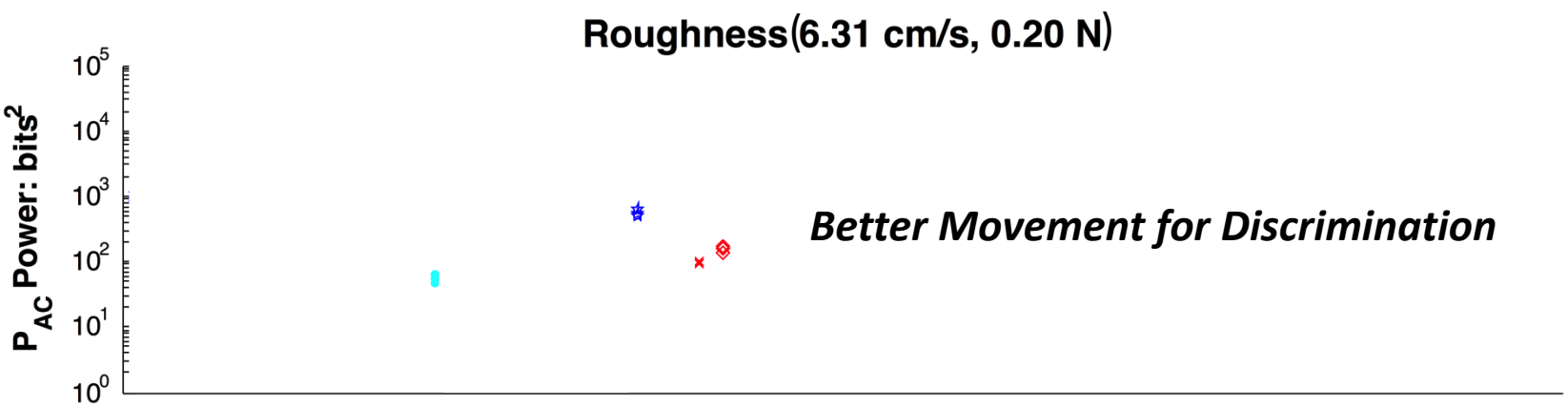
Art Supplies Woods Metal Finishes Plastics Vinyls

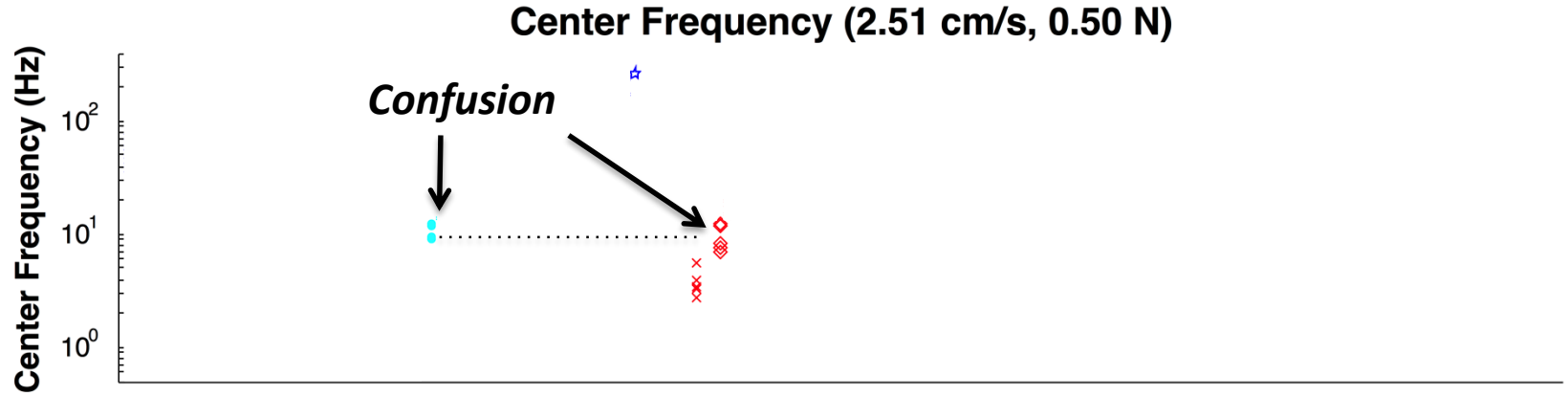

Traction (1 cm/s, 1.26 N)
Motor Current: A
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Papers
Art Supplies
Foam
Leathers
Textiles
Coarse Fabrics
Furs
Rubber
Glass
Laminate
Engineering Materials
Vinyls
Cottons
Textiles
Coarse Fabrics
Misc
5 Trials Each Movement
Roughness(6.31 cm/s, 0.20 N)
P_AC Power: bits^2
10^5
10^4
10^3
10^2
10^1
10^0
Center Frequency (2.51 cm/s, 0.50 N)
Center Frequency (Hz)
10^2
10^1
10^0

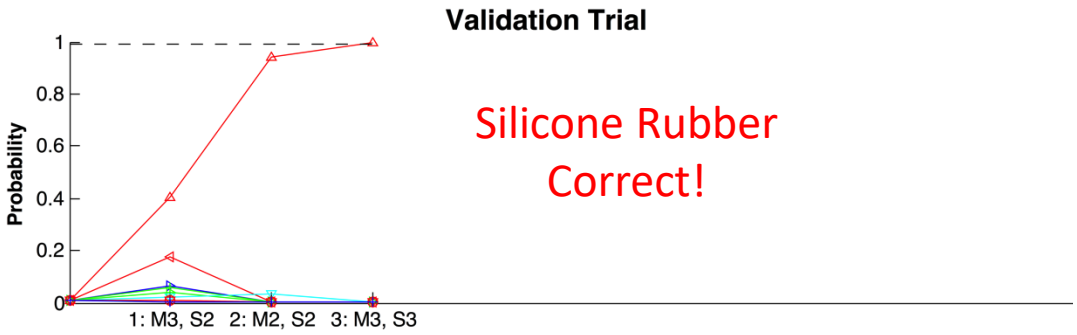
1st Movement



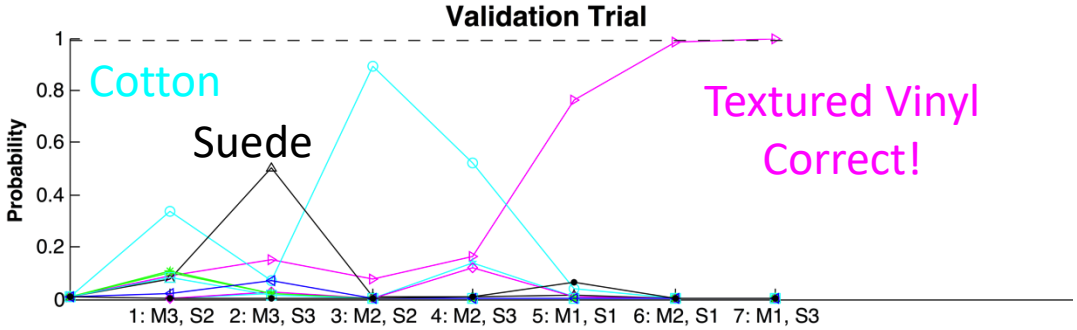
Possible Future Movements



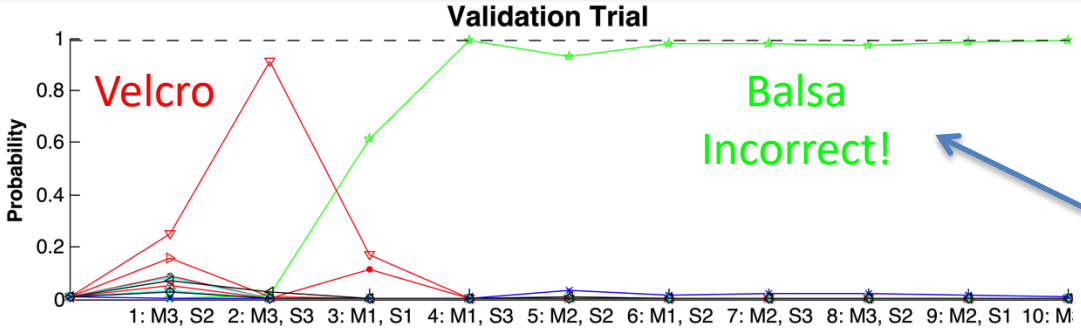


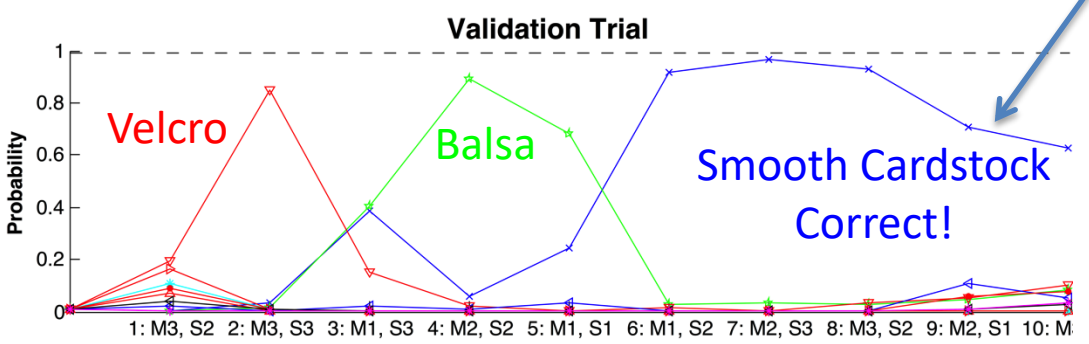


Sometimes rapid identification



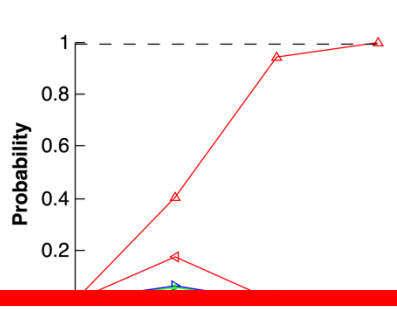
Sometimes tests a few hypotheses before a correct identification





Sometimes difficulty distinguishing two materials that humans cannot distinguish either

1)



Silicone Rubber
Correct!

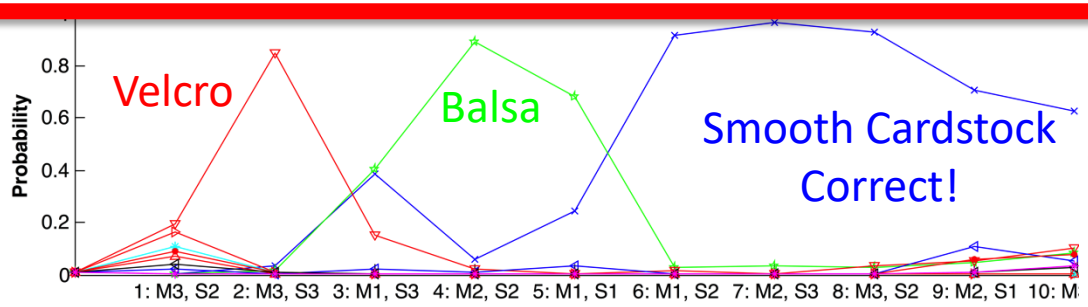
Sometimes, Quick
Identification

16 Validation Textures

Average: 95.4% Correct Classification

Median Movements to Converge: 5

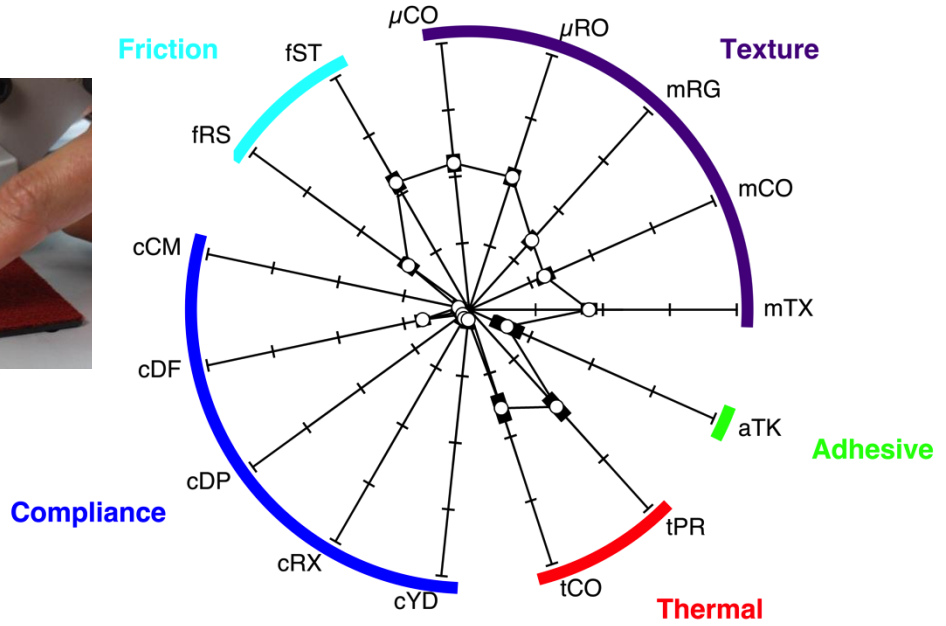
4)



two: Smooth Cardstock
and Balsa Wood

Quantifying Touch

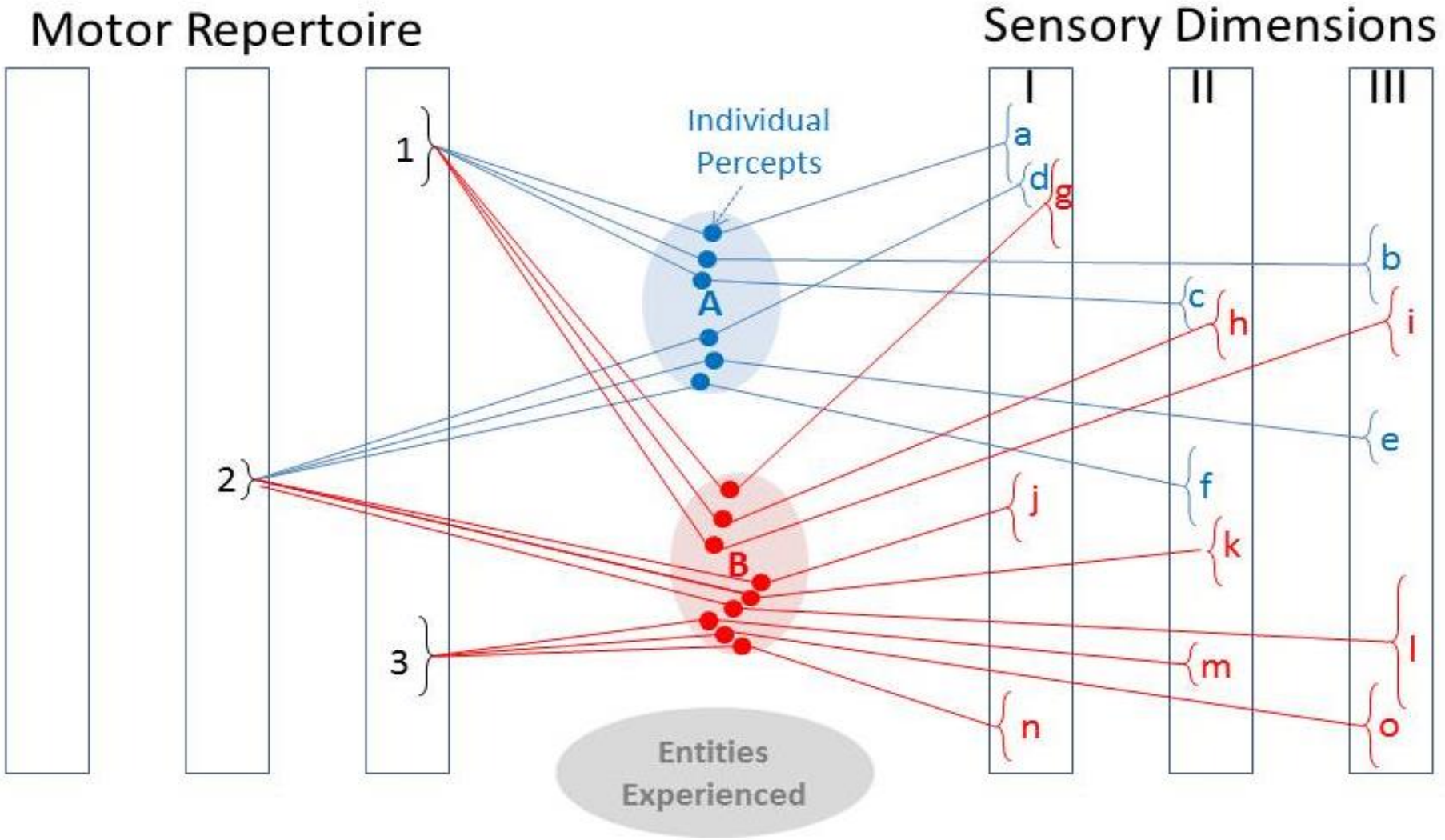
Measures 15 properties related to:
Texture, Friction, Compliance,
Thermal Properties and Adhesion



**If you can feel the difference,
we can quantify it!**

syntouch

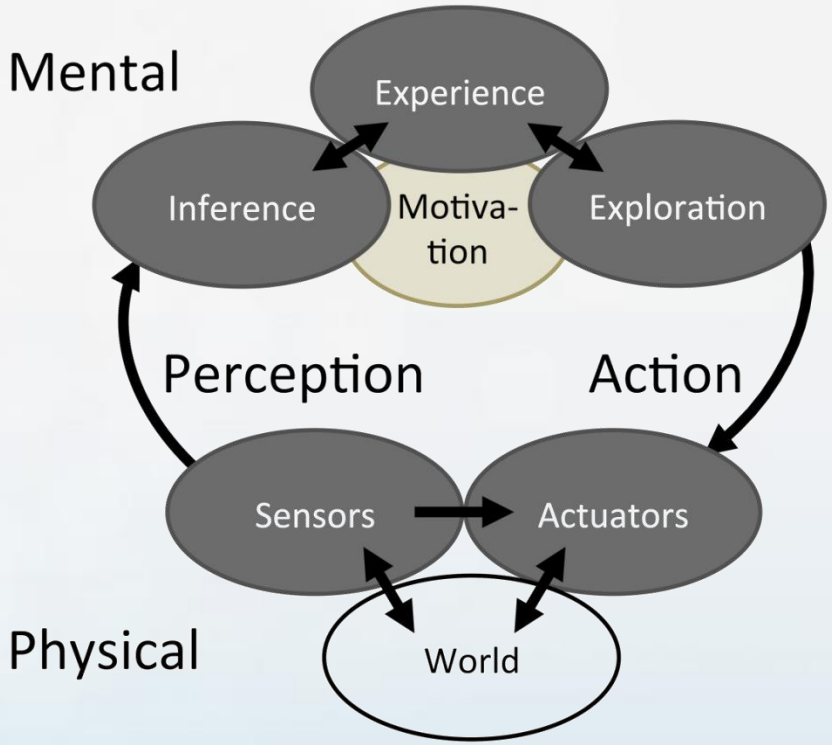
Representing the World in the Brain



Bayesian Action&Perception:

Representing the World in the Brain

Recently expanded to 500 materials explored by 5 movements to create 15 perceptual dimensions, resulting in MORE ACCURATE and FASTER performance.
Avoids "curse of dimensionality"



G.E. Loeb and J.A. Fishel, 2014
Frontiers in Neuroscience, doi: 10.3389/fnins.2014.00341

syntouch