Partial squeeze-film levitation modulates fingertip friction

Controlling macroscopic friction *in vivo*

Michaël Wiertlewski, Rebecca Fenton Friesen, J. Edward Colgate

NORTHWESTERN UNIVERSITY

why does touch matter?

Courtesy of R. Johansson, Umea University

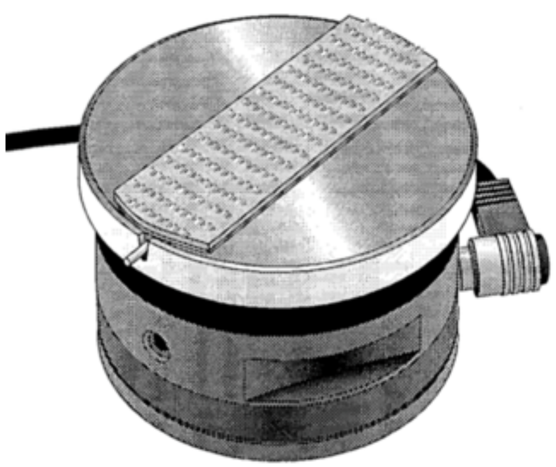
the role of shear force

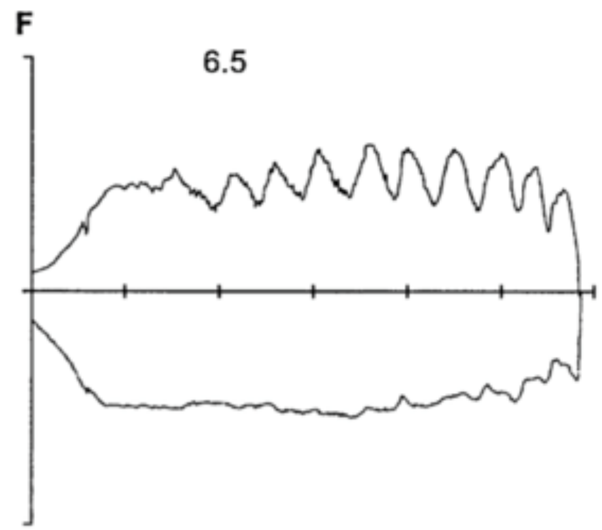
Exp Brain Res (2002) 144:211–223
DOI 10.1007/s00221-002-1015-y

RESEARCH ARTICLE

Allan M. Smith · C. Elaine Chapman
Mélanie Deslandes · Jean-Sébastien Langlais
Marie-Pierre Thibodeau

Role of friction and tangential force variation in the subjective scaling of tactile roughness

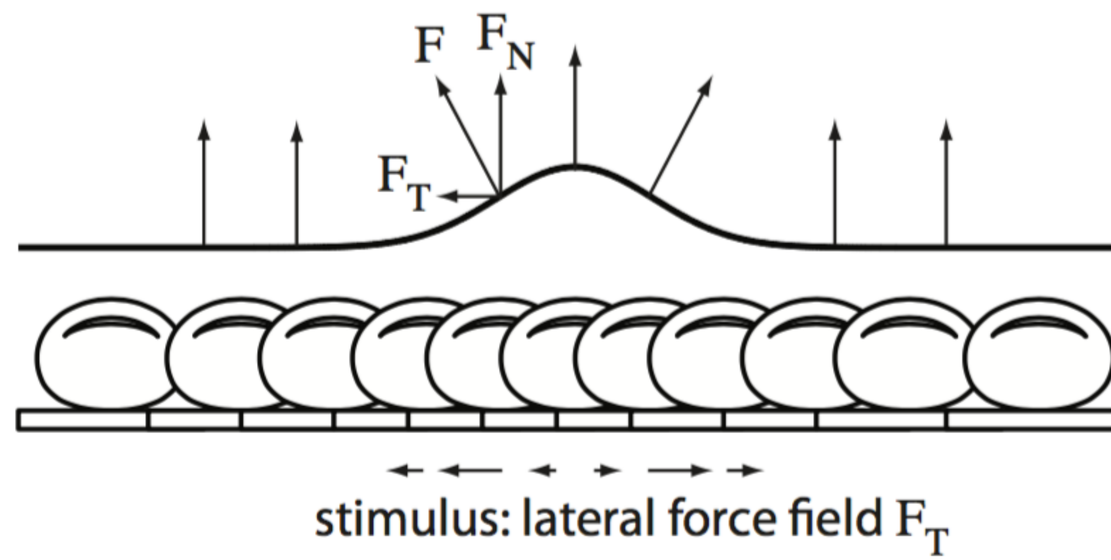




Force can overcome object geometry in the perception of shape through active touch

Gabriel Robles-De-La-Torre & Vincent Hayward

McGill University, Center for Intelligent Machines, Montréal, Canada H3A 2A7



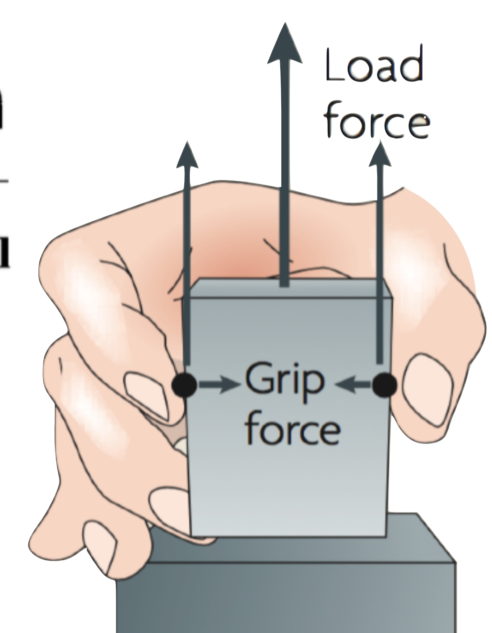
Exp Brain Res (1984) 56: 550–564

Experimental Brain Research

Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects

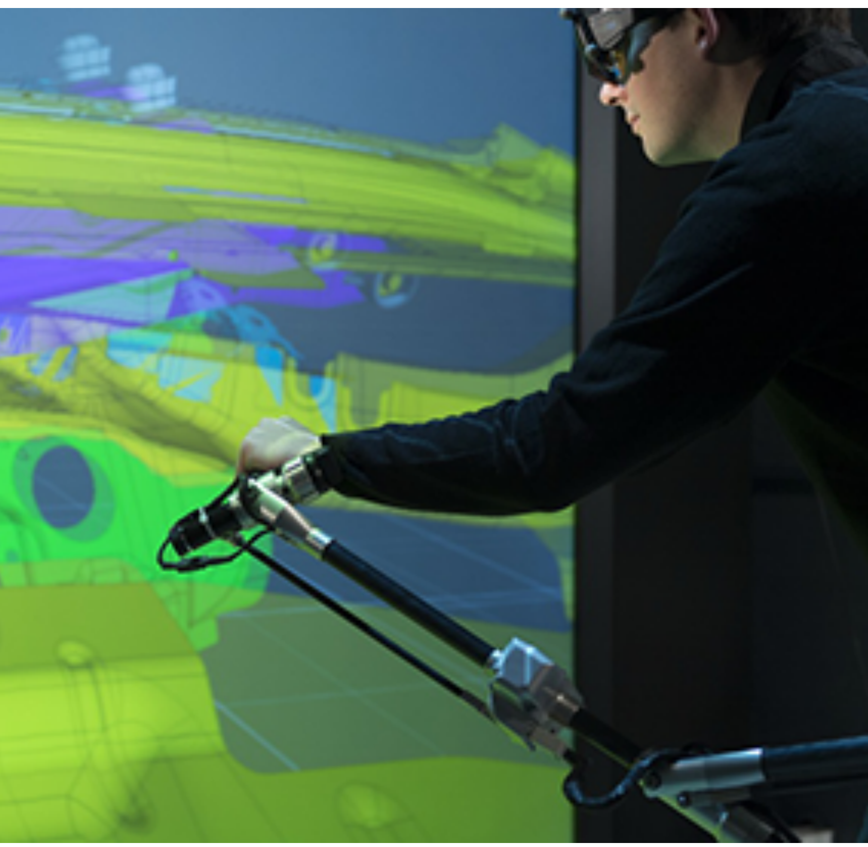
R. S. Johansson and G. Westling

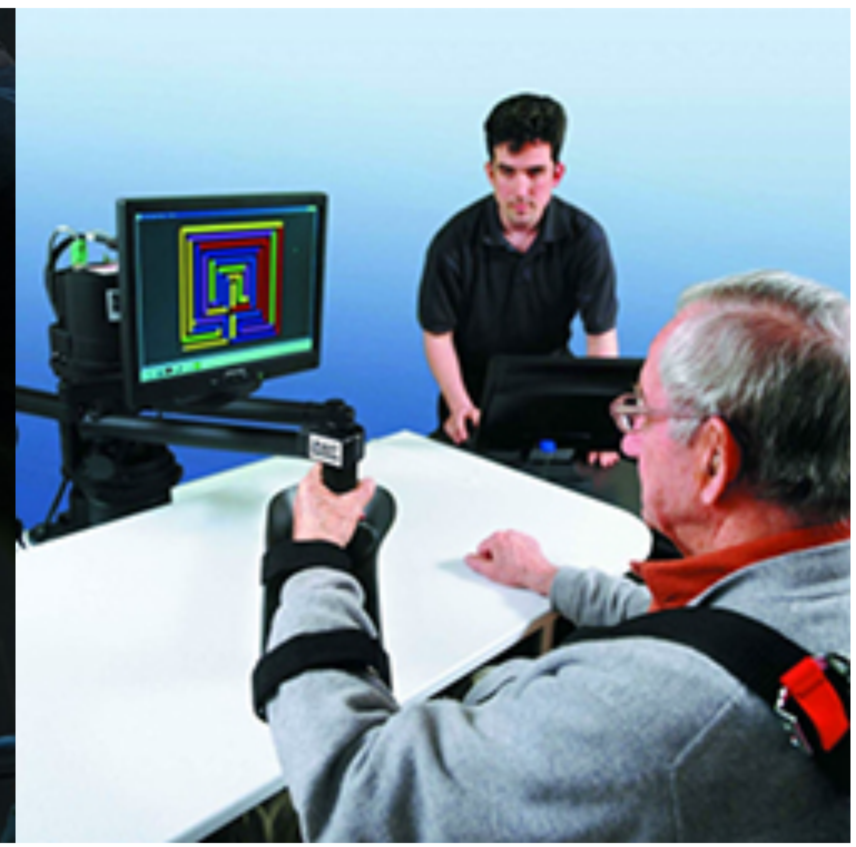
Department of Physiology, University of Umeå, S–901 87 Umeå, Sweden



haptic interfaces

Controlling forces on the user via manipulandum






18°C
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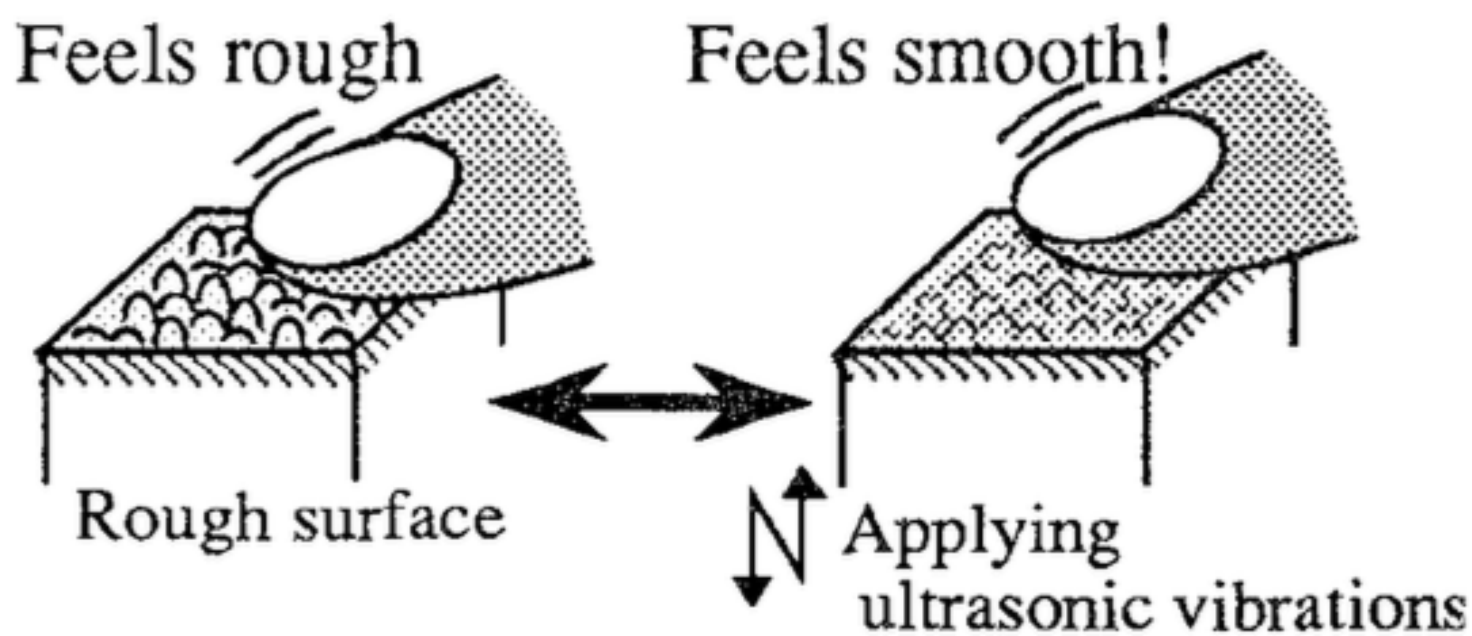
ultrasonic friction modulation

A Method for Controlling Tactile Sensation of Surface Roughness Using Ultrasonic Vibration

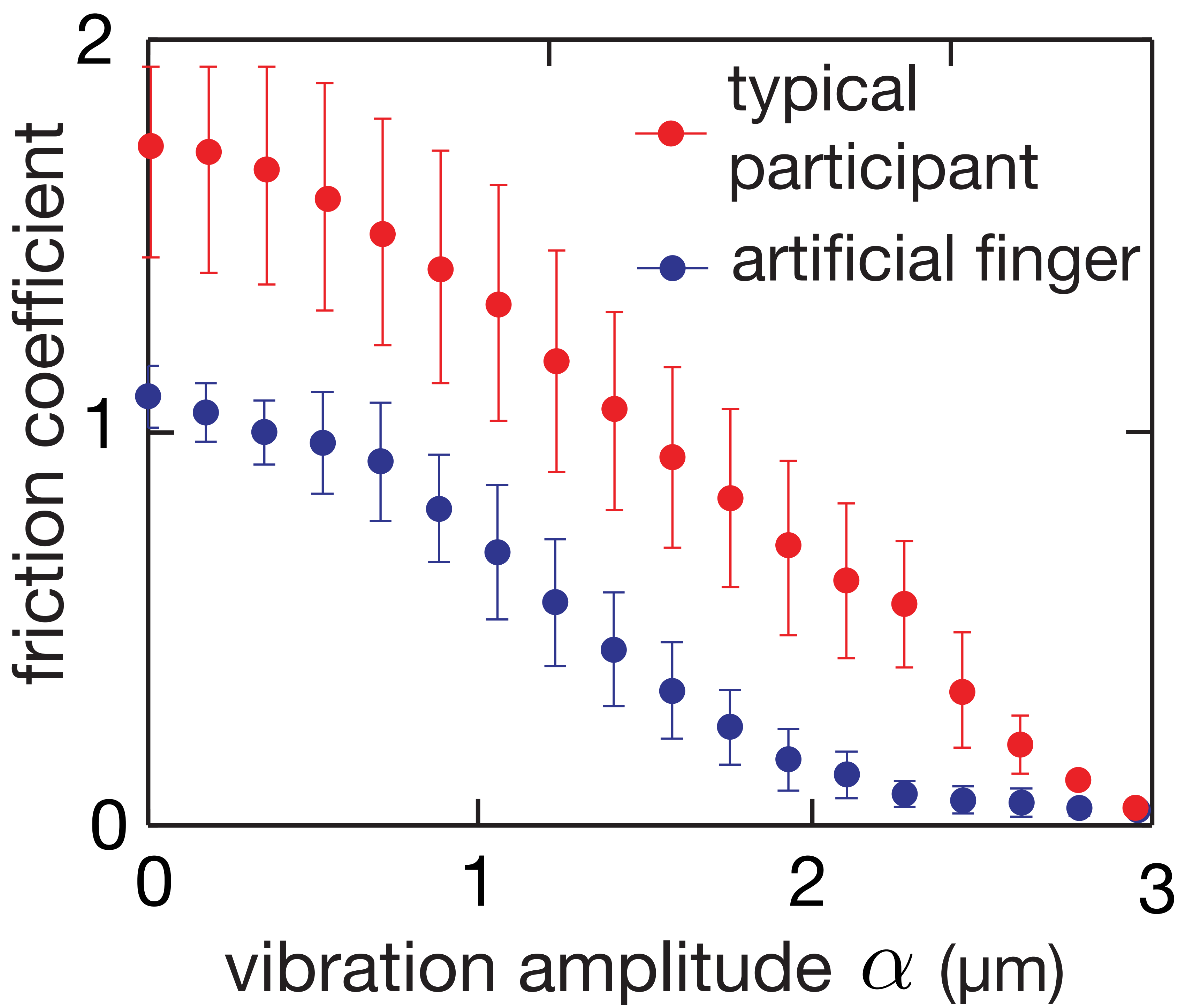
Toshio Watanabe and Shigehisa Fukui

NTT Interdisciplinary Research Laboratories
3-9-11, Midori-cho, Musashino-shi, Tokyo 180, Japan
email: nabe@aela.ntt.jp



Watanabe and Fukui, 1995

amplitude dependency



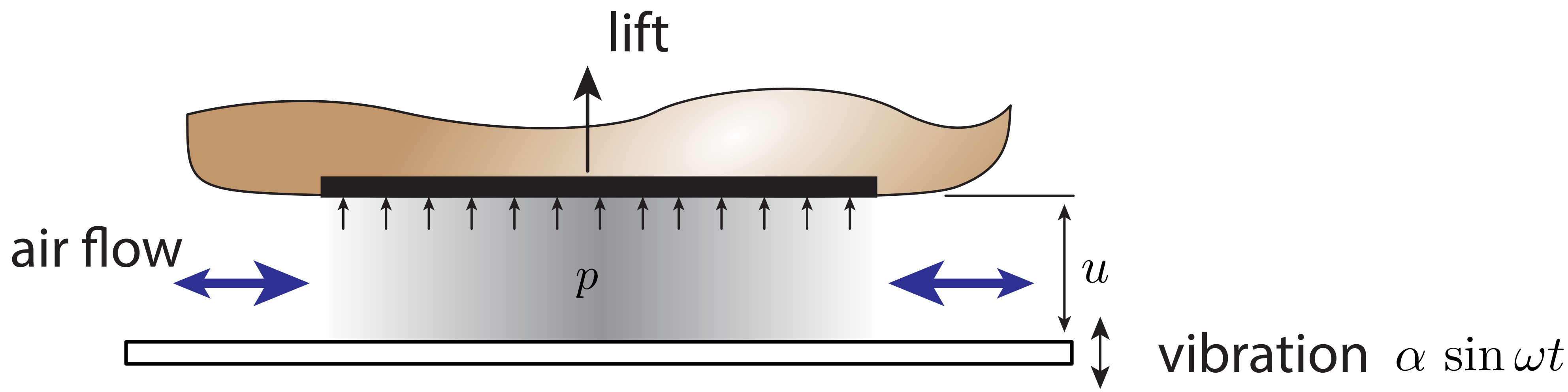
vibration modulation

Slow down x4

The green LED shows the vibration amplitude

Light on: amplitude ~2.5μm and low friction
Light off: no vibration and high friction

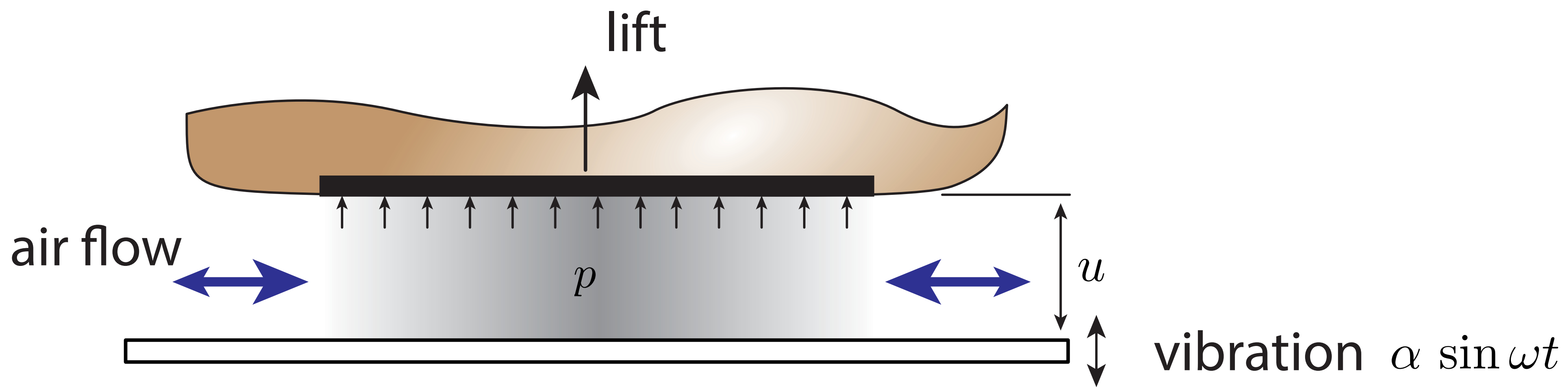
previous hypotheses : squeeze film



$$\frac{\partial}{\partial x}\left(\frac{\bar{u}^3 p}{12\mu}\frac{\partial p}{\partial x}\right) = \frac{\partial (p\bar{u})}{\partial t}$$

Watanabe and Fukui, 1995
Winfield et al. 2007
Biet et al. 2007

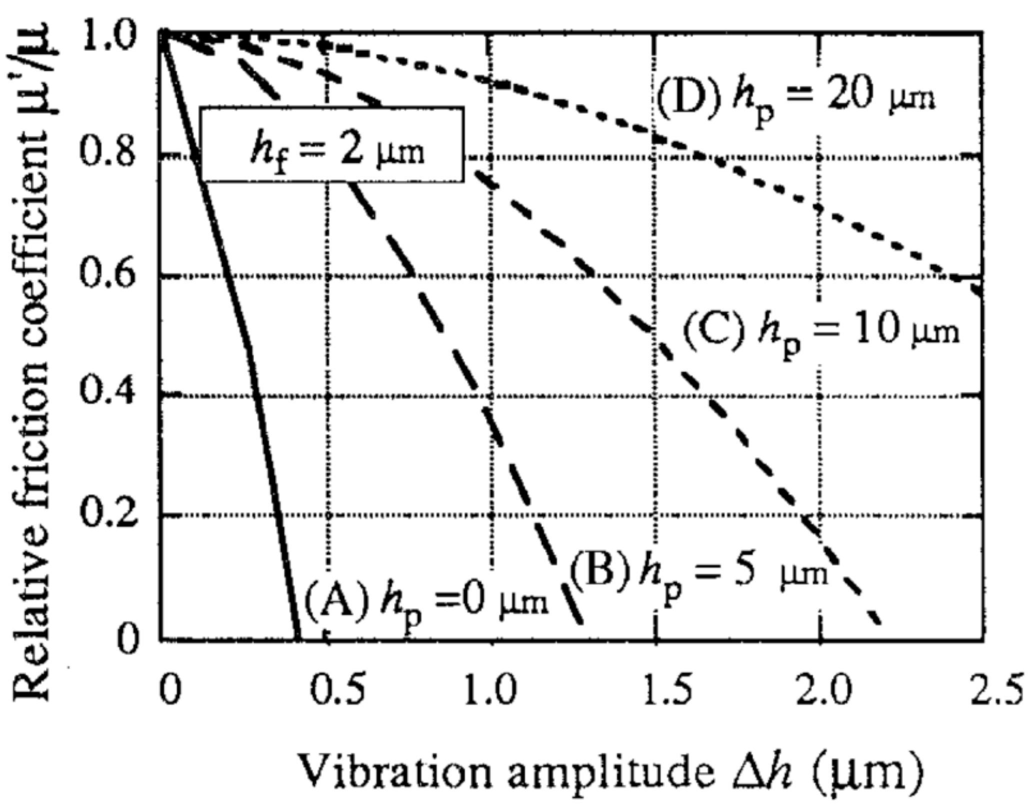
previous hypotheses : squeeze film



$$\frac{\partial}{\partial x}\left(\frac{\bar{u}^3 p}{12\mu}\frac{\partial p}{\partial x}\right) = \frac{\partial (p\bar{u})}{\partial t}$$

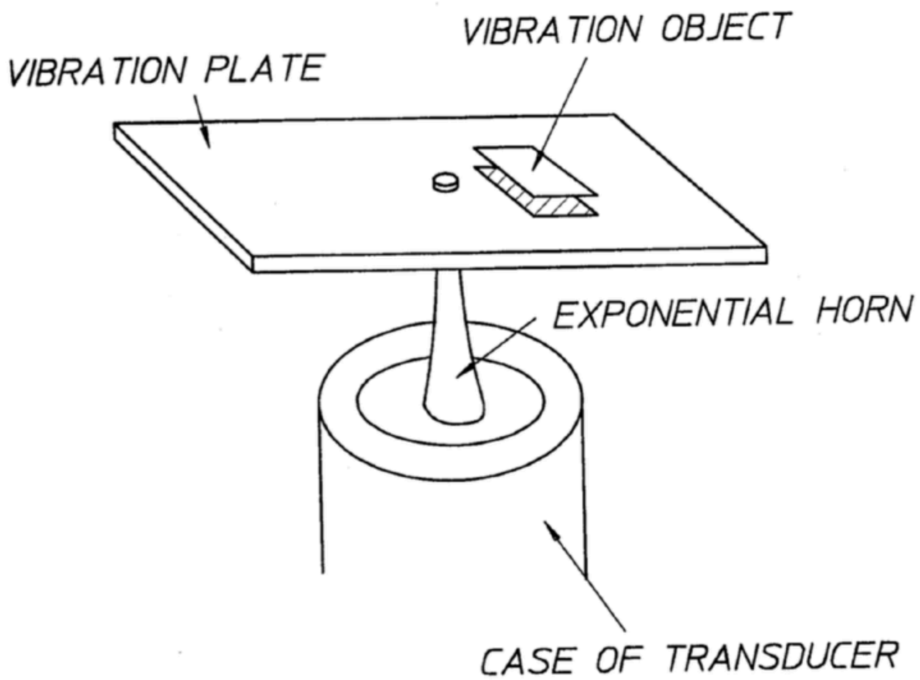
$$f_{sq} = \int_S p_0 \left(\sqrt{\frac{u^2 + \frac{3}{2}\alpha^2}{u^2 - \alpha^2}} - 1\right)$$

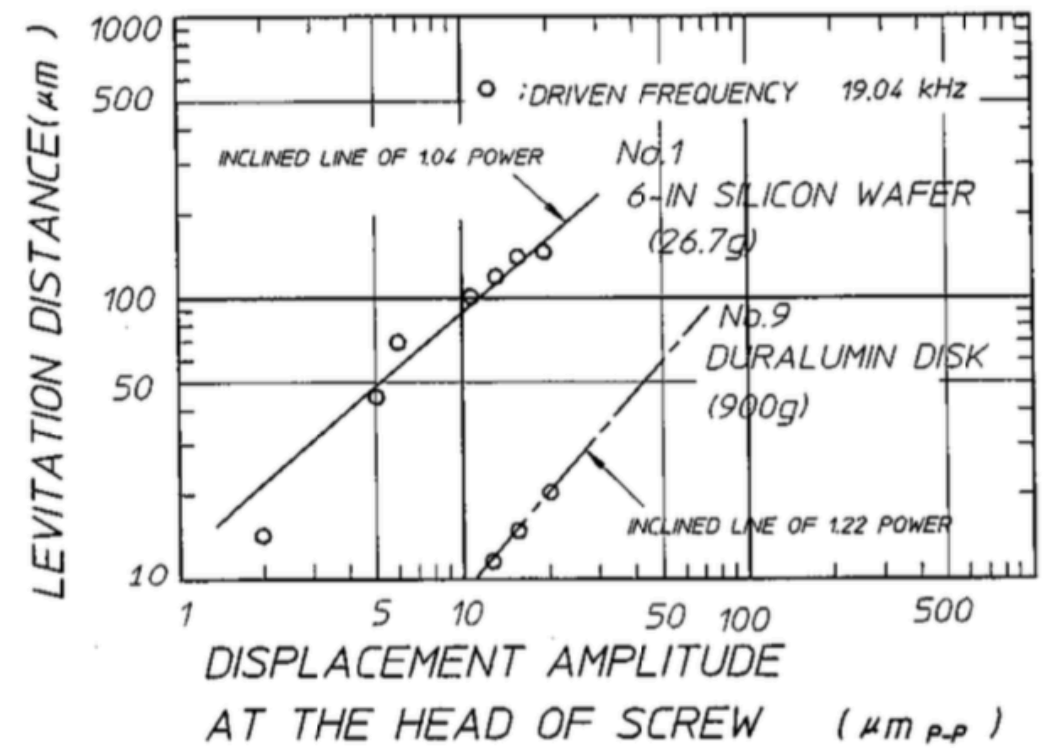
$$\frac{\mu'}{\mu} = 1 - \frac{f_{sq}}{f_n}$$



Watanabe and Fukui, 1995
Winfield et al. 2007
Biet et al. 2007

near-field acoustic levitation

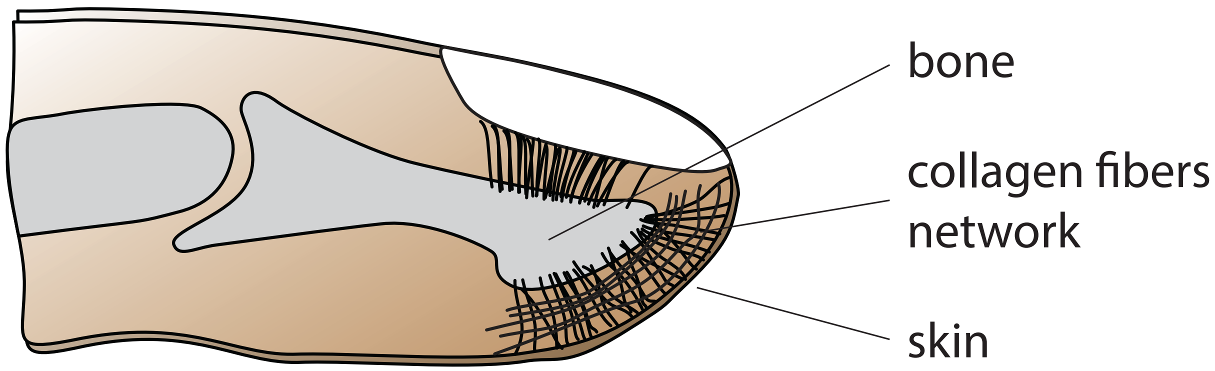


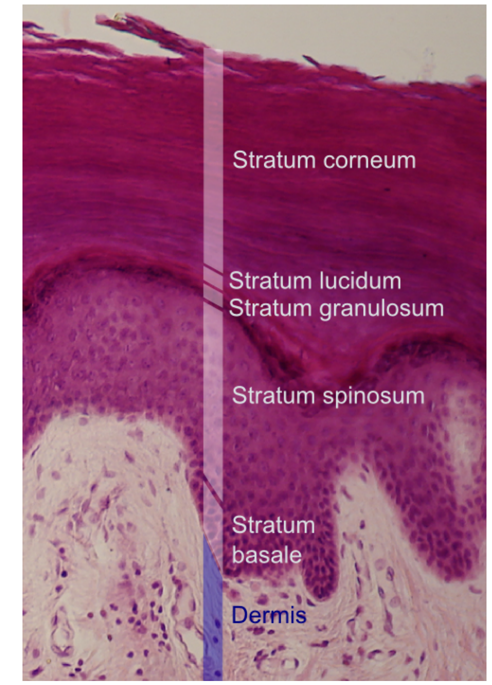


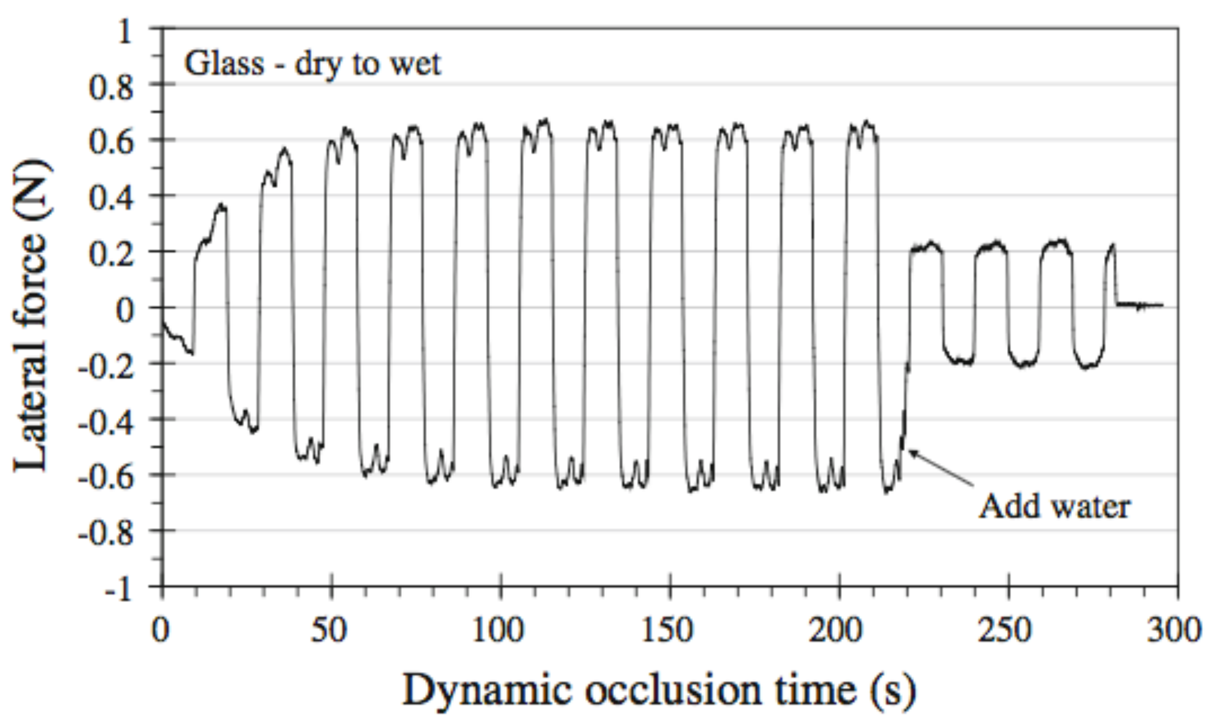
$$u \propto \sqrt{\frac{\beta}{f_p}}\alpha$$

Chu and Apfel 1982
Hashimoto et al 1996

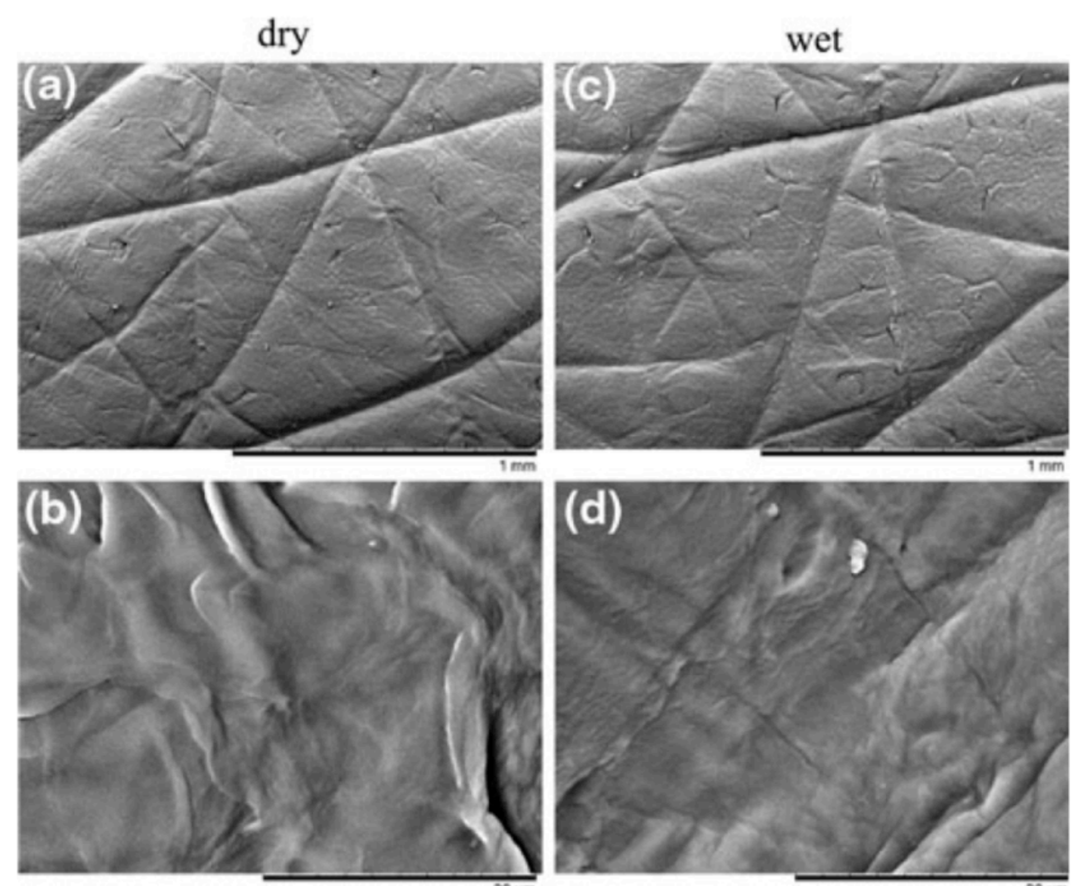
structure of the fingertip





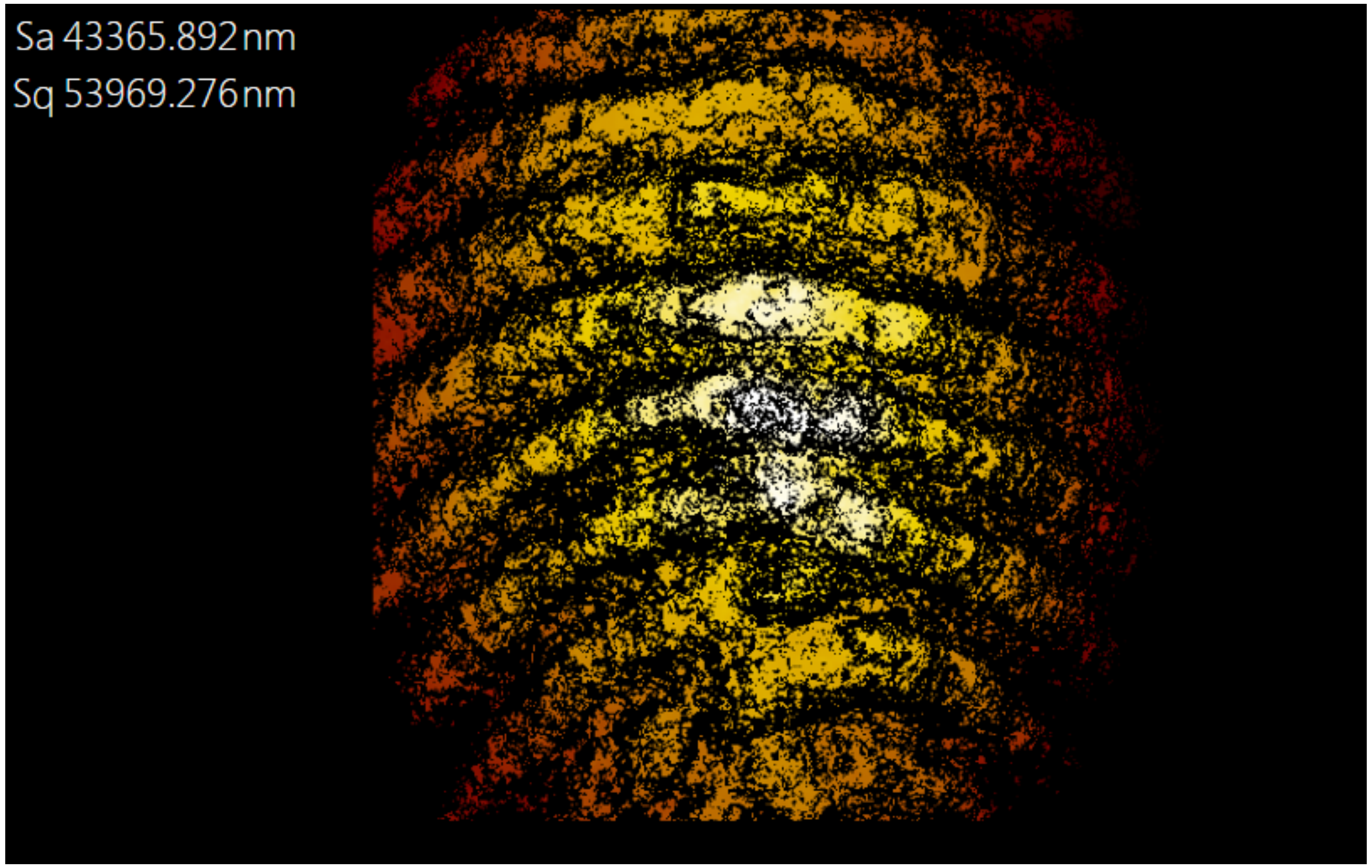


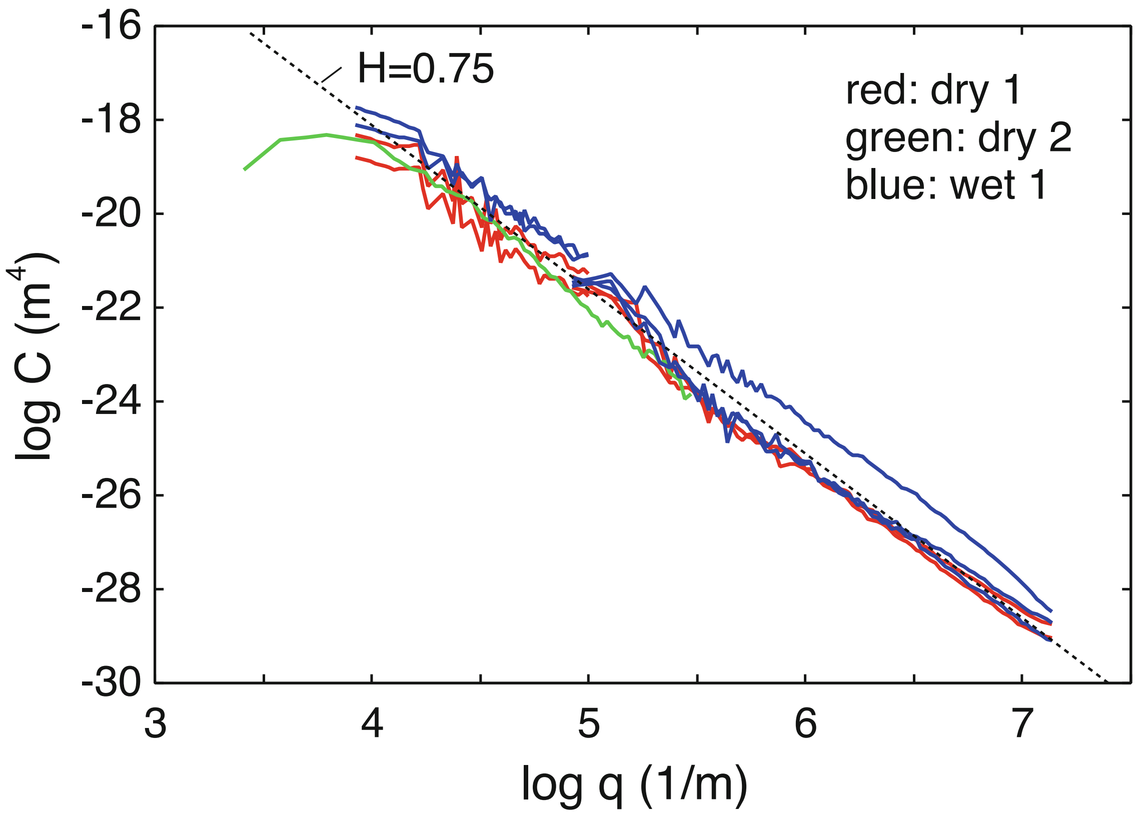
Pasumarty et al. 2011



Persson et al. 2013

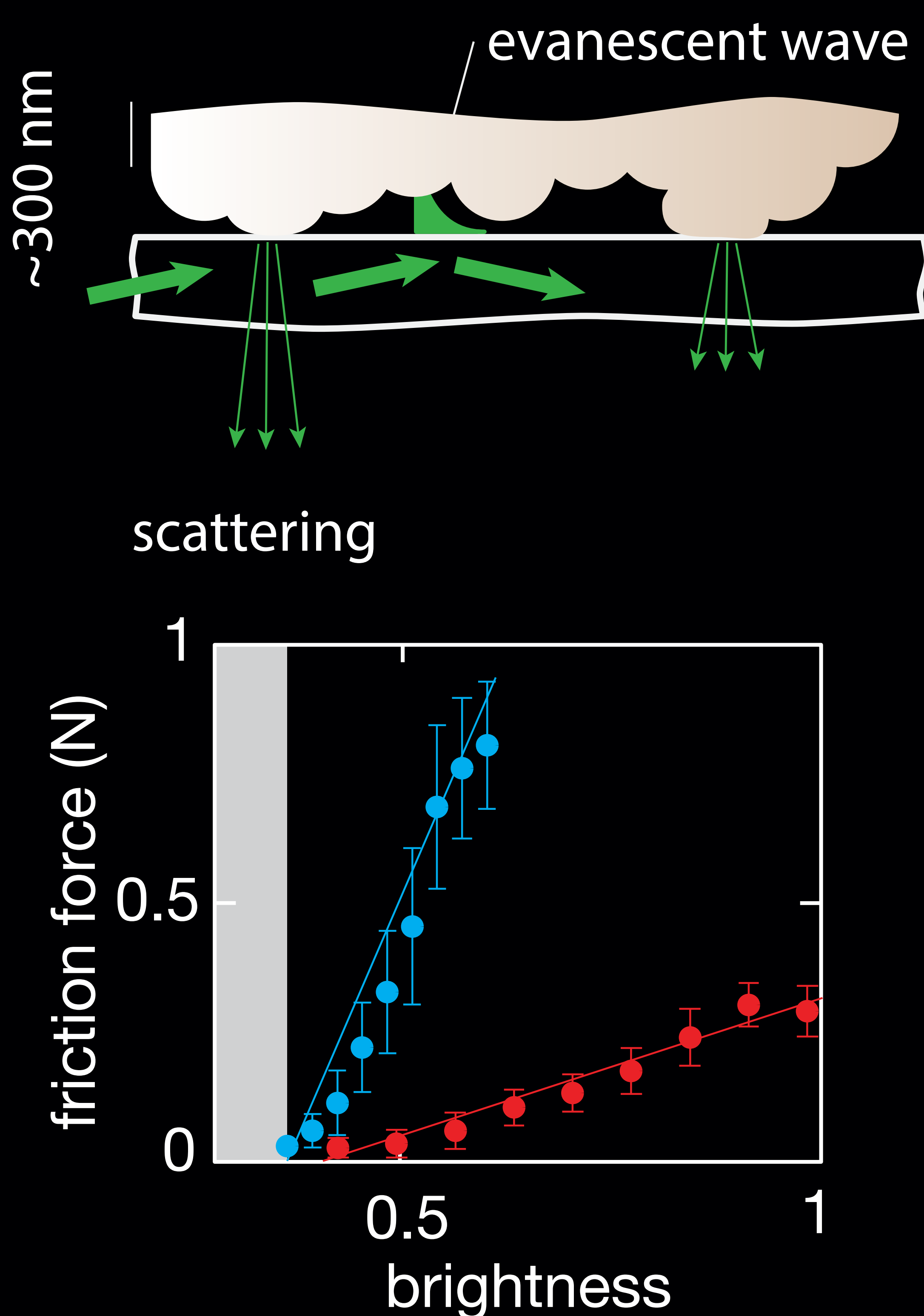
surface topography

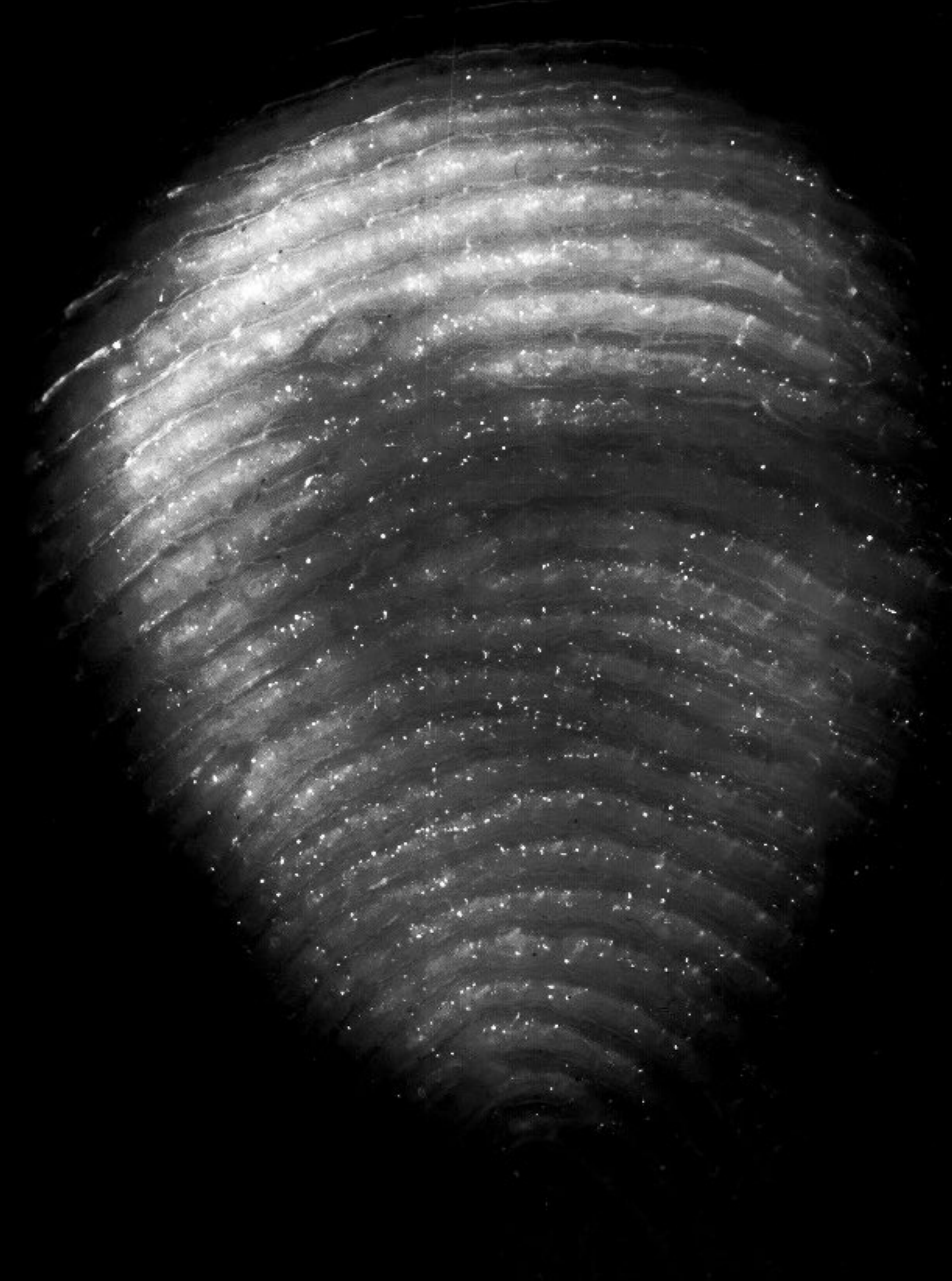




Persson et al. 2013

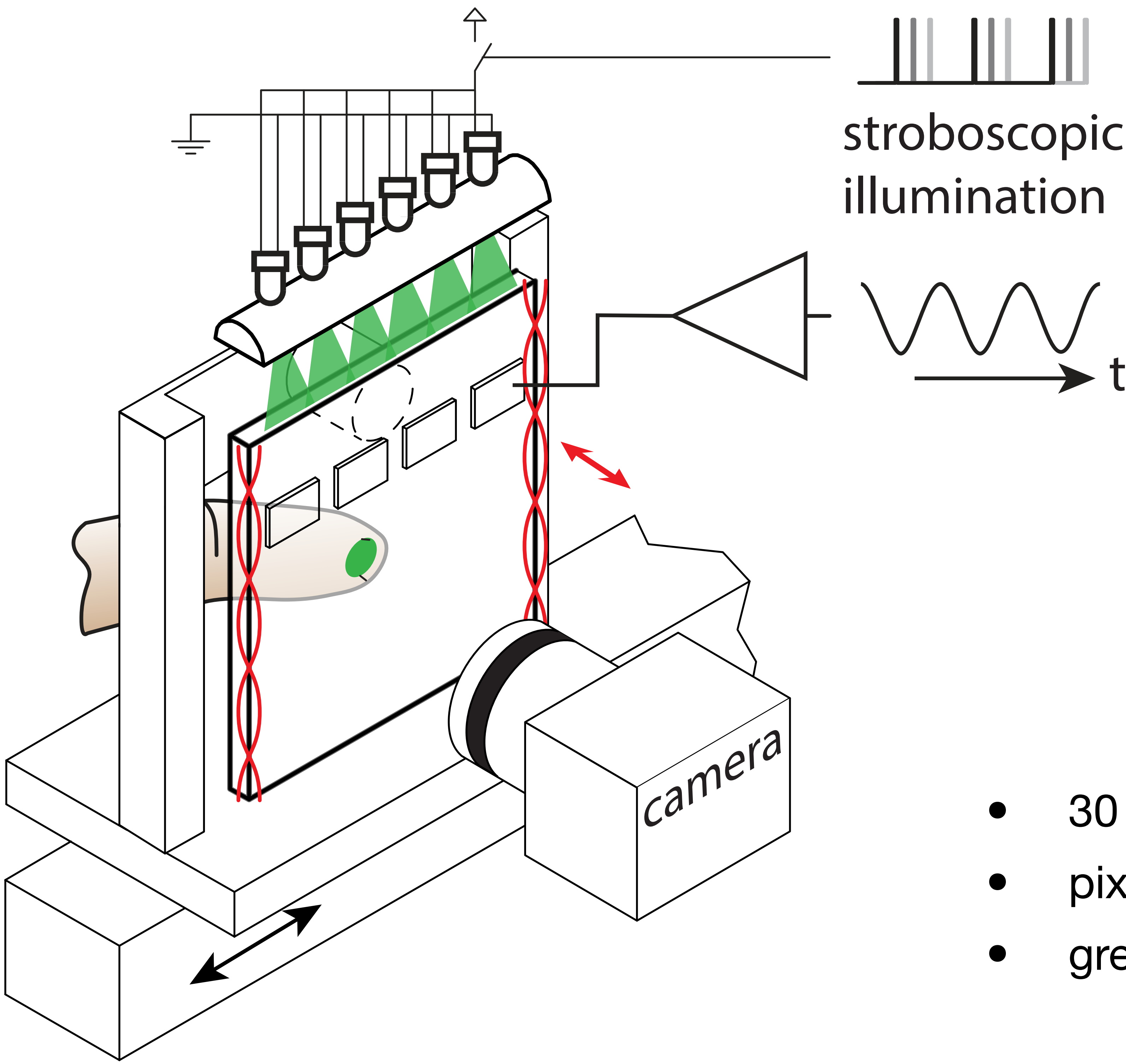
measurement real area of contact





Wiertlewski, M., Fenton Friesen R., Colgate, E., PNAS 2016

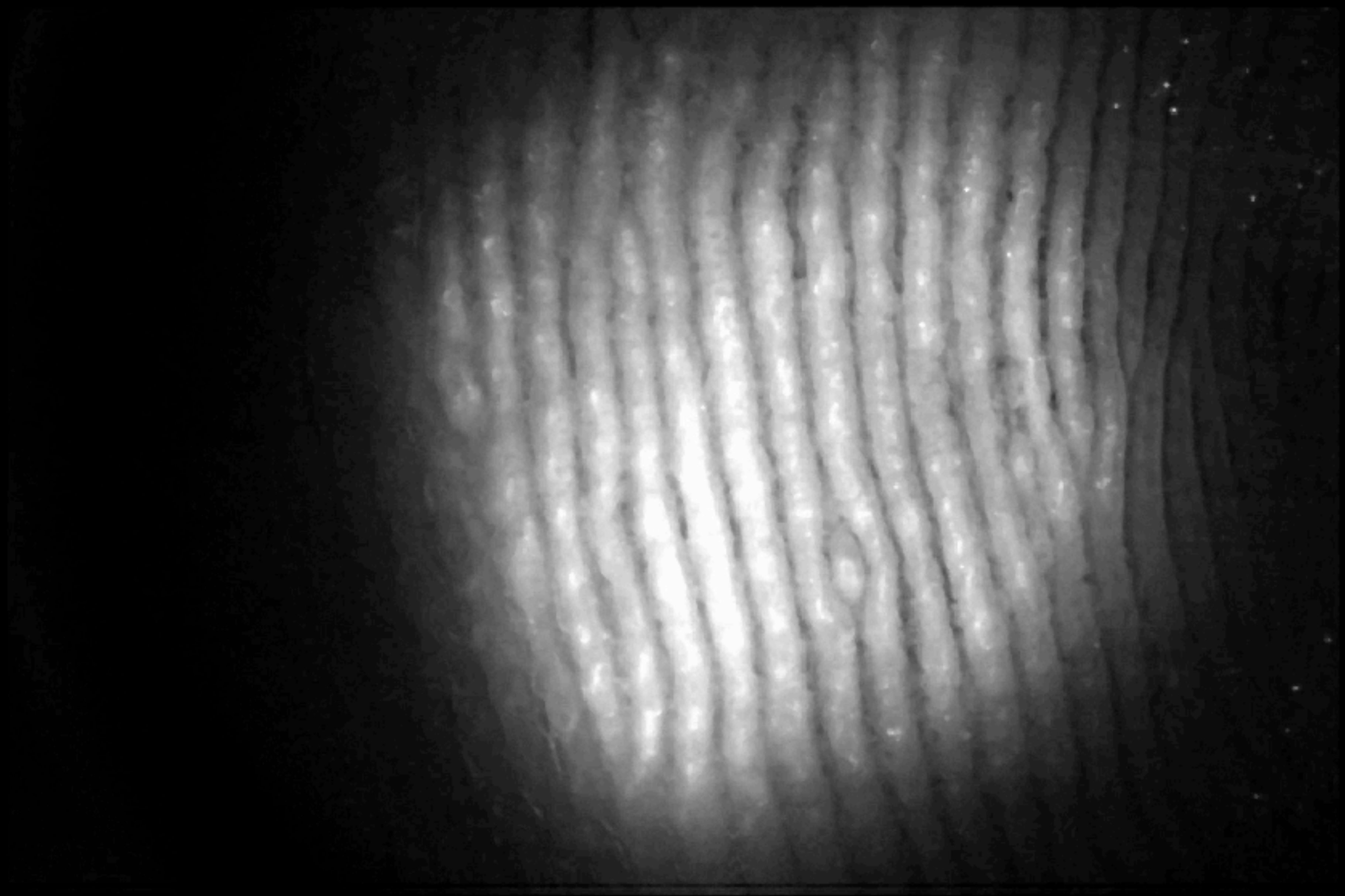
setup



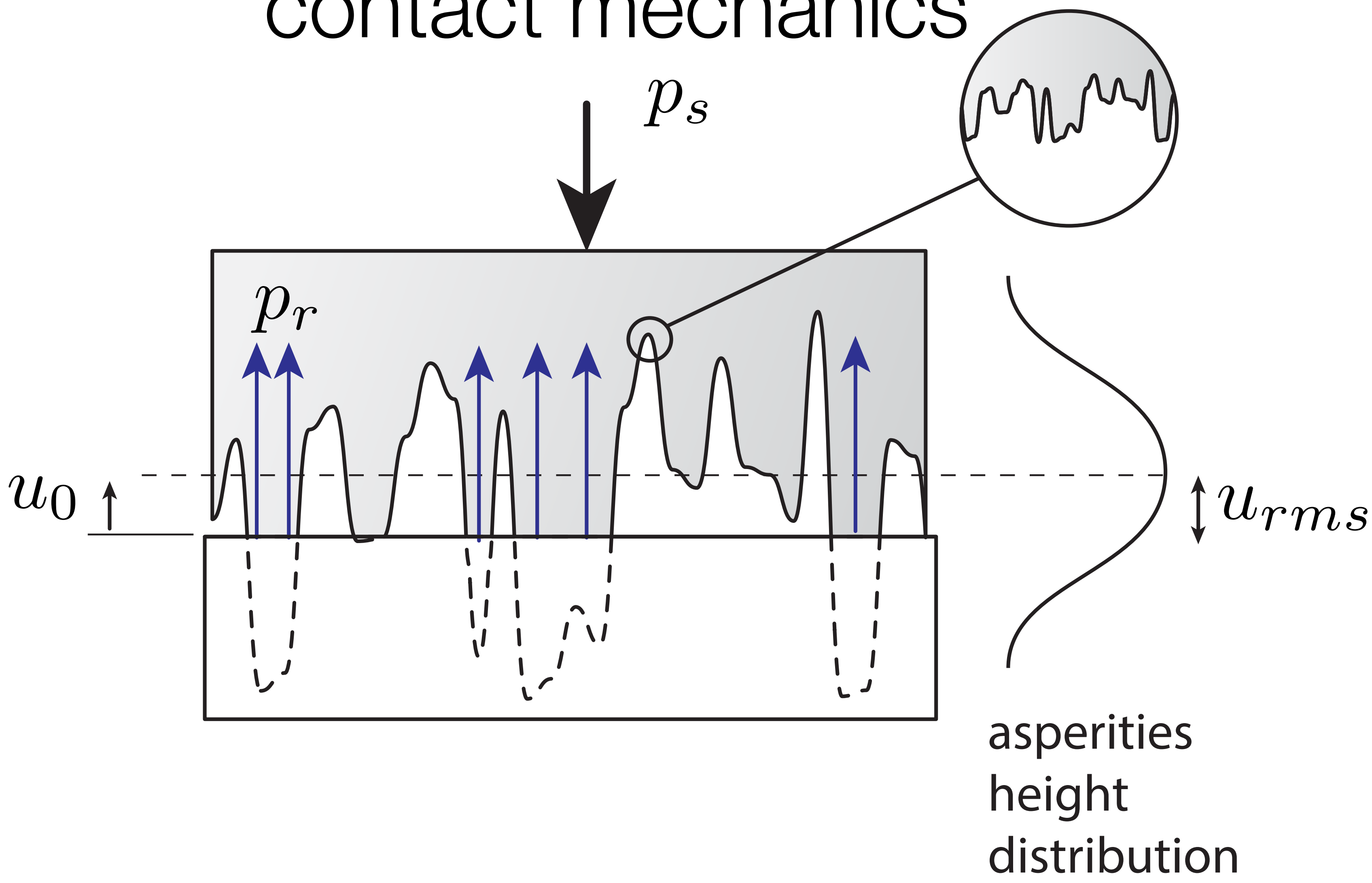
- 30 kHz resonance frequency
- pixel size of 10 µm
- green light to limit diffusion

Wiertlewski, M., Fenton Friesen R., Colgate, E., PNAS 2016

variable friction



contact mechanics



$$\boxed{p_r = p_c\, e^{-u/u_{rms}}}$$

with $p_c = 0.375\, q_0\, u_{rms} \dfrac{E}{1-\nu^2}$

$E = 20\,\mathrm{MPa}$

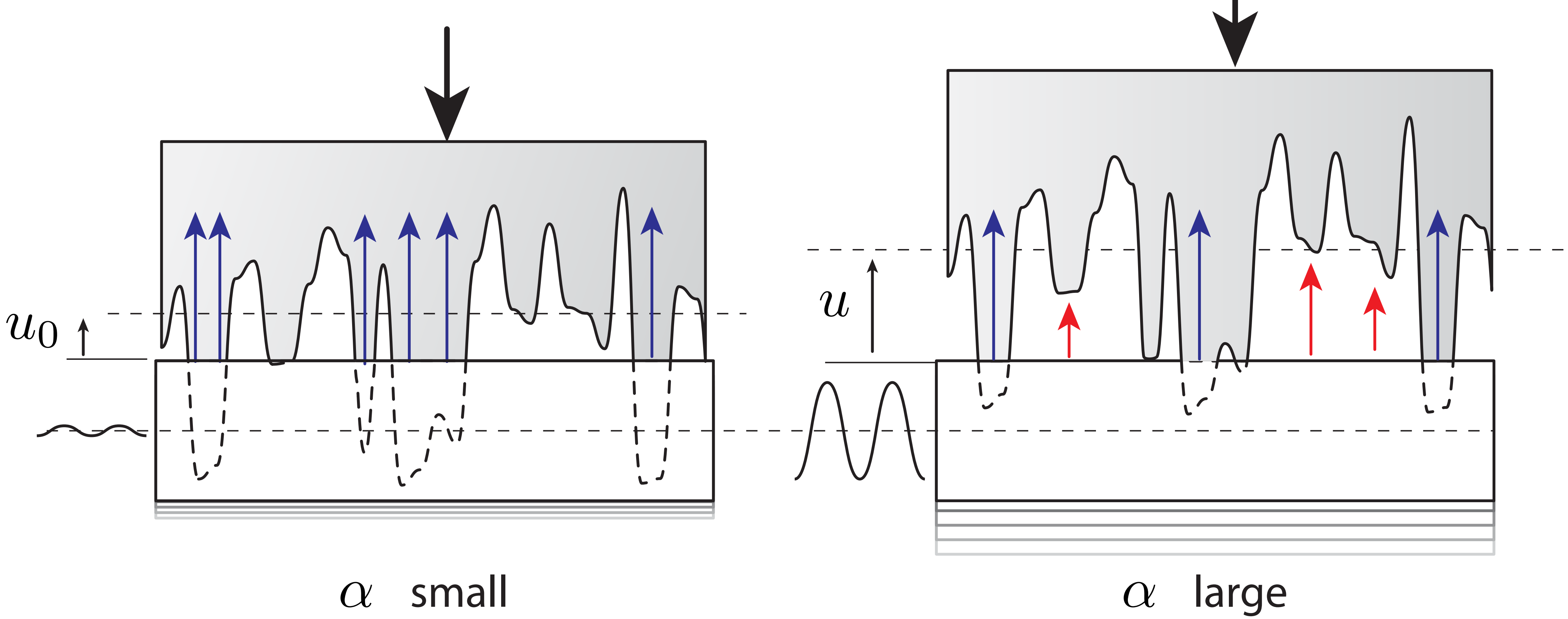
$u_{rms} = 2.5\mu\mathrm{m}$

$q_0 = 10^4 \mathrm{m}^{-1}$

Greenwood & Williamson 1966

Persson 2007

squeeze-film levitation



Reynold's lubrication equation for laminar flow:

$$\frac{\partial}{\partial x}\left(\frac{\bar{u}^3 p}{12\mu}\frac{\partial p}{\partial x}\right) = \frac{\partial (p\bar{u})}{\partial t}$$

leads to :

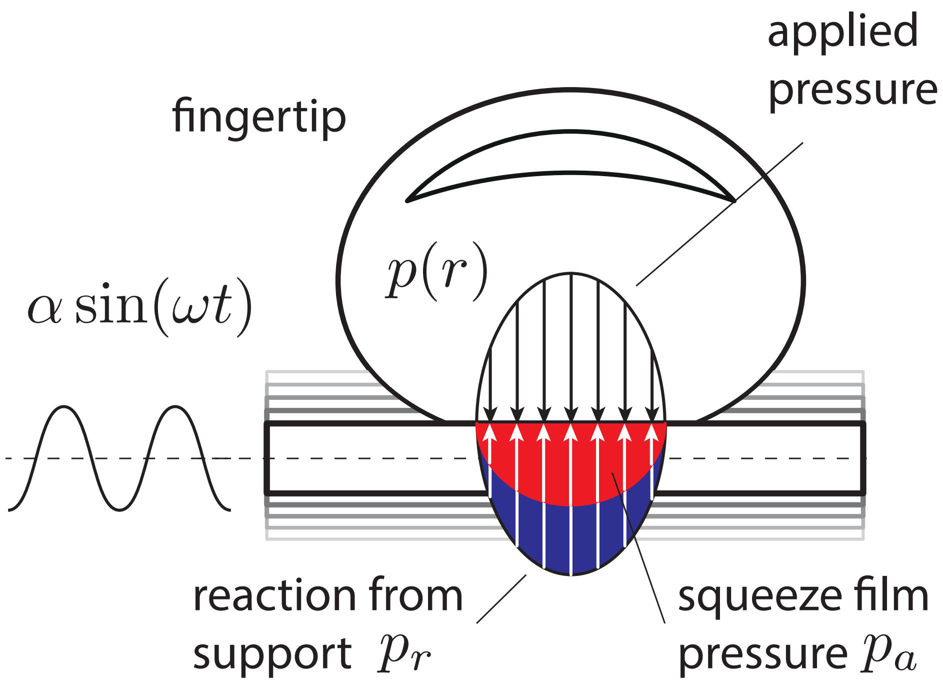
$$\text{if} \quad \sigma = 12\frac{\omega \mu L^2}{p_0 u^2} > 36$$

$$p_a = p_0\left(\sqrt{\frac{u^2 + \frac{3}{2}\alpha^2}{u^2 - \alpha^2}} - 1\right) \boxed{\approx \frac{5}{4} p_0 \frac{\alpha^2}{u^2}}$$

Salbu 1964

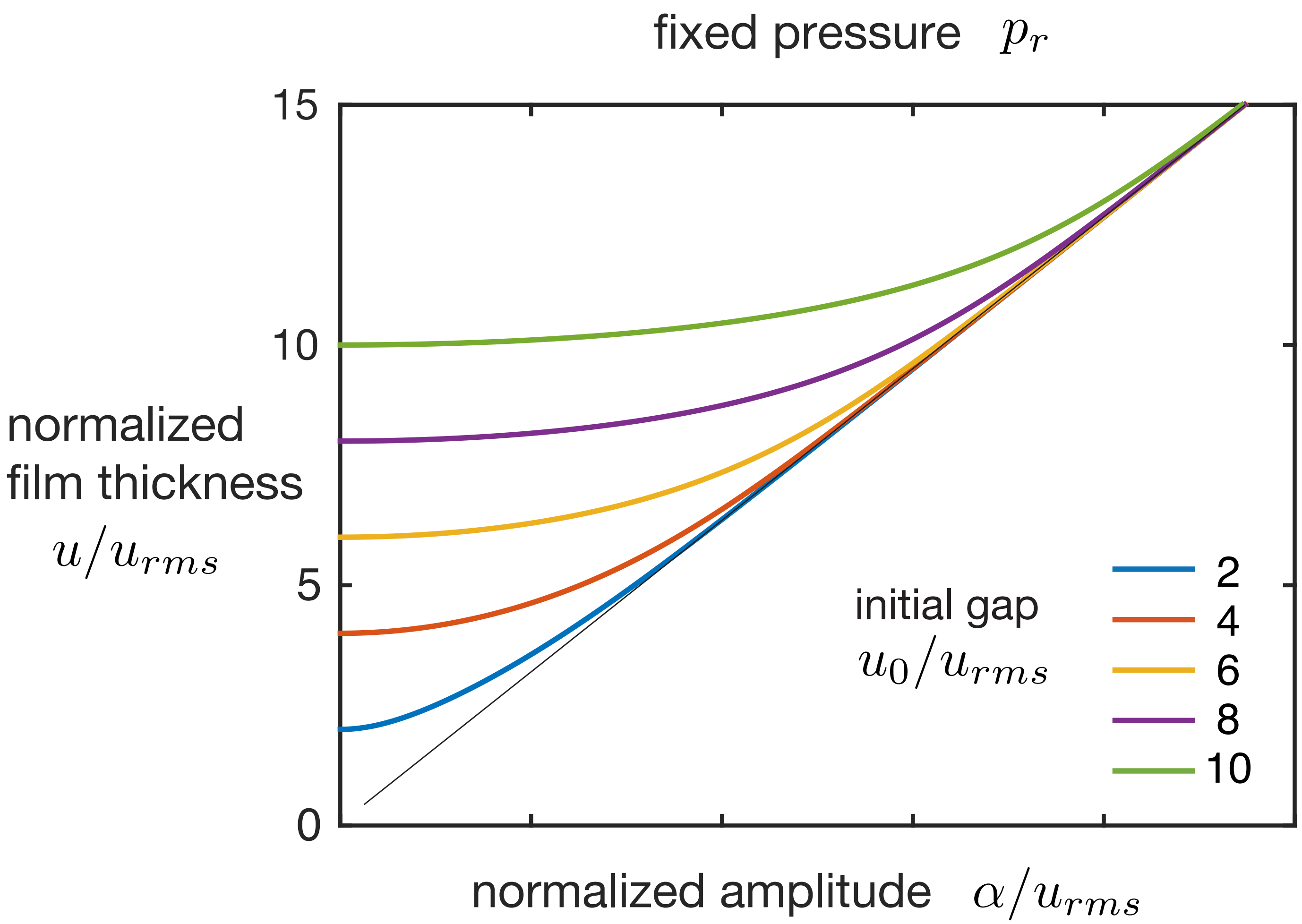
Minikes et al. 2004

equilibrium

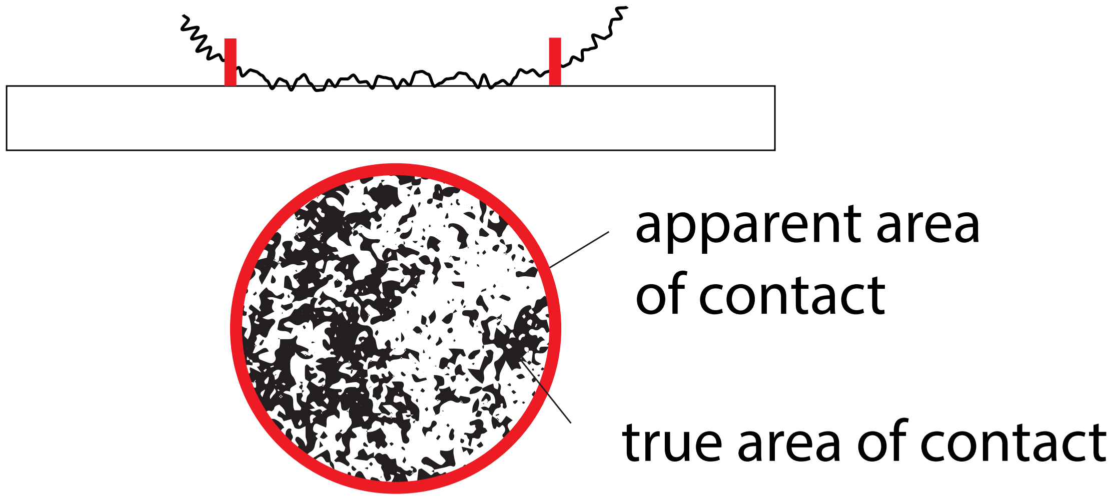


$$p_s - p_r = p_a$$

$$p_s \left(1 - e^{\frac{-u+u_0}{u_{rms}}}\right) = \frac{5}{4} p_0 \frac{\alpha^2}{u^2}$$



relation to friction



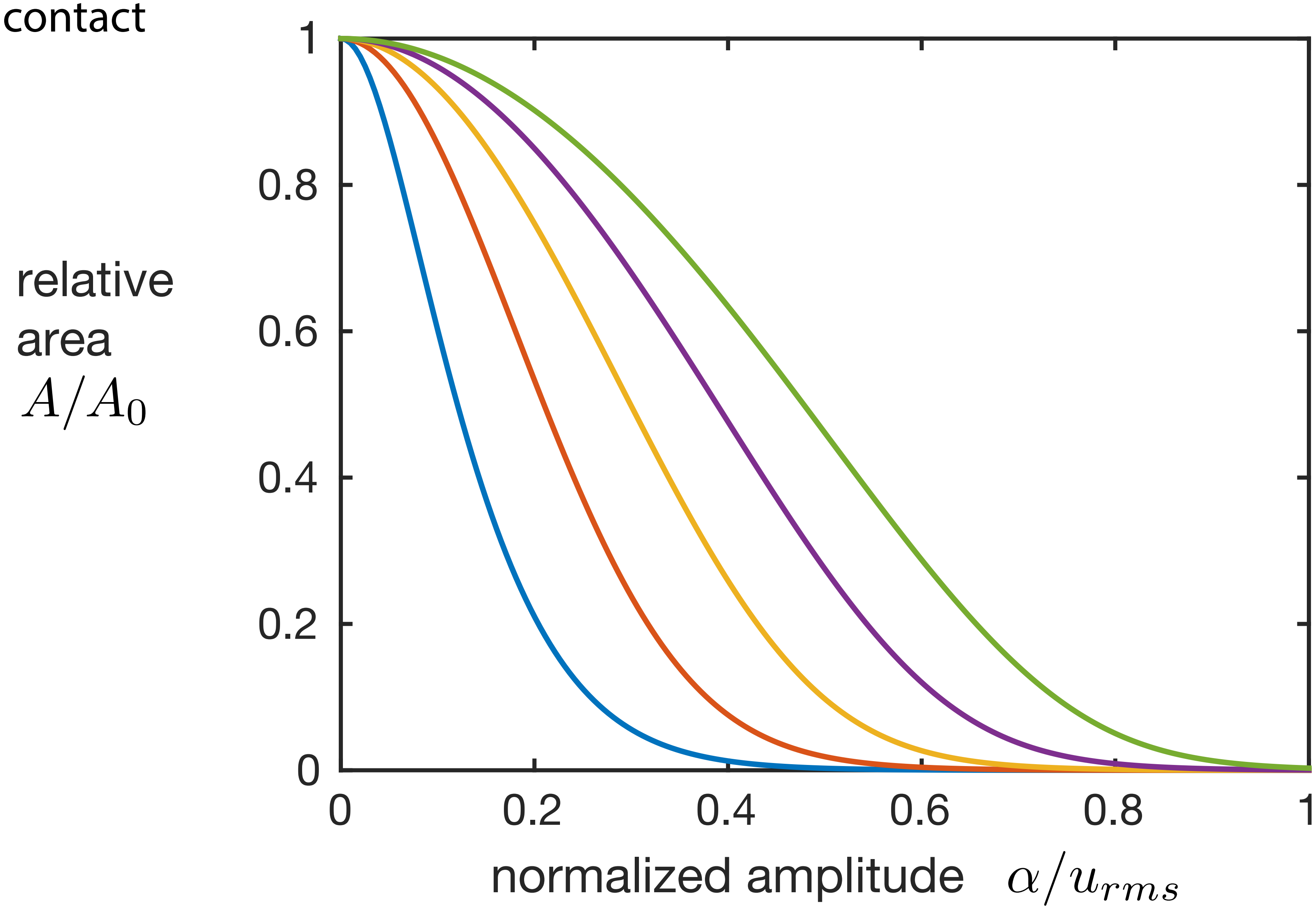
Bowden and Tabor 1939

Persson 2007

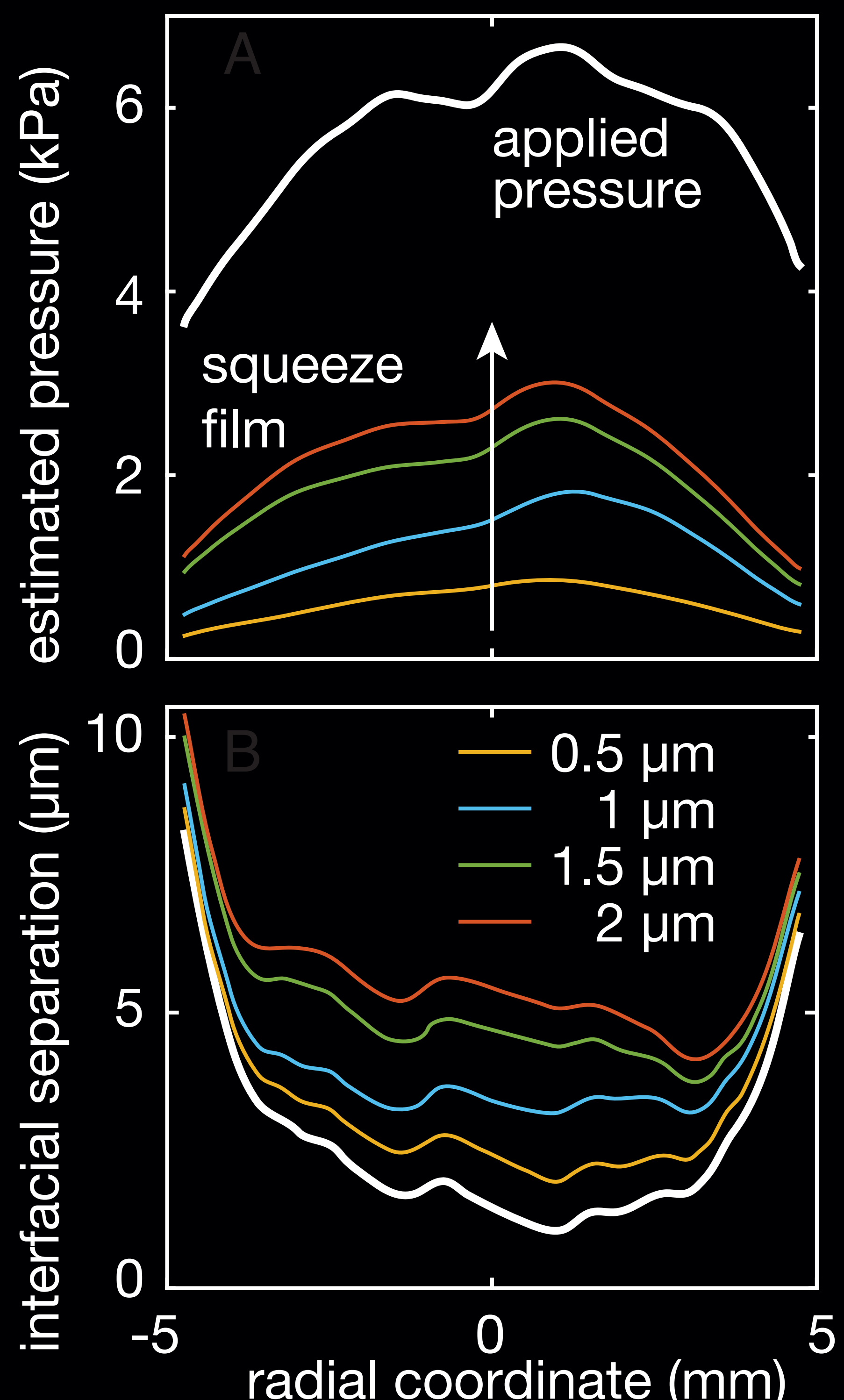
$$f_t = \tau_0 \, A$$

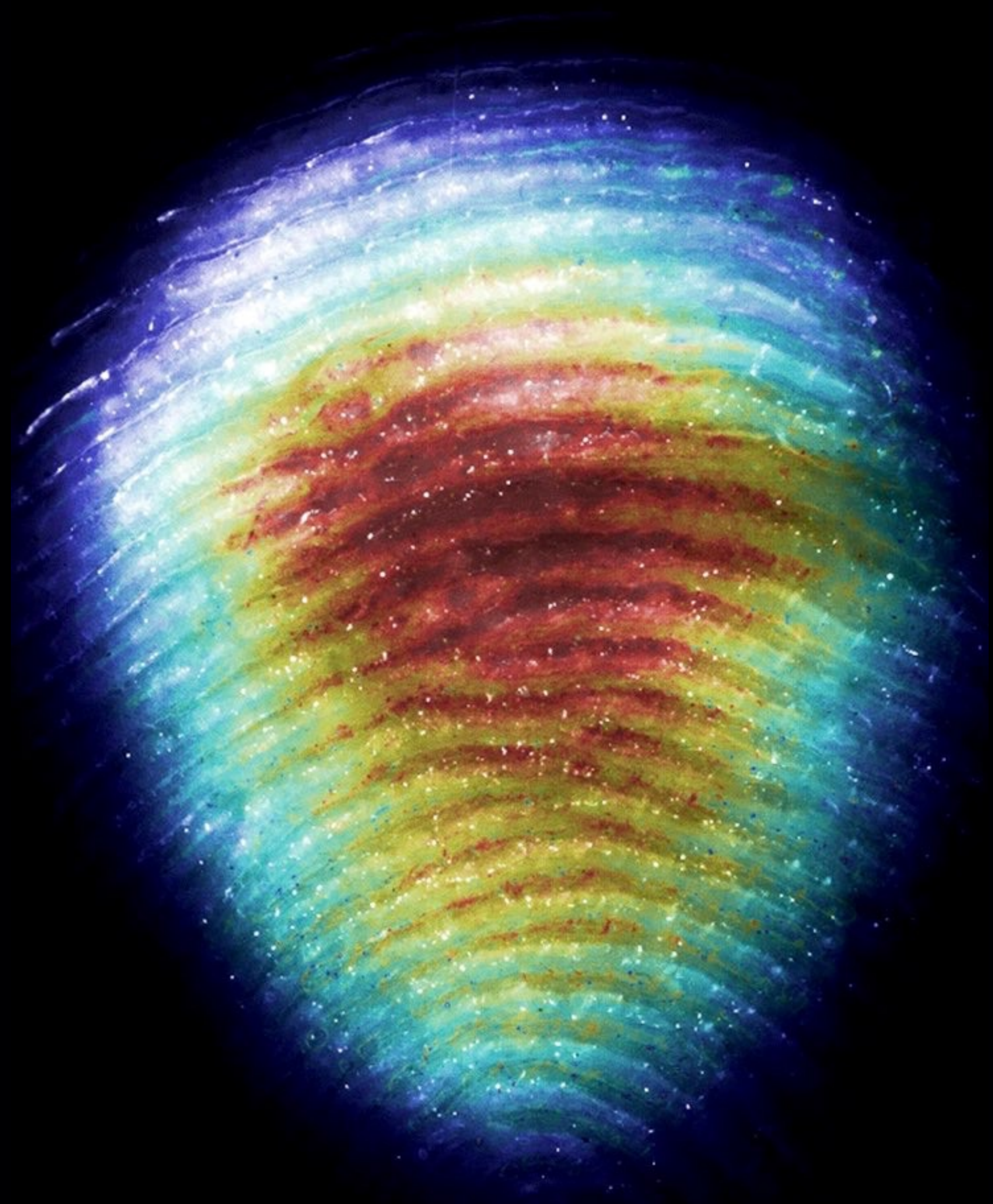
$$A = A_0 \, e^{\frac{-u+u_0}{u_{rms}}}$$

$$\approx A_0 \, e^{\frac{-\alpha^2}{2\Gamma}}$$



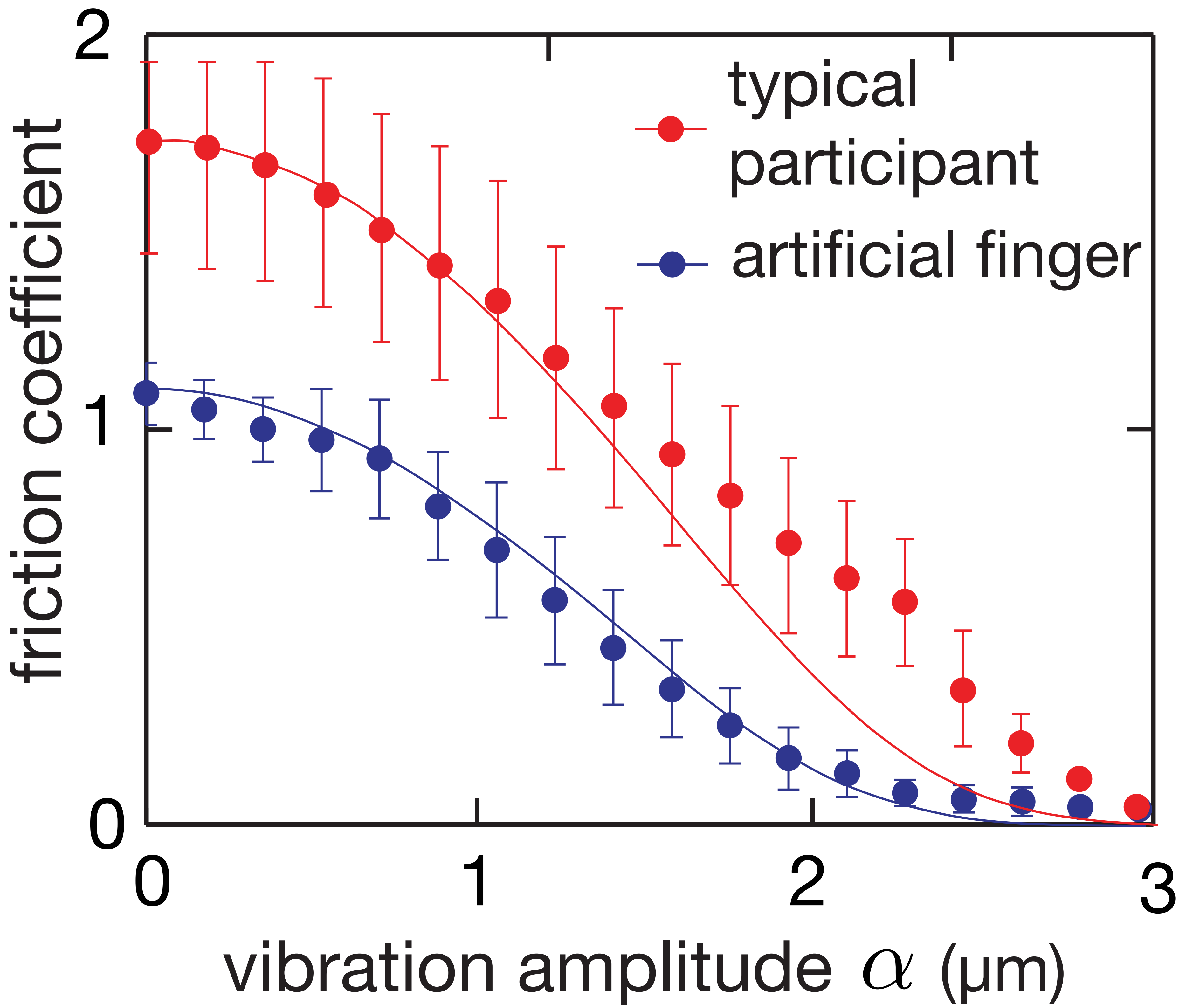
real area of contact





Wiertlewski, M., Fenton Friesen R., Colgate, E., PNAS 2016

model vs data



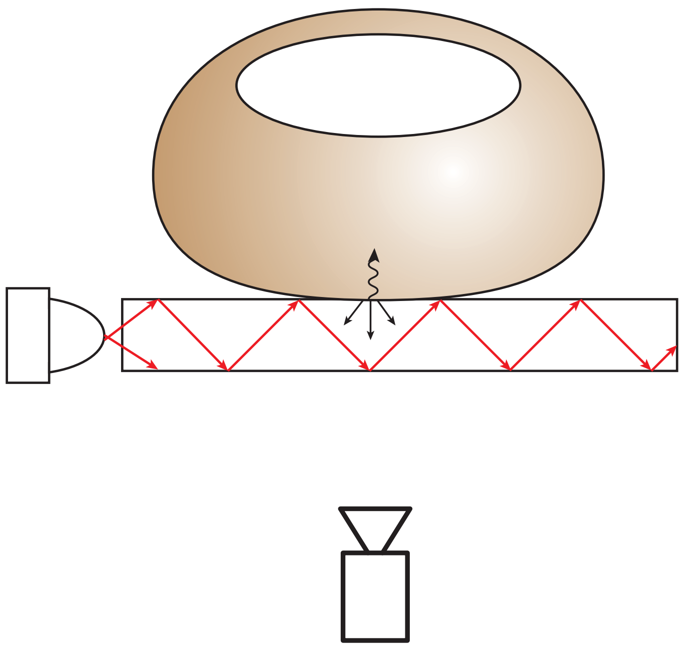
effect of moisture

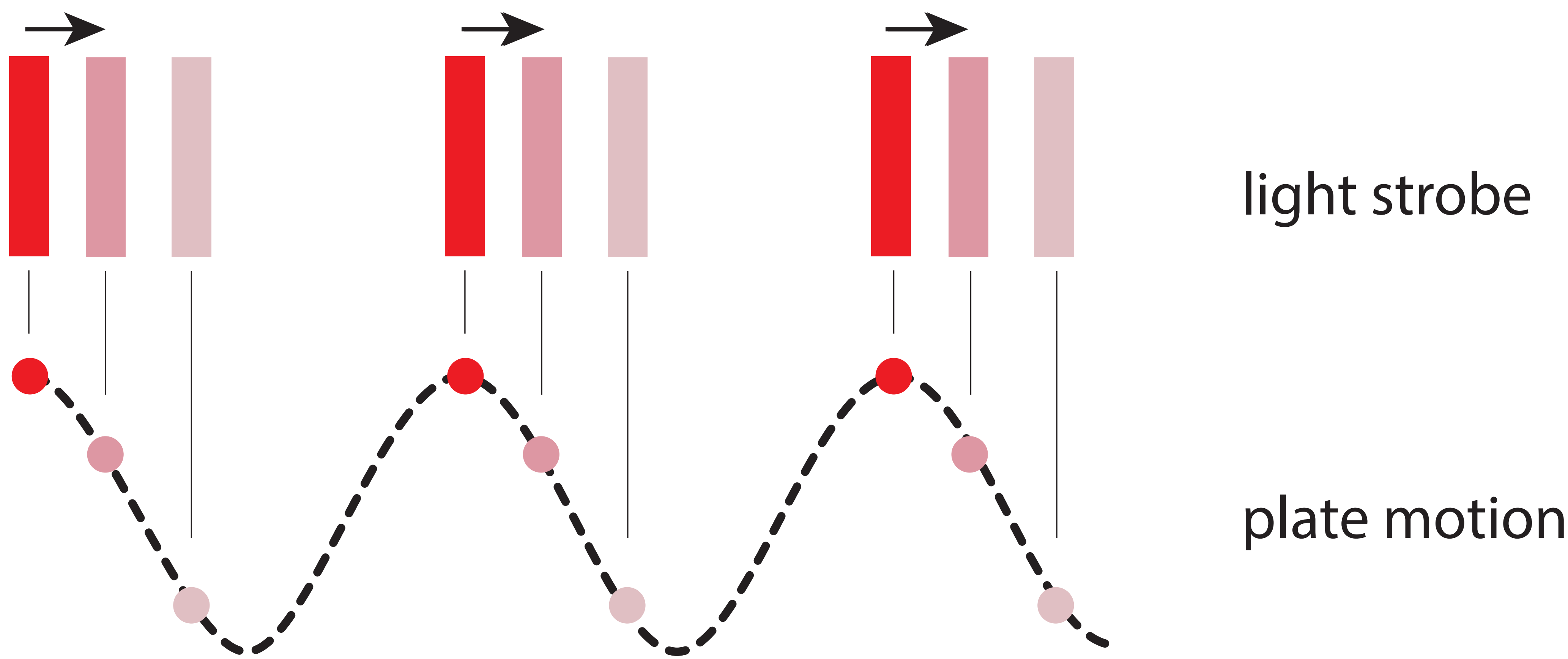
Adhesion from moisture

Squeeze film air pocket formation

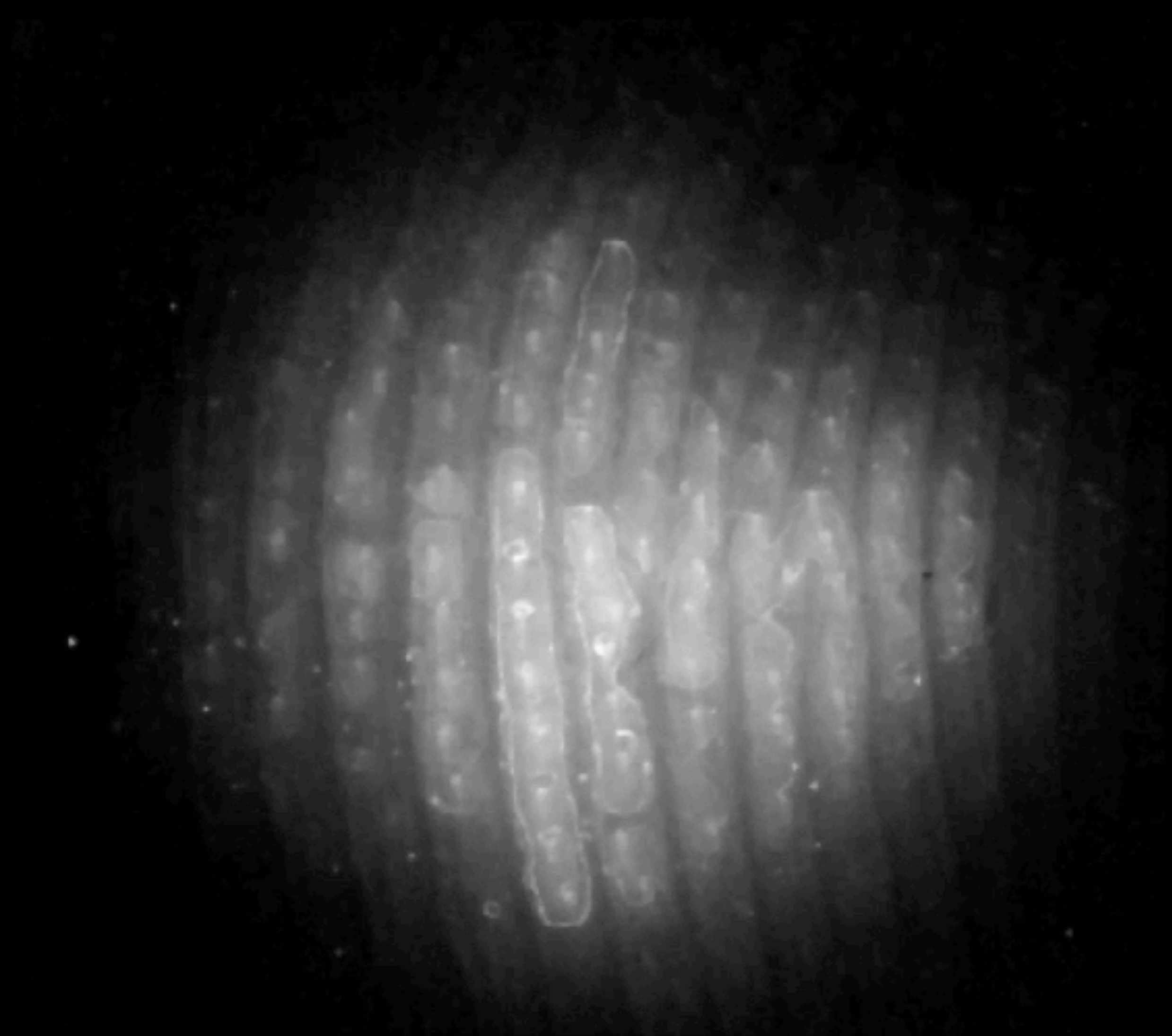
Amplitude ±2μm

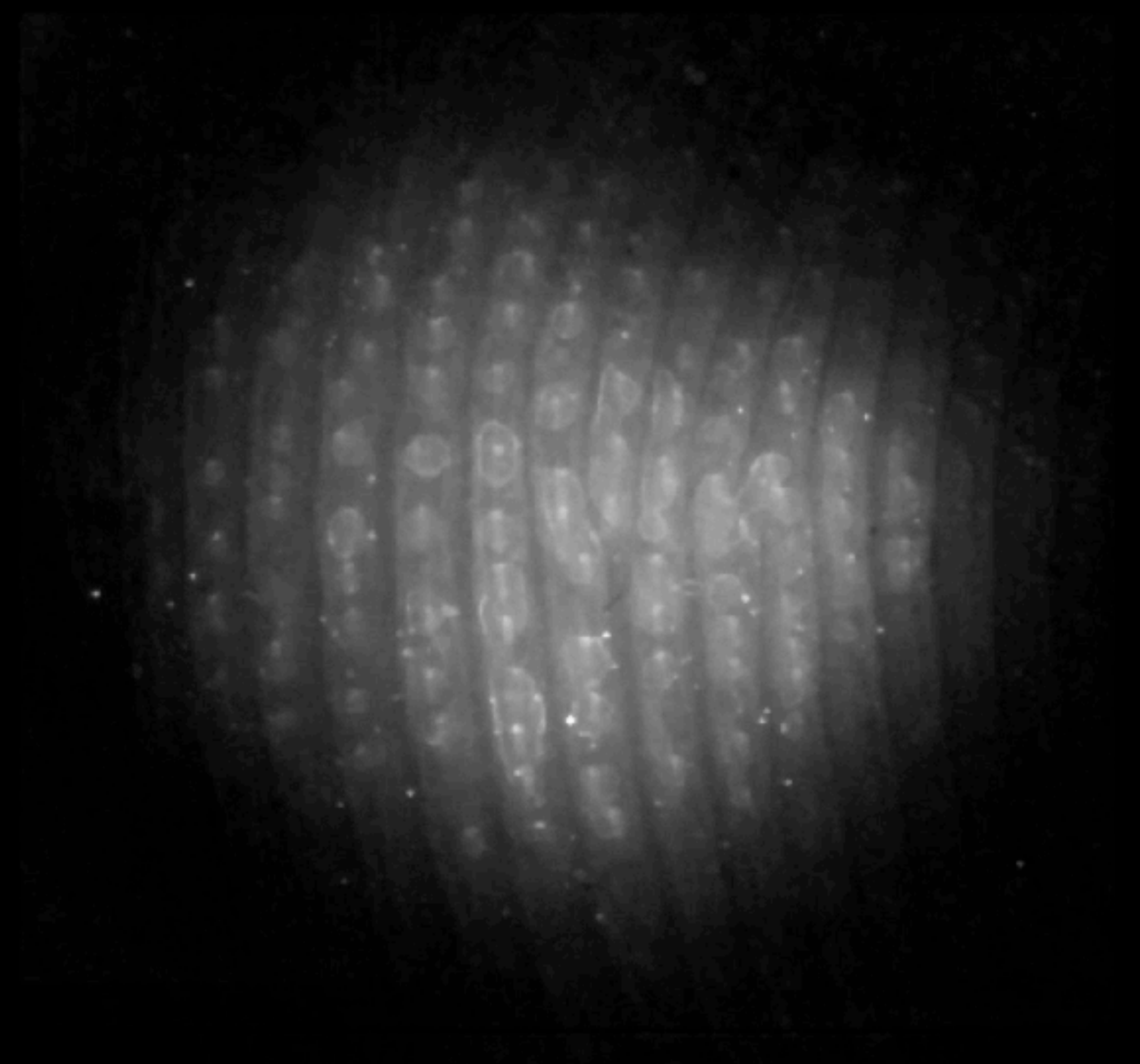
strobing





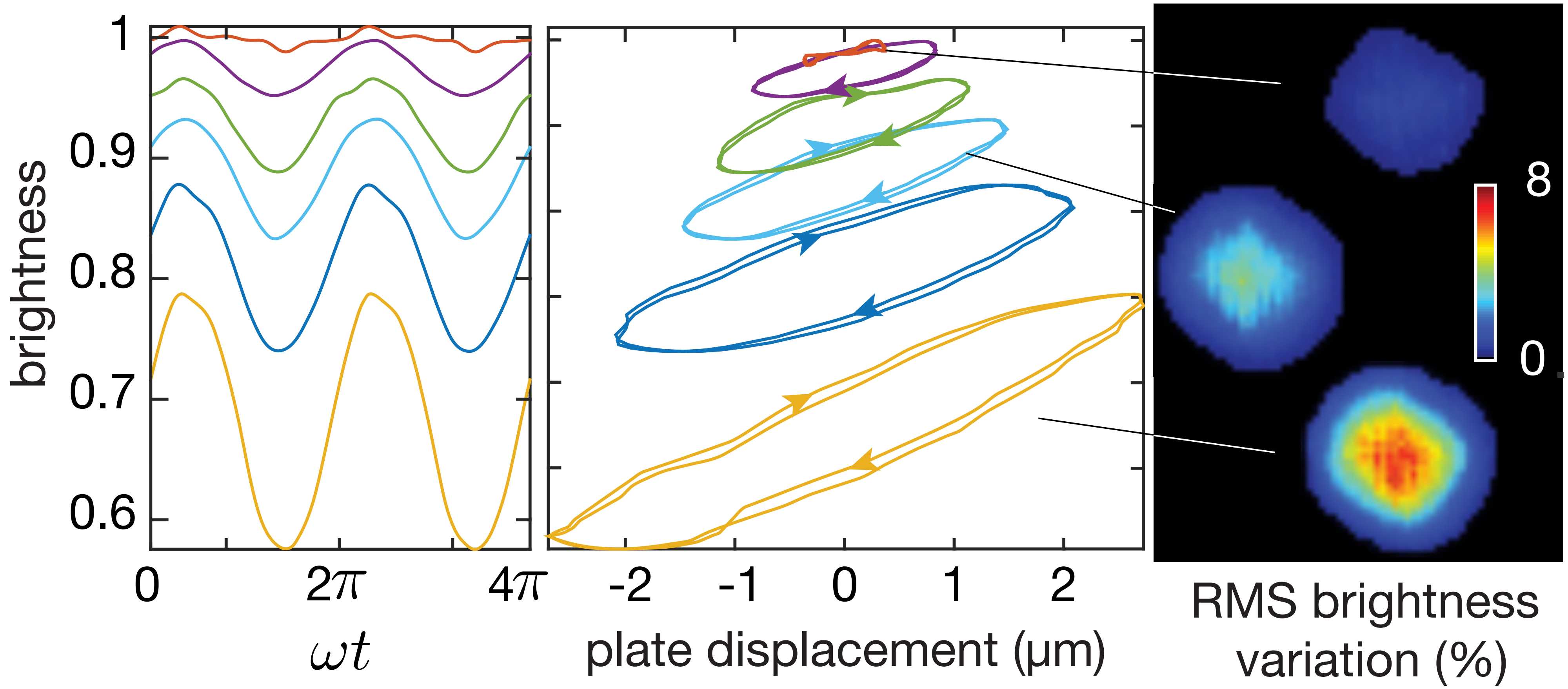
micro-second stroboscopy

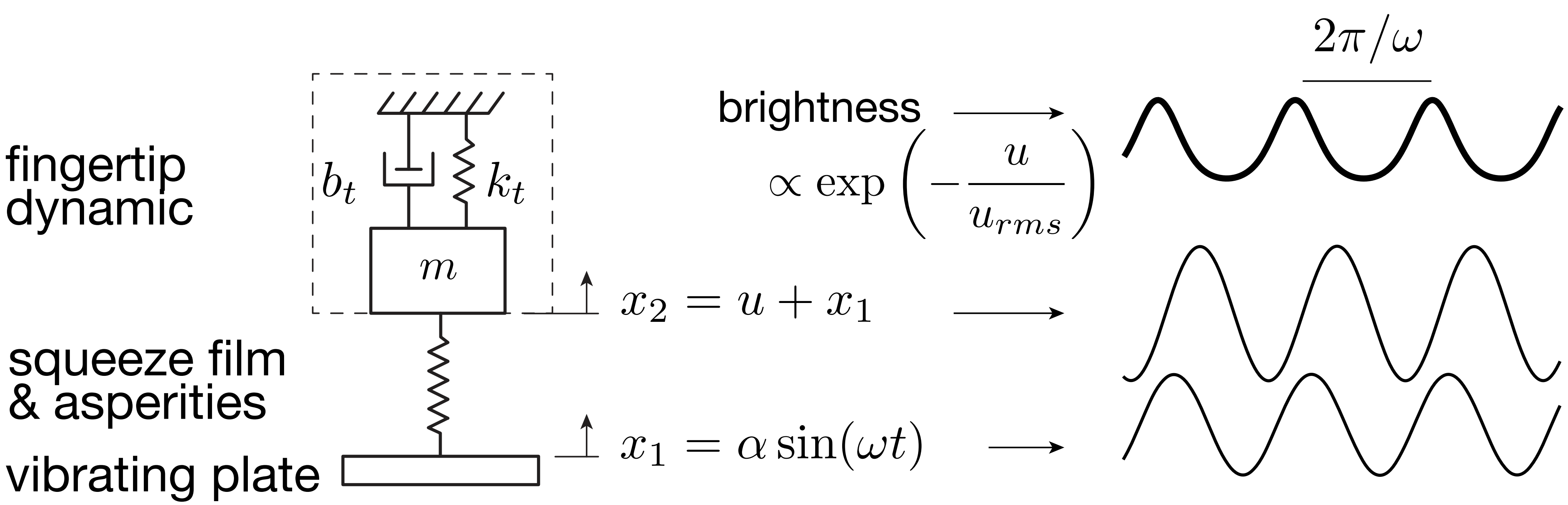




amplitude : **±1µm** **±2.5µm**

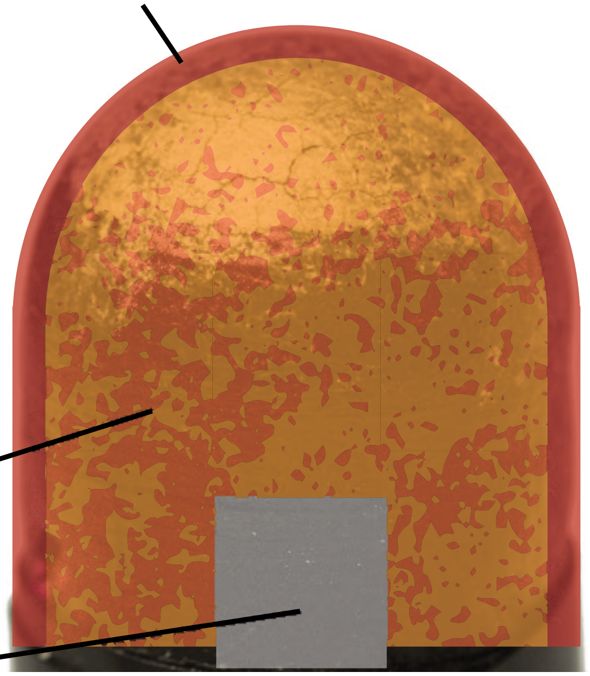
dynamic of the contact area





artificial fingers

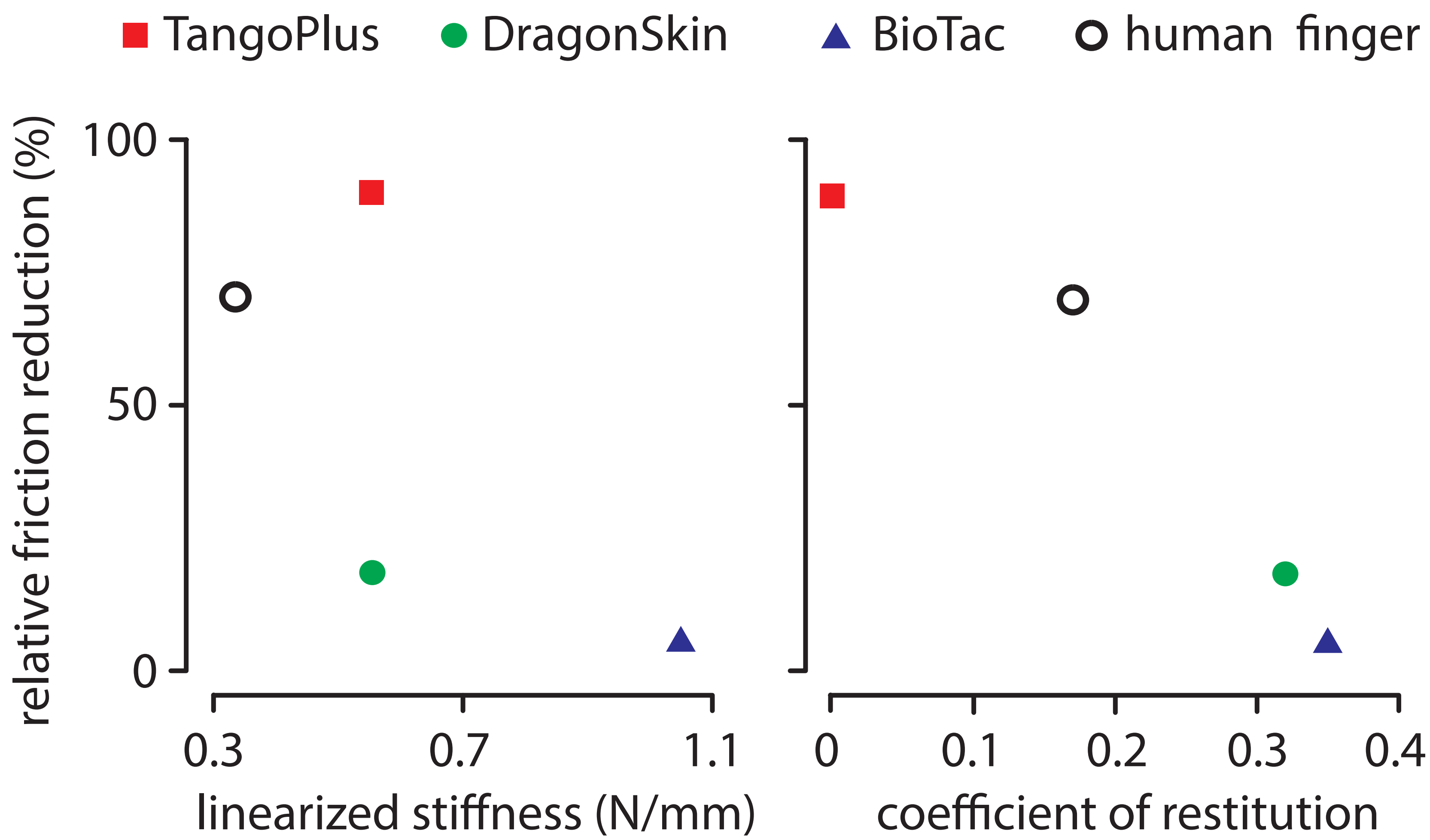
Rebecca
Fenton Friesen



Fenton Friesen R. Wiertlewski, M., Peshkin M.A, Colgate, E., Worldhaptics 2015

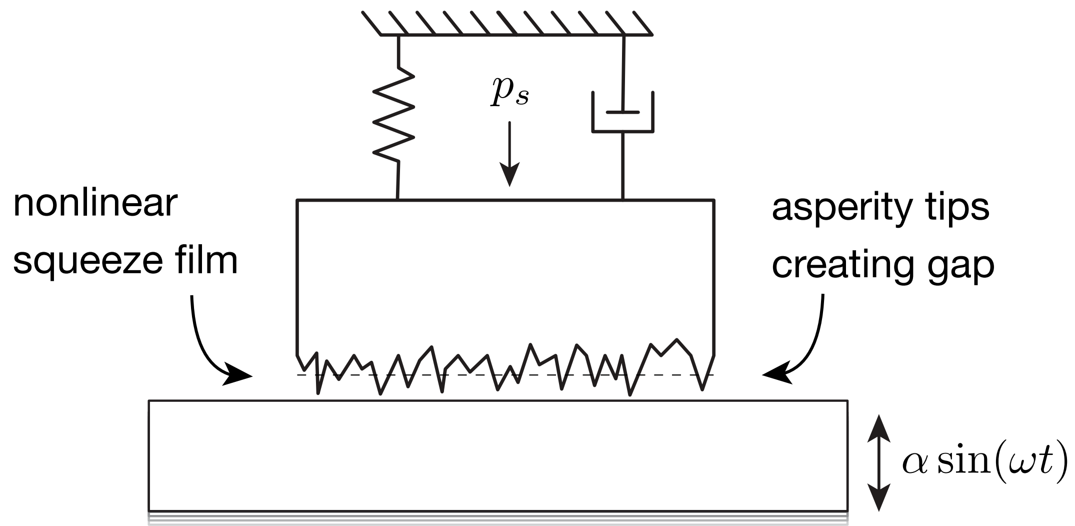
artificial fingers

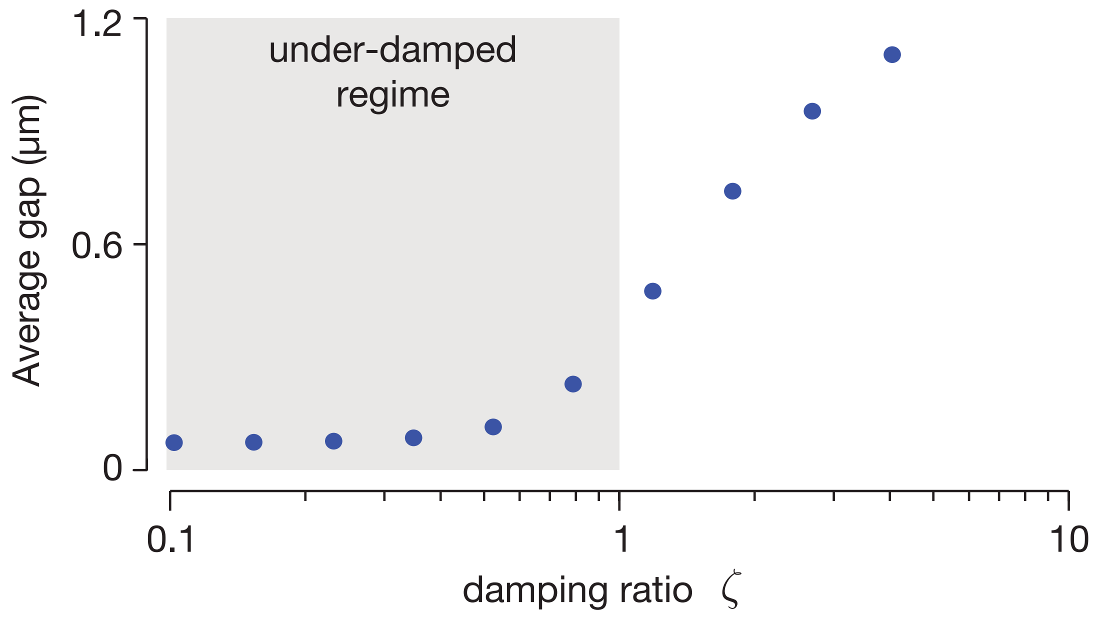
Rebecca
Fenton Friesen

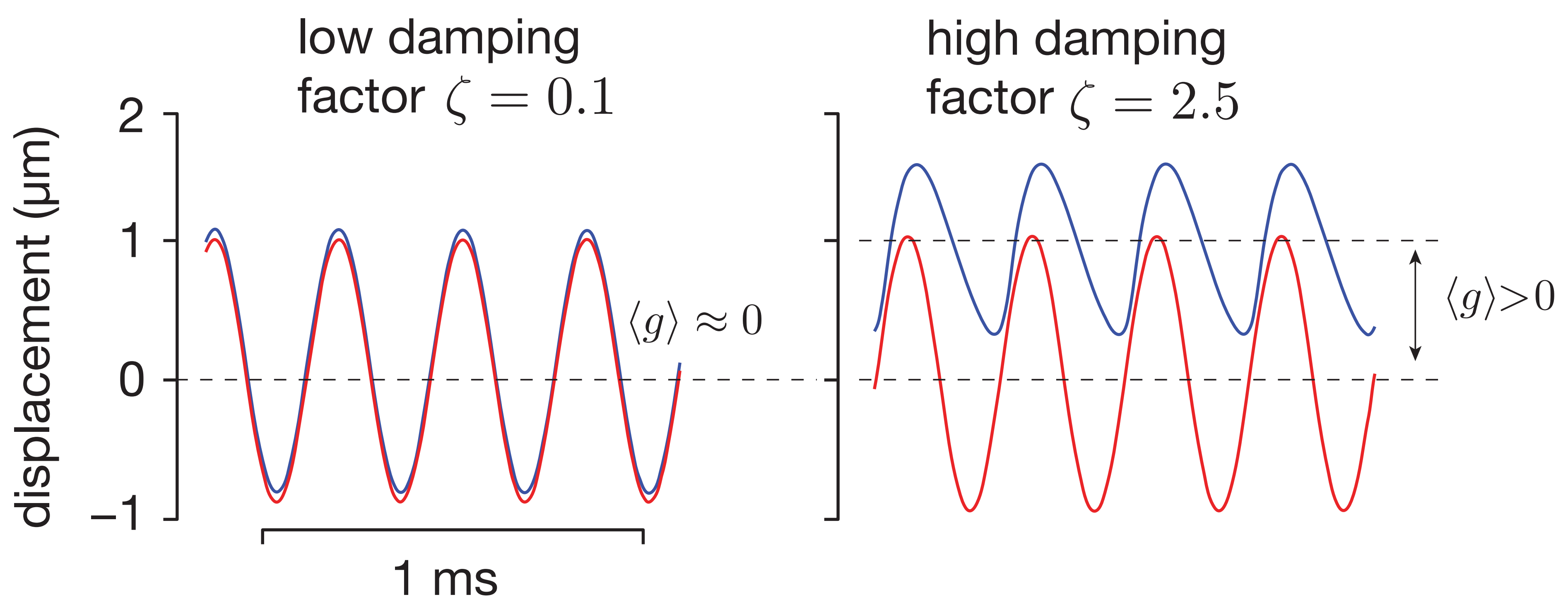


Fenton Friesen R. Wiertlewski, M., Peshkin M.A, Colgate, E., Worldhaptics 2015

influence of damping in the tissues

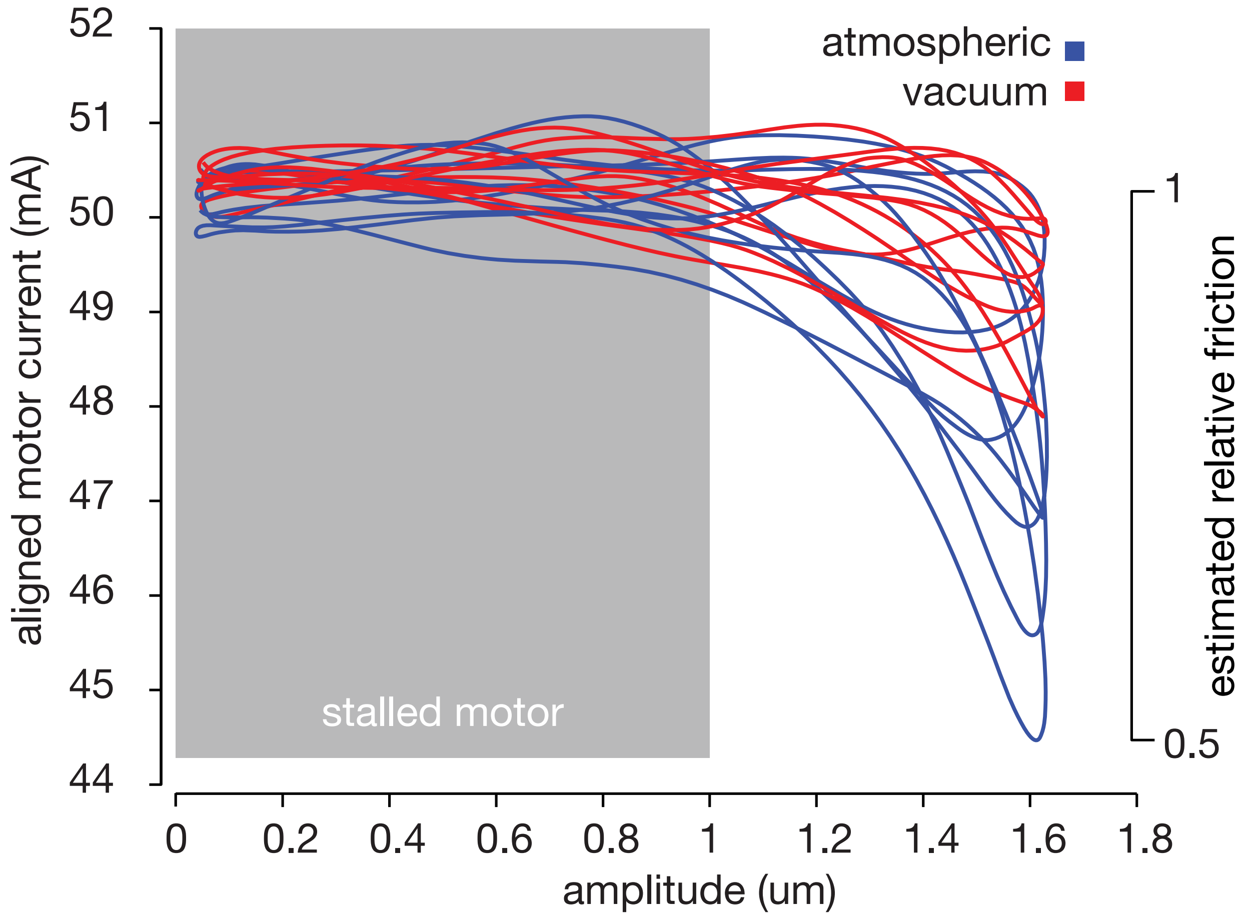


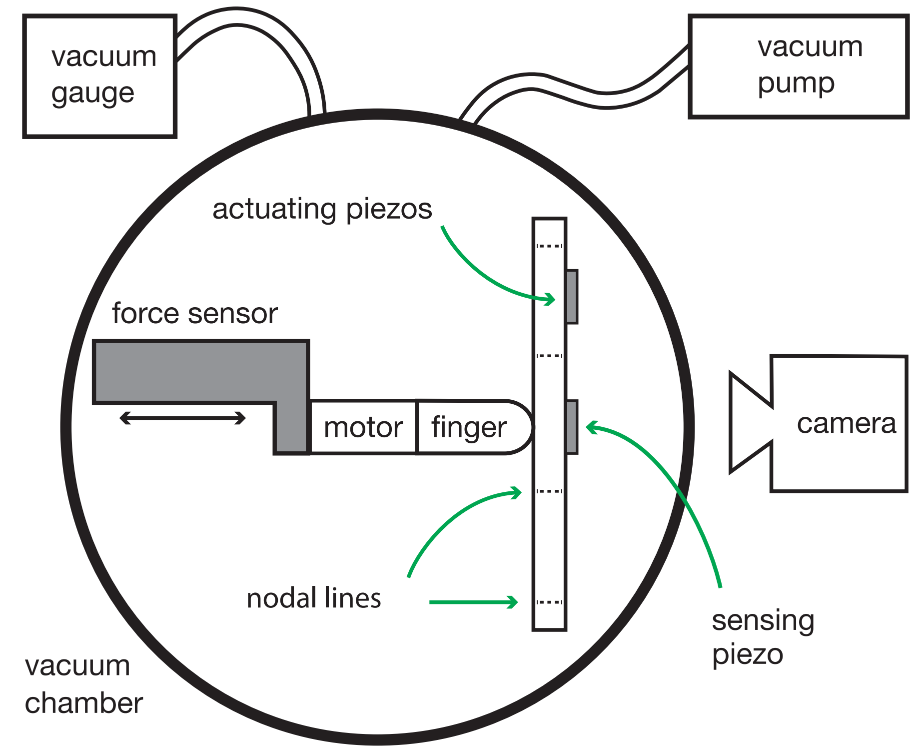


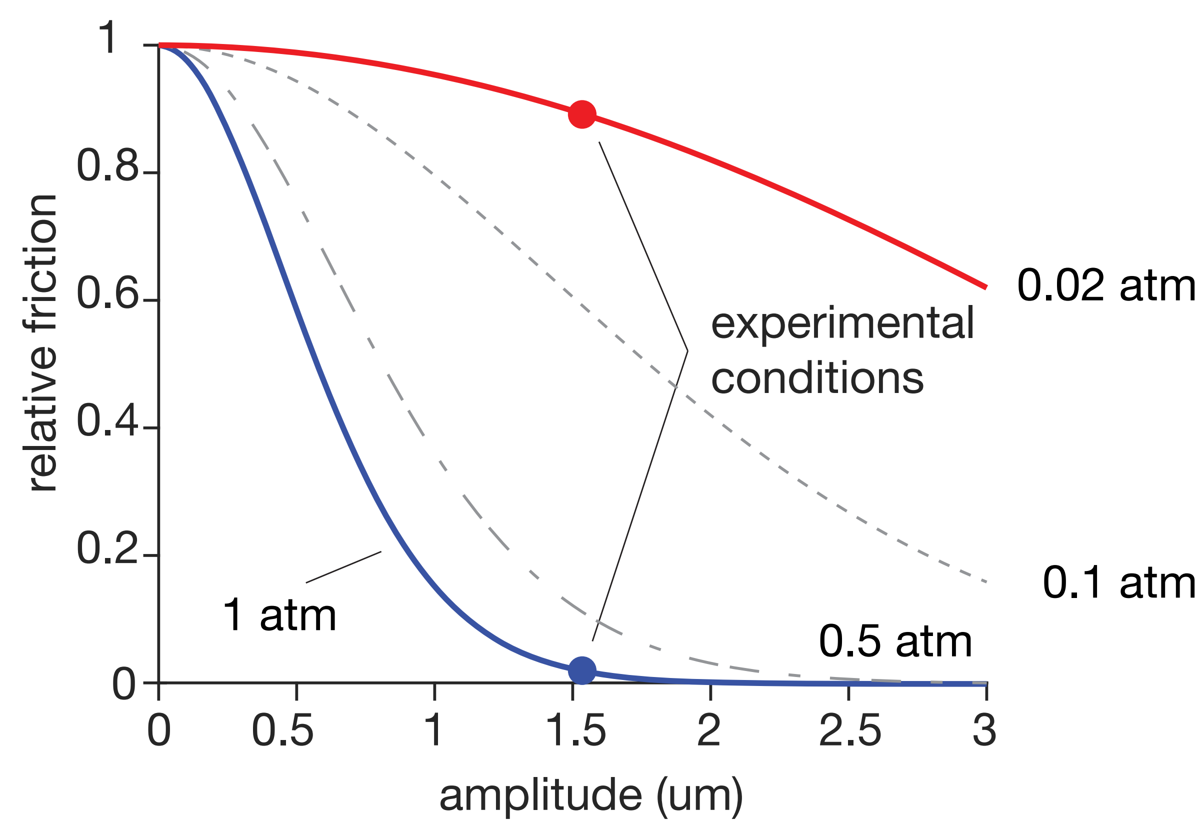


Fenton Friesen R. Wiertlewski, M., Colgate, E., Haptic Symposium 2016.

friction modulation under vacuum

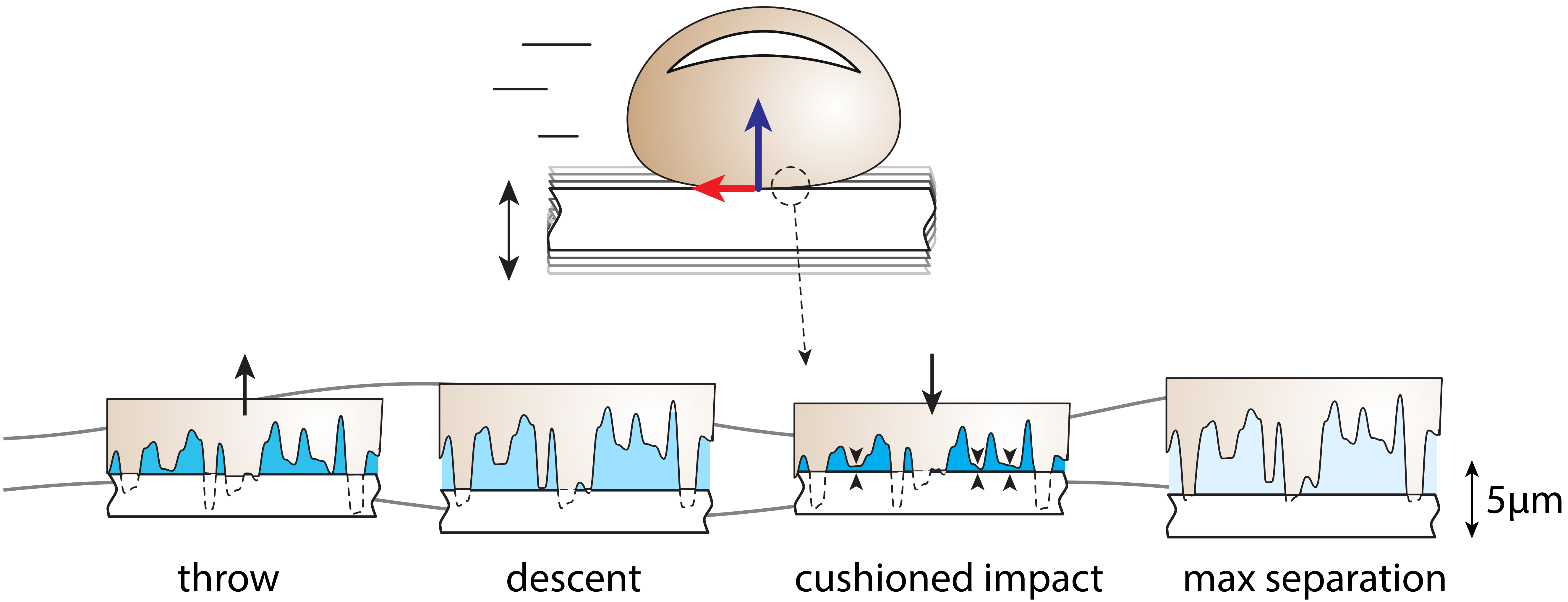


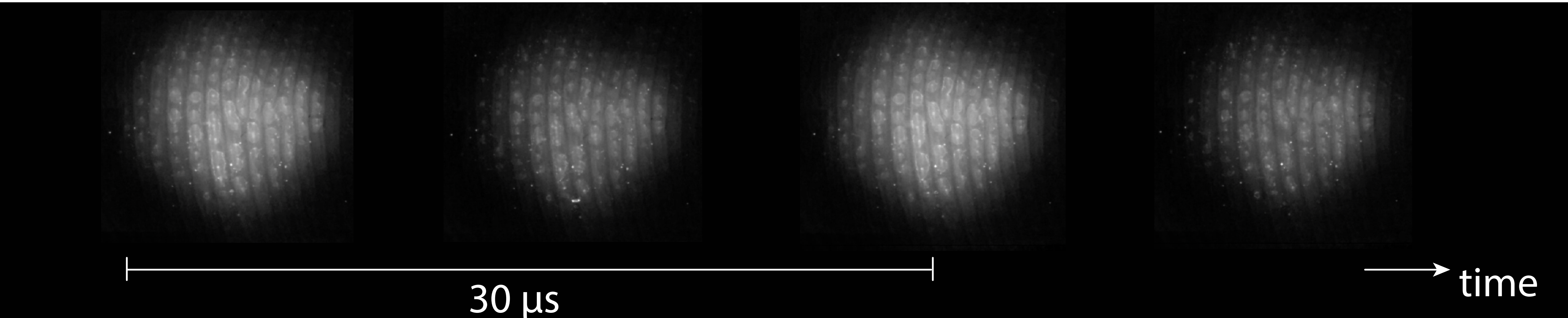




Fenton Friesen R. Wiertlewski, M., Peshkin M.A, Colgate, E., Worldhaptics 2017

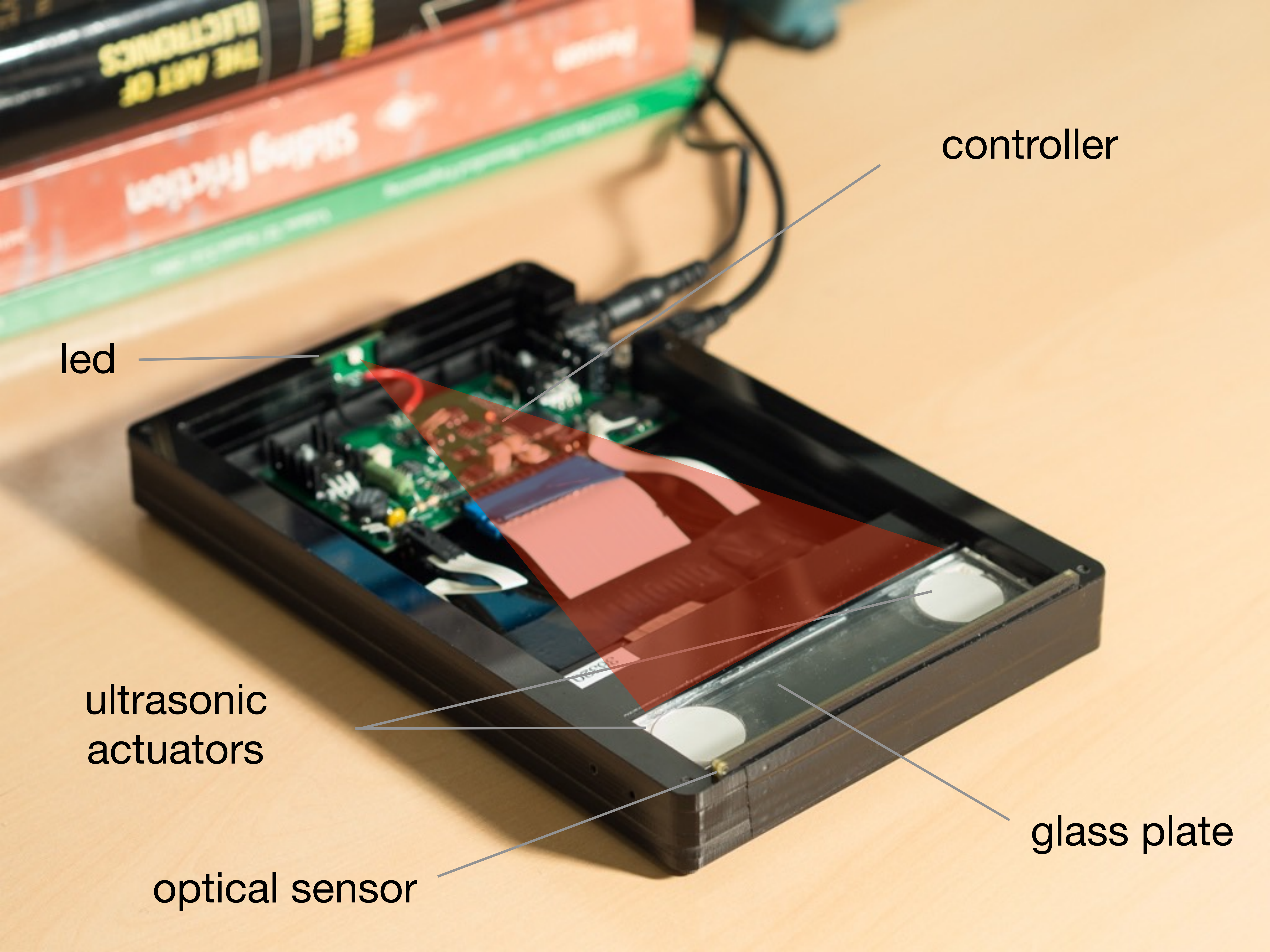
lastest hypothesis : partial levitation



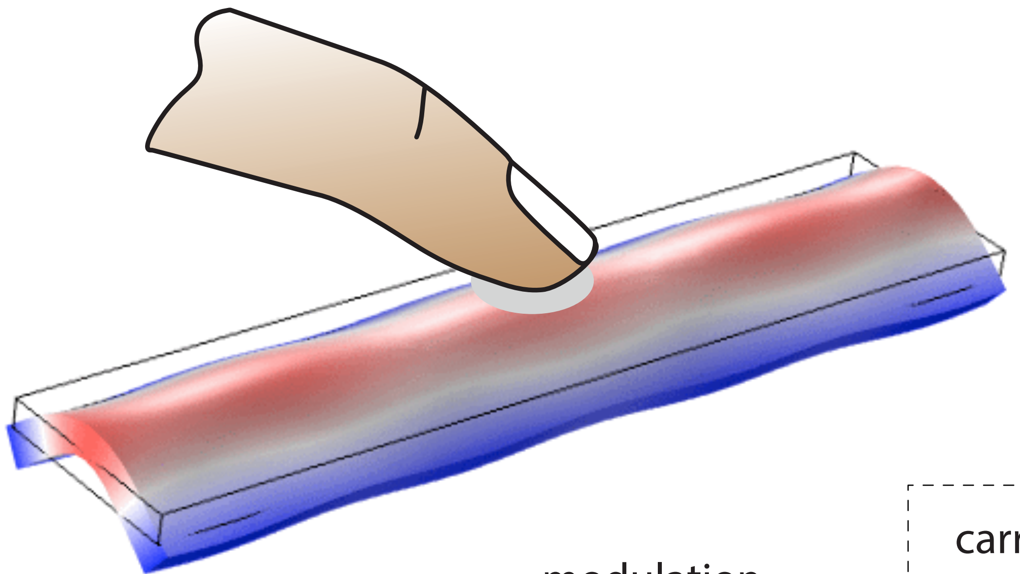


what can we do with it?


THE ART OF
ELECTRONICS
Sliding Friction

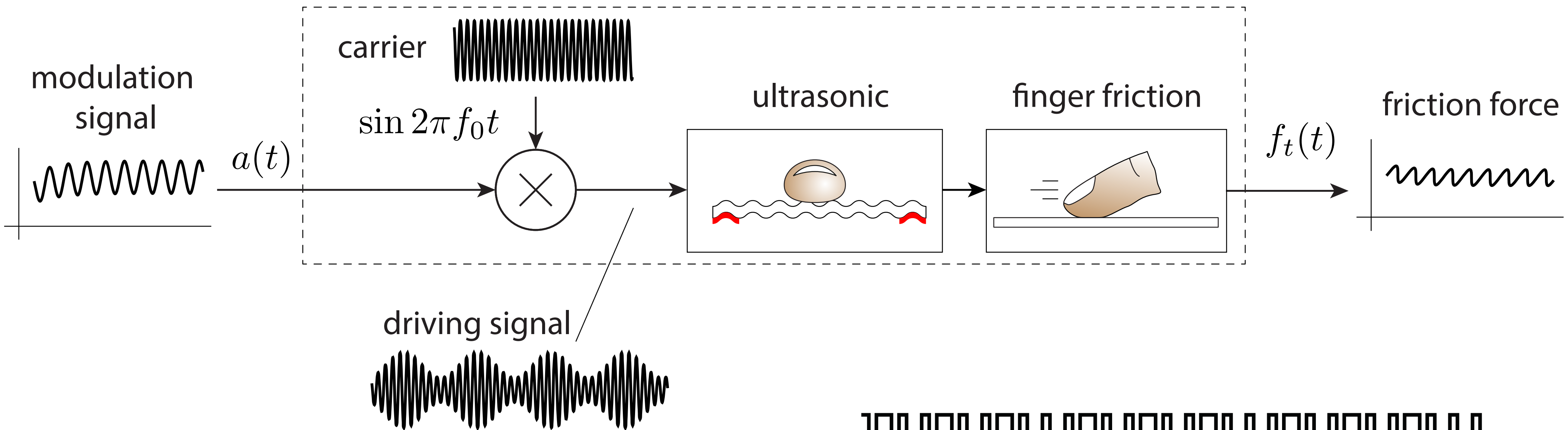

controller
led
ultrasonic
actuators
glass plate
optical sensor

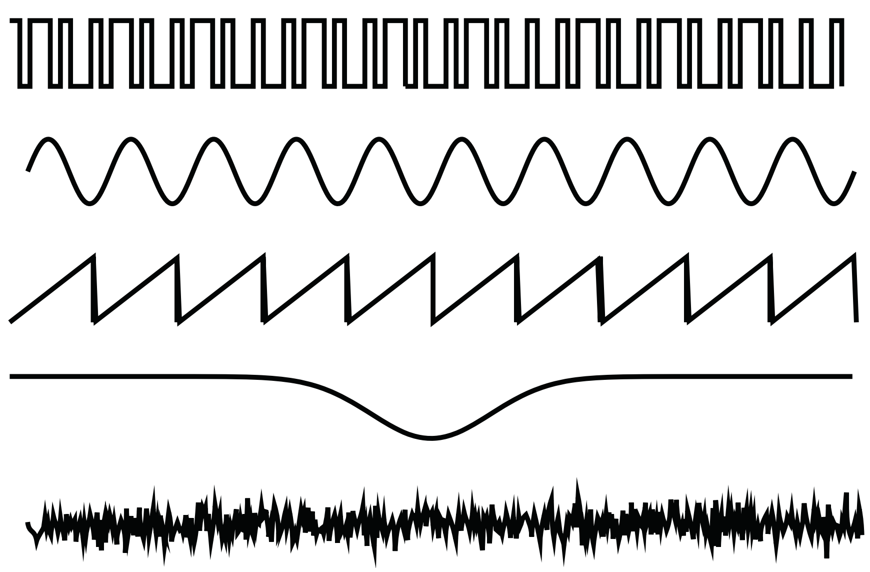
high-fidelity rendering



David Meyer

Daniele Leonardis

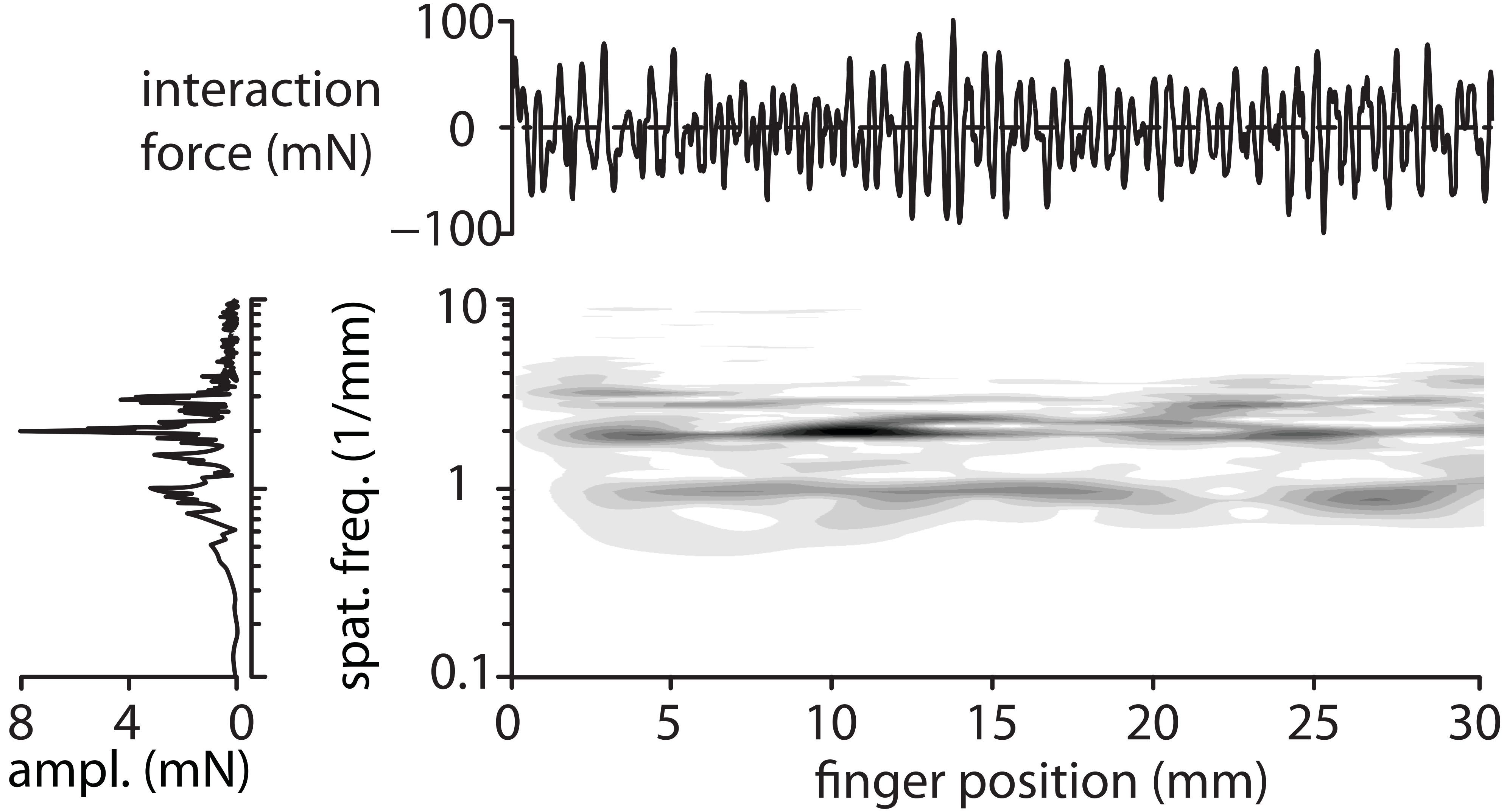


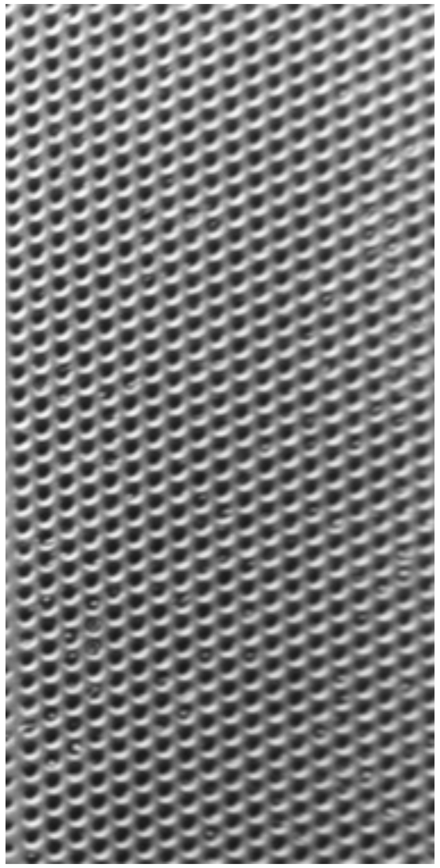


- fast non-contact position sensor (8 μm - 5 kHz)
- 6.25 points per cycle with v_c = 250mm/s
- 12 bit dac and linear amplifier
- compensation filters

Wiertlewski, M., Leonardis D., Meyer, D., Peshkin, M., Colgate, E., Eurohaptics 2014.

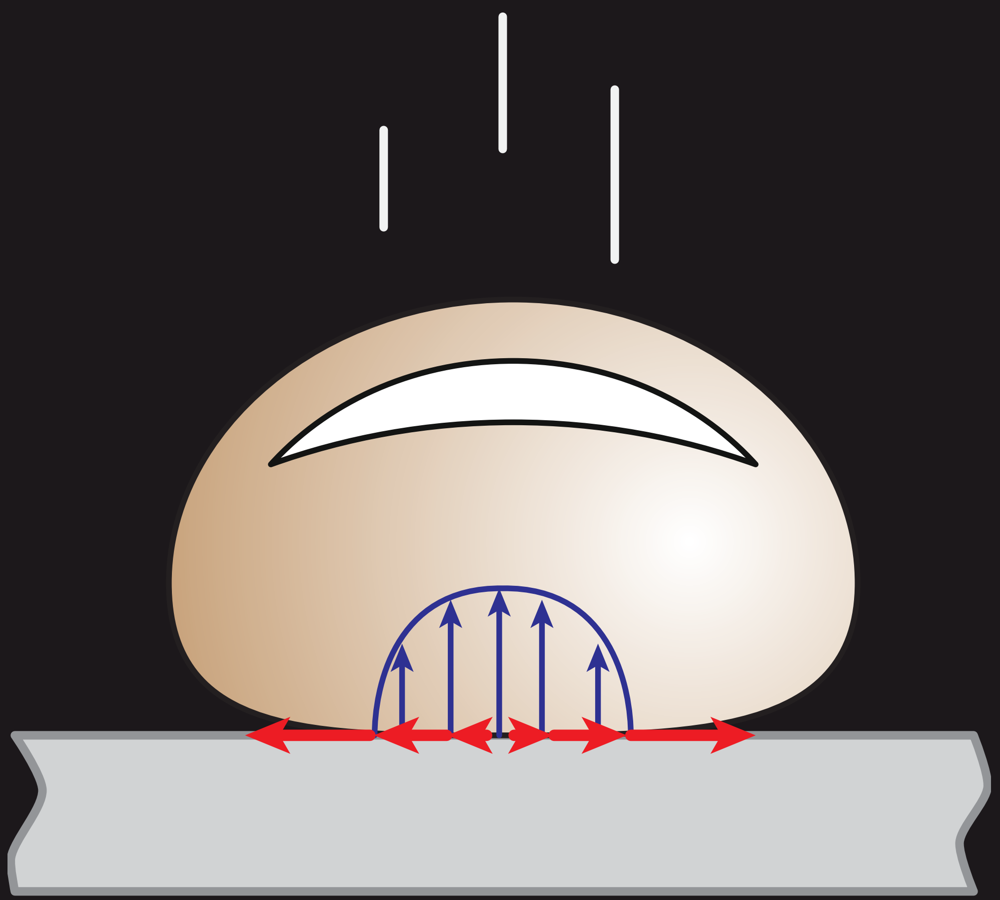
vibration of texture





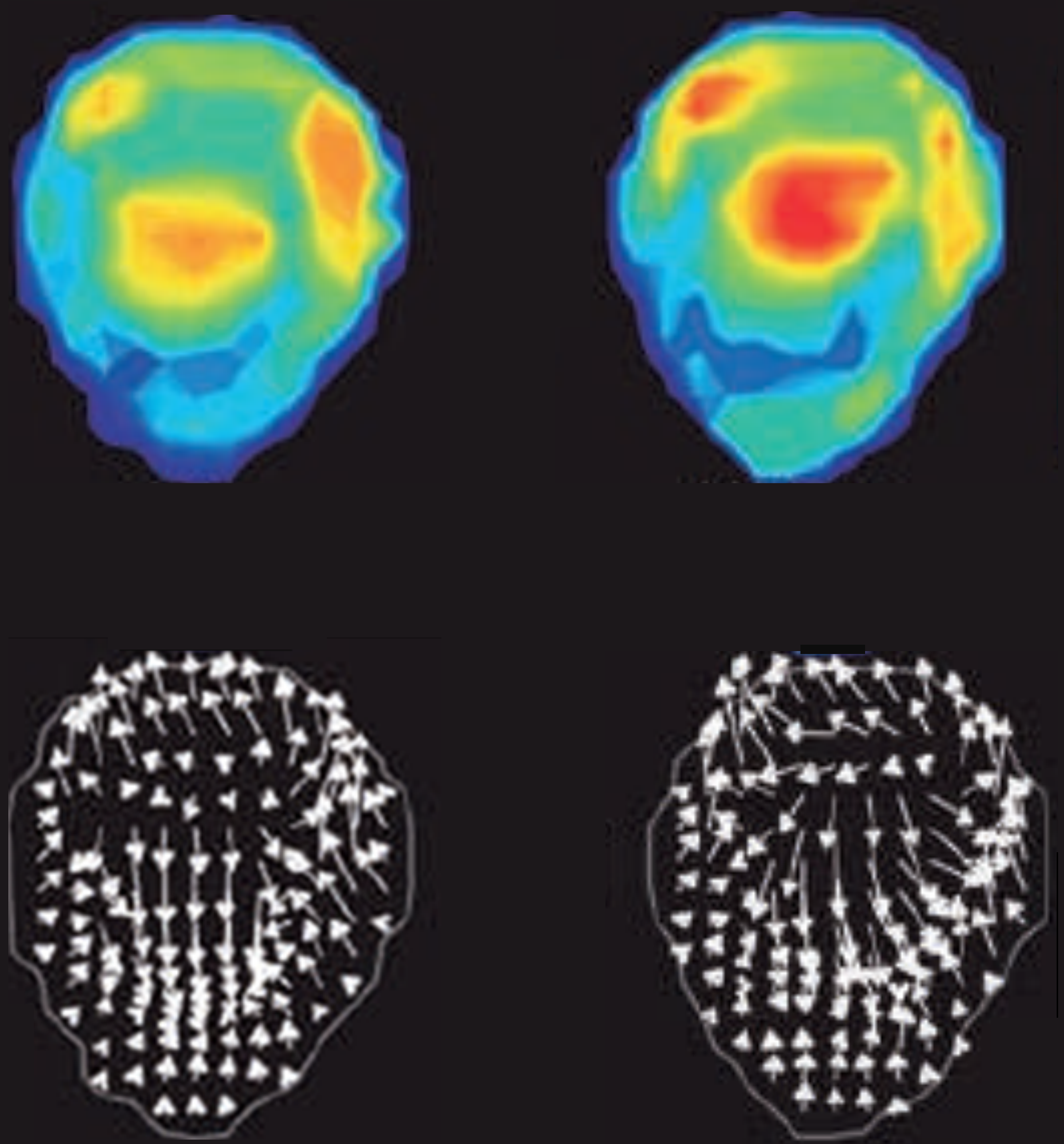
Wiertlewski, M., Lozada,J., Hayward, V. IEEE Transactions on Robotics, 2011

normal force modulation



low friction

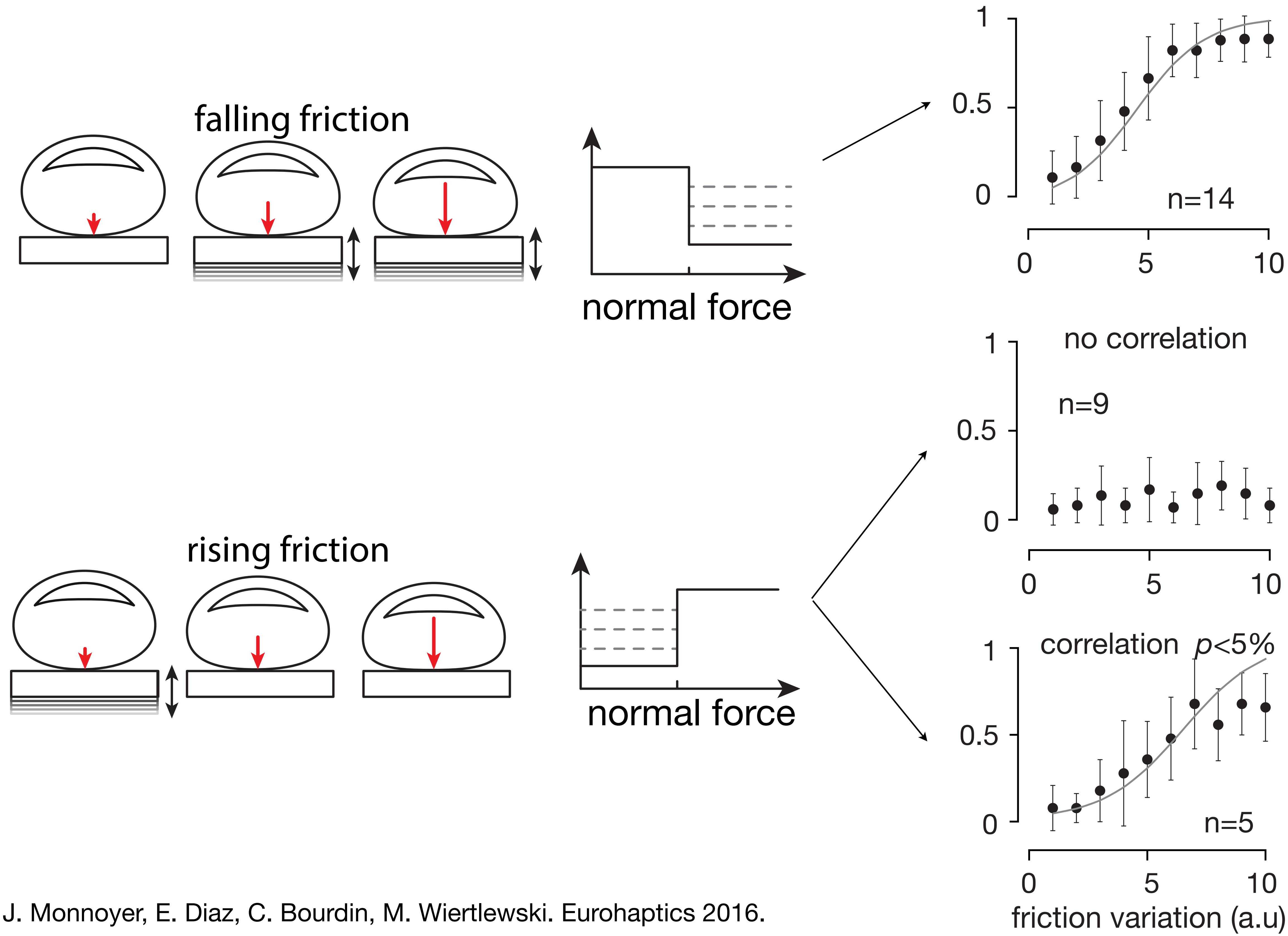
high friction



Johansson & Flanagan 2009

J. Monnoyer, E. Diaz, C. Bourdin, M. Wiertlewski. Eurohaptics 2016

normal force modulation

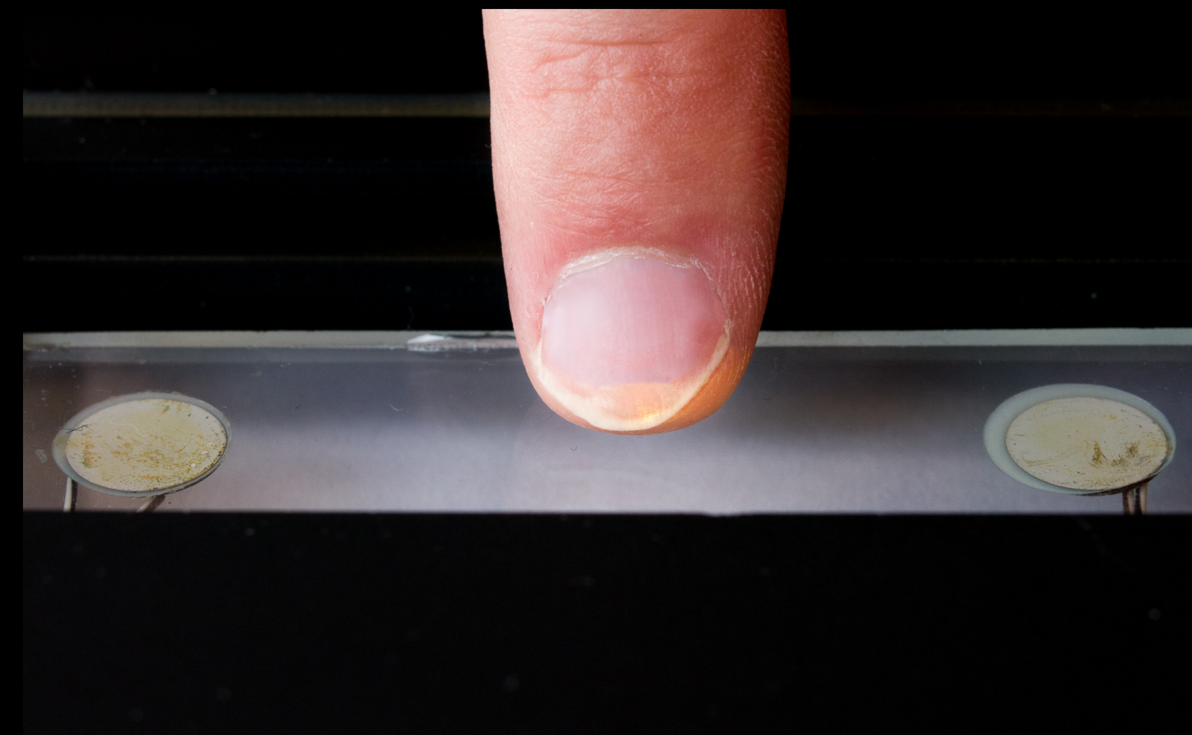


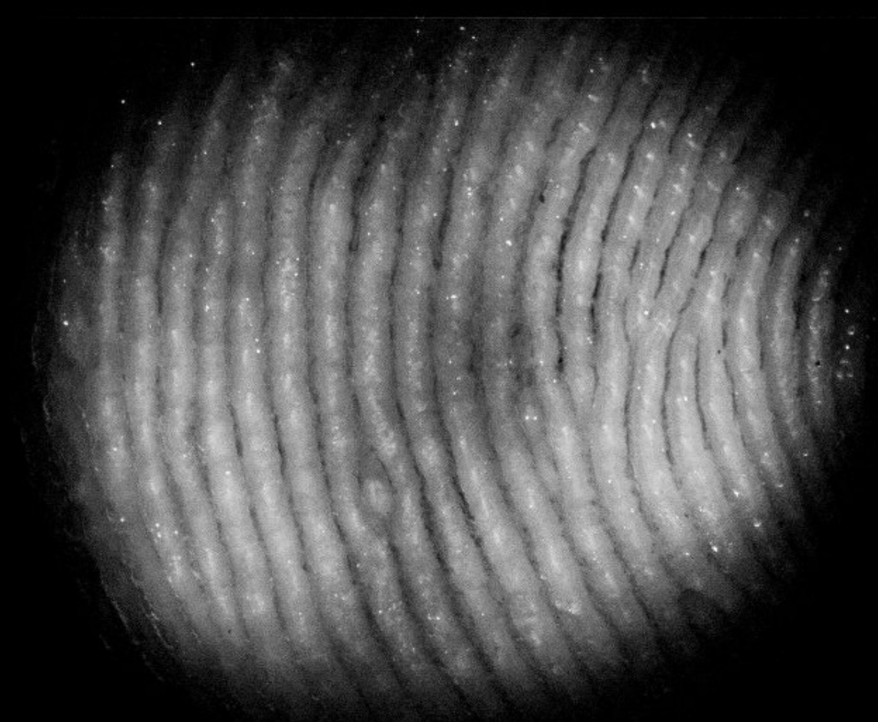
Jocelyn Monnoyer

J. Monnoyer, E. Diaz, C. Bourdin, M. Wiertlewski. Eurohaptics 2016.

conclusion

- Friction carries rich tactile information
- Multi-scale model is useful to capture the behavior of ultrasonic levitation
  - ongoing work to understand sliding friction force fluctuations
- *in vivo* friction is messy
  - large variability
  - multi-physics





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