Perception and Interfaces (COMP0160)

Lecture 4:

Tactile and Kinaesthetic Perception and Interfaces

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Topics covered in this lecture:

- The variety of physiological mechanisms that we collectively refer to as touch.
- The interactions of our touch senses with our other senses.
- The design of mechanical interfaces that directly engage our tactile and kinaesthetic sensory mechanisms, and the difficulties in creating effective systems
- How haptic illusions can be enlisted to bypass limitations of current technology

Overview (Part One)

Human haptic perception

- Touch vs Vision/Audio
- Tactile, Kinaesthetic and Proprioceptive Senses
- Psychophysics of Touch and Sensory Requirements
- Human Tactile & Kinaesthetic capabilities
- Mechanoreceptors of Human Haptics
- Vestibular component of Proprioception
- Sensory Integration & Conflict

Overview (Part Two)

Tactile and Kinaesthetic Interfaces

- Tactile interfaces
- Kinaesthetic interfaces
- Haptic rendering
- Contactless Haptics
- Passive haptics
- Pseudohaptics

Haptic Interfaces

- Complex robotics represents cutting edge…
- But almost all interfaces enlist our haptic senses
- Choices and design of buttons, joysticks, levers and pedals is informed by our haptic capabilities

Importance of Touch

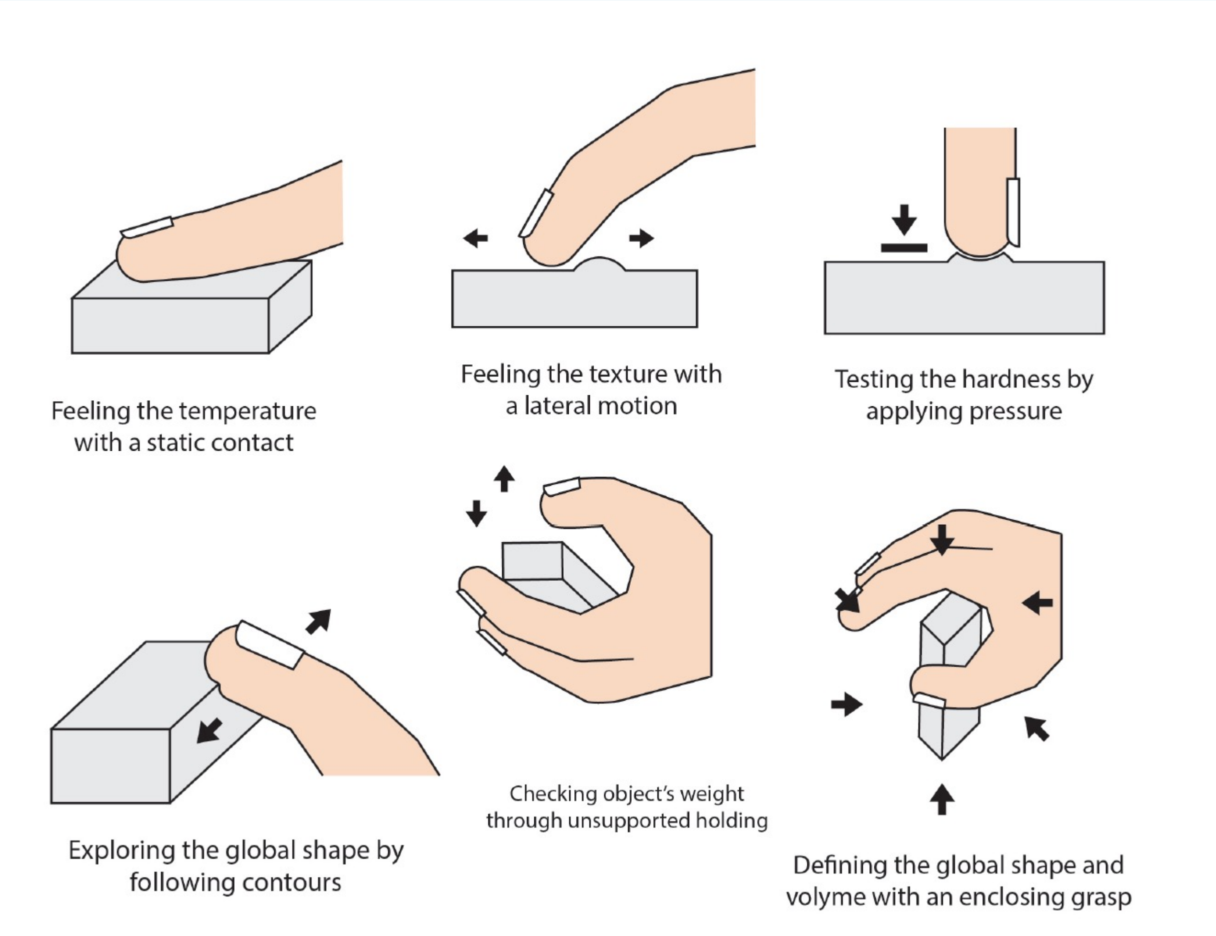
- Try to imagine losing your sense of touch
- Can simulate loss of vision or hearing, but not touch
- Robles-de-la-Torre describes 2 people who experienced loss of touch due to nerve damage
- Effects:
  - Inability to stand or walk
  - Could still move limbs, but without precision
  - Used vision to help compensate and relearn physical movements
  - Took many months + lifetime of concerted effort

Robles-De-La-Torre, G. (2006). The Importance of the Sense of Touch in Virtual and Real Environments. *IEEE Multimedia*, *13*(3), 24–30. https://doi.org/10.1109/MMUL.2006.69

Comparison with visual and acoustic senses

Touch	Vision/Audio
Active	Passive
Bidirectional	Unidirectional
Distributed all over body	Sensors at 2 locations
Multiple receptor types	Single/limited receptor types

Manual Exploration



Tactile, Kinaesthetic and Proprioceptive Perception

- Tactile
  - Surface characteristics
  - Sensors are part of our skin
- Kinaesthesia
  - Sense of our body's posture, position of our limbs
  - Forces acting on the body
  - Sensors located in muscles, joints and tendons
- Vestibular
  - Balance mechanism
  - Extends kinaesthesia
  - Sensors in inner ear

Psychophysics of Touch

- **Psychophysics:** relationship between physical stimuli and subjective sensation

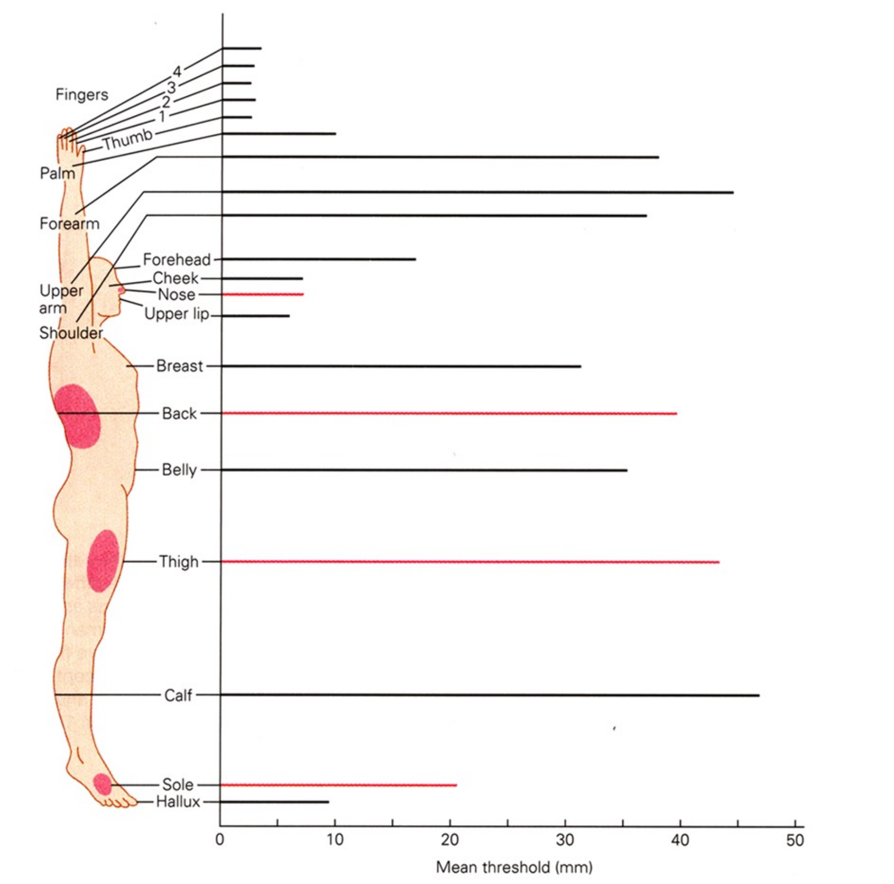
- Variety of haptic receptor mechanisms complicates psychophysics of touch

Haptic sensations

Physical Stimulus	Sensory System(s)	Description and Requirements
Texture	Tactile	Detection of small vibrations as we move our hand across a surface
Friction	Tactile + kinaesthetic	Friction due to rough surface, but (lack of) slippage of smooth surfaces also important. Latter requires sensors that detect skin stretch.
Force/Weight	Kinaesthetic	Detection of musculoskeletal forces and tension
Inertia	Kinaesthetic + proprioceptive/vestibular	Same mechanisms as above + enlists higher-level evaluation of changes in body posture
Viscosity	Kinaesthetic + tactile	Requires both kinaesthetic and tactile receptors to capture the inertia of the liquid and the effect of it moving over the surface of our skin.
Temperature	Tactile	Requires sensors responsive to temperature!

Human Tactile Capabilities

- Two-point Threshold



- Smallest detectable separation of two stimuli
- Separation varies across surface of skin
- Difficult to measure accurately

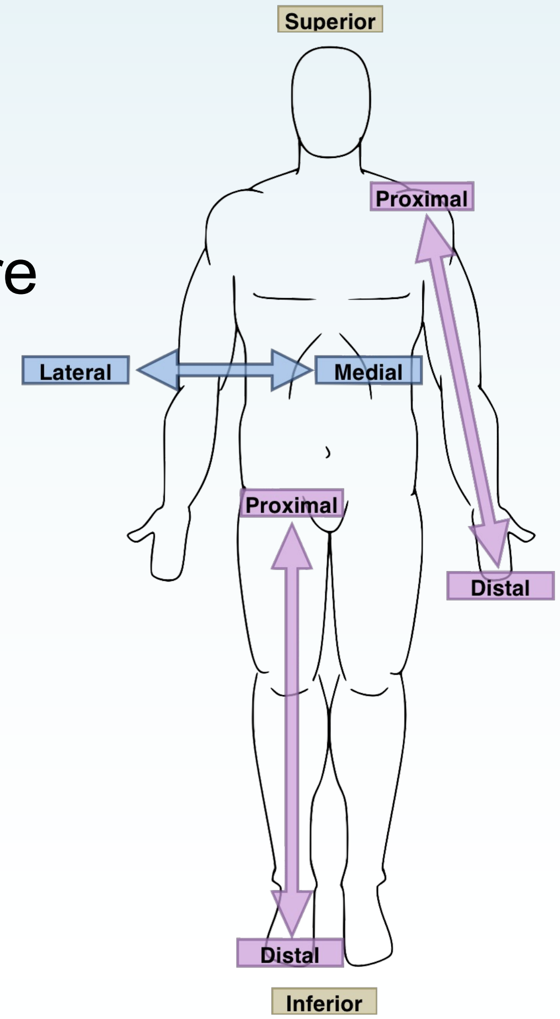
Human Tactile Capabilities

Limits of tactile perception:

- Fingertip can detect 1μm (1/1000th mm) raised dot on smooth plane surface
- Frequencies up to 500Hz reliably detected

Human Kinaesthetic Capabilities

- Accuracy and resolution better for proximal joints
- Limb position typically measured using a matching procedure
- Some errors larger than we might expect
- Proprioceptive drift in absence of visual cues
- Force resolution also measured by matching
  - Tends to be around 7% threshold for weights over 0.5N (50g)

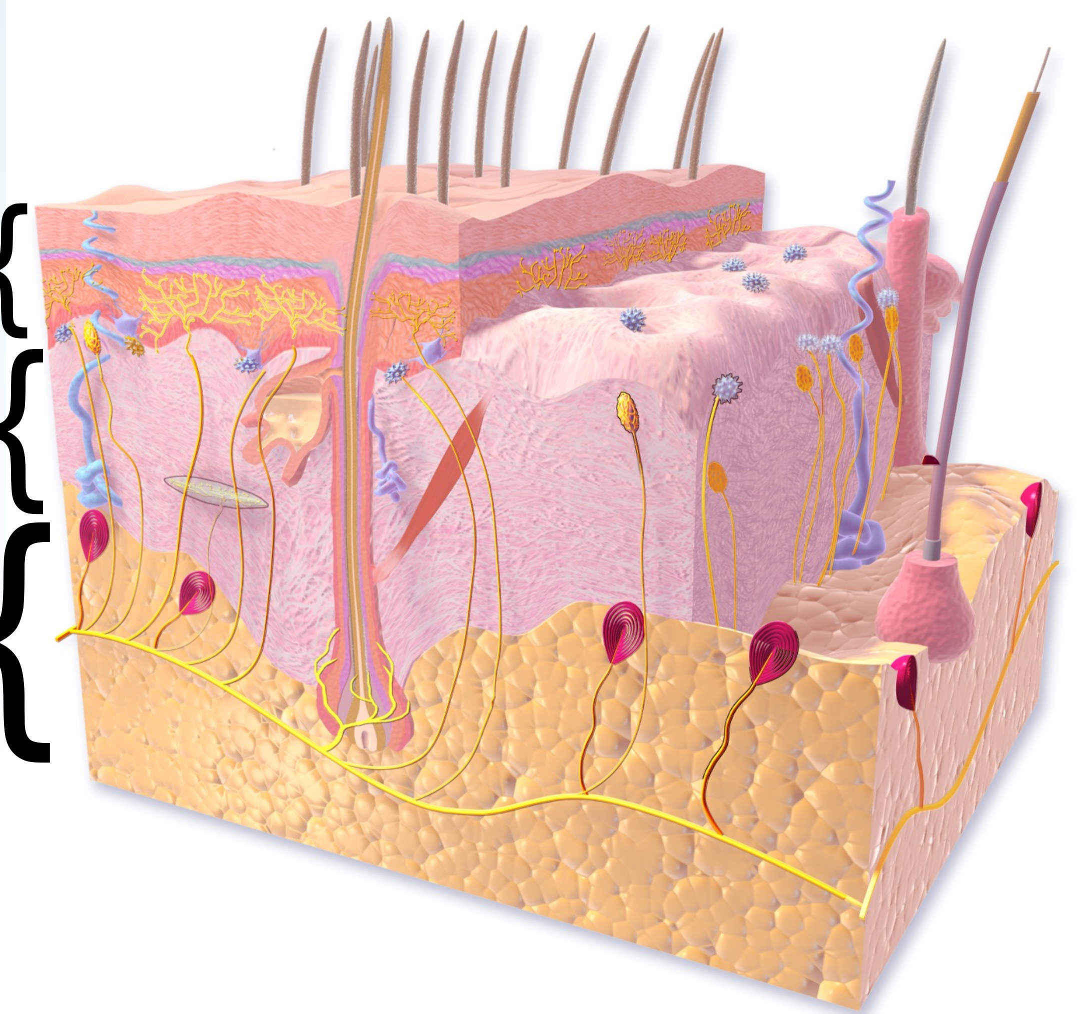


Mechanoreceptors of Human Haptics

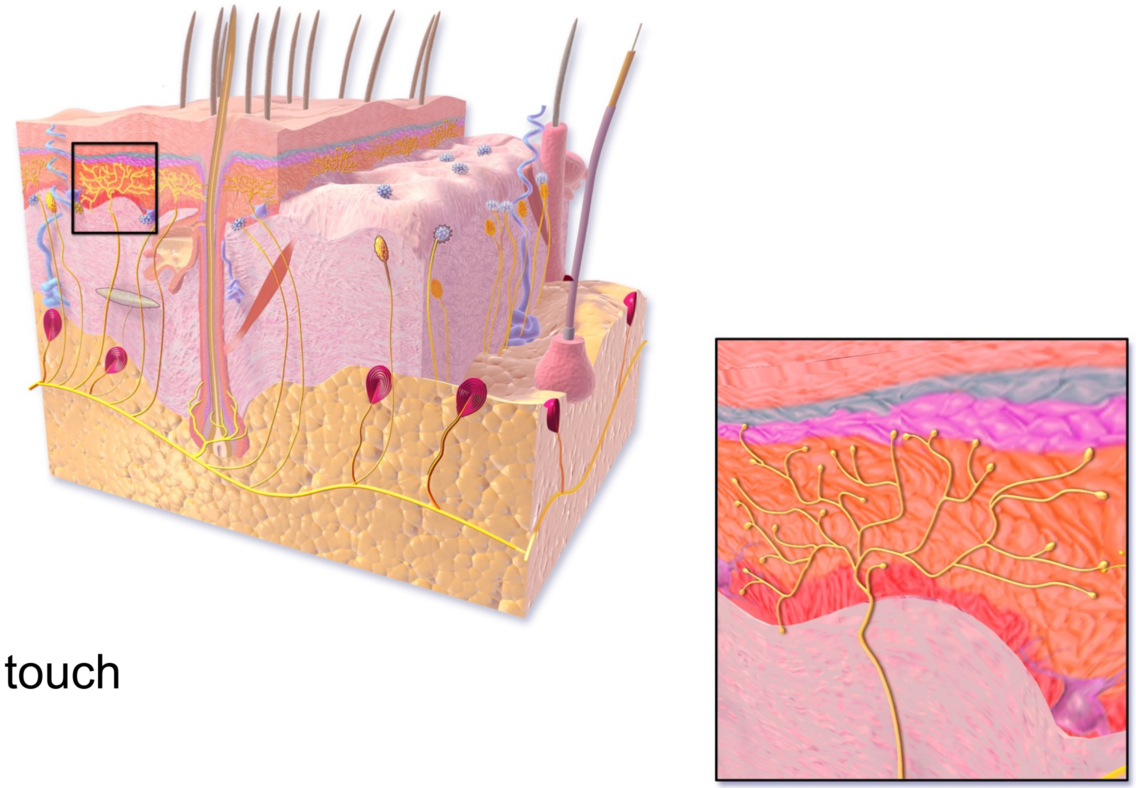
Epidermis

Dermis

Hypodermis



Free Nerve Endings



- Light discriminative touch
- Slow-adapting

Taxonomy of Tactile Mechanoreceptors

Frequency Response

- Slow-adapting (SA):
  - Low frequency response (0-20Hz)
  - Continuous response to stimulus
- Rapid-adapting (RA):
  - High frequency response (20-500Hz)
  - Responds to rapidly-changing stimulus e.g. vibration, texture

Taxonomy of Tactile Mechanoreceptors

Receptive Field Size

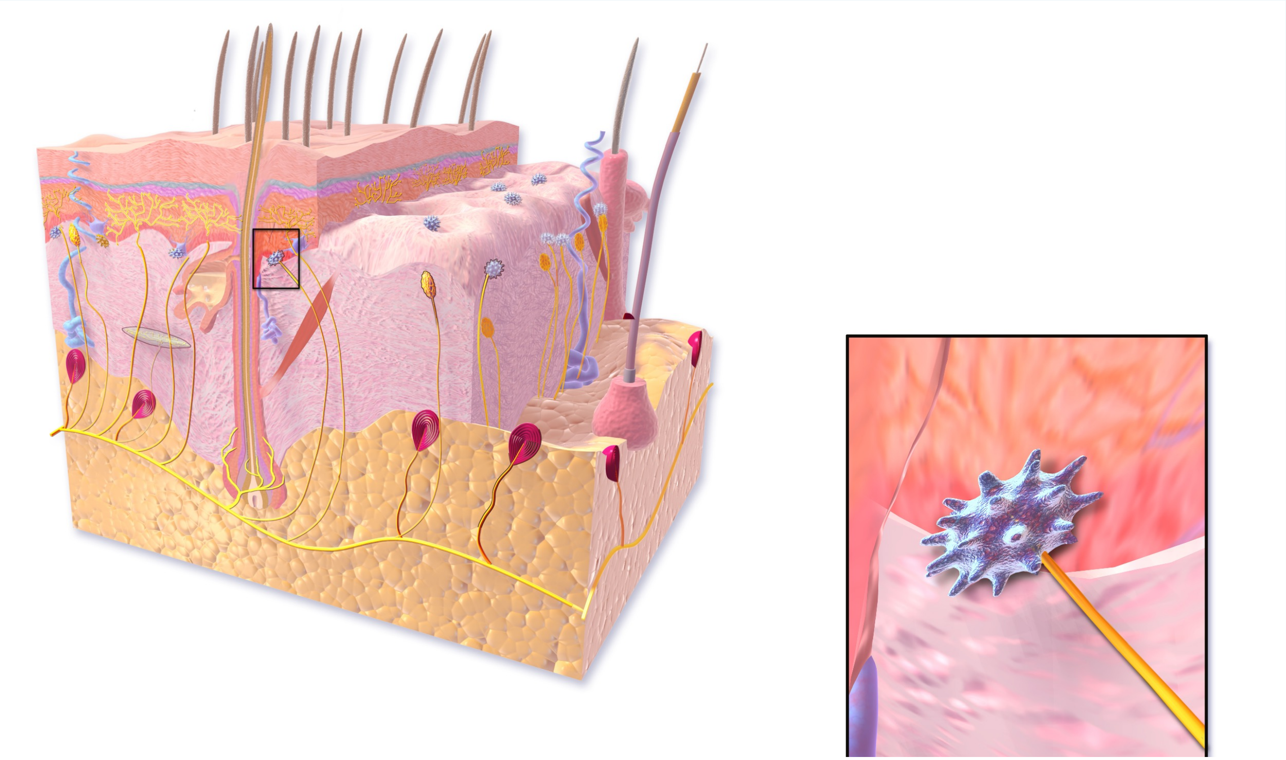
Type 1:

- Small receptive field
- Discrimination of fine detail

Type 2:

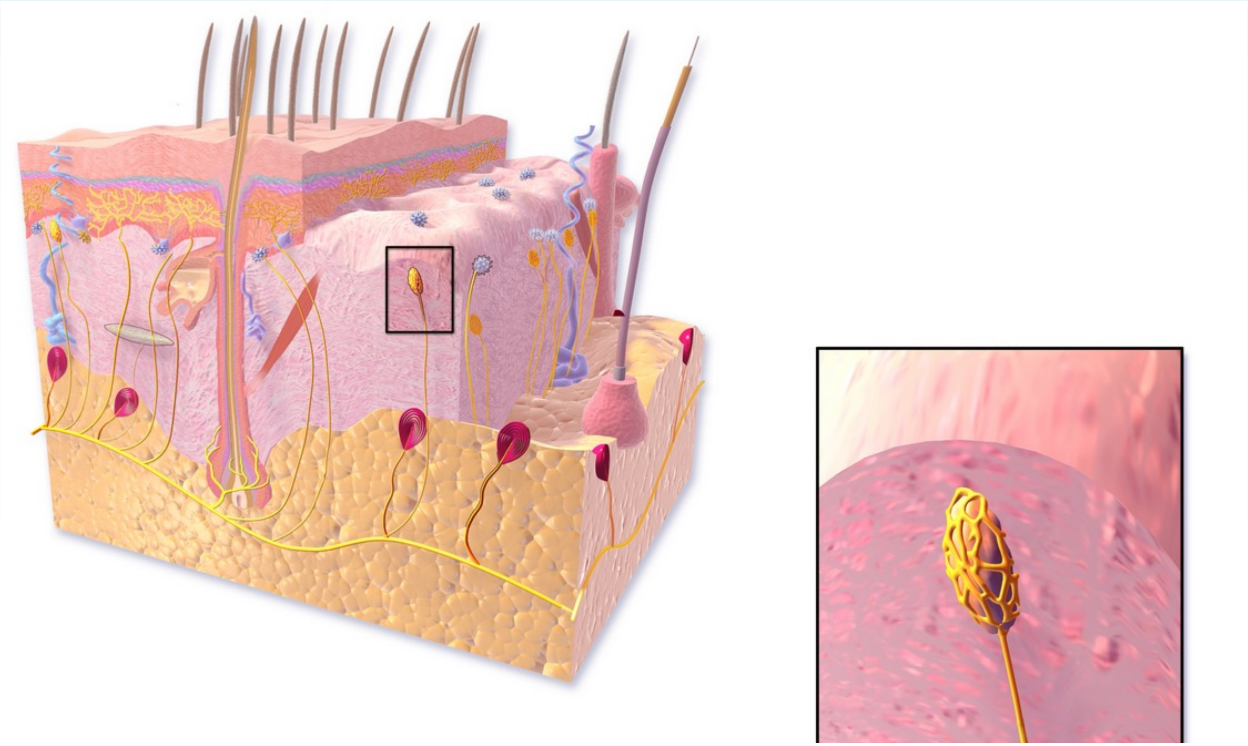
- Large receptive field
- Receptive to stimulus across larger area of skin, but lower spatial discrimination

Tactile Mechanoreceptors: Merkel's Disk



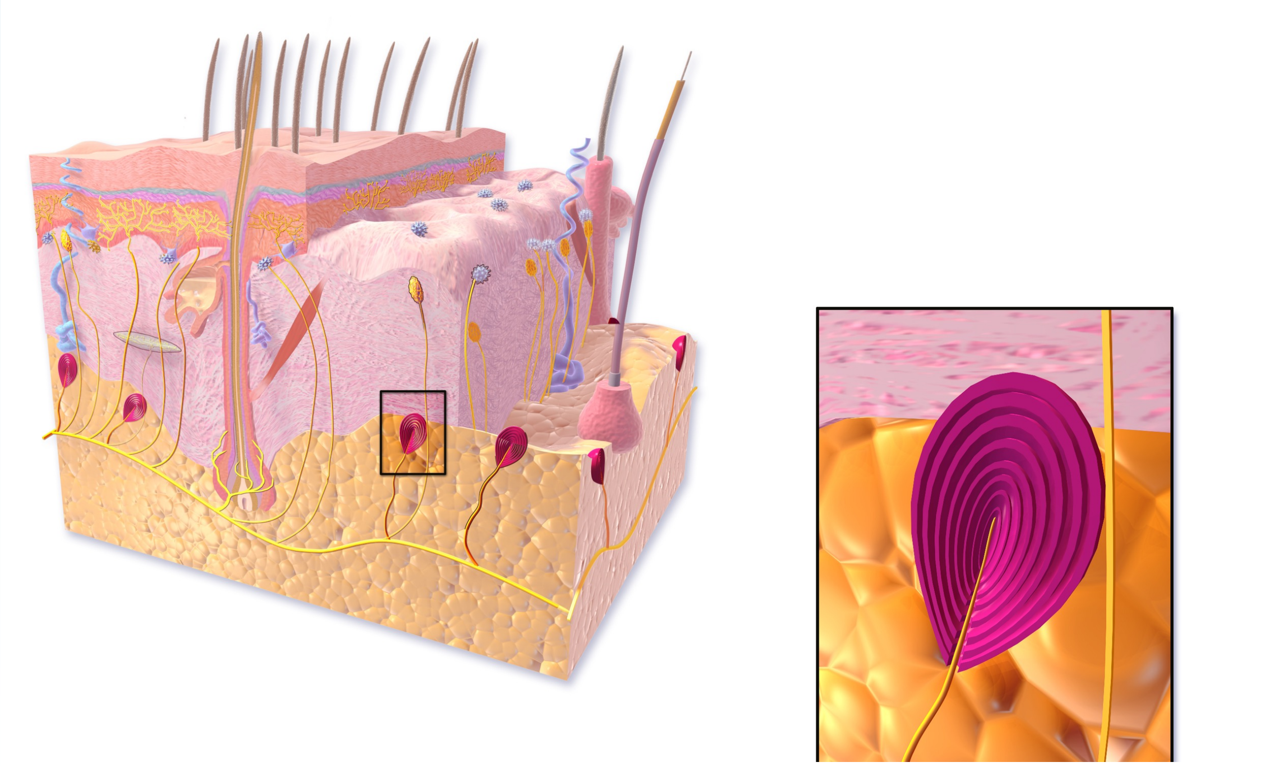
- Slow-adapting, Type 1 (SA1)
- Peak response ~0-15Hz
- Small receptive field (~0.5mm)
- Accurate location of touch, detailed form
- Very sensitive to small displacement (1 μm)
- High density on fingertips (~500/cm^2)

Tactile Mechanoreceptors: Meissner Corpuscle



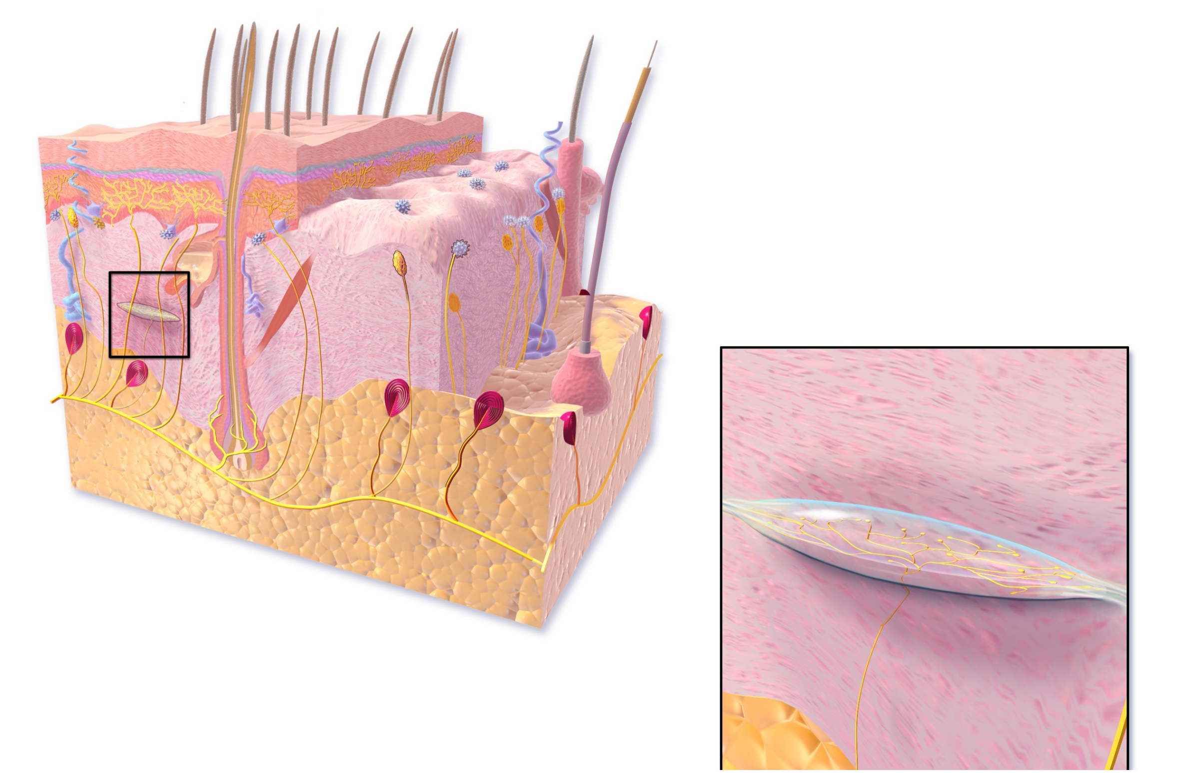
- Rapid-adapting, Type 1 (RA1)
- Peak response ~15-50Hz
- Small receptive field (~3mm)
- Light touch, texture perception
- Detailed form and texture
- High density on fingertips (>100/cm^2)

Tactile Mechanoreceptors: Pacinian Corpuscle



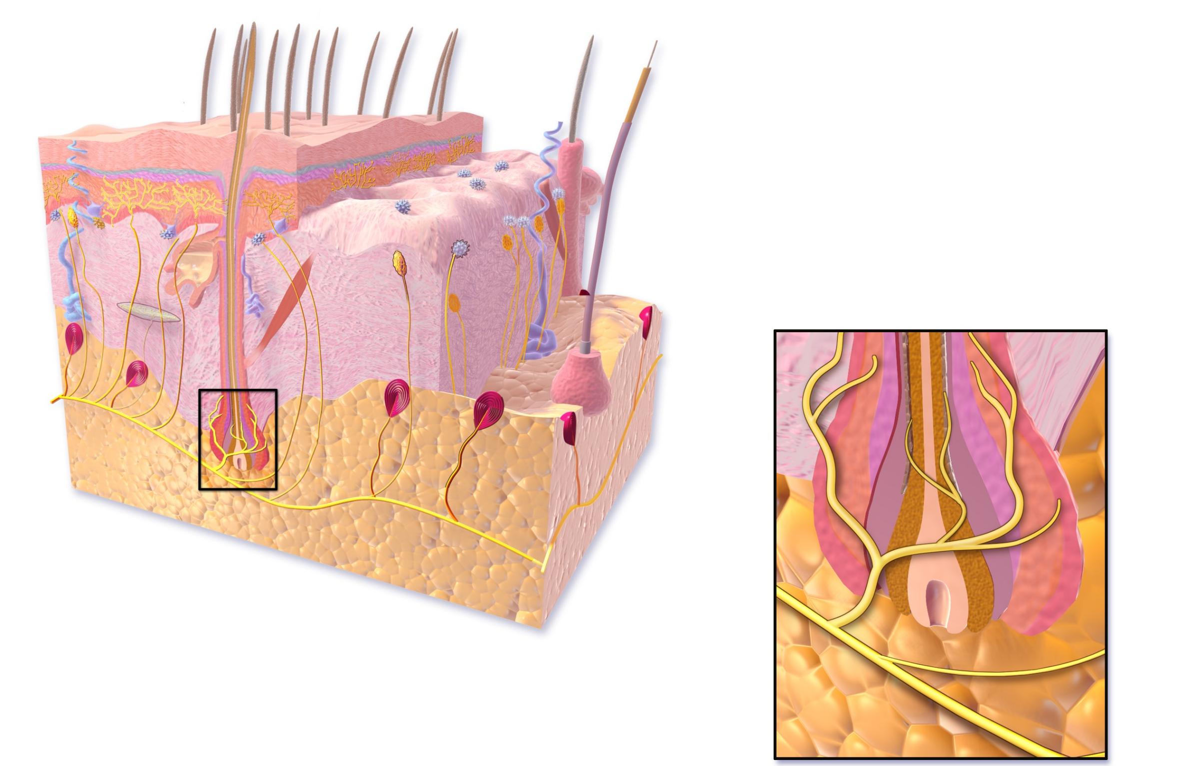
- Rapid-adapting, Type 2 (RA2)
- Peak response ~200-300Hz
- Large receptive field (>20mm)
- Spatially diffuse response
- Sensitive to vibration

Tactile Mechanoreceptors: Ruffini Corpuscle



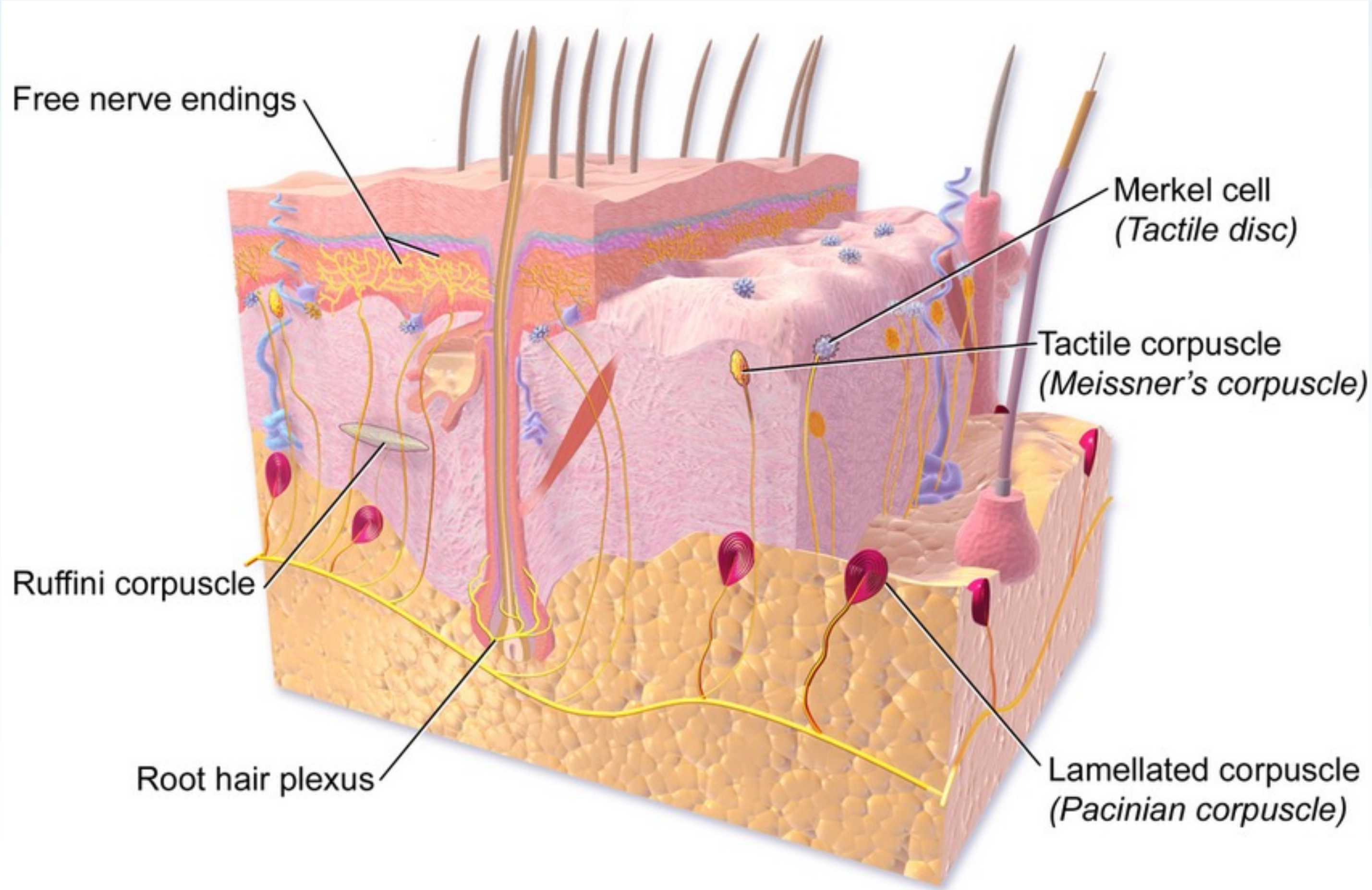
- Slow-adapting, Type 2 (SA2)
- Very low frequency (< 1Hz)
- Large receptive field (>10mm)
- Enlongated capsule located deep in skin
- Stretch and torque
- Also has kinaesthetic role

Tactile Mechanoreceptors: Hair Plexus



- Not a corpuscle!
- Specialised nerve endings at root of hair
- Respond to movement of hair

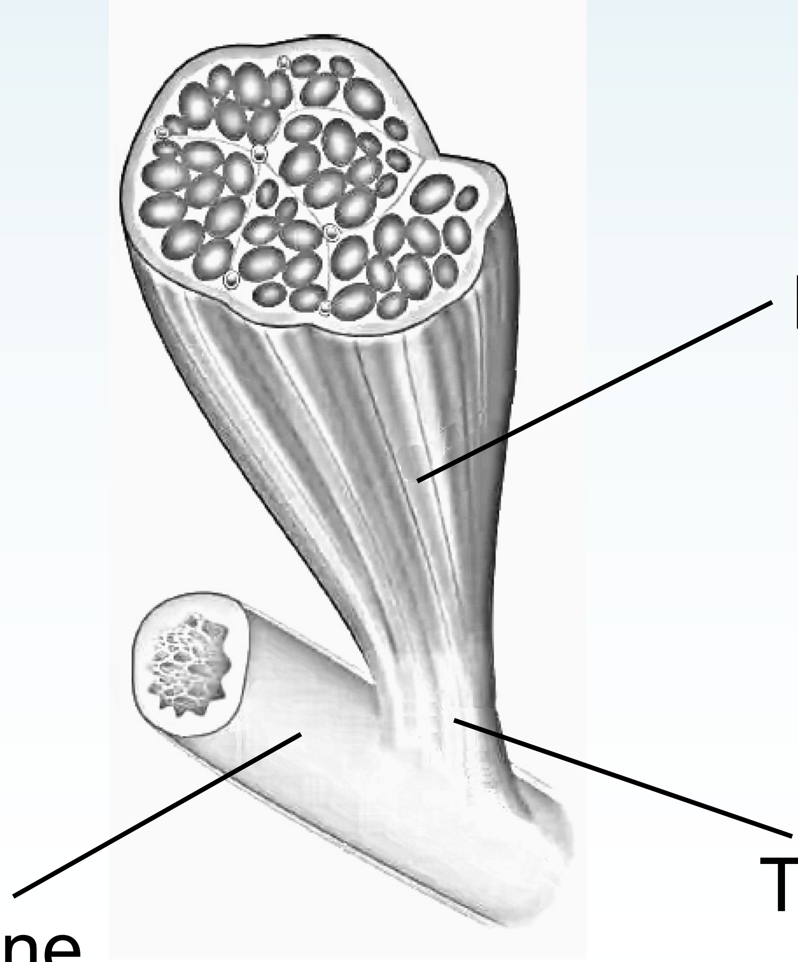
Tactile Mechanoreceptors



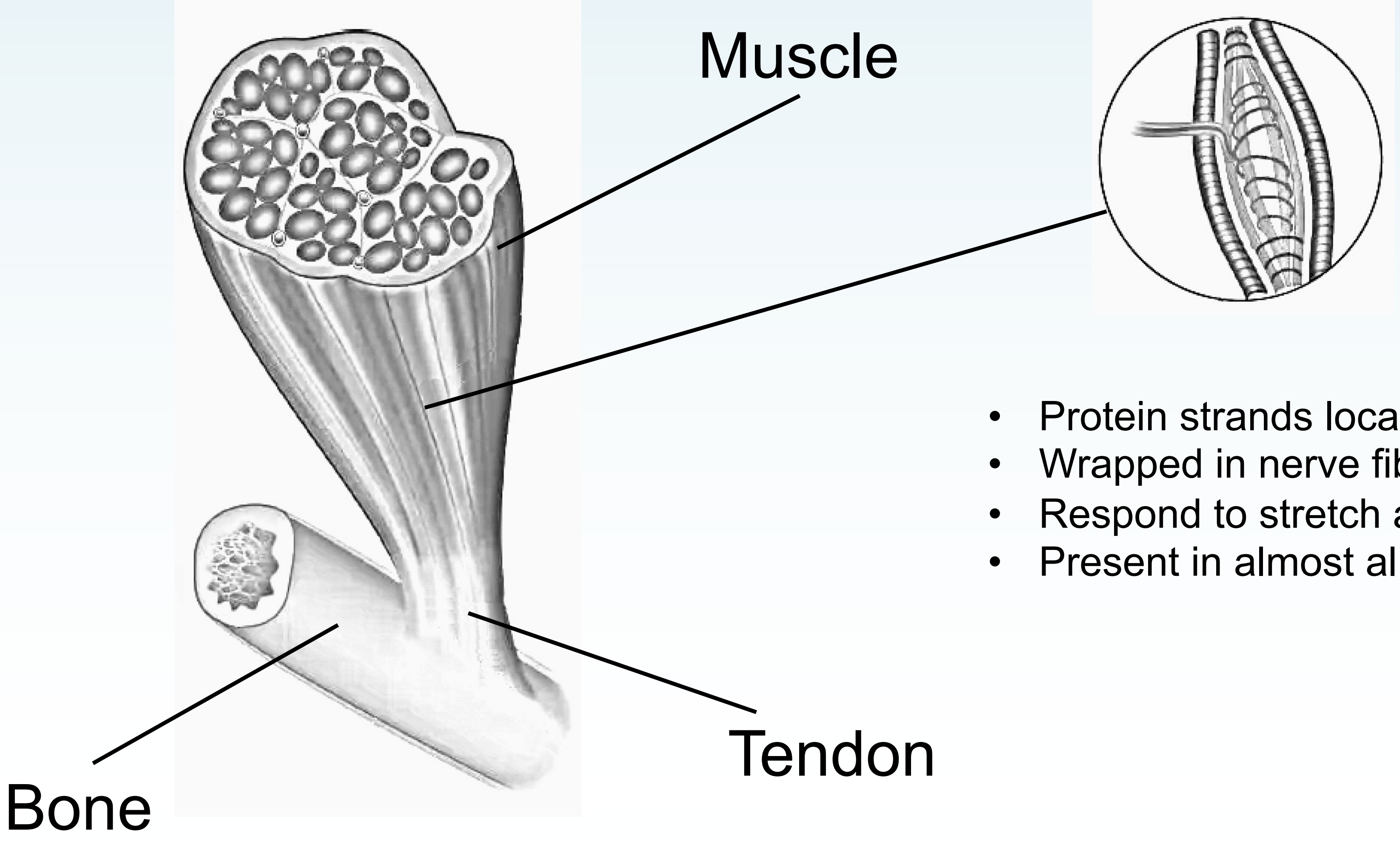
Kinaesthesia / proprioception

- Terms often used interchangeably
- Information about
  - Body posture
  - Body movement
  - Forces acting on the body
- Receptors located in muscles and tendons
- Proprioception can also include sense of balance

Kinaesthetic Mechanisms

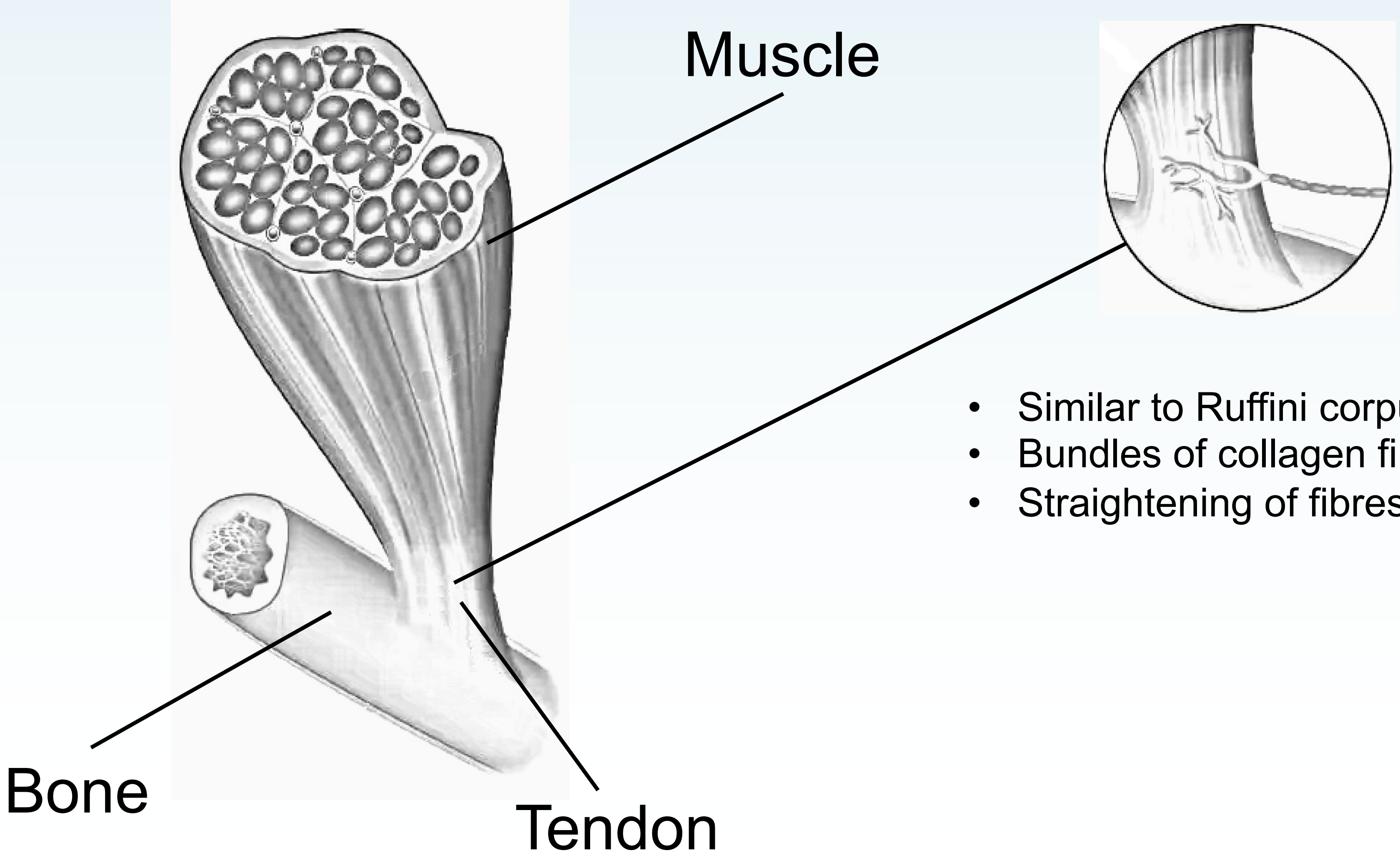


Kinaesthetic Mechanisms: Muscle Spindle



- Protein strands located alongside muscle fibres
- Wrapped in nerve fibres
- Respond to stretch and speed of stretch
- Present in almost all muscles

Kinaesthetic Mechanisms: Golgi Tendon Organ

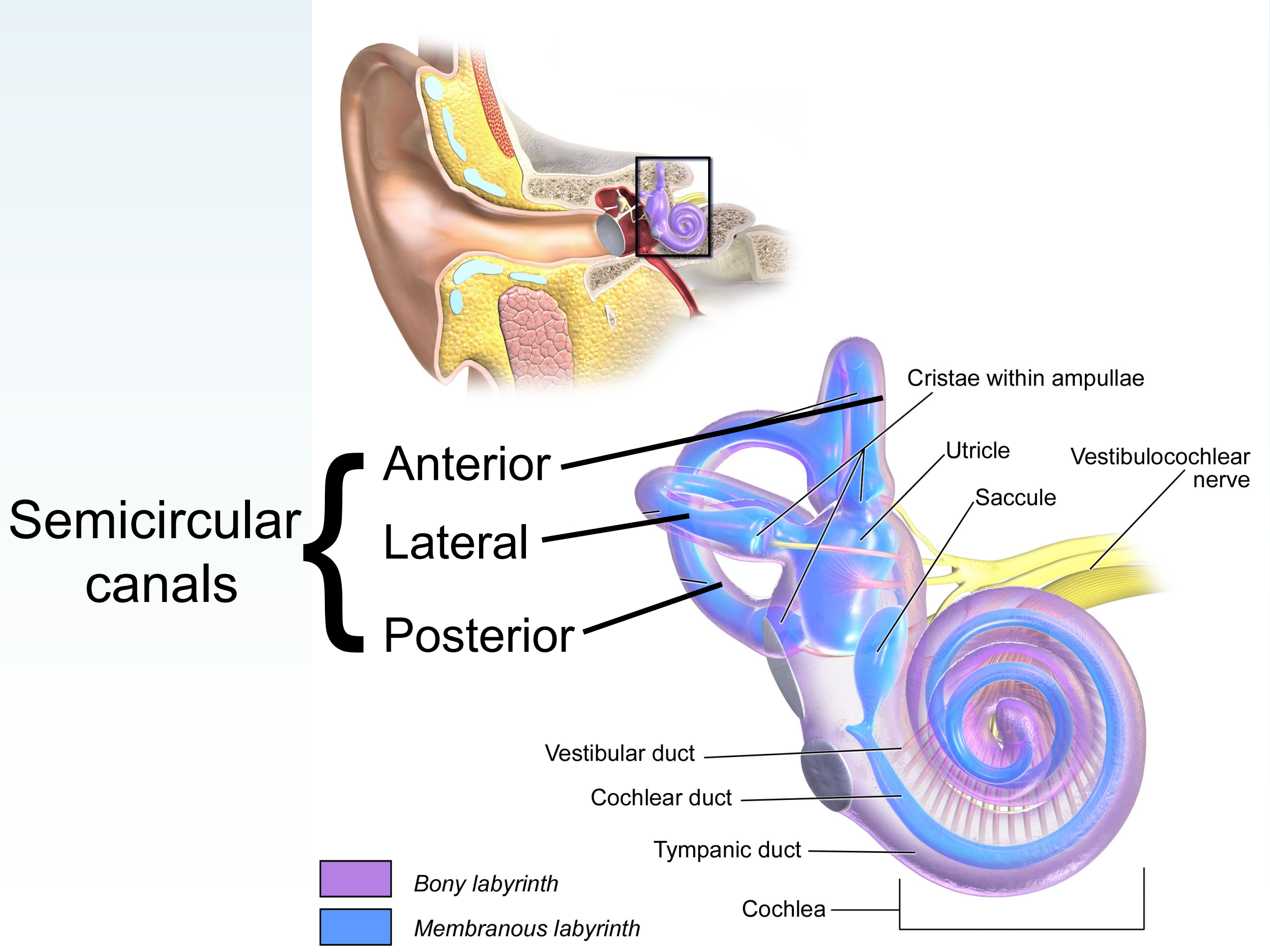


- Similar to Ruffini corpuscles
- Bundles of collagen fibres
- Straightening of fibres activates nerves

Joint kinaesthetic receptors

- Ruffini and Pacinian corpuscles also have a role in detecting movement of small joints (e.g. fingers)
- The function of these receptors serves both tactile and kinaesthetic sensation
- => our neat categorization doesn’t always work!

Vestibular component of Proprioception



- Semicircular canals contain slightly viscous fluid
- Inertia causes this to flow opposite to head rotations
- Flow stimulates fine hair cells (cilia) in canals
- Response from 3 canals aggregated for head rotation estimates

Sensory Integration

- Normally refers to integration of data from our main senses
- Also occurs at a lower level to integrate data from different types of mechanoreceptor, distributed throughout the body

Sensory Conflict

- Visual-vestibular conflict → dizziness, nausea
- Visual-kinaesthetic conflict → proprioceptive drift

Recap

- Haptic senses are moderated by a variety of different mechanisms
- Tactile information:
  - Pressure (compression of skin), Vibration, Texture (vibration caused by movement across the skin), Stretch
  - Captured by mechanoreceptors in skin
- Kinaesthetic data:
  - Musculoskeletal posture, forces and balance
  - Captured by force and stretch receptors in muscles and tendons, and vestibular organ in ears

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Lecture 4:

Tactile and Kinaesthetic Perception and Interfaces

(Part 2)

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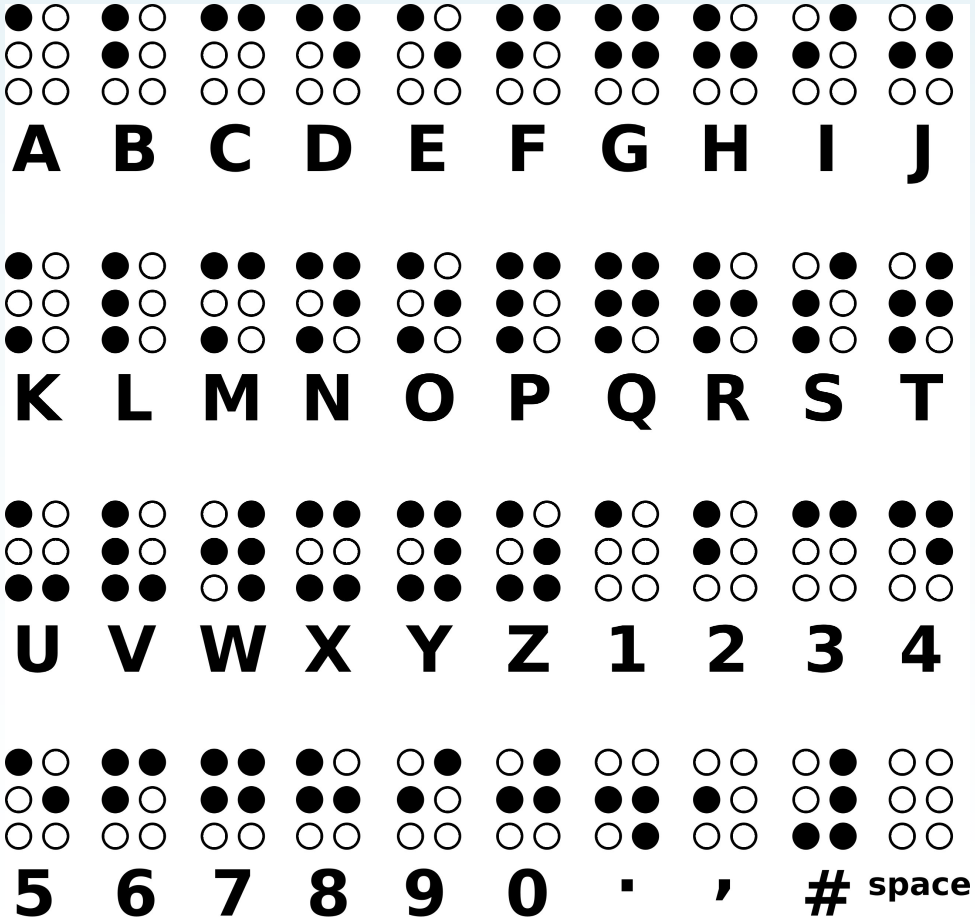
Tactile & Kinaesthetic Interfaces

- Wide range of approaches to haptics
- Technologies usually designed to engage specific elements of the human haptic system
- Devices that combine actuators to engage multiple haptic senses referred to as Multimodal Haptic Devices (MHD)

Culbertson, H., Schorr, S. B., & Okamura, A. M. (2018). Haptics: The Present and Future of Artificial Touch Sensation. *Annual Review of Control, Robotics, and Autonomous Systems*, *1*(1), 385–409. https://doi.org/10.1146/annurev-control-060117-105043

Wang, D., Ohnishi, K., & Xu, W. (2020). Multimodal Haptic Display for Virtual Reality: A Survey. *IEEE Transactions on Industrial Electronics*, *67*(1), 610–623. https://doi.org/10.1109/TIE.2019.2920602

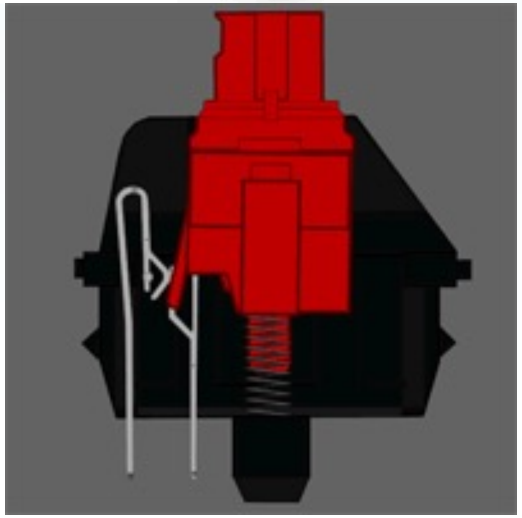
Tactile Displays: Braille



- Characters represented by raised dots
- Allows letter identification from single fingertip touch
- Stimulates Merkel Disk mechanoreceptors

Tactile Displays: Buttons

- Tactile click tells us that button has been pressed
- Designed for specific actuation force
- Allows binary input only
- VR controller additionally has axis controls (trigger and grip) returning range of values



Tactile Displays: Real vs Virtual Keyboards

- Virtual Keyboards lack haptic feedback
- => Demand more visual attention
- However are highly configurable (visually)

• Vibrotactile Actuators

Ryo Tada https://www.fulu.site/

Used in

- Fingertip-mounted devices (usually mounted on fingerpad)
  - Simulation of surface texture
- Mobile devices
  - Alerts and notifications
- VR and games controllers
  - Rudimentary haptic signalling, pseudohaptics (see later!)

Further reading:

Choi, S., & Kuchenbecker, K. J. (2013). Vibrotactile Display: Perception, Technology, and Applications. *Proceedings of the IEEE*, *101*(9), 2093–2104. https://doi.org/10.1109/JPROC.2012.2221071

Vibrotactile Actuators

Ryo Tada https://www.fulu.site/

- 3 types of actuator:
  - **Piezoelectric**
    - Piezoelectric material changes shape when voltage applied
    - Fingertip devices
  - **Linear Resonant Actuator**
    - Magnetic coil pushes small mass against spring
    - Fingertip devices, mobile devices, VR controllers
  - **Eccentric Rotating Mass (ERM)**
    - Small motor with off-axis mass
    - Mobile devices, VR Controllers

Further reading:

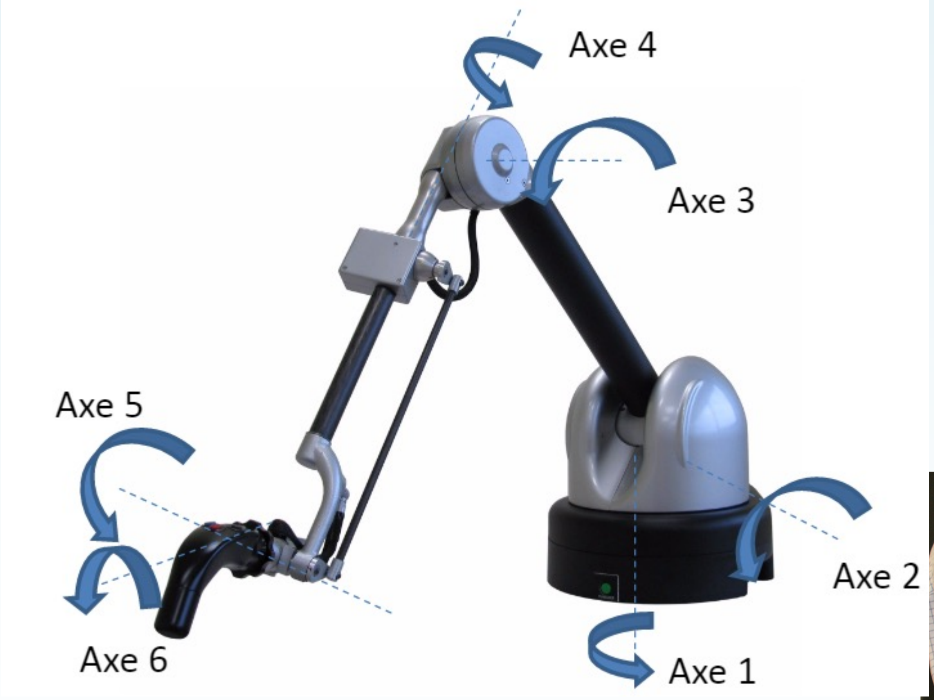
Choi, S., & Kuchenbecker, K. J. (2013). Vibrotactile Display: Perception, Technology, and Applications. *Proceedings of the IEEE*, *101*(9), 2093–2104. https://doi.org/10.1109/JPROC.2012.2221071

Kinaesthetic Interfaces: Force feedback displays

Phantom Omni

- Widely used design over 25 years
- Forces are transmitted to stylus held by user
- Motors in base apply linear forces in 3 directio
- No rotational force (torque)
- Very accurate tracking

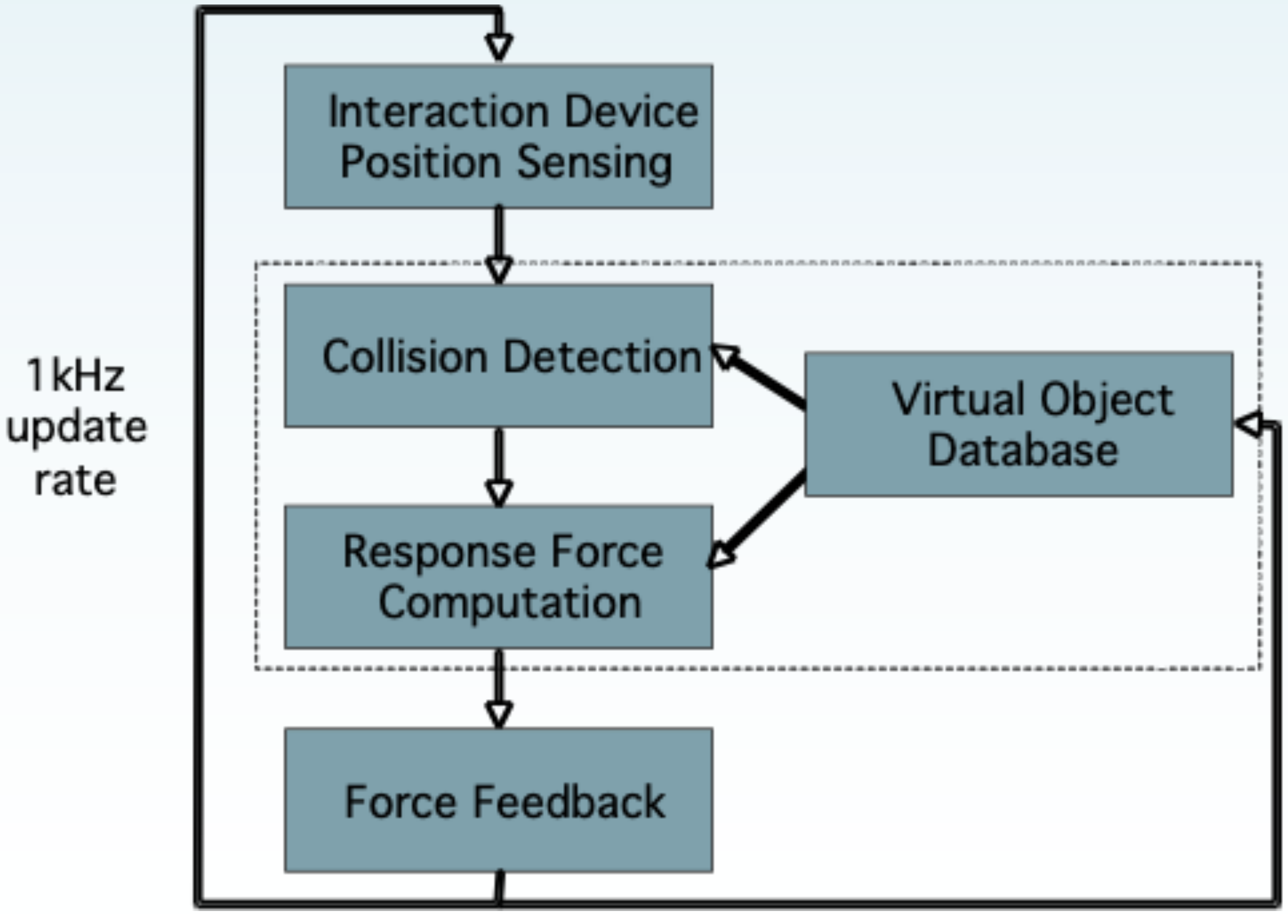
Kinaesthetic Interfaces: Force feedback displays



Haption Virtuose

- Similar design in larger form factor
- Larger design allows full range of motion of human arms
- Motors in base and linkage axes provide linear and rotational forces

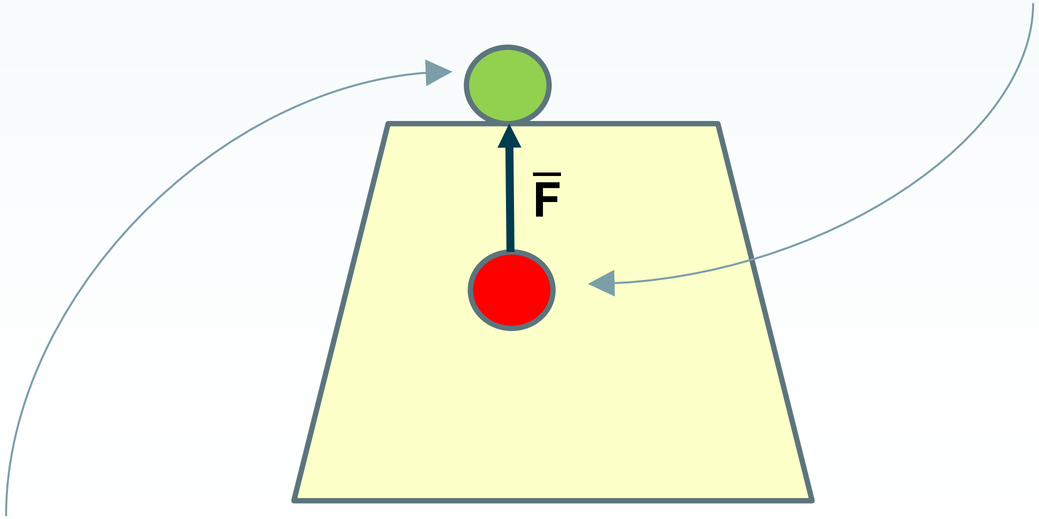
Haptic Rendering



Haptic Rendering Using Virtual Proxies

- The actual location of the haptic device is the haptic interface point (**H**)
- The virtual cursor (**V**) does not intersect the object
- Device produces force to move **H** back to **V** i.e. along vector **V - H**

Haptic Interface Point, **H**

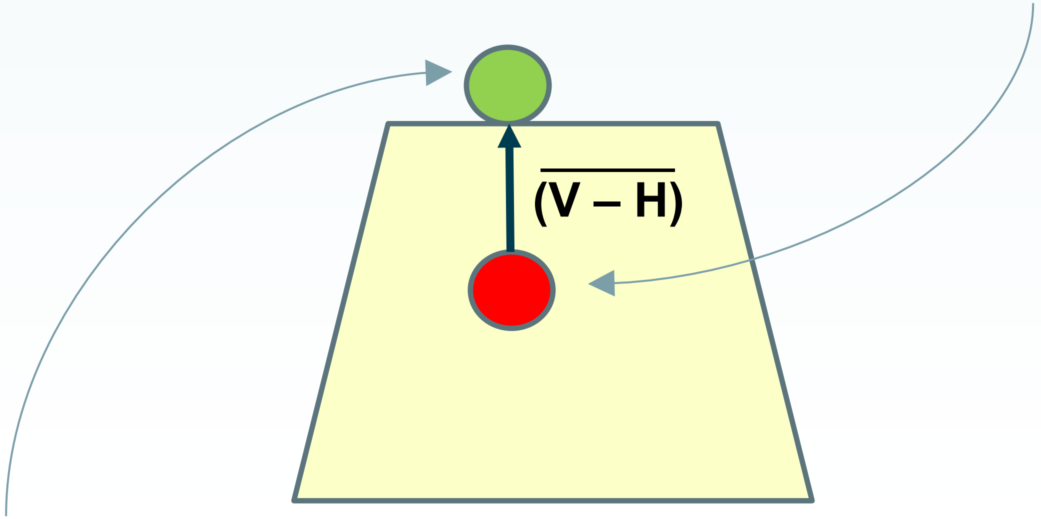


Virtual Proxy, **V**

$$\overline{F} = f(\overline{V - H})$$

How Much Force To Apply?

- Should be some function of vector **V – H**
- Force needs to overcome inertia of actuator
- Should also consider the compliance of the virtual object (how pliable is it?)
- Requires complex mechanical and control algorithms



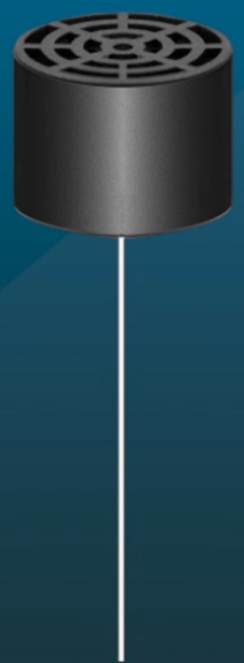
Tool-based Interaction

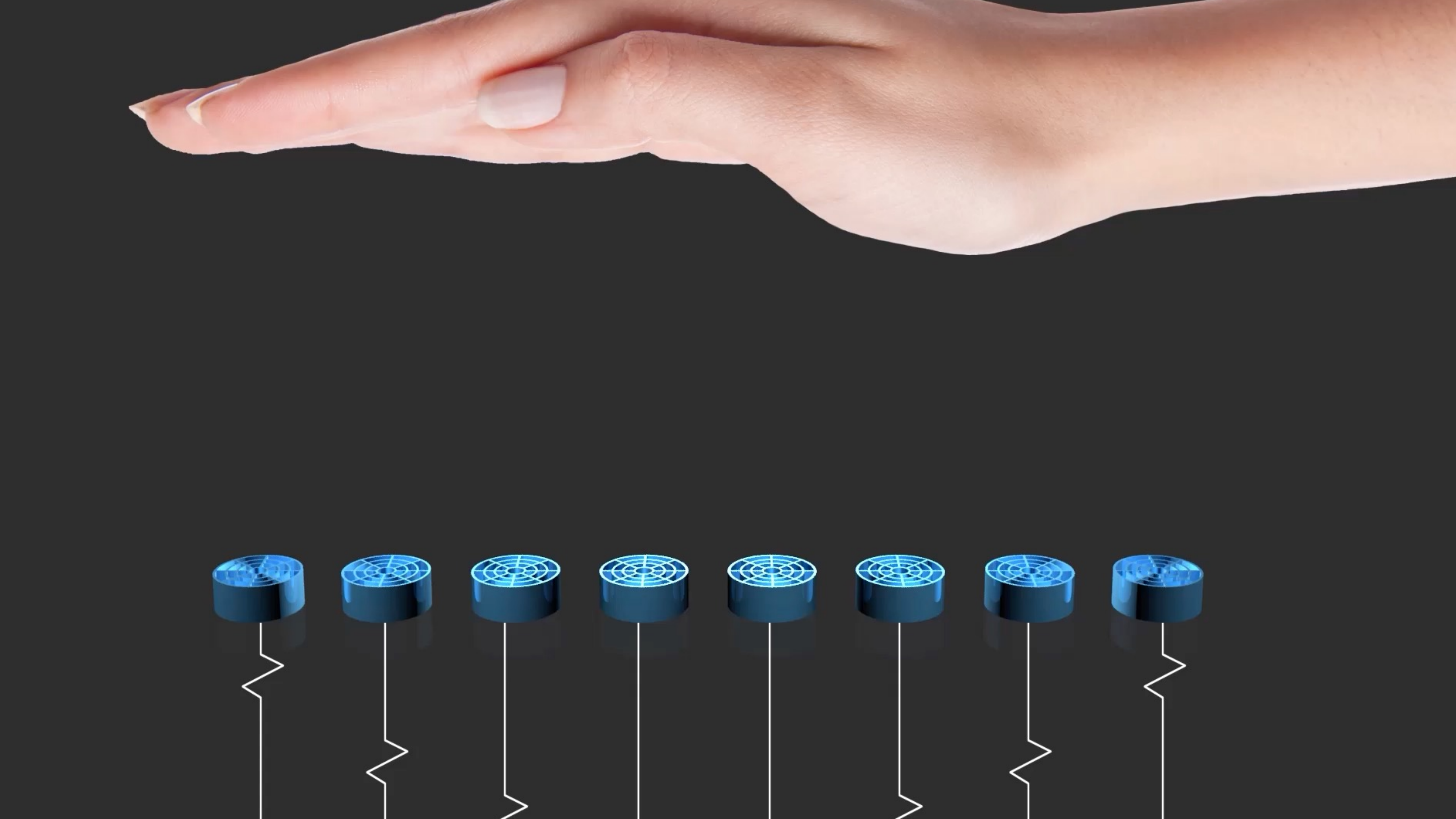
- Force feedback at single point
- Forces transmitted through device’s end-effector
- Useful for tool-based training e.g.:
    - Surgical or dental training
    - Industrial applications

Grasping Haptics

Dexmo Glove

- Force feedback applied to individual fingers
- 1D linear force at each finger (no torque)
- Not grounded => cannot simulate weight
- Consider *encumbrance* of device





Passive Haptics

- Uses real objects in user's environment as haptic proxies for virtual objects
- No active mechanical devices
- Requires production and accurate placement of proxy objects
- Real world and physics simulation may not align!
- Useful for objects that have limited and/or defined ranges of motion
- Also useful for simulating underfoot terrain

Hoffman, H. G. (1998). Physically touching virtual objects using tactile augmentation enhances the realism of virtual environments. *Proceedings. IEEE 1998 Virtual Reality Annual International Symposium (Cat. No.98CB36180)*, 59–63. https://doi.org/10.1109/VRAIS.1998.658423

Pseudohaptics: background

Yuan, Y., & Steed, A. (2010).

Burns et al (2005)

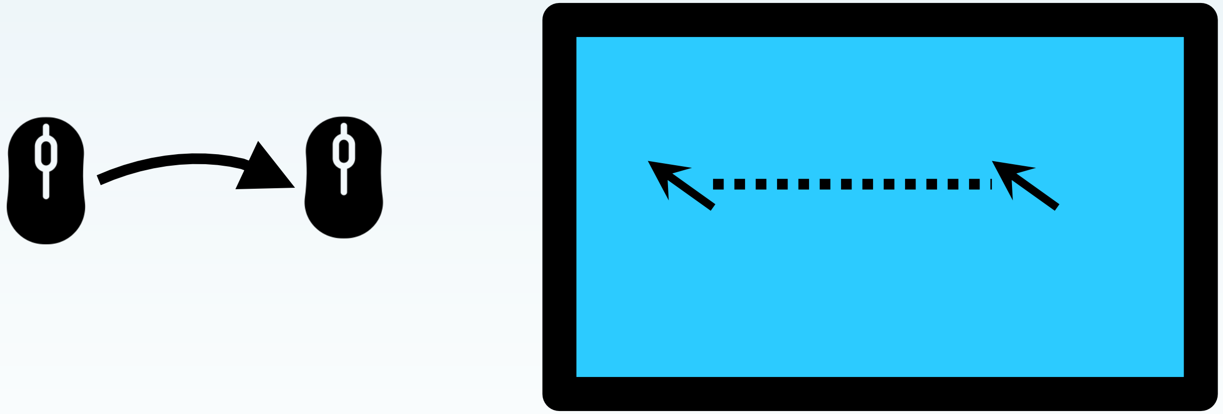
- Embodiment is the user's feeling of *ownership* or *agency* over avatar that they control
- Embodiment illusions derived from sensory dominance of vision over touch
- Based on warping the user's sense of embodiment
- Proprioceptive drift: virtual limb position is allowed to drift away from real position (Burns et al, 2005)
- Not noticed by user unless drift becomes large

Burns, E., Razzaque, S., Panter, A. T., & Whitton, M. C. (2005). The hand is slower than the eye: A quantitative exploration of visual dominance over proprioception. *Proceedings of IEEE Virtual Reality 2005*, 3–10.

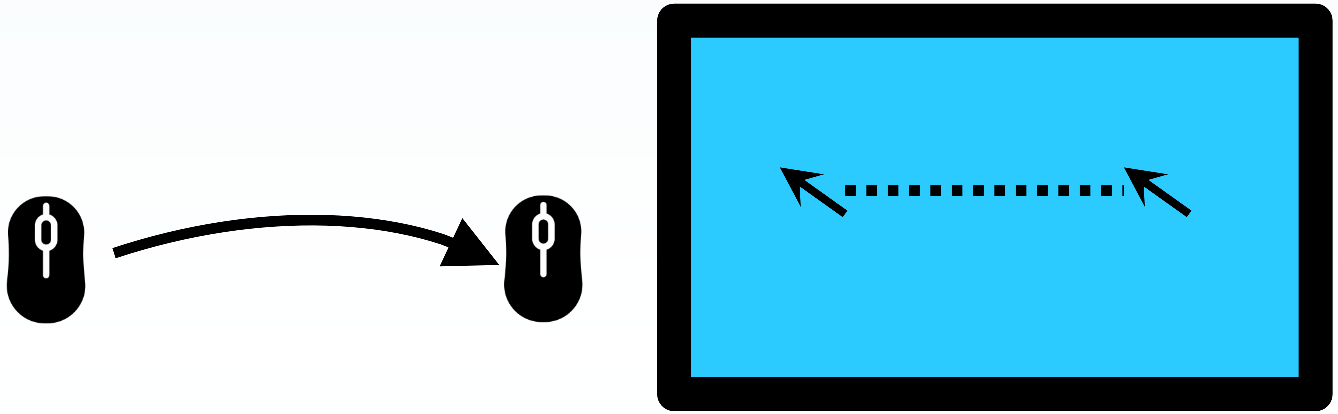
Yuan, Y., & Steed, A. (2010). Is the rubber hand illusion induced by immersive virtual reality? *2010 IEEE Virtual Real. Conf*, *95–102*, 95–102. https://doi.org/10.1109/VR.2010.5444807

Controller/Display (C/D) ratio

- Ratio of controller (e.g. mouse) displacement to movement of cursor on screen

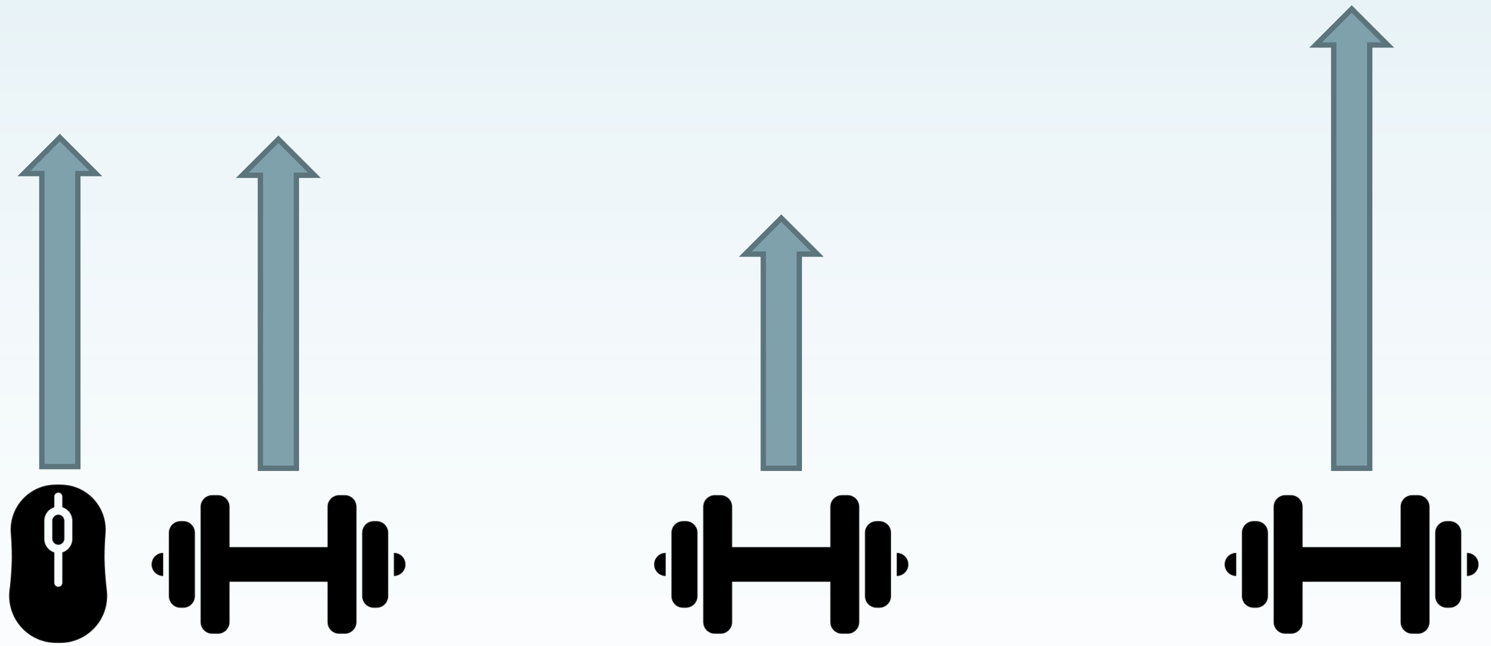


Low C/D ratio:
small controller
movement produces
large cursor movement



High C/D ratio:
larger controller
movement required
to produce same
cursor movement

Pseudohaptics: Adjusting Linear C/D ratio



Pseudohaptics applies embodiment drift to the user controlled avatar (or cursor) when they lift or move a virtual object.

(1) Controller movement moves object by same amount (C/D = 1)

(2) If same controller movement produces reduced object movement (C/D > 1), object feels heavier

(3) If same controller movement produces increased object movement (C/D < 1), object feels lighter

Lécuyer, A. (2009). Simulating Haptic Feedback Using Vision: A Survey of Research and Applications of Pseudo-Haptic Feedback. *Presence: Teleoperators and Virtual Environments*, *18*(1), 39–53. https://doi.org/10.1162/pres.18.1.39

Pseudohaptics: Adjusting Rotational C/D ratio

- Yu and Bowman (2020) applied CD ratio adjustments to rotations
- One cube has CD =1, the other has CD < 1 or CD >1
- Almost all users selected cube with higher CD as heavier

Yu, R., & Bowman, D. A. (2020). Pseudo-Haptic Display of Mass and Mass Distribution During Object Rotation in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics*, *26*(5), 2094–2103. https://doi.org/10.1109/TVCG.2020.2973056

Haptic Retargeting

Azmandian, M., Hancock, M., Benko, H., Ofek, E., & Wilson, A. D. (2016). Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, 1968–1979. https://doi.org/10.1145/2858036.2858226

Pseudohaptics: variations on C/D ratio

- Exploit illusions based on cross-sensory correspondences
- *Audio-haptic* correspondences lead us to associate high pitched sounds with lightness and low-pitched sounds with heaviness.
- *Visuo-haptic* correspondences leads us to associate bright-shaded objects with lightness and dark-shaded objects with heaviness.

Colocated Haptics

- Not feasible for a desktop haptic interface
- Desirable for Immersive VR
- Straightforward for HMD setup
- Complicated for projection-based setups (e.g. CAVES) since:
  - Small errors in tracking or projection become noticeable
  - Accommodation mismatch for virtual and real objects

Loscos, C., Tecchia, F., Frisoli, A., Carrozzino, M., Widenfeld, H., Swapp, D., & Bergamasco, M. (2004). The Museum of Pure Form: Touching real statues in an immersive virtual museum. *VAST*, 271–279. https://doi.org/10.2312/VAST/VAST04/271-279
Hoffman et al, Journal of Vision March 2008, Vol.8, 33

Recap (Part2: Tactile & Kinaesthetic Interfaces)

- Tactile Interfaces:
  - Static stimuli: Braille, buttons
  - Dynamic stimuli: Vibrotactile devices
- Kinaesthetic Interfaces:
  - Force feedback
  - Rendering
- Passive Haptics: proxy objects
- Pseudohaptics
  - Sensory dominance
  - Proprioceptive drift
  - Cross-sensory illusions
- Colocated haptics

Further reading (1/3)

Azmandian, M., Hancock, M., Benko, H., Ofek, E., & Wilson, A. D. (2016). Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, 1968–1979. https://doi.org/10.1145/2858036.2858226

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Choi, S., & Kuchenbecker, K. J. (2013). Vibrotactile Display: Perception, Technology, and Applications. *Proceedings of the IEEE*, *101*(9), 2093–2104. https://doi., org/10.1109/JPROC.2012.2221071

Culbertson, H., Schorr, S. B., & Okamura A. M. (2018). Haptics: The Present and Future of Artificial Touch Sensation. *Annual Review of Control, Robotics, and Autonomous Systems*, *1*(1), 385–409. https://doi.org/10.1146/annurev-control-060117-105043

Hayward, V., Astley, O. R., Cruz-Hernandez, M., Grant, D., & Robles-De-La-Torre, G. (2004). Haptic interfaces and devices. *Sensor Review*, *24*(1), 16–29. https://doi.org/10.1108/02602280410515770

Hoffman, D. M., Girshick, A. R., Akeley, K., & Banks, M. S. (2008). Vergence–accommodation conflicts hinder visual performance and cause visual fatigue. *Journal of Vision*, *8*(3), 33. https://doi.org/10.1167/8.3.33

Further reading (2/3)

Hoffman, H. G. (1998). Physically touching virtual objects using tactile augmentation enhances the realism of virtual environments. *Proceedings. IEEE 1998 Virtual Reality Annual International Symposium (Cat. No.98CB36180)*, 59–63. https://doi.org/10.1109/VRAIS.1998.658423

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