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Bioinspired Tactile Perception

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Objective of the talk

- To analyse the human tactile system as a model for designing robot tactile sensors
- To describe the main technologies for developing tactile sensors for robots
- To analyse a case-study of biomechatronic design of tactile sensors

Outline of the talk

- Human sense of touch:
  - Human tactile receptors and their characterization
  - The fingertip as a tactile organ
- Main technologies of developing artificial tactile sensors:
  - Working principles
  - Mathematical relations
  - Examples of tactile sensors developed with each technology
- Case study of biomechatronic tactile sensor

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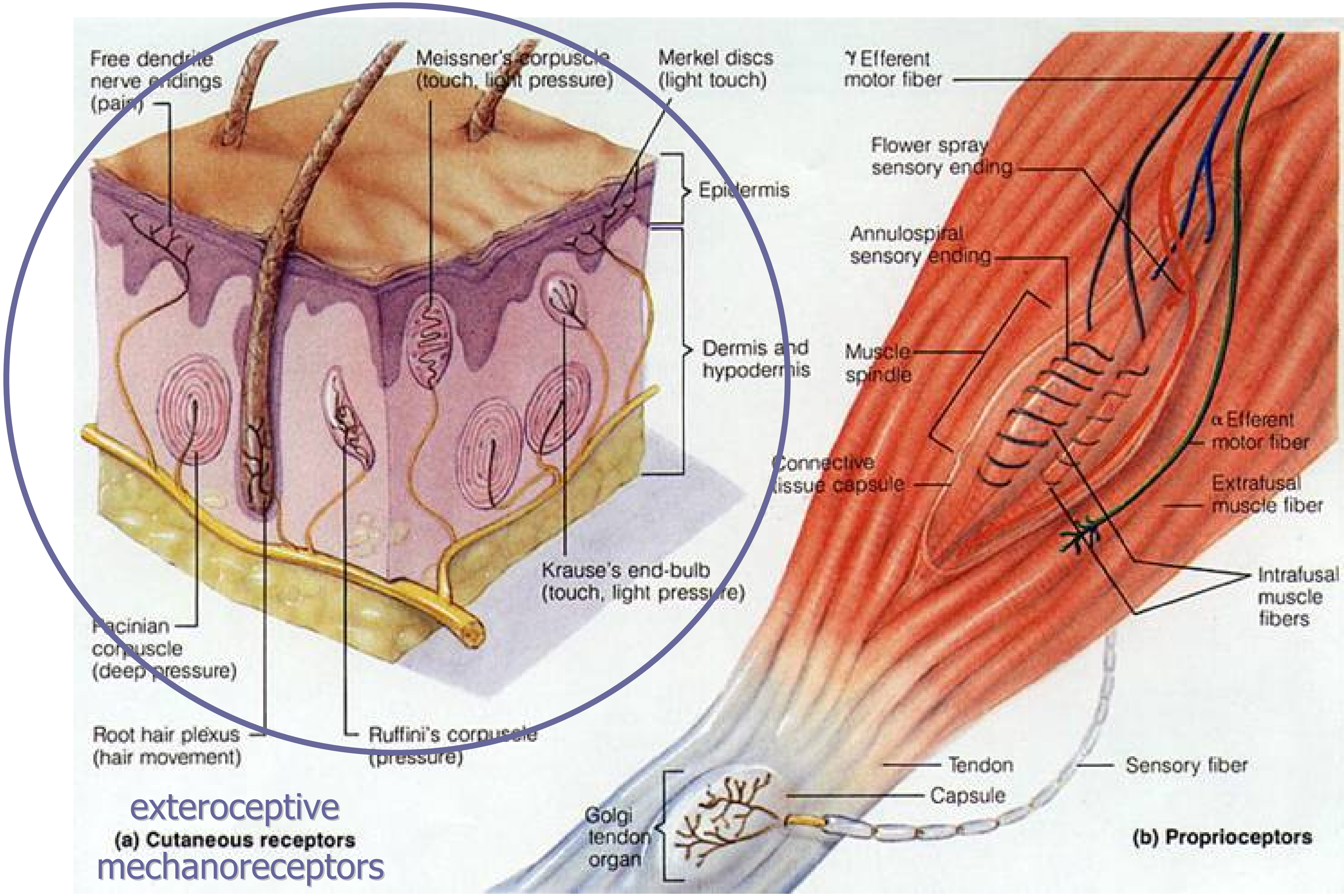
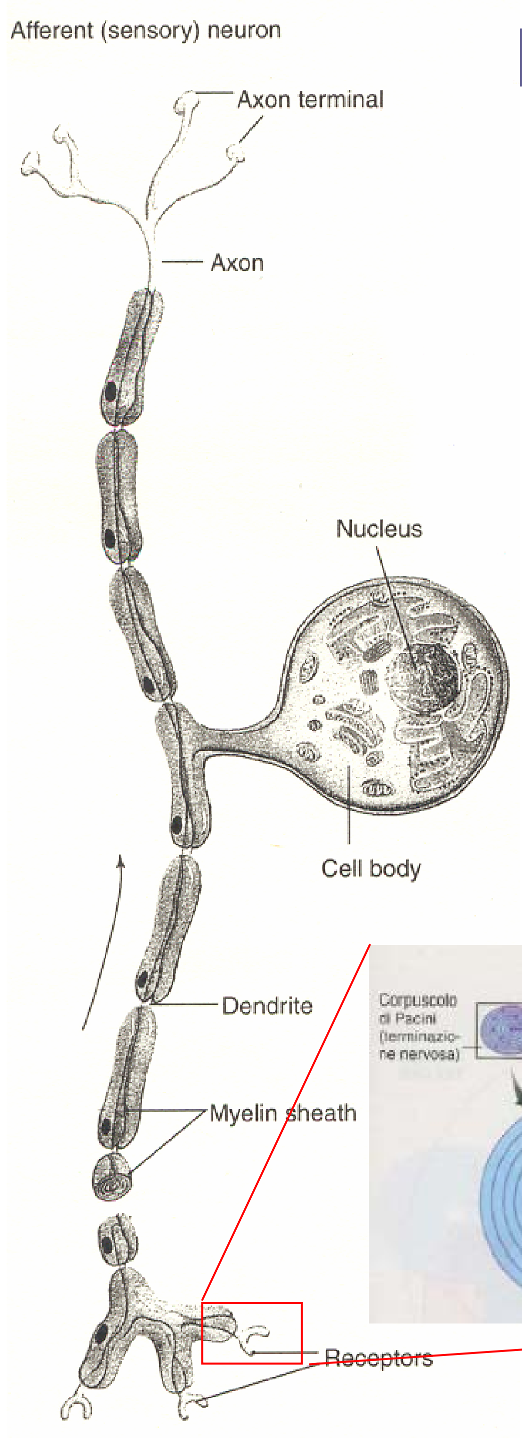
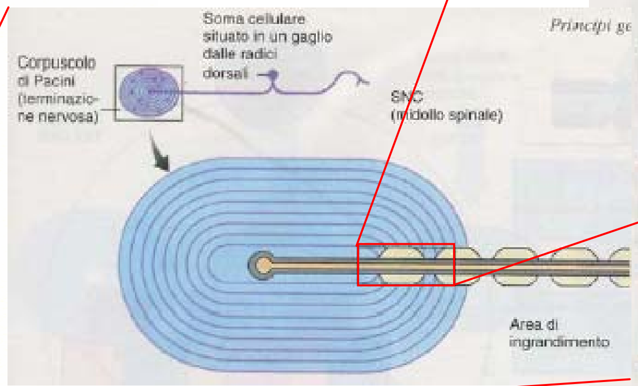
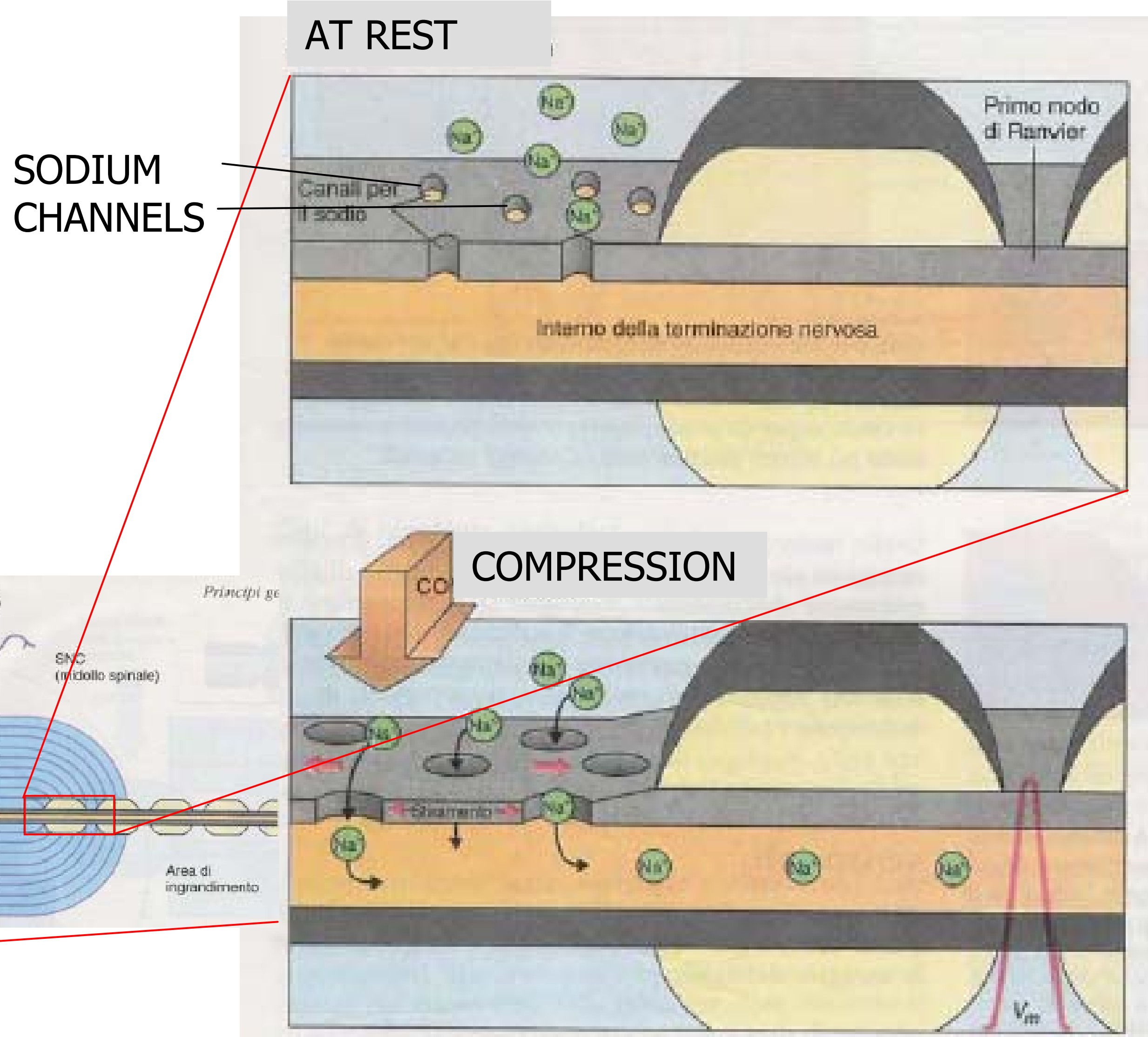
The human somato-sensory system



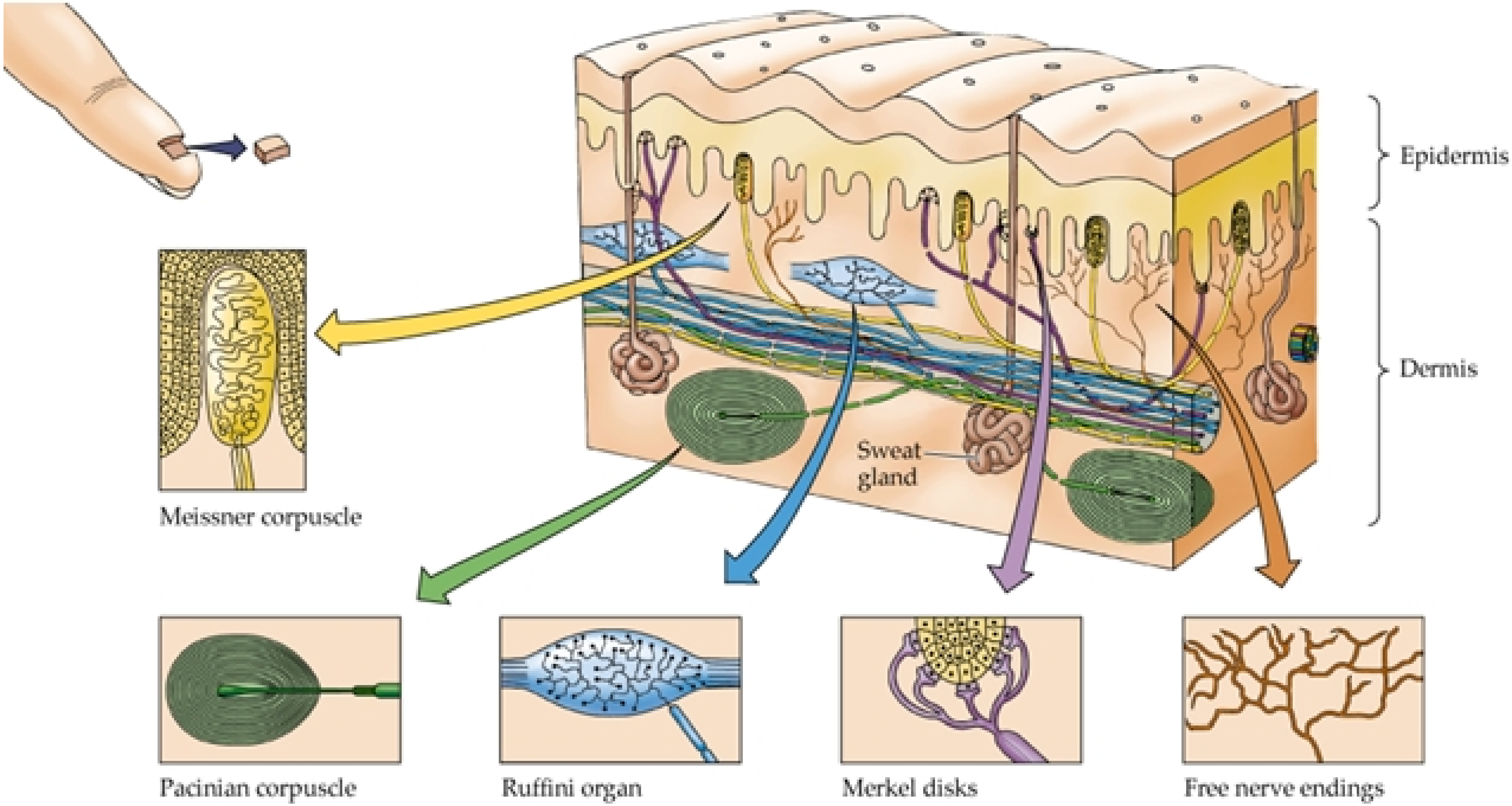
Mechanism of mechanical stimulation







Tactile receptors of the glabrous skin

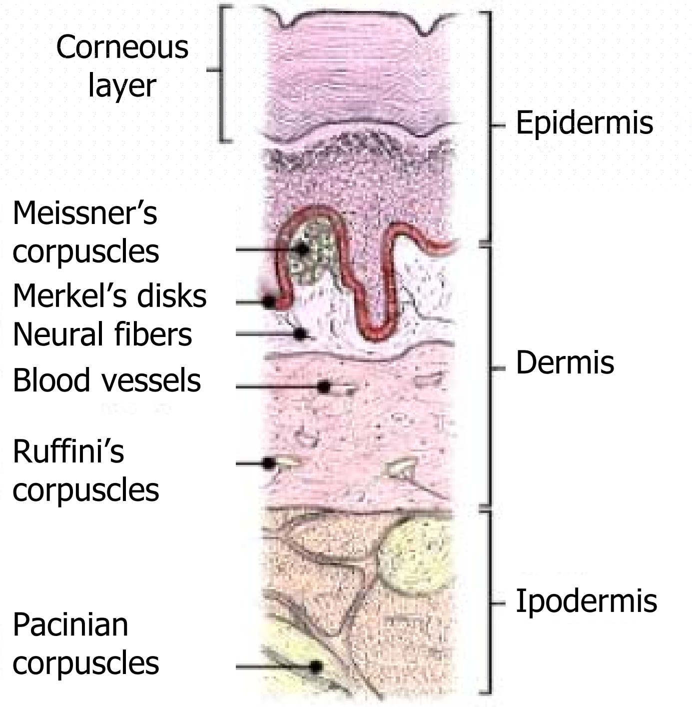


Corneous layer

- Robust cells, pulled out by the tissue rigenerative process
- Its mechanical characteristics determine the distribution of forces on the underlying sensitive areas

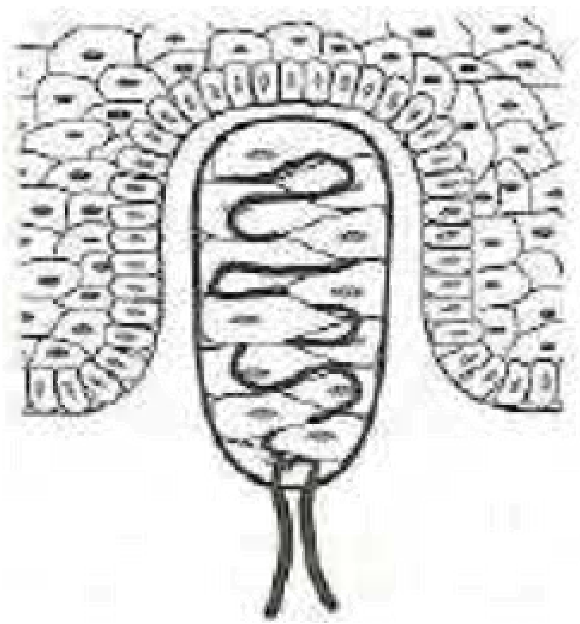
Extroflections

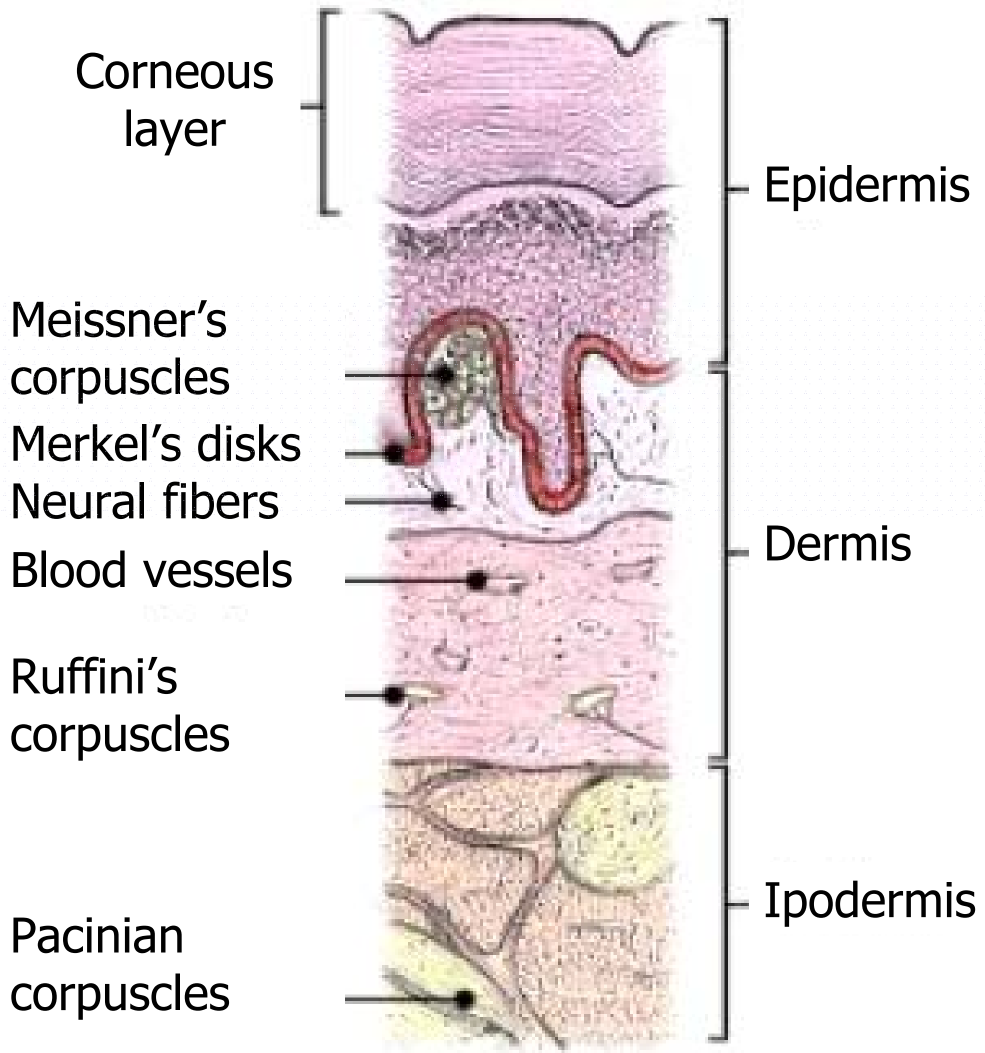
- Constituted by thicker tissue, with irregular shape
- Corresponding to the fingerprints
- By their nature and morphology, the move together with the epidermis grooves
- Transmit amplified the strain due to tangential stress on the corneous layer



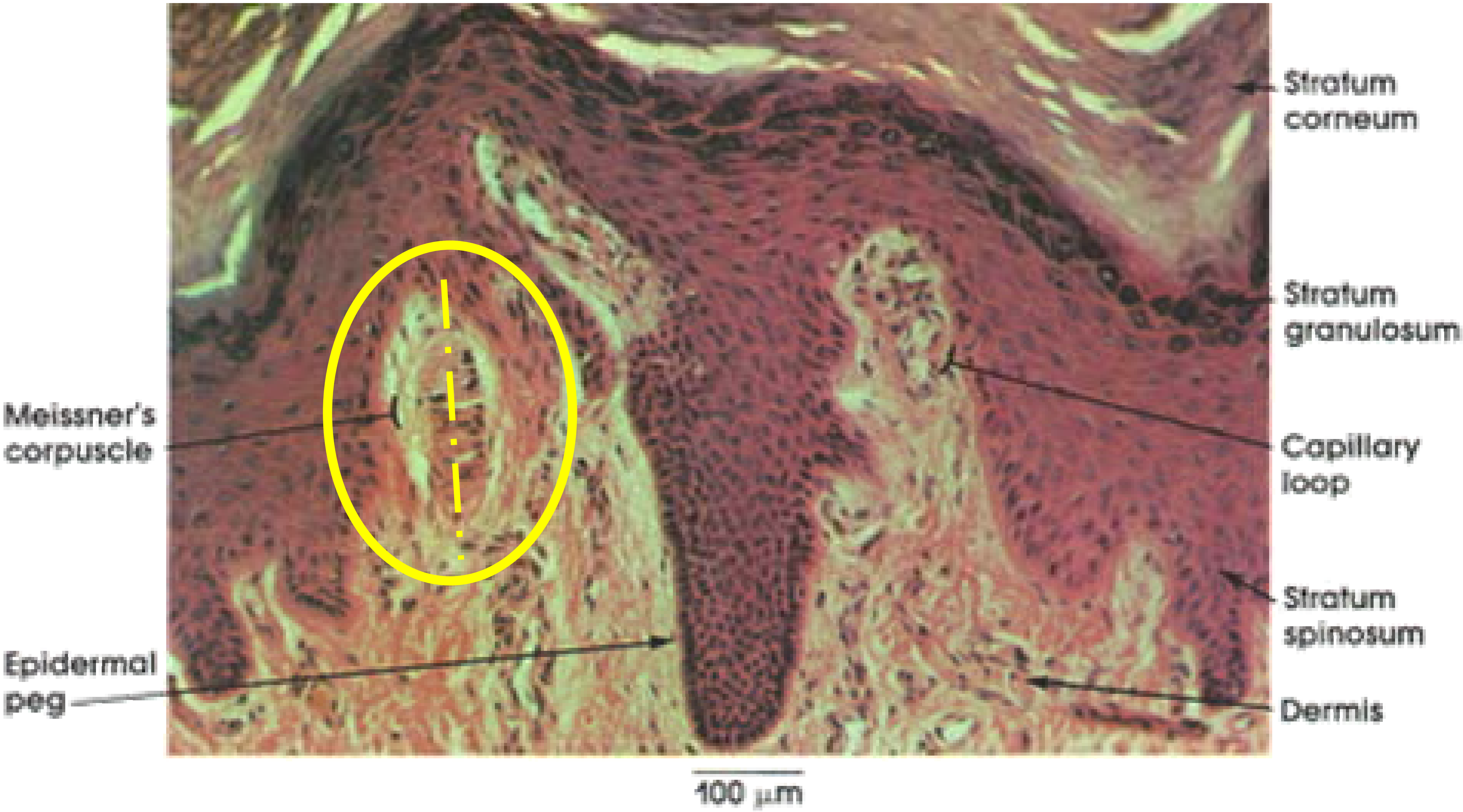
Meissner’s corpuscles

- 43% of hand tactile units
- dimensions: 80 x 30 μm
- main axis normal to the skin surface
- threshold: 10.2 mN/mm^2



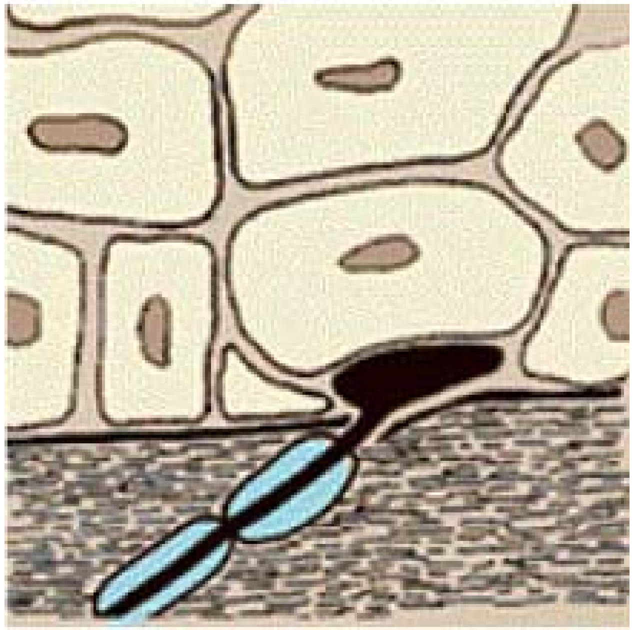


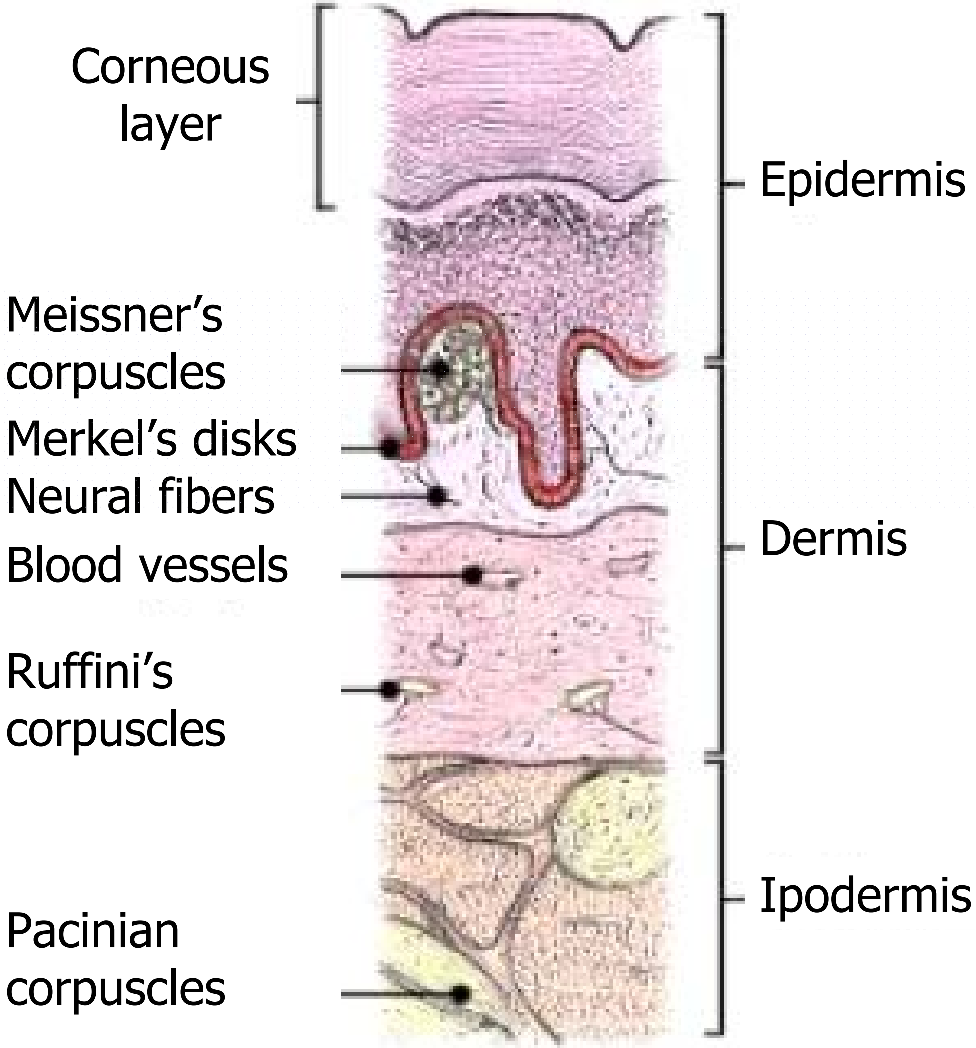
Meissner's corpuscles



Merkel's disks

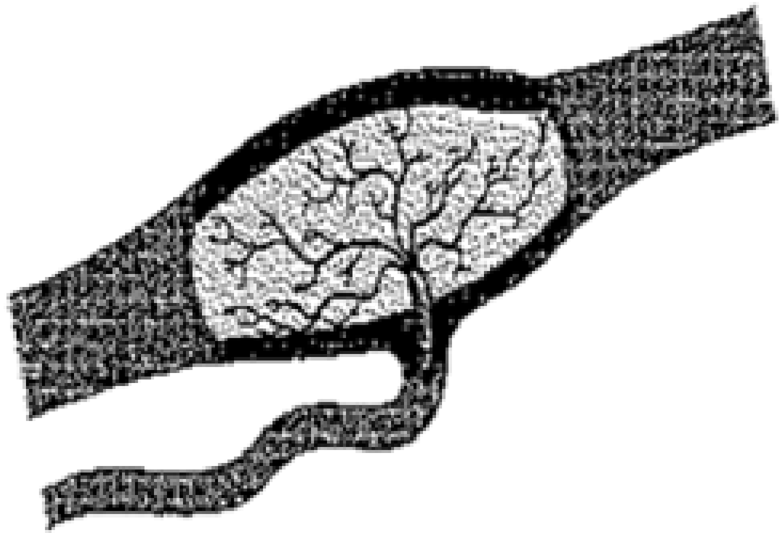
- 25% of hand tactile units
- disk-like shape
- 10-15 μm diameter
- arranged parallel to the skin surface
- threshold: 22.8 mN/mm^2

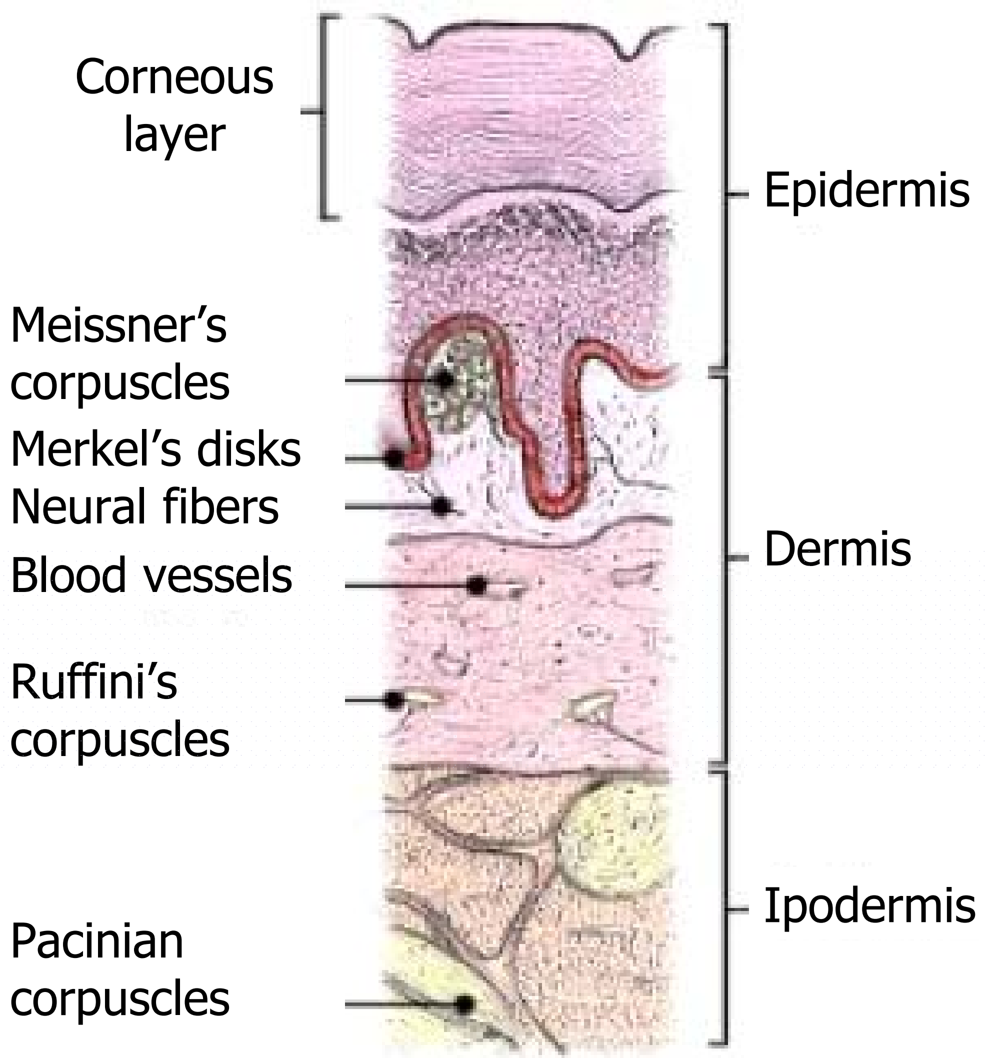




Ruffini’s corpuscles

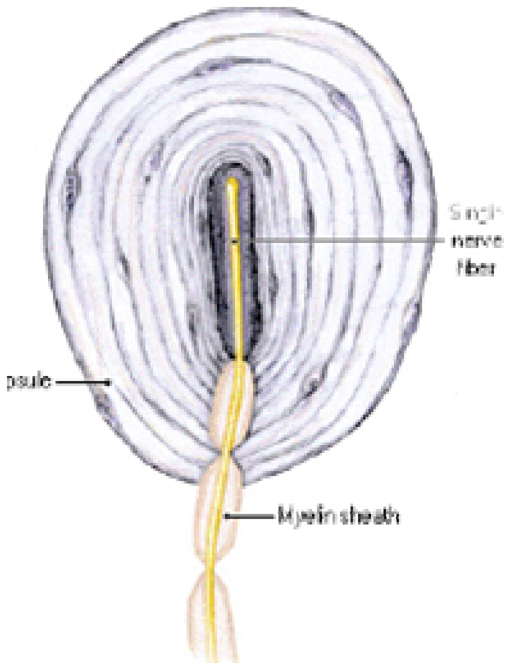
- 19% of hand tactile units
- threshold: 131.6 mN/mm^2

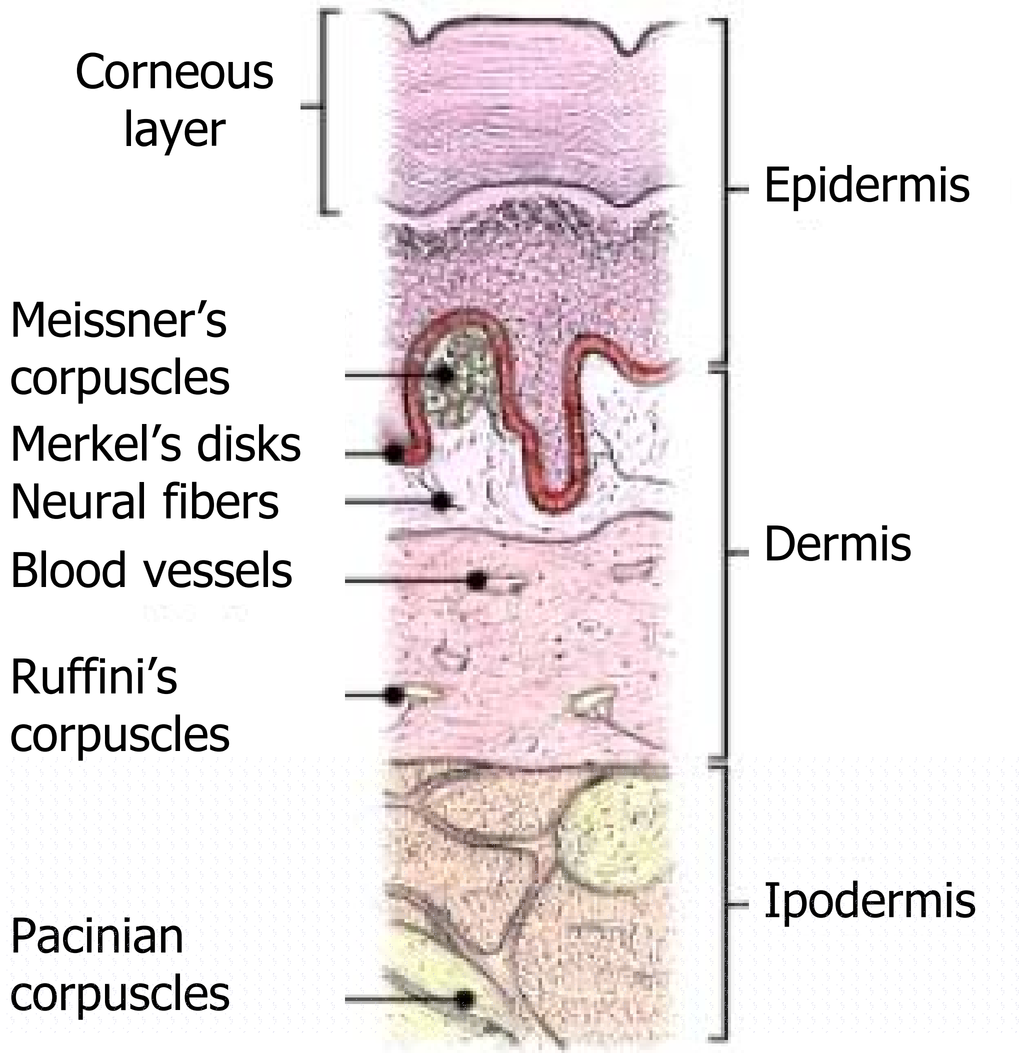




Pacinian corpuscles

- 13% of hand tactile units
- length: 1-4 mm
- diameter: 0.5-1 mm
- horizontal main axis
- threshold: 9.5 mN/mm^2

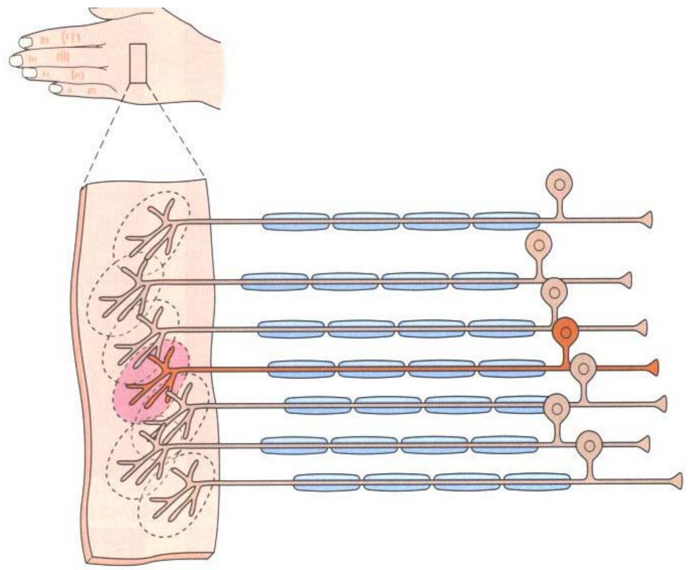




Pacinian corpuscles

Receptive fields

- Receptive field of a receptor:
  cutaneous area from which the receptor receives stimuli
- Receptive field of an afferent neuron:
  cutaneous area from which its receptors receive stimuli

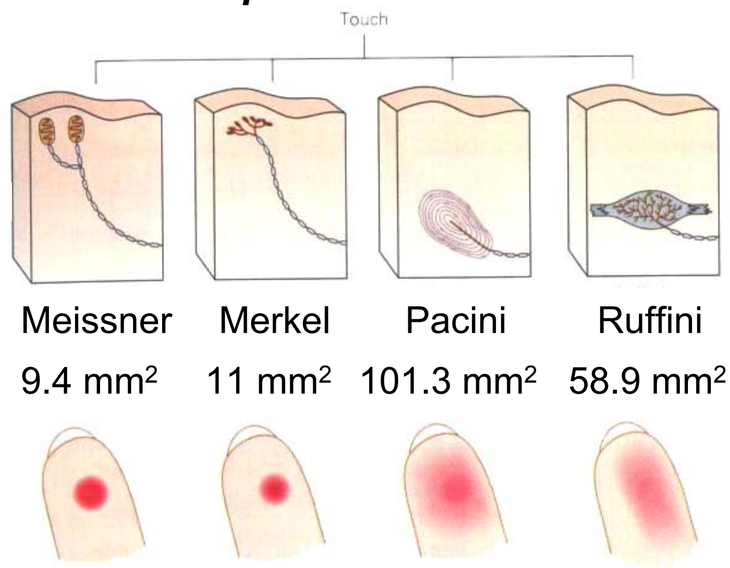


If the skin is stimulated in two points belonging to the same receptive field, the spatial difference is not perceived

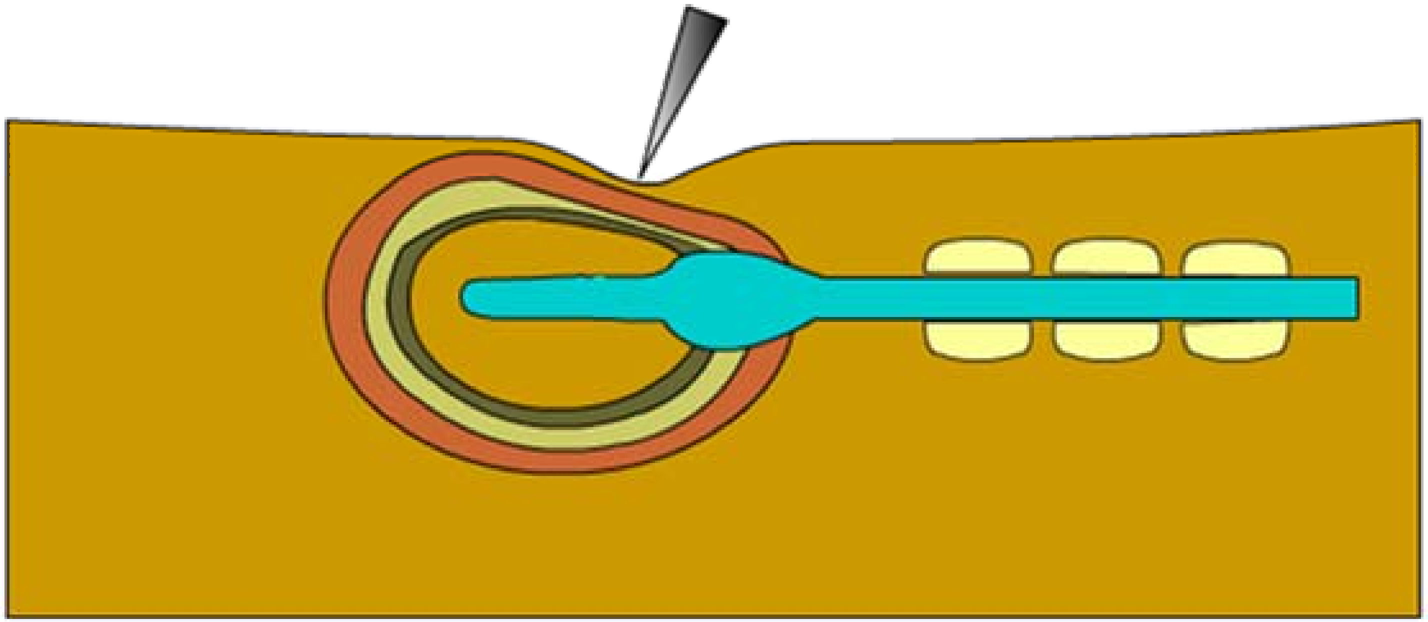
⇒ The dimension of the receptive field determines the spatial resolution of perception

The overlapping between receptive fields increases the spatial resolution, up to 2 mm on the fingertip

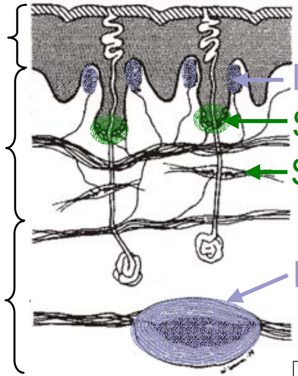
- The dimension of the receptive field of a **receptor** increases with the depth in the epidermis

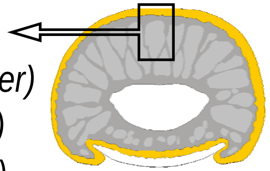


Mechanism of adaptation to the stimulus

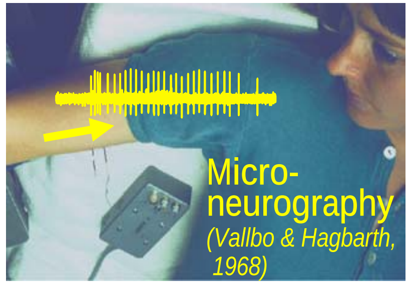


Classification of tactile receptors

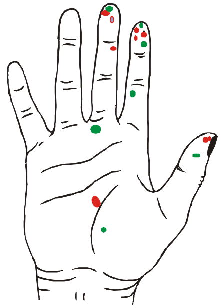
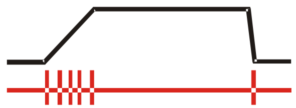
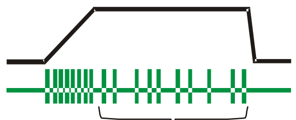
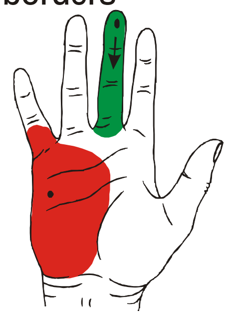
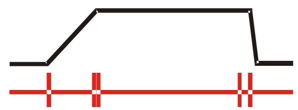
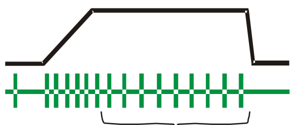




Complex filtering mechanisms by the fingertip tissues, which determine the encoding properties of the receptors

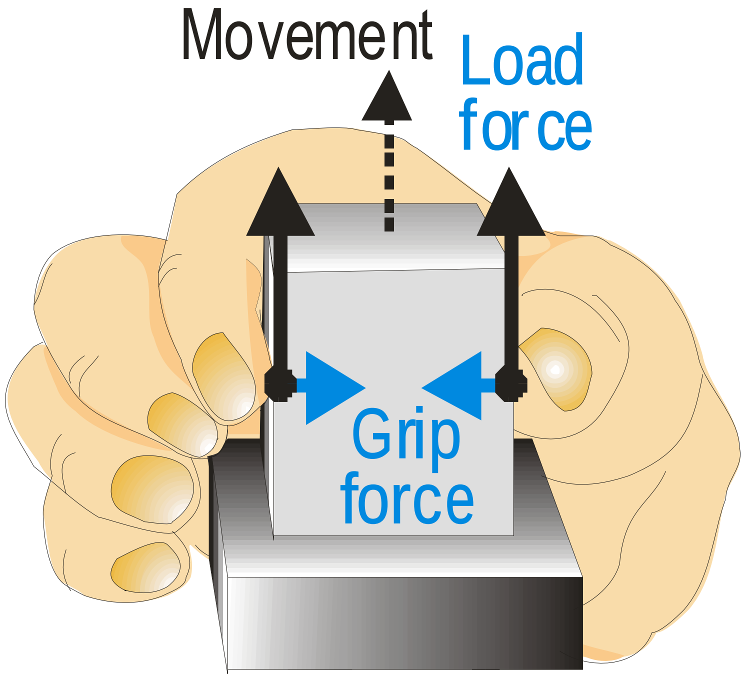


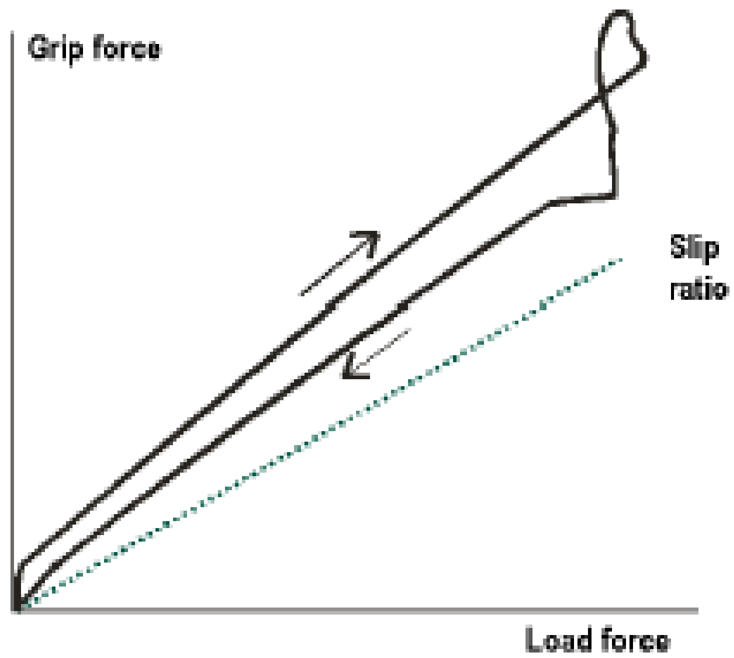
Four kinds of receptors encode different aspects of the fingertip deformation

		ADAPTATION	
		Fast Adapting *No static response*	**Slowly Adapting** *Static response*
RECEPTIVE FIELDS	Small, sharp borders 	 Changes in fingertip forces, fine form, moving stimuli, friction etc. FA I (43 %) Meissner	 Irregular Fingertip forces, fine form, edge contours etc. SA I (25 %) Merkel
	Large, obscure borders 	 Mechanical transients & vibration FA II (13 %) Pacini & Golgi-Mazzoni	 Regular Lateral skin stretch, proprioception SA II (19 %) Ruffini

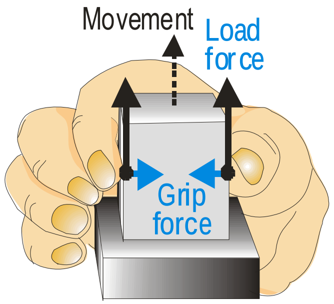
Johansson, *J Physiol (Lond)*, 1978: Johansson & Vallbo, *J Physiol (Lond)*, 1979

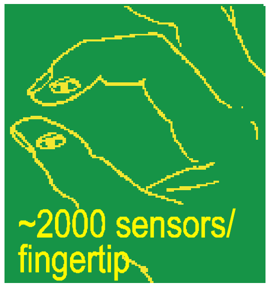
Human grasp strategy
in a prototypic pick-and-lift task

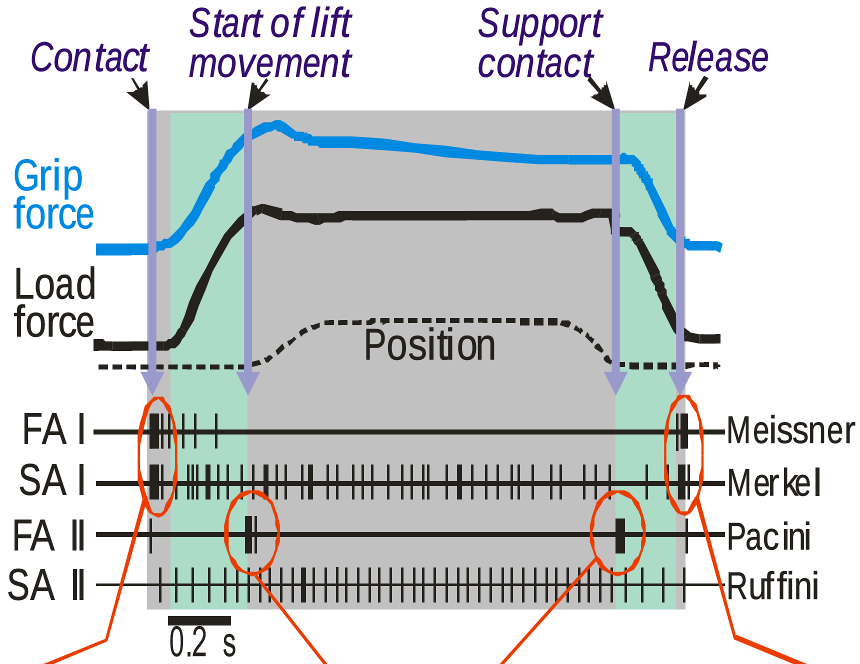


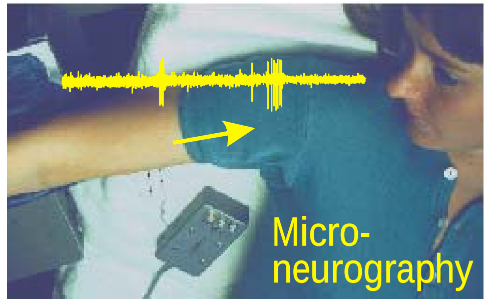


Response of tactile receptors in a prototypical pick-and-lift task









Contact response

- Time of contact
- Position of contact on the fingertip
- Force vector on the fingertip

Mechanical transients

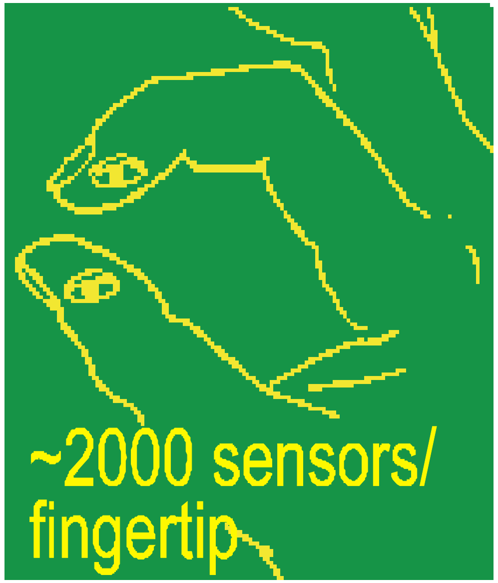
- Start and end of contact between the picked object and other objects

Release response

- End of contact between the object and the fingertip

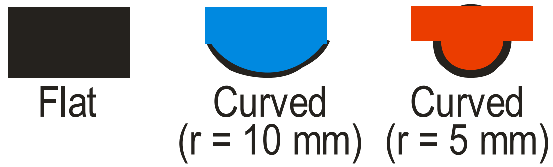
'Tactile control events' for task accomplishment

The fingertip as a tactile organ



Populations of tactile afferents encode:

- Force on the fingertip:
  - intensity
  - direction
  - spatial distribution
- Contact local shape (curvature of the object surface)



- Tactile control events:
  - slippages
  - contact start and end
  - start and end of contact between the picked object and other objects

Synthesis of human touch characteristics

TACTILE AFFERENT	CLASS	DIMENSION	RECEPTIVE FIELD (diameter)	RESPONSE THRESHOLD* (pressure)	FREQUENCY	FUNCTION	ROLE IN GRASP CONTROL (FINGERTIP)
MEISSNER	FA-I	80x30 µm	9,4 mm^2 (3.4 mm)	0.58 mN (10.2 mN/mm^2)	8-64 Hz	THIN SHARP EDGES, VELOCITY CHANGES AND PRESSURE CHANGES	CONTACT, LOCAL SHAPES, FORCES ON THE FINGERTIP
MERKEL	SA-I	10-15 µm (diameter)	11 mm^2 (3.7 mm)	1.3 mN (22.8 mN/mm^2)	2-32 Hz	THIN SHARP EDGES, PRESSURE INTENSITY	CONTACT, FORCES ON THE FINGERTIP
RUFFINI	SA-II		58.9 mm^2 (8.7 mm)	7.5 mN (131.6 mN/mm^2)	< 8 Hz	THICK SMOOTH EDGES, PRESSURE INTENSITY	SKIN LATERAL STRETCH, FORCE ON THE FINGERTIP
PACINI	FA-II	1-4 mm x 0.5-1 mm	101.3 mm^2 (11.4 mm)	0.54 mN (9.5 mN/mm^2)	64-400 Hz	THICK SMOOTH EDGES, VIBRATIONS	MECHANICAL TRANSIENTS
FINGERTIP						■ **FORCE ON THE FINGERTIP**: INTENSITY AND DIRECTION ■ **CONTACT LOCAL SHAPE** (CURVATURE OF OBJECT SURFACE) ■ **TACTILE CONTROL EVENTS**: SLIPPAGE, CONTACT START AND END, START AND END OF CONTACT OF THE OBJECT WITH THE ENVIRONMENT	

90% of receptors of type SA-I and FA-I react to a stimulus of 5 mN*, or 87mN/mm^2

*force applied with a Von Frey hair, of diameter 0.27 mm

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- Main technologies of developing artificial tactile sensors:
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Contact sensors and tactile sensors

- Contact sensors:

  provide binary information on the **contact** on the sensor surface

- Tactile sensors:

  provide information on the **force** applied on the sensor surface

  - magnitude only, along the normal direction
  - magnitude and direction (2 or 3 components of the force vector)

- Both types can be arranged into arrays to provide tactile images

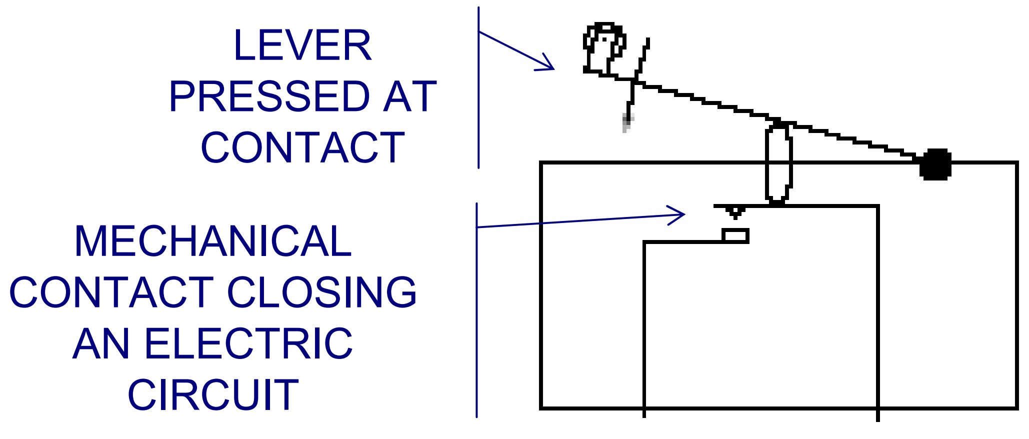
Main technologies for tactile sensors

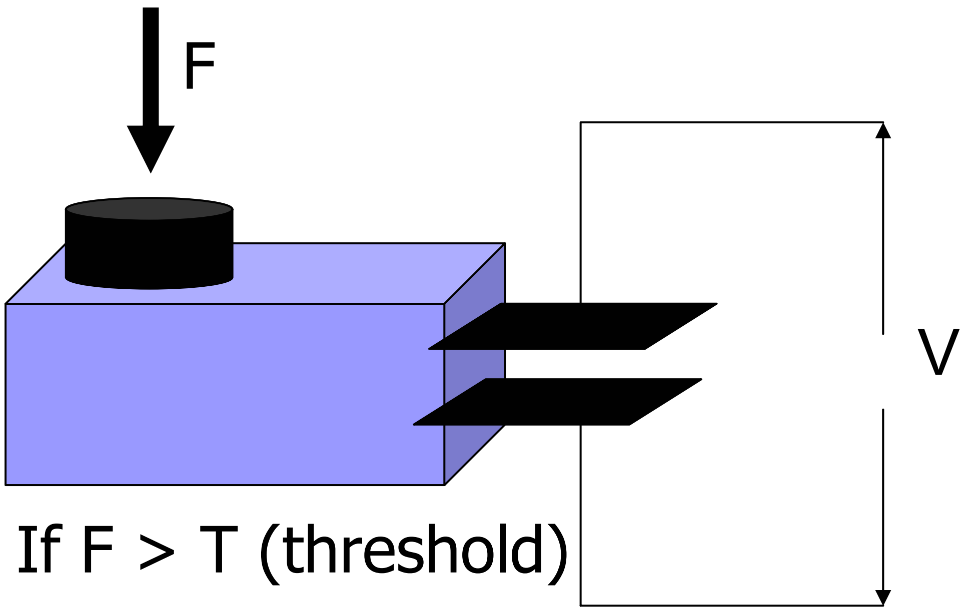
- Switches as tactile sensors
- Piezoresistive sensors
- Optical sensors
- Magnetic sensors
- Capacitive sensors
- FSR – Force Sensing Resistors
- QTC – Quantum Tunnelling Composites

Mechanical switches

- Simplest contact sensors
- Provide one binary datum:

  contact / no contact
- Applications as tactile sensors:
  - impact sensors on mobile robots
  - whiskers
  - endstop sensors for manipulator joints





Arrays of switches

[Raibert, 1984]

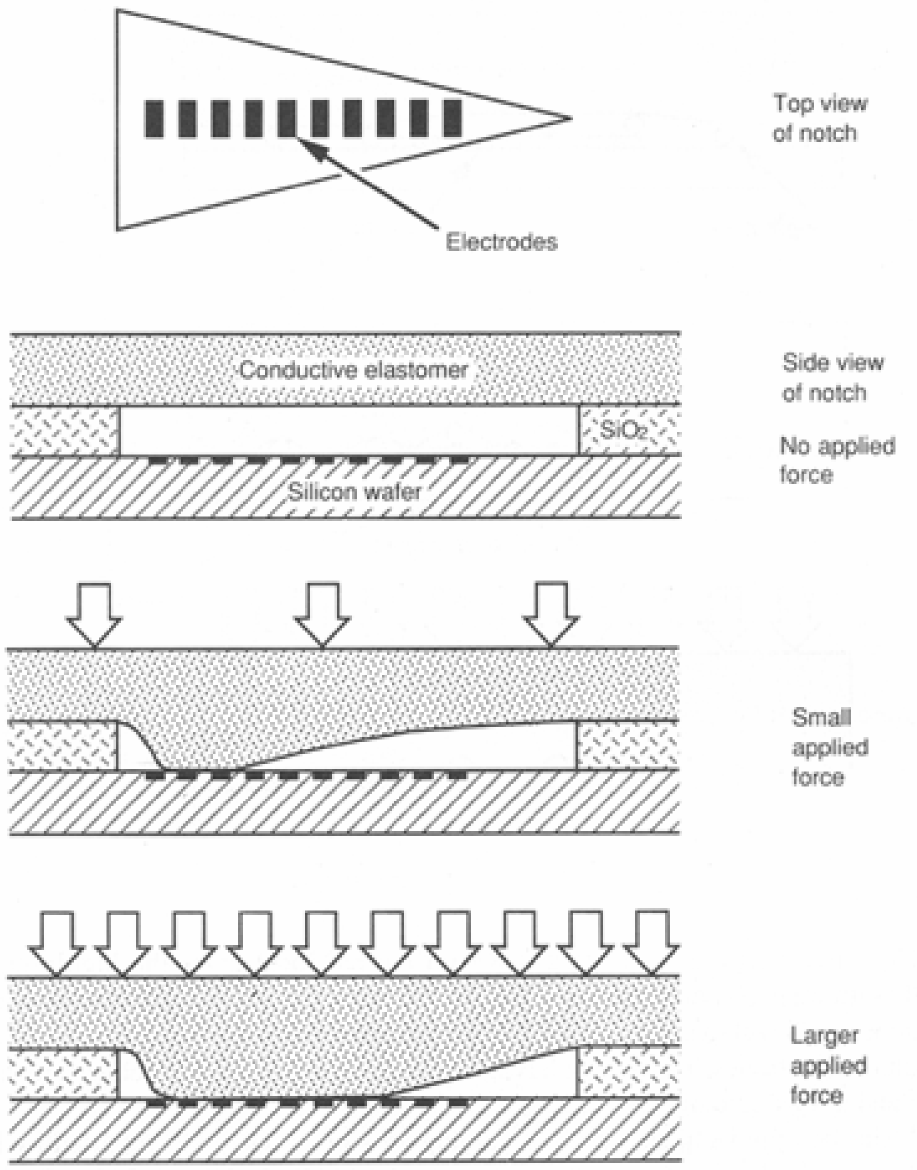
An array of switches with different contact threshold can measure the value of pressure applied.

The maximum depth that a metal sheet can reach inside a circular hole when pressed is given by:

$$\delta \propto \frac{pa}{E}$$

$$\begin{aligned} &with: \\ &\delta = \max deflection \\ &p = applied pressure \\ &a = radius\ of\ hole \\ &E = Young's\ module \end{aligned}$$

- 48 units
- unit area: 0.3 x 0.6 mm
- 15 electrodes for 16 levels of pressure
- by varying the hole shape we can obtain linear, logarithmic or exponential responses

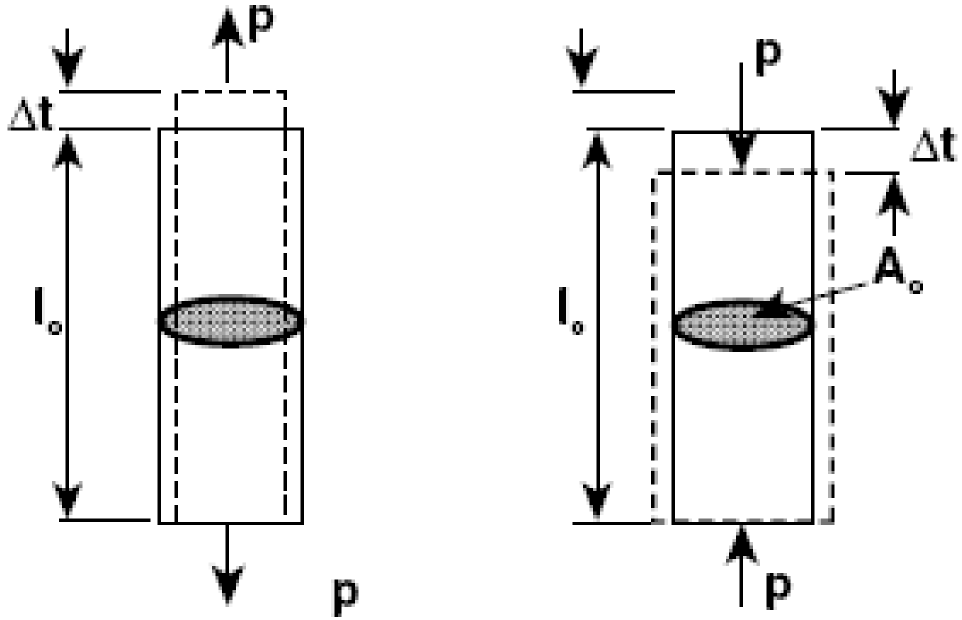


Piezoresistive effect

Every material changes its electrical resistance with **strain**

Basics of mechanical behavior of materials

Stress applied to a material causes strain. The material has an elastic behavior until a stress threshold (elastic limit), beyond which the material deformation is plastic



stress

$$\sigma = {p}/{A_0}$$

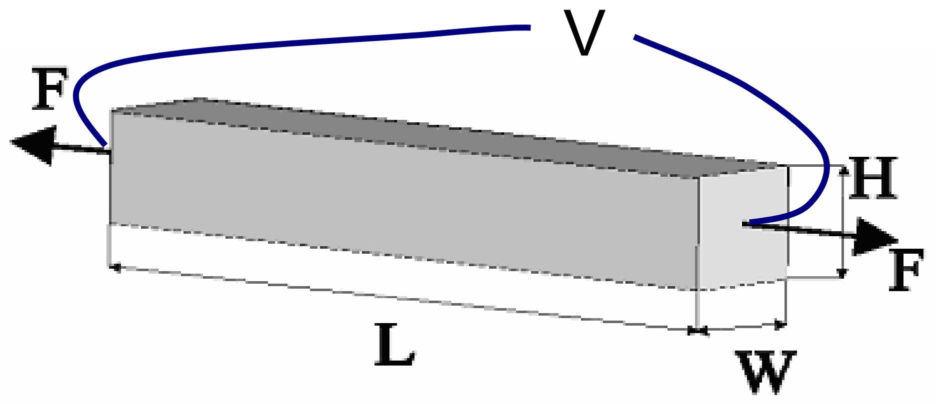
strain

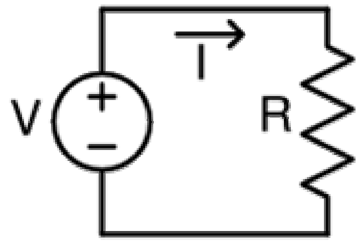
$$\varepsilon = {\Delta l}/{l_0}$$

Poisson's ratio: $\nu = -\dfrac{\delta A / A_0}{\varepsilon}$ Elasticity module: $E = \dfrac{\sigma}{\varepsilon}$

Piezoresistive effect

Every material changes its electrical resistance with **strain**





V=RI

In a metal block: $R = \rho \dfrac{L}{WH}$

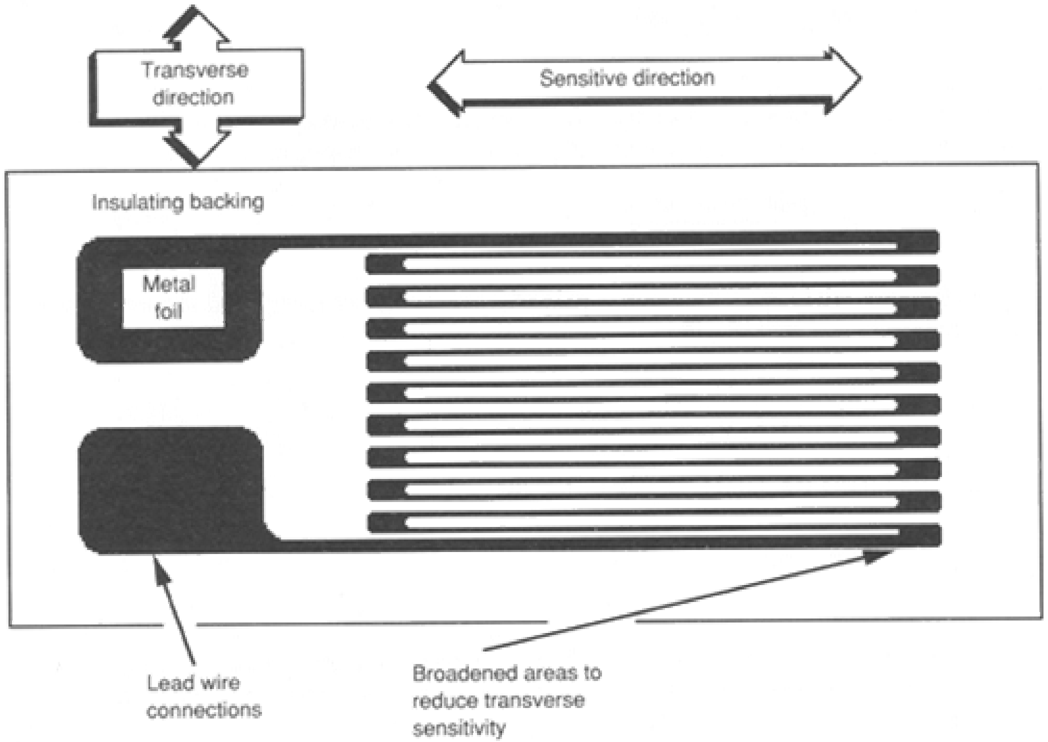
with *ρ* = resistivity of the material,

L, W, H = dimensions of the block

$$\frac{\Delta R}{R} = \varepsilon + 2\nu\varepsilon + \frac{\Delta\rho}{\rho}$$

v = Poisson's ratio of the material

Strain gauge

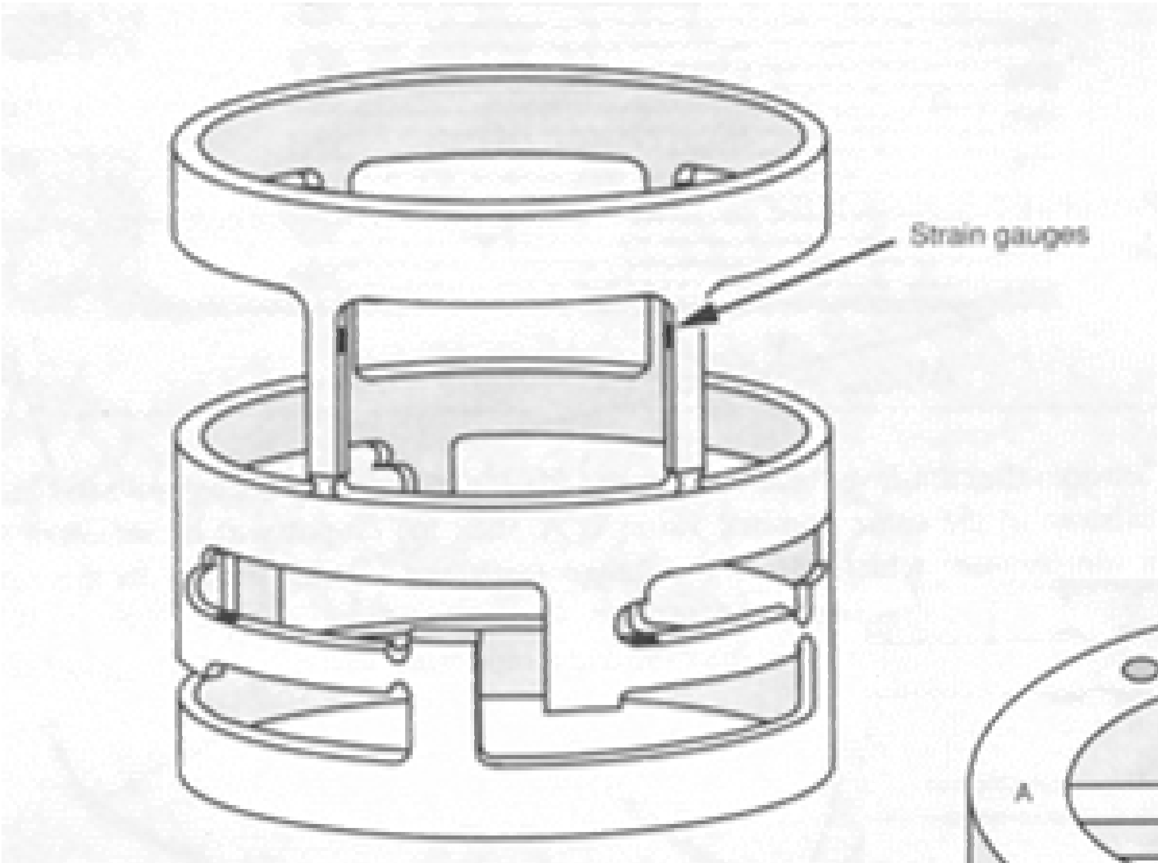


The sensor shape increases sensitivity in one direction

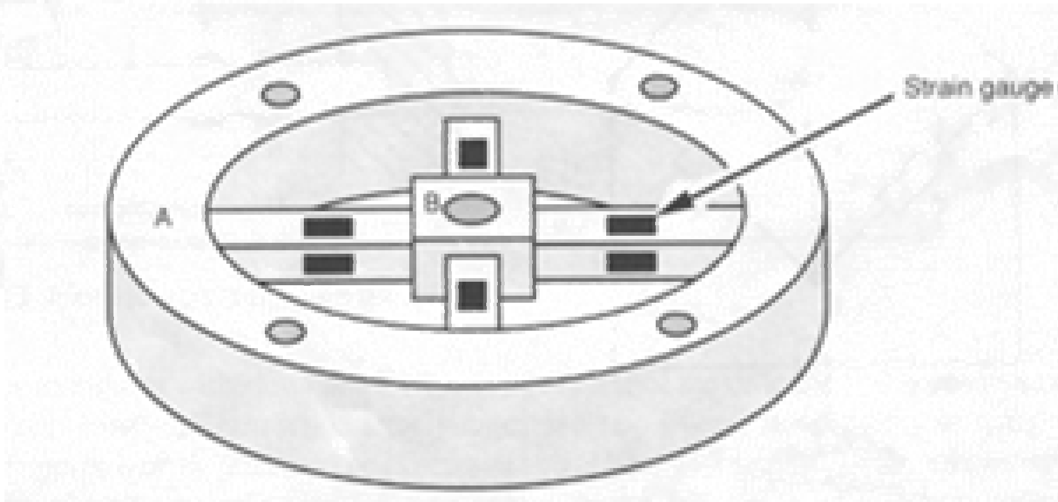
Gauge factor: $$G = \frac{\Delta R / R}{\varepsilon} = 1 + 2\nu + \frac{\Delta\rho / \rho}{\varepsilon}$$

v = Poisson's ratio of the material

Three-axial force/torque sensors

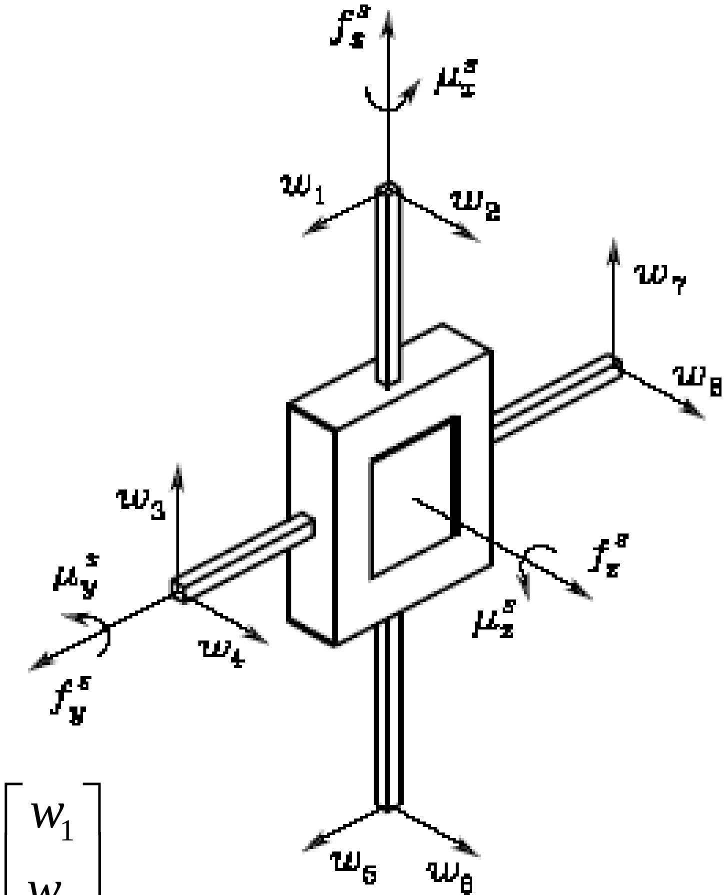


- Mechanical structure with preferred strain directions, along 3 axes
- Strain gauges arranged accordingly



Three-axial force/torque sensors

- Forces and torques are measured from measures of the resistance variations of the strain gauges, multiplied by a coefficient array, typical for each sensor
- The coefficient array is built by a calibration procedure in which known forces are applied



$$\begin{bmatrix} f_x^s \\ f_y^s \\ f_z^s \\ \mu_x^s \\ \mu_y^s \\ \mu_z^s \end{bmatrix} = \begin{bmatrix} 0 & 0 & c_{13} & 0 & 0 & 0 & c_{17} & 0 \\ c_{21} & 0 & 0 & 0 & c_{25} & 0 & 0 & 0 \\ 0 & c_{32} & 0 & c_{34} & 0 & c_{36} & 0 & c_{38} \\ 0 & 0 & 0 & c_{44} & 0 & 0 & 0 & c_{48} \\ 0 & c_{52} & 0 & 0 & 0 & c_{56} & 0 & 0 \\ c_{61} & 0 & c_{63} & 0 & c_{65} & 0 & c_{67} & 0 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ w_5 \\ w_6 \\ w_7 \\ w_8 \end{bmatrix}$$

Optical sensors

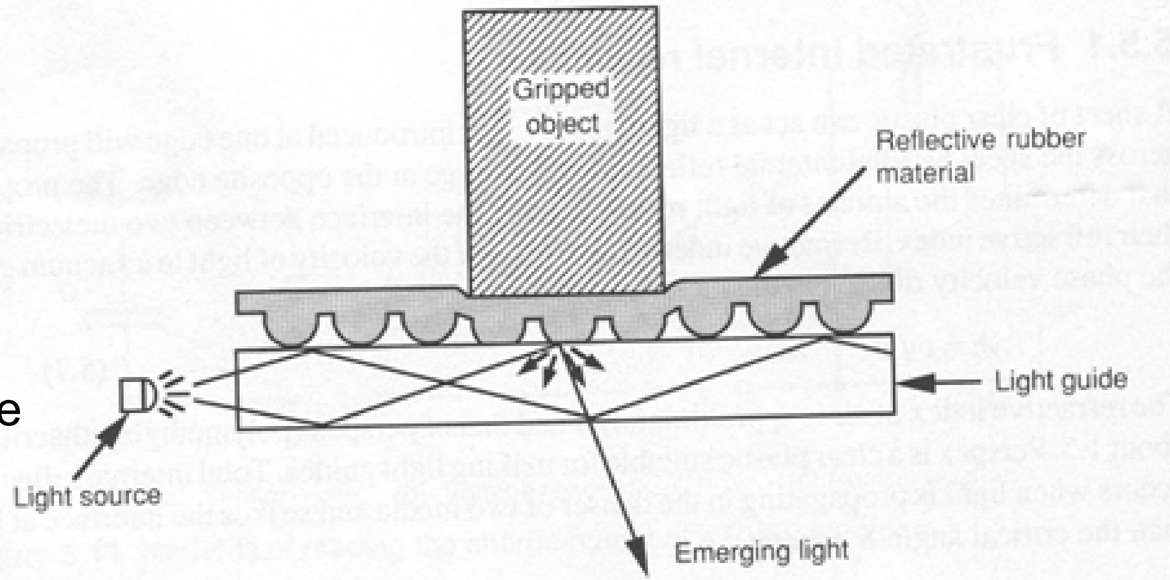
Rifractive index of a material:

$$n=c/v$$

with

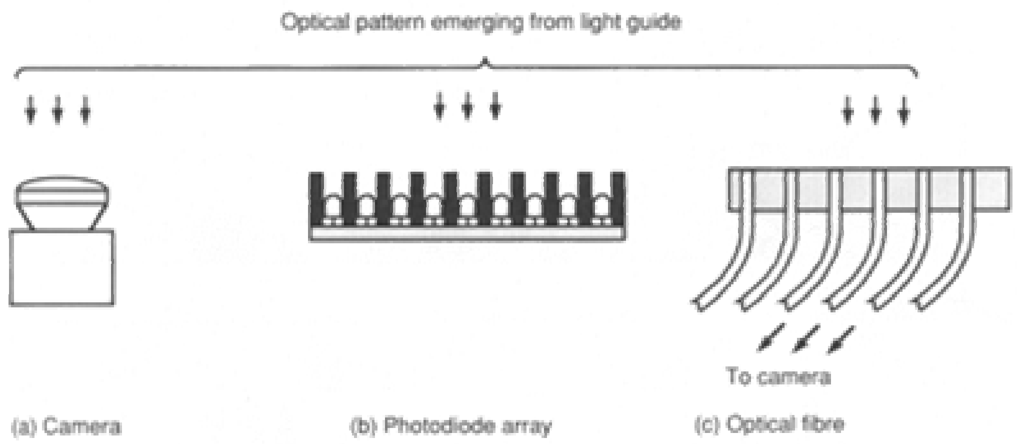
c = velocity of light in a vacuum

v = velocity of light in the material



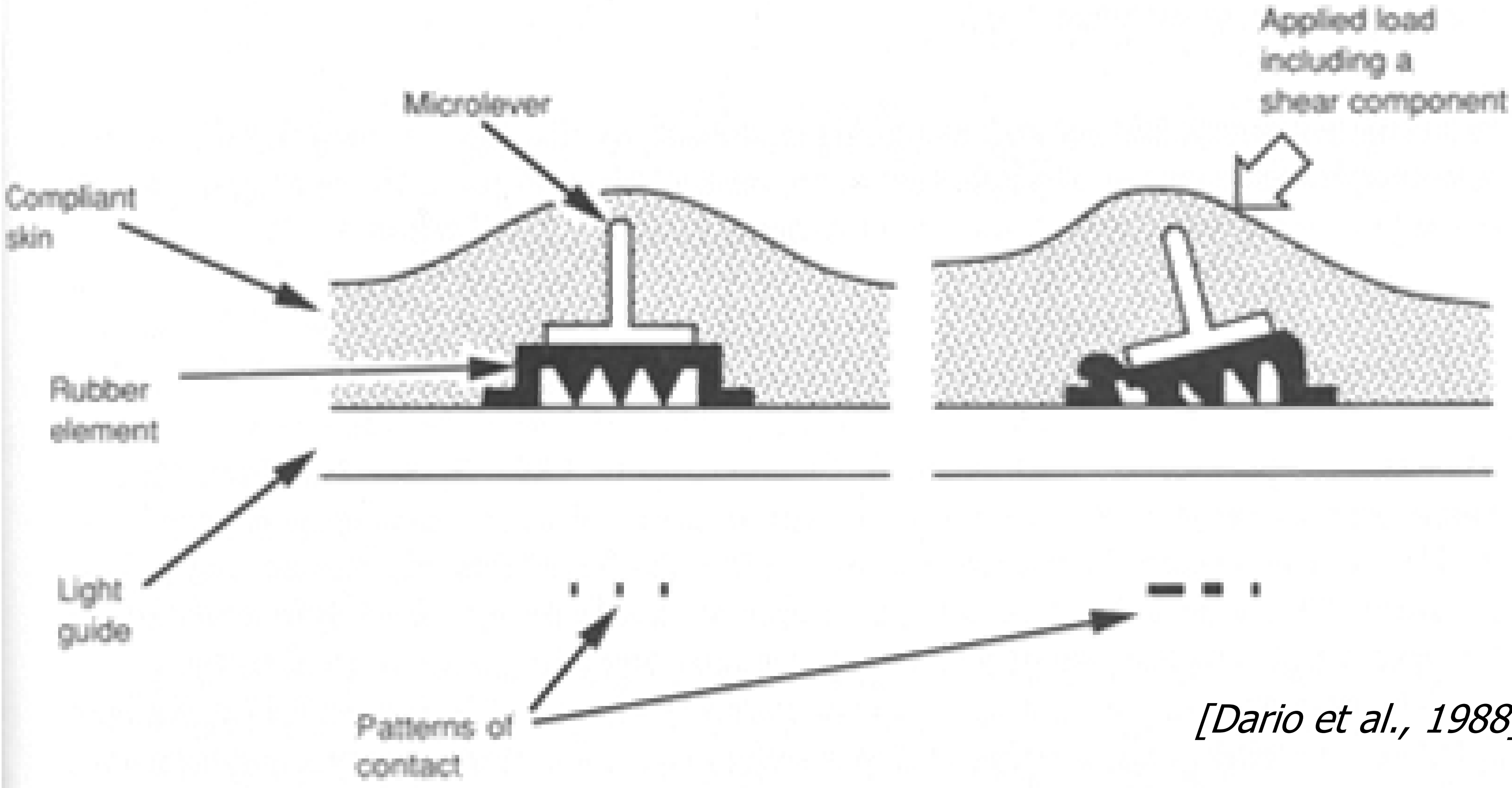
Total internal reflection:
when light strikes the surface of the interface between two materials at less than θ_c (measured from the interface normal)

Critical angle θ_c:
$\sin \theta_c = n_2/n_1$ with $n_1>n_2$



Light propagates along an optical guide provided it strikes the guide/air interface at an angle smaller than θ_c,
The contact with an external object frustrates the total internal reflection and light emerges from the opposite side of the guide

Optical sensors



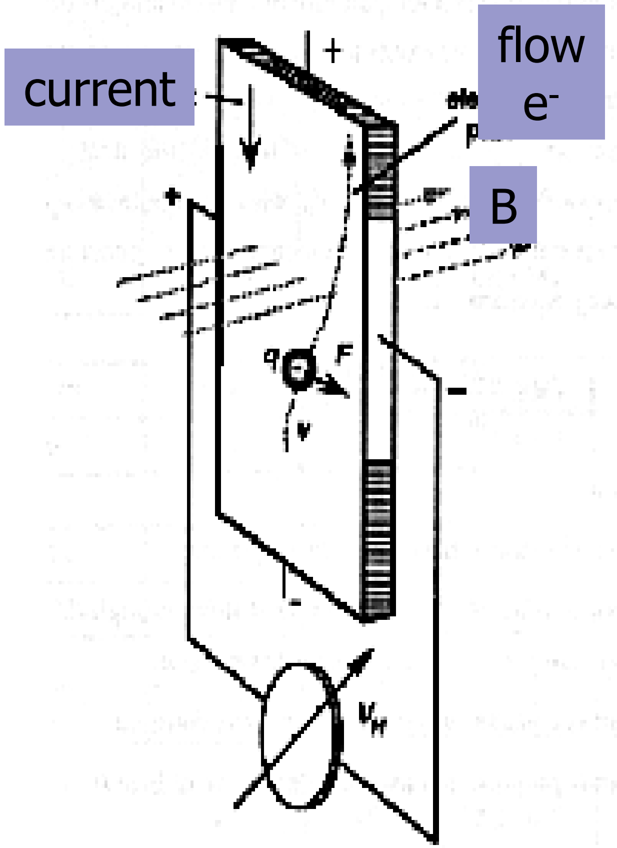
[Dario et al., 1988]

By varying the shape of the object in contact with the light guide it is possible to obtain a response proportional to the applied force and to tangential forces

Magnetic sensors

Hall-Effect sensors

In a conductor where a current i flows, immersed in a magnetic field of intensity B, a voltage V originates in the direction normal both to the current and to the magnetic field.



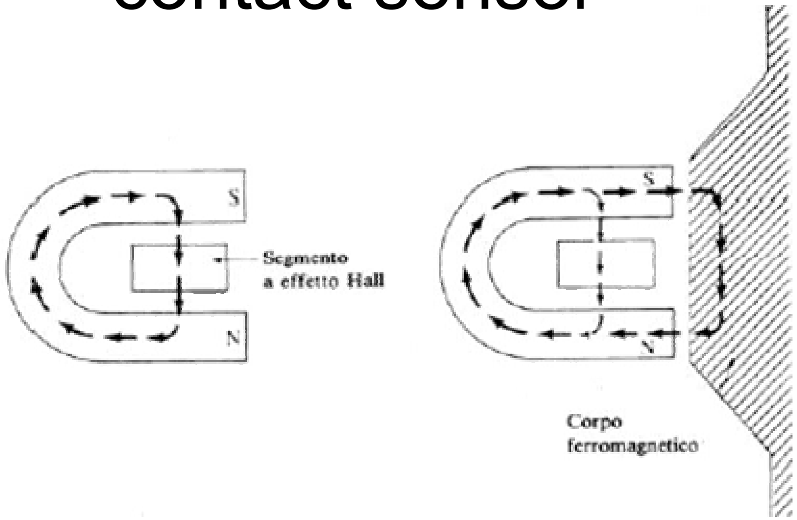
The value of the voltage is proportional to the intensity of the current i and to the intensity of the magnetic field B, while it is inversely proportional to the thickness of the material d:

$$V = R\, i\, B / d$$

where R = Hall costant or coefficient.

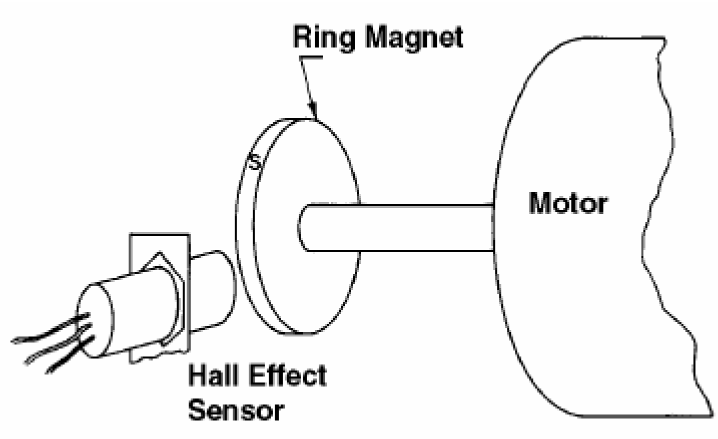
Hall-effect magnetic sensors

Hall-effect proximity and contact sensor



A permanent magnet generates a magnetic field.
The contact with a ferromagnetic object modifies the magnetic field.
The Hall effect allows to measure this variation as a voltage

Hall-effect position sensor



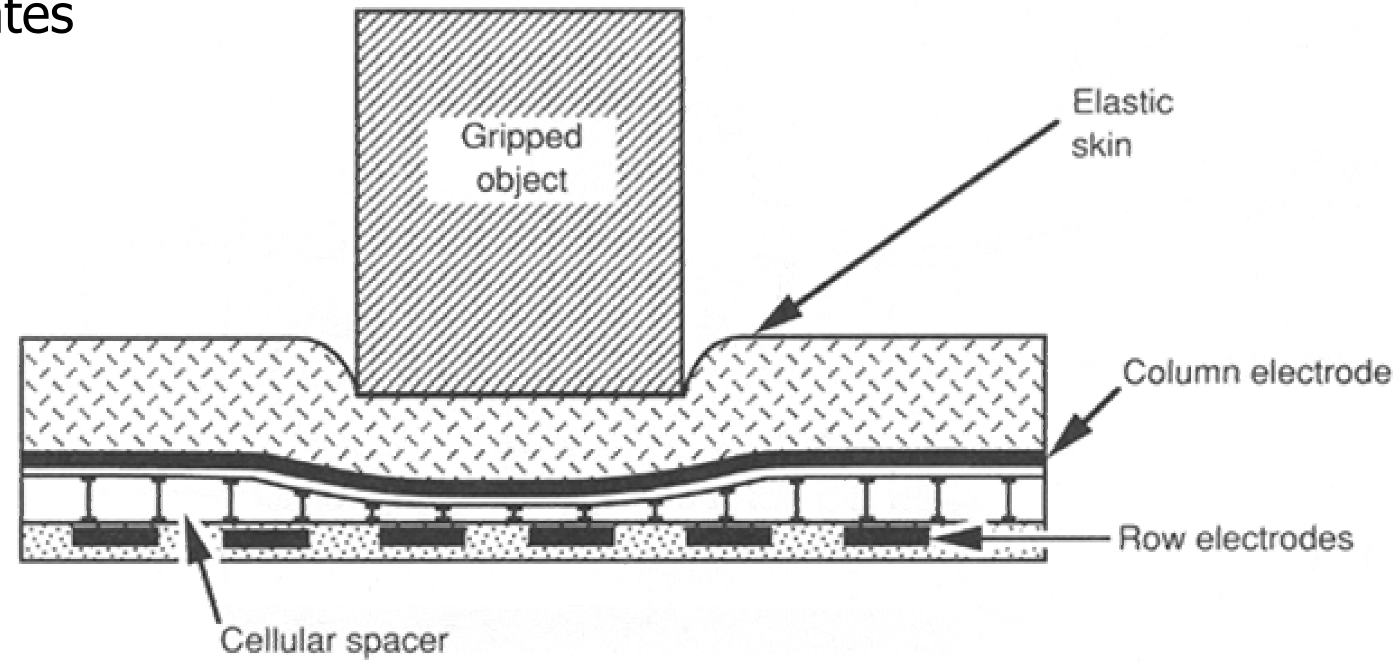
Capacitive sensors

Capacitance between two parallel conductive plates:
A = plate area
d = plate distance
ε = characteristic of the material between the two plates

$$C = \frac{\varepsilon A}{d}$$

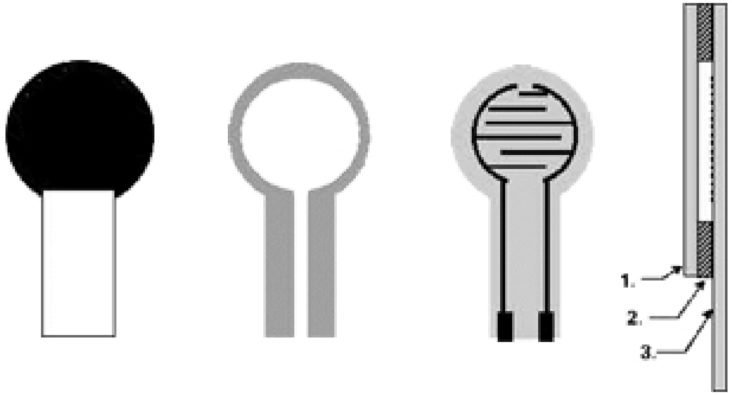
Tangential forces can vary the overlap area

Normal forces can vary the distance

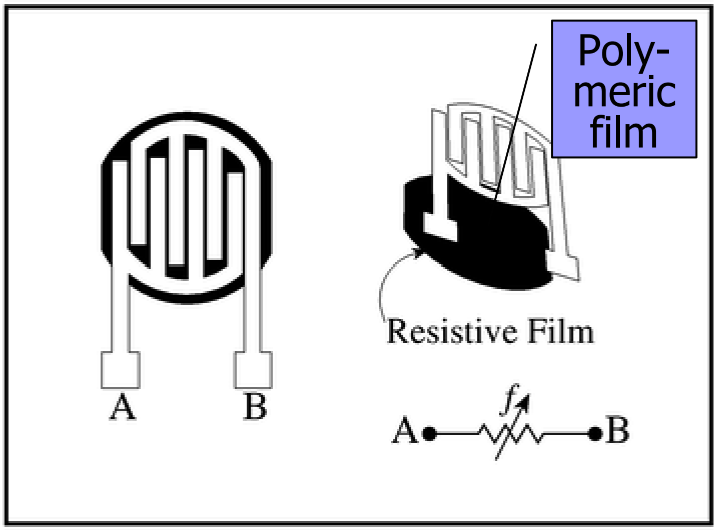


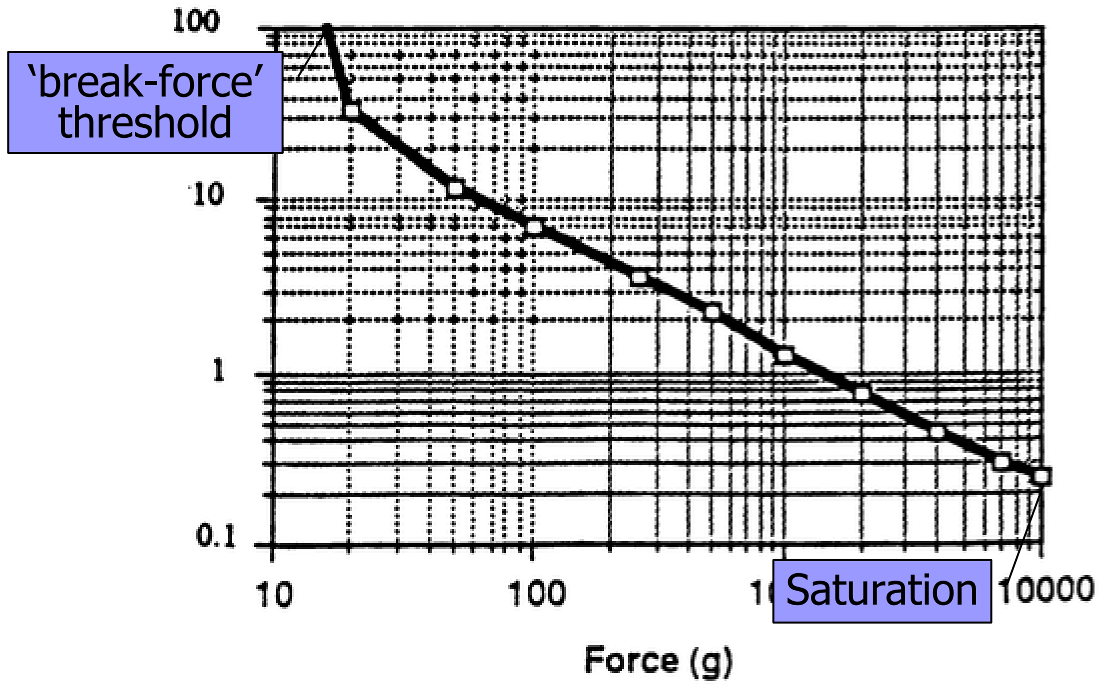
8 x 8 units
1.9 mm distance

FSR – Force Sensing Resistors

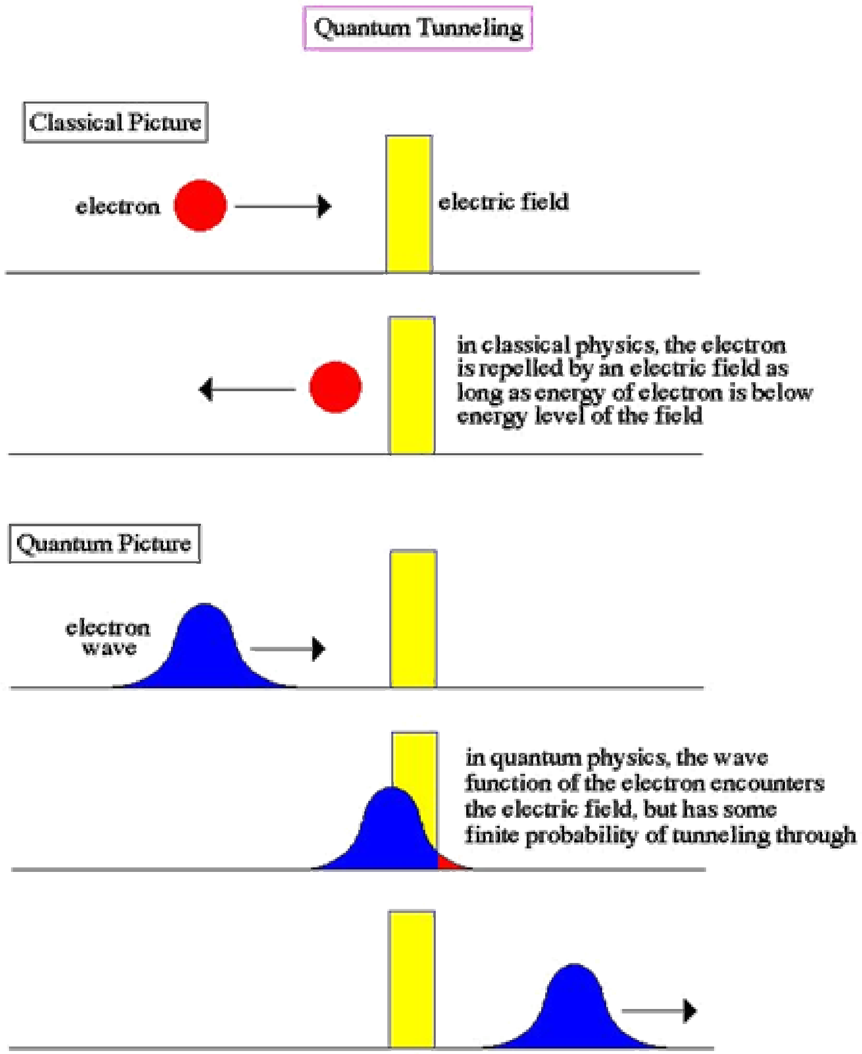


- Polymeric-film device
- Decreasing resistance with increasing applied forces



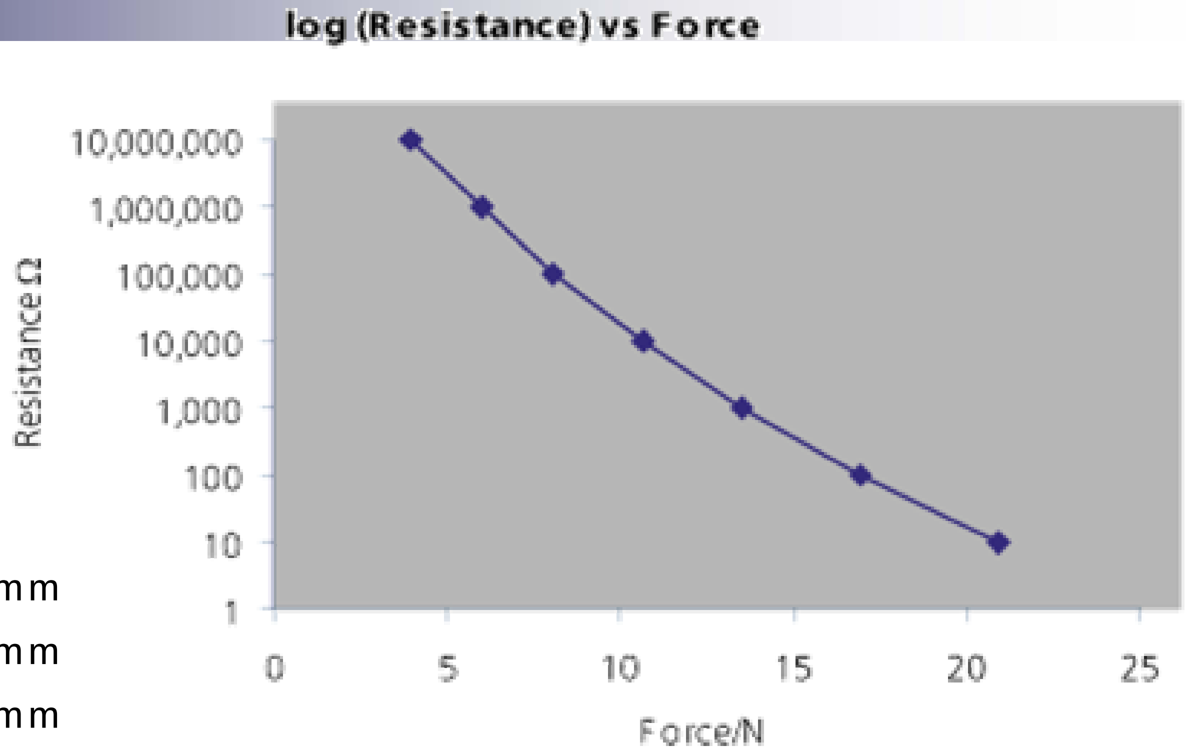


QTC (Quantum Tunnelling Composites) Sensors

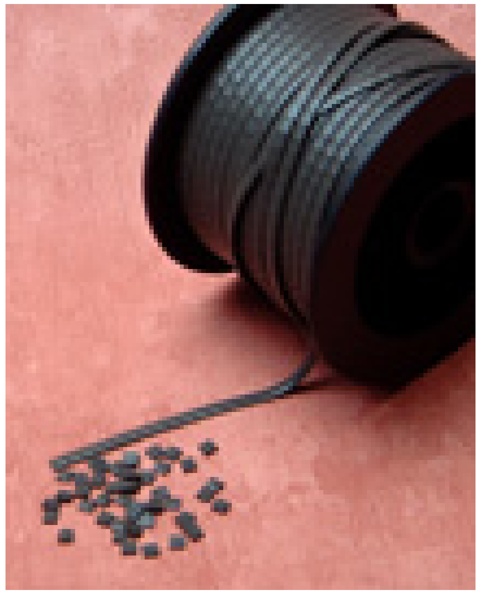


- QTCs have the unique capability of transformation from a virtually perfect insulator to metal- like conductor when deformed.
- That deformation can result from the compression, twisting or stretching of the material
- QTC's response can be tuned appropriately to the spectrum of forces applied.
- The transition from insulator to conductor follows a smooth and repeatable curve, with the resistance dropping exponentially

QTC sensors



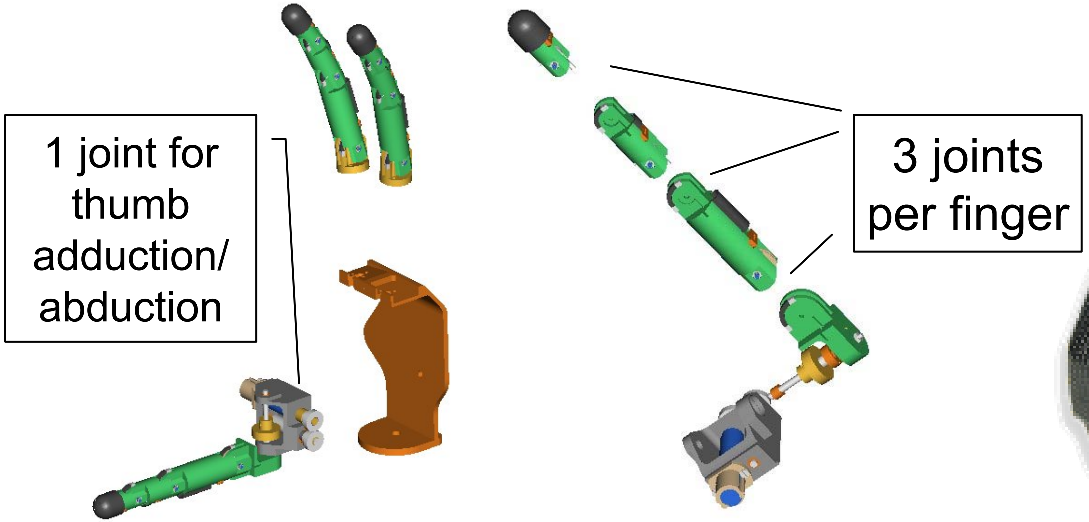
Dimensions	
Width	3.6 mm
Length	3.6 mm
Thickness	1.0 mm
Mechanical properties	
Weight	0.04g
Density	4.0 g/cm^3
Force range	0 - 100 N
Lifetime	>1,000,000 compressions
Electric properties	
Resistivity at rest	> 7 x 10^{12} Ohm cm
Typical range of resistance	> 10^{12} Ohms to < 1 Ohm
Operative voltage	0 to 40 V
Max current	10 A

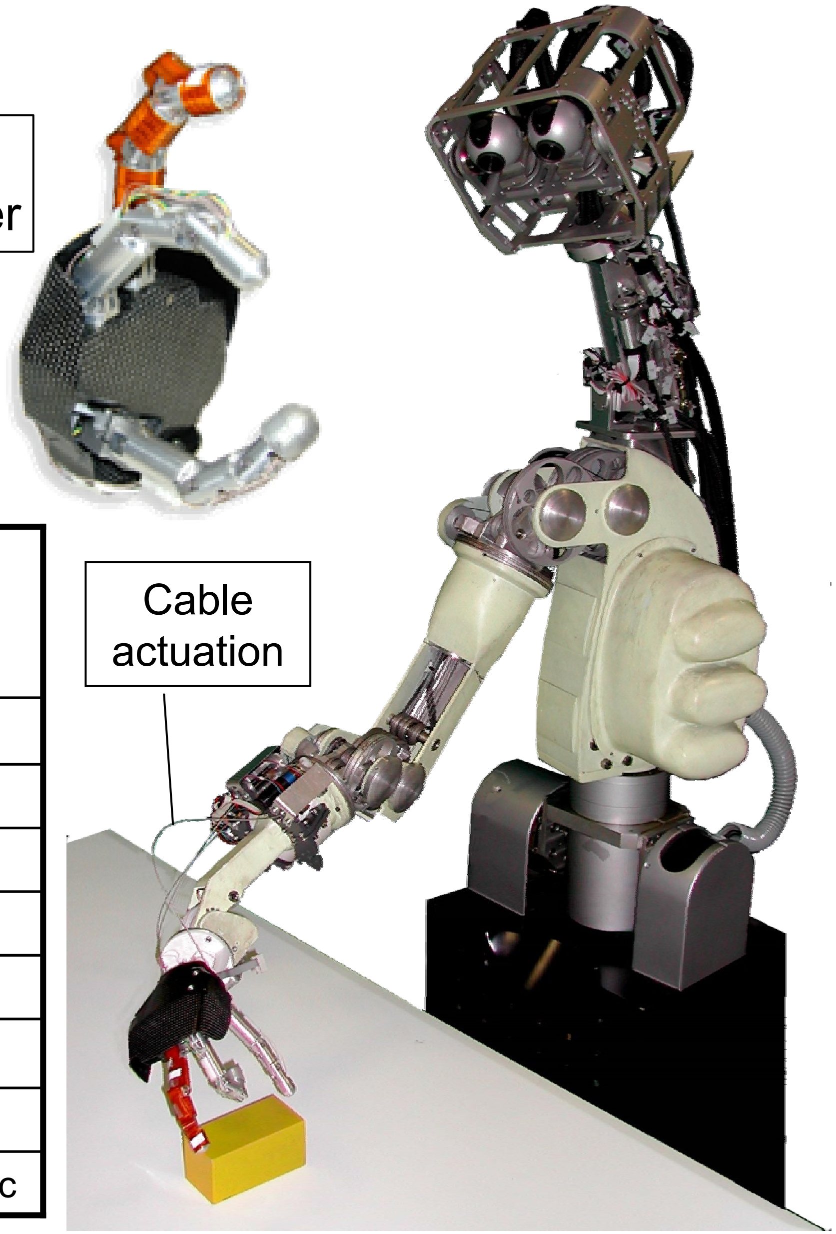


Outline of the talk

- Human sense of touch:
  - Human tactile receptors and their characterization
  - The fingertip as a tactile organ
- Main technologies of developing artificial tactile sensors:
  - Working principles
  - Mathematical relations
  - Examples of tactile sensors developed with each technology
- Case study of biomechatronic tactile sensor

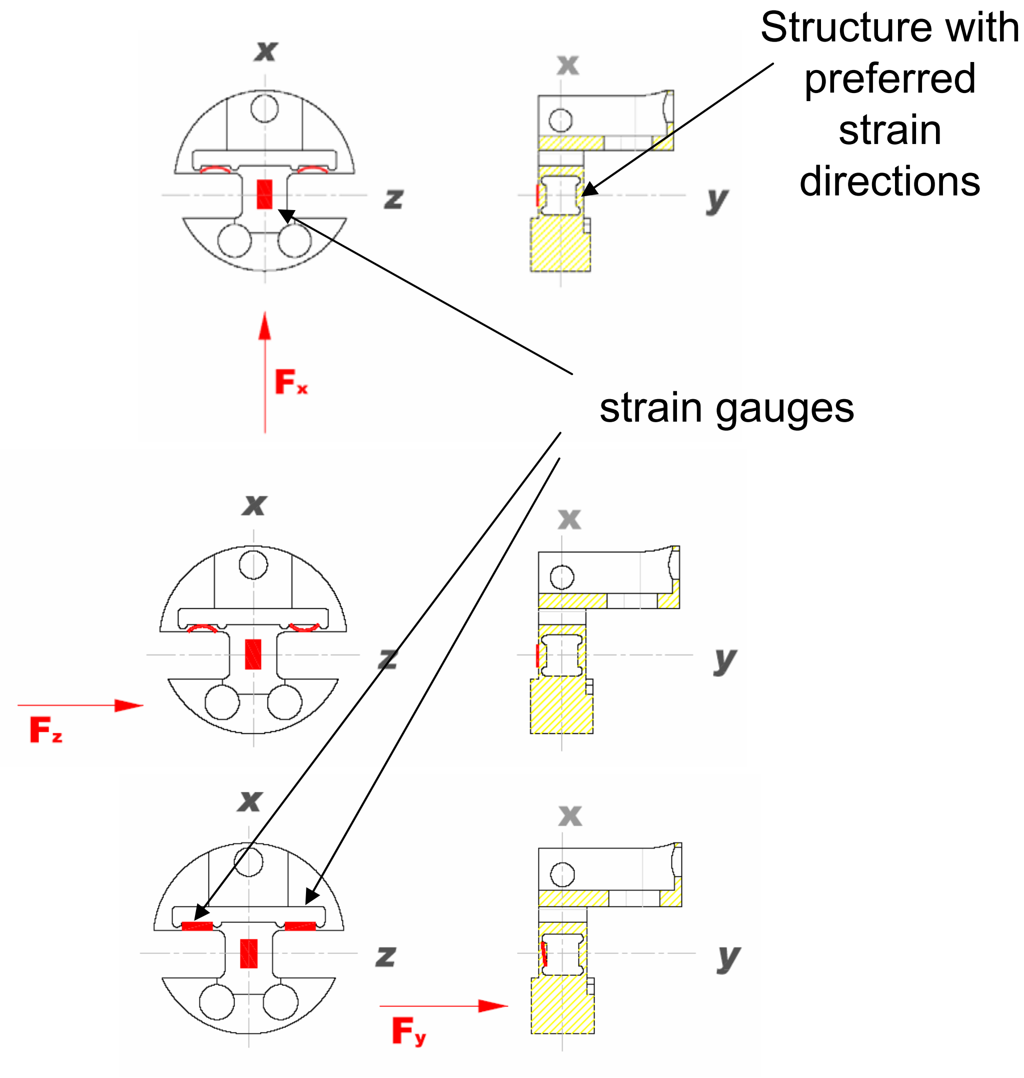
Tactile system for a robot hand

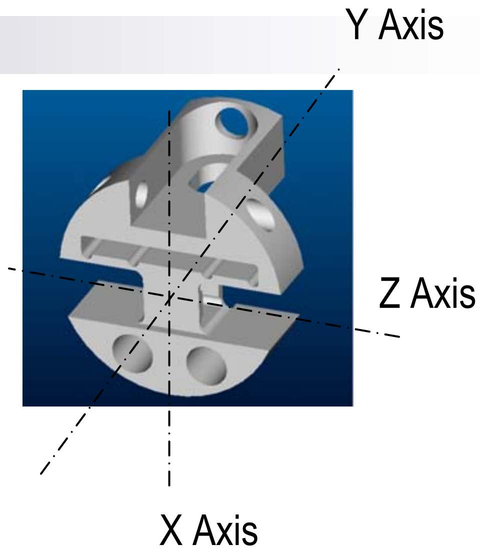


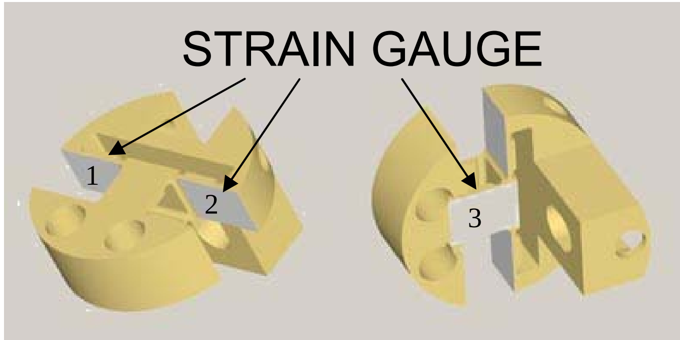


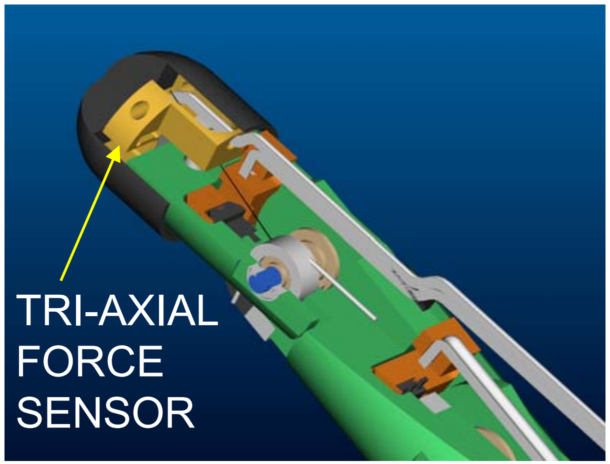
Degrees of Freedom	10, of which: 4 actuated, 6 underactuated
Range of motion thumb adduction/abduction	0°-120°
Range of Motion of finger joints	0°-90°
Max payload	450 gr
Grasp force	40N
tip-to-tip force	15N
Closure time	2 s
Weight	400 gr
Size	Anthropomorphic

Tri-axial fingertip force sensor







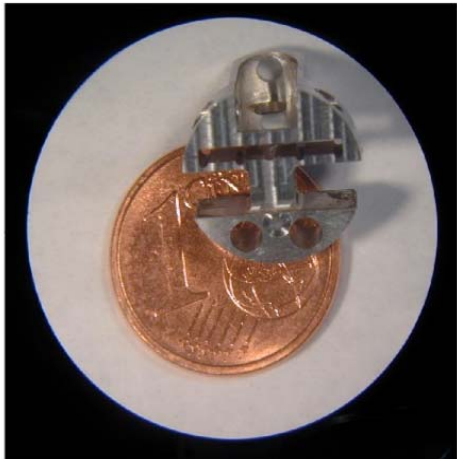


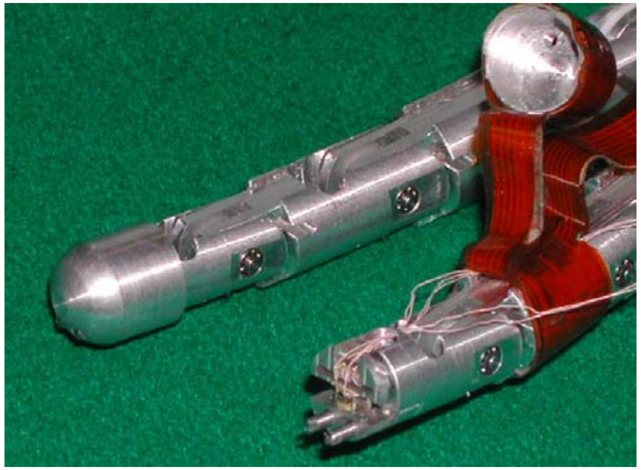
Tri-axial fingertip force sensor

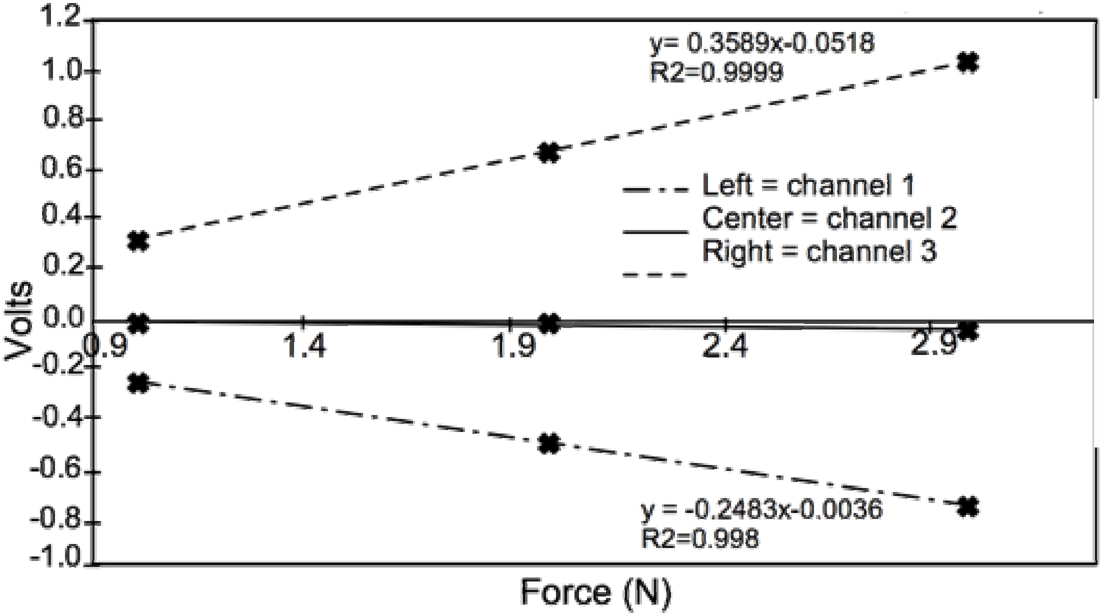
material: aluminium

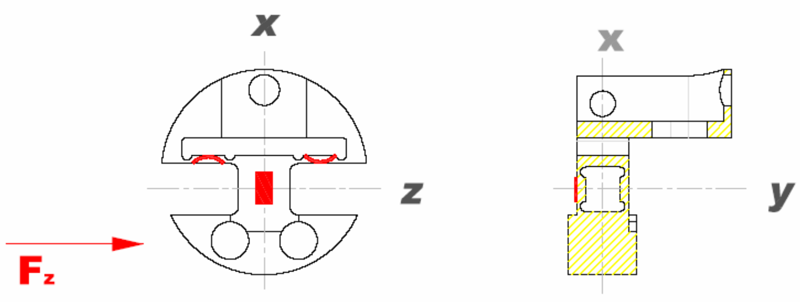
dimension: ϕ=12 mm

h= 9,5 mm

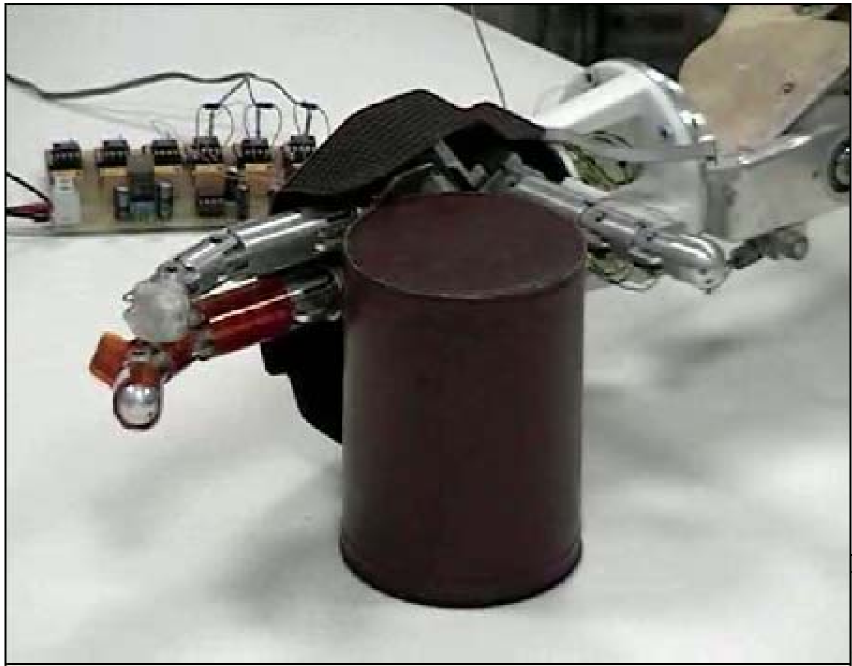




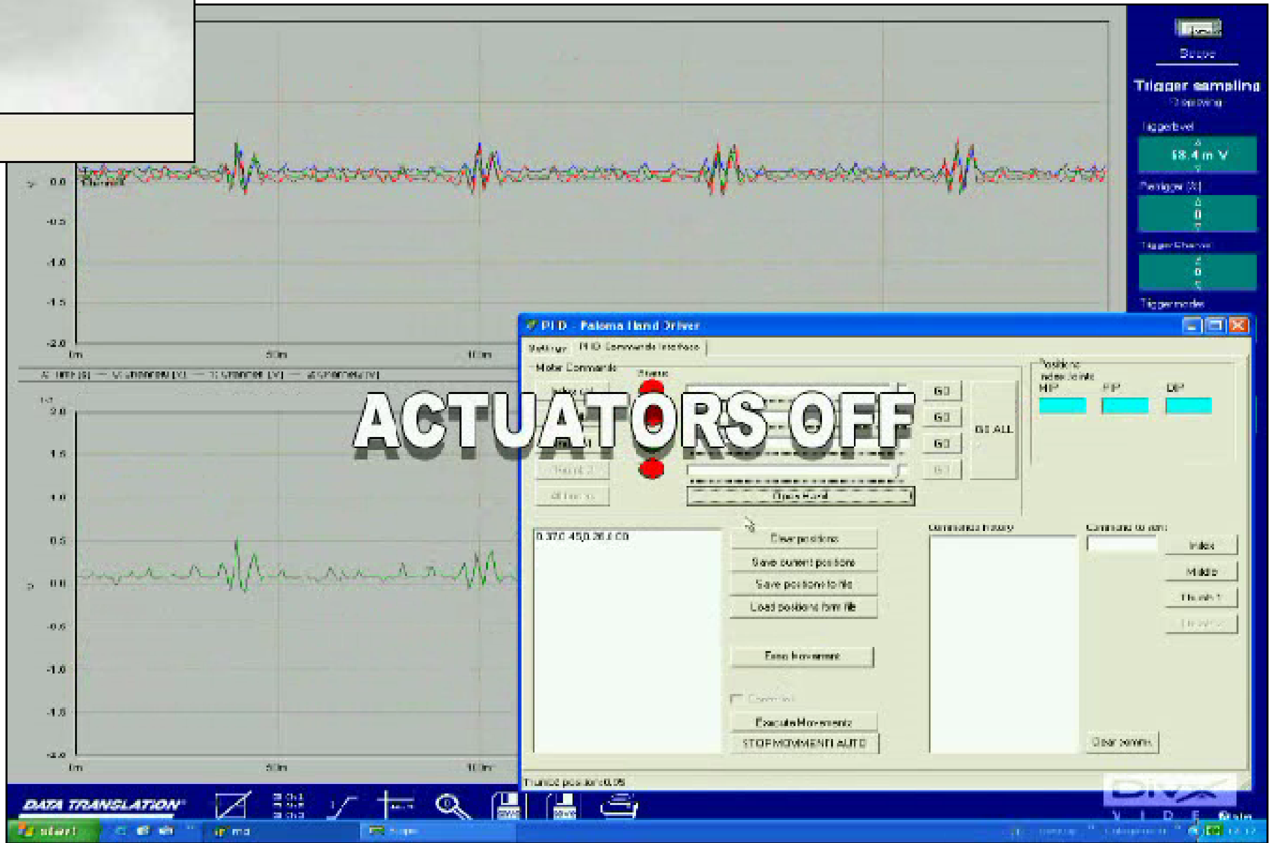




3D Force Sensor output

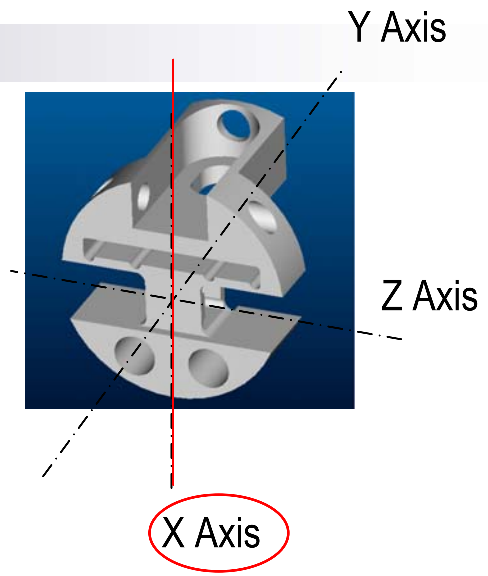


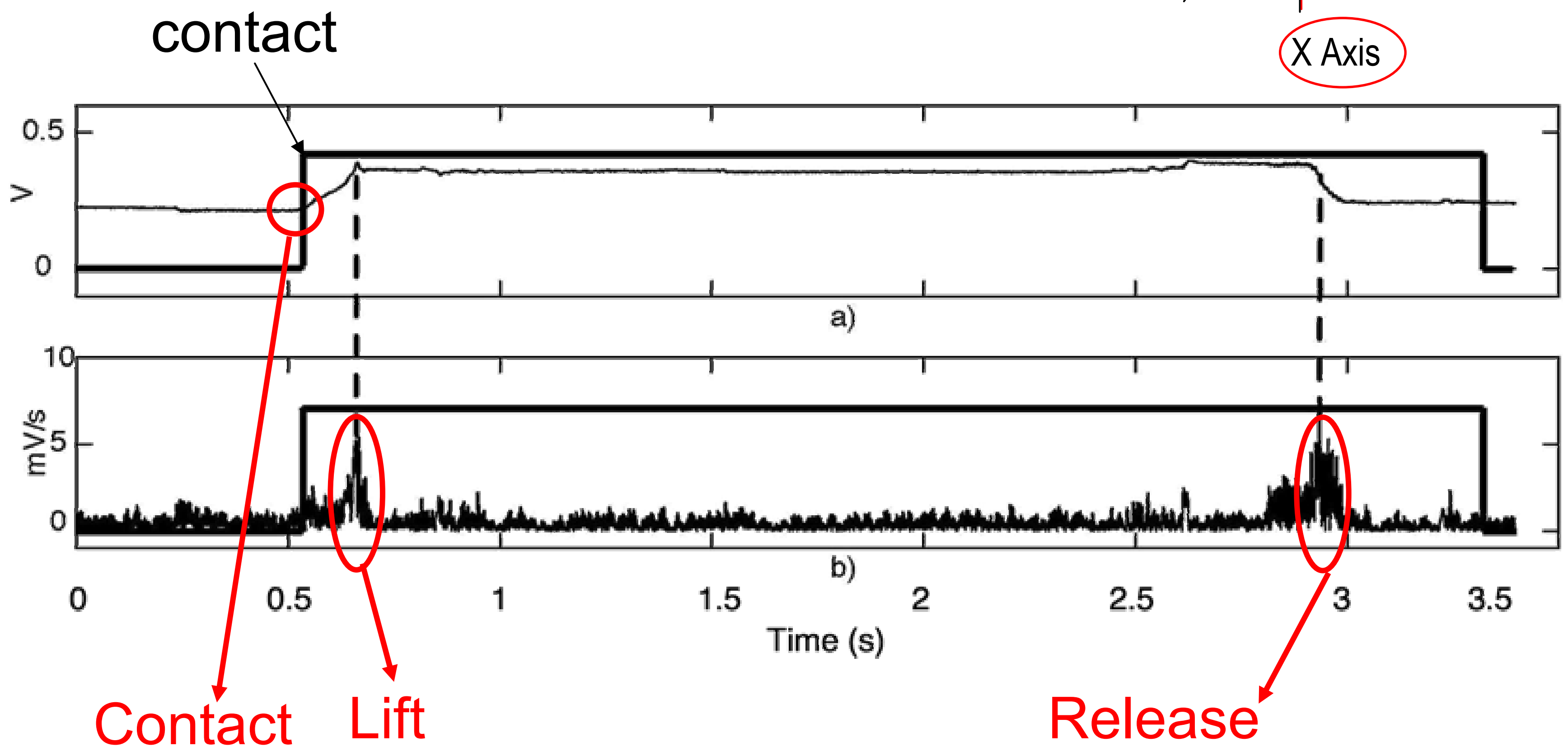
presa oggetto



3D record

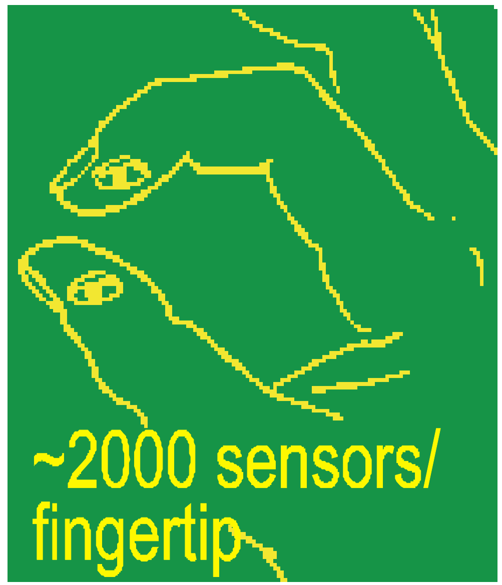
Behavior of the tactile fingertip in the prototypic pick-and-lift task



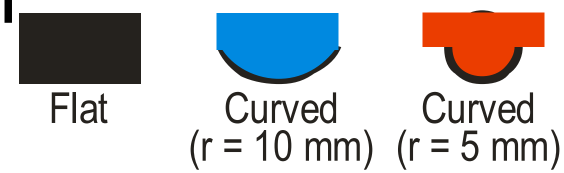


B.B. Edin, L. Beccai, L. Ascari, S. Roccella, J.J. Cabibihan, M.C. Carrozza, "A bio-inspired approach for the design and characterization of a tactile sensory system for a cybernetic prosthetic hand", ICRA 2006, Orlando, FL, May 15-17, 2006

Functionality of the tri-axial fingertip force sensor with respect to the human fingertip

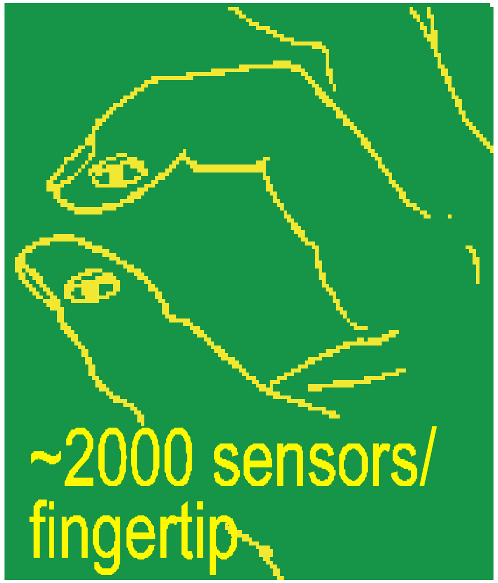


- Forces applied on the fingertip:
  - magnitude
  - direction
- Contact local shape (curvature of the object surface)

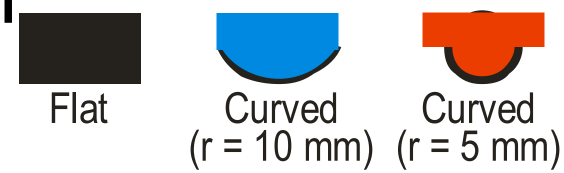


- Tactile control event:
  - slippage
  - contact start and end
  - lift and release

Functionality of the tri-axial fingertip force sensor with respect to the human fingertip

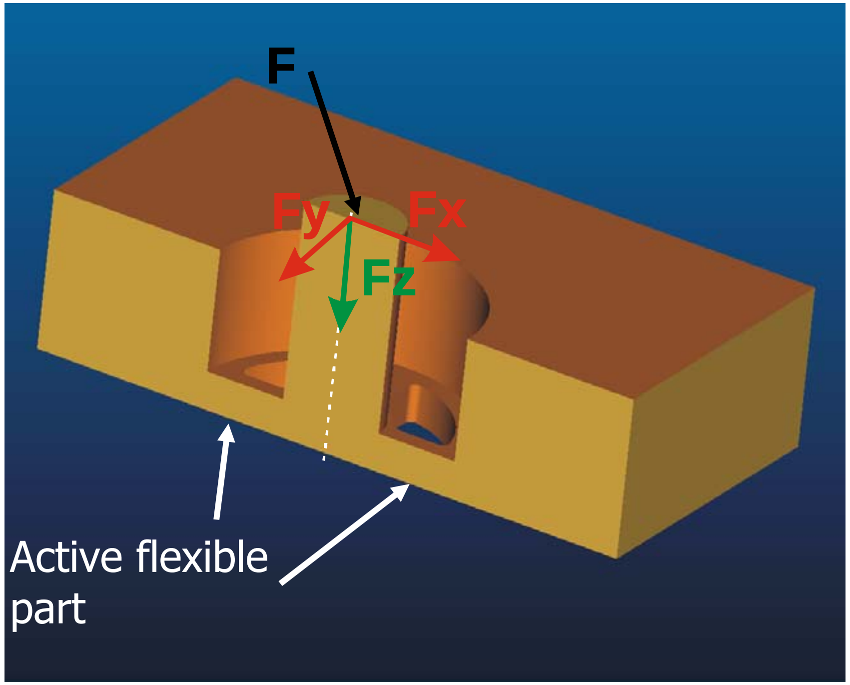


- Forces applied on the fingertip:
  - magnitude
  - direction
- Contact local shape (curvature of the object surface)



- Tactile control event:
  - slippage
  - contact start and end
  - lift and release

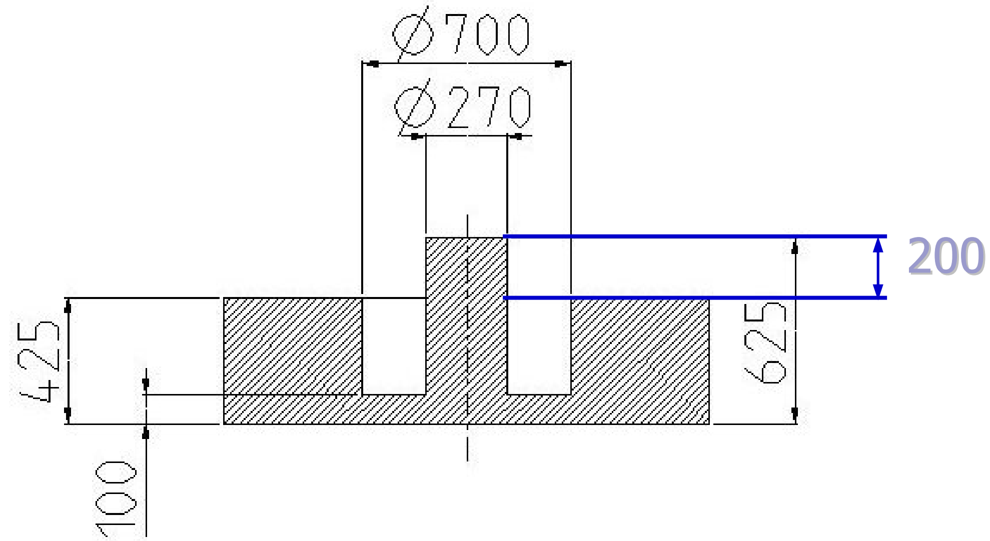
Tri-axial micro force sensor



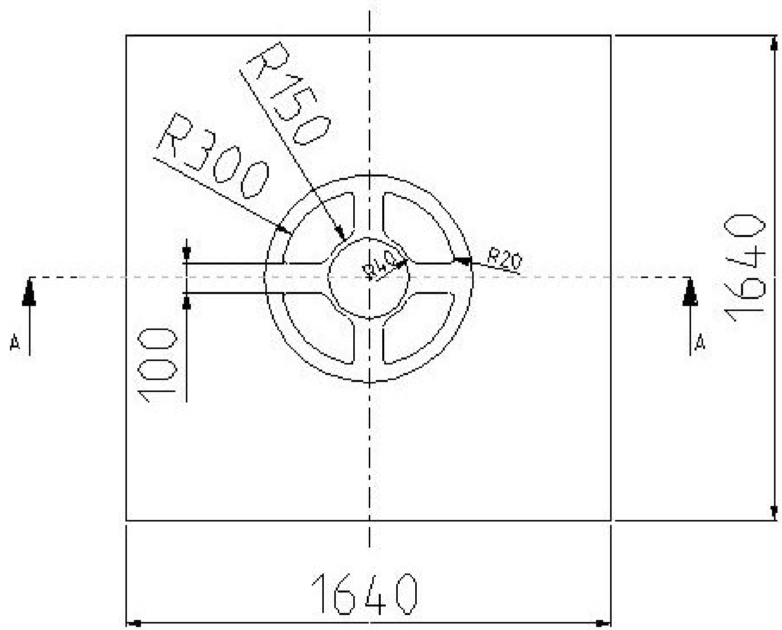
Section of the sensor 3D model

The sensor is based on piezoresistive transduction obtained by embedding piezoresistors in the arms of the flexible structure

Sensor size

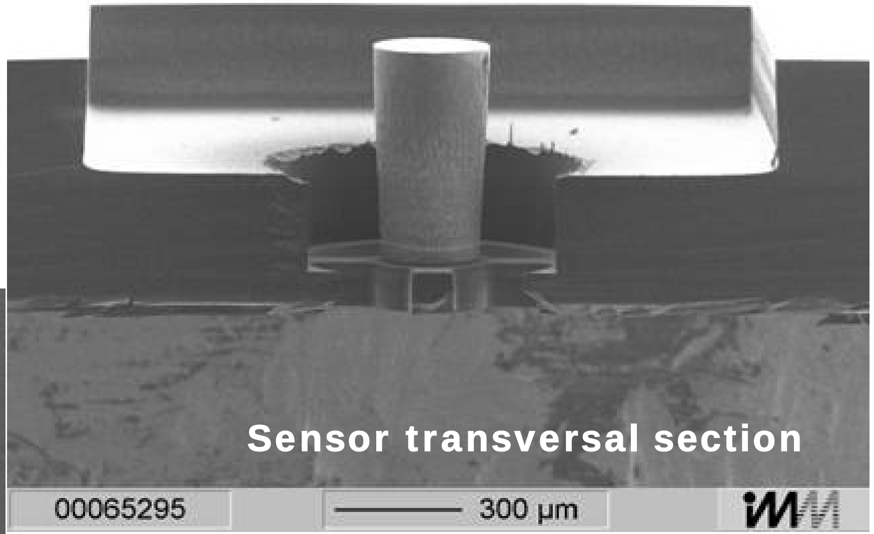


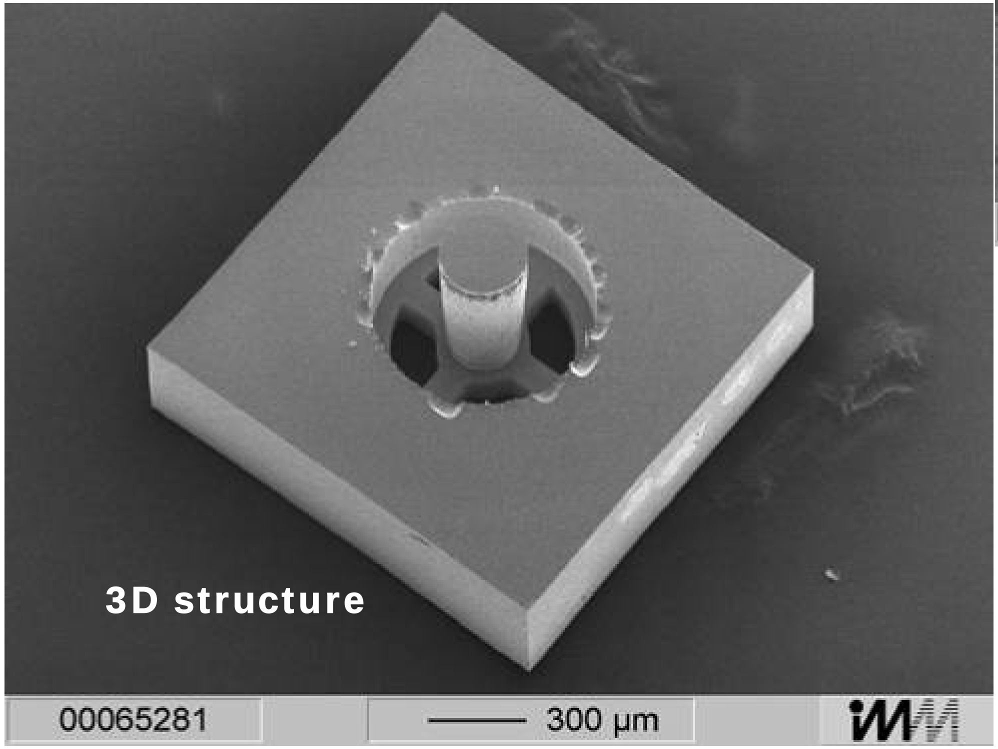
Size in µm



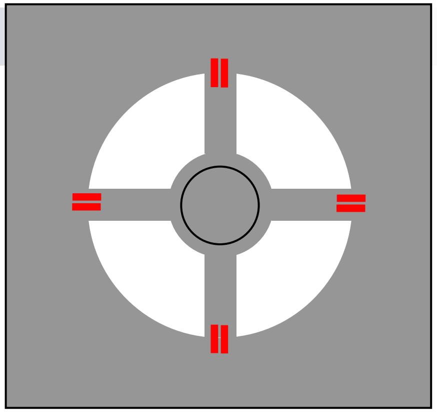
- Cross shape, 4 normal arms, high sensitivity to tangential forces
- central cylinder to transfer the load to the arms – silicon block completely embedded with the rest of the structure

Sensor structure





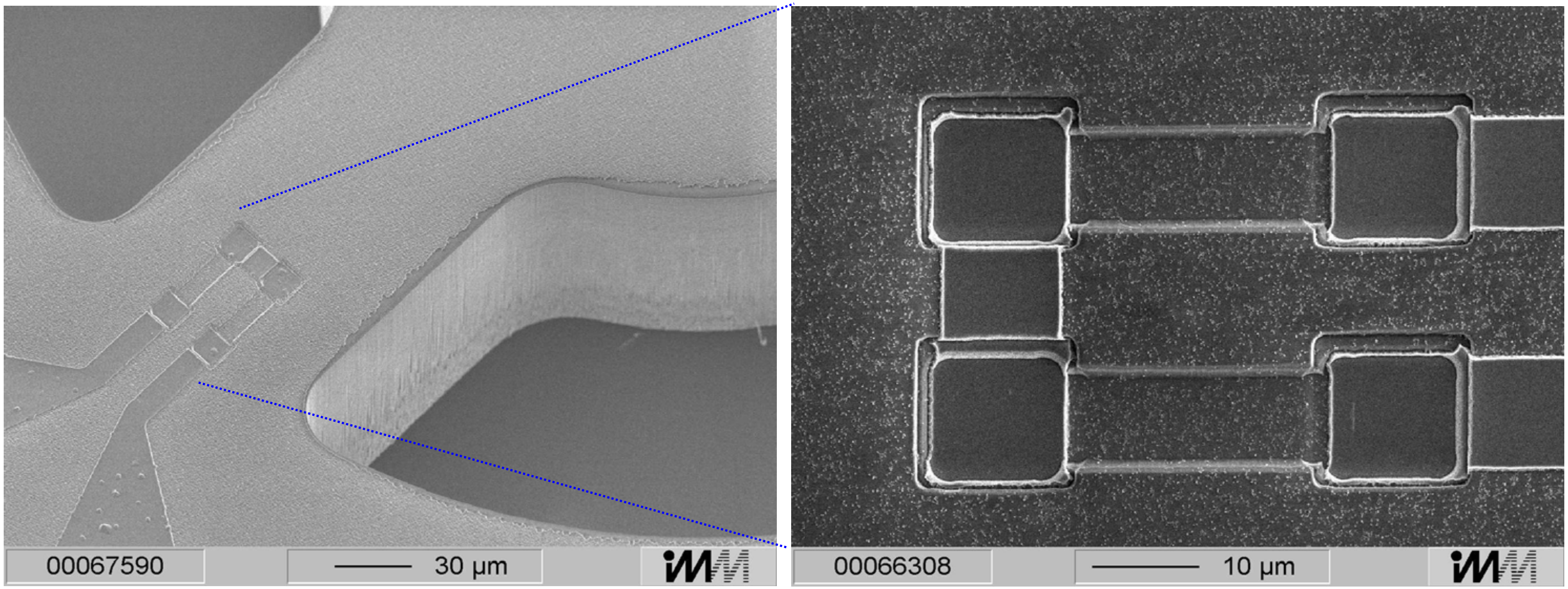
Piezoresistors



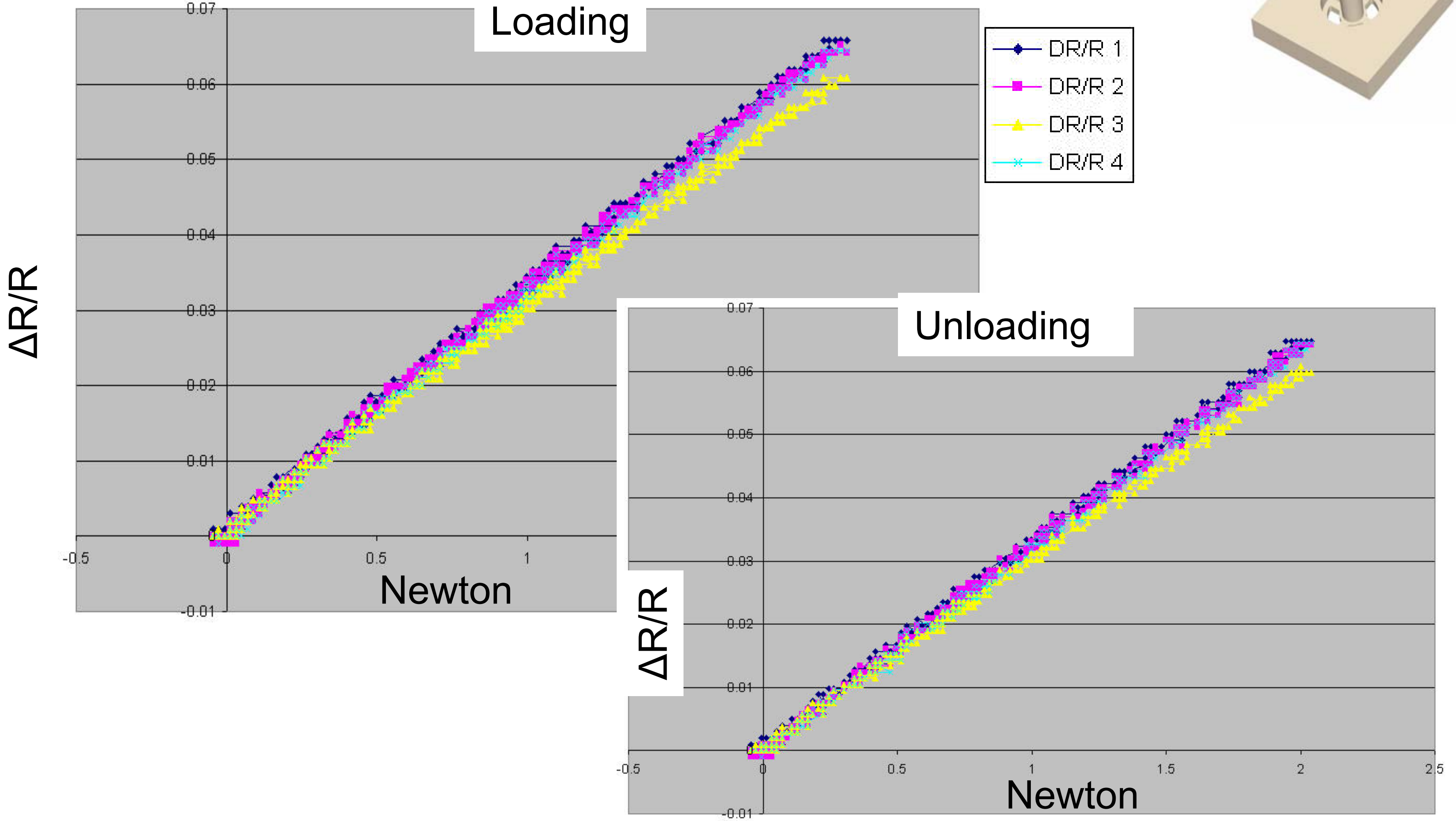
$$G = \frac{\Delta R / R}{\varepsilon} = 1 + 2\nu + \frac{\Delta \rho / \rho}{\varepsilon}$$

$$\frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} \approx \frac{\pi}{2}\sigma_l$$

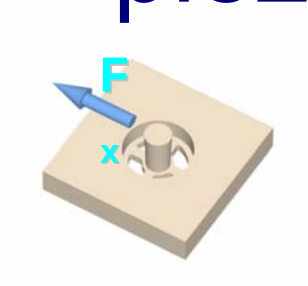
in semiconductors 1+2v negligible

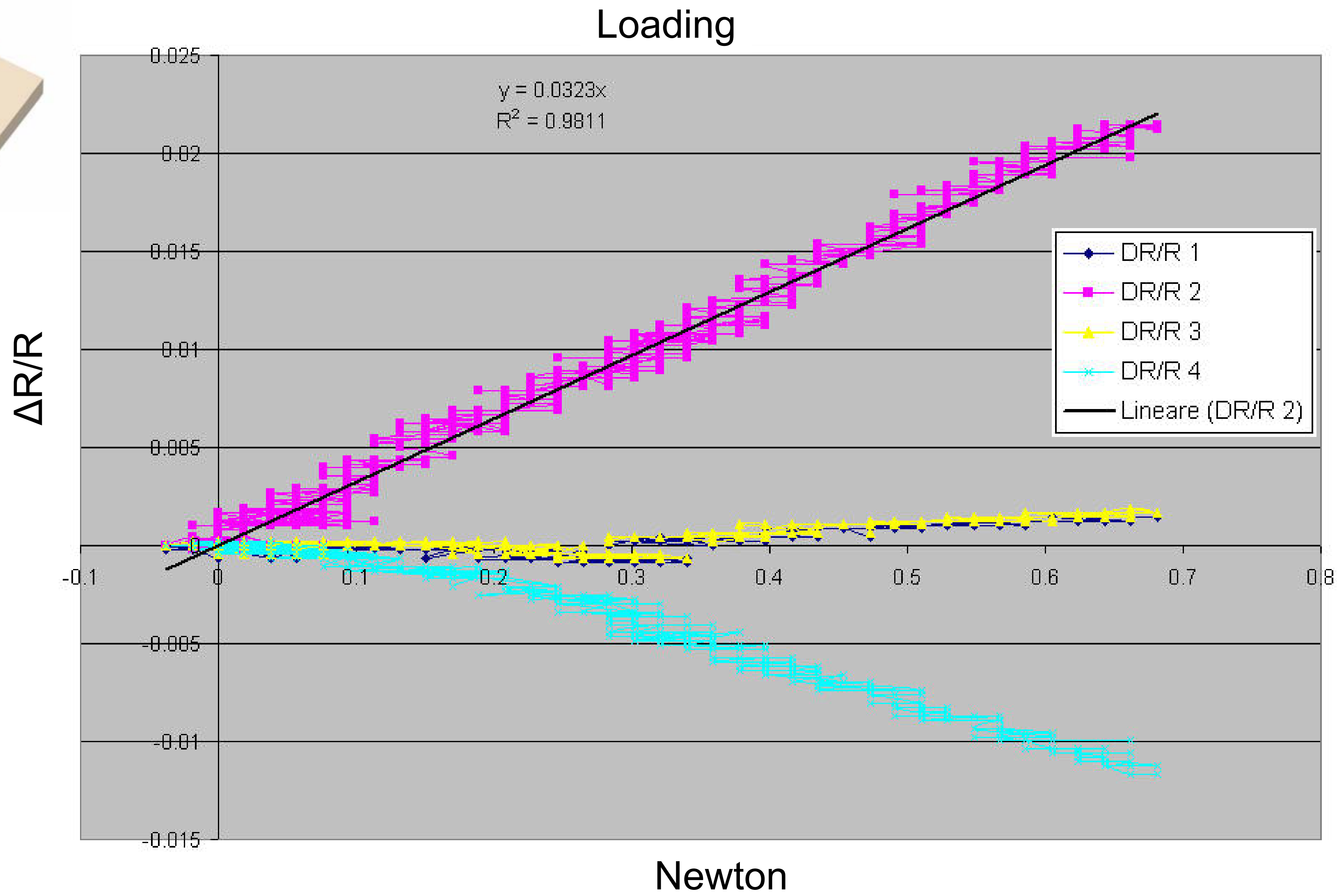


ΔR/R response of the 4 piezoresistors with a normal force



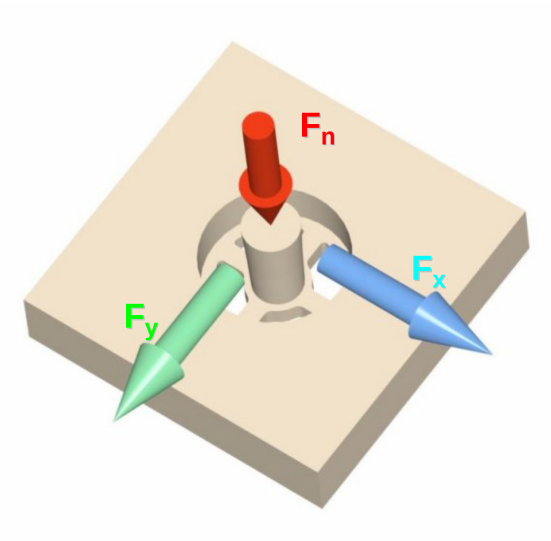
ΔR/R response of the 4 piezoresistors with a tangential force





Force measurement

$$F = K\frac{\Delta R}{R}$$



F_n normal force

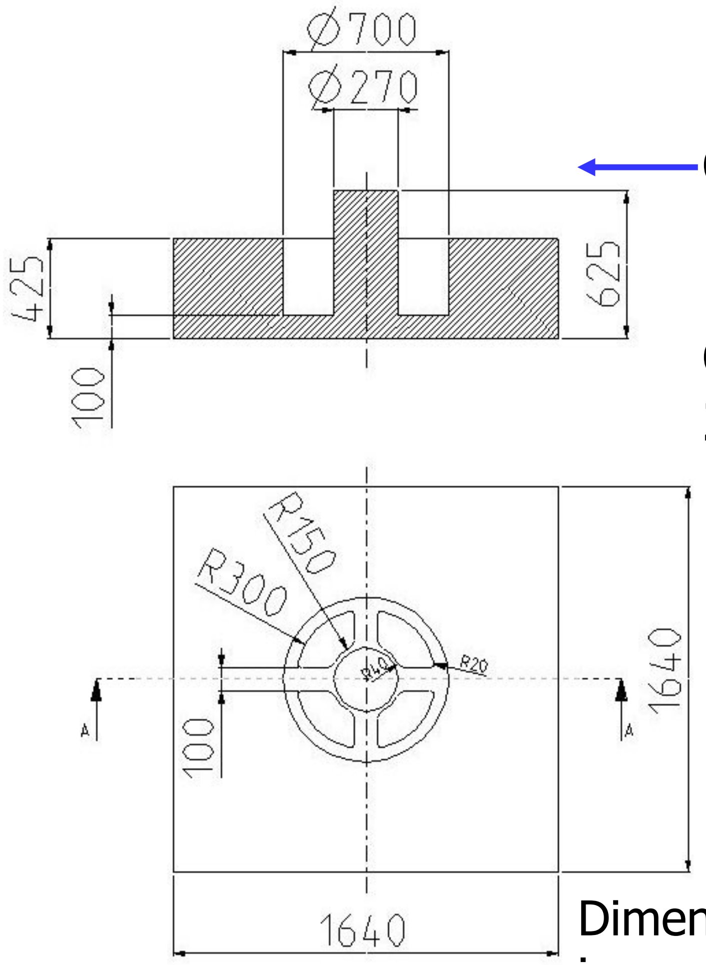
F_x e F_y tangential components

Calibration procedure:

Increasing force 0.5 N to 2.5 N in the normal direction;
Increasing force 0.1 N to 0.4 N in two tangential directions, normal to each other.

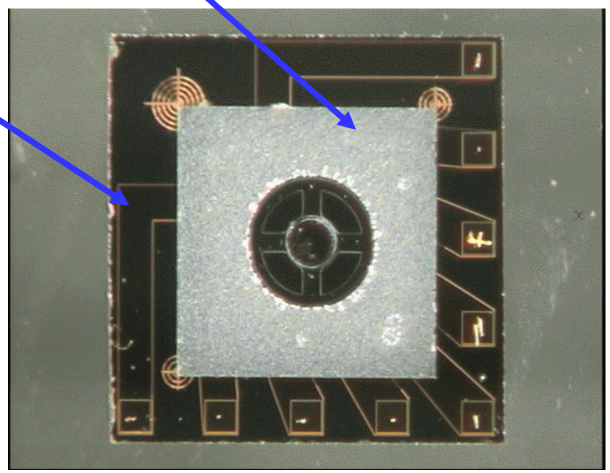
$$K = \begin{pmatrix} -1.71 & 15.65 & -8.57 & -16.70 \\ -16.75 & 2.83 & 11.75 & 14.97 \\ 3.18 & 5.86 & 20.78 & 33.81 \end{pmatrix} N$$

Final size



Chip A (Sensor Chip):
1.5 x 1.5 mm

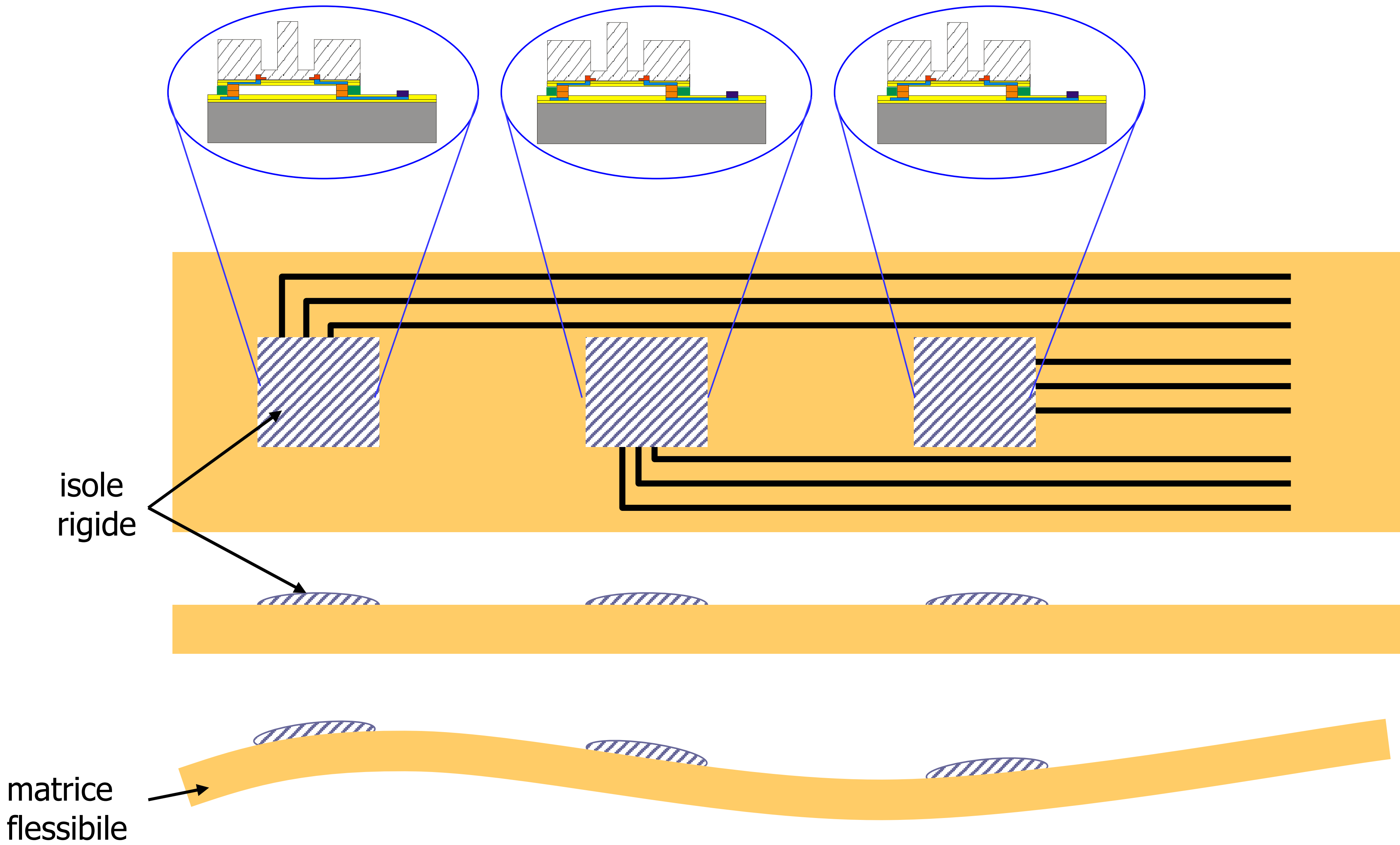
Chip B (Carrier Chip):
2.3 x 2.3 mm



Dimensions in µm

Sensor final size:
2300µm x 2300µm x 1300µm

Possible integration on a flexible skin



Conclusions

- The human tactile system:
  - at the receptor level
    - detects pressure and pressure variations
    - high performance especially in terms of spatial resolution (2mm), sensitivity (87 mN/mm^2 activate 90% of receptors)
  - does not have a localized sensory organ, but the fingertip can be considered as such
    - measures the applied force (3 components)
    - plays an important role in the control of grasp, detecting the key events:
      - vibrations (related to slippage) (frequency 400Hz)
      - contact with object
      - contact lift and release
- Piezoresistive technologies allow to measure:
  - at the sensor level:
    - force applied on a 2,3 x 2,3 mm area
  - at the level of sensory organ (tactile fingertip):
    - force applied on the fingertip (3 components)
    - tactile control events
      - vibrations (related to slippage) (frequency 700Hz)
      - contact with object
      - contact lift and release

Acknowledgments

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- John-John Cabibihan

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