



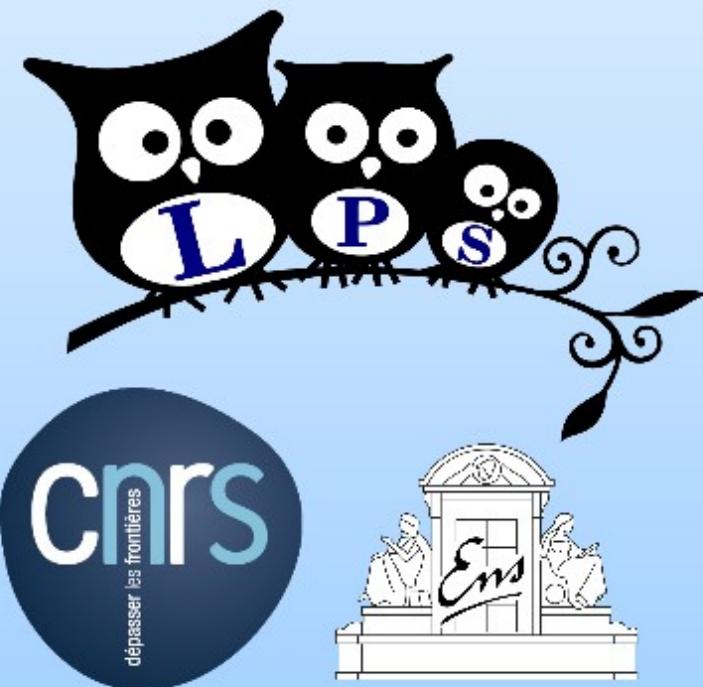
Tactile perception

A touch of Physics

Raphaël Candelier



Georges Debrégeas
Alexis Prevost





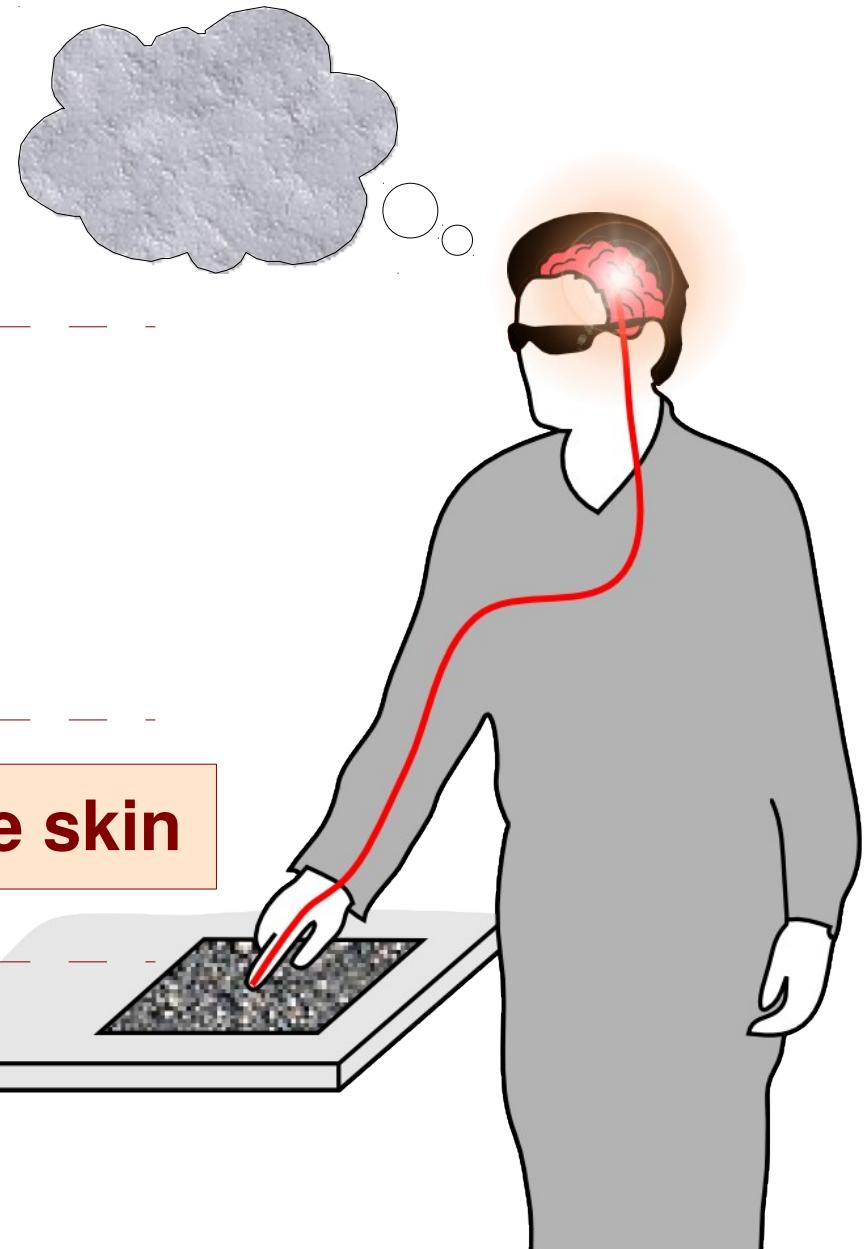
The path of tactile information

Representation

Nerve signal transmission

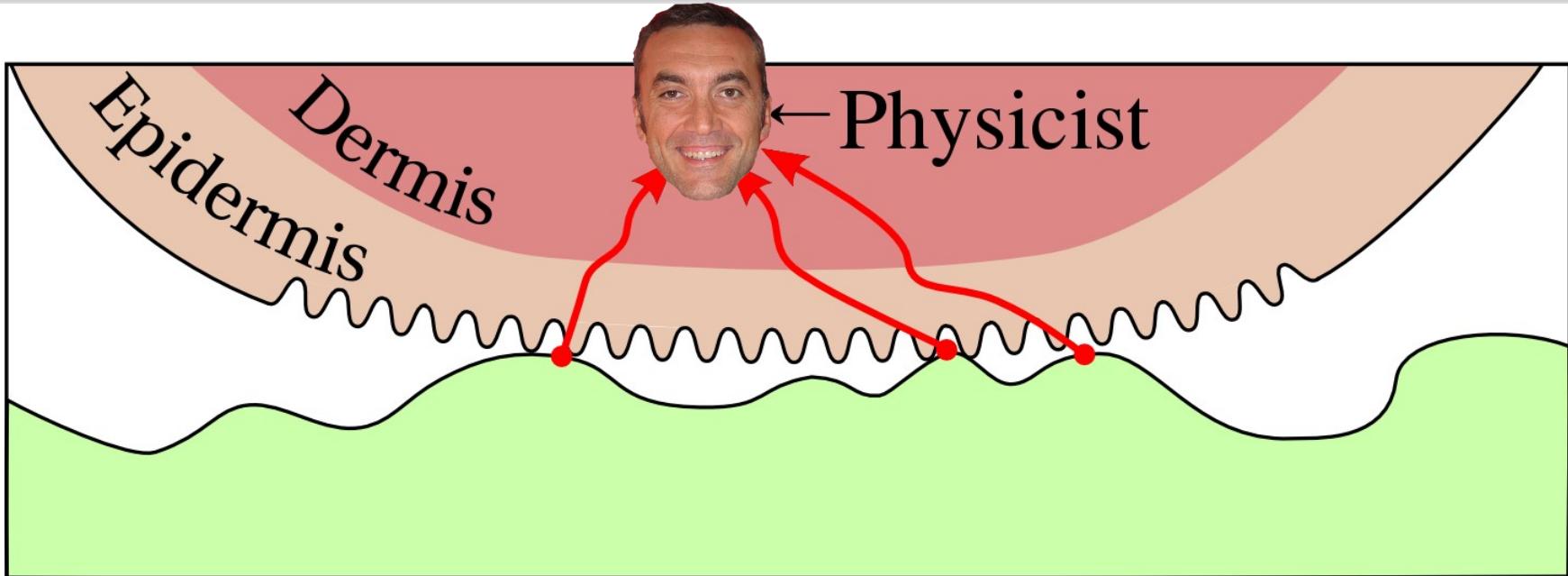
Deformations and vibrations of the skin

Texture





Where things happen



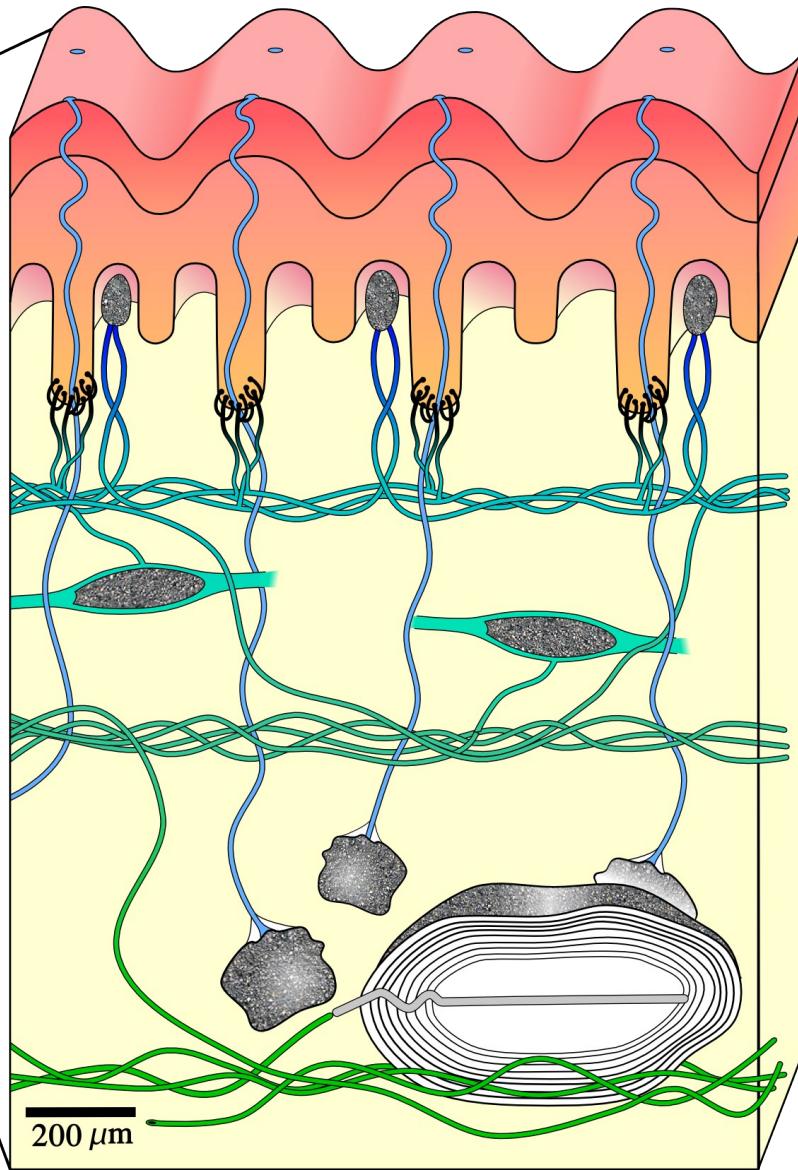
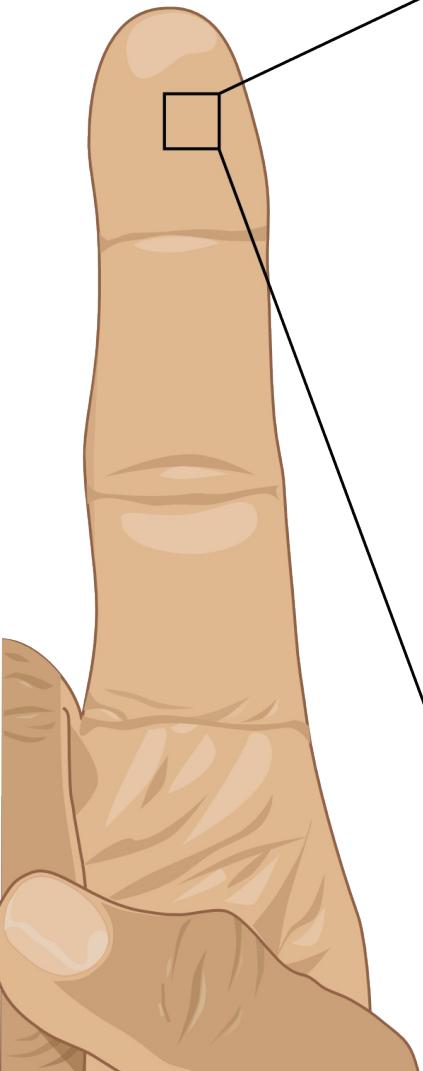
- The texture can be of *any* shape and type
- The problem is not linear (*e.g.* skin inhomogeneities, friction)
- Information stems from several continuously renewing contact zones at the same time
- Skin surface is patterned, typically with fingerprints

How does the receptor « feel » the relevant information ?





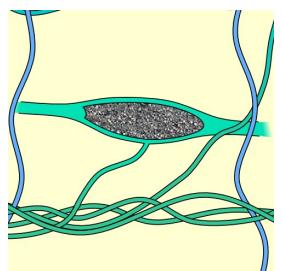
Inside the skin



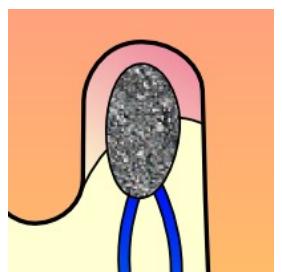
Merkel's cell complex



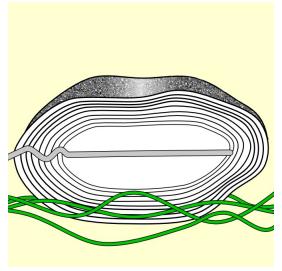
Ruffini ending



Meissner's corpuscle



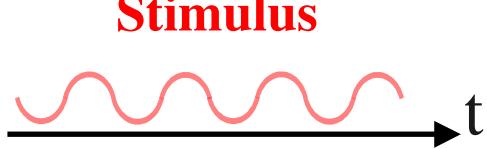
Pacinian corpuscle



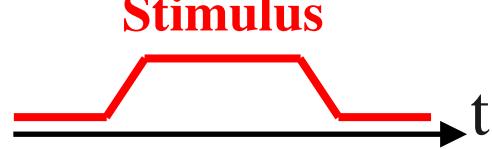


Mechanical receptors

Stimulus



Stimulus



Slow Adaptation



500 μm

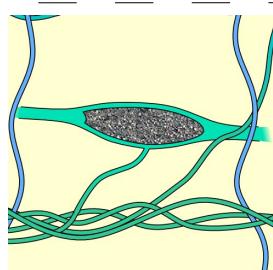
Merkel's cell complex



Ruffini ending



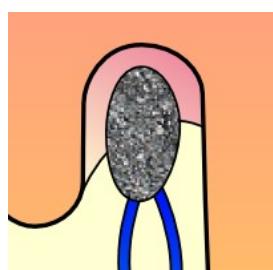
1 mm



Meissner's corpuscle



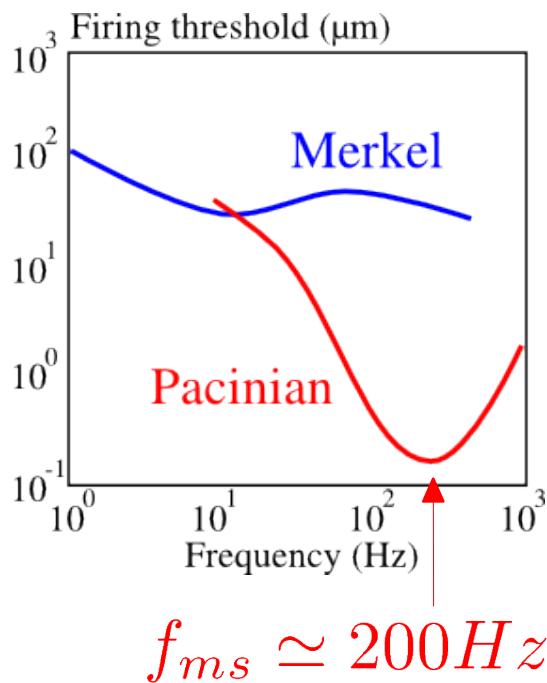
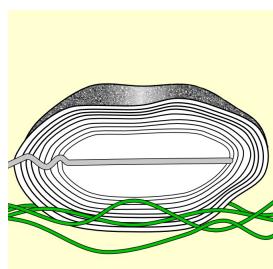
500 μm



Pacinian corpuscle



2 mm



Bolanowski et al., 1988





Roughness perception: the duplex theory

Coding of coarse roughness

$> \sim 200\mu\text{m}$

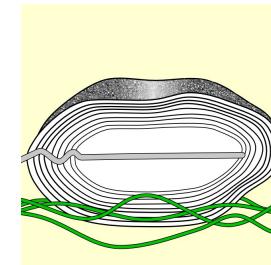
- SA I (Merkel) channel
- Resolution limited by the small receptive field (few hundred μm)
- Spatial coding (static)
- Fairly independent of finger's motion



Coding of fine roughness

$< \sim 200\mu\text{m}$

- Mediated by Pacinian corpuscles exclusively
- Fine resolution due to the large receptive field
- Requires active tactile exploration





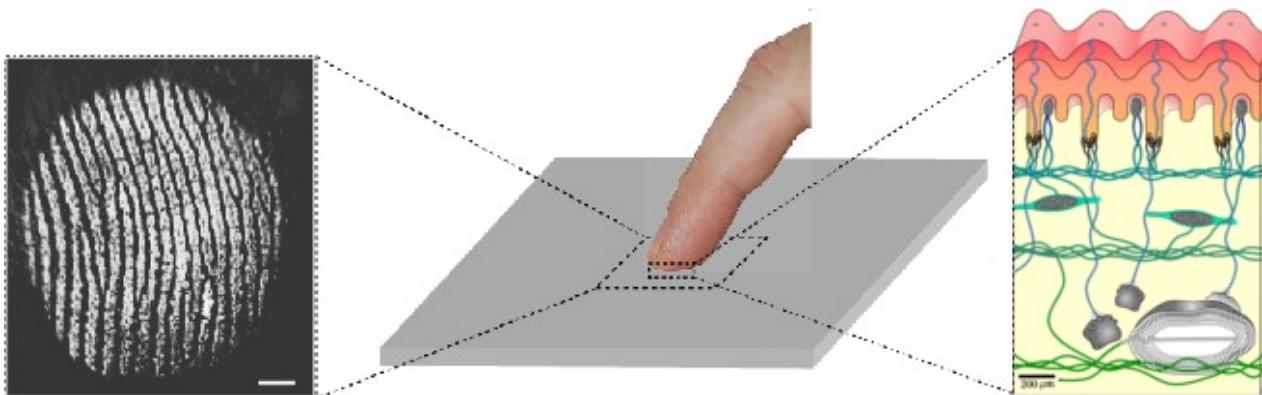
Roadmap

- Introduction
- A simple MEMS experiment
- A linear model for tactile transduction
 - The model
 - Dynamic impulse response and receptive fields
- Reverse correlation and response prediction
 - What is reverse correlation ?
 - The linear kernel
- Exploring the role of fingerprints
- Conclusion

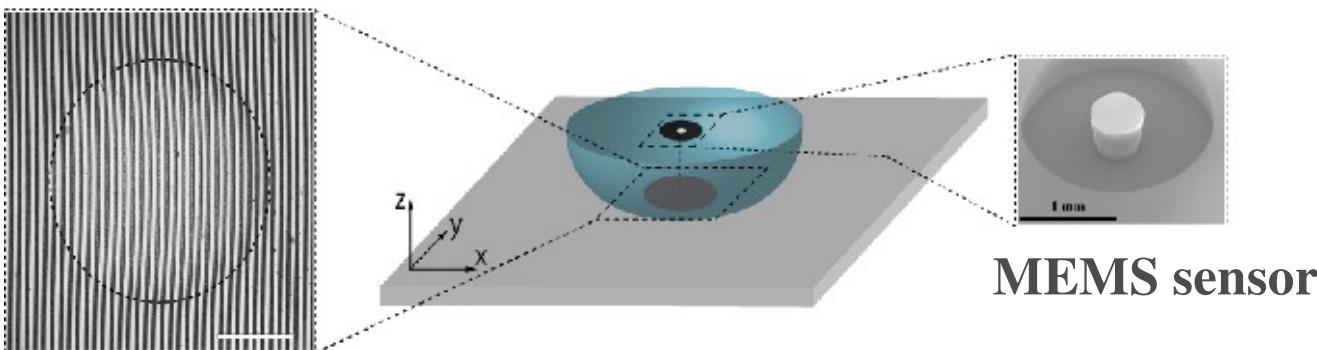
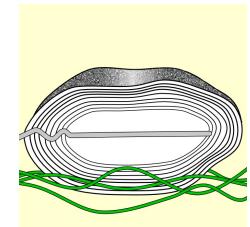




The biomimetic approach

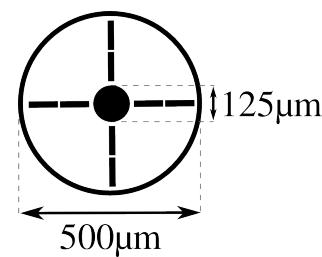


*Real
finger*



MEMS sensor

*Artificial
finger*

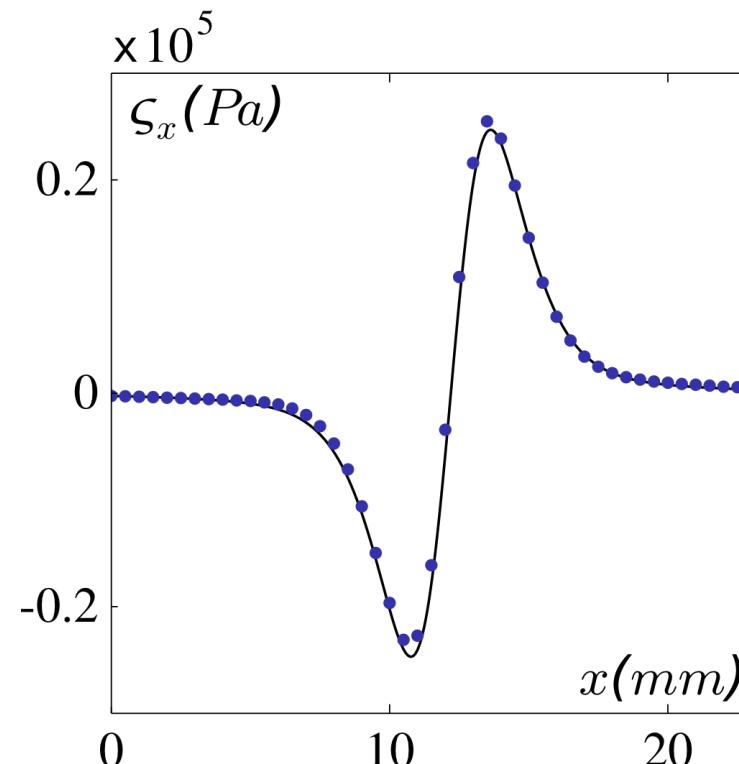
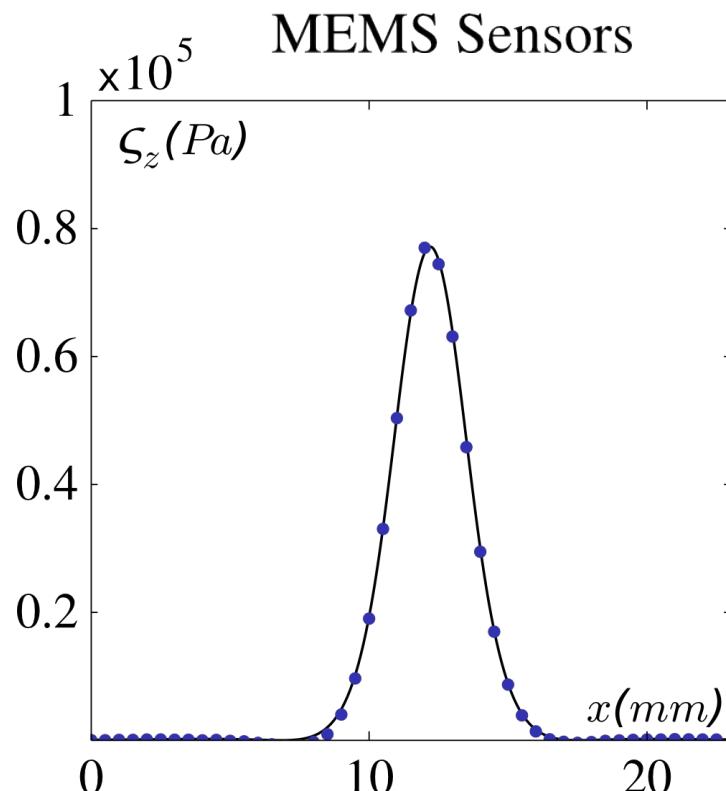
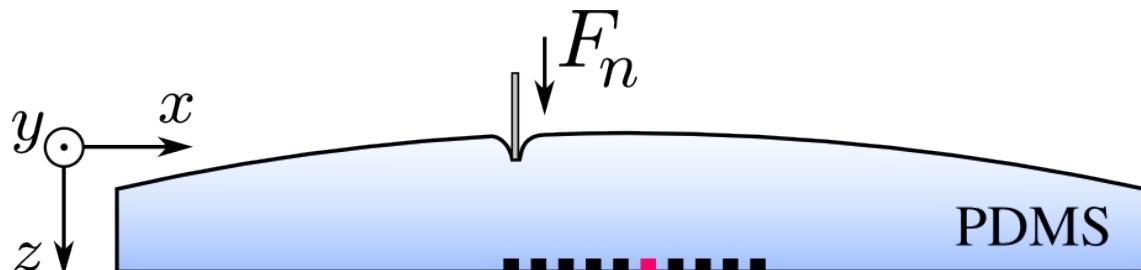


	Sensitive area	Sensor deth	Contact diameter	Skin elastic modulus	Ridges period	Ridges height
Human finger	0.5 – 1 mm	2-3 mm	~13mm (P~0.5N)	1-4 MPa	~500μm	50-80μm
Artificial finger	2 mm	3 mm	~6mm (P~1.5N)	2.2±0.1Mpa	20μm →1mm	20μm →1mm





Simple MEMS experiment

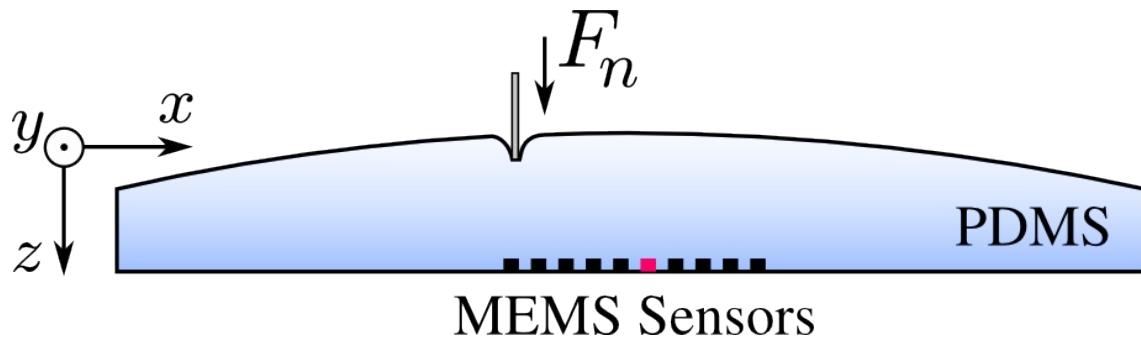


- Receptive fields measured by our MEMS sensors
- Predicted receptive field for a punctual sensor in a perfectly elastic material

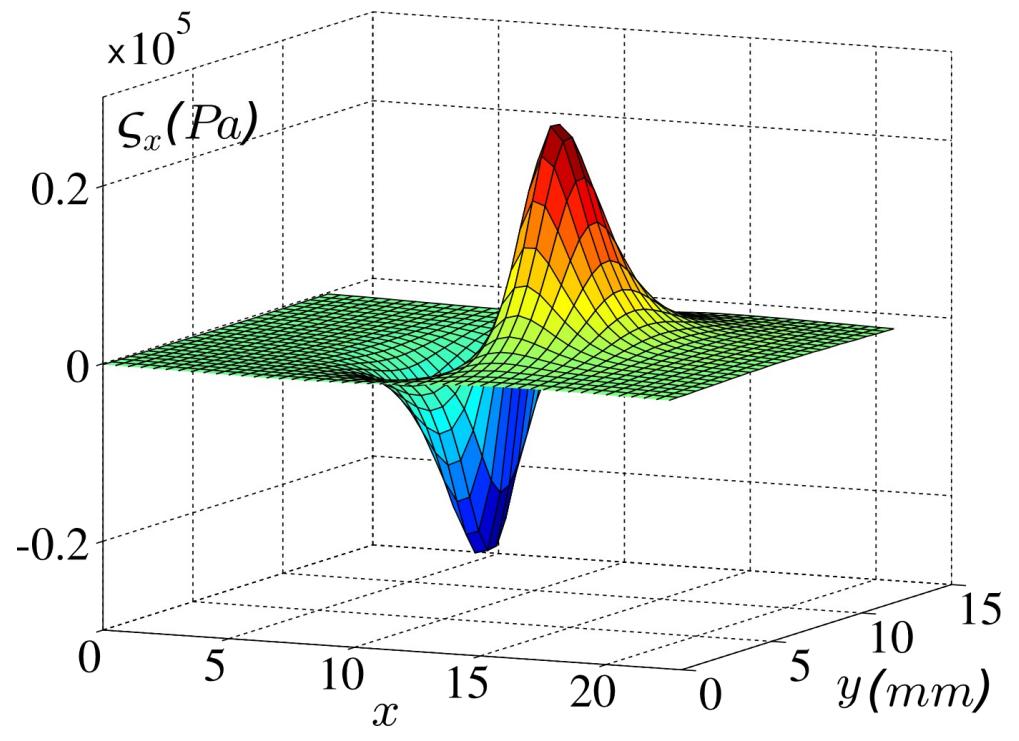
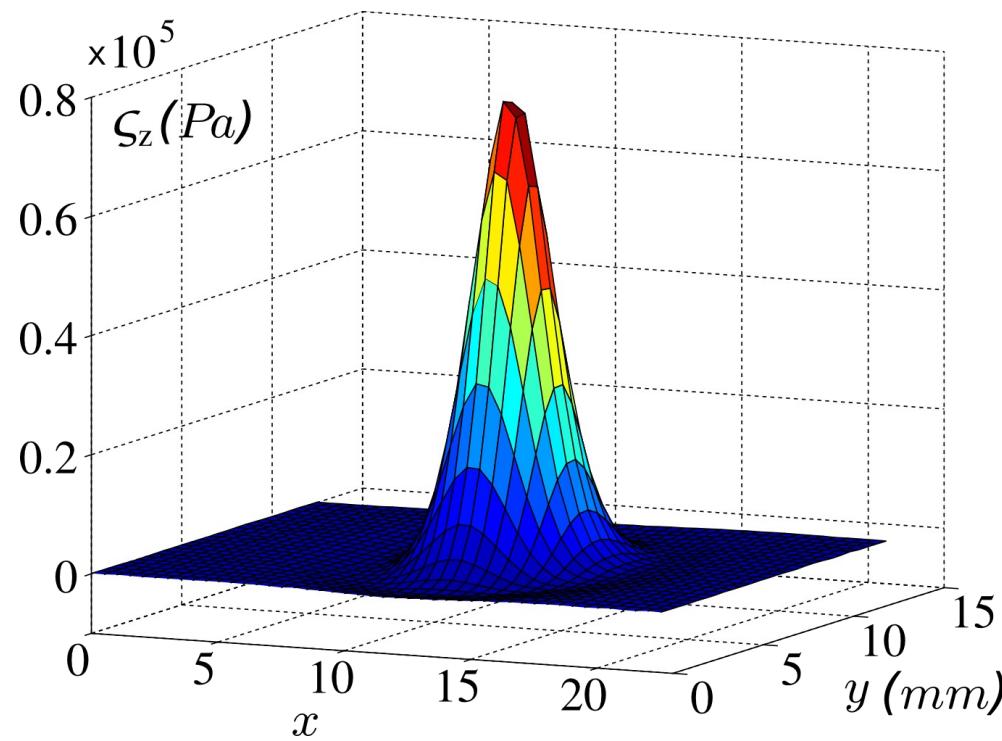




Simple MEMS experiment

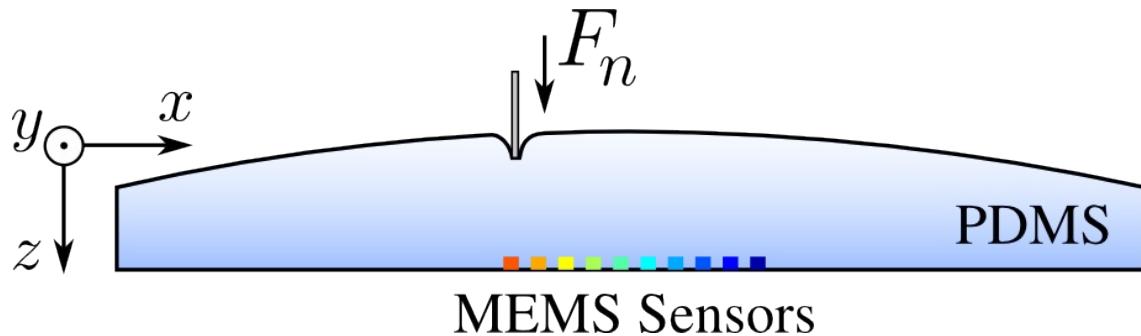


Indentation protocol:
Apply a ponctual force \vec{F} at (x, y) on the surface with a $500\mu m$ rod.

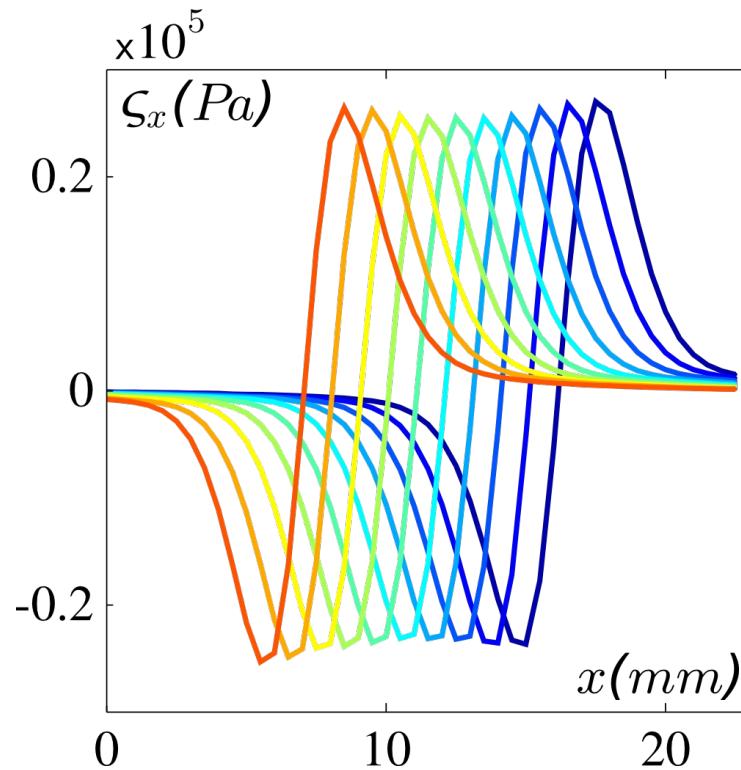
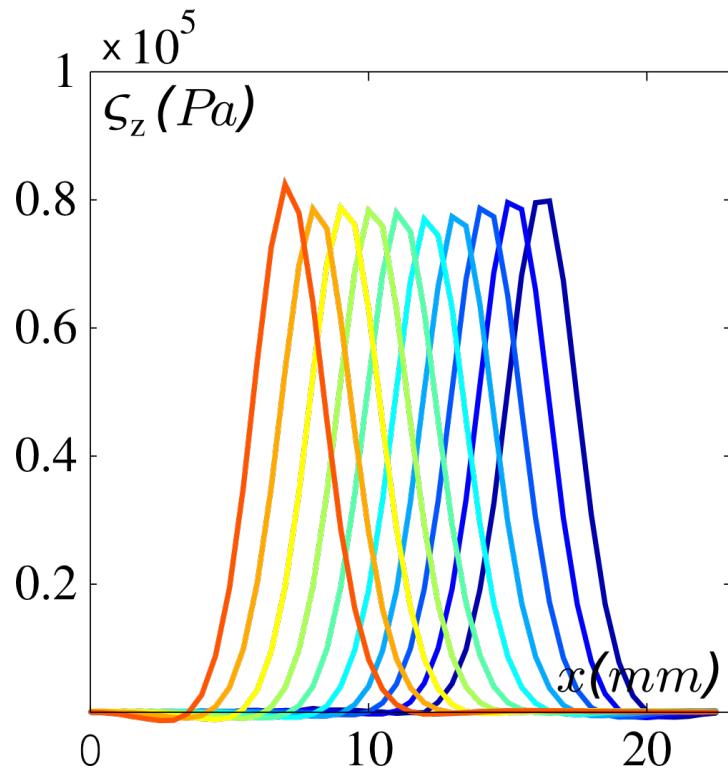




Simple MEMS experiment



Indentation protocol:
Apply a ponctual force \vec{F} at (x, y) on the surface with a $500\mu m$ rod.



Without exploration: roughly the same response for the 10 sensors





Roadmap

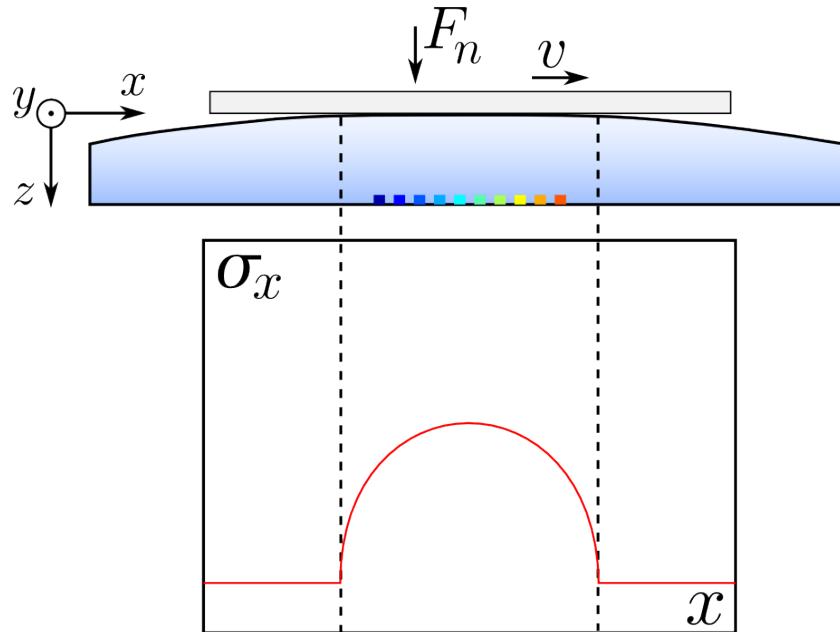
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A linear model for tactile transduction

Hertz contact



$$+$$

Coulomb law: $\sigma_x = \mu \sigma_z$

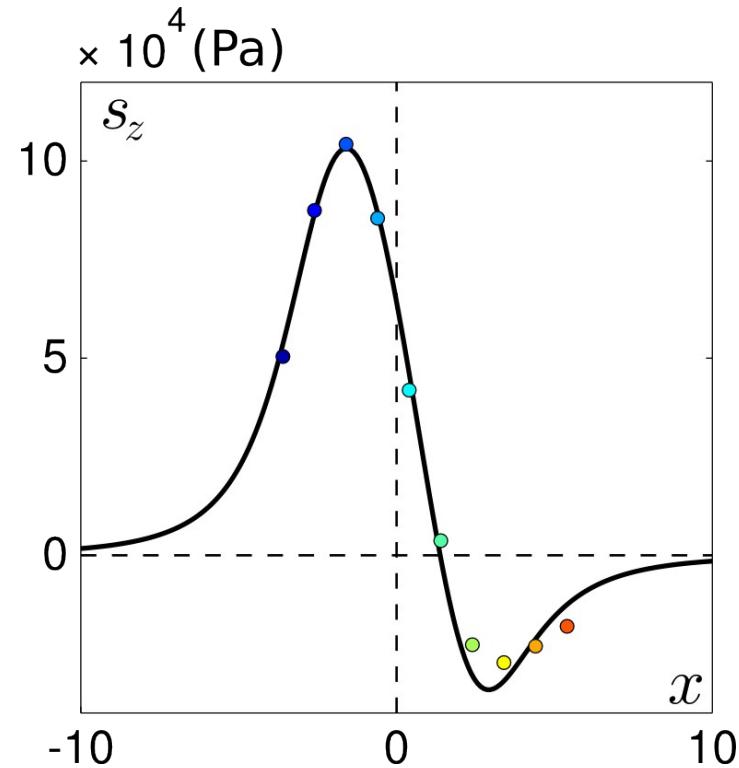
+

Green function for a ponctual force at the surface:

$$s_i = G_{ik} F_k$$

The stress felt by the sensor is given by:

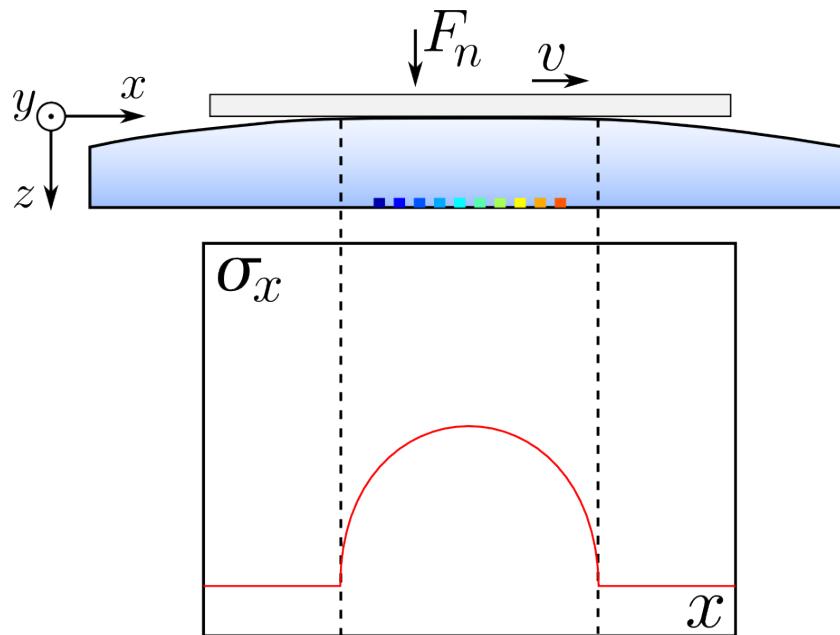
$$s_z(x_0, y_0) = \iint_S \sigma_x(x, y) g_{xz}(x - x_0, y - y_0) dx dy \\ + \iint_S \sigma_z(x, y) g_{zz}(x - x_0, y - y_0) dx dy$$





A linear model for tactile transduction

Hertz contact



$$+$$

Coulomb law: $\sigma_x = \mu \sigma_z$

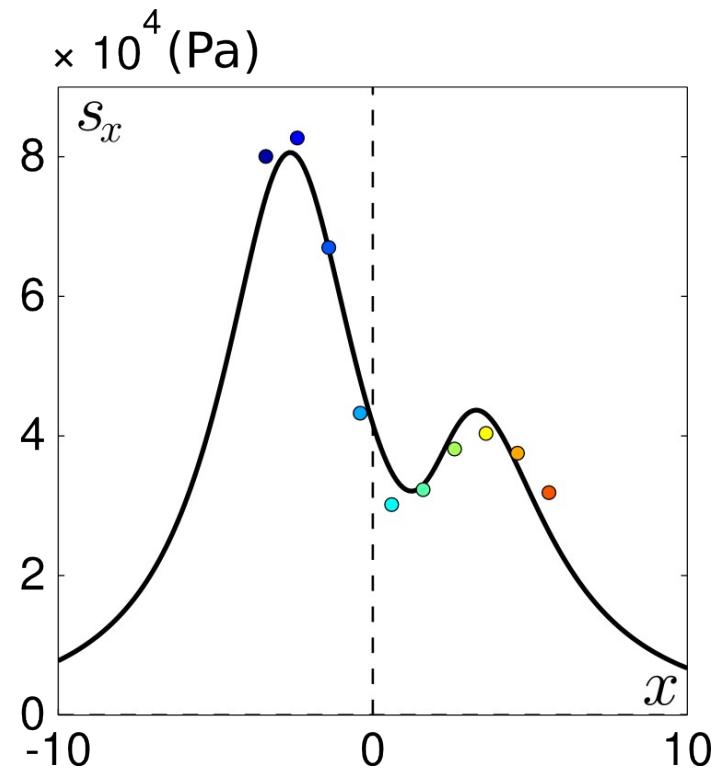
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Green function for a ponctual force at the surface:

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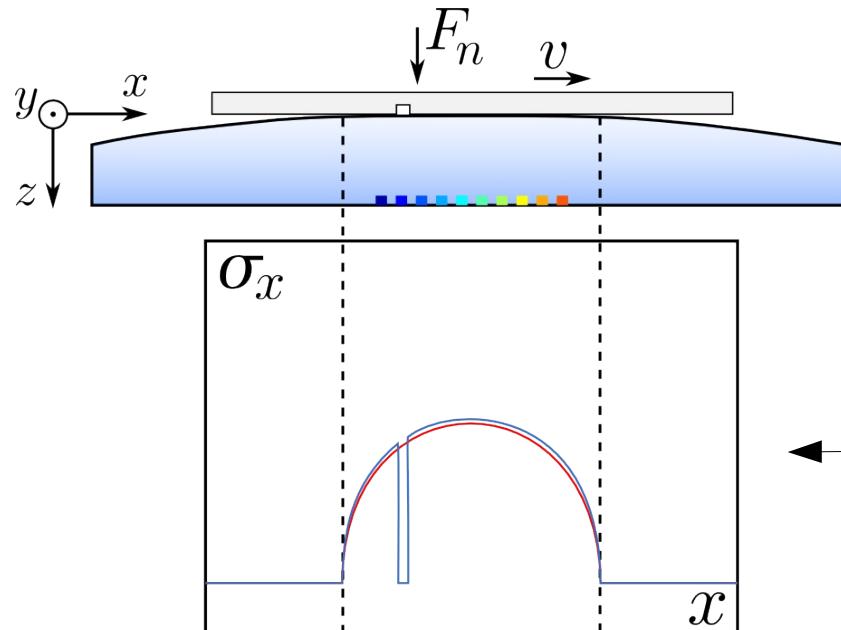
The stress felt by the sensor is given by:

$$s_x(x_0, y_0) = \iint_S \sigma_x(x, y) g_{xx}(x - x_0, y - y_0) dx dy \\ + \iint_S \sigma_z(x, y) g_{zx}(x - x_0, y - y_0) dx dy$$





Dynamic impulse response



Consider the *fluctuations* of the response due to a small, isolated defect :

The stress profile at the interface now depends on the position u of the defect

One can approximate the fluctuations felt by the sensors with:

$$\delta s_z(u) \simeq - [\sigma_x(u)g_{xz}(u - x_0) + \sigma_z(u)g_{zz}(u - x_0)] S_d$$

$$\delta s_x(u) \simeq - [\sigma_x(u)g_{xx}(u - x_0) + \sigma_z(u)g_{zx}(u - x_0)] S_d$$

The response highly depends on the sensor's position inside the skin

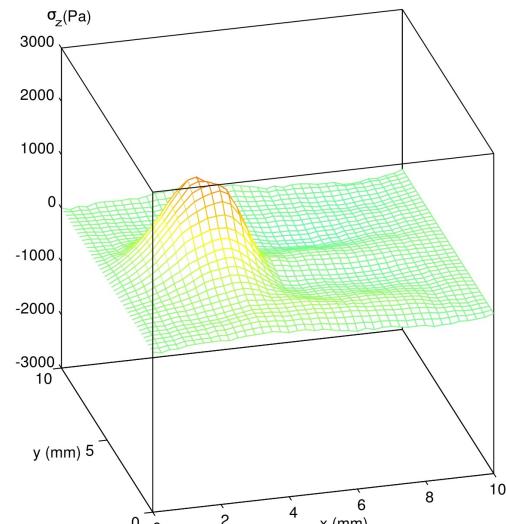




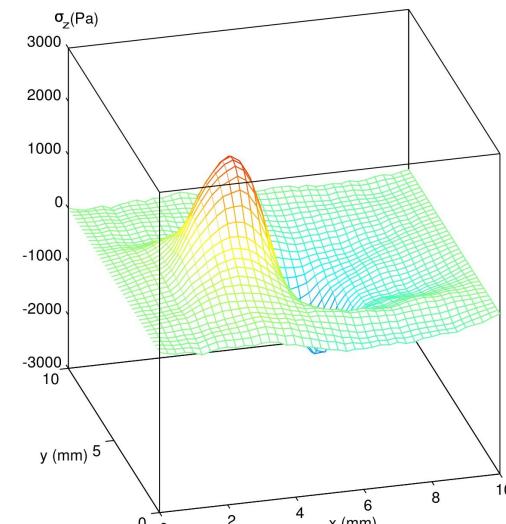
Normal dynamic impulse response

Experiment

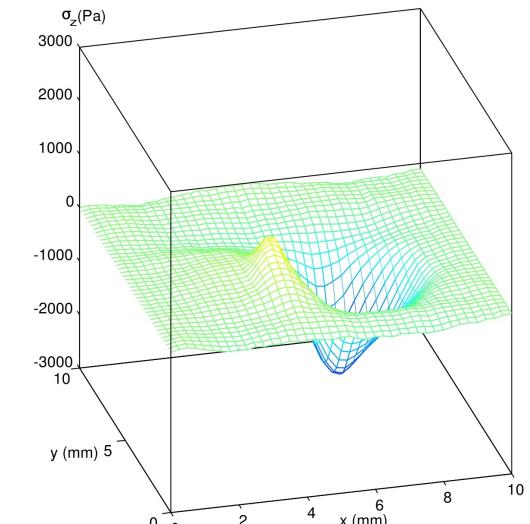
Left



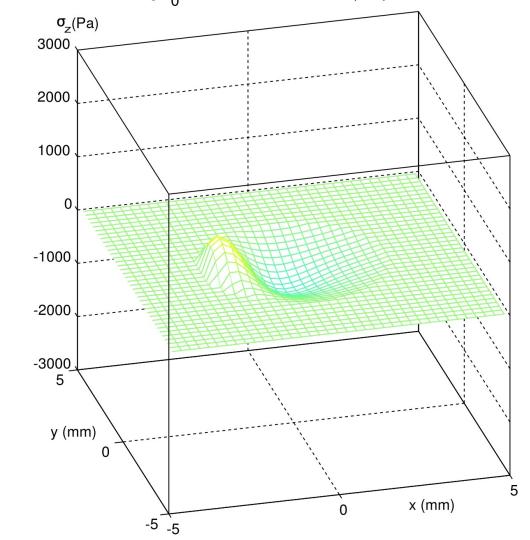
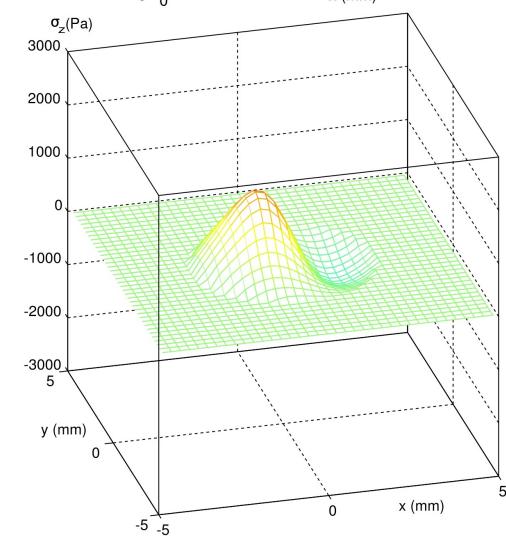
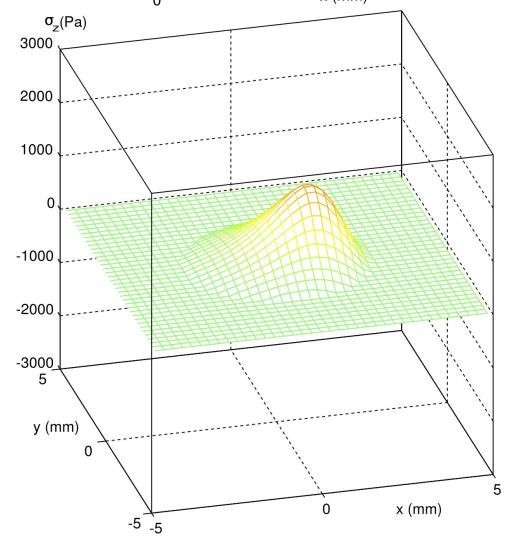
Middle



Right



Model

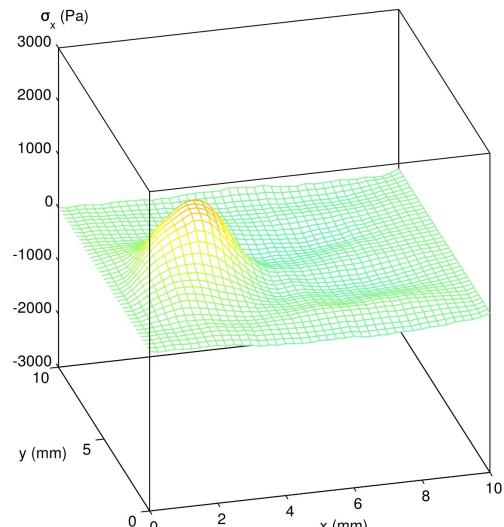




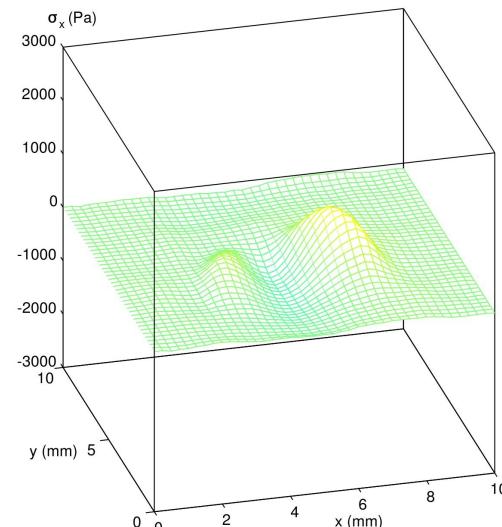
Tangential dynamic impulse response

Experiment

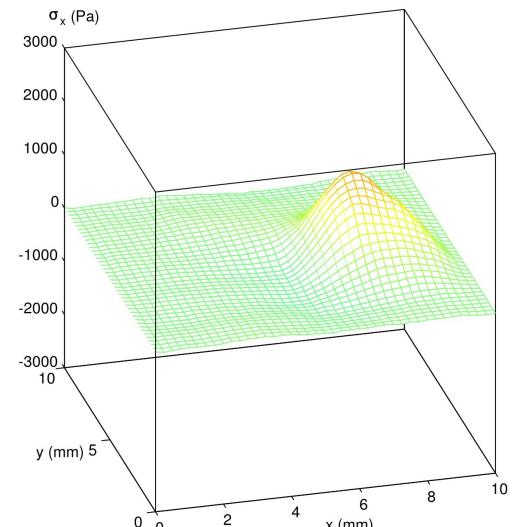
Left



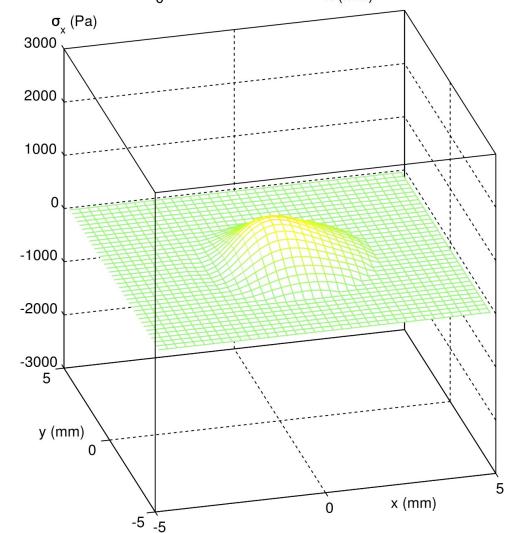
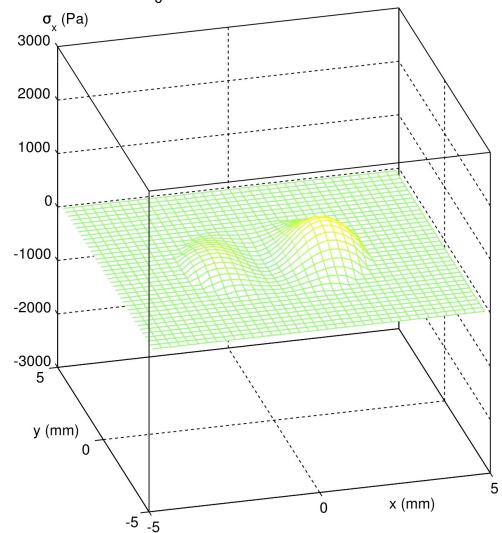
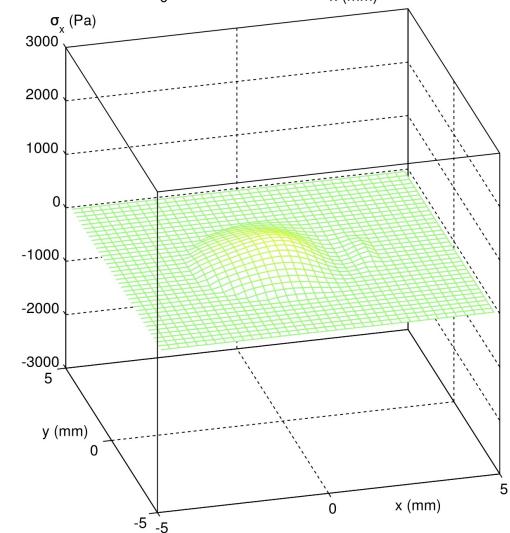
Middle



Right



Model





Response specification

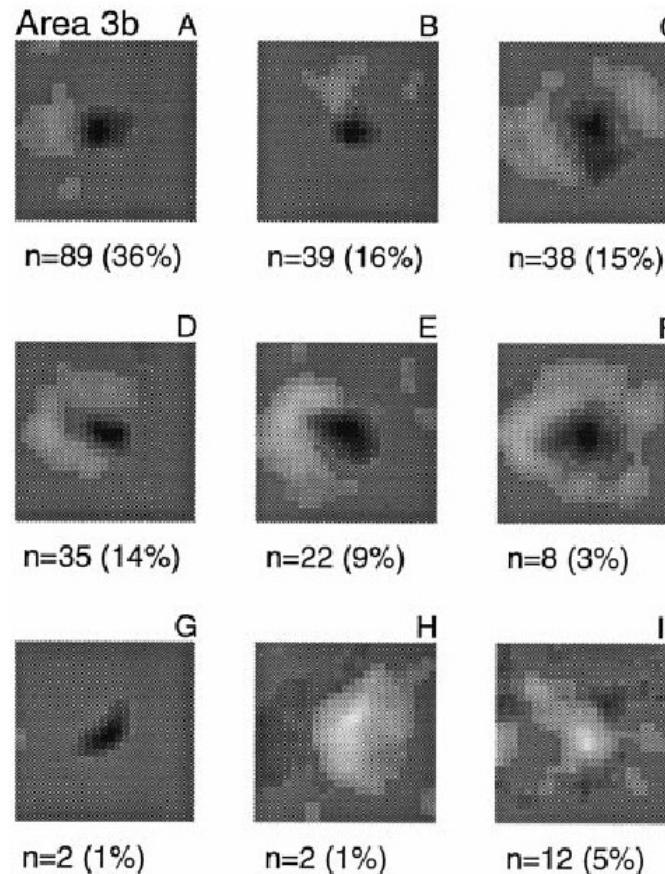
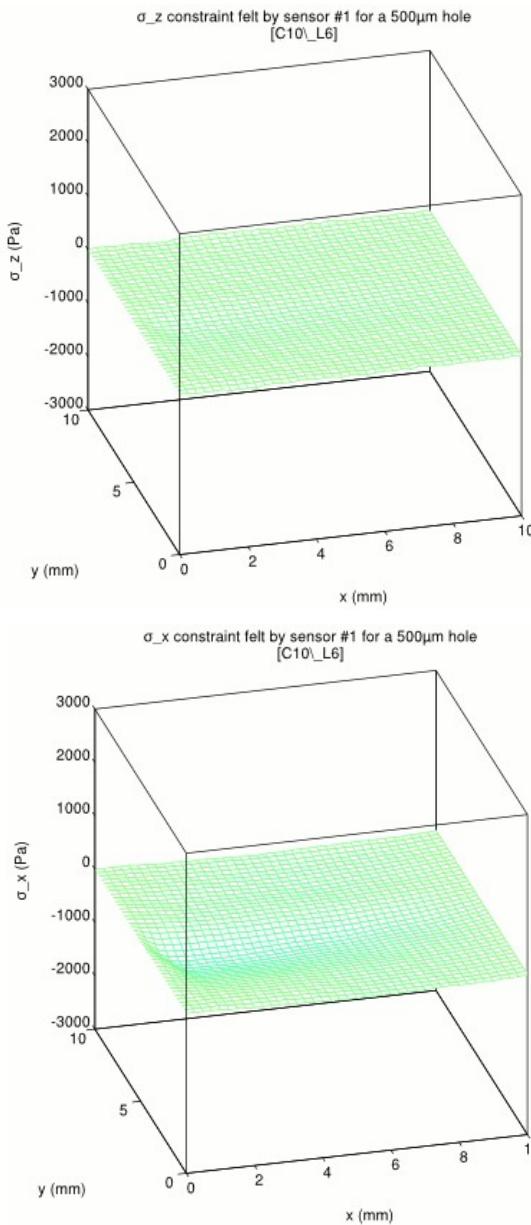
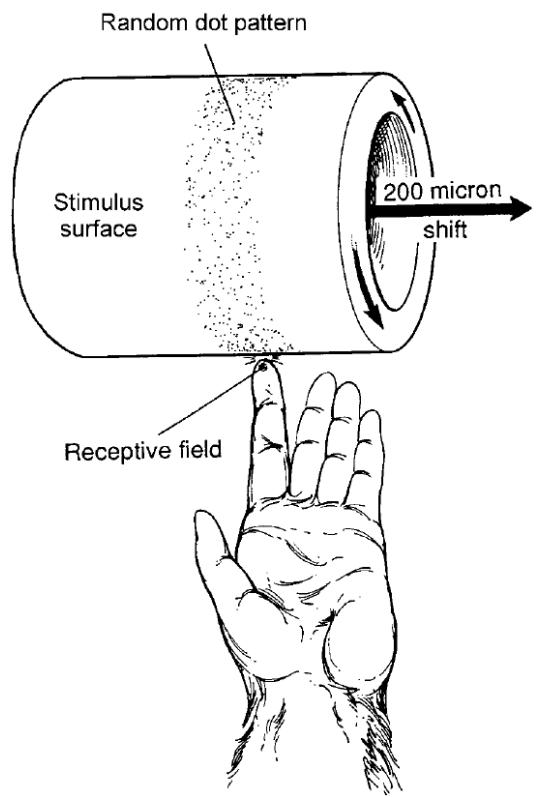


Figure 3. RF structures observed in area 3b. Each panel gives a typical example of the type, the total number of RFs fitting the description, and their percent of the total RF sample ($n = 247$).



DiCarlo *et. al.*, 1998
The journal of Neuroscience

« *The shape, area and strength of excitatory and inhibitory receptive fields regions ranged widely.* »





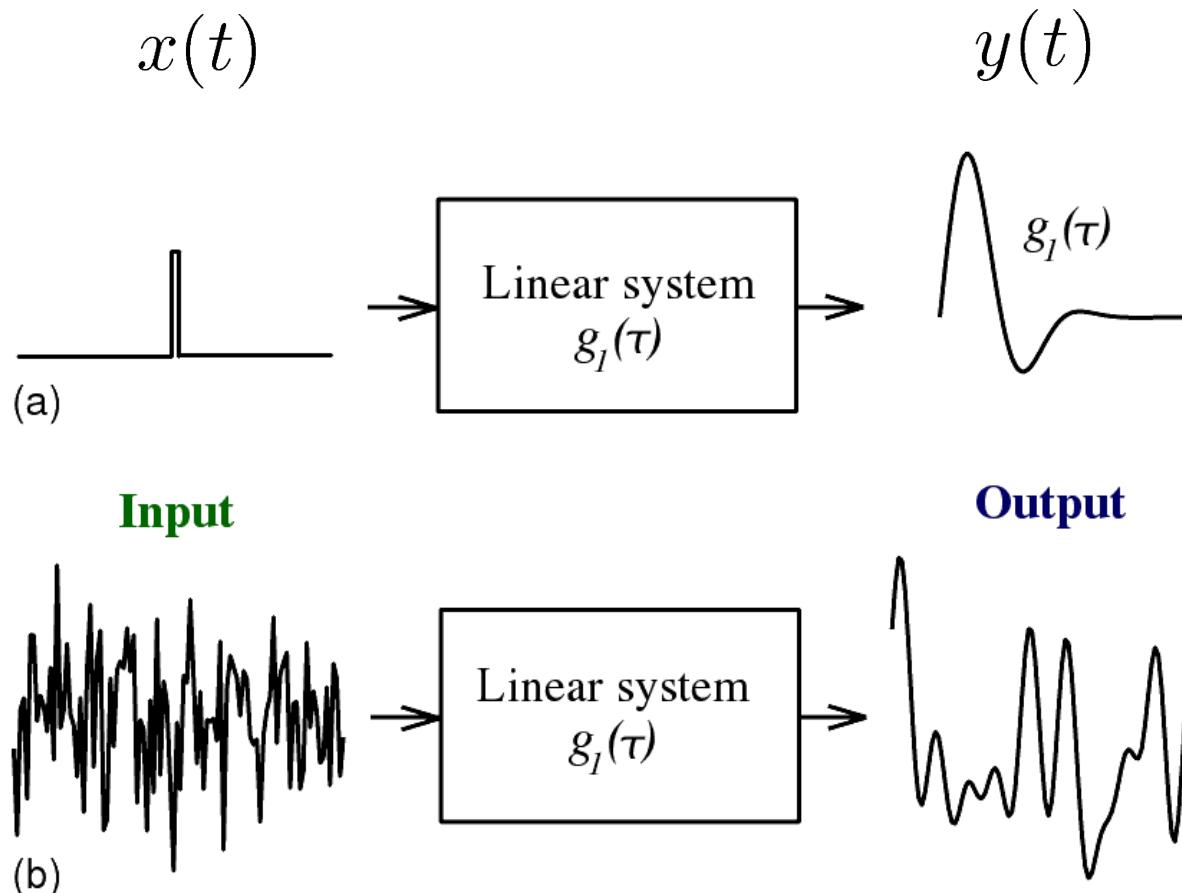
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Reverse correlation



The impulse response $g_l(\tau)$ can be computed as the correlation between the input signal $x(t)$ and the output response $y(t)$

$$g_l(\tau) \propto \langle x(t).y(t + \tau) \rangle$$

Ringach and Shapley, 2004

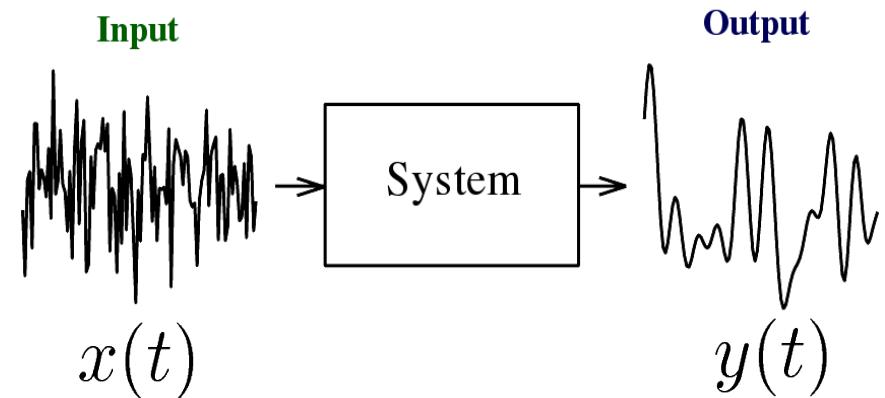




The Volterra decomposition

The Volterra series is the analog of the Taylor series, but for *functionals*:

$$\begin{aligned} y(t) = & h_0 + \int d\tau_1 h_1(\tau) x(t - \tau_1) \\ & + \iint d\tau_1 d\tau_2 h_2(\tau_1, \tau_2) x(t - \tau_1) x(t - \tau_2) \\ & + \iiint d\tau_1 d\tau_2 d\tau_3 h_3(\tau_1, \tau_2, \tau_3) x(t - \tau_1) x(t - \tau_2) x(t - \tau_3) \\ & + \dots \end{aligned}$$



The Volterra kernels h_n give a mapping from $x(t)$ to $y(t)$.

NB: it is hard to extract the Volterra kernels ...





The Wiener decomposition

$$\begin{aligned}y(t) = & g_0 + \int_0^\infty d\tau_1 g_1(\tau_1) x(t - \tau_1) \\& + \iint_0^\infty d\tau_1 d\tau_2 g_2(\tau_1, \tau_2) x(t - \tau_1) x(t - \tau_2) - S_x \int_0^\infty d\tau g_2(\tau, \tau) \\& + \iiint_0^\infty d\tau_1 d\tau_2 d\tau_3 g_3(\tau_1, \tau_2, \tau_3) x(t - \tau_1) x(t - \tau_2) x(t - \tau_3) \\& \quad - 3S_x \int_0^\infty d\tau_1 d\tau_2 g_3(\tau_1, \tau_1, \tau_2) x(t - \tau_2) \\+ & \dots\end{aligned}$$

For *Gaussian white noise* inputs, the Wiener kernels are independant.

They can be computed through correlations:

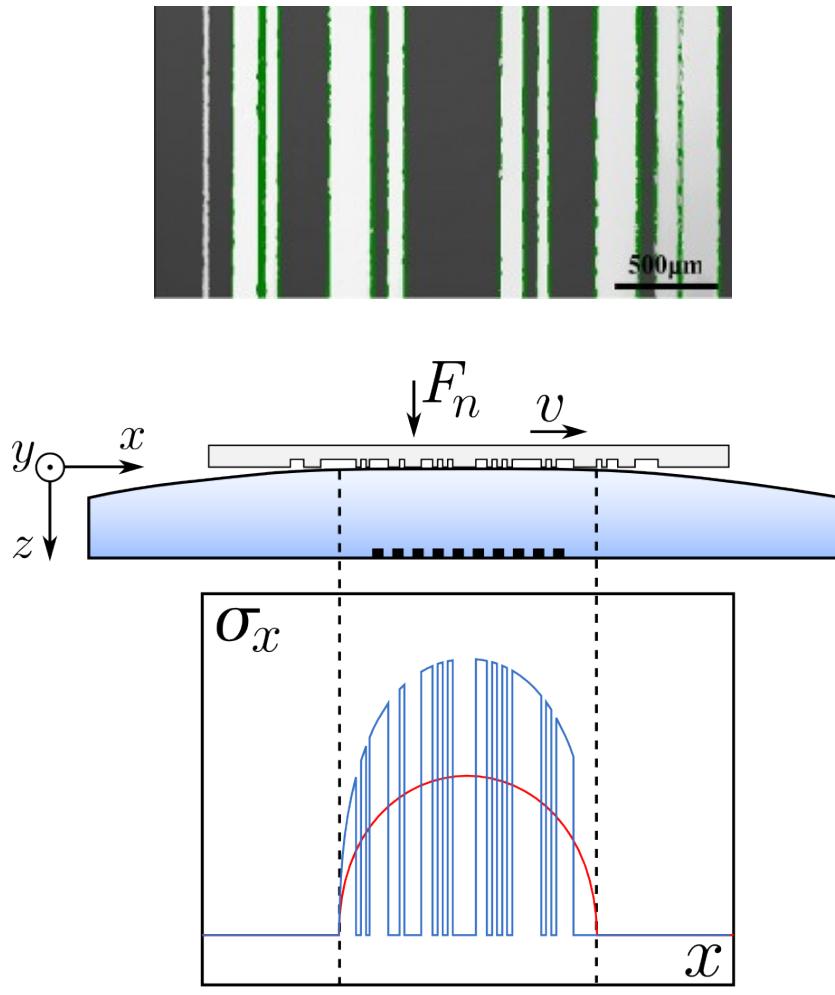
$$\begin{aligned}g_0 &= \langle y(t) \rangle & g_1(\tau) &= \frac{1}{S_x} \langle y(t).x(t - \tau) \rangle \\&& g_2(\tau_1, \tau_2) &= \frac{1}{S_x^2} \langle y(t).x(t - \tau_1).x(t - \tau_2) \rangle \\&&&\dots\end{aligned}$$





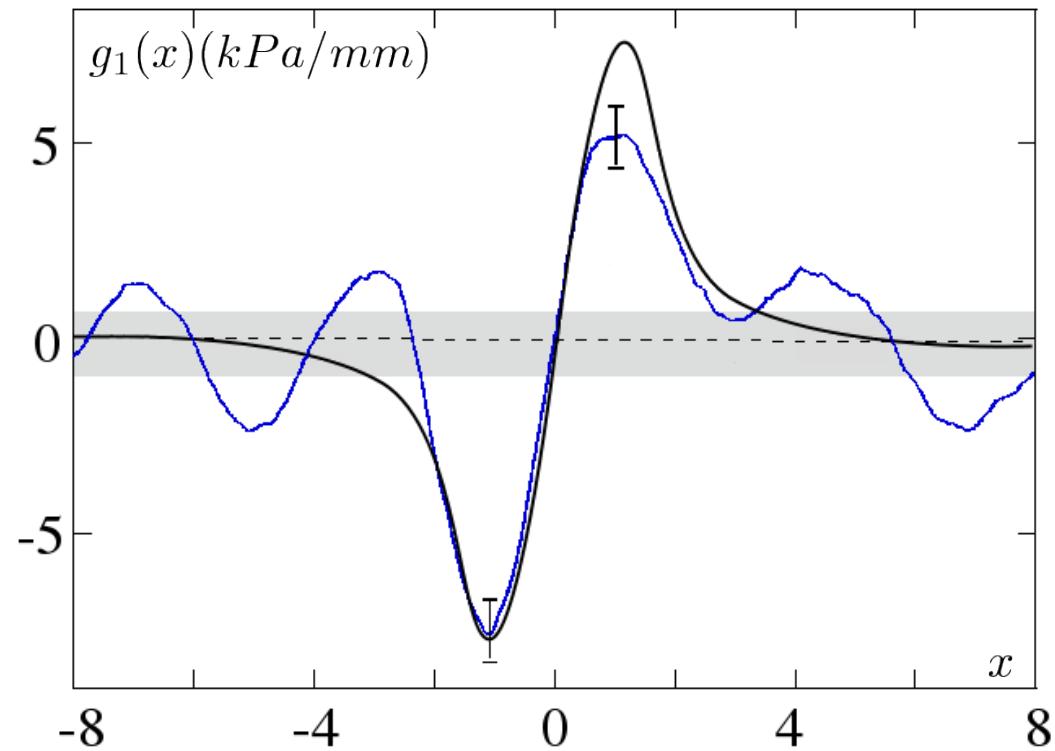
Getting the linear kernel

Rub the skin with binary random white noise substract $T(u) = \pm 1$:



... and compute the linear impulse response :

$$g_1(x) = \frac{1}{S_x} \langle s_z(u).T(u - x) \rangle$$





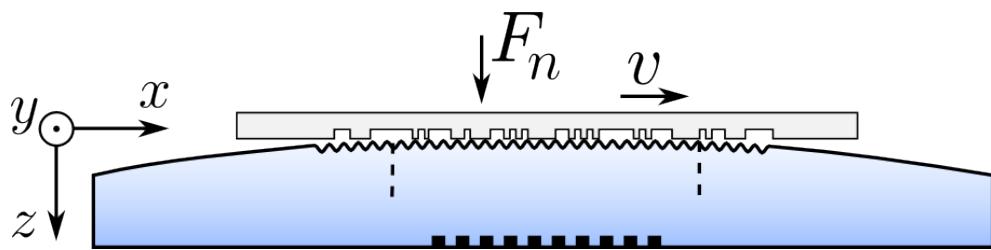
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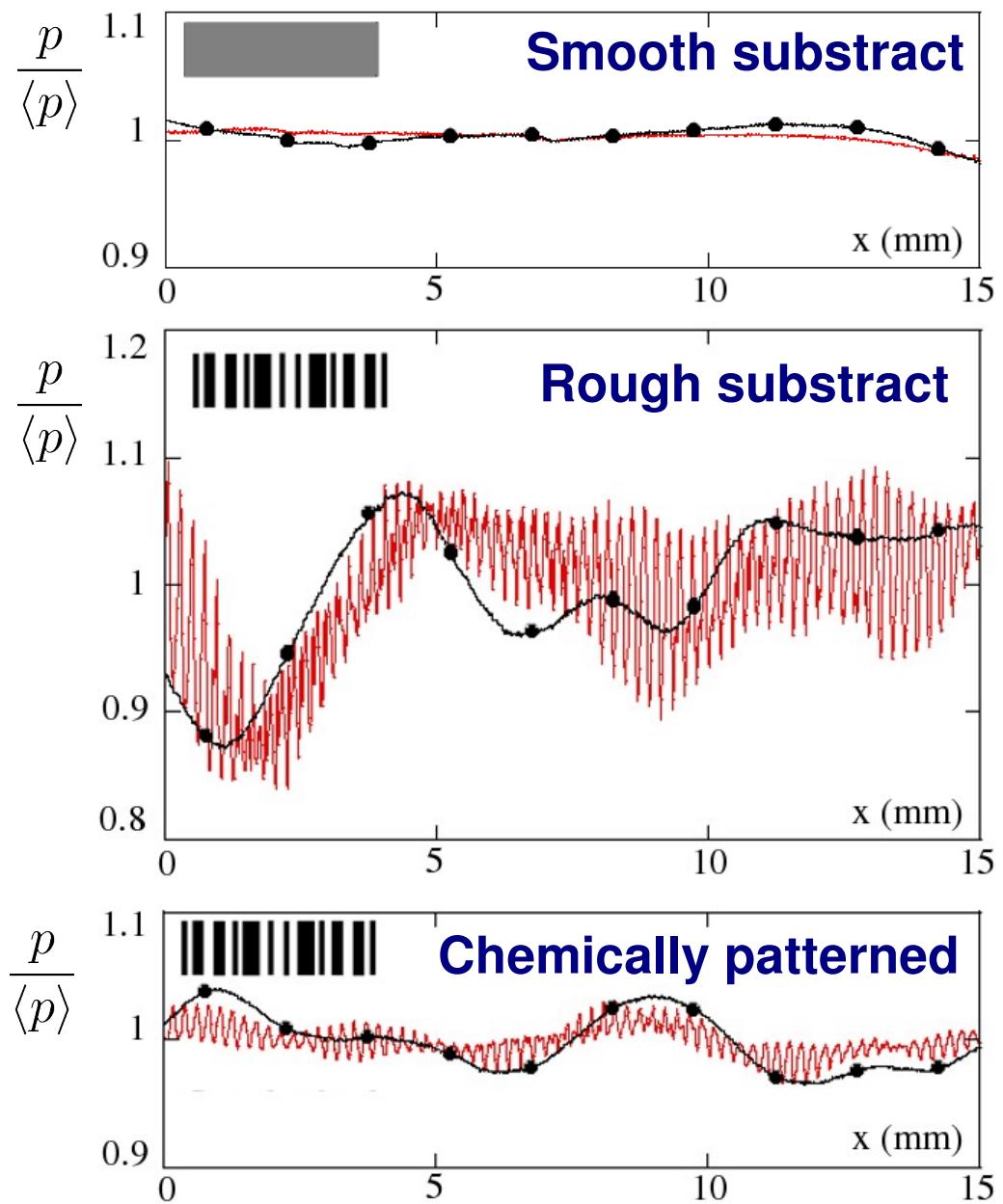
The effect of fingerprints



Artificial fingerprints

$500\mu\text{m}$ regular ridges
on the skin's surface

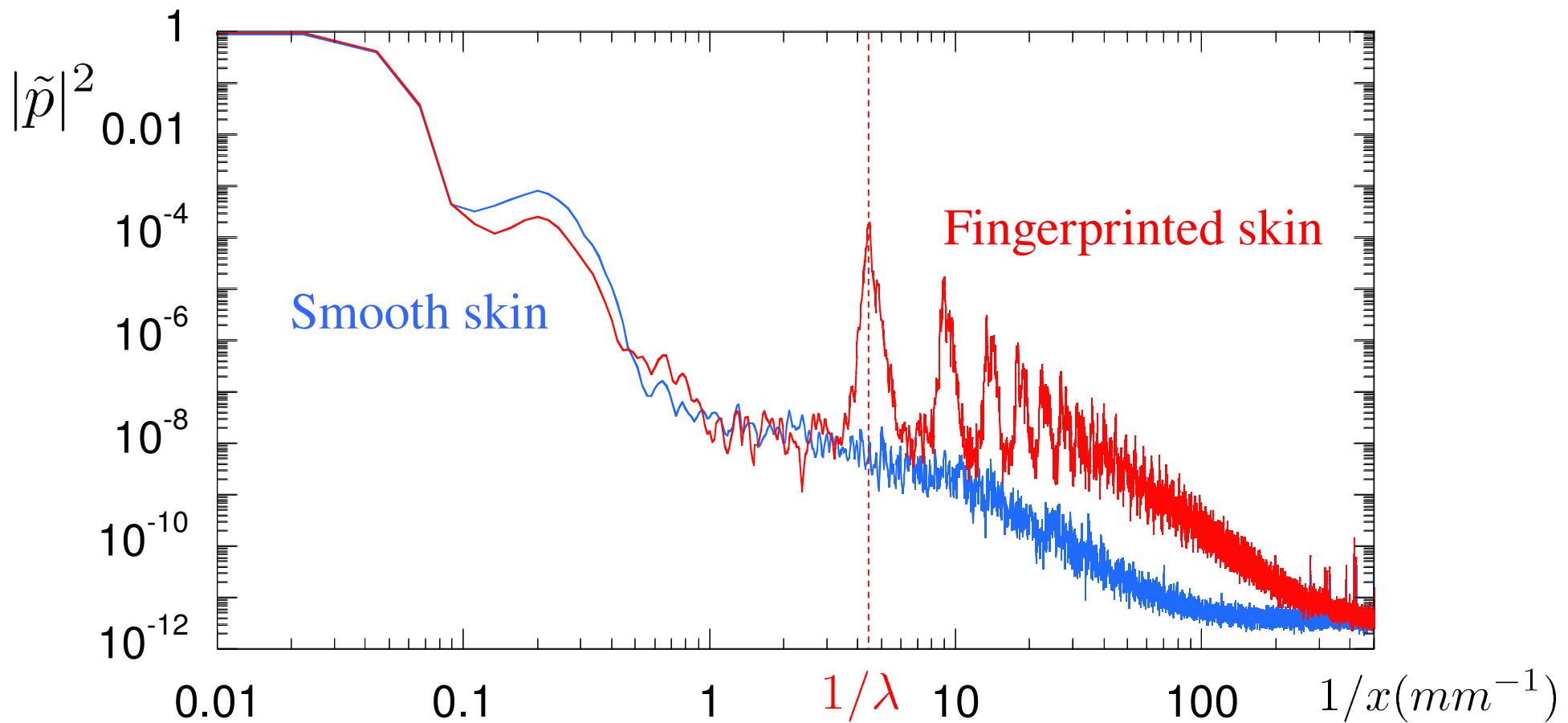
→ adds a characteristic frequency





Power spectrum

Rough substract



Note that: $v/\lambda = f_{ms}^{\text{Pacinian}}$

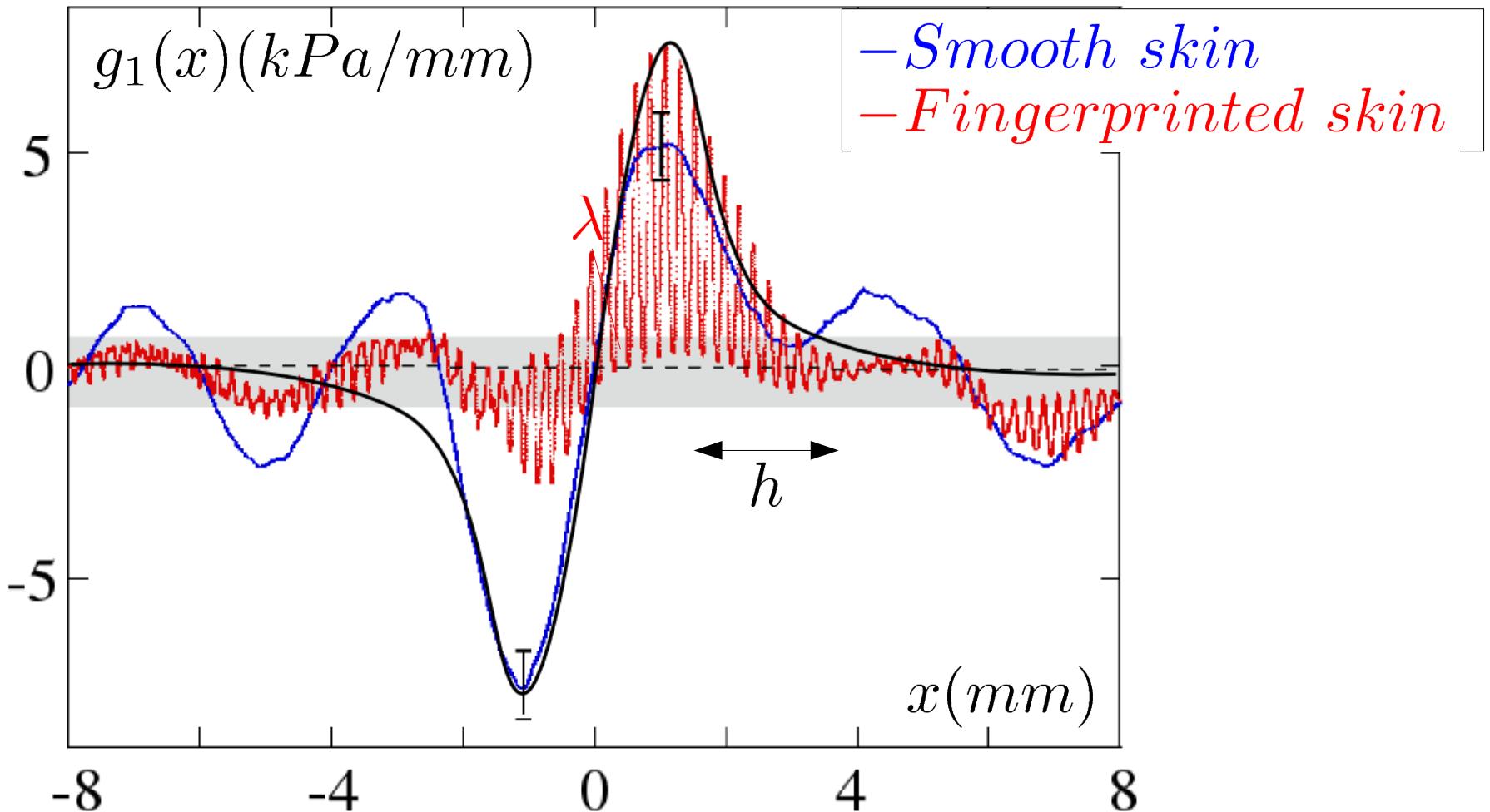
Scheibert et al. 2009





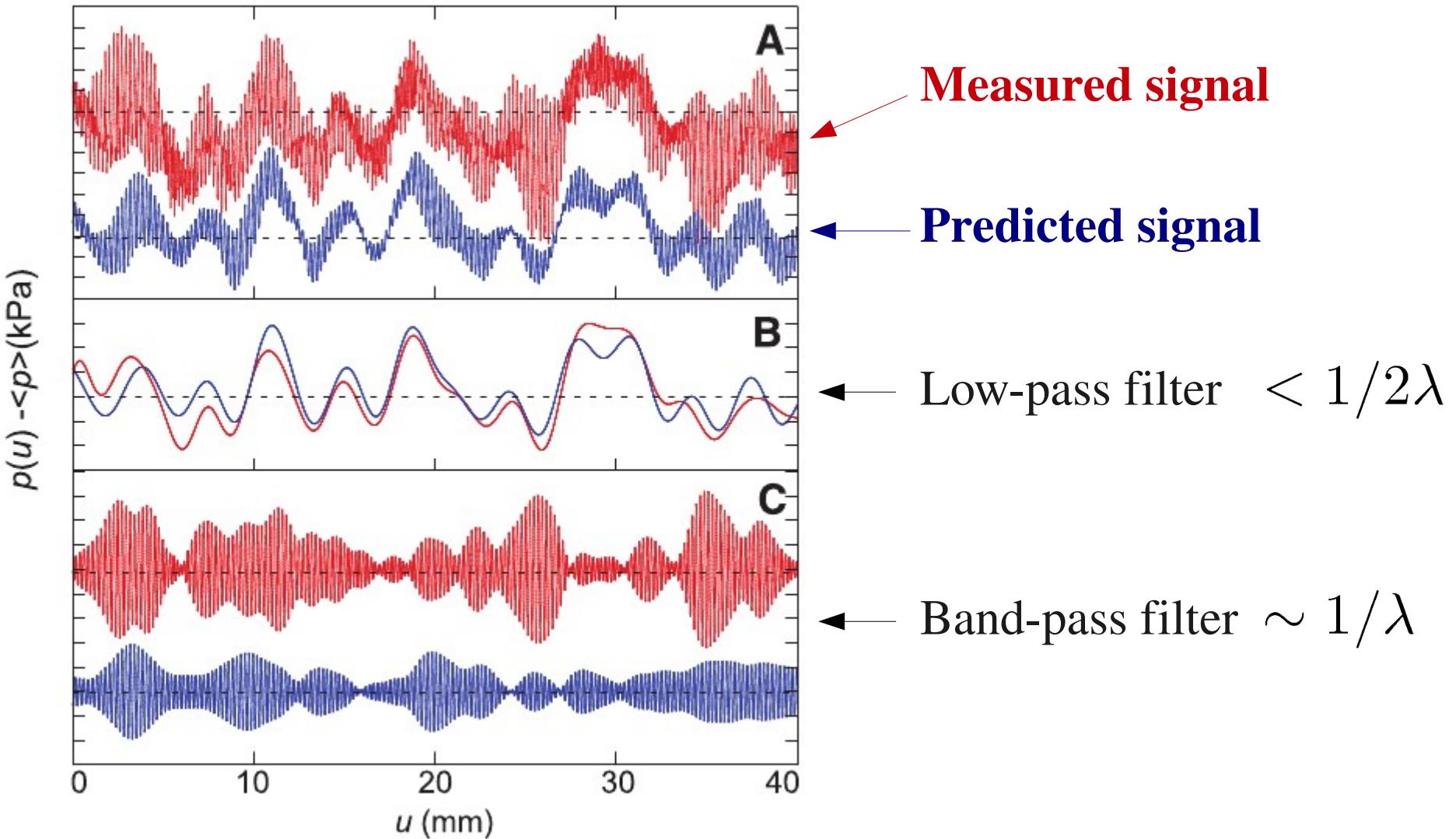
Dynamic impulse response

$$g_1(x) = \langle \text{[wavy line]} \cdot \text{[wavy line]} \rangle$$





Prediction





Conclusion

- Perception is not *only* processed in the brain
→ *Biomimetic approaches can unveil the physical mechanisms underlying the first steps of tactile signal processing*
- Receptive fields specifies under the contact zone
→ dynamical coding strategy ?
- Reverse correlation fully characterizes the system
→ predictions on the stress state inside the skin
- Fingerprints increase tactile perception accuracy
→ permit fine roughness discrimination

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