Rendering material properties through touch

Roberta Klatzky, CMU Psychology and HCII
Outline

• What are material properties? What are not?
• Biological foundations of material property perception by touch
• Rendering texture on various devices
• Rendering compliance/stiffness
• Modeling complex interactions
What are material properties? What are not?

• **Geometry/Material** Distinction
  • Geometry describes a specific sample
    • Material irrelevant
    • Shape metrics
    • Size in 1, 2 or 3 dimensions

• Material properties apply to arbitrary samples
  • Surface (roughness, friction...)
  • Compliance (stiffness, viscosity, ...)
  • Thermal conductivity
Vision and touch: Modality specialization for geometry and material

• **Geometric properties**
  • highly accessible to vision; limited with touch

• **Material Properties**
  • highly accessible to touch; limited with vision

• **Material can be rendered** to touch by a variety of devices and algorithms
  • If you understand the biological transform
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  • Can people perceive material properties through a tool?
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1970s: Neural projections from “mechanoreceptors” beneath skin tied to 4 channels of touch characterized by resolution and temporal adaptation.
1980s: “Exploratory Procedures” link **action** to perceiving object properties

Material properties more accessible than geometric

Lederman & Klatzky 1987
1980s to present: Modeling underlying processes
Receptor channels + actions material properties

• Example -- Surface roughness
• *Temporal* variation induced by passing the finger over *spatial* variation (action) activates sensory channels.

*Model asks, what channels matter: Time or space?*
Time and space both matter!

Roughness perception macro scale (mm size elements)

~Spatial variation in SA I receptor responses

Subjective roughness increases as dots get sparser.

Connor, Hsaio, Phillips, Johnson, 1990
Roughness perception micro scale (sub mm scale)

Timing variation in rapid-adapting receptors

Plate is passed across the skin
Very finely textured, then smooth

Slow adapting receptors (SA I) fire continuously as fine texture varies

Rapidly adapting receptors differentiate very fine textures:

Srinivasan, Whitehouse, & LaMotte, 1990; Weber et al., PNAS 2013
It’s all in the timing:
Power spectra of firing rates of rapid adapting receptors (PC, RA) track skin vibrations for fine texture

Weber et al., PNAS 2013
**Mechanoreceptors + action + neural algorithms**  
**Material properties**

<table>
<thead>
<tr>
<th>Receptor</th>
<th>Exploratory Procedure</th>
<th>Material Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAI: slow adapting, high acuity</td>
<td>Lateral motion between skin and surface</td>
<td>Coarse Texture: Roughness, microstructure</td>
</tr>
<tr>
<td>RAI: rapid adapting, high acuity</td>
<td>Lateral motion between skin and surface</td>
<td>Fine Texture: Roughness, stickiness, friction...</td>
</tr>
<tr>
<td>RAIi: rapid adapting, low acuity</td>
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<tr>
<td>Kinesthetic: muscle, tendon, joint</td>
<td>Pressure applied to surface against resistance</td>
<td>Softness, elasticity...</td>
</tr>
</tbody>
</table>

Material properties perceived even with a tool...
Material property perception through a tool

• Tools *eliminate*
  • Array sensing from the fingertip /surface interaction
  • No shape/density/orientation of edges on finger

• Tools *preserve*, but *moderate*
  • Kinesthetic/temporal information from interaction
    • Texture from Vibration
    • Compliance, viscosity, friction stick/slip
Texture is perceived with a tool

- Jittered conical textures varying in spacing
- Explored with finger or sphere-tipped probe

Perceived roughness modulated by spacing between elements

Probe size effects predicted by “drop point” from texture to substrate

A large probe simulates the finger

Klatzky, Lederman et al., 2003
Most haptic devices act like tools

Butterfly Haptics Magnetic Levitation Device

Can we perceive material with a haptic device?
Can we use a haptic device to study how people perceive roughness?

Yes to both!
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• Rendering softness
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Texture Perception with the Maglev Device

- Manipulate geometric and surface parameters over large parameter space; not possible without virtual environment
- Measure perceived roughness and just-noticeable difference of virtual surface
- Compare results to human data; model underlying human process

Bert Unger thesis
Constraint Surface Algorithm

• Maps the haptic interaction point to a simulated probe on virtual surface
• Generates counter-force proportional to penetration depth
• Probe orientation maintained vertical
• When not in contact, probe flies freely, subject to gravity.
Rendered Sine Textures under Algorithm

Texture induced motion: the vibrotactile signal:

What leads to the perception of roughness?

Unger et al., ToH, 2013
Perceived roughness of rendered sinusoidal surface is *not* predicted by exploratory motion kinematics.

Each data point is a different texture (sine period).
Perceived roughness of rendered sinusoidal surface is correlated with total spectral power in force/time signal.
Rendering textures without a tool
Friction variation: Direct skin contact

- **TPad:**
  - Piezoelectric friction modulation
    - Colgate/Peshkin lab
    - Created by squeeze film effect of ultrasonic vibration

- Can friction render texture?
  - Spatio-temporal friction variation should activate rapidly adapting receptors
  - Timing of receptor firing should discriminate textures

Wiertlewski, Friesen, & Colgate 2016
Size of finger limits perception of spatio-temporal variation: Acts like a window for spectral analysis

“Textured” Surface

Spectrograms: Power at each wavelength by position

Large window: a textural “smear” representing all frequencies – gaps not perceived

Small window: Local spectral variations create temporal signal: texture differences detected

Meyer, Peshkin, Colgate, 2015
What is the scale limit for friction-based texture?

- Test with detection of local friction variation
  - ~.25 mm spatial period found to be threshold of gap detection
  - Below this is where finger is too big a Fourier “window” for the spatio-temporal variation in friction
Starting small gives room to grow: Friction gradient is easily perceived

Continuous Friction gradient (amplitude modulation) in space/time

Discrimination test:
Increasing or decreasing rightward?

High accuracy (d’>2.5) with 1-inch swipe

What creates a friction gradient?
Amplitude modulation
Frequency modulation
Noise modulation

Klatzky, Adkins, Bodas, Osgouei, Choi, Tan 2017
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Rendering Compliance / Stiffness

• What are the sensory cues in touch?

• Kinesthetic
  • Force/Displacement relation

• Haptic/ Cutaneous
  • Skin Contact area, pressure array

Fig. 1.3 Sources of information about an object's softness. Left Amount of linear displacement of the fingers when a force is applied. Right Shape and size of the contact area, and force distribution over this area. Bergmann Tiest & Kappers, 2014
Can people perceive compliance through a tool? Necessary for rendering with haptic device. Yes!

Similar softness rankings for materials explored with finger and stylus

(shown: 1 subject
Diagonal = accurate rank by physical measure)

Tool and Stylus produce Comparable average ranking accuracy

LaMotte, 2000
Rendering stiffness with a haptic device

- Stiffness is the relation between force and distance: By Hooke’s Law, $k = F/d$.

- Mechanoreceptors (particularly kinesthetic) signal information about $F$ (linear force) and $d$.

- So in theory, stiffness can be extracted from pressing between two fixed points along a spring.

- Is $k$ extracted from $F$ and $D$? Is it perceived from a single distance?

- Stiffness rendered by haptic device used to answer these questions.
Haptic devices provide an interesting test: Nonlinear stiffness, where F/d relation varies with d

Are people sensitive to variations in k?

If so, violates assumption that stiffness is perceived from a single location.

Explore within visually demarked range. Rate stiffness relative to modulus (linear spring).

Wu & Klatzky, in press
Experiments render linear & nonlinear springs of various k values and profiles

Full sine, initial positive vs. negative modulation

Half sine vs. full sine, initial positive modulation

Full sine, variations in direction, stiffness

Note: Work is the same in all 3 full sine conditions.

Wu & Klatzky, 2018
Results: sensitivity to nonlinearity, but complex
Effect of direction of modulation reverses between full and half sine shape
Modeling nonlinear spring stiffness estimates with step-by-step accumulation, perceptual distortion, and Bayesian discounting of noise

Only 1 free parameter

Enter time step j with prior force F, current stiffness estimate k & variance of k to date

Displace distance d,
Perceive new F,
Compute local stiffness \( k_{\text{new}} \)

Compute new global k estimate as weighted sum of \( k_{\text{new}} \) and previous estimate

<table>
<thead>
<tr>
<th>Timestep = j-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current stiffness k</td>
</tr>
<tr>
<td>Variance of k estimates</td>
</tr>
<tr>
<td>Force at time j-1</td>
</tr>
</tbody>
</table>

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<thead>
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<th>Timestep = j</th>
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<tbody>
<tr>
<td>Move = d (constant distance)</td>
</tr>
<tr>
<td>Perceive ( F_j = F_{\text{physical}}^{1.4} )</td>
</tr>
<tr>
<td>Compute ( k_{\text{new}} = \frac{\Delta F}{d} = \frac{(F_j - F_{j-1})}{d} )</td>
</tr>
</tbody>
</table>

Compute updated k estimate;
\[
k_j = k_{j-1} + w \cdot (k_{\text{new}} - k_{j-1})
\]

Weight given to new information is:
- inversely related to local change in estimate (avoid sudden changes)
- directly related to s.d. of previous k estimates (change estimate if old is unreliable)

\[
w = \alpha \cdot \left( \frac{1}{1 + z} \right)
\]

\[
z = \text{abs}[k(j) - K_{\text{estimated}}(j-1)] / \text{STDEV}(k_0, k_1, ..., k_{j-1})
\]

\( \alpha \) is the only free parameter.
Weight given to new information is:

- inversely related to local change in estimate (avoid large changes)
- directly related to s.d. of previous \( k \) estimates (change estimate if old is unreliable)
Fit to the data for all conditions: variations in wave form, underlying stiffness, direction of modulation
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Haptic devices render complex spring phenomena like buckling, puncture

Figure 1: Graphical representations of a (a) Compressed spring and an (b) Elongated spring

Figure 3: 2D view of forces and moments.

Varadharajan, Klatzky, Unger, Swendsen, Hollis, 2008
Modeling Complex Interactions: Puncture of Biological Materials

- We asked subjects to puncture a simulated membrane with minimal “skid” on the far side.

- A simple membrane model: visco-elastic

Klatzky et al., EBR 2013
Simulated-Membrane Task

Approach and compress membrane (viscous spring, parameter K varies)

Spring release = puncture
Burst and skid until brake to 0
Try to minimize skid
Our Model: Physics + Brain

Velocity declines for two reasons:

- Passive exponential force decay
  - Effects of muscle and soft tissue damping
- Perceptually initiated active braking
  - Larger signal for stiffer membrane (larger $K$ parameter)

Parameter Fitting

- Inertial mass of the hand-to-device coupling
- Time-constant of exponential force decay $\tau$
- Onset of active braking (fast cortical loop)
Distance/time behavior of model and data:
Deviation from the model indicates perceptually initiated control

Model predicted distance after breakthrough
Longer skid for stiffer membrane

Data with model fit

Point of deviation from model: Onset of cortical control

Time from burst (s)
Deviation from the passive model earlier with higher simulated K value: stronger perceptual signal
Despite more force to control with stiffer membrane, strong perceptual signal shortens total braking time.
But higher forces lead to longer skids and less control over active braking.

Position oscillations after deviation from model that signals active braking

Amplitude of oscillations increases with membrane stiffness
And away we go: Rendering “haptic semantics” for children’s reading and entertainment (with Disney)

Israr et al., ACM TAP 2014

Upscaled version: The “Force Jacket”

Delazio et al., CHI 218
Lessons learned

• Material properties can be rendered on haptic devices
• Successful rendering adapts device capabilities to biology of human perceiver
• Conversely, successful rendering allows us to understand biology of human perceiver
• Modeling complex interactions steps beyond material, with implications for applications
Thanks to collaborations and influences

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