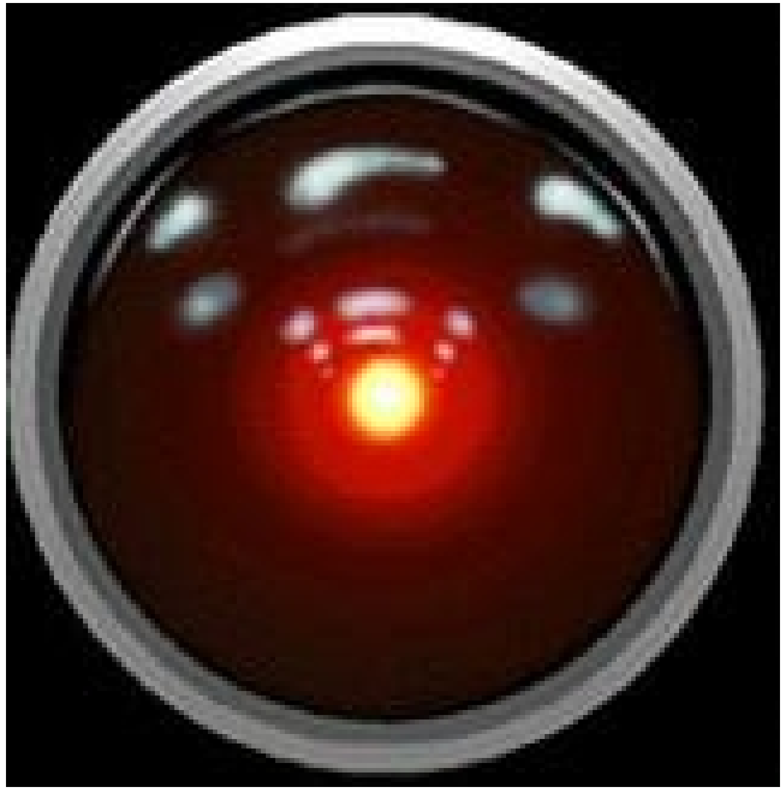
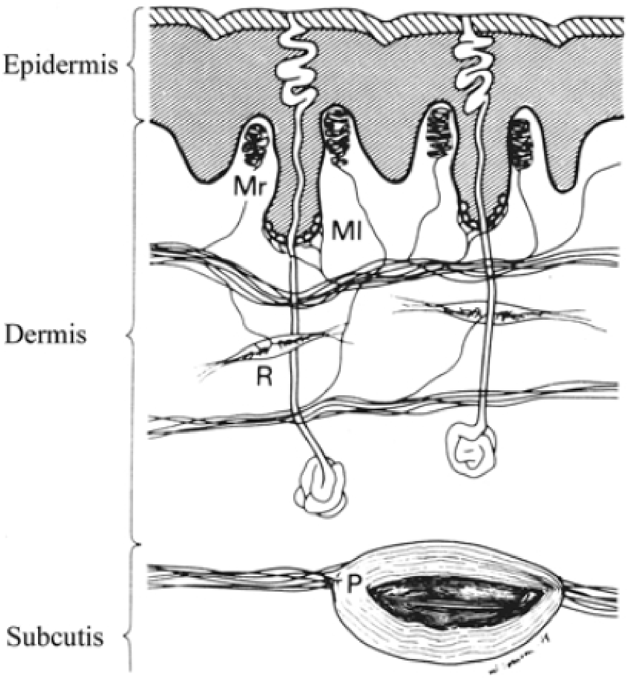


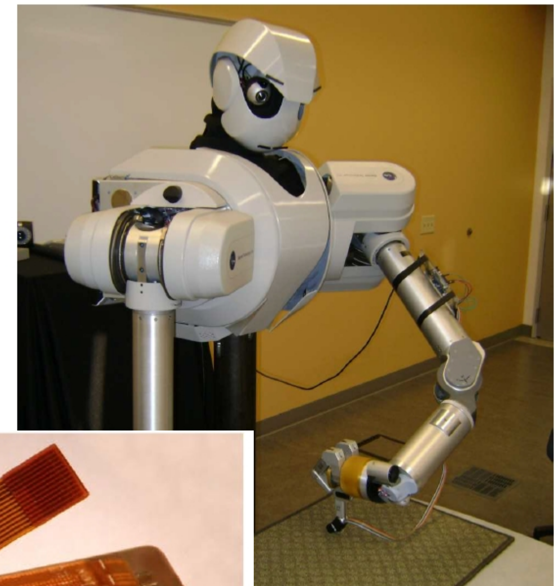
CS 378: Autonomous Intelligent Robotics

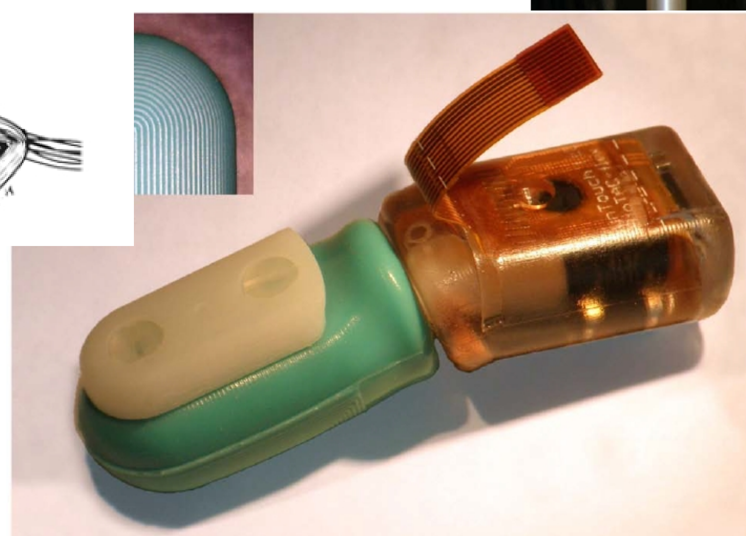
Instructor: Jivko Sinapov

http://www.cs.utexas.edu/~jsinapov/teaching/cs378/

The Sense of Touch

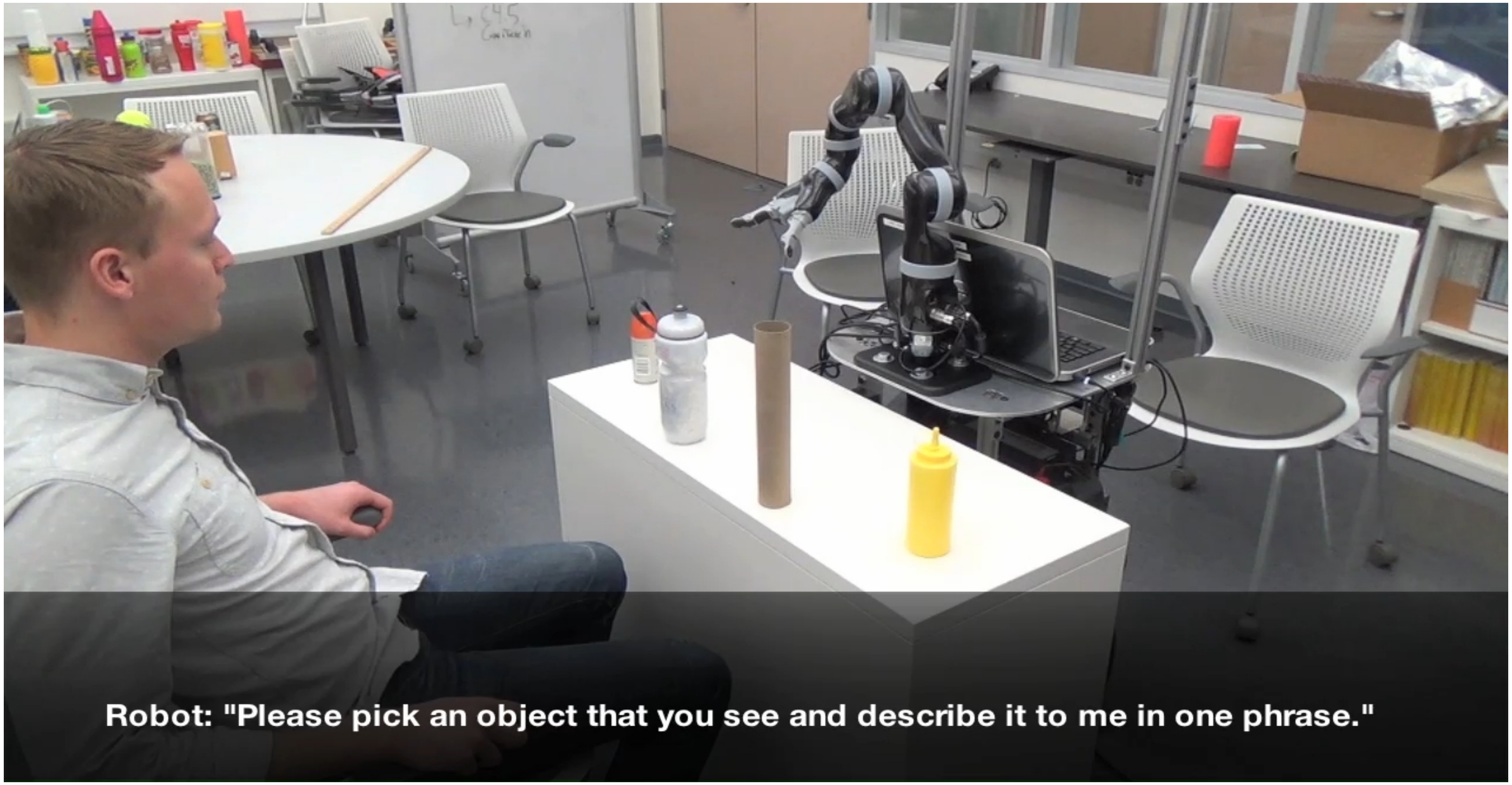






Announcements

Remember this?



Announcements

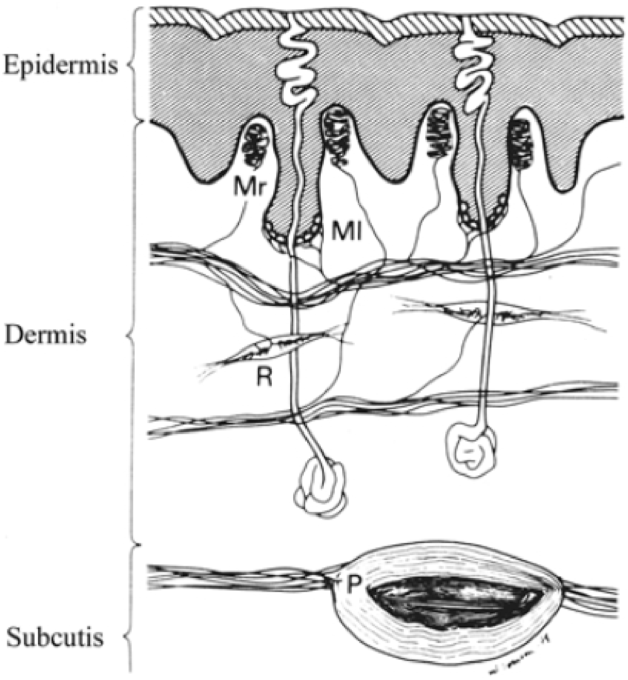
Project Deliverables

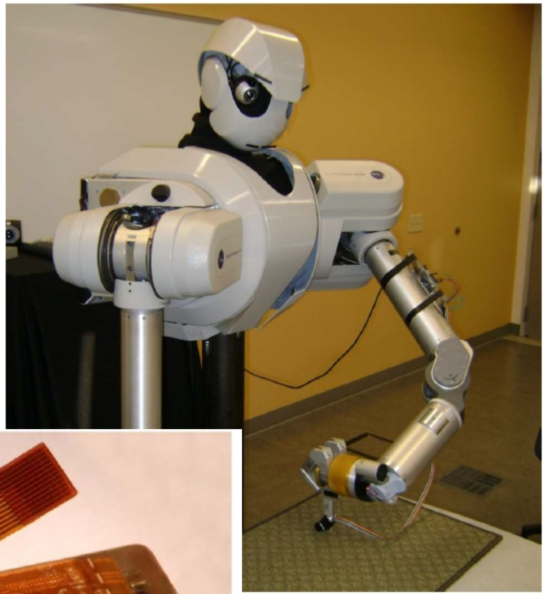
- Final Report (6+ pages in PDF)
- Code and Documentation (posted on github)
- Presentation including video and/or demo

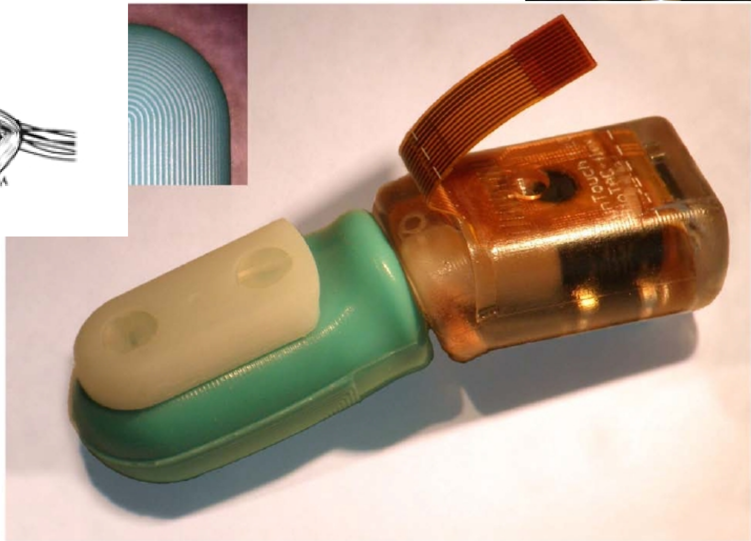
Readings for next week

As before, your pick.

The Sense of Touch

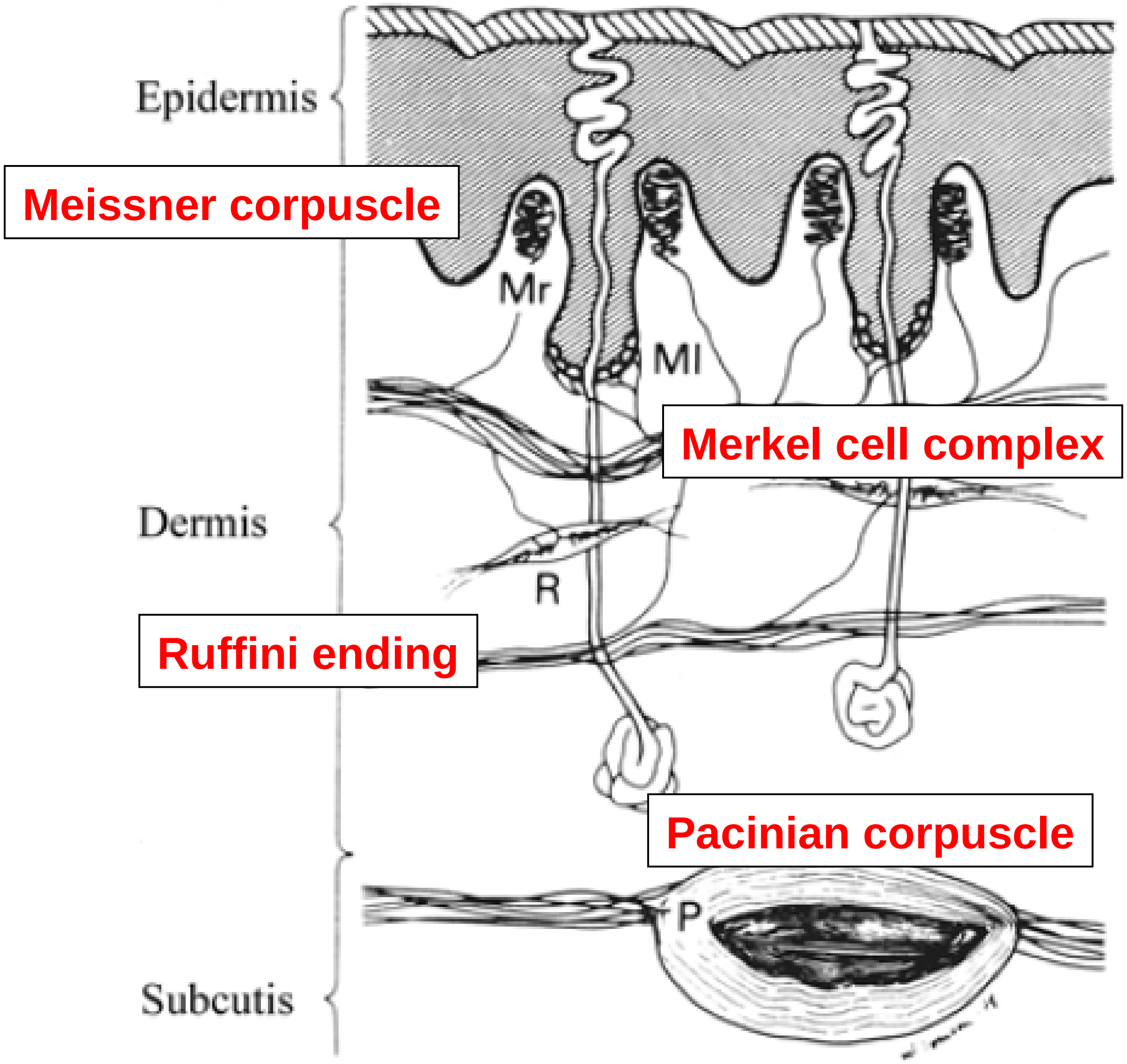






Overview of Haptic Sensing

"The haptic system uses sensory information derived from mechanoreceptors and thermoreceptors embedded in the skin ("**cutaneous**" inputs) *together with mechanoreceptors* embedded in muscles, tendons, and joints ("**kinesthetic**" inputs)."



Epidermis
Meissner corpuscle
Mr
MI
Merkel cell complex
Dermis
R
Ruffini ending
Pacinian corpuscle
P
Subcutis

Properties of Mechanoreceptors

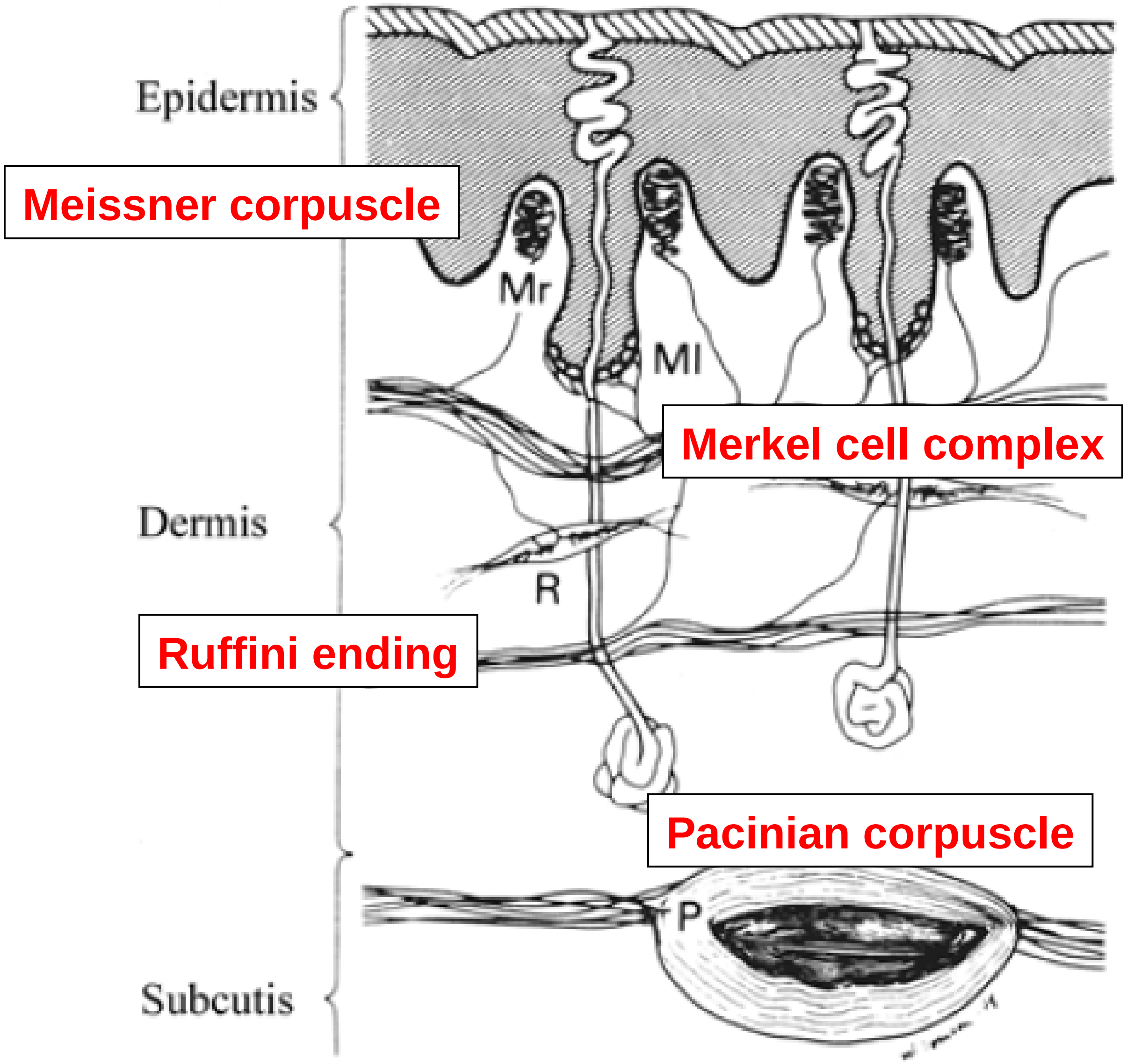
- Relative size of receptive field
  - Small vs. Large

- Relative adaptation rate
  - Response to onset/offset of skin deformation vs. continued response during sustained skin deformation

Table 1A
Response Characteristics of the Four Mechanoreceptor Populations

	Size of Receptive Field	
Adaptation Rate	Small	Large
Slow	Slow-adapting type I (SA I) (Merkel)	Slow-adapting type II (SA II)[a] (Ruffini)
Fast	Fast-adapting type I (FA I) (Meissner)	Fast-adapting type II (FA II) (Pacinian)

Note—The terminal ending associated with each type of tactile nerve fiber is shown in parentheses. [a]Note that primate research has failed to find evidence for the existence of SA II units (see, e.g., Johnson, 2001). From *Sensation and Perception* (2nd ed., p. 302), by J. M. Wolfe et al., 2008, Sunderland, MA: Sinauer.



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Meissner corpuscle
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Ml
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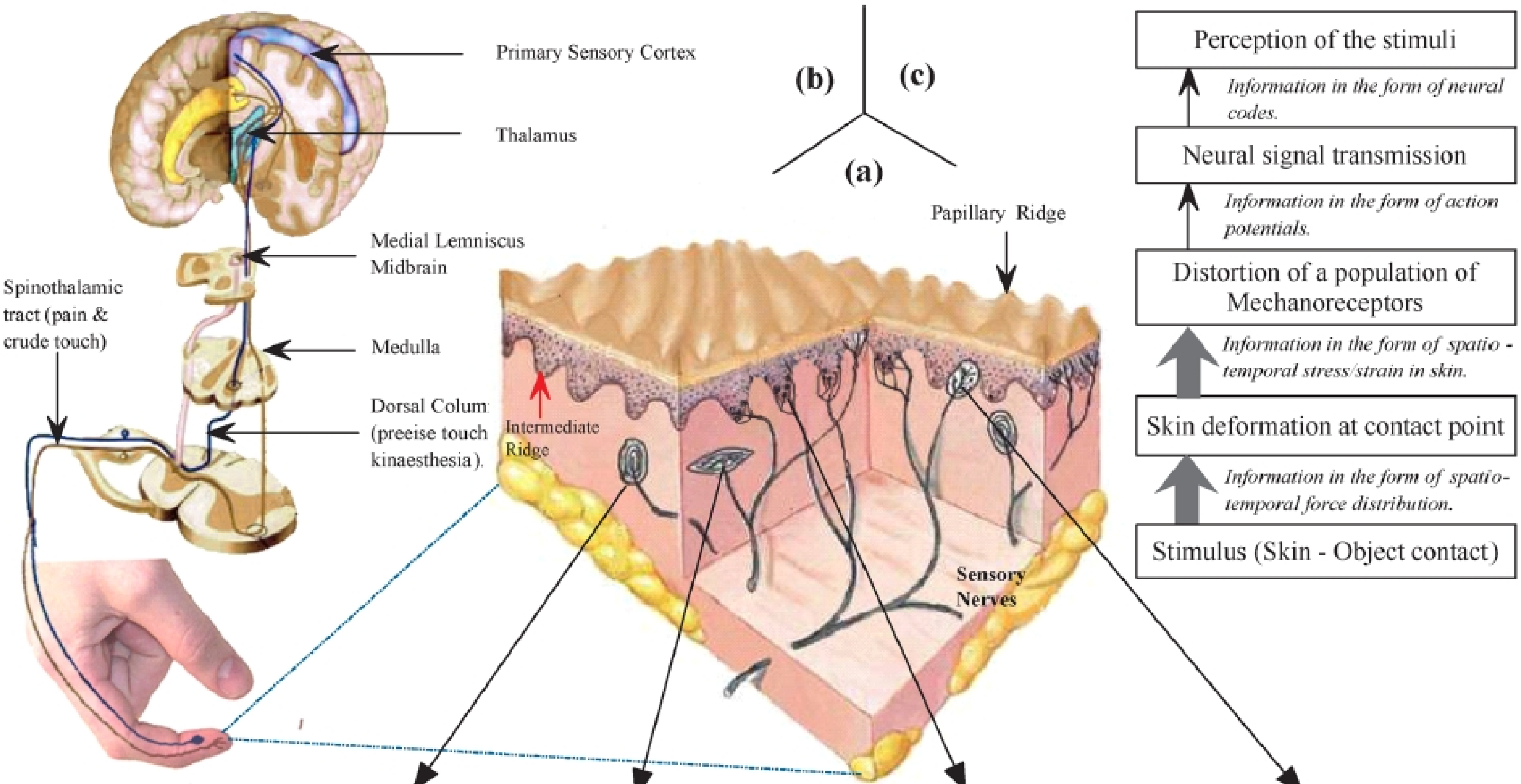
P
Subcutis



Classification Basis		Pacinian Corpuscle	Ruffini Corpuscle	Merkel Cells	Meissner's Corpuscle
Type		FA II	SA II	SA I	FA I
Adaptation Rate		Fast	Slow	Slow	Fast
Spatial Acuity (mm)		10+	7+	0.5	3-4
Vibration/rapid indent. threshold	Best(μm)	0.01	40	8	2
	Mean(μm)	0.08	300	30	6
Stimuli Frequency (Hz)		40-500+	100-500+	0.4-3	3-40
Conduction Velocity (m/s)		35-70	35-70	40-65	35-70
Effective Stimuli		Temporal changes in the skin deformation	Sustained downward Pressure; Lateral skin stretch; Skin slip.	Spatial deformation; Sustained pressure; Curvature, edge, corners.	Temporal changes in skin deformation
Sensory Function		High frequency vibration detection; Tool use.	Finger position; Stable grasp; Tangential Force; Motion direction	Pattern/form detection; texture perception; Tactile flow perception.	Low frequency vibration & motion detection; Grip control; Tactile flow perception.

Mechanoreceptor Population	Maximum Feature Sensitivity
SA I	Sustained pressure; maximally sensitive to very low frequencies (<~5 Hz) (Johansson, Landström, & Lundström, 1982); spatial deformation (Johnson & Lamb, 1981)
FA I	Temporal changes in skin deformation (~5 to ~40 Hz) (Johansson et al., 1982); spatial deformation (Johnson & Lamb, 1981)
FA II	Temporal changes in skin deformation (~40 to ~400 Hz) (Johansson et al., 1982)
SA II	Sustained downward pressure, lateral skin stretch (Knibestöl & Vallbo, 1970); low dynamic sensitivity (Johansson et al., 1982)

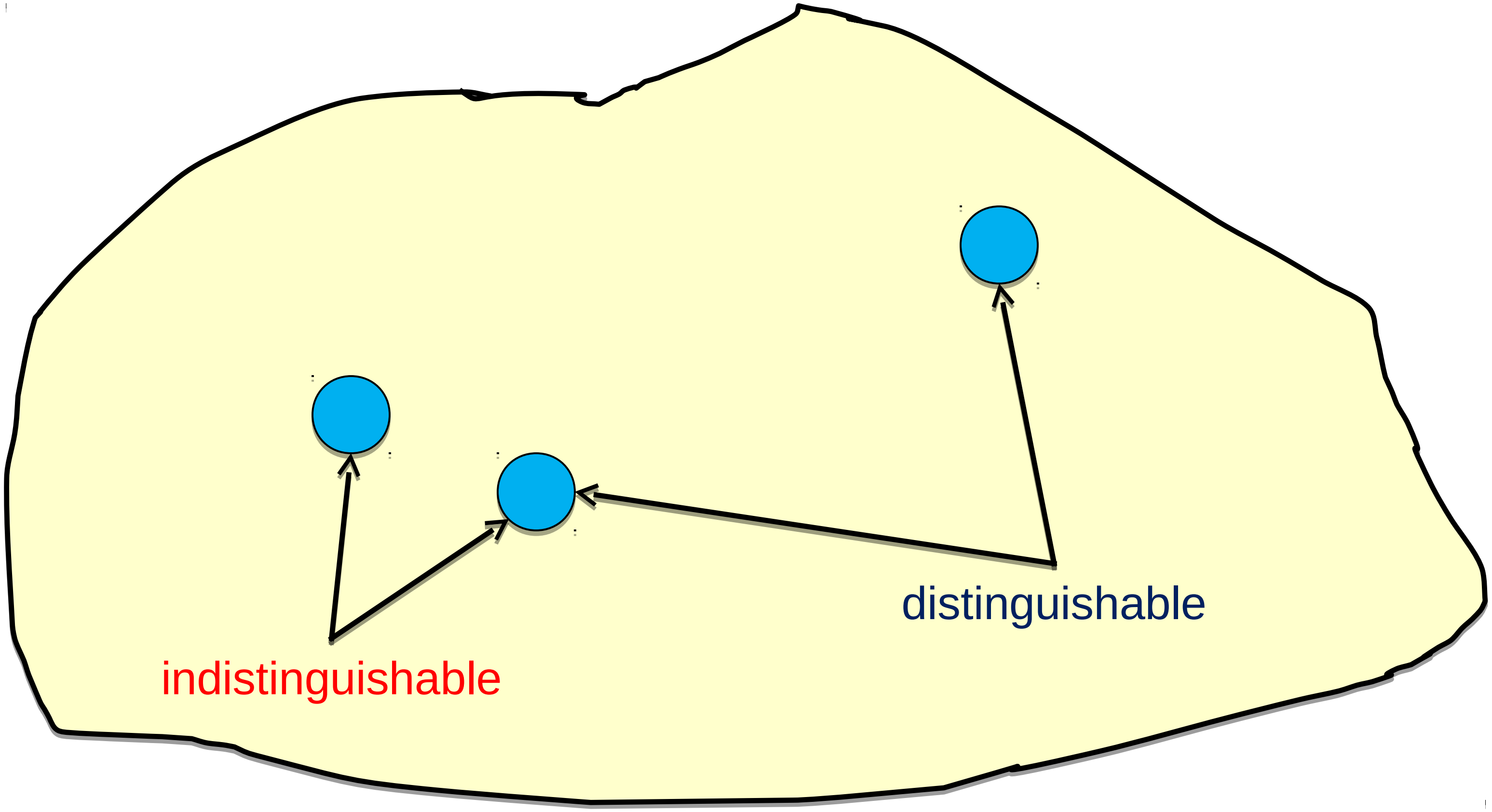
Mechanoreceptor Population	Primary Functions
SA I	Very-low-frequency vibration detection (Löfvenberg & Johansson, 1984) Coarse texture perception (D. T. Blake, Hsiao, & Johnson, 1997) Pattern/form detection (Johnson & Phillips, 1981) Stable precision grasp and manipulation (Westling & Johansson, 1987)
FA I	Low-frequency vibration detection (Löfvenberg & Johansson, 1984) Stable precision grasp and manipulation (Westling & Johansson, 1987)
FA II	High-frequency vibration detection (Löfvenberg & Johansson, 1984) Fine texture perception (Bensmaïa & Hollins, 2005) Stable precision grasp and manipulation (Westling & Johansson, 1987)
SA II	Direction of object motion and force due to skin stretch (Olausson, Wessberg, & Kakuda, 2000) Stable precision grasp and manipulation (Westling & Johansson, 1987) Finger position (Edin & Johansson, 1995)

Measuring Spatial Acuity

Measuring Spatial Acuity

- Two-point touch threshold:
  - Represents the smallest spatial separation that can be detected some arbitrary percentage of the time

Measuring Spatial Acuity



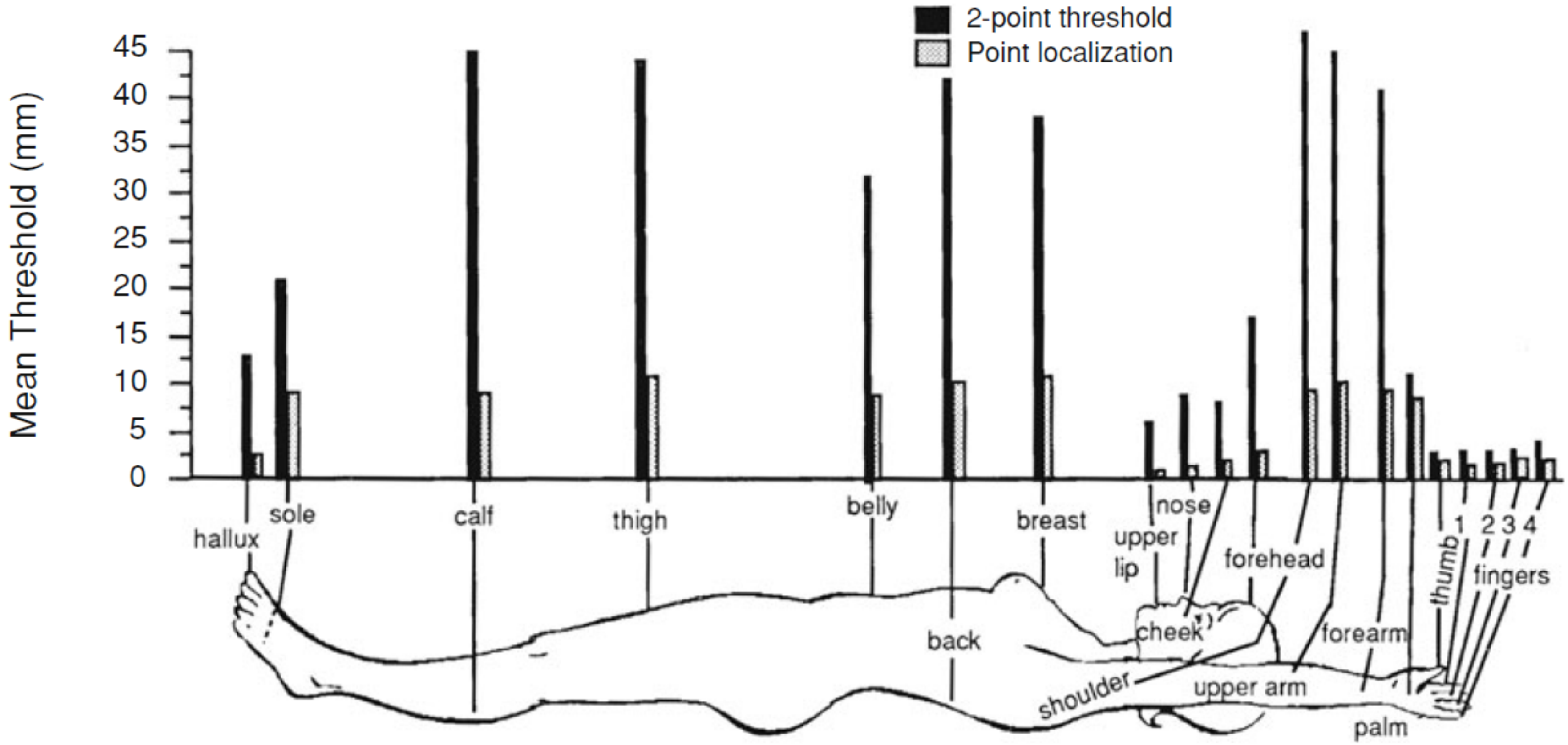
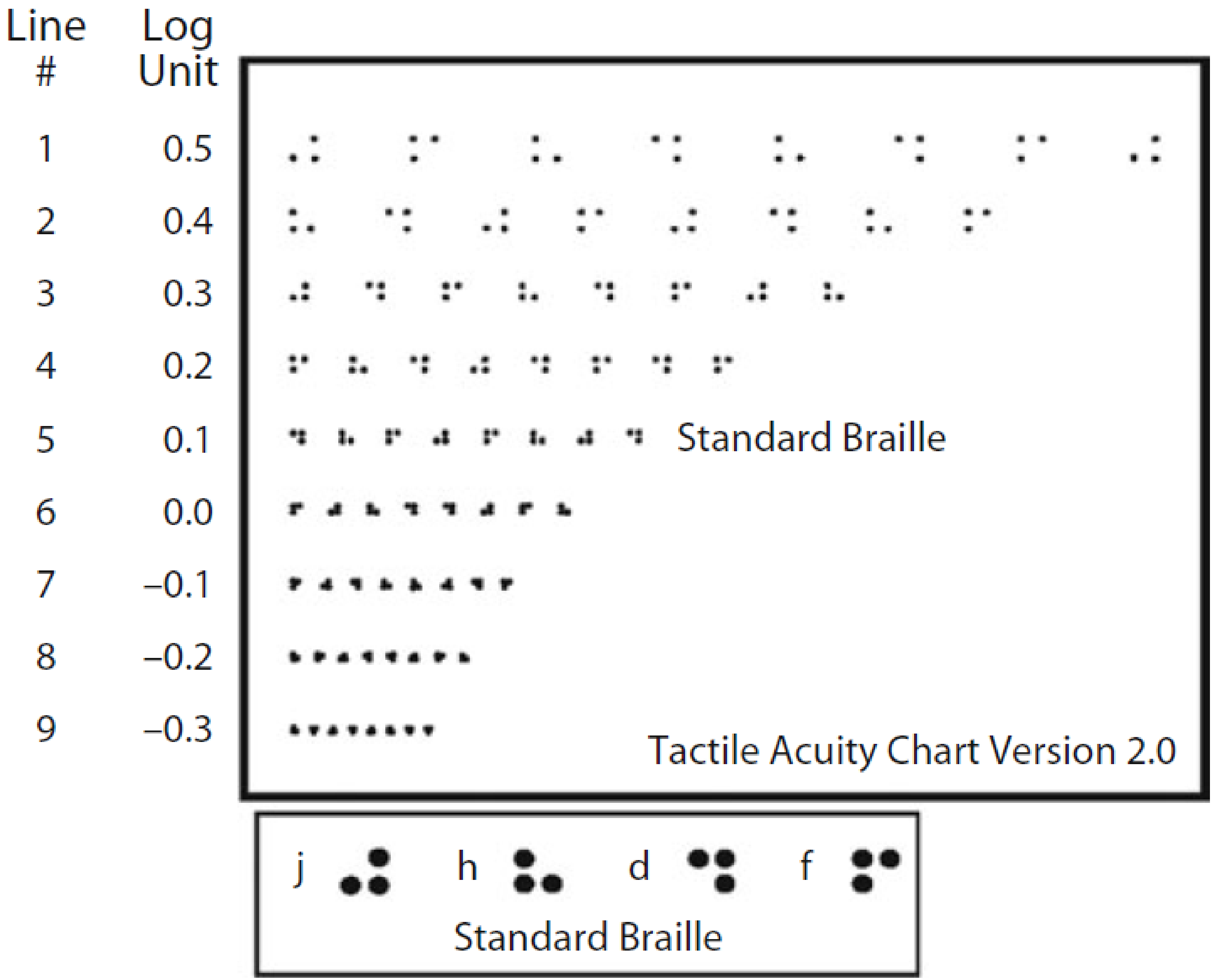
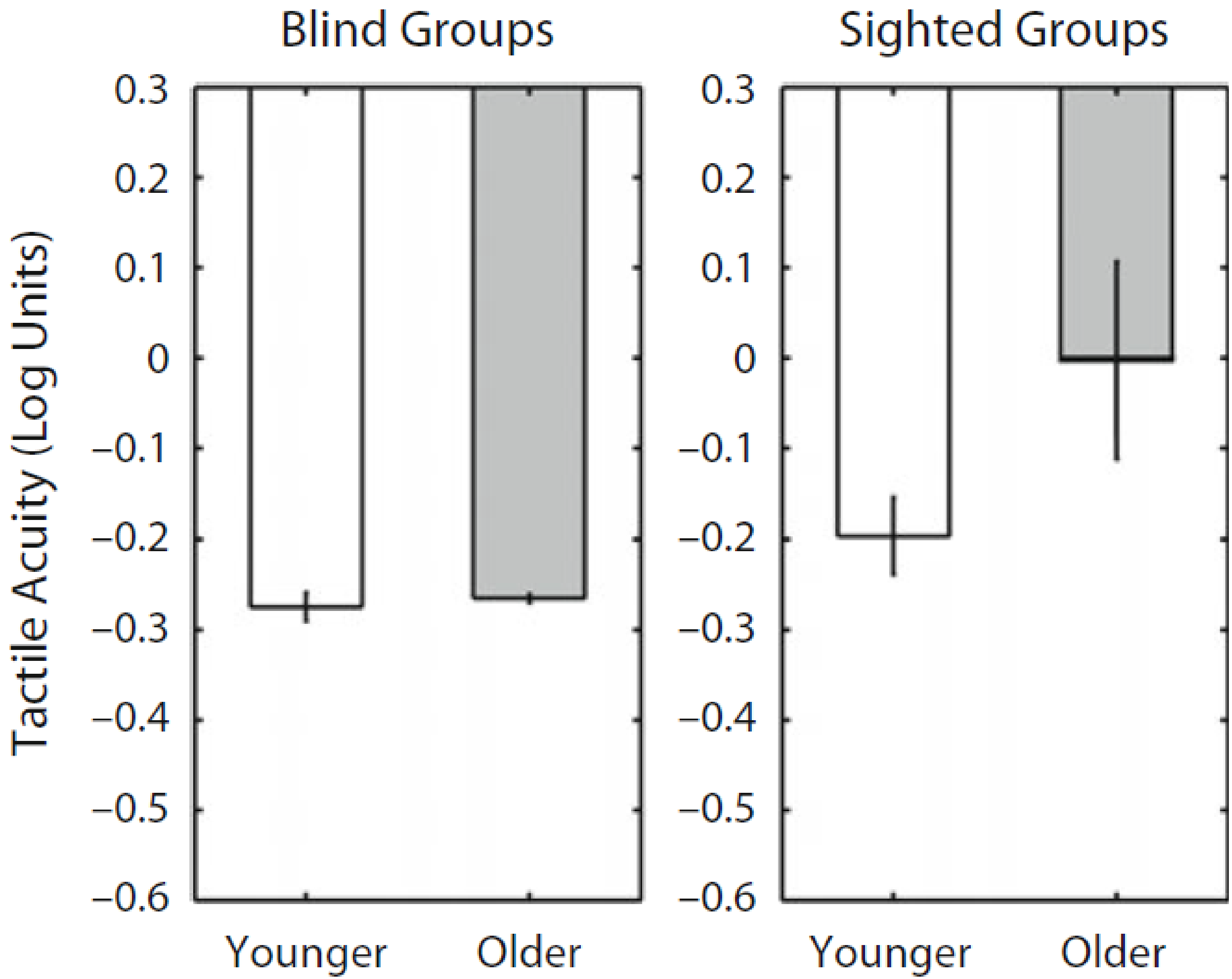


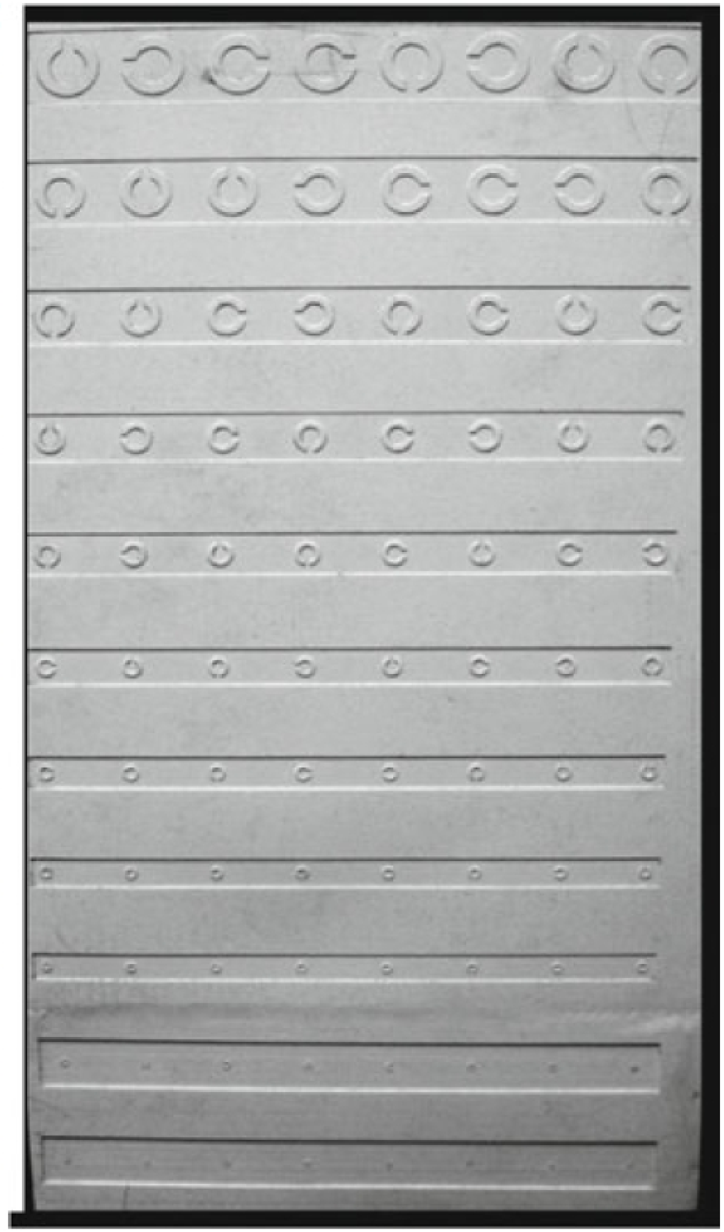
Figure 2. **Two-point touch and point localization thresholds are shown for various body sites. Although only the data for women are presented, the corresponding data for males show close parallels in their general patterns. The data represent mean threshold values for left and right sides of the body because, with few exceptions, there was no effect of laterality. Although the point localization thresholds are usually lower than the corresponding two-point values, the measures are highly correlated. The results indicate that the more distal parts of the body are more spatially acute. From "Skin and Touch," by S. J. Lederman, 1991, *Encyclopedia of Human Biology, Vol. 7*, p. 55. Copyright 1991 by Academic Press. (Figure adapted from S. Weinstein, 1968.) Reprinted with permission.**

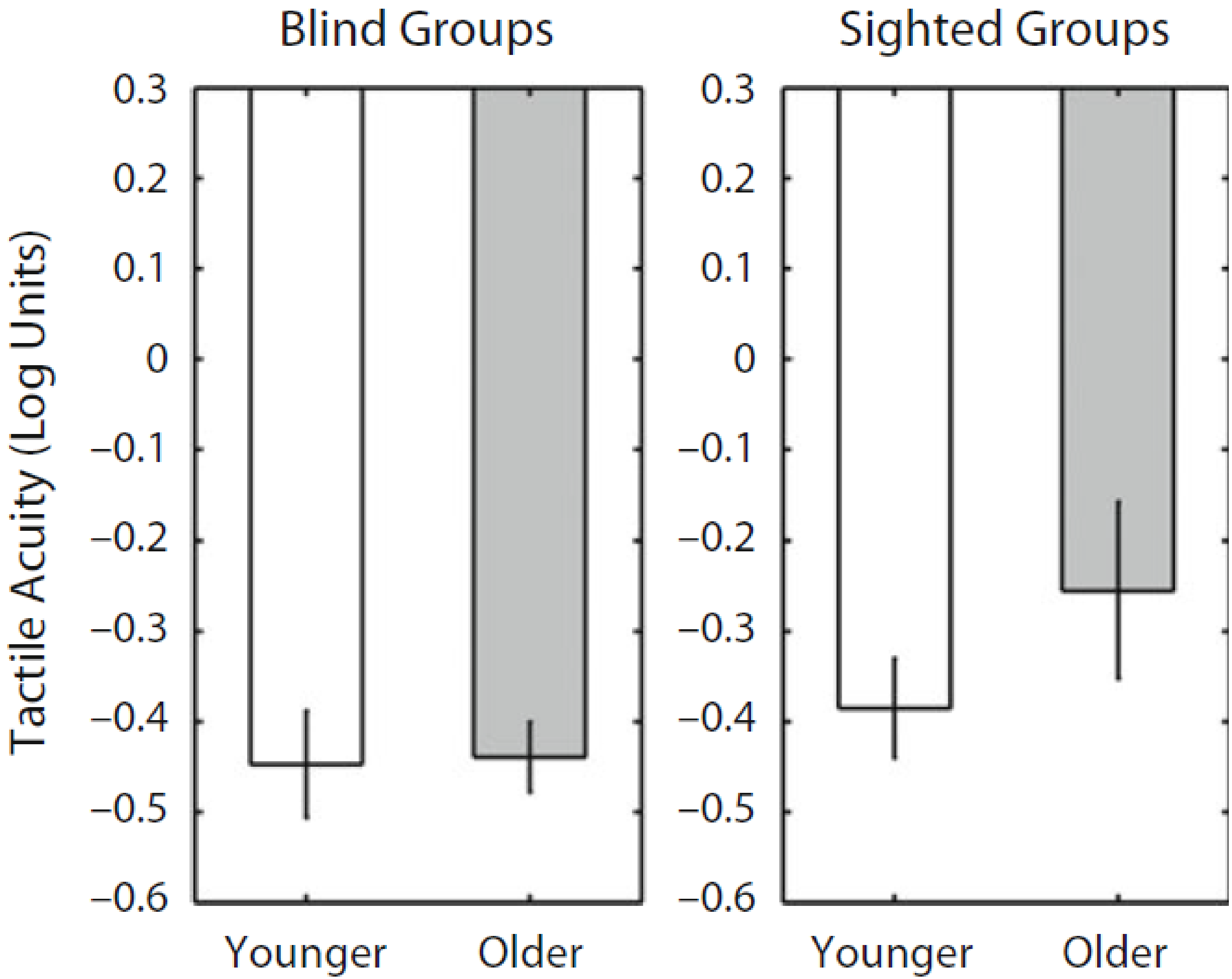

Line #
Log Unit
1 0.5
2 0.4
3 0.3
4 0.2
5 0.1
6 0.0
7 –0.1
8 –0.2
9 –0.3
Standard Braille
Tactile Acuity Chart Version 2.0
j
h
d
f
Standard Braille



Blind Groups
Sighted Groups
Tactile Acuity (Log Units)
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
Younger
Older
Younger
Older

Line #	Log Unit
1	0.3
2	0.2
3	0.1
4	0.0
5	–0.1
6	–0.2
7	–0.3
8	–0.4
9	–0.5
10	–0.6
11	–0.7





Blind Groups
Sighted Groups
Tactile Acuity (Log Units)
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
Younger
Older
Younger
Older

Temporal Resolving Capacity

- People can resolve a temporal gap of 5 msec between successive taps on the skin

- The temporal resolving capacity of skin is better than that of vision but worse than that of audition

How do people use haptic / tactile sensations to perceive objects?

Exploratory Procedures

Lateral Motion

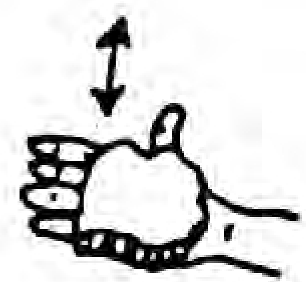
Pressure

Contour Following

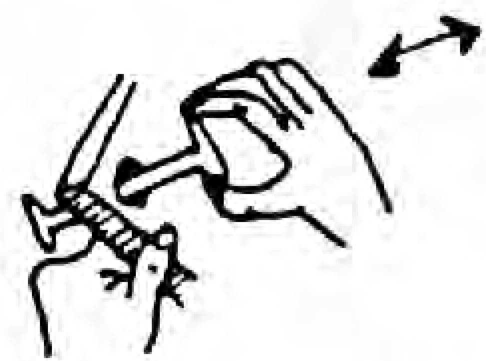
Enclosure

Static Contact

Insertion



Unsupported Holding



Part Motion Test

[Lederman and Klatzky, 1987]

Object Properties

- Material properties:
  - Surface texture, compliance, thermal quality
- Geometric Properties:
  - Shape and size
- The weight of an object reflects both its material density and its size

KNOWLEDGE ABOUT OBJECT	EXPLORATORY PROCEDURE
Substance-related properties	
Texture	Lateral motion
Hardness	Pressure
Temperature	Static contact
Weight	Unsupported holding
Structure-related properties	
Weight	Unsupported holding
Volume	Enclosure, contour following
Global shape	Enclosure
Exact shape	Contour following
Functional properties	
Part motion	Part motion test
Specific motion	Function test

[Power, 2000]

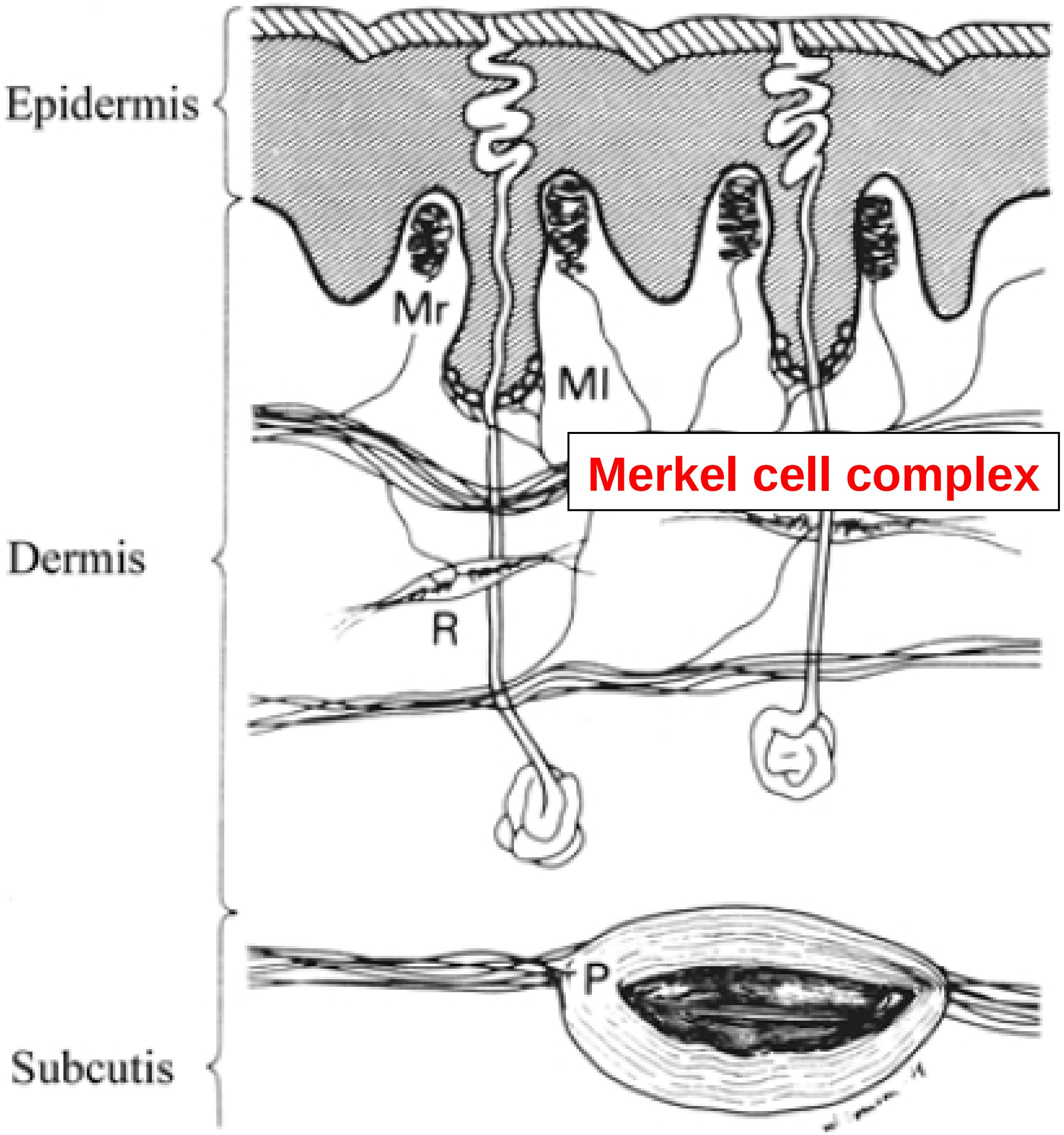
[Lederman and Klatzky, 1987]

The Sense of Touch: A Case Study with a Robot

Sinapov, J., Sukhoy, V., Sahai, R., & Stoytchev, A. (2011). Vibrotactile recognition and categorization of surfaces by a humanoid robot, IEEE Transactions on Robotics, 27(3), 488-497.

http://home.engineering.iastate.edu/~alexs/lab/publications/papers/IEEEtran_Robotics_2011/IEEEtran_Robotics_2011.pdf

The Vibrotactile Sensory Modality



Epidermis
Dermis
Subcutis
Mr
Ml
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P
Merkel cell complex

Mechanoreceptor Population	Maximum Feature Sensitivity
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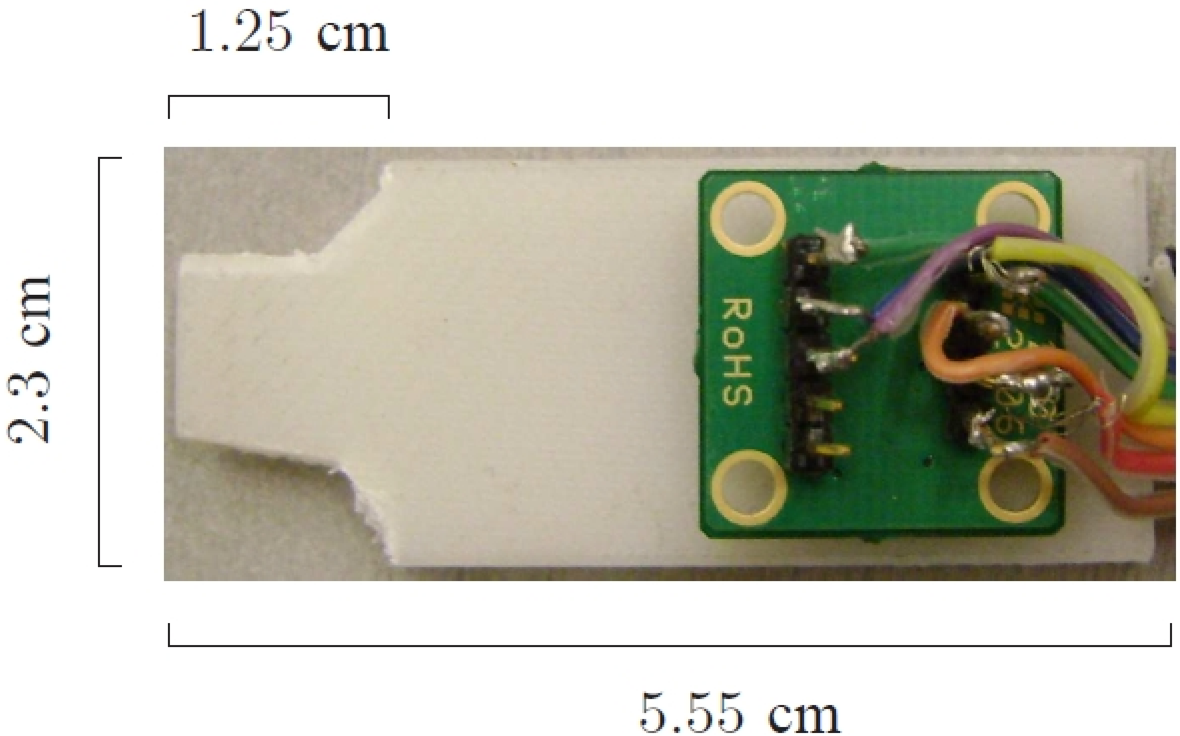
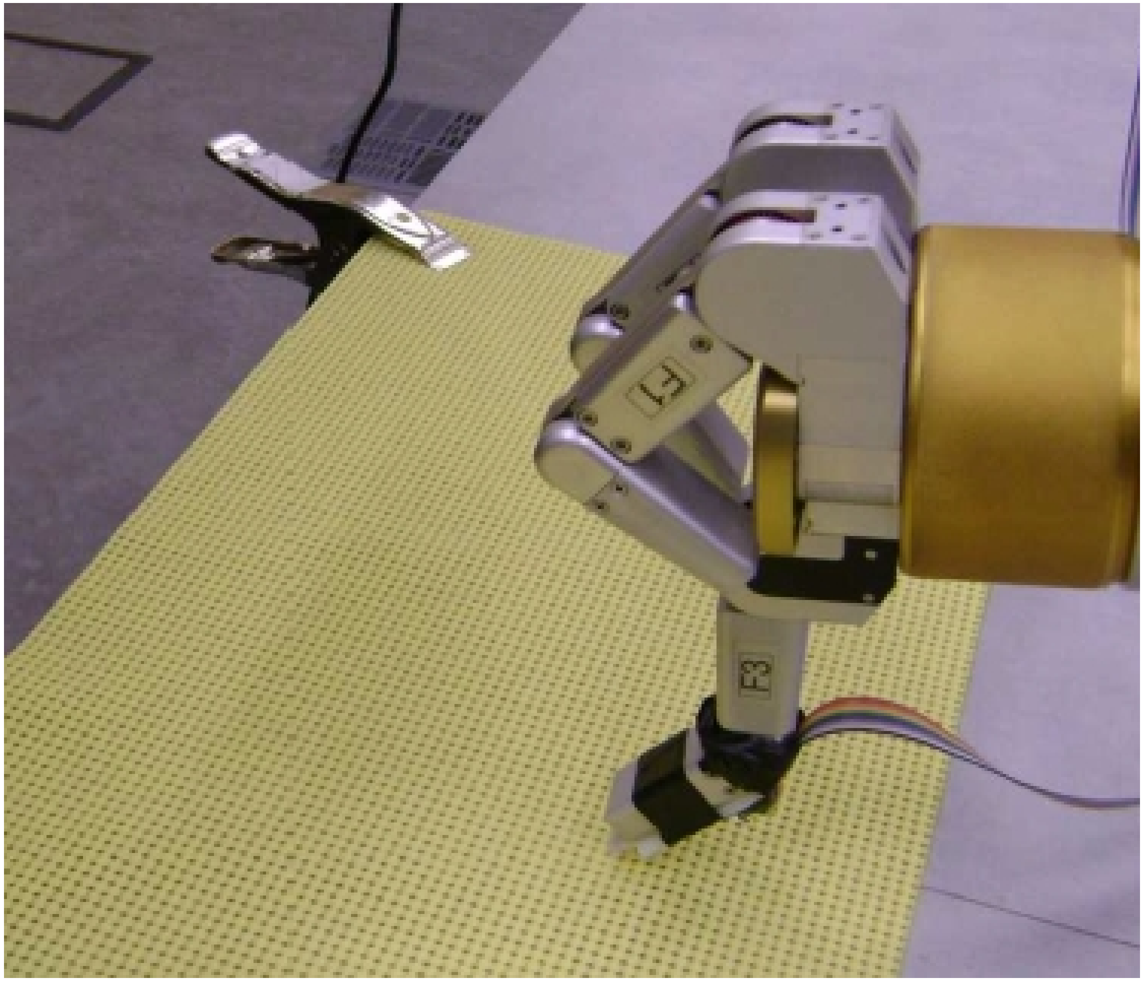
Can a robot use the vibrotactile sensory modality to recognize surface textures?

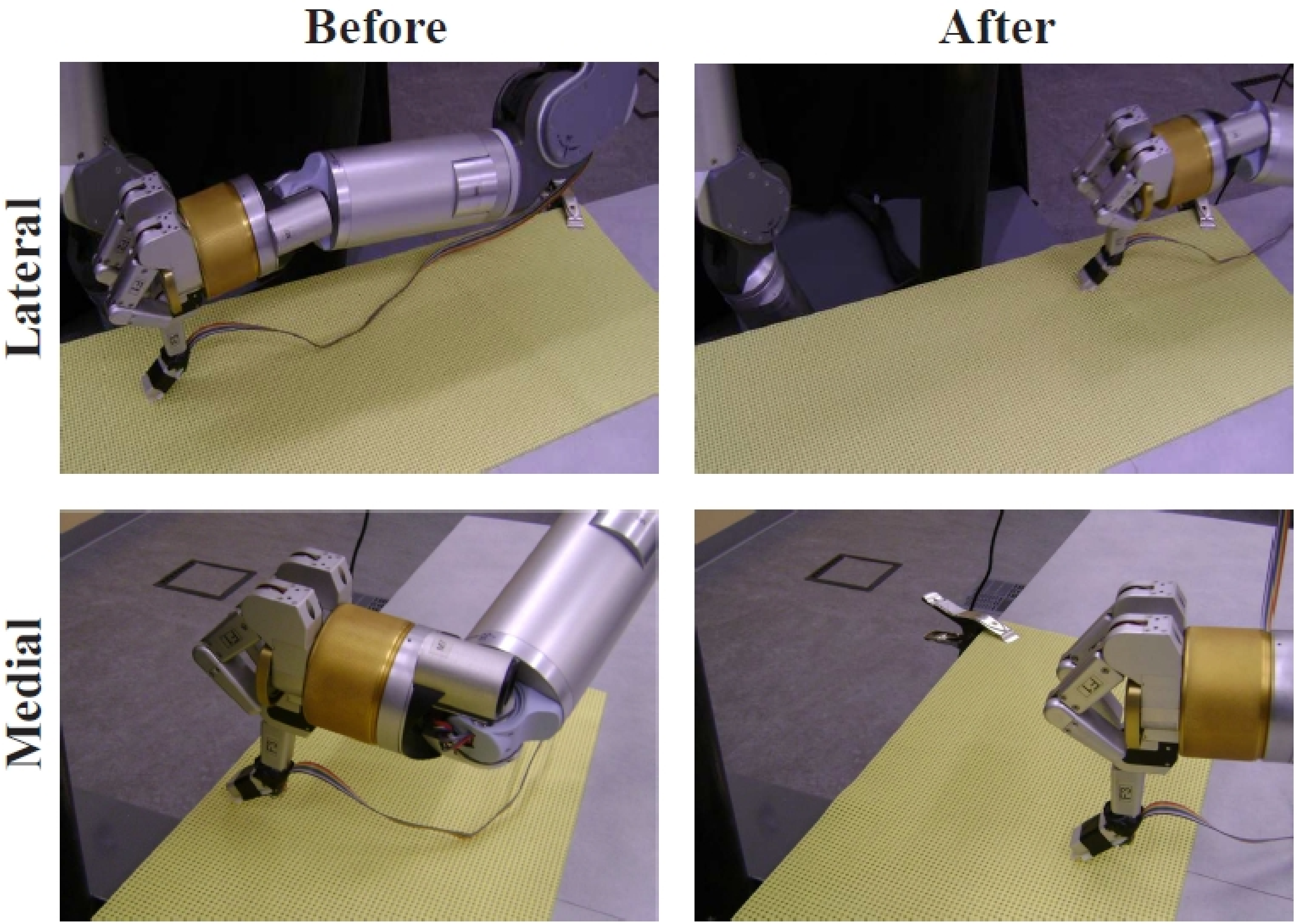
Artificial Finger Tip



Artificial Finger Tip



Exploratory Behaviors

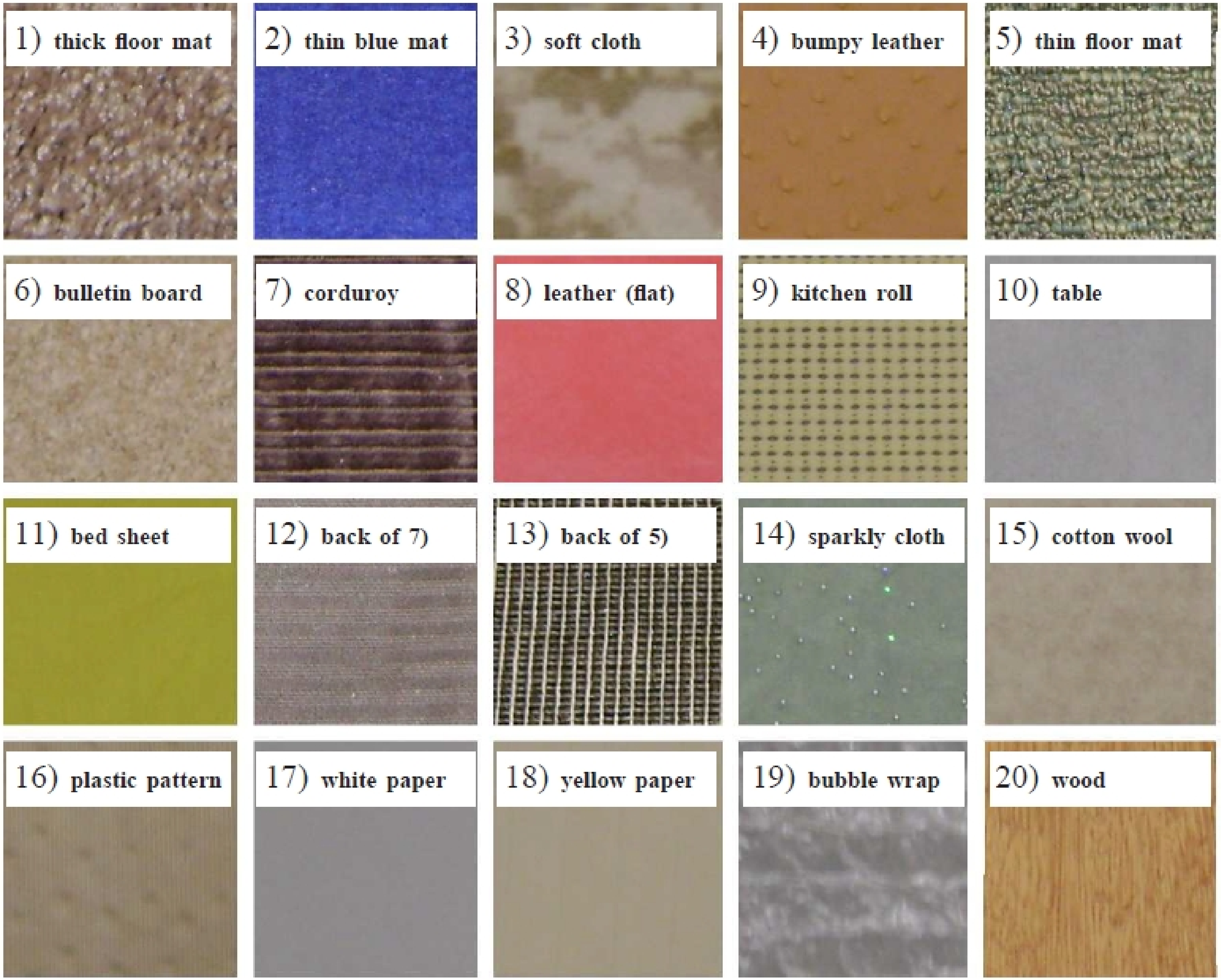


Exploratory Behaviors

TABLE I
THE FIVE EXPLORATORY SCRATCHING BEHAVIORS

Behavior	Sliding Direction	Duration
lateral-fast	left to right	3.9 sec
lateral-medium	left to right	7.5 sec
lateral-slow	left to right	14.7 sec
medial-fast	back to front	4.6 sec
medial-medium	back to front	7.9 sec

Surfaces


1) thick floor mat
2) thin blue mat
3) soft cloth
4) bumpy leather
5) thin floor mat
6) bulletin board
7) corduroy
8) leather (flat)
9) kitchen roll
10) table
11) bed sheet
12) back of 7)
13) back of 5)
14) sparkly cloth
15) cotton wool
16) plastic pattern
17) white paper
18) yellow paper
19) bubble wrap
20) wood

Control Condition

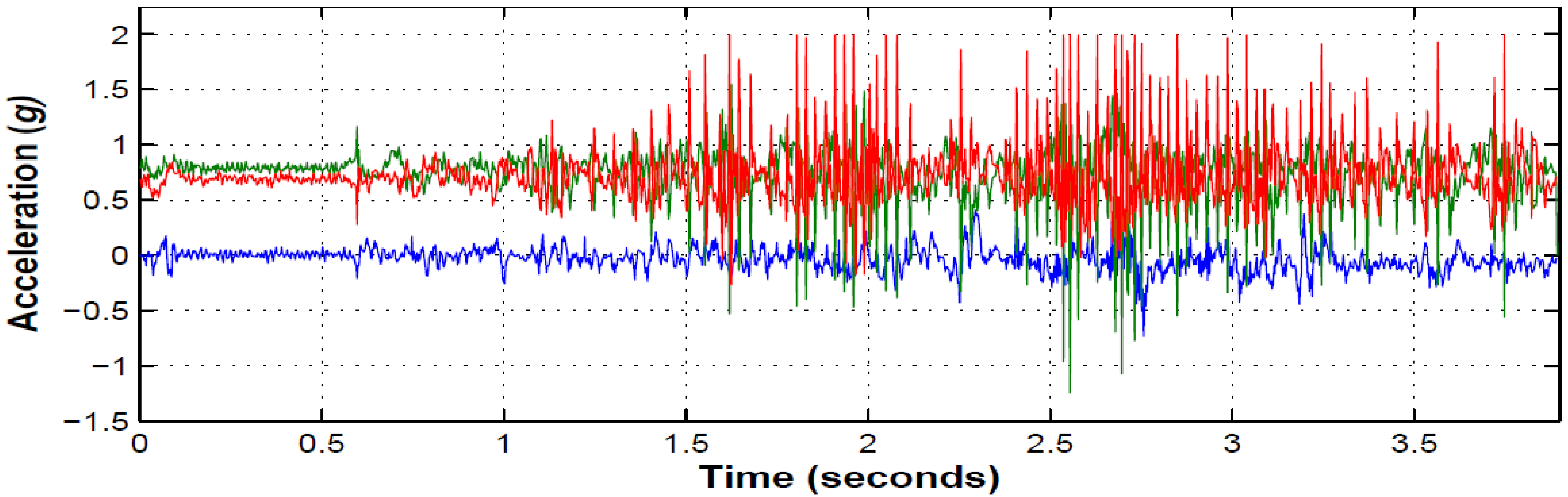
- The 21st “surface” consisted of scratching in mid-air

Data Collection

- Each scratching behavior was performed on each surface a total of 10 times
- This produced a total of 5 x 21 x 10 = 1050 behavioral interactions
- Each surface was changed after the robot scratched it once with all five exploratory behaviors and not scratched again until the robot scratched all other surfaces

Signal Processing Pipeline

Signal Processing Pipeline



a) Raw 3-axis accelerometer readings $\mathbf{A_i}$

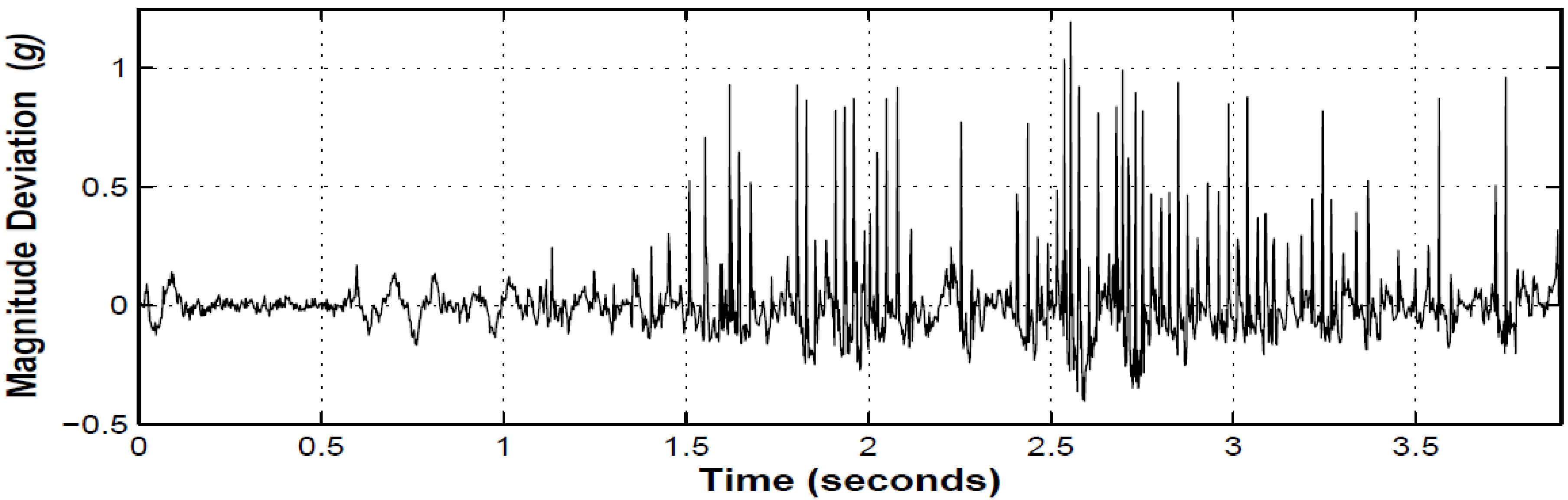
Signal Processing Pipeline

Magnitude vector: $\mathbf{M_i} = [m^1, m^2, \ldots, m^{n_i}]$

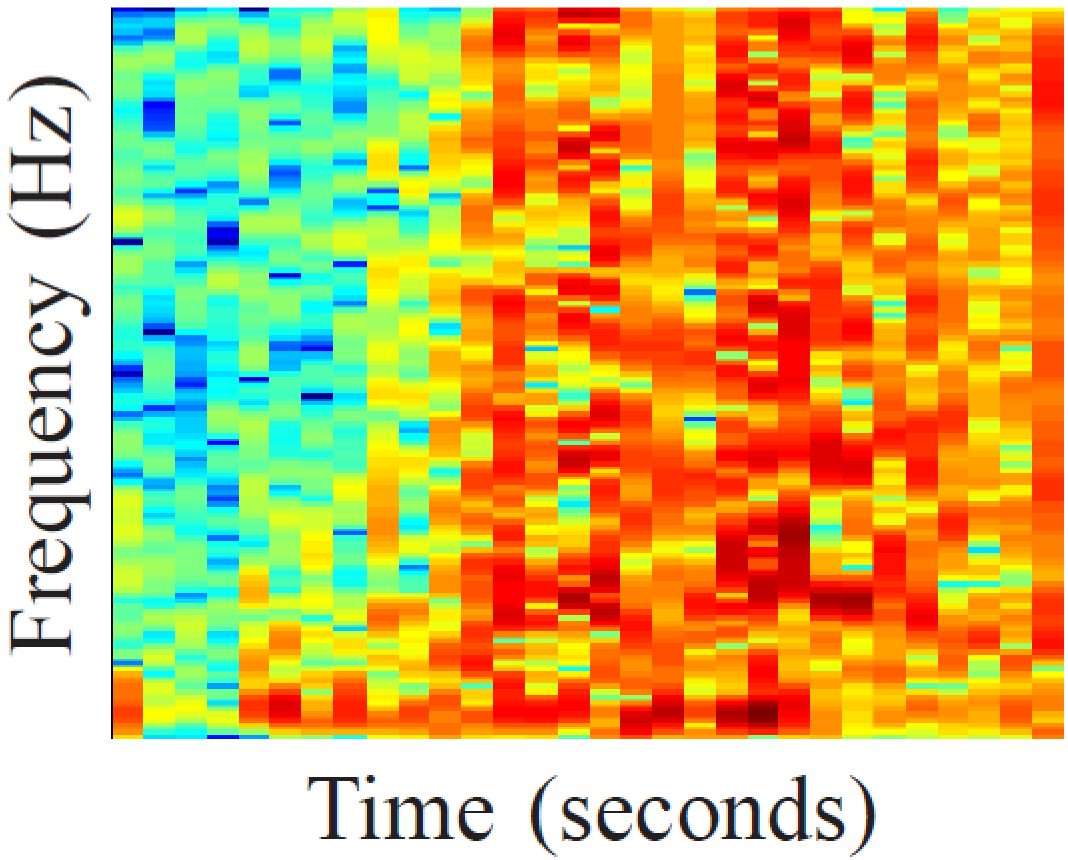
$$m^j = |\mathbf{a^j}|_2 = \sqrt{(a_x^j)^2 + (a_y^j)^2 + (a_z^j)^2}$$

Magnitude deviation vector: $\mathbf{D_i} = \mathbf{M_i} - \tilde{\mathbf{M}}_\mathbf{i}$

Signal Processing Pipeline

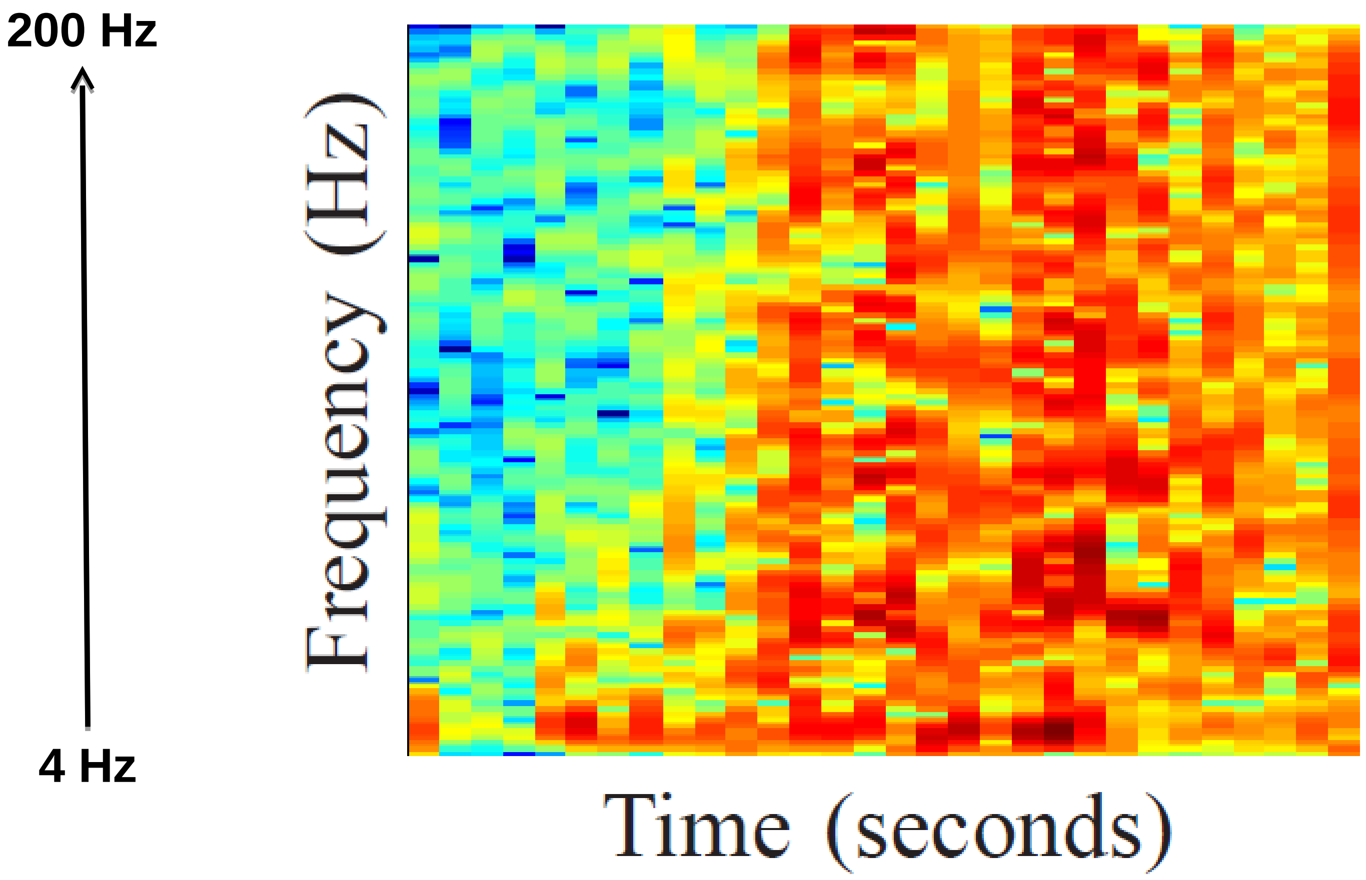


Signal Processing Pipeline



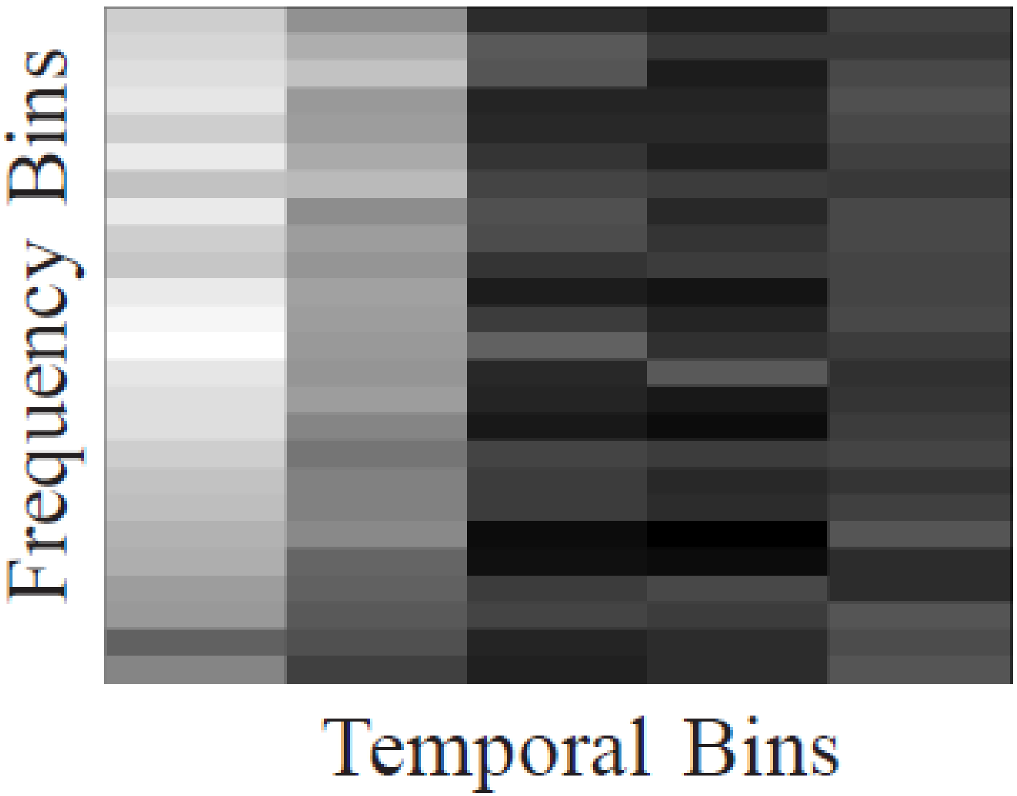
Spectrogram of Magnitude Deviation Vector

Signal Processing Pipeline



Spectrogram of Magnitude Deviation Vector

Signal Processing Pipeline



$$\mathbf{X_i} \in \mathbb{R}^{5\times 25}$$

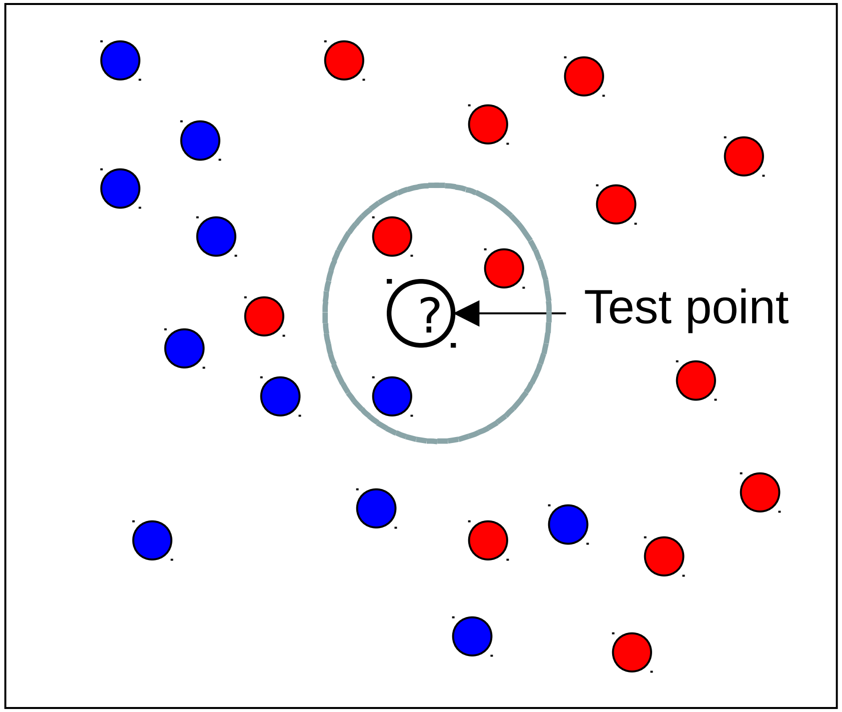
Surface Recognition Formulation

- Given a sensory signal, estimate the probability that a given surface was present, i.e.:

$$\mathbf{Pr}_b(S_i = s|\mathbf{X_i})$$

Machine Learning Models

- k-NN: *memory-based* learning algorithm



With k = 3:

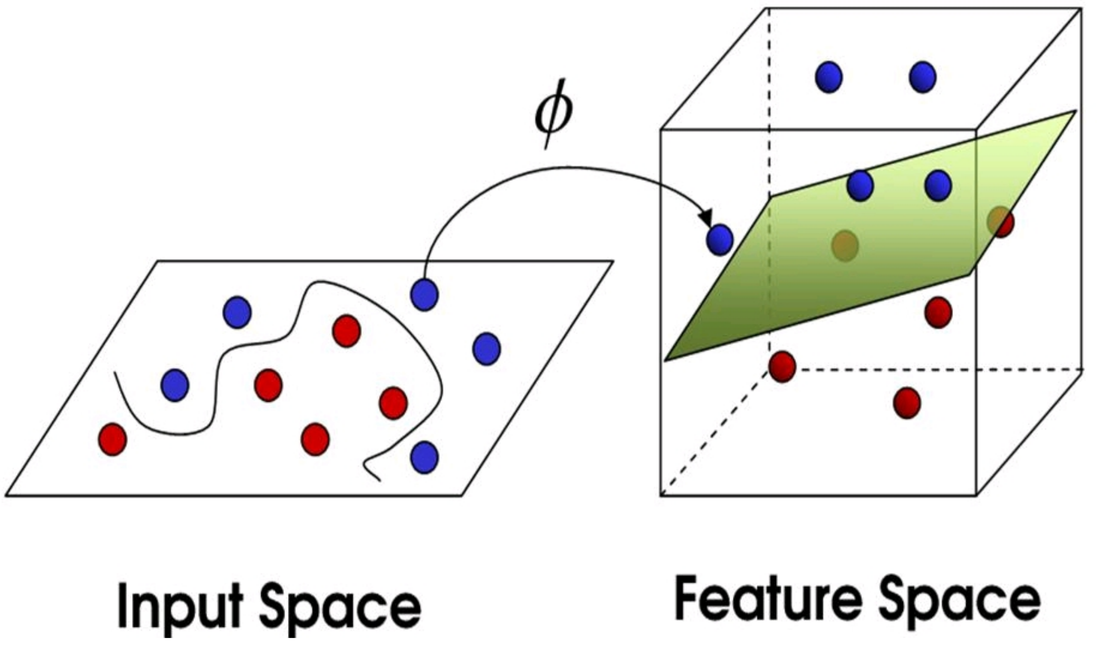
2  neighbors

1  neighbors

Therefore,
Pr(red) = 0.66
Pr(blue) = 0.33

Machine Learning Models

- Support Vector Machine: a discriminative learning algorithm

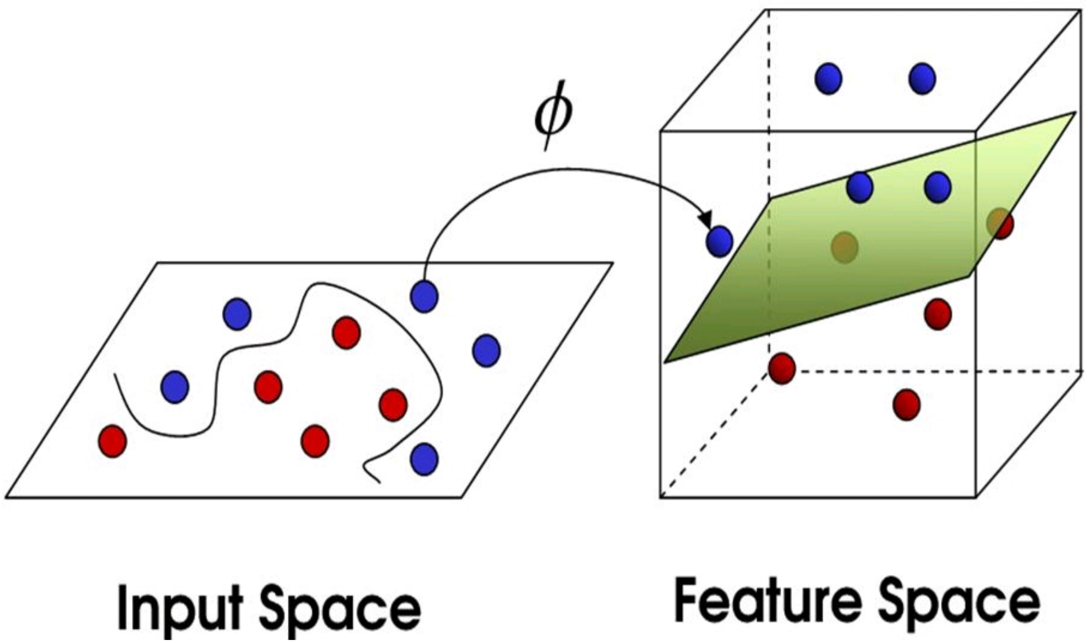


1. Finds maximum margin hyperplane that separates two classes

2. Uses Kernel function to map data points into a feature space in which such a hyperplane exists

[http://www.imtech.res.in/raghava/rbpred/svm.jpg]

Machine Learning Models



$$\boxed{K(\mathbf{X_i}, \mathbf{X_j}) = (\mathbf{X_i}^{\mathbf{T}} \mathbf{X_j} + 1)^2}$$

Surface Recognition Rate for a Single Behavior

Surface Recognition Rate for a Single Behavior

TABLE II
SURFACE-RECOGNITION ACCURACY FROM A SINGLE BEHAVIOR

Behavior	k-Nearest Neighbor	Support Vector Machine
lateral-fast	59.5%	64.8%
lateral-medium	52.4%	65.7%
lateral-slow	46.7%	58.6%
medial-fast	43.8%	56.7%
medial-medium	39.5%	45.7%
Average	48.4%	58.3%

Surface Recognition Rate for a Single Behavior

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Average	48.4%	58.3%

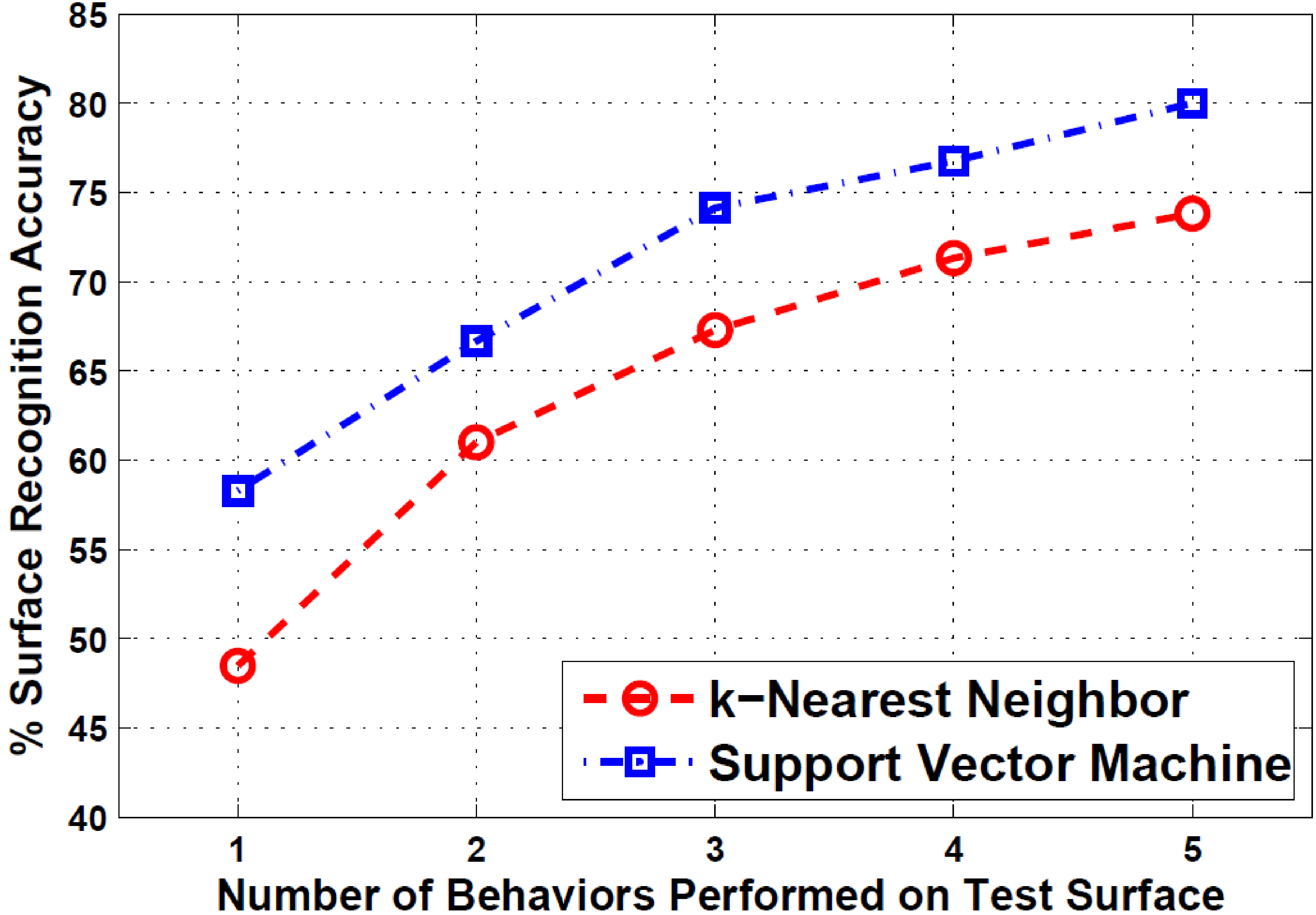
Chance accuracy = 5 %

Can we improve the recognition of surfaces after applying all 5 behaviors?

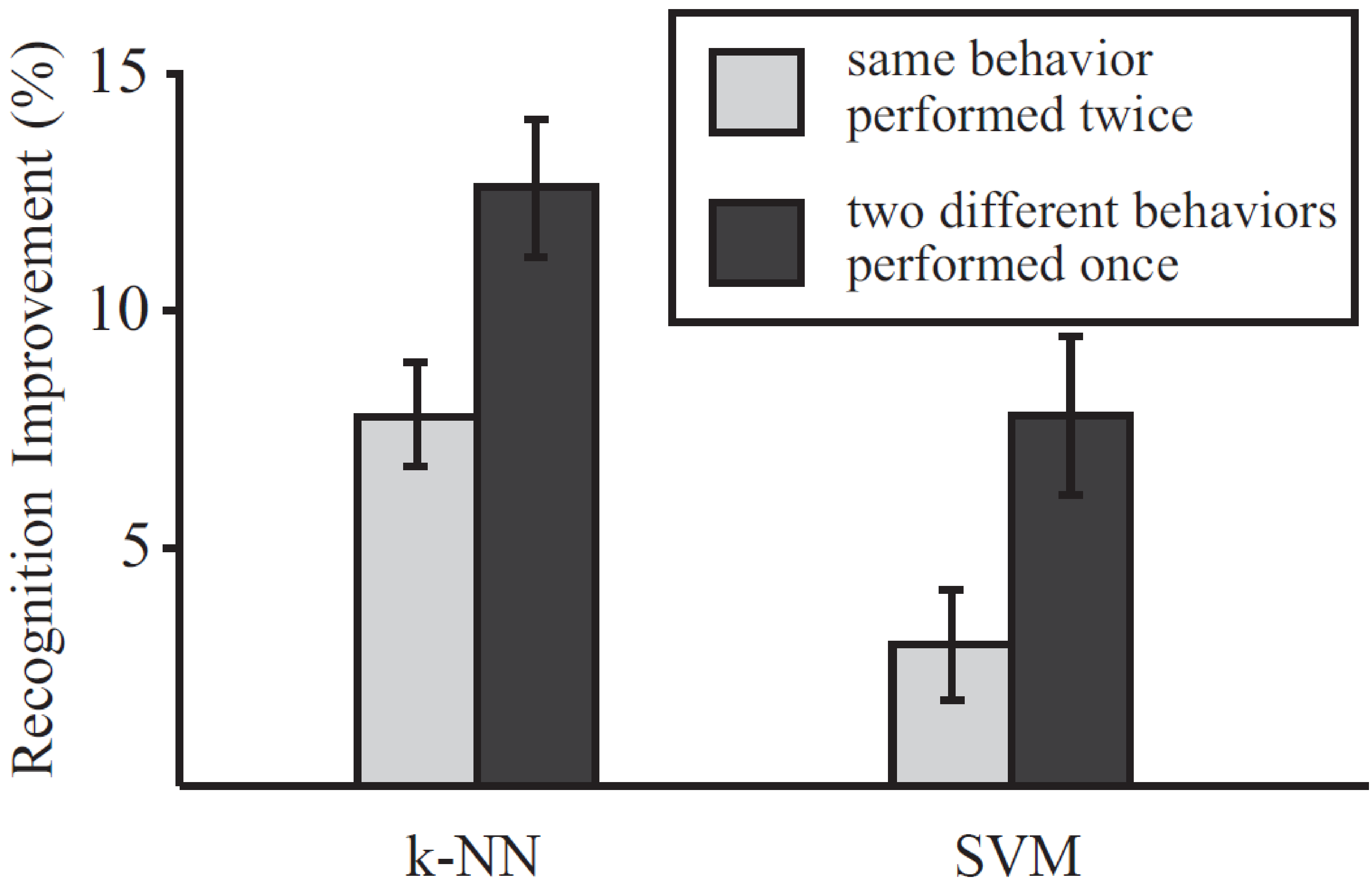
Can we improve the recognition of surfaces after applying all 5 behaviors?

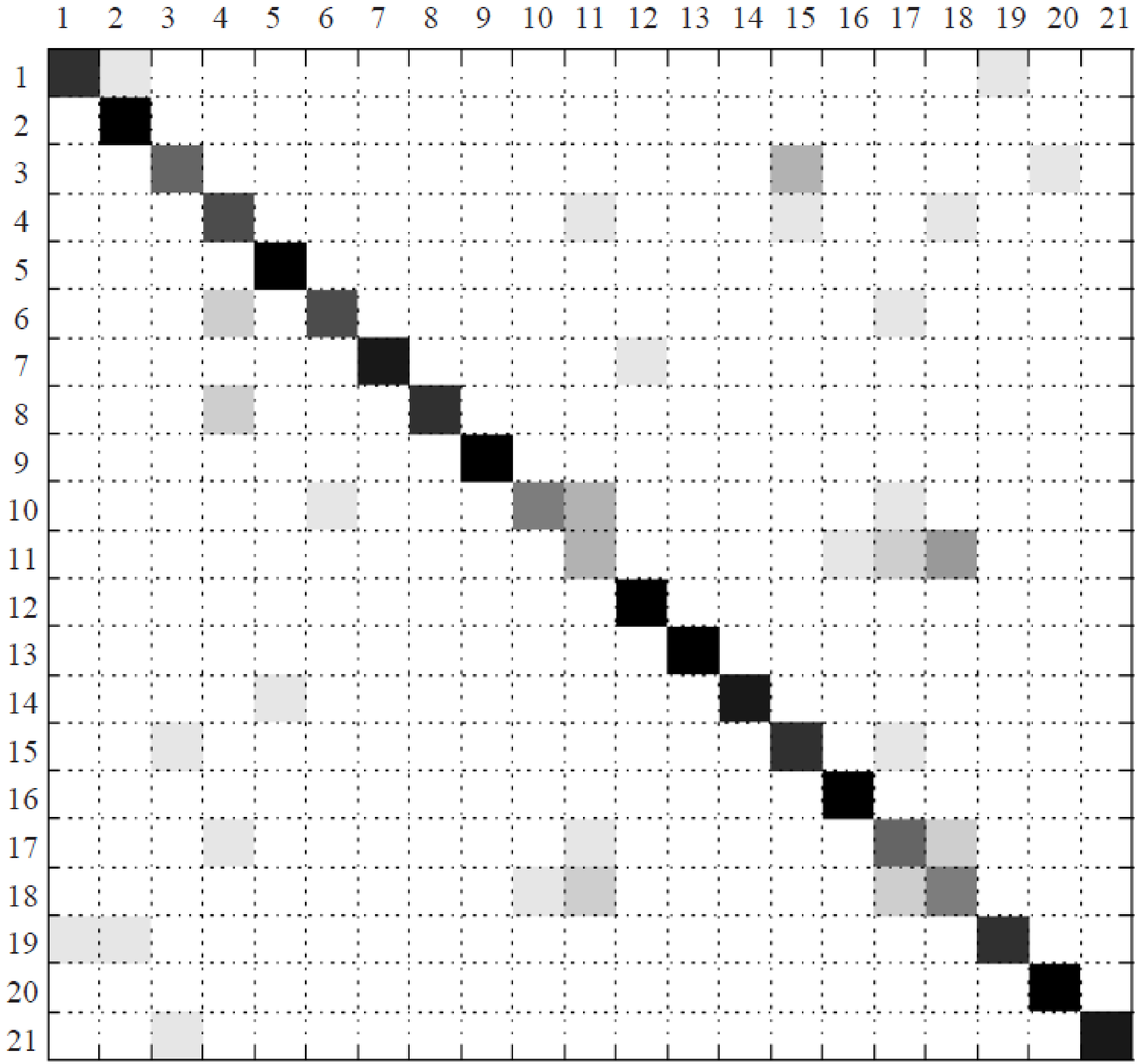
Next, let $\mathbf{X_1}, \mathbf{X_2}, \ldots, \mathbf{X_N}$ be spectrotemporal features extracted after performing behaviors $b_1, b_2, \ldots, b_N$, respectively, on the test surface $S_{test} \in \mathcal{S}$. Given these data, the robot assigned the prediction to the surface s that maximized:

$$\sum_{i=1}^{N} w_{b_i} \mathbf{Pr}_{b_i}(S_{test} = s|\mathbf{X_i})$$



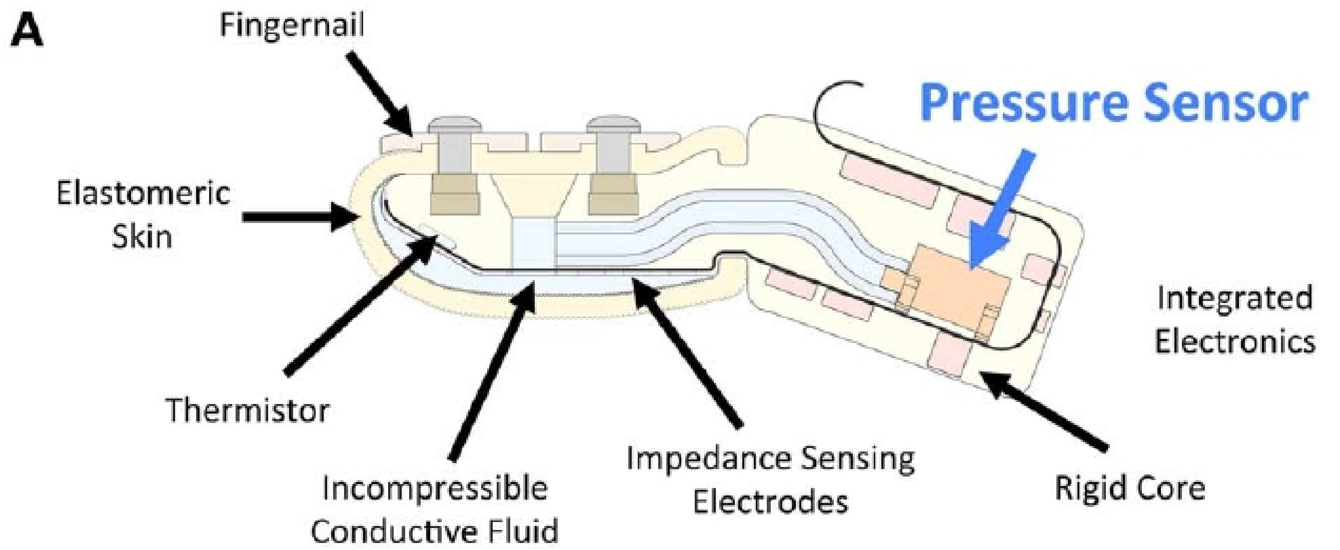
% Surface Recognition Accuracy
85
80
75
70
65
60
55
50
45
40
1
2
3
4
5
Number of Behaviors Performed on Test Surface
k−Nearest Neighbor
Support Vector Machine


Recognition Improvement (%)
15
10
5
same behavior performed twice
two different behaviors performed once
k-NN
SVM


1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21

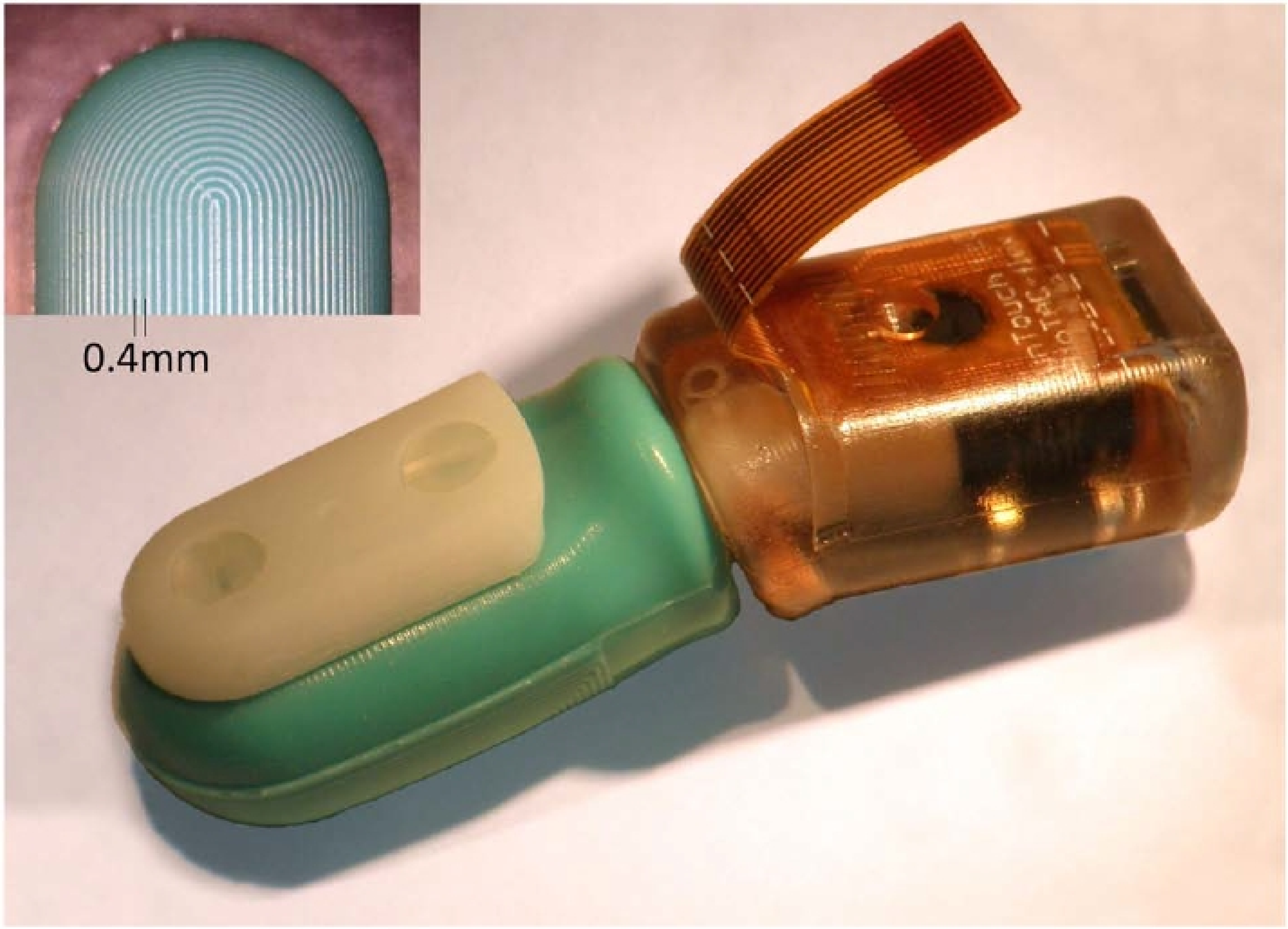
Summary of Results

Latest and Greatest in Tactile Sensing



Fishel, Jeremy A., and Gerald E. Loeb. "Bayesian exploration for intelligent identification of textures." *Frontiers in neurorobotics* 6 (2012).

The BioTac Artificial Finger



Fishel, Jeremy A., and Gerald E. Loeb. "Bayesian exploration for intelligent identification of textures." *Frontiers in neurorobotics* 6 (2012).

Surface Texture Exploration Setup

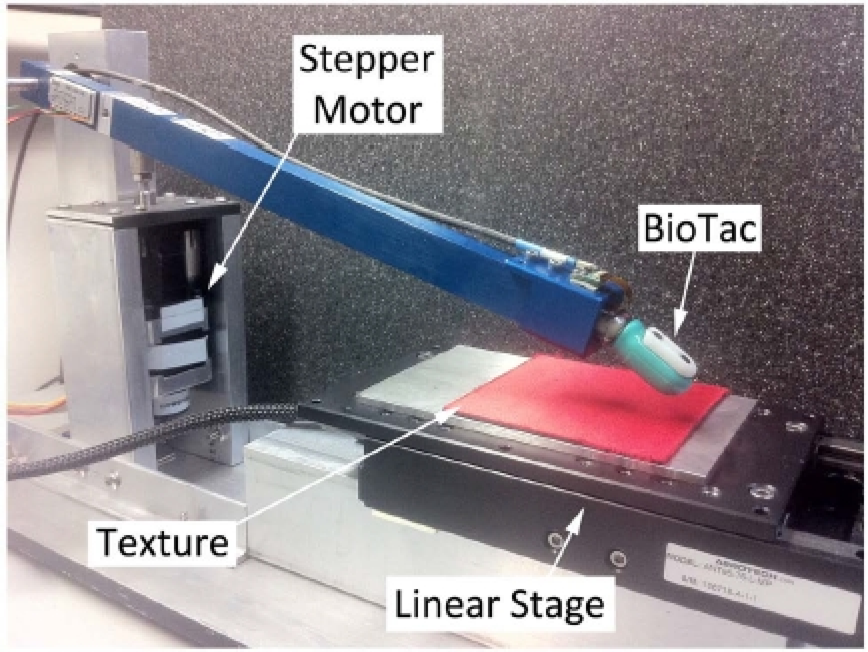
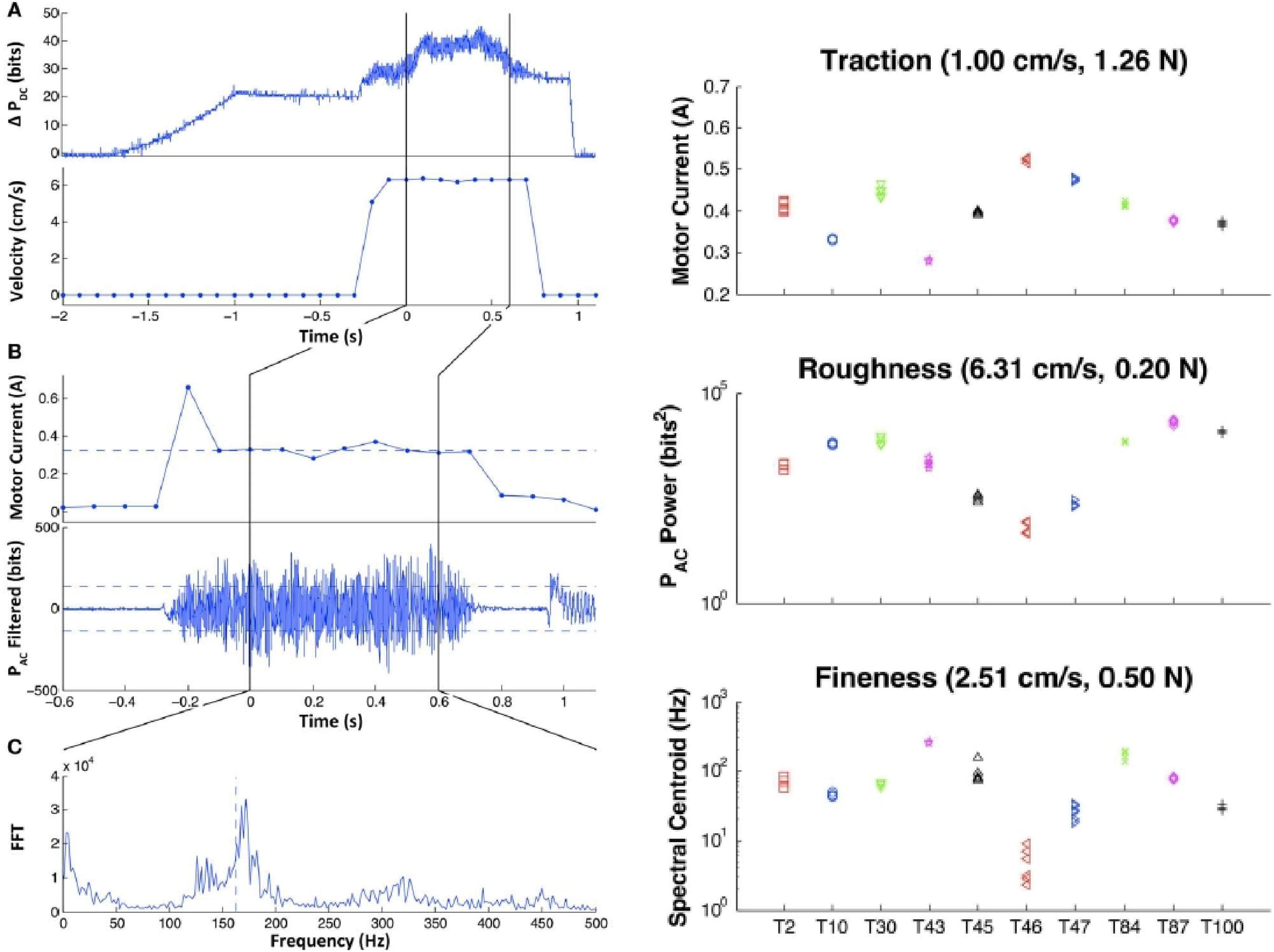


FIGURE 2 | Texture exploration apparatus with the BioTac and texture. A stepper motor (left) is attached to a lever (blue) that can raise or lower the BioTac on textures. Adjusting the vertical position of the stepper motor provides control of contact force. To produce lateral motion, a special vibration-free linear stage is used to slide textures past the BioTac. Textures are adhered to flat, square magnets that can be mounted and dismounted rapidly on a steel plate attached to the linear stage.

Fishel, Jeremy A., and Gerald E. Loeb. "Bayesian exploration for intelligent identification of textures." *Frontiers in neurorobotics* 6 (2012).



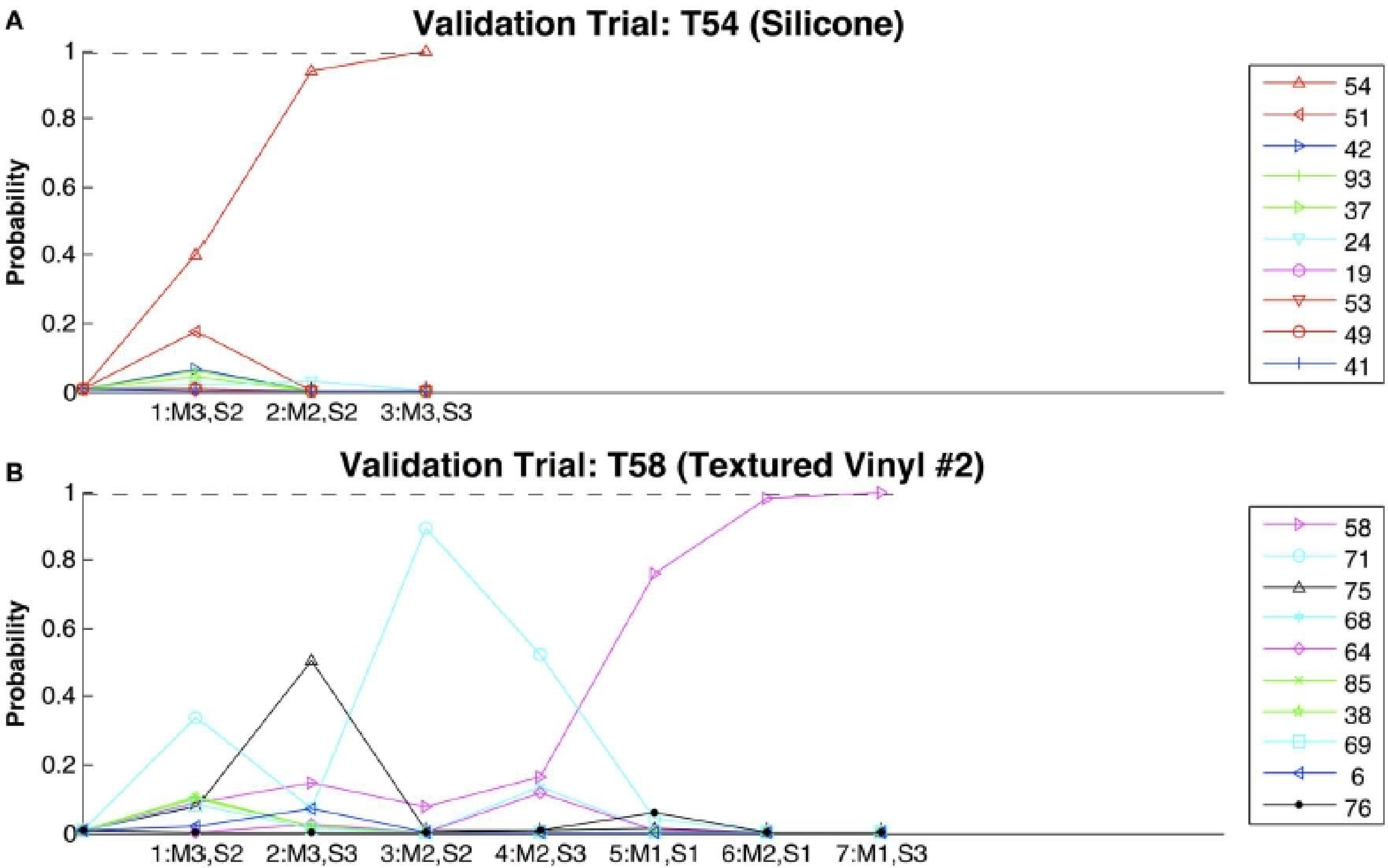
A
B
C
Δ P_{DC} (bits)
Velocity (cm/s)
Time (s)
Motor Current (A)
P_{AC} Filtered (bits)
FFT
x 10^4
Frequency (Hz)
Traction (1.00 cm/s, 1.26 N)
Roughness (6.31 cm/s, 0.20 N)
Fineness (2.51 cm/s, 0.50 N)
P_{AC} Power (bits^2)
Spectral Centroid (Hz)
T2
T10
T30
T43
T45
T46
T47
T84
T87
T100

Surface Recognition using Bayesian Inference

$$P\left(T_i \mid X, M_m\right) = \frac{P\left(X \mid T_i, M_m\right) P\left(T_i\right)}{P\left(X, M_m\right)}$$

Active Selection of Exploratory Movements

- Using prior estimates of pair-wise surface confusion, select the behavior that is most likely to be informative and/or resolve the current ambiguity


A
Validation Trial: T54 (Silicone)
Probability
1
0.8
0.6
0.4
0.2
0
1:M3,S2
2:M2,S2
3:M3,S3
54
51
42
93
37
24
19
53
49
41
B
Validation Trial: T58 (Textured Vinyl #2)
Probability
1
0.8
0.6
0.4
0.2
0
1:M3,S2
2:M3,S3
3:M2,S2
4:M2,S3
5:M1,S1
6:M2,S1
7:M1,S3
58
71
75
68
64
85
38
69
6
76

Surface Texture Recognition Results

Table 5 | Summary of performance for absolute classification task for uninformed cycling, random selection, and Bayesian Exploration.

Summary of performance	Uninformed cycling	Random selection	Bayesian exploration
Correct identifications	49.9%	84.1%	**95.4%**
And converged	36.4%	68.3%	**89.3%**
Median # of movements	10*	8	**5**
PERFORMANCE DETAIL			
Computer paper (T1)	0.0%	57.8%	**82.0%**
Smooth cardstock (T3)	0.0%	81.2%	**99.6%**
Buna-N rubber (T50)	58.0%	84.4%	**100.0%**
Silicone rubber (T54)	88.6%	86.6%	**99.6%**
Acrylic felt (T12)	**100.0%**	94.2%	96.4%
Velour (T96)	33.4%	83.4%	**100.0%**
Textured vinyl #1 (TS7)	**100.0%**	99.6%	**100.0%**
Textured vinyl #2 (T58)	0.0%	51.4%	**67.2%**
Pineapple fiber weave (T107)	99.2%	94.0%	**99.8%**
Linen cloth (T111)	14.2%	90.6%	**99.6%**
Plastic paper (T18)	27.6%	86.4%	**100.0%**
Template plastic (T19)	86.2%	88.0%	**94.4%**
Cotton duck (T102)	**100.0%**	99.2%	**100.0%**
Jean denim (T104)	26.6%	91.8%	**96.8%**
Santoprene rubber (T51)	3.0%	75.4%	**93.6%**
Haplon rubber (T53)	61.2%	80.8%	**97.6%**

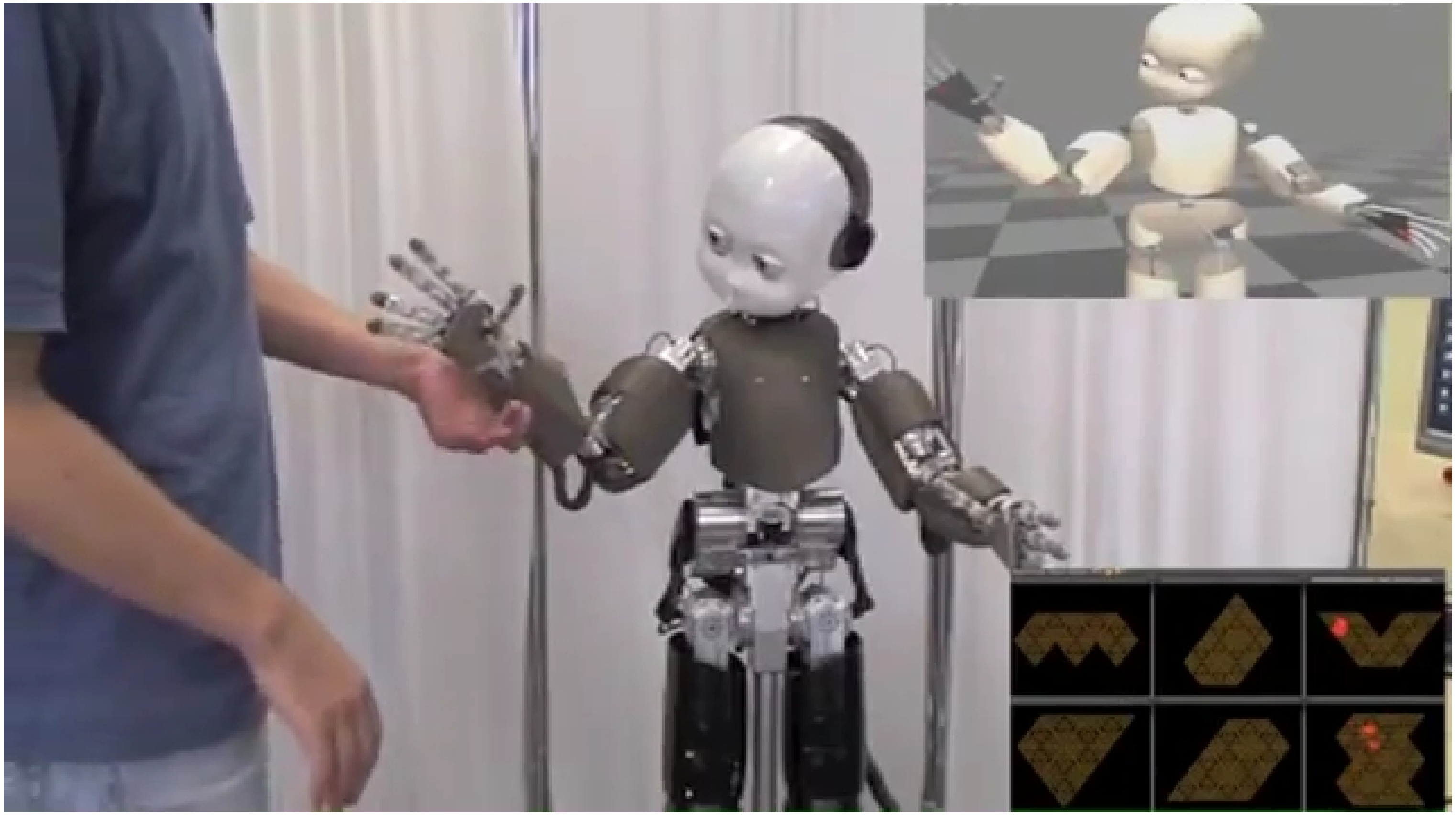
Surface Texture Recognition Results

Table 4 | Comparison of AB discrimination of similar texture pairs between human subjects and the Bayesian exploration classifier.

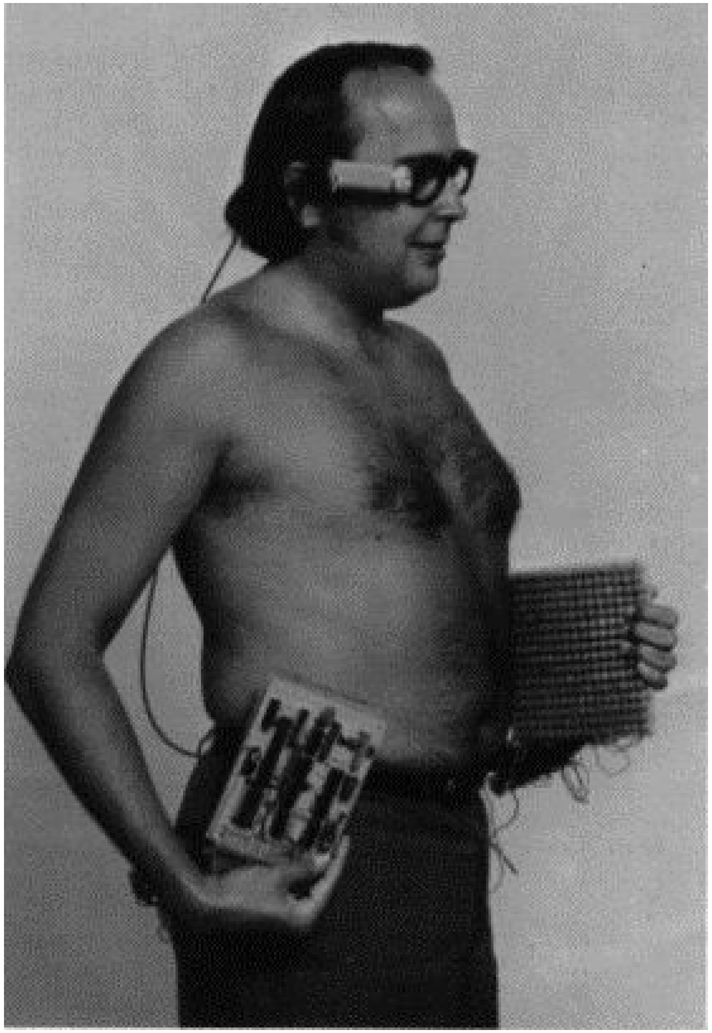
Texture pairs	Percentage of correct classifications	
	Human subjects	Bayesian exploration
Computer paper (TI) vs. smooth cardstock (T3)	60%	**99.3%**
Buna-N rubber (T50) vs. silicone rubber (T54)	80%	**100.0%**
Acrylic felt (T12) vs. velour (T96)	90%	**100.0%**
Textured vinyl #1 (T57) vs. textured vinyl #2 (T58)	70%	**100.0%**
Pineapple fiber weave (T107) vs. linen cloth (T111)	**100%**	**100.0%**
Plastic paper (T18) vs. template plastic (T19)	85%	**97.7%**
Cotton duck (T102) vs. jean denim (T104)	90%	**100.0%**
Santoprene rubber (T51) vs. haplon rubber (T53)	75%	**100.0%**

The Skilsense Project

The Roboskin Project



Sensory Substitution



Other ongoing projects:

- Skilsens:
  - http://www.youtube.com/watch?v=FQkC-gJGKmw
- RoboSKIN:
  - http://www.youtube.com/watch?v=yQGXYGS0Ojo
- In the news:
  - http://www.youtube.com/watch?v=49KmS0IkyW8
  - http://www.youtube.com/watch?v=APTNpGZ7mWc

THE END