Key Barriers to Haptic Intelligence in Robotics

Katherine J. Kuchenbecker, Ph.D.
Mechanical Engineering and Applied Mechanics,
Computer & Information Science, Electrical & Systems Engineering, and Bioengineering
Haptics Group, GRASP Laboratory
University of Pennsylvania

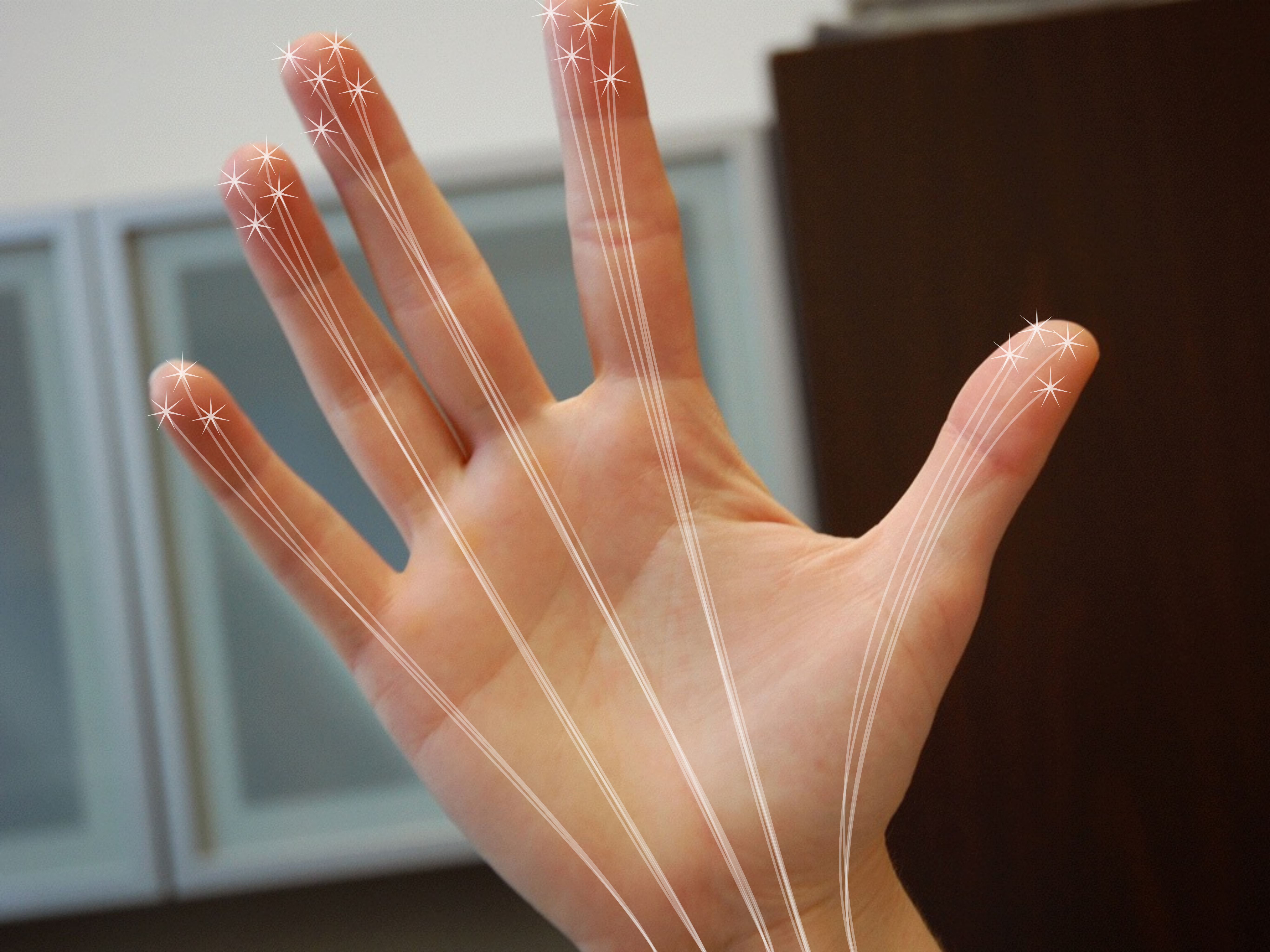
Penn Haptics

https://flic.kr/p/8XYzPQ


https://flic.kr/p/9i4vFj

Can you light a match
with **numb** fingers?


KOMET
KOMET



Haptics

the scientific study of human and robot interaction with physical objects through the sense of touch


Penn
Haptics
GRASP
LABORATORY


motor
Penn
Haptics

Both robotic **locomotion** and robotic **manipulation** systems would benefit from improvements in **haptic intelligence**.

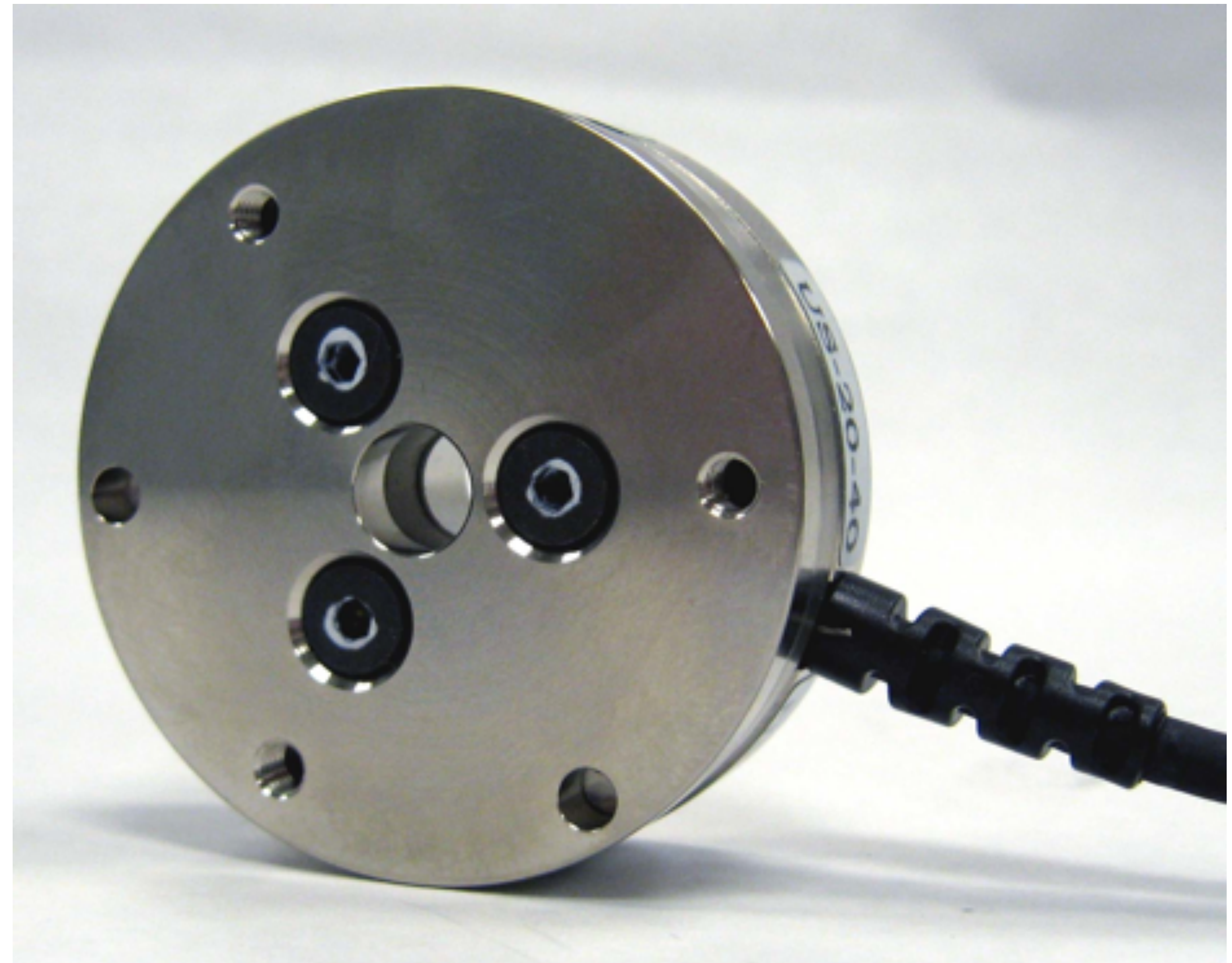
Why don't all modern robots incorporate rich **haptic sensing**?

beyond force

dig deeper

feel with the eyes

haptics $\overset{>}{\neq}$



expensive

delicate

series mounting

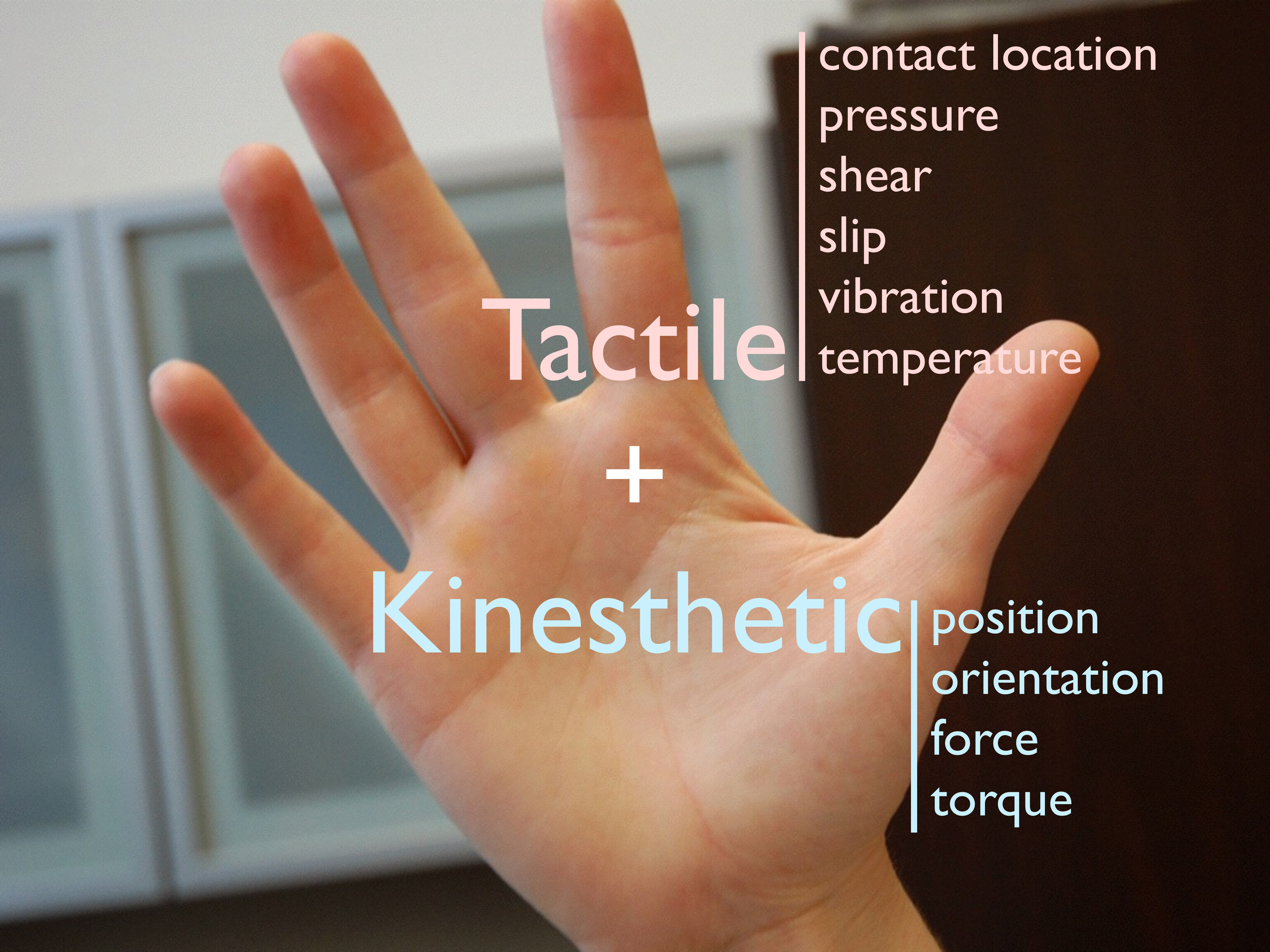
We need to think beyond the force sensor to include tactile cues.

robotic surgery

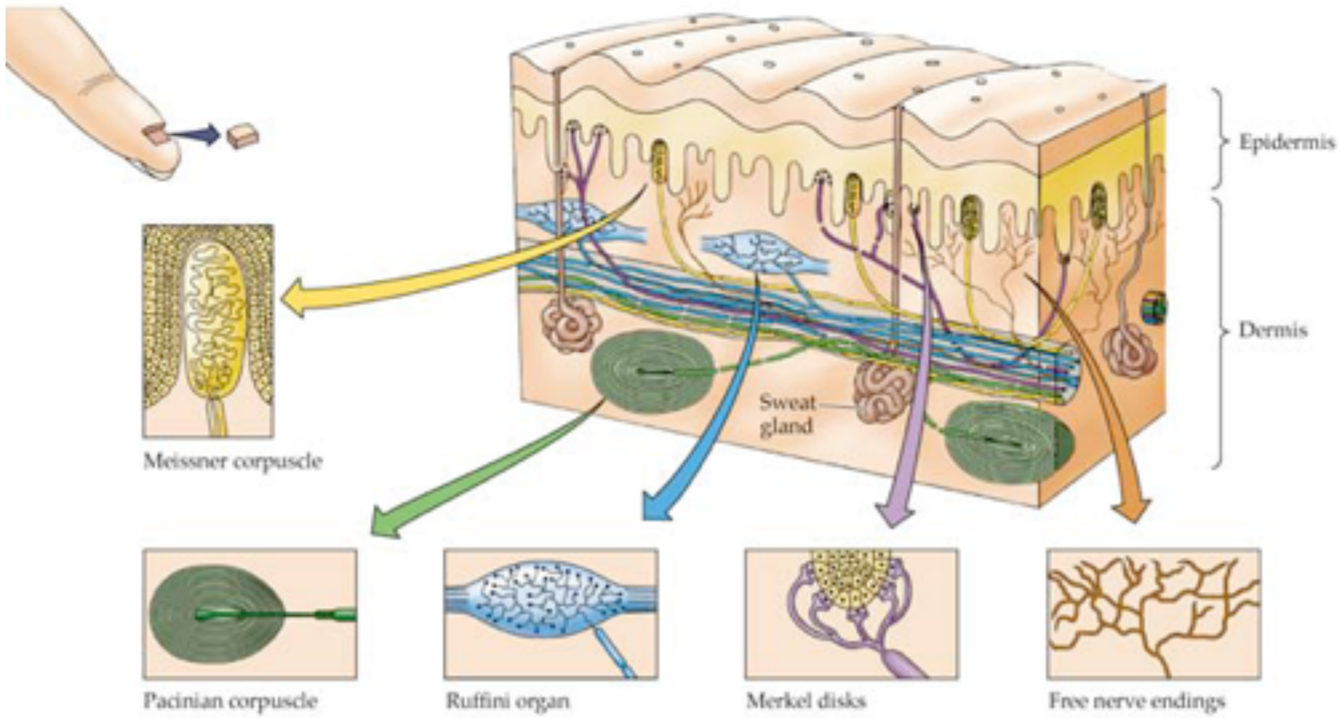
da Vinci Standard robot by Intuitive Surgical, Inc.

Excellent visualization and dexterity...

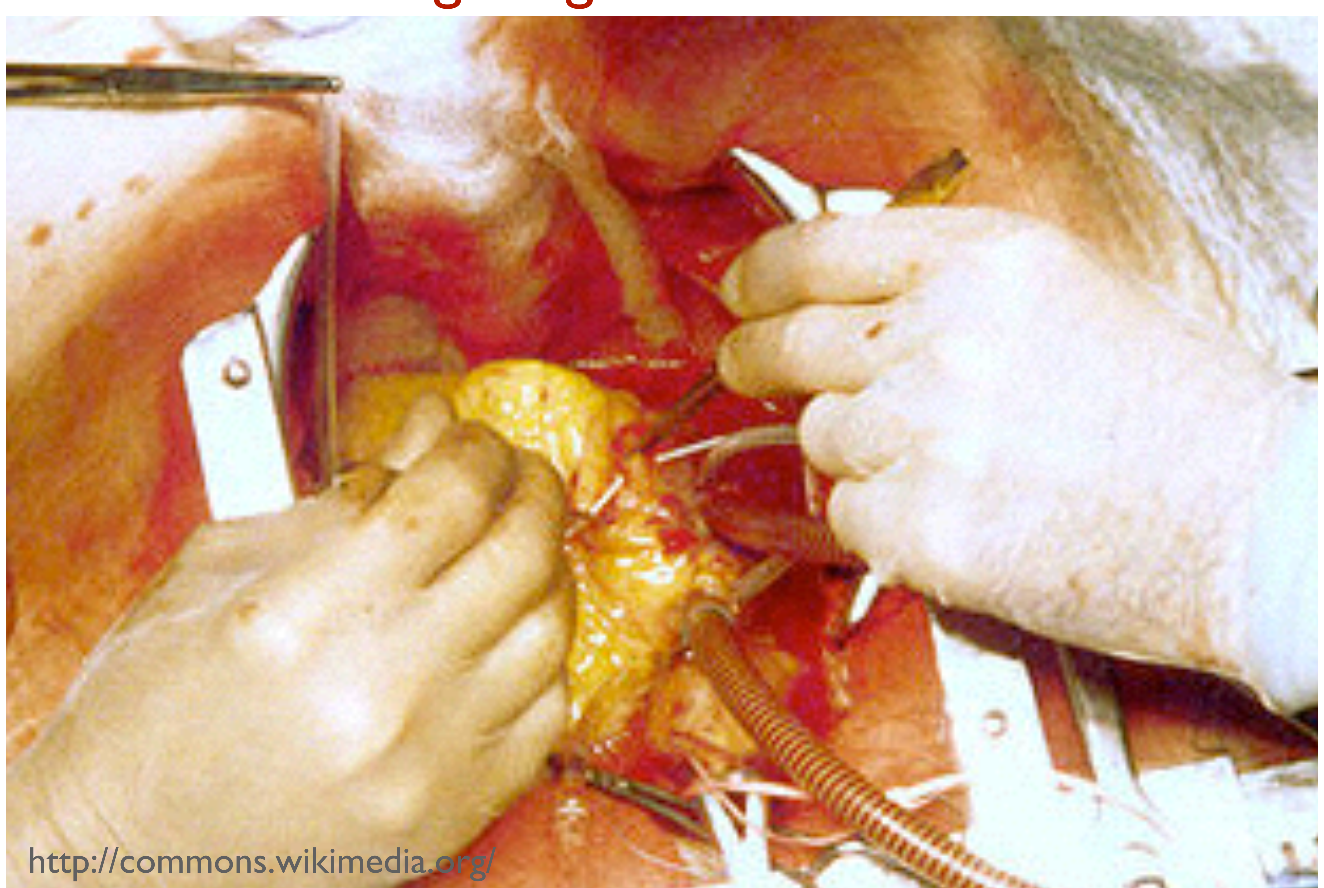
...but you cannot feel what the tools are touching.

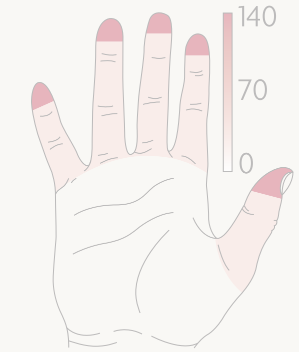
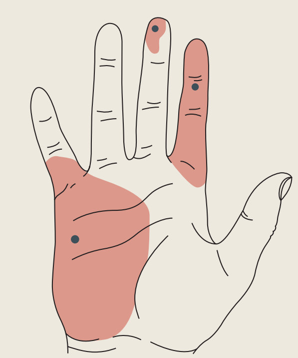

Tactile
contact location
pressure
shear
slip
vibration
temperature
+
Kinesthetic
position
orientation
force
torque

Are any types of haptic feedback both **technically feasible** and **clinically beneficial**?

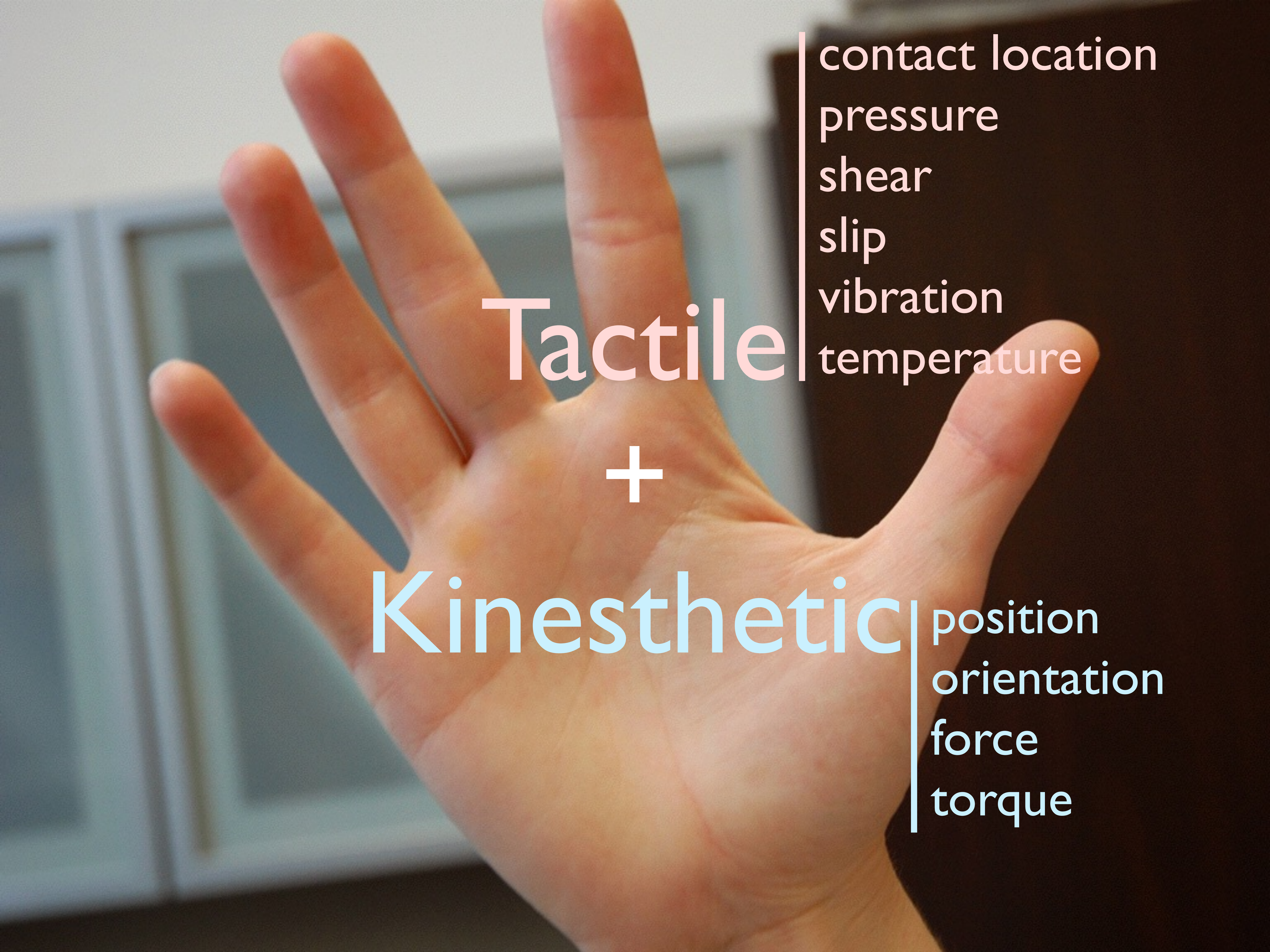


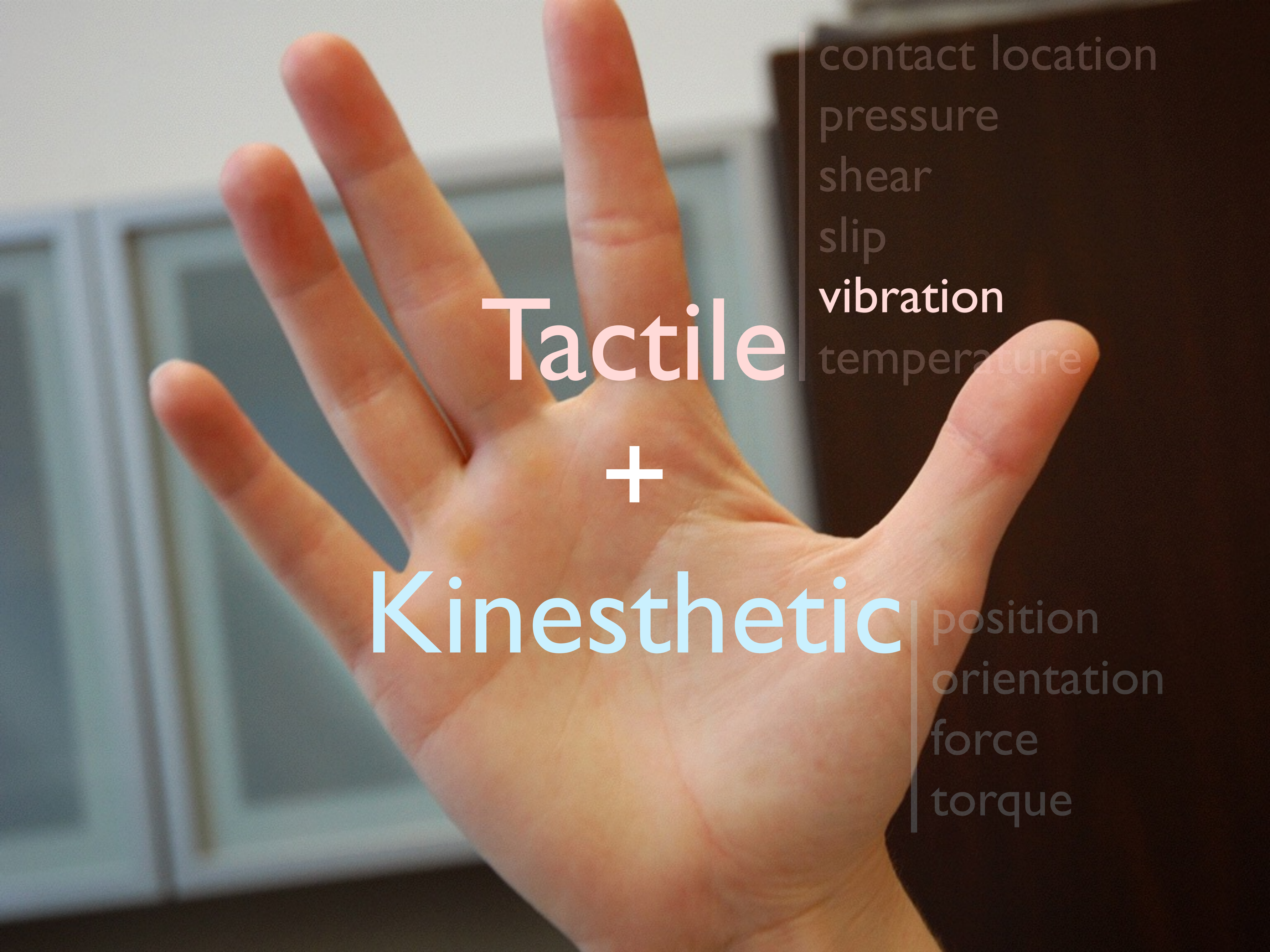
Using Surgical Instruments

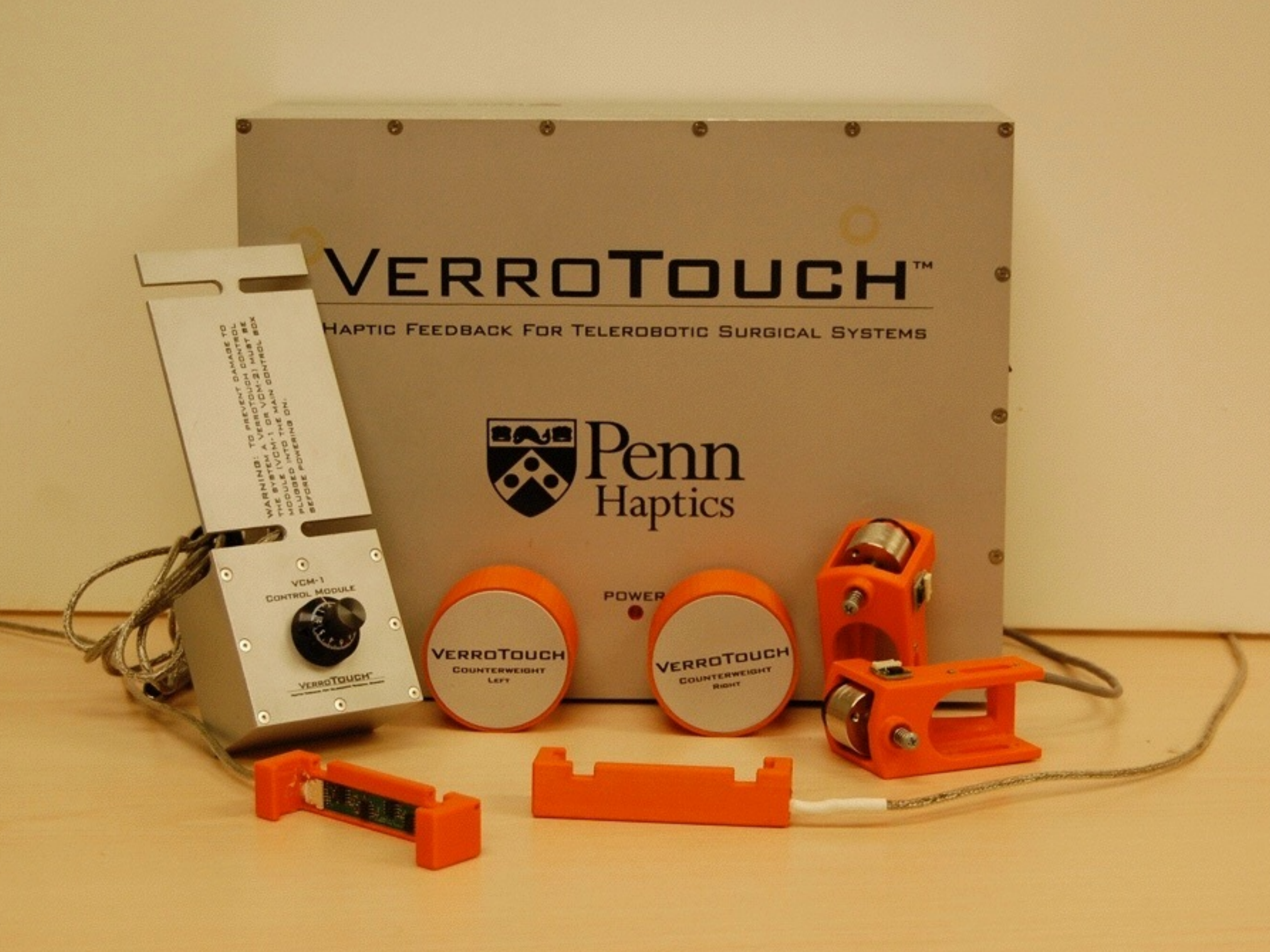


Afferent type (and response properties)	Receptive field (and probe)	Density (afferents per cm²)
FA-I (fast-adapting type I) Meissner endings • Sensitive to dynamic skin deformation of relatively high frequency (~5–50 Hz) • Insensitive to static force • Transmit enhanced representations of local spatial discontinuities (e.g., edge contours and Braille-like stimuli)	 Weak pointed touch	
SA-I (slowly-adapting type I) Merkel endings • Sensitive to low-frequency dynamic skin deformations (<~5 Hz) • Sensitive to static force • Transmit enhanced representations of local spatial discontinuities	 Weak pointed touch	
FA-II (fast-adapting type II) Pacini ending • Extremely sensitive to mechanical transients and high-frequency vibrations (~40–400 Hz) propagating through tissues • Insensitive to static force • Respond to distant events acting on hand-held objects	 Light tapping	
SA-II (slowly-adapting type II) Ruffini-like endings • Low dynamic sensitivity • Sensitive to static force • Sense tension in dermal and subcutaneous collagenous fibre strands • Can fire in the absence of externally applied stimulation and respond to remotely applied stretching of the skin	 Touch or skin stretch	

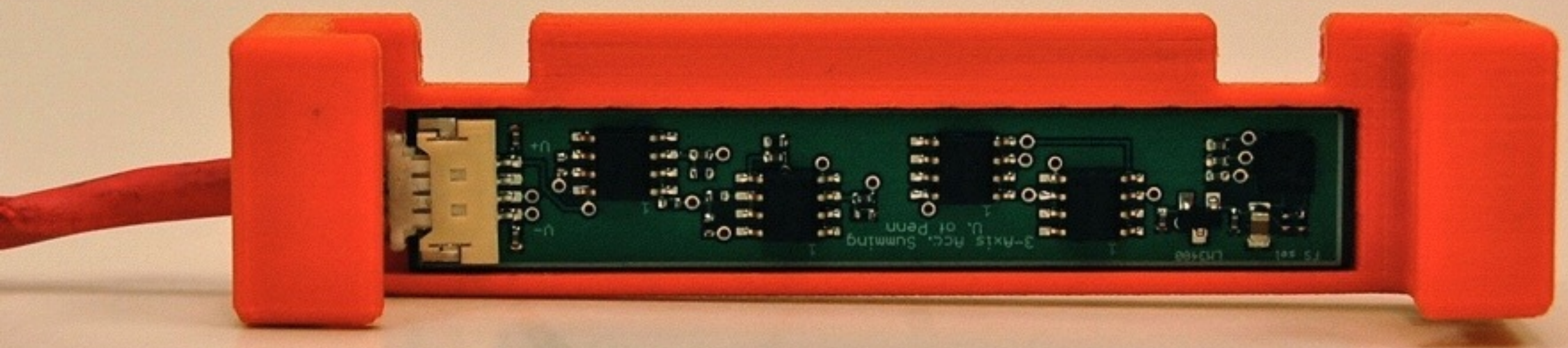
Johansson and Flanagan, Nature Reviews Neuroscience, 2009


Tactile
contact location
pressure
shear
slip
vibration
temperature
+
Kinesthetic
position
orientation
force
torque


Tactile
contact location
pressure
shear
slip
vibration
temperature
+
Kinesthetic
position
orientation
force
torque


VERROTOUCH™
HAPTIC FEEDBACK FOR TELEROBOTIC SURGICAL SYSTEMS
Penn
Haptics
WARNING: TO PREVENT DAMAGE TO THE SYSTEM A VERROTOUCH CONTROL MODULE (VCM-1 OR VCM-2) MUST BE PLUGGED INTO THE MAIN CONTROL BOX BEFORE POWERING ON.
VCM-1
CONTROL MODULE
VERROTOUCH
POWER
VERROTOUCH
COUNTERWEIGHT
LEFT
VERROTOUCH
COUNTERWEIGHT
RIGHT

sensor

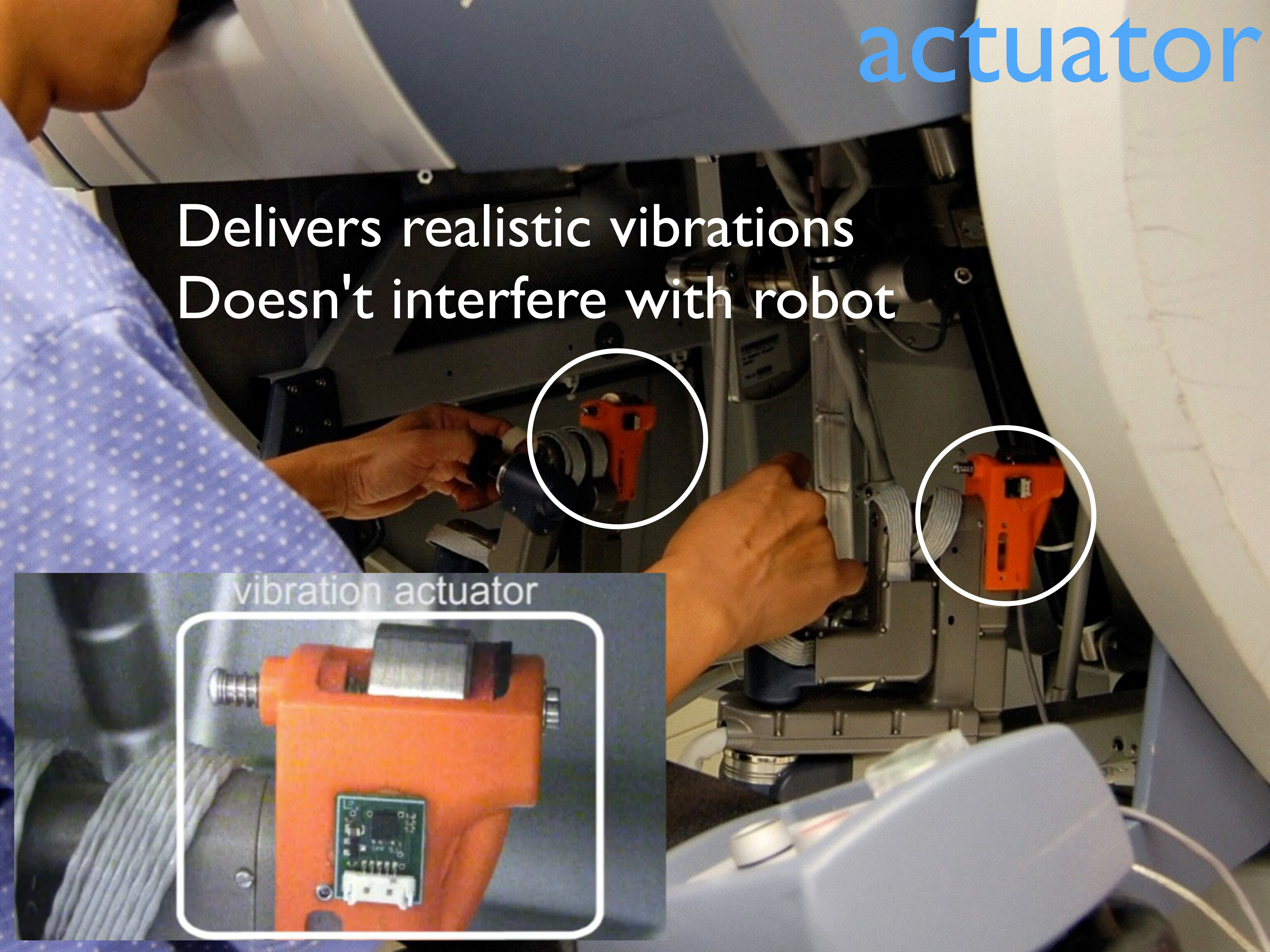


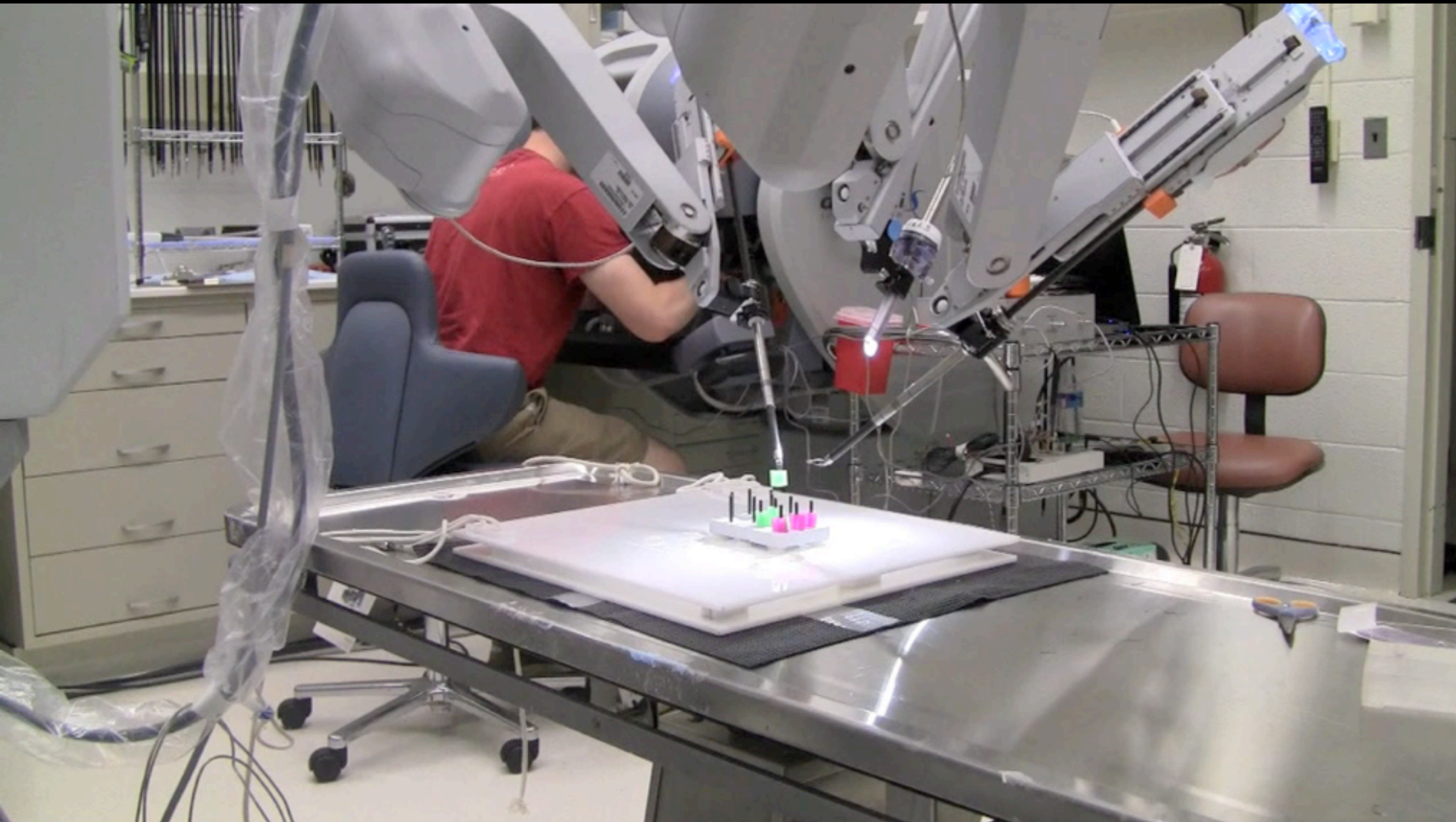
Three-axis high-bandwidth
MEMS-based accelerometer
$10


sensor
Works for all tools
No need for sterilization

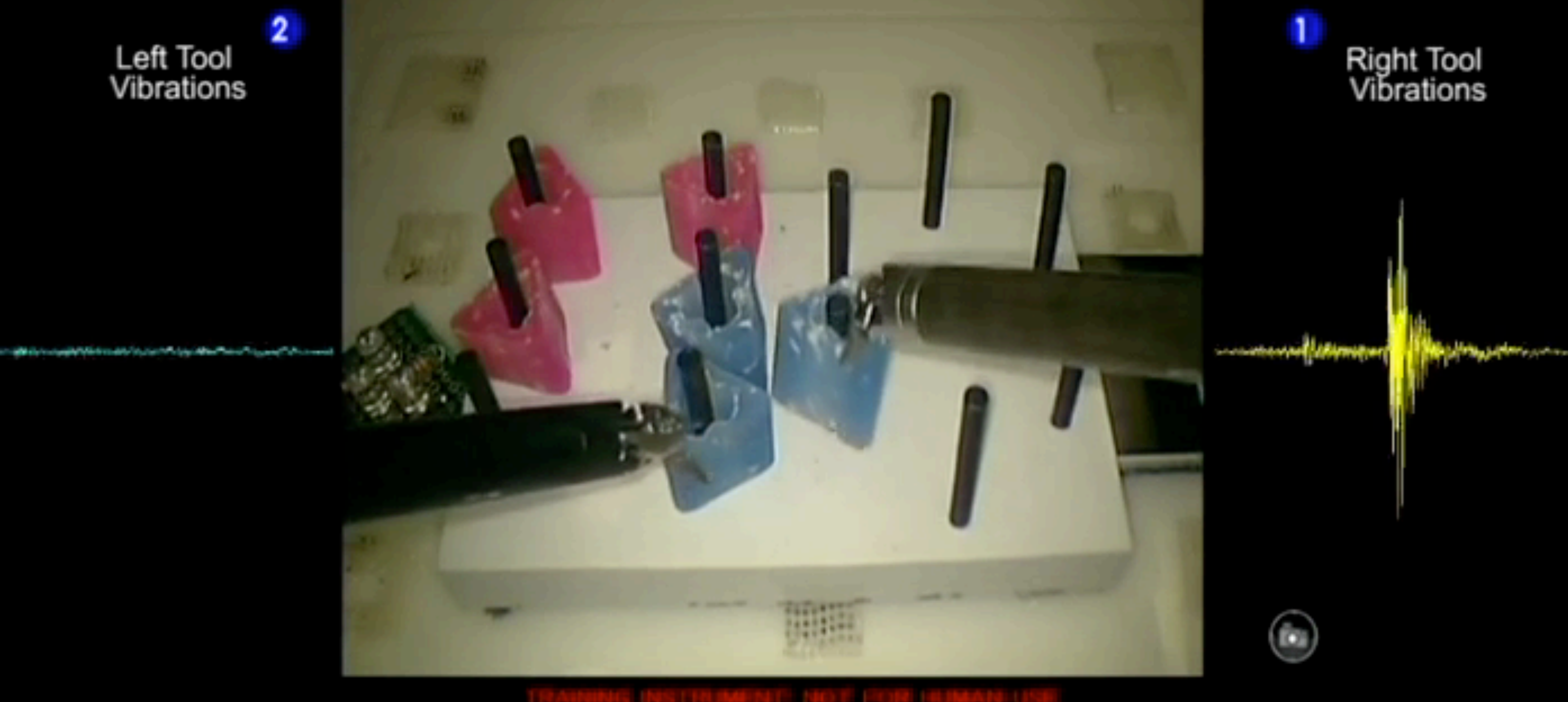
actuator

One-axis high-bandwidth
voice coil actuator
$300


actuator
Delivers realistic vibrations
Doesn't interfere with robot
vibration actuator



Peg Transfer

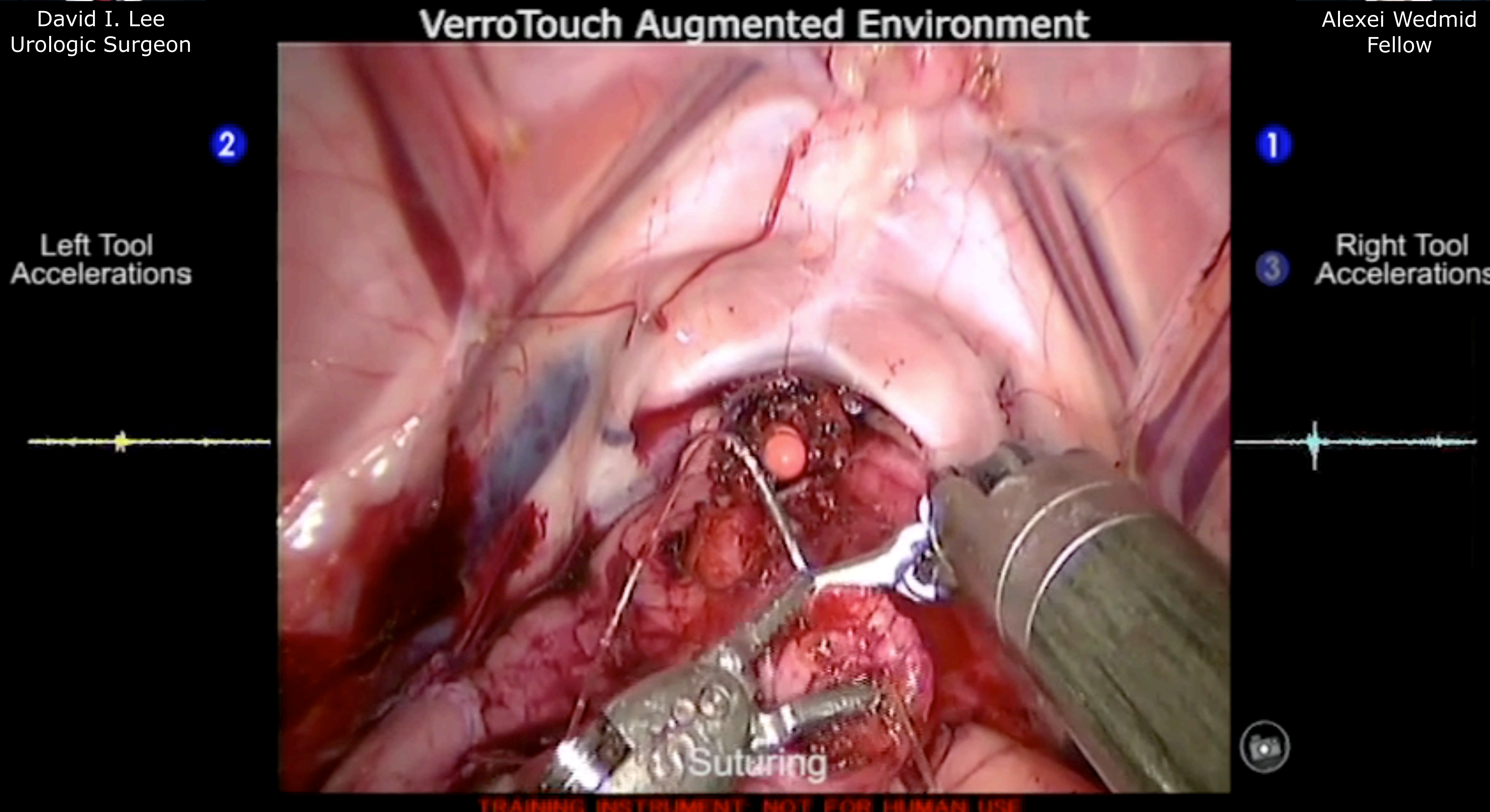


Tool vibration signals occur during **real surgery**.

Warning: Surgery video!

Urologic Procedures on a Porcine Model

David I. Lee
Urologic Surgeon

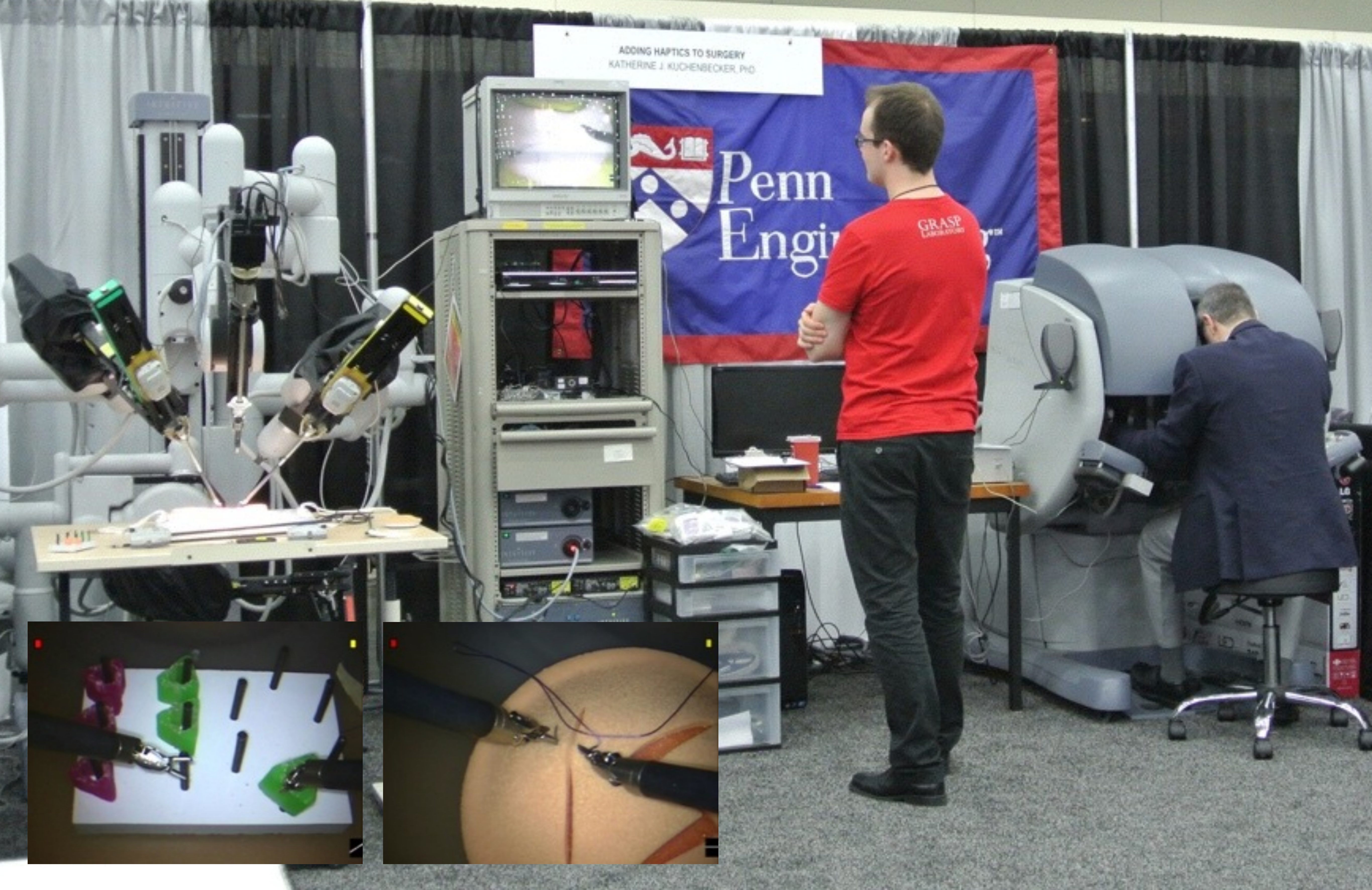


Alexei Wedmid
Fellow

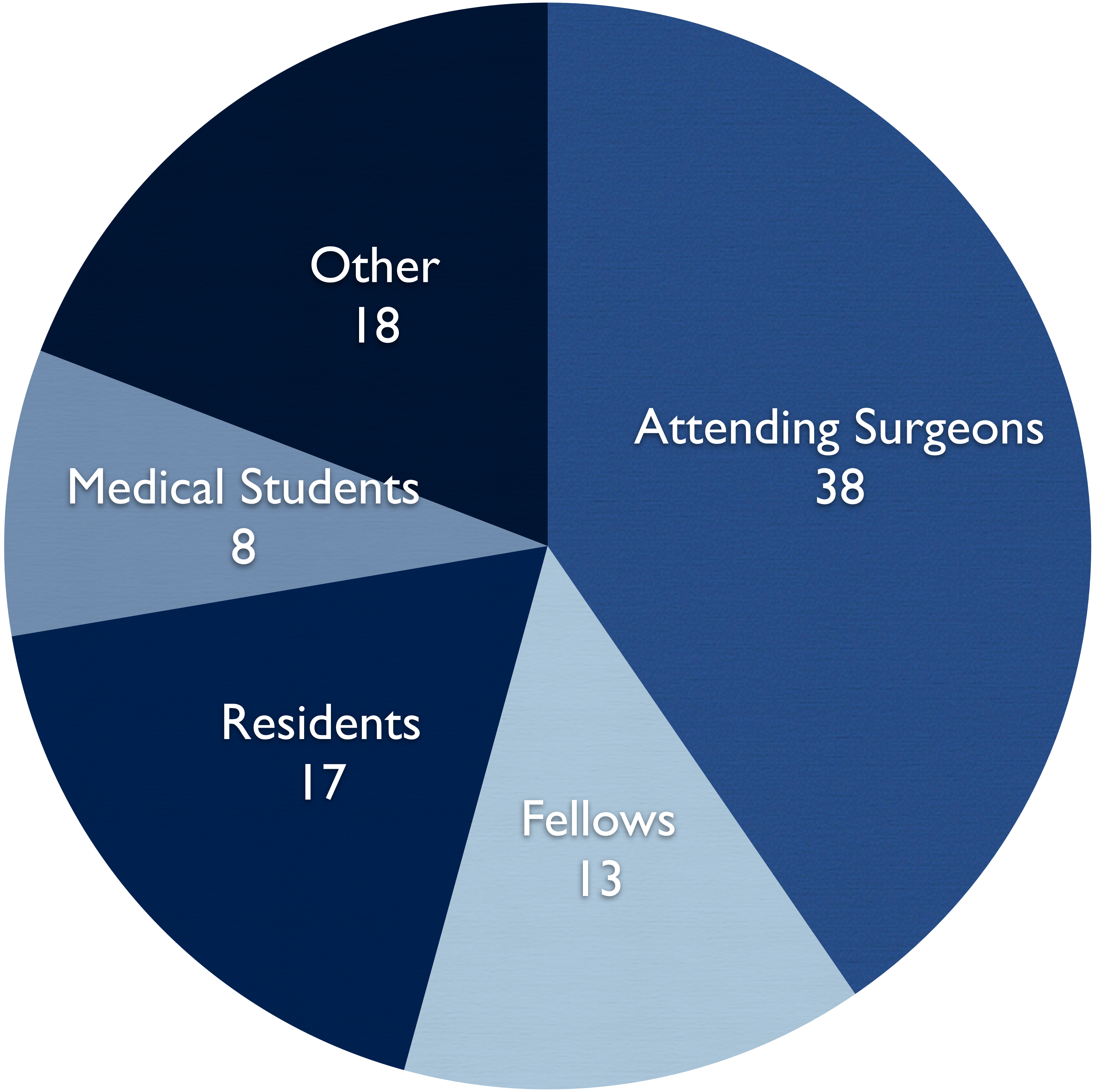
Surgeons **really like** tactile feedback of tool vibrations.

2013 SAGES Learning Center in Baltimore

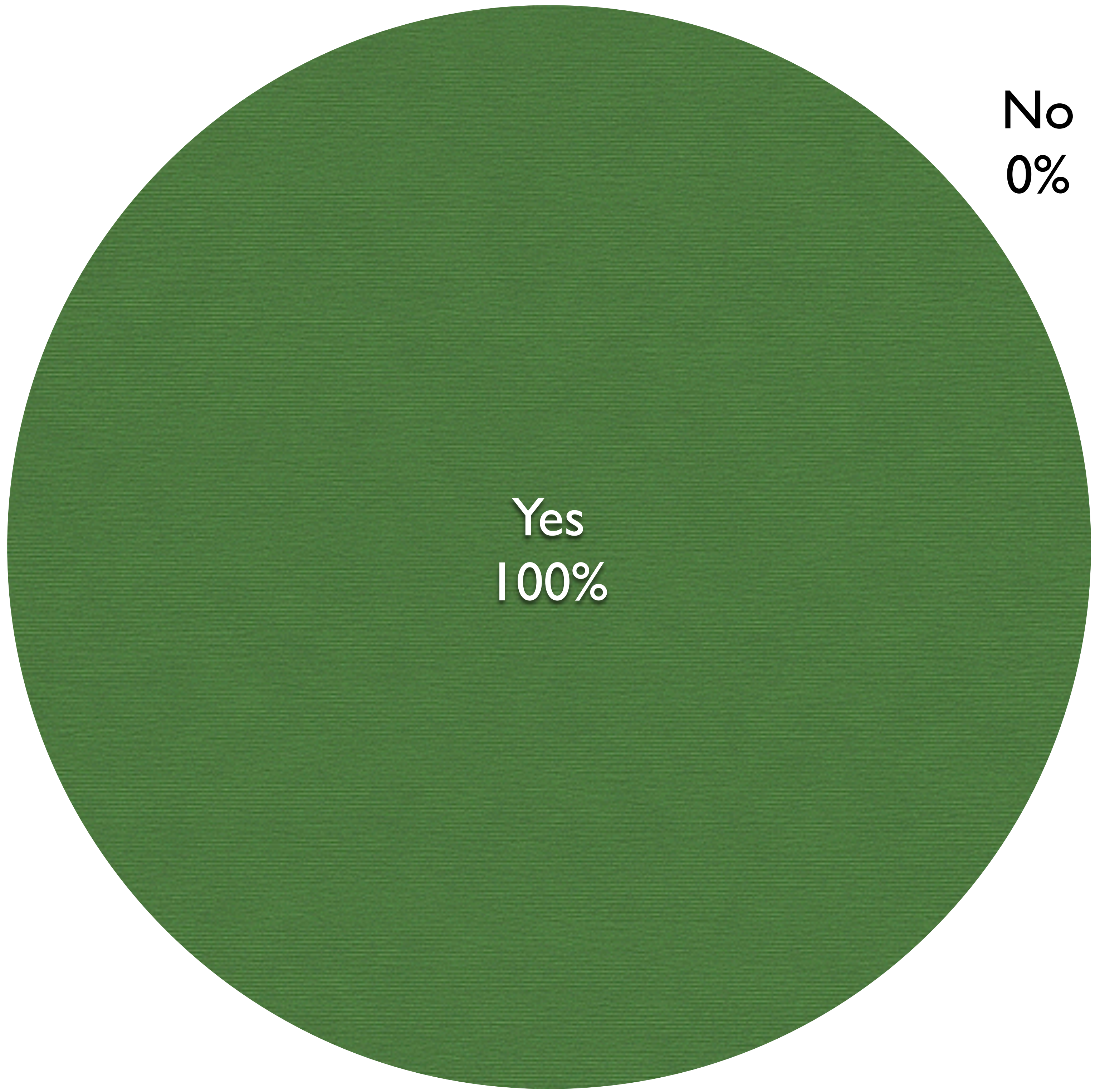
haptic and audio feedback of tool vibrations



94 Participants



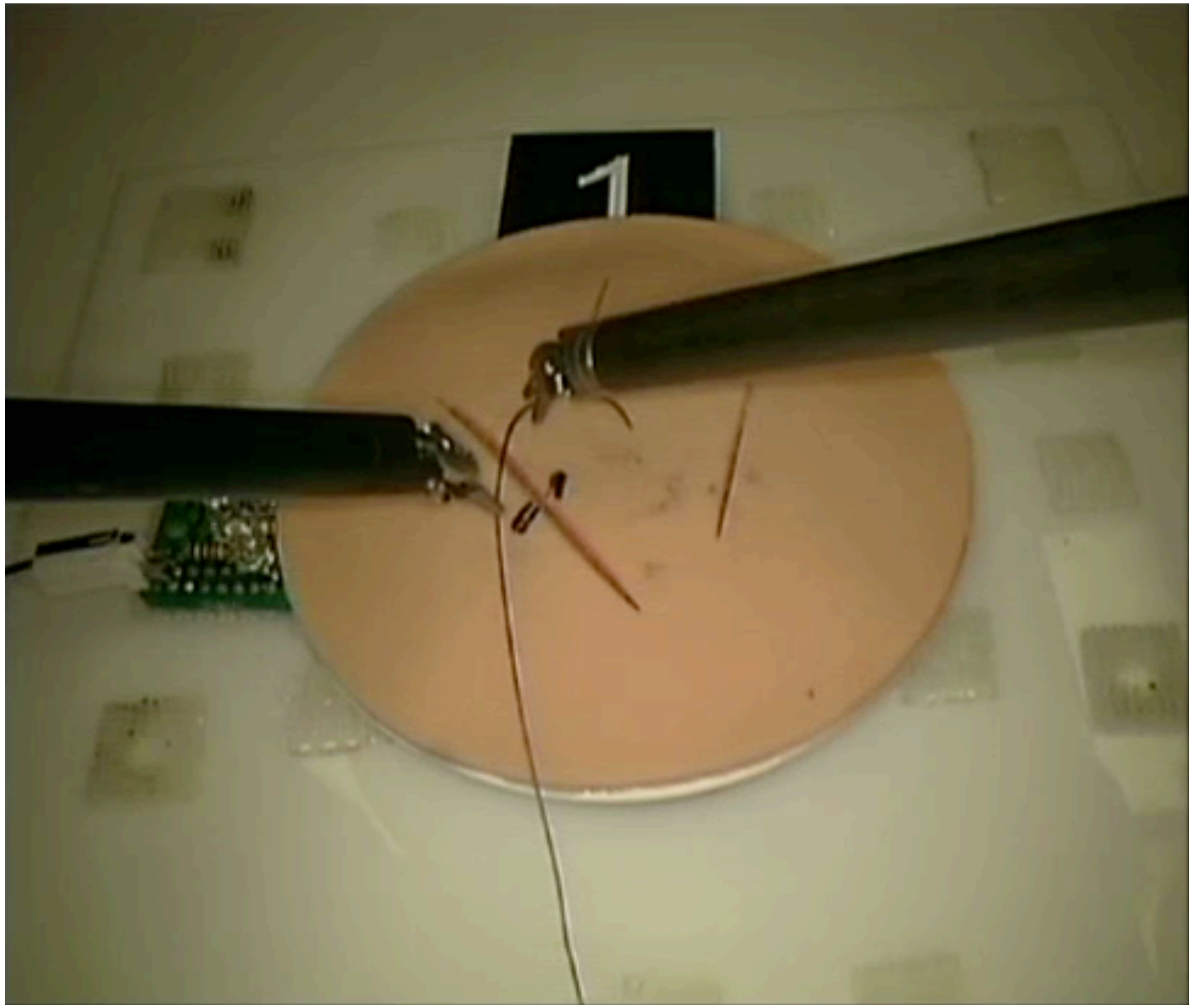
Do you think it would be useful for you or other surgeons to have the option of using vibrotactile feedback?



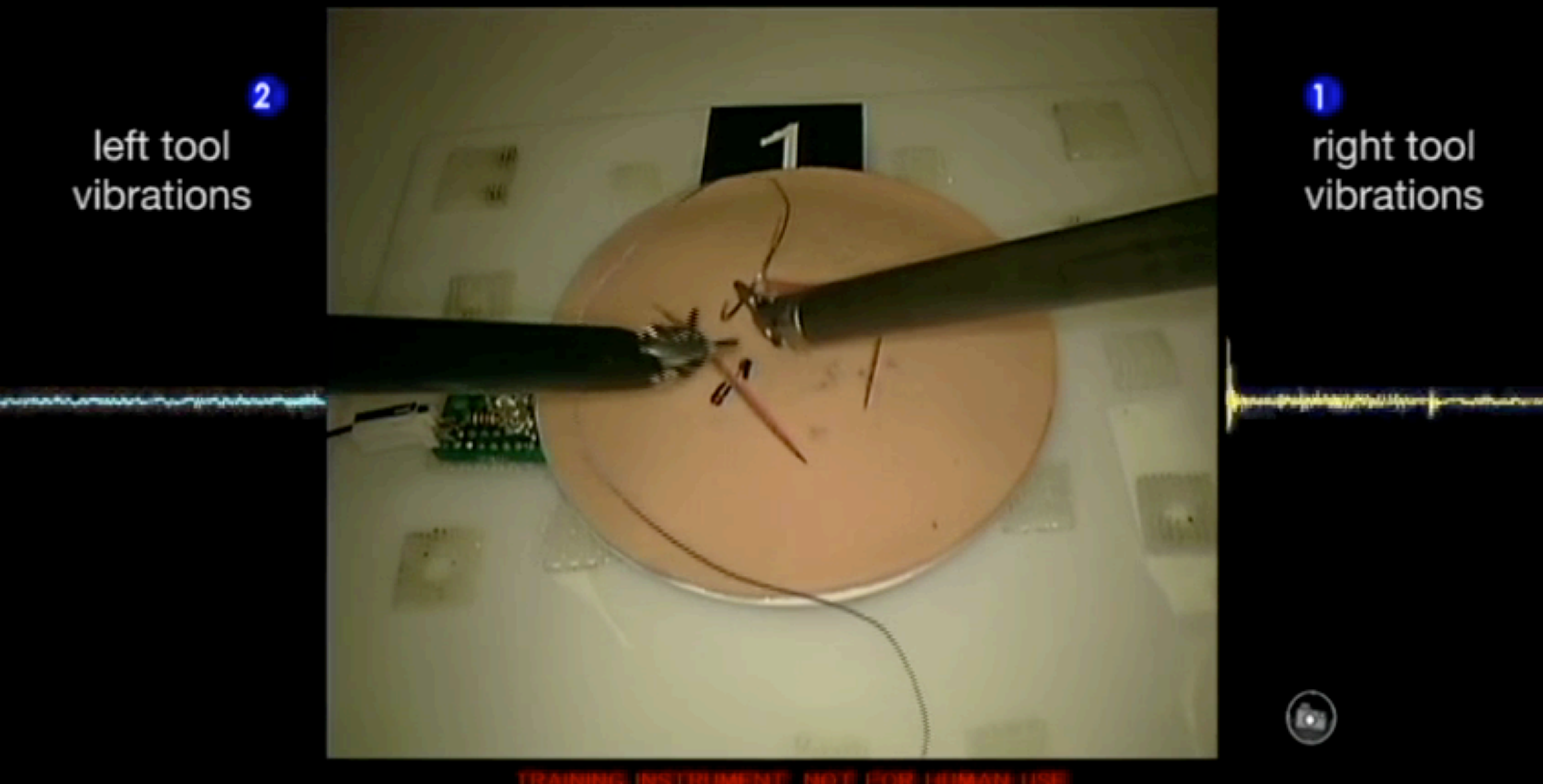
Which type of tool vibration feedback do you prefer?

Tactile tool vibrations reflect the **surgeon's skill level**.

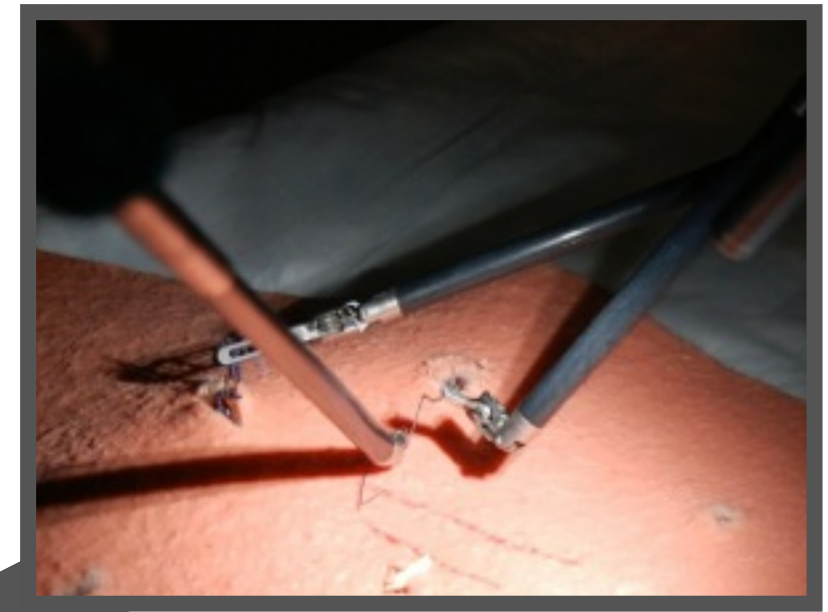
Is this an experienced robotic surgeon?

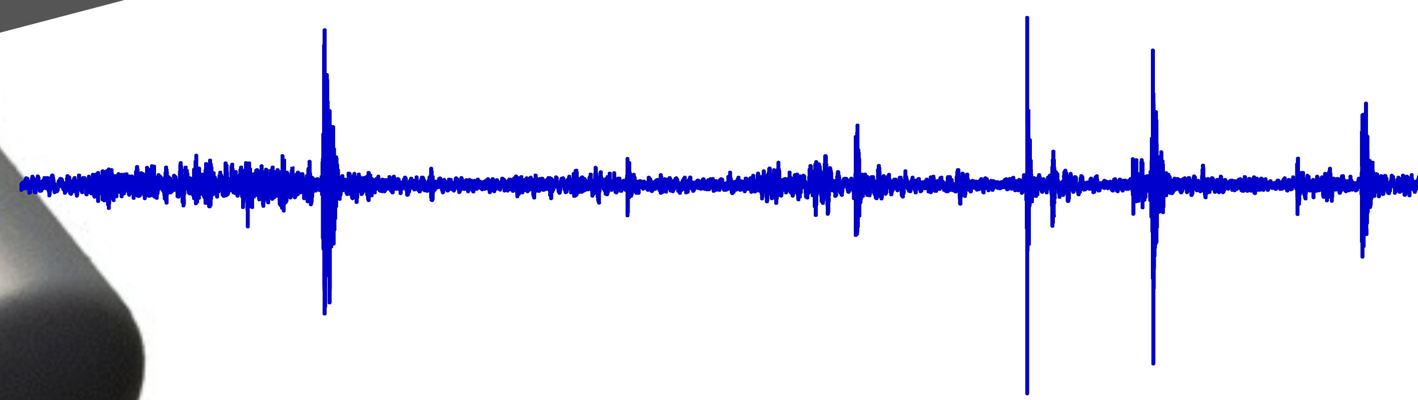


No. It is a novice.



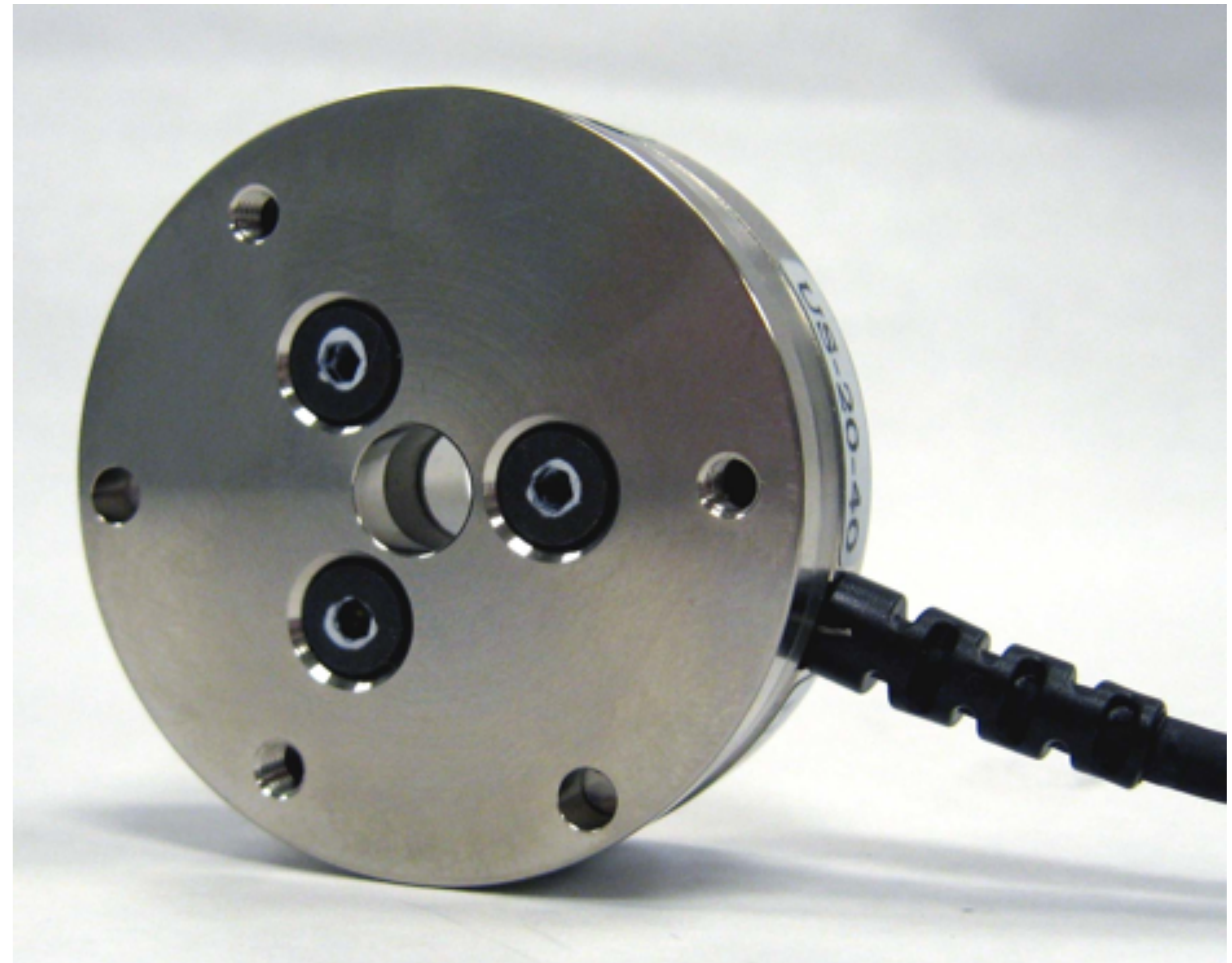
Many awkward motions cause big vibrations.



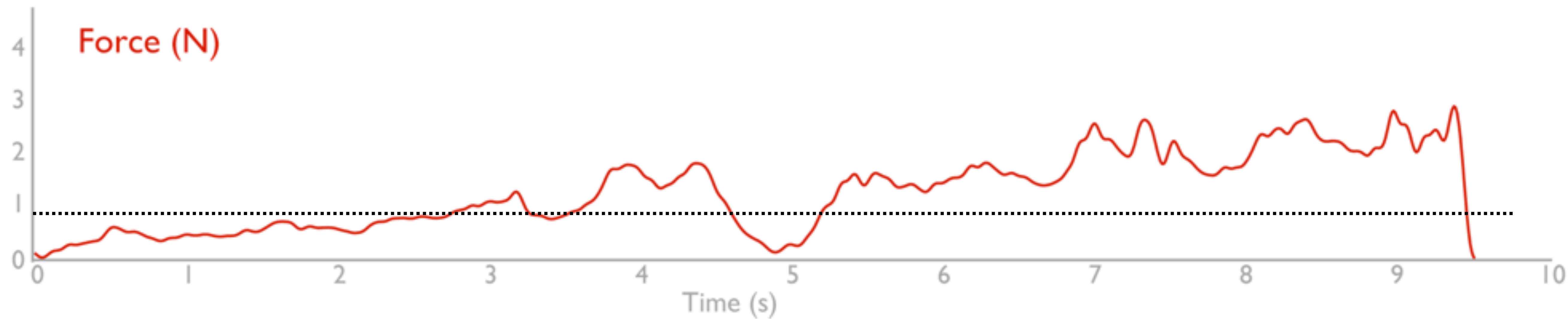


Tactile tool vibration feedback is technically feasible and helps the surgeon.

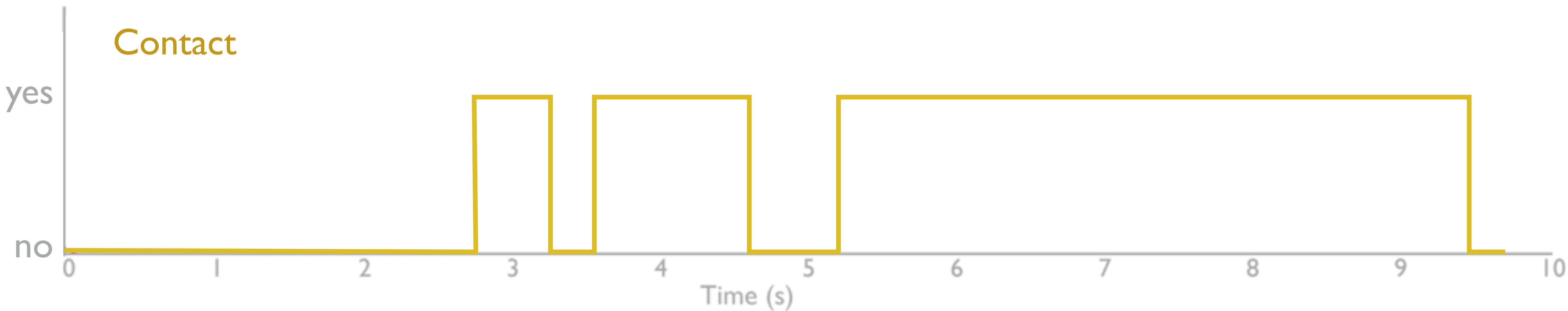
haptics >



We need to think beyond the force sensor to include tactile cues.

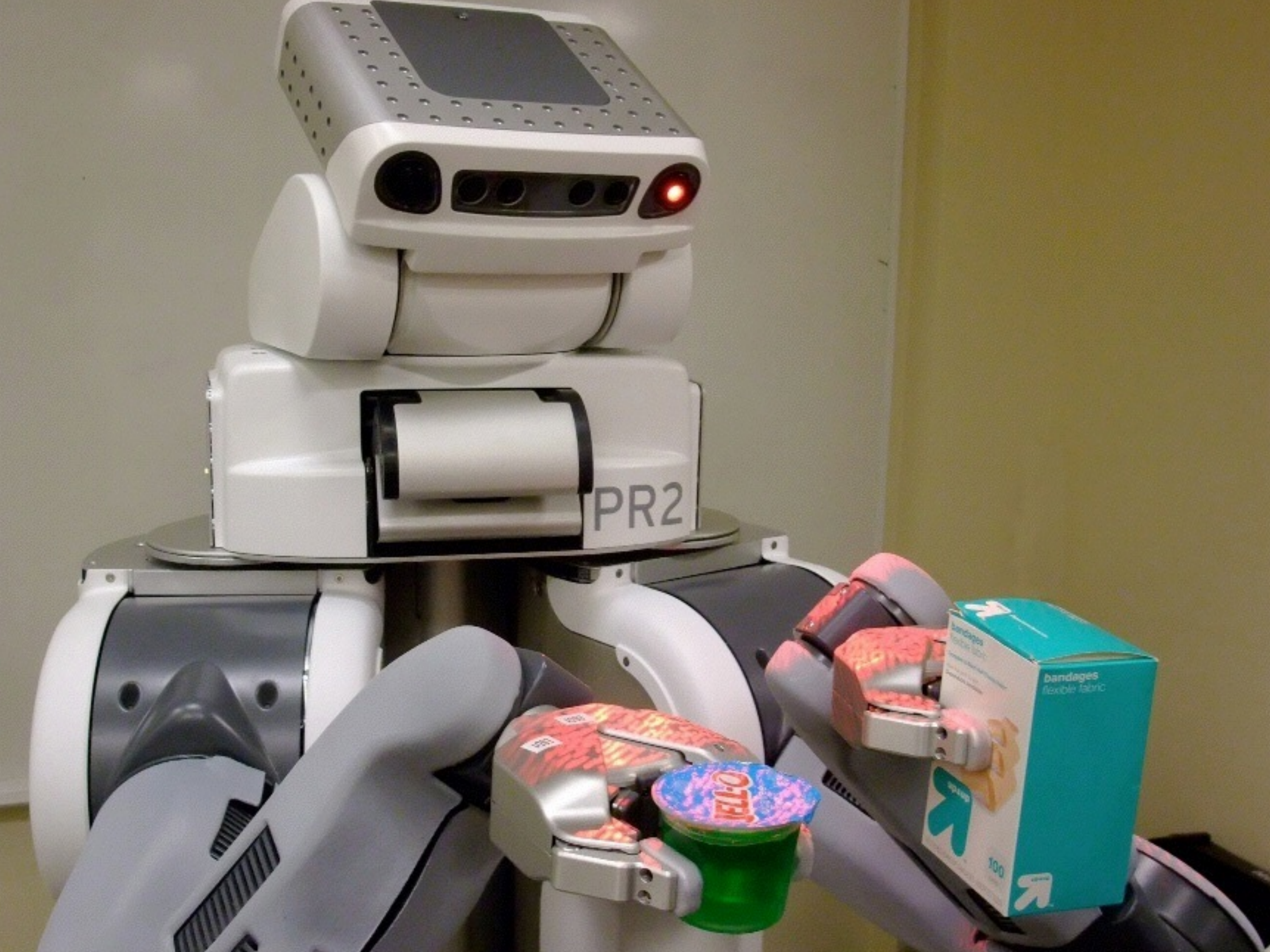


threshold crossing



simple but wasteful

We need to dig deeper into the haptic signals that we do acquire.


PR2
JELL-O
bandages
flexible fabric
100


Nutrition Facts

Coding and use of tactile signals from the fingertips in object manipulation tasks

Roland S. Johansson and J. Randall Flanagan‡*

Abstract | During object manipulation tasks, the brain selects and implements action-phase controllers that use sensory predictions and afferent signals to tailor motor output to the physical properties of the objects involved. Analysis of signals in tactile afferent neurons and central processes in humans reveals how contact events are encoded and used to monitor and update task performance.

Tactile afferents
Fast-conducting myelinated afferent neurons that convey signals to the brain from low-threshold mechanoreceptors in body areas that actively contact objects — that is, the inside of the hand, the sole of the foot, the lips, the tongue and the oral mucosa.

Proprioceptive afferents
Fast-conducting myelinated afferents that provide information about joint configurations and muscle states. These include mechanoreceptive afferents from the hairy skin, muscles, joints and connective tissues.

**Physiology Section, Department of Integrative Medical Biology, Umeå University, SE-901 87 Umeå, Sweden.*
‡Department of Psychology and Centre for Neuroscience Studies, Queen's University, Kingston, Ontario, K7L 3N6, Canada.
Correspondence to R.S.J. e-mail: roland.s.johansson@physiol.umu.se
doi:10.1038/nrn2621
Published online 8 April 2009

The tactile afferents that innervate the inside of the hand signal the transformation of soft tissues that occurs when the hand interacts with objects and thus provide information about the physical properties of the object and the contact between the object and the hand. People with impaired tactile sensibility have difficulties with many everyday activities because the brain lacks the information about mechanical contact states that is needed to plan and control object manipulations. Vision provides only indirect information about such mechanical interactions, and proprioceptive afferents exhibit low sensitivity to mechanical fingertip events[1–4].

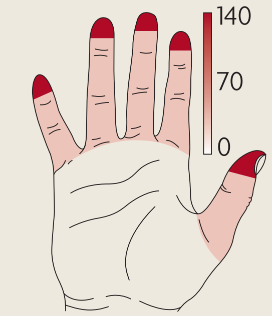
In this Review, we address emerging concepts regarding the use of tactile information by the brain in manipulation tasks. In doing so, we discuss the notion that the planning and control of manipulation tasks is centred on mechanical events that mark transitions between consecutive action phases and that represent subgoals of the overall task. We highlight recent findings that help explain the speed with which the brain detects and classifies tactile fingertip events in object manipulation. Finally, we discuss multisensory representation of action goals in object manipulation. Our account differs from a recent review of tactile signals in manipulation[5] by emphasizing the use of these signals in the control of manipulatory tasks, by considering how other sensory signals contribute to this control and by discussing the central neural mechanisms involved in manipulation tasks.

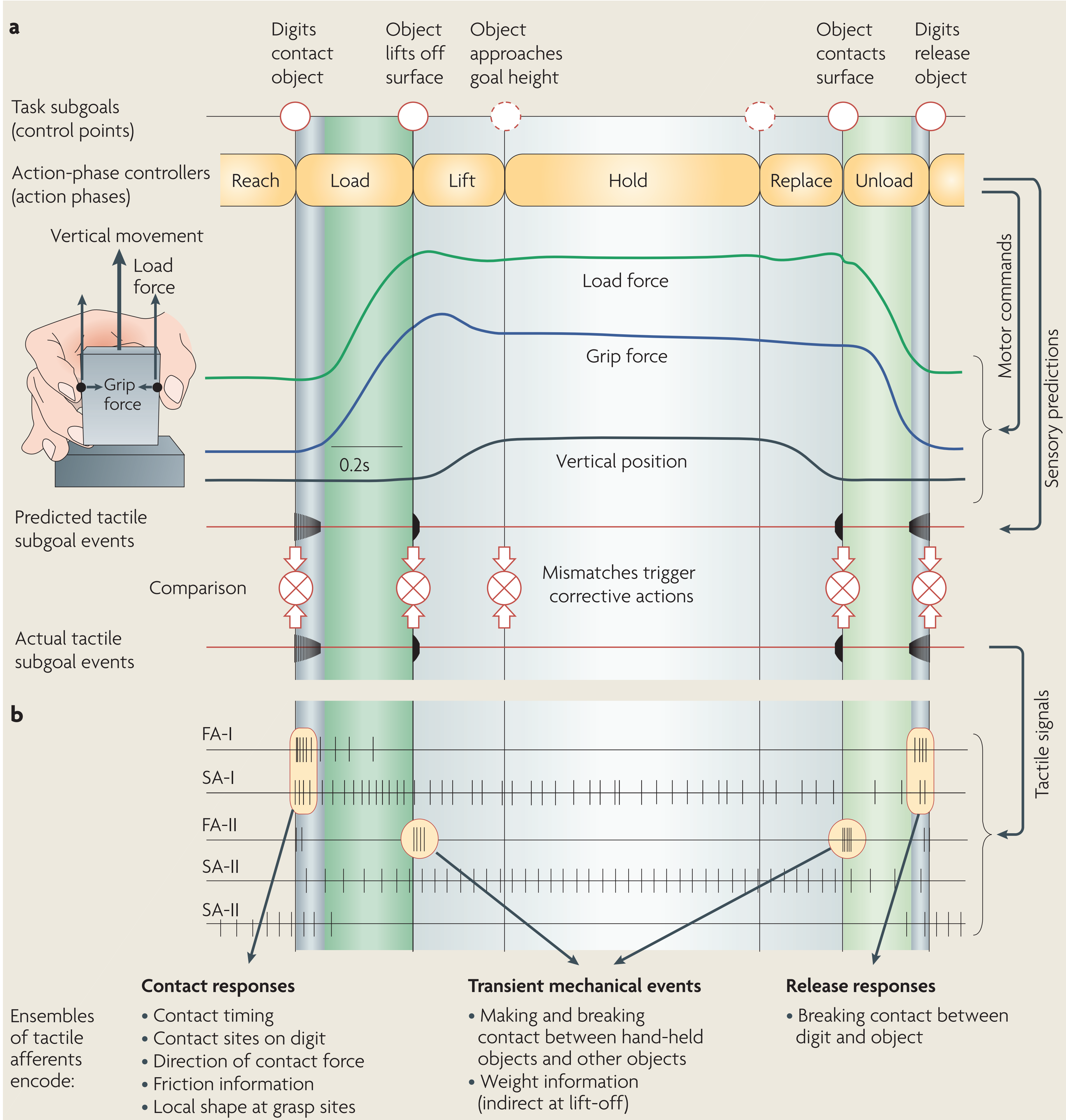
Tactile sensors encoding fingertip transformations

When humans manipulate objects, the brain uses tactile afferent information related to the time course, magnitude, direction and spatial distribution of contact forces, the shapes of contacted surfaces, and the friction between contacted surfaces and the digits. The inside of the human hand is equipped with four functionally distinct types of tactile afferents (TABLE 1; reviewed in more detail in REFS 5,6). FA-I (fast-adapting type I) and SA-I (slow-adapting type I) afferents terminate superficially in the skin, with a particularly high density in the fingertips. FA-Is exhibit sensitivity to dynamic skin deformations of relatively high frequency[7,8], whereas SA-Is are most easily excited by lower-frequency skin deformations[7,8] and can respond to sustained deformation. There are more FA-I afferents than SA-I afferents in the fingertips (TABLE 1), reflecting the importance of extracting spatial features of dynamic mechanical events, such as the skin forming and breaking contact with objects or scanning across a textured surface.

FA-II and SA-II afferents innervate the hand with a lower and roughly uniform density and terminate deeper in dermal and subdermal fibrous tissues. FA-II afferents are optimized for detecting transient mechanical events[7–10]. Hundreds of FA-II afferents, distributed throughout the hand, can be excited when hand-held objects contact or break contact with other objects[11]. SA-II afferents can respond to remotely applied lateral stretching of the skin[12,13] and can be sensitive to the tangential shear strain to the skin that occurs during object manipulation[2,11]. SA-II-like afferents are found in most fibrous tissues (such as muscle fascias and joint capsules and ligaments)[14] and there is evidence that they can act as proprioceptors (BOX 1).

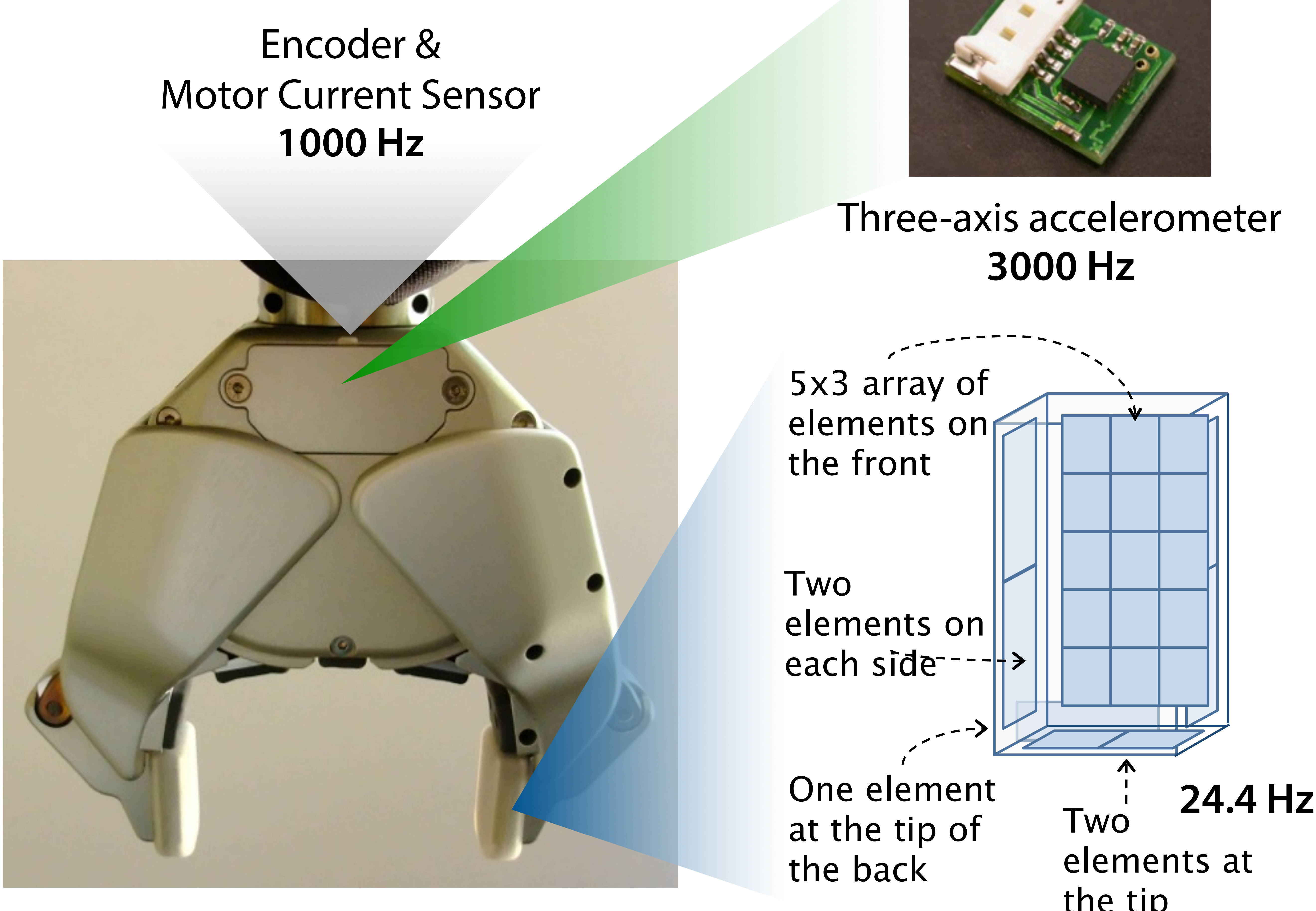
Traditional studies on tactile sensing that examine correlations between afferent signals and perceptual (declarative) phenomena evoked by gently touching passive digits (for reviews see REFS 6,14–20) provide little information about the encoding and use of tactile information in object manipulation for several reasons: the control processes that are active in manipulation operate

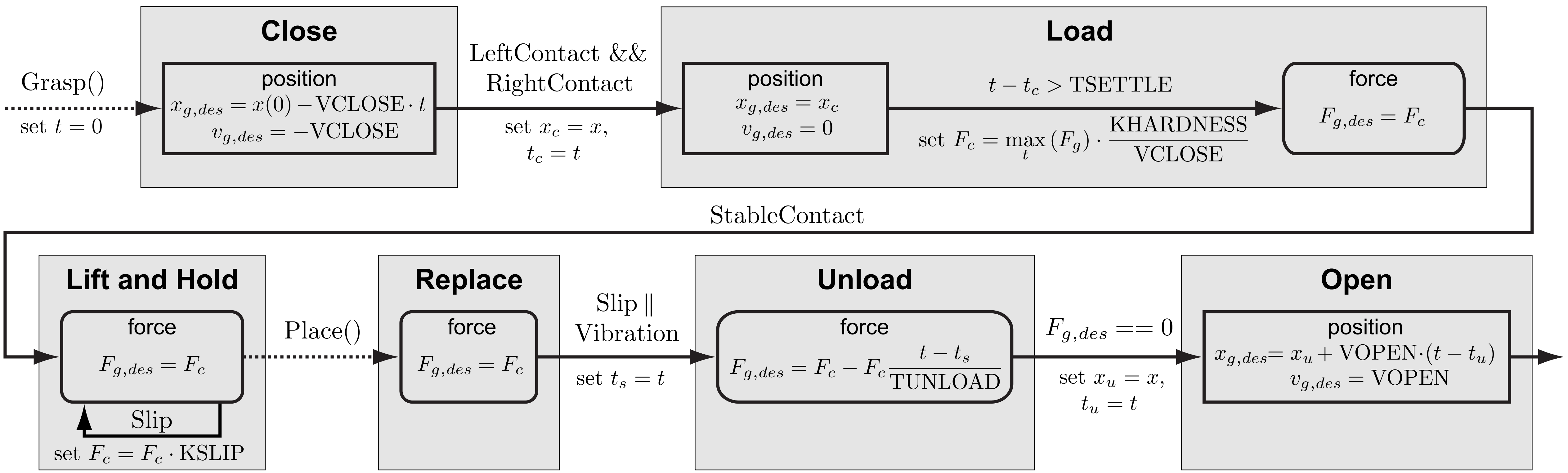
Afferent type (and response properties)	Receptive field (and probe)	Density (afferents per cm²)
FA-I (fast-adapting type I) Meissner endings • Sensitive to dynamic skin deformation of relatively high frequency (~5–50 Hz) • Insensitive to static force • Transmit enhanced representations of local spatial discontinuities (e.g., edge contours and Braille-like stimuli)	 Weak pointed touch	
SA-I (slowly-adapting type I) Merkel endings • Sensitive to low-frequency dynamic skin deformations (<~5 Hz) • Sensitive to static force • Transmit enhanced representations of local spatial discontinuities	 Weak pointed touch	
FA-II (fast-adapting type II) Pacini ending • Extremely sensitive to mechanical transients and high-frequency vibrations (~40–400 Hz) propagating through tissues • Insensitive to static force • Respond to distant events acting on hand-held objects	 Light tapping	
SA-II (slowly-adapting type II) Ruffini-like endings • Low dynamic sensitivity • Sensitive to static force • Sense tension in dermal and subcutaneous collagenous fibre strands • Can fire in the absence of externally applied stimulation and respond to remotely applied stretching of the skin	 Touch or skin stretch	



Johansson and Flanagan, Nature Reviews: Neuroscience, 2009

Standard PR2 Haptic Sensors

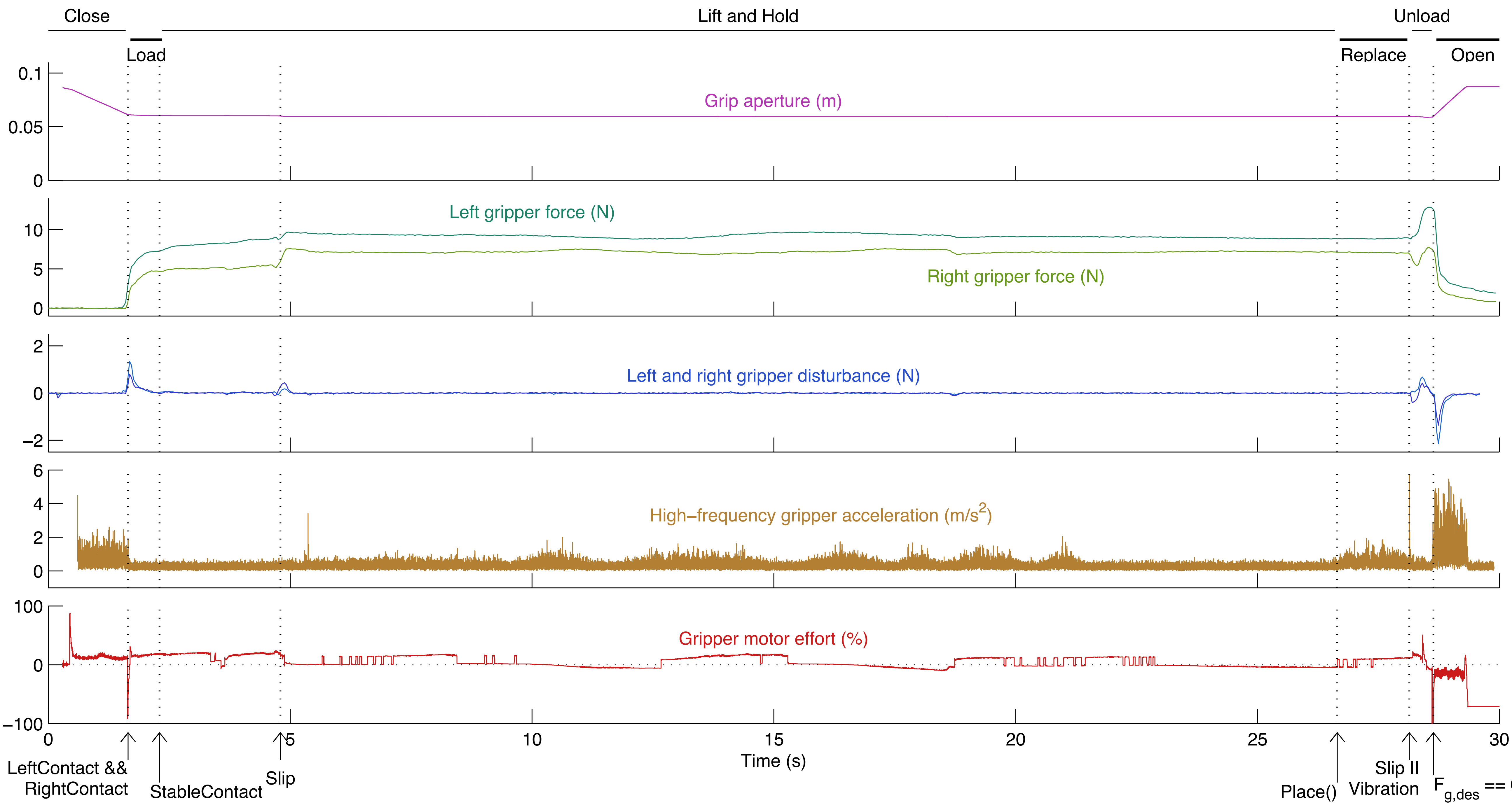




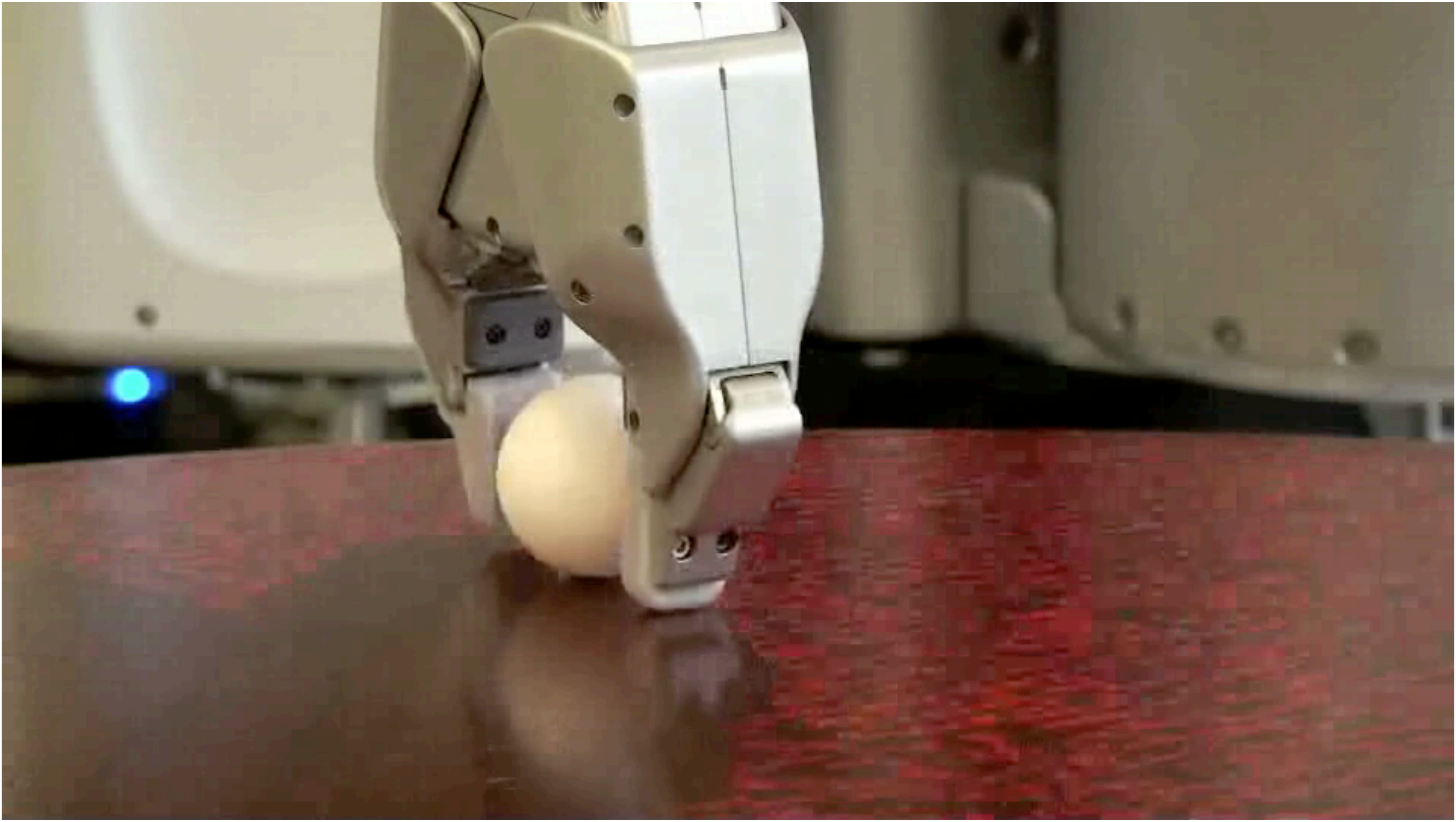
high-pass and low-pass filtered tactile pressure signals, plus high-pass filtered acceleration

closed-loop force control with tactile pressure sensors

state transitions driven by tactile events

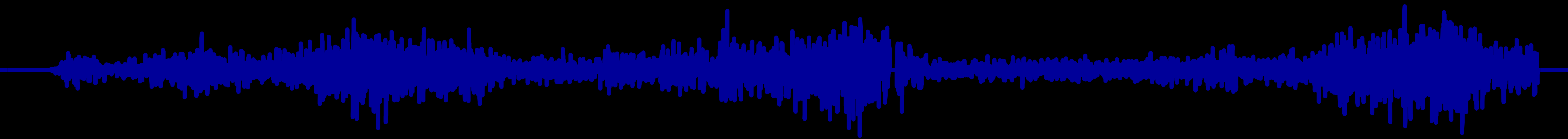


Close
Lift and Hold
Unload
Load
Replace
Open
Grip aperture (m)
0.1
0.05
0
Left gripper force (N)
Right gripper force (N)
10
5
0
Left and right gripper disturbance (N)
2
0
−2
High−frequency gripper acceleration (m/s^2)
6
4
2
0
Gripper motor effort (%)
100
0
−100
0
5
10
15
20
25
30
Time (s)
LeftContact &&
RightContact
StableContact
Slip
Place()
Slip II
Vibration
$F_{g,des}$ == 0




Merriam
Webster's
Collegiate
Thesaurus

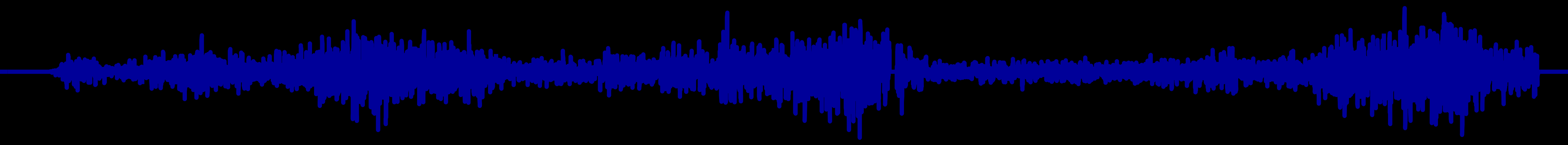

Silk
ORIGINAL
CRYSTAL GEYSER
Peppermint
BAGGED TEA
365 ORGANIC
Organic
Honey & Nut
Morning O's
Made with Whole Grain Oats, Honey & Almonds
9 ESSENTIAL VITAMINS AND MINERALS • LOW FAT
Minute Maid
100% JUICE
JELL-O
Scotch
SARAN
PREMIUM WRAP
HEAVY DUTY · DURABLE
MICROWAVE SAFE
100 SQ FT
Cling Plus
IT'S NOT JUST ANY WRAP. IT'S SARAN WRAP!



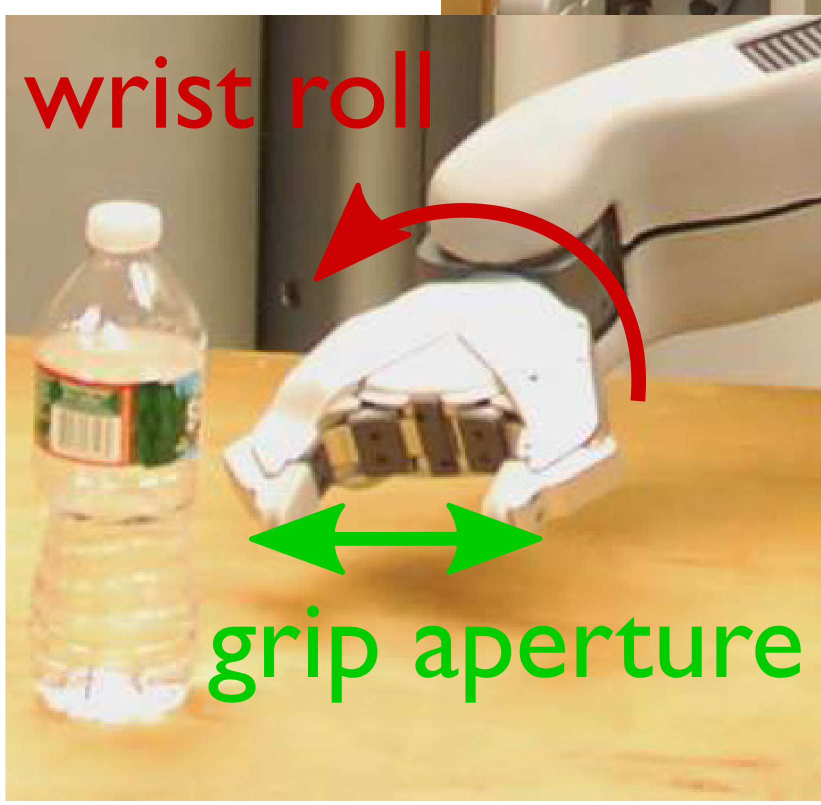
high frequency vibrations
convey
rich tactile information

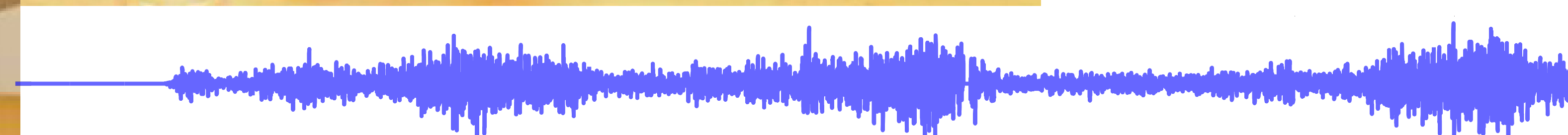
but robot movement also generates
discernible vibrations

Kinesthetic ↔ Tactile



robots should anticipate and ignore
tactile sensations caused by their own movement
(ego vibrations)



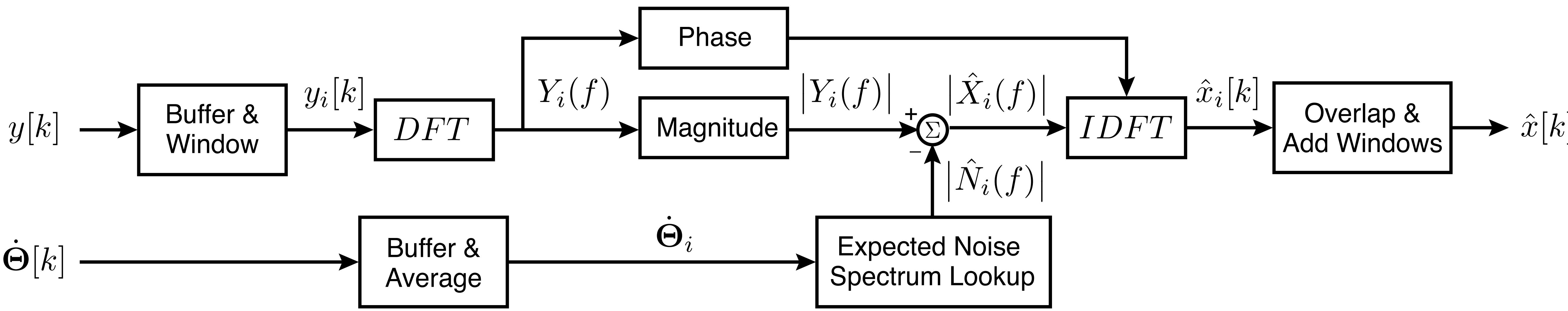


$$\underbrace{y[k]}_{\text{measurement}} = \underbrace{x[k]}_{\text{signal}} + \underbrace{n[k]}_{\text{noise}}$$

$$y[k] = x[k] + n[k]$$

measurement signal noise

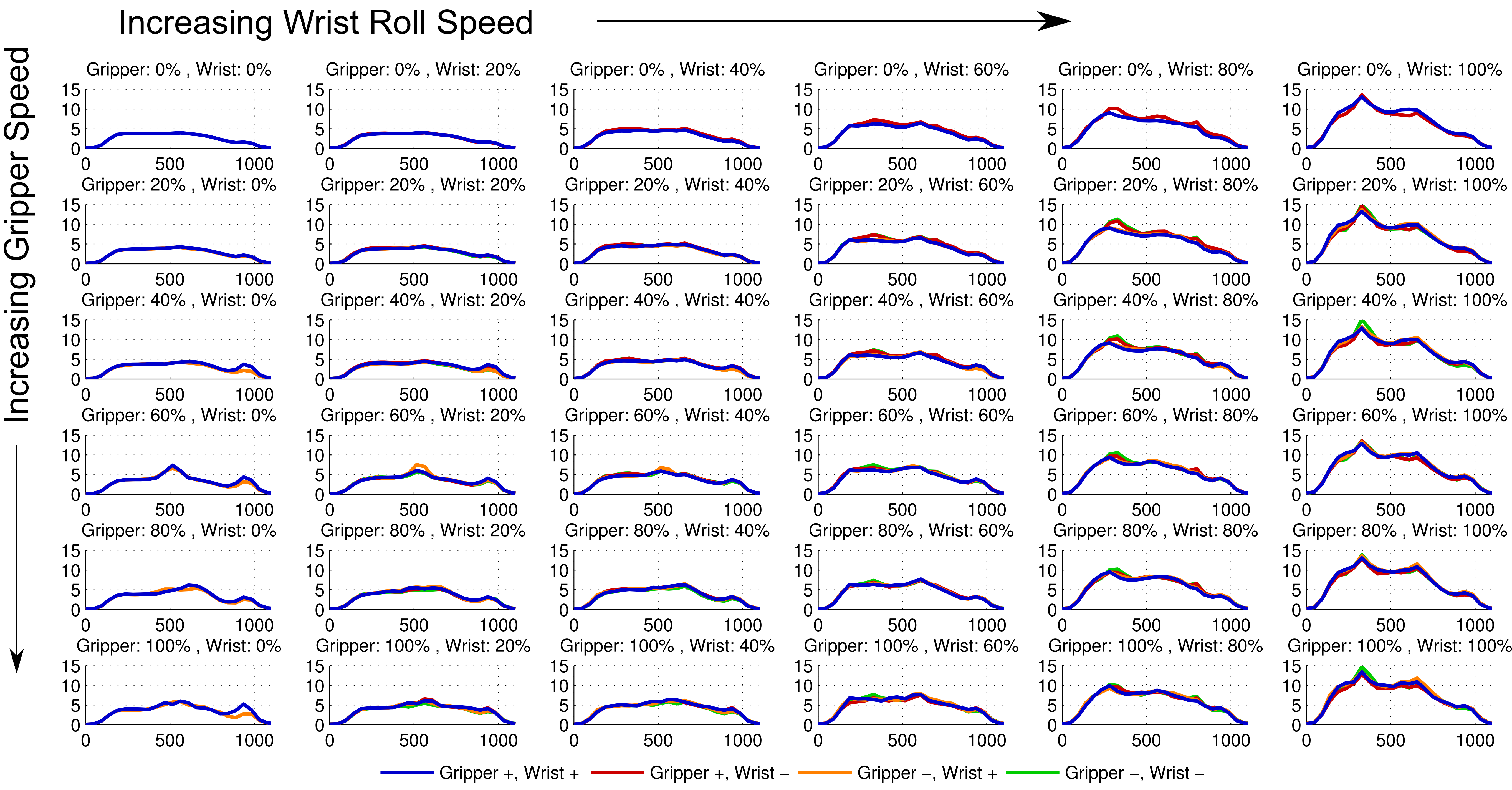
Windowed Spectral Subtraction Process



$$|\hat{X}_i(f)| = |Y_i(f)| - |\hat{N}_i(f)|$$

signal measurement noise

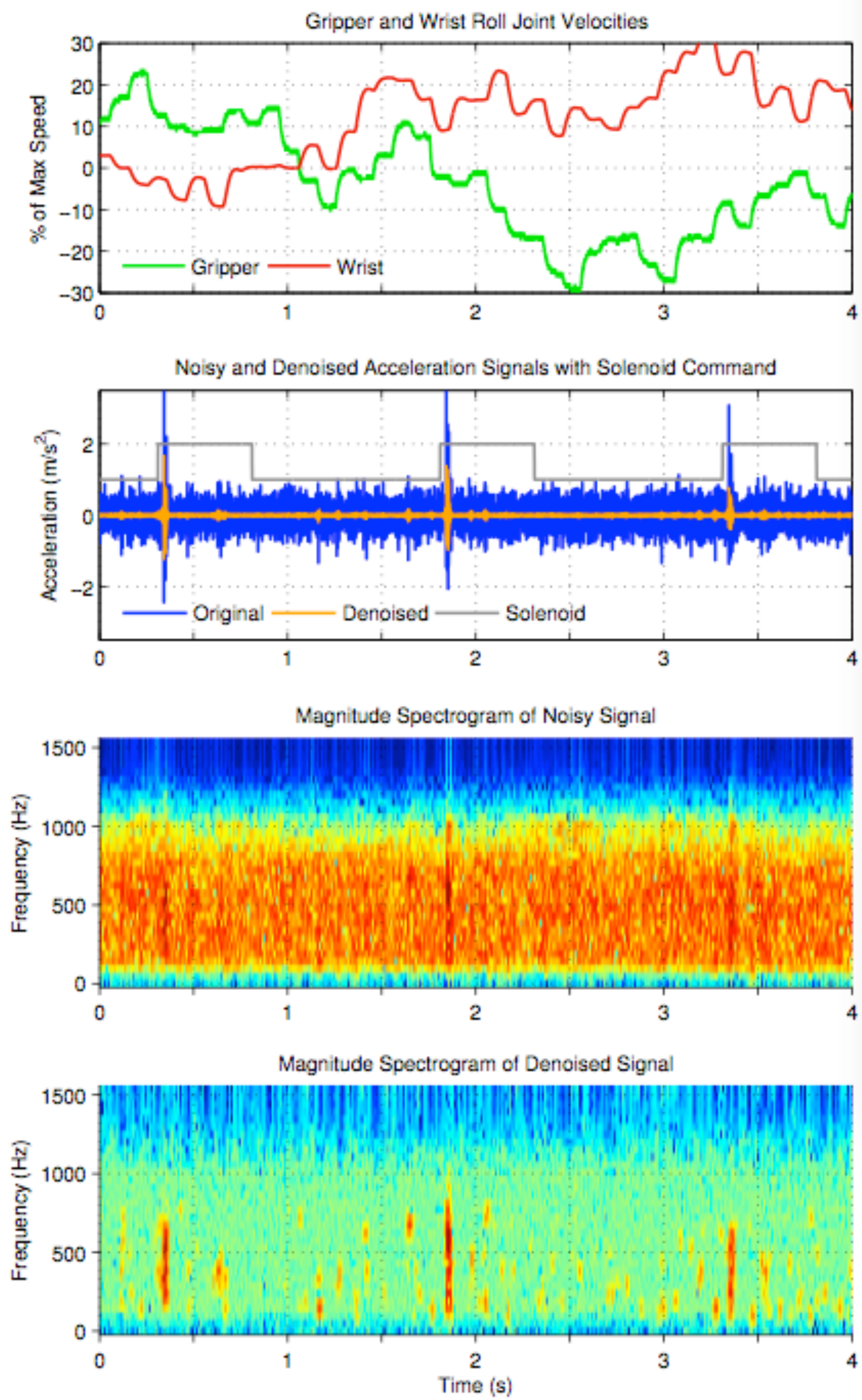
Recorded vibrations for 21 wrist roll velocities combined with 21 grip aperture velocities

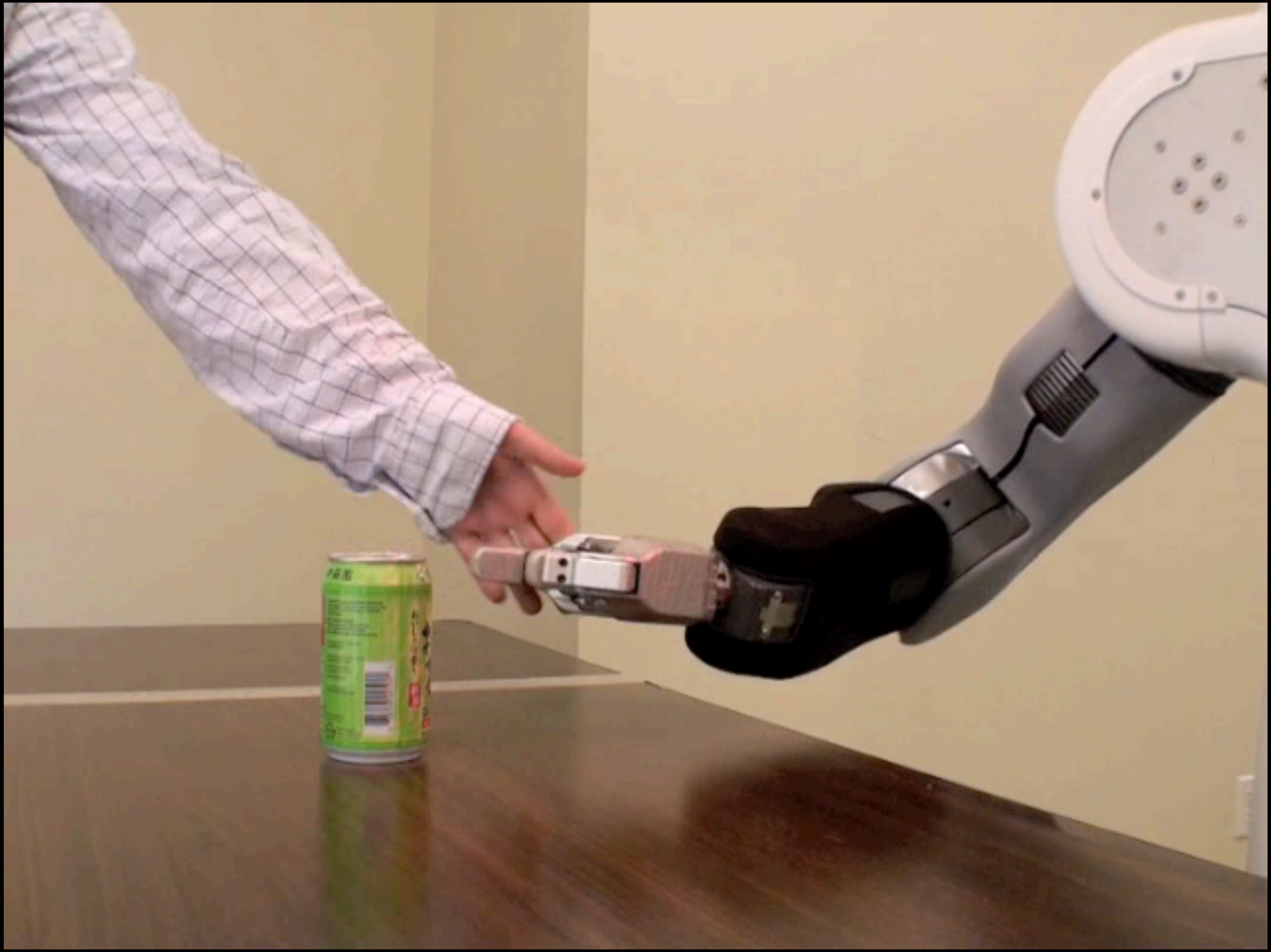


Experimental Results

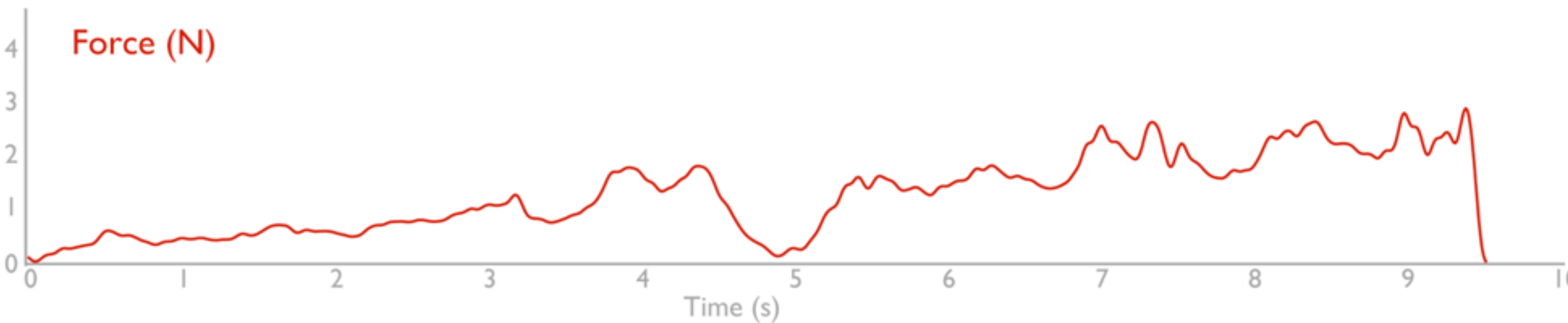
Experimental Results

Experimental Results





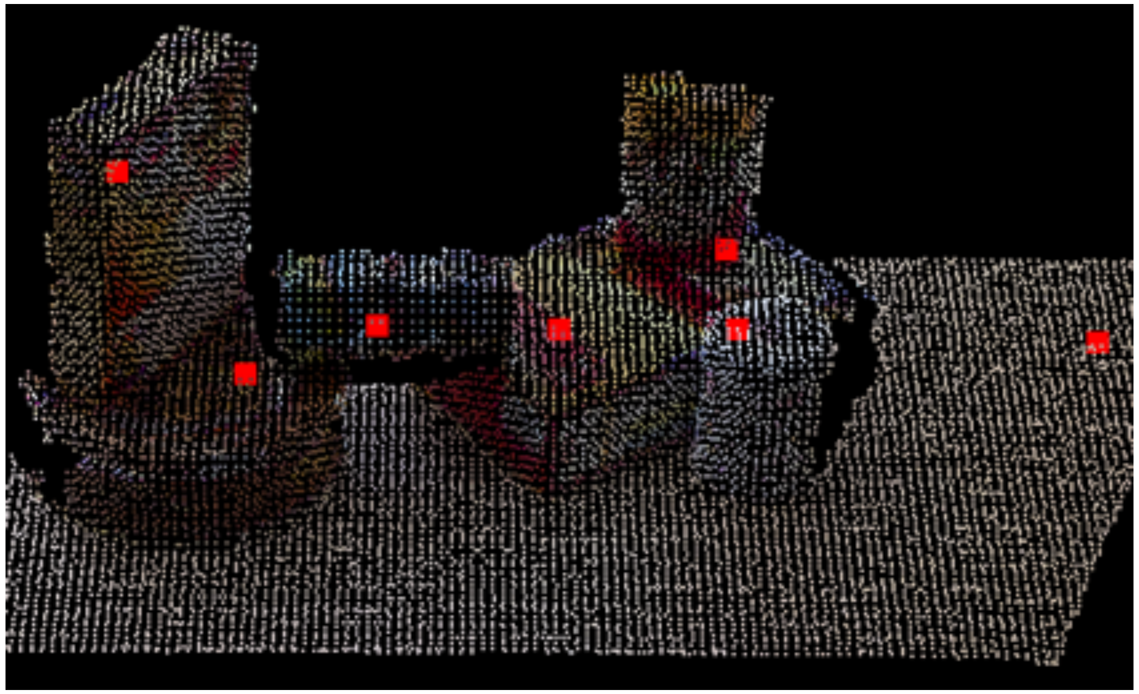

PR-M
PR2
rosrun pr2_props high_five



We need to dig deeper into the haptic signals that we do acquire.


you see physical properties

robots see only shape and color

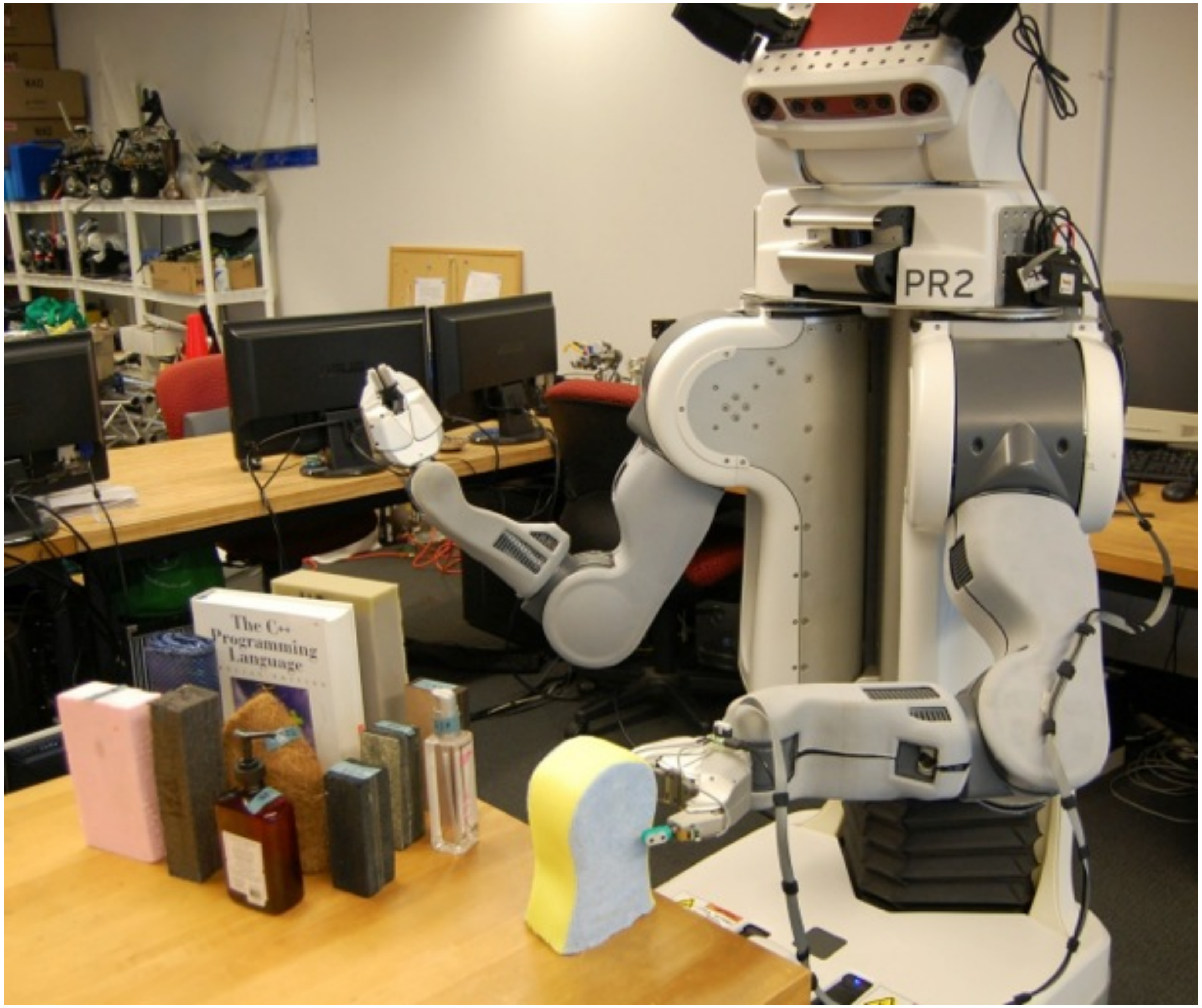


We need to enable robots to feel with their eyes, as humans do.

planning and executing actions

planning and executing actions

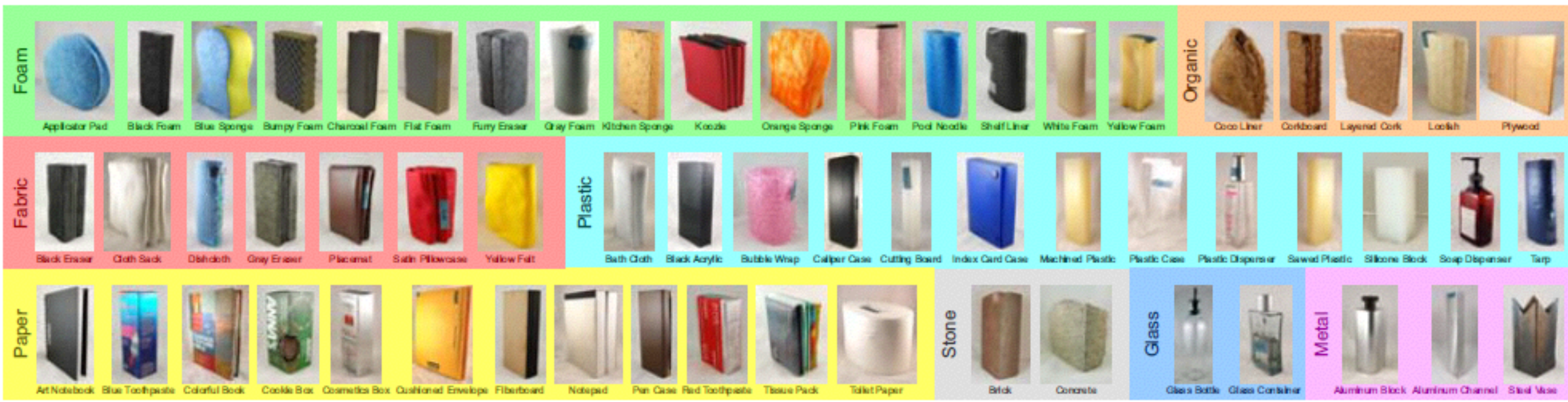
NRI: Collaborative: "Shall I Touch This?" Navigating the Look and Feel of Complex Surfaces (1427425)



PI's: Trevor Darrell (UC Berkeley) and Katherine J. Kuchenbecker (U. Penn)

Objective:

To develop a general visuo-haptic perceptual capability that enables a co-robot to look at a surface and infer haptic properties that are relevant to mobility and manipulation.



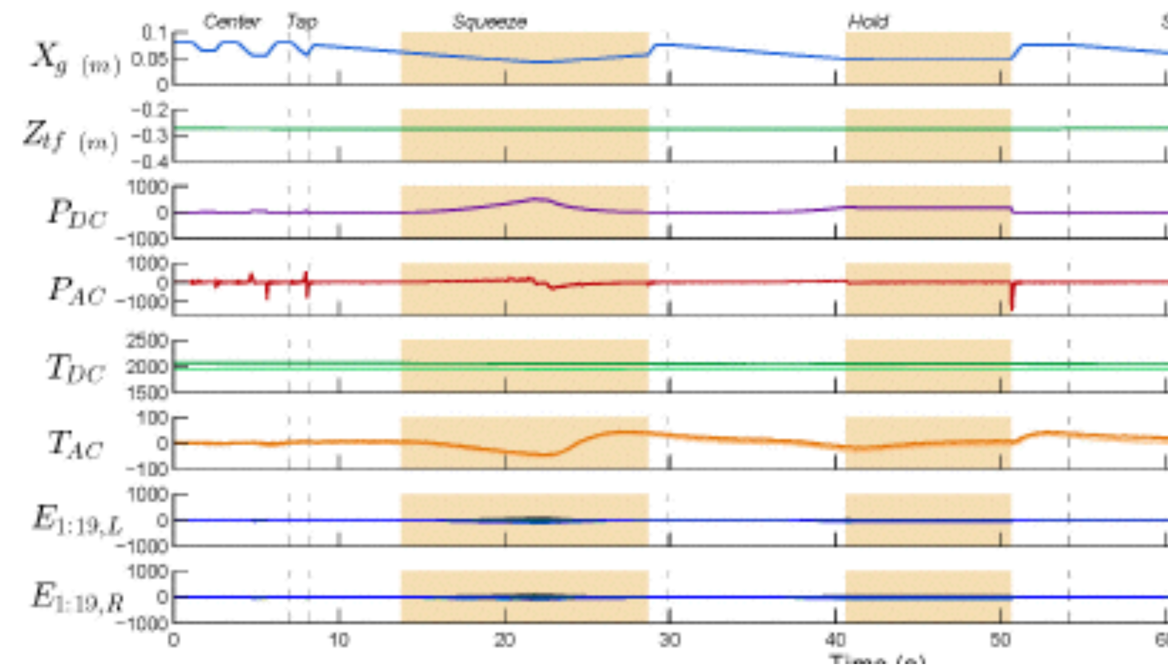
Penn Haptic Adjective Corpus

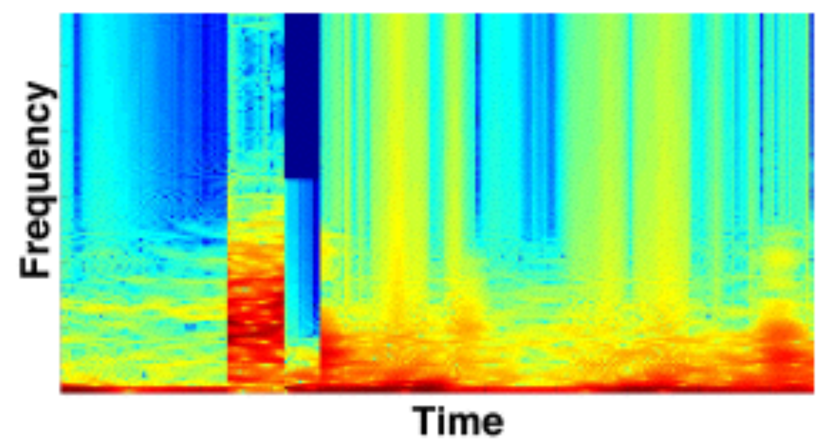
Hypotheses:

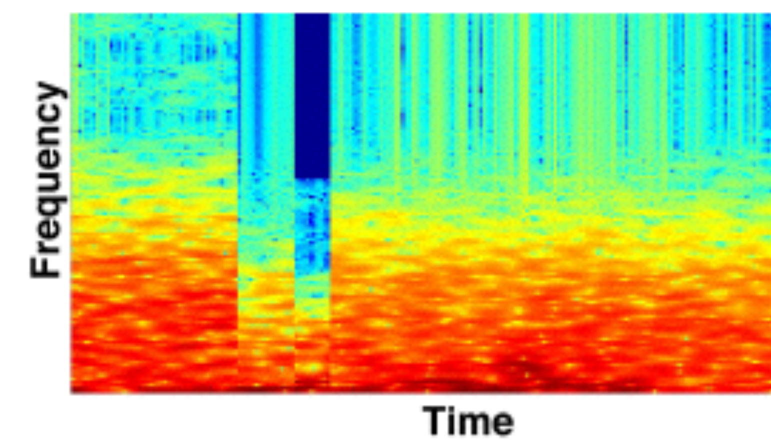
(1) Haptic and visual properties of real surfaces are systematically associated across sensory modalities in ways that can be learned.

(2) Co-robots can harness these learned cross-modal sensory associations for striking improvements in their capabilities, especially mobility and manipulation

Aims

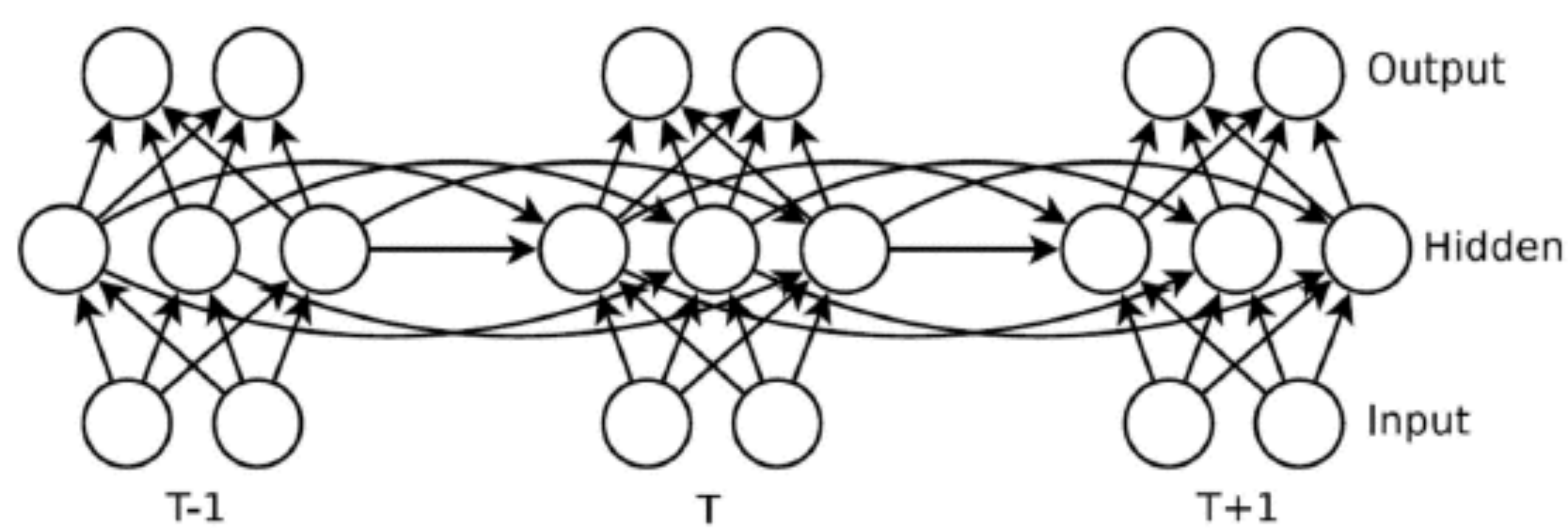






New:

- collection rig for paired haptic and visual data
- dataset(s)
- deep cross-modal time-series learning schemes
- inference models conditioned on local materials and object affordances




We need to enable robots to feel with their eyes, as humans do.

Why don't all modern robots incorporate rich **haptic sensing**?

beyond force

dig deeper

feel with the eyes

Funding Sources

University of Pennsylvania students and colleagues

NSF #0845670: "CAREER: Haptography: Capturing and Recreating the Rich Feel of Real Surfaces"

NSF #1427425: "Shall I Touch This? Navigating the Look and Feel of Complex Surfaces"

Coulter Translational Research Award: "Vibrotactile and Auditory Feedback for Robotic Minimally Invasive Surgery"

INTUITIVE SURGICAL® da Vinci Equipment and Funding

Willow Garage PR2 Robot

DARPA Broad Operational Language Translation (BOLT) Perceptually Grounded Robotic Language Acquisition

Thank you!

Katherine J. Kuchenbecker, Ph.D.
Associate Professor, University of Pennsylvania
kuchenbe@seas.upenn.edu
http://haptics.grasp.upenn.edu

Penn Haptics

Questions?

Katherine J. Kuchenbecker, Ph.D.
Associate Professor, University of Pennsylvania
kuchenbe@seas.upenn.edu
http://haptics.grasp.upenn.edu

Penn Haptics