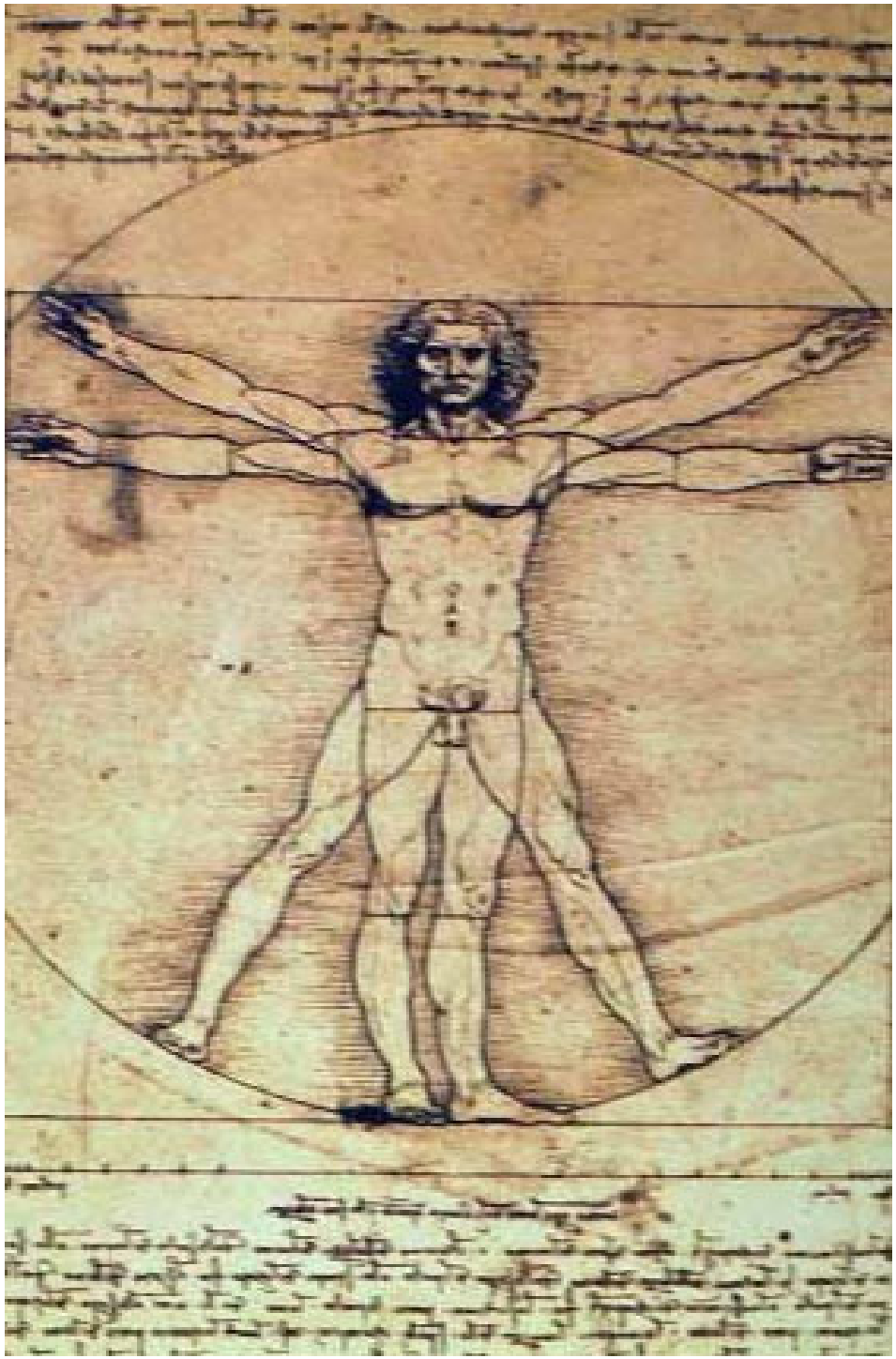


Interactive System
インタラクティブシステム特論
(6)

Hiroyuki Kajimoto
kajimoto@uec.ac.jp
Twitter kajimoto

Outline of the lecture

1. 人間計測手法／Measuring Human
2. 視覚／Human Vision System
3. 視覚センシング／Visual Sensing
4. 視覚ディスプレイ／Visual Display
5. 聴覚、聴覚インタフェース／Auditory Interface
6. 触覚、触覚インタフェース／Tactile Interface
7. 触覚、触覚インタフェース応用／Tactile Interface2
8. 力覚、力覚インタフェース／Haptic Interface
9. 移動感覚インタフェース／Locomotion Interface

触覚＝体性感覚＋皮膚感覚

Haptic Sense = Proprioception + Cutaneous Sense

触覚＝接触によって生じる感覚

（Haptic＝「接触(Contact)」(ギリシャ語／in Greece)）

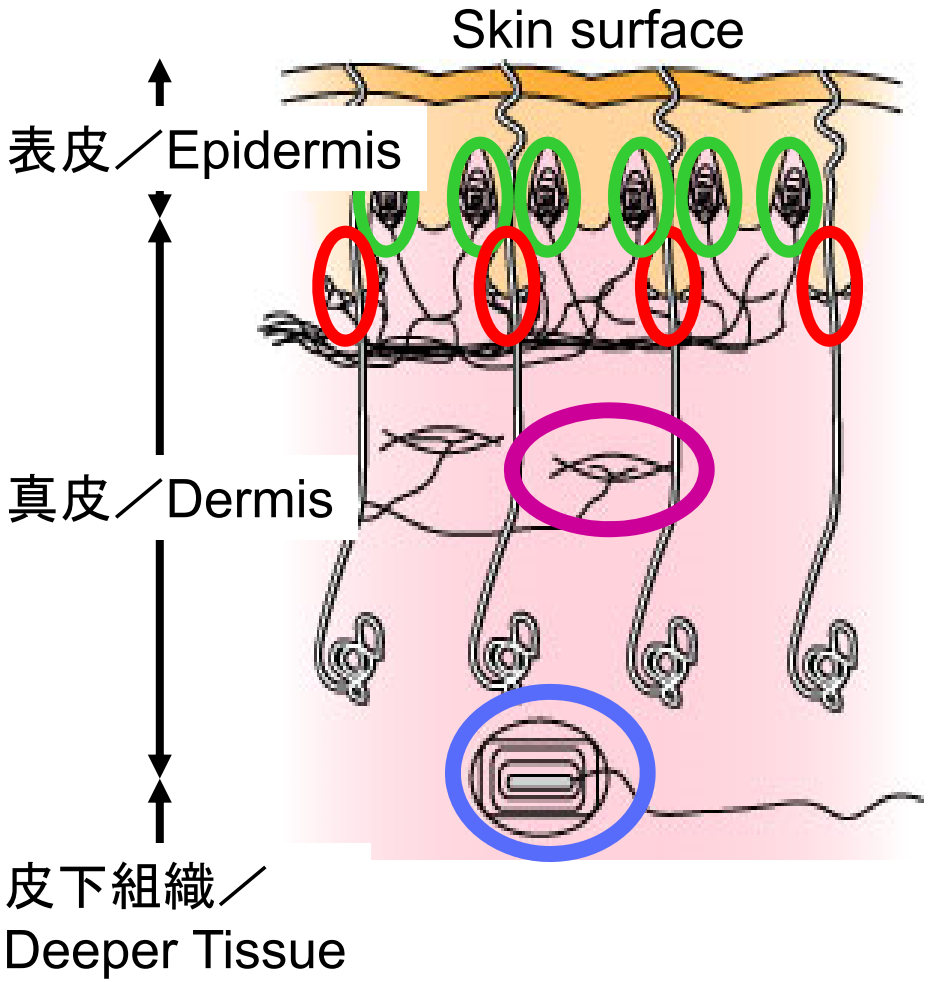
- 皮膚表面の変形（皮膚感覚／Cutaneous Sense, Skin Sense)
- 筋肉の伸縮，関節角（深部感覚・力覚／Proprioception, Force Sense）

今日の話：狭義の皮膚感覚／Today’s Talk focuses on skin

TODAY's TOPIC

1. Skin Sensation Mechanism
2. Tactile Illusion
3. Tactile Display

皮膚構造(無毛部)Skin Structure (Hairless Parts)



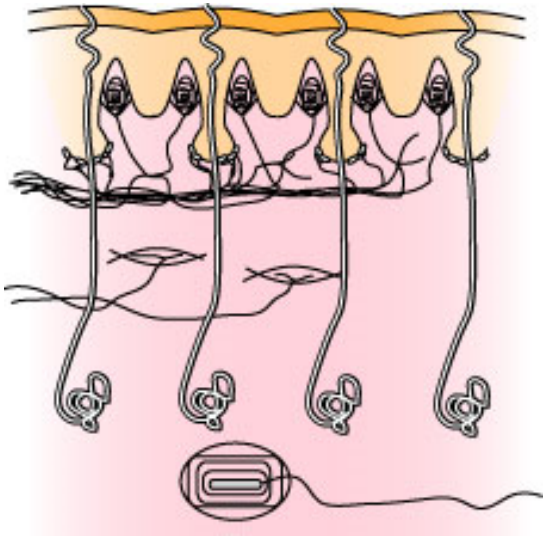
機械受容器：機械的変形に応答
Mechanoreceptor: Sense Mechanical Deformation

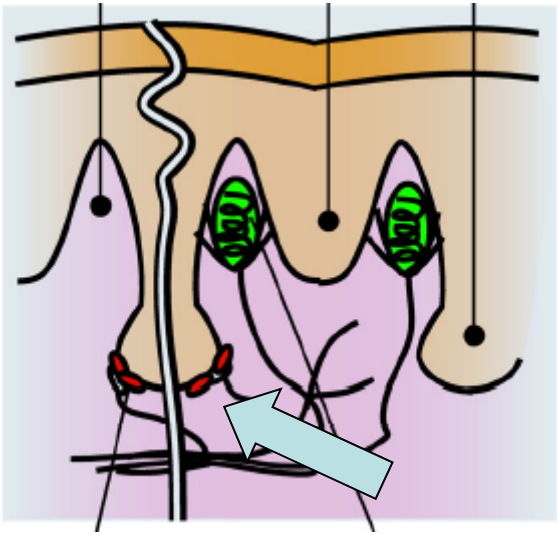
浅部／Shallow part
- ●マイスナー小体／MeissnerCorpuscle
- ●メルケル細胞／Merkel Cell

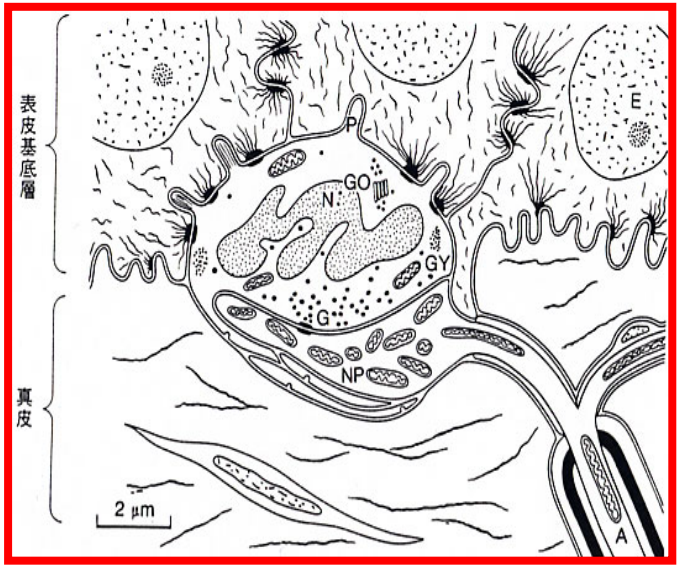
深部／Deep part
- ●ルフィニ終末／Ruffini Ending
- ●パチニ小体／Pacinian Corpuscle

その他／Misc
自由神経終末(痛覚、温度感覚)
FreeEnding (Pain, Temperature)

メルケル細胞／Merkel Cell





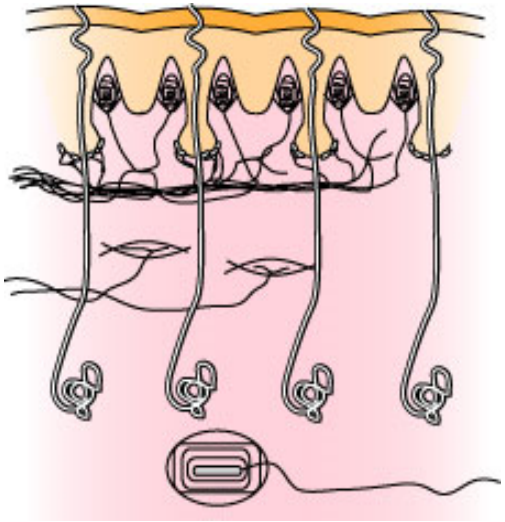


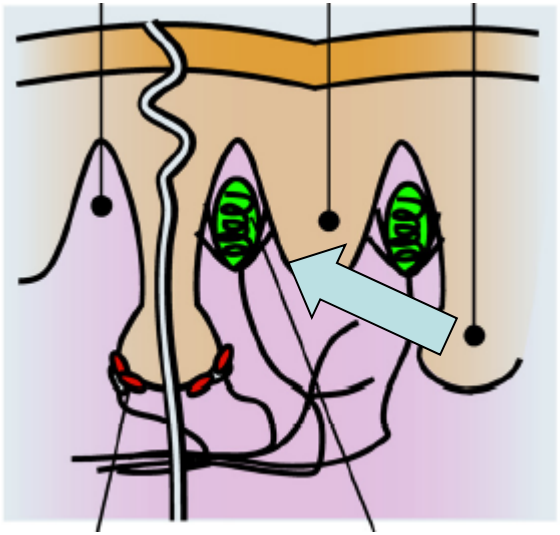
新編　感覚・知覚心理学ハンドブック
http://www.seishinshobo.co.jp/book/b88071.html

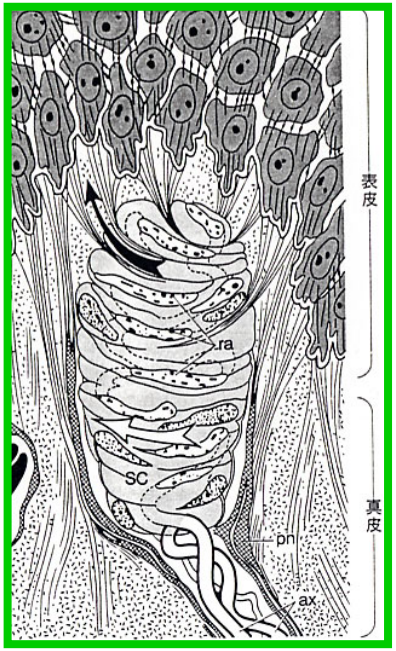
カンデル神経科学(Principles of Neural Science)
https://www.medsi.co.jp/kandelkyousai/index.html

- 表皮と真皮の境界に密に存在.
- 唯一の細胞性受容器. 神経とシナプス接合
- 静的な歪に応答
- 発火頻度は歪の大きさに比例
- 単独の活動では純粋な圧覚を生成
- Densely Populated at the bottom of epidermis.
- Sense Static Deformation.
- Pulse Frequency is Proportional to Deformation.
- When activated, Pure Pressure Sensation is generated.

マイスナー小体／Meissner Corpuscle

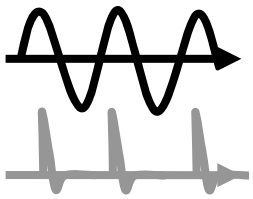


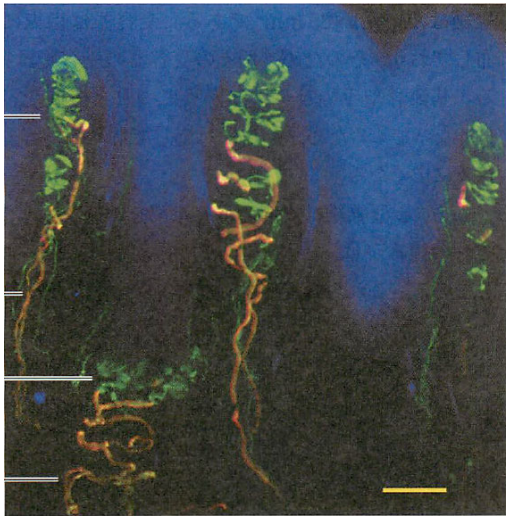




新編　感覚・知覚心理学ハンドブック
http://www.seishinshobo.co.jp/book/b88071.html

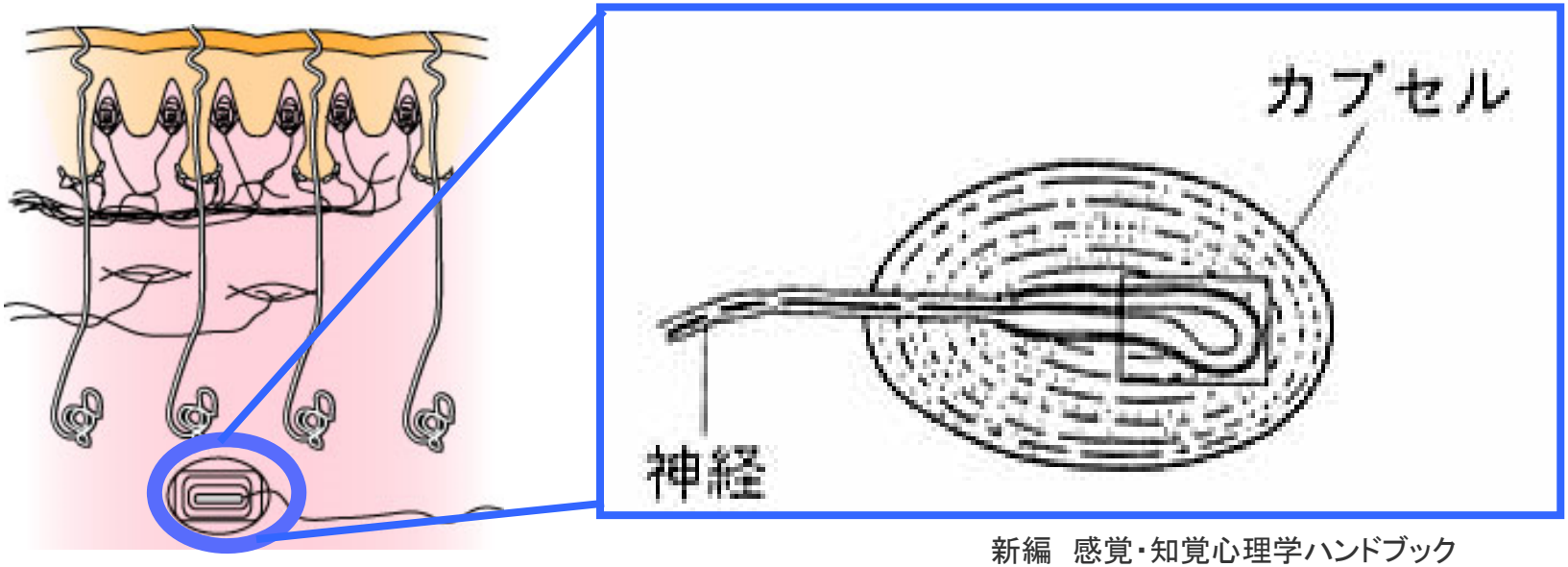
- 真皮乳頭部に密に存在.
- 低周波振動(15-100Hz)に応答（共振30Hz)
- 発火周波数～振動周波数
- 単独の活動では振動感覚，パタパタ感を生じる
- Densely populated at 0.5 – 0.7mm depth.
- Sense Low Frequency Vibration (15-100Hz)
- Has Resonant Frequency（30Hz)
- Pulse Frequency ～Vibration Frequency
- Single Activity Generates “Flutter” Vibratory Sensation





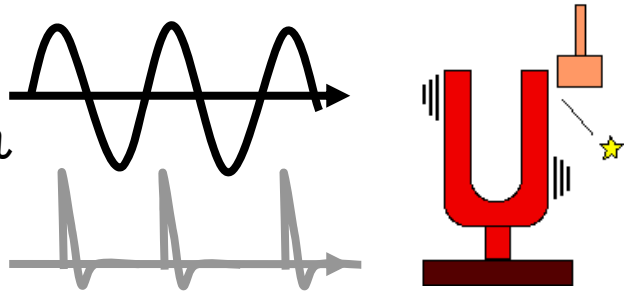
カンデル神経科学(Principles of Neural Science)
https://www.medsi.co.jp/kandelkyousai/index.html

パチニ小体／Pacinian Corpuscle



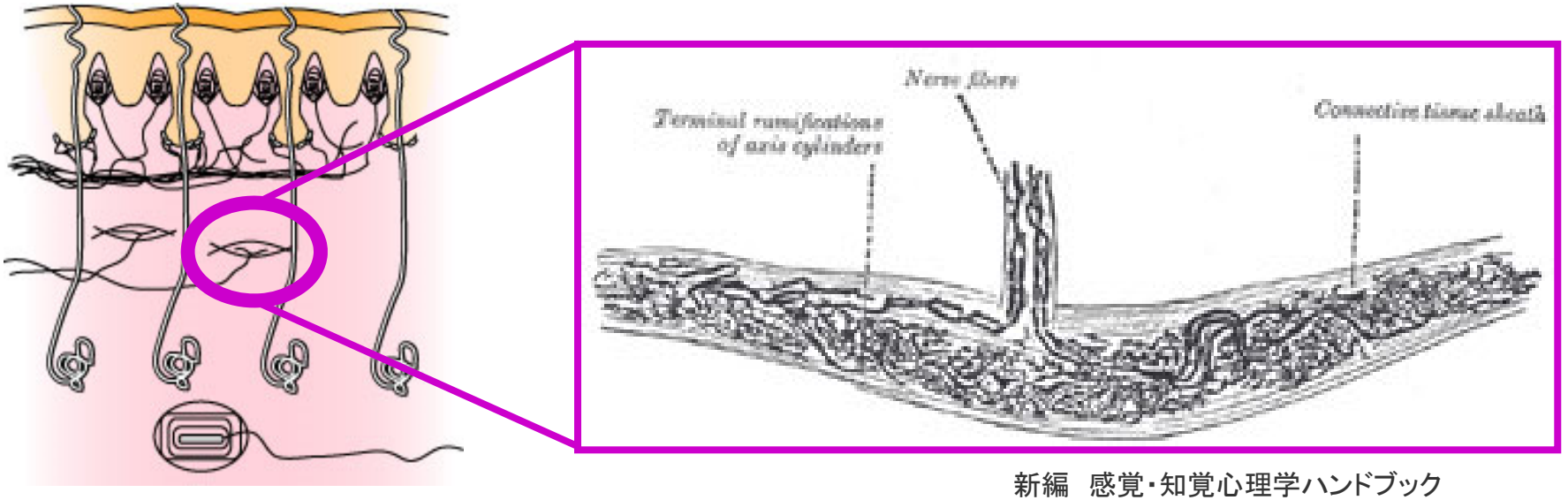
新編　感覚・知覚心理学ハンドブック
http://www.seishinshobo.co.jp/book/b88071.html

•皮下組織にまばらに存在.
•高周波振動に応答(60-800Hz)(共振250Hz)
•発火周波数～振動周波数
•単独の活動では音叉に触れたような振動感覚，指全体の痺れ



•Sparsely populated at deep region (2mm～)
•Sense High Frequency Vibration (60-800Hz)
•Has Resonant Frequency (250Hz)
•Pulse Frequency～Vibration Frequency
•Single Activity Generates “numb” sensation, just like touching a tuing fork or speaker

ルフィニ終末／Ruffini Ending

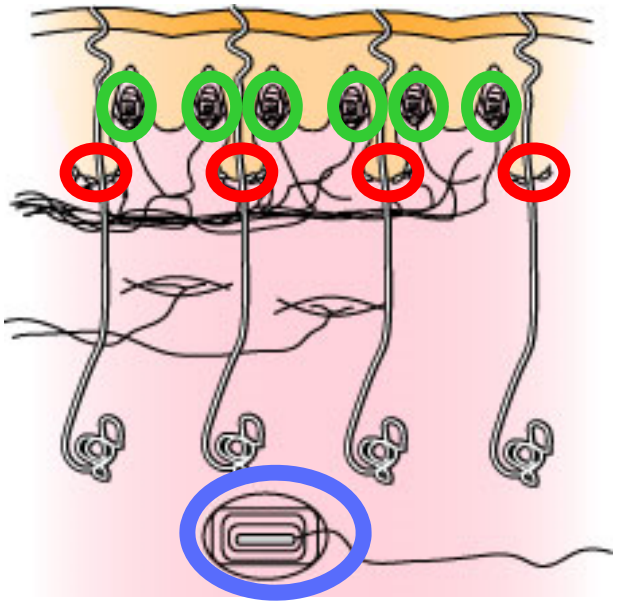


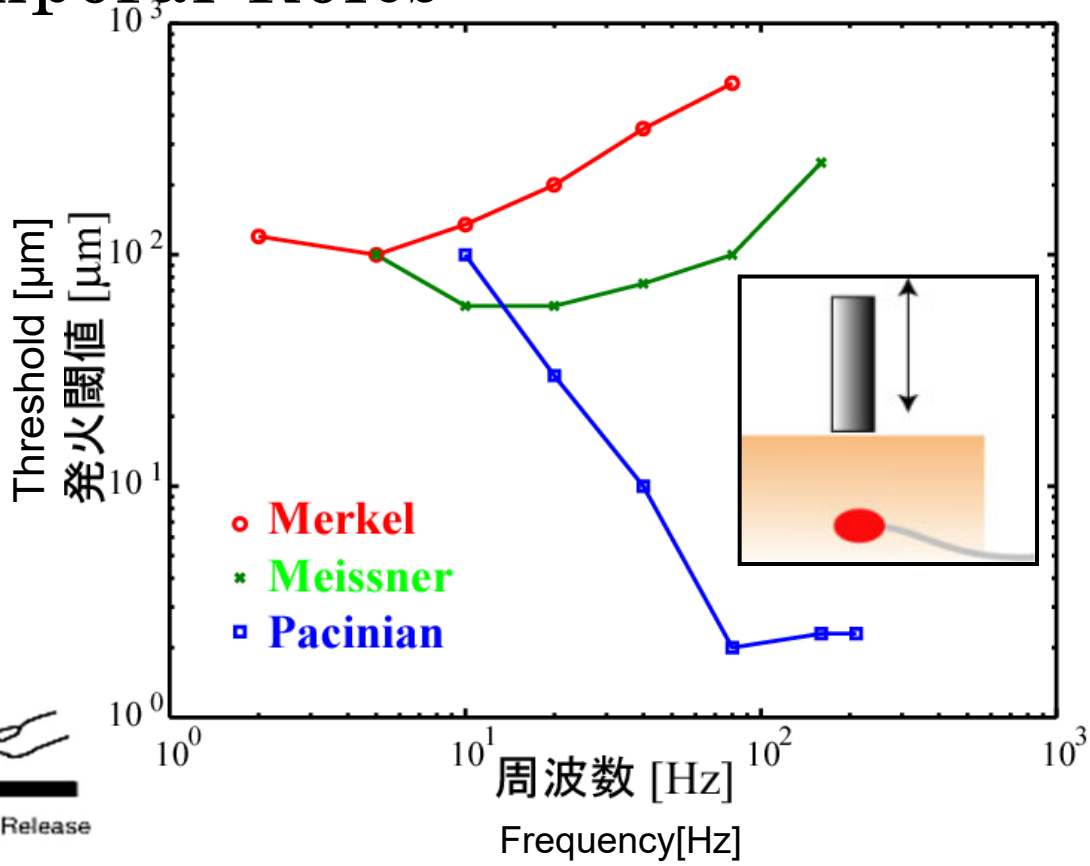
新編　感覚・知覚心理学ハンドブック
http://www.seishinshobo.co.jp/book/b88071.html

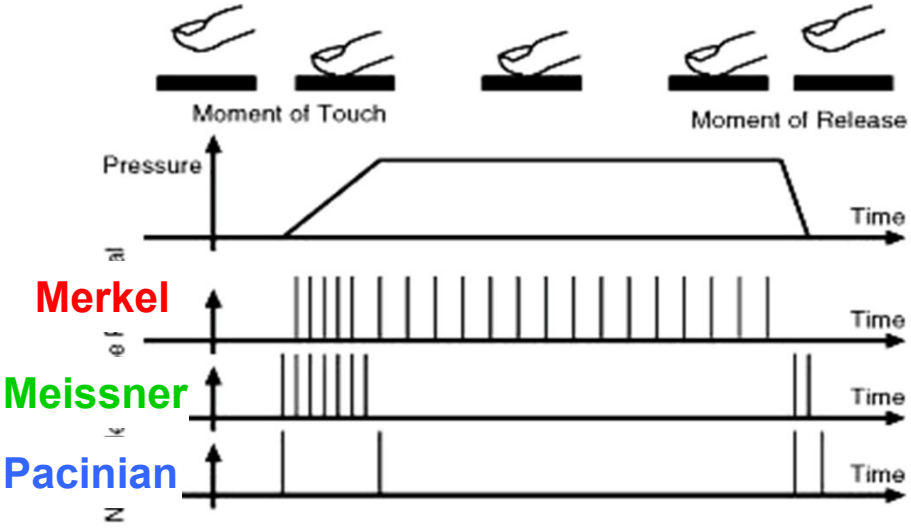
- 皮下組織に疎らに存在.
- 静的な横ずれに応答
- 発火頻度は横ずれの大きさに比例
- 単独の活動では感覚を生じない

- Sparcely Populated in a deep region (2mm～ depth)
- Senses Static Horizontal Deformation
- Pulse Frequency is Proportional to Horizontal Deformation.
- Single activation does not generate sensation

時間的役割分担／Temporal Roles



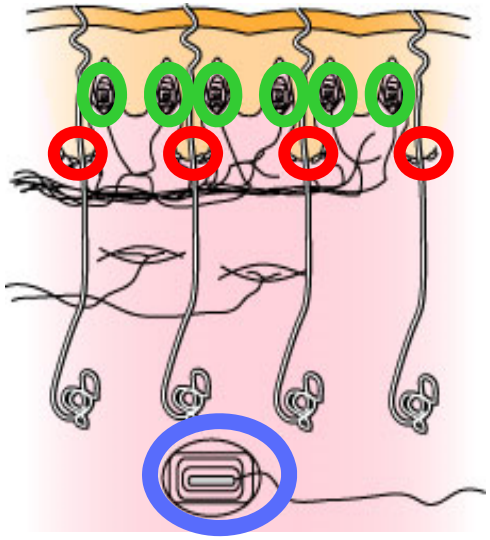


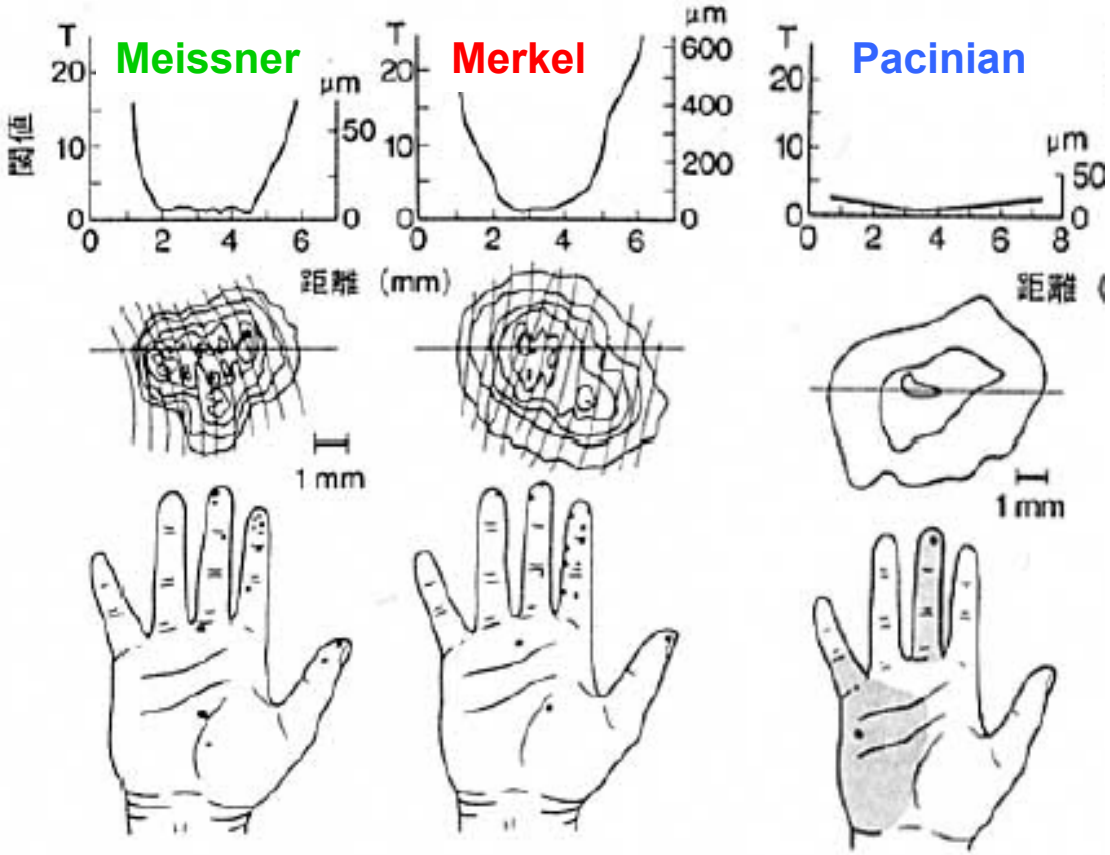


- Merkel：直流成分／圧力
- Meissner：低周波成分／速度
- Pacinian：高周波成分／加速度

- Merkel：DC / Displacement & Pressure
- Meissner：Low Freq. Vibration / Velocity
- Pacinian：High Freq. Vibration / Acceleration

空間的役割分担／Spatial Roles

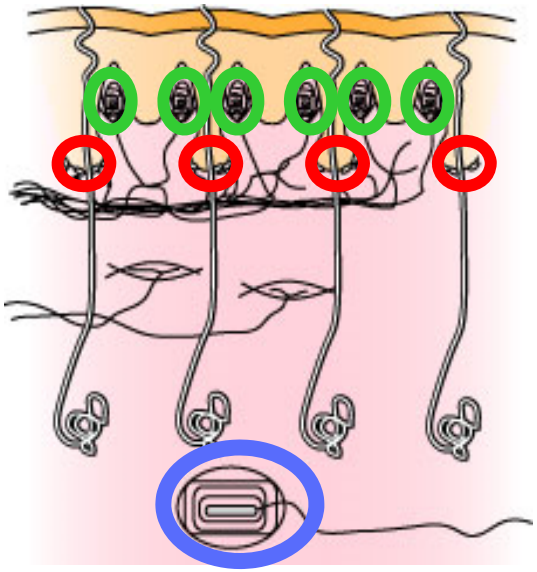


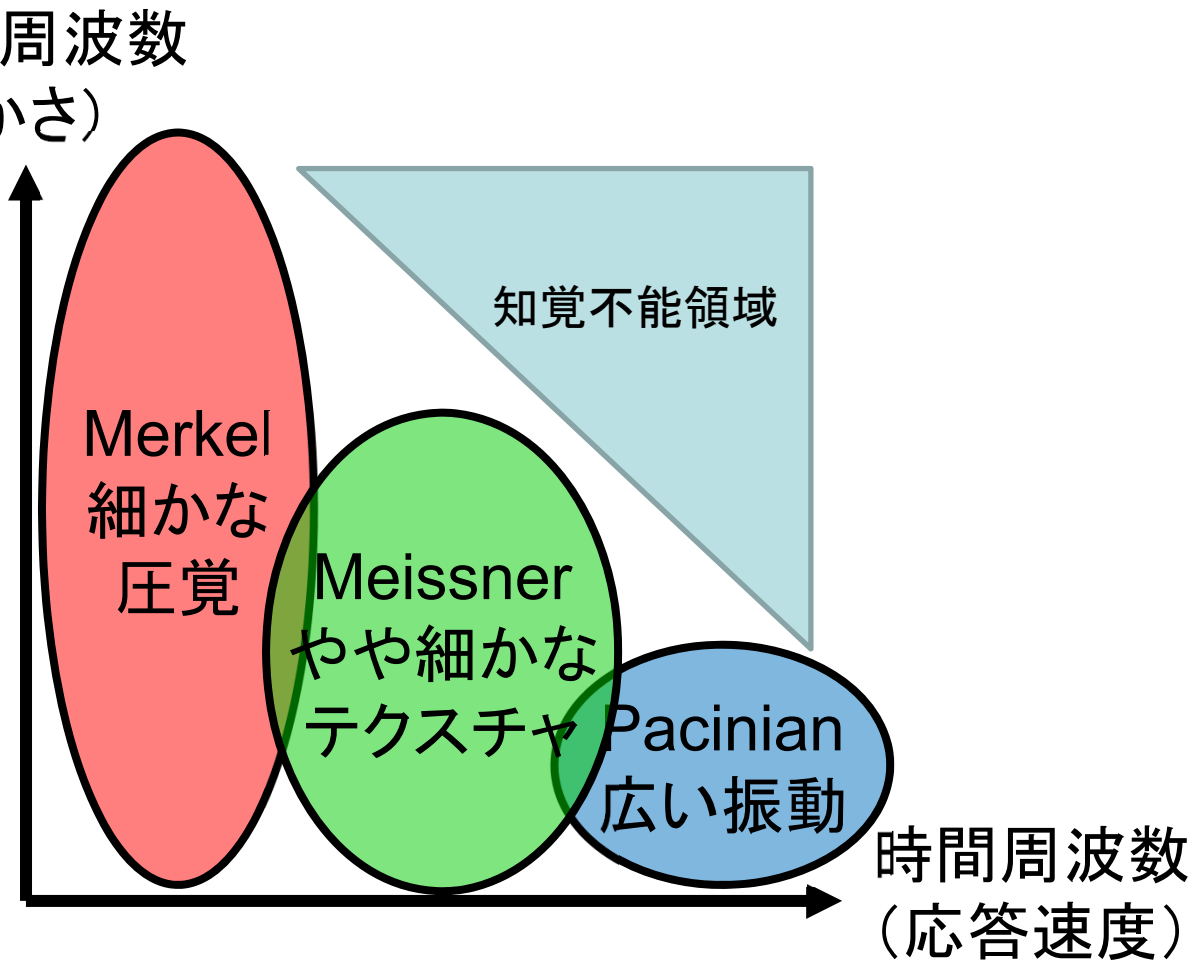


新編　感覚・知覚心理学ハンドブック
http://www.seishinshobo.co.jp/book/b88071.html

- Merkel：細かいパターン／Small Pattern
- Meissner：皮膚上の細かい動き／Small Area Movement
- Pacini：広い面積の動き／Large Area Movement

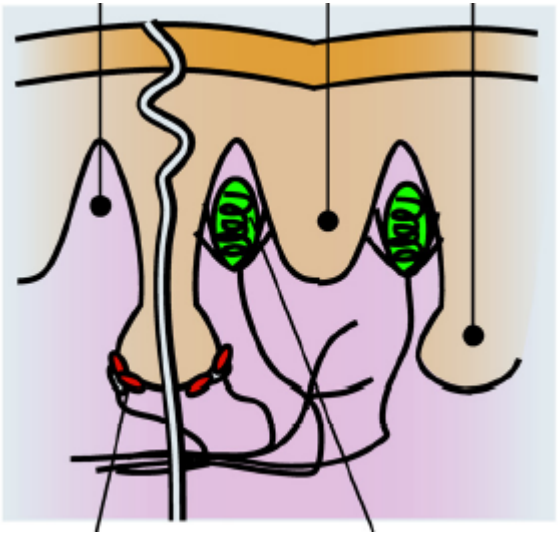
各機械受容器の役割分担
Spatial temporal roles





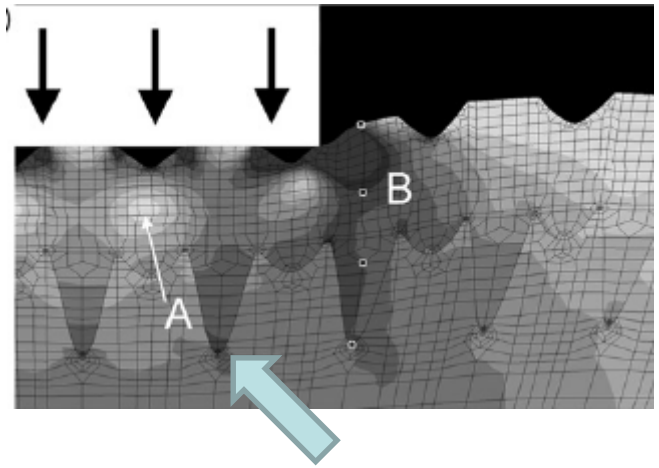
ポイント：時間的，空間的な相補性

皮膚構造と受容器
Skin Structure and Mechanoreceptors

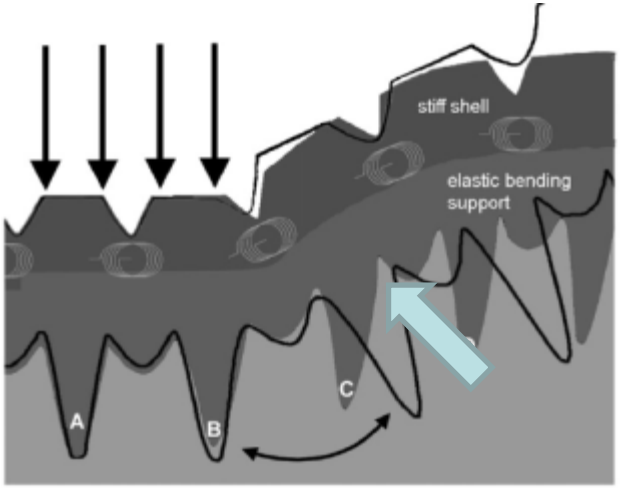


・表皮：硬い
・真皮：柔らかい
・MerkelとMeissnerは境界に存在

・Epidermis：Hard
・Dermis：Soft
Merkel and Meissner are at the interface of the two layers.



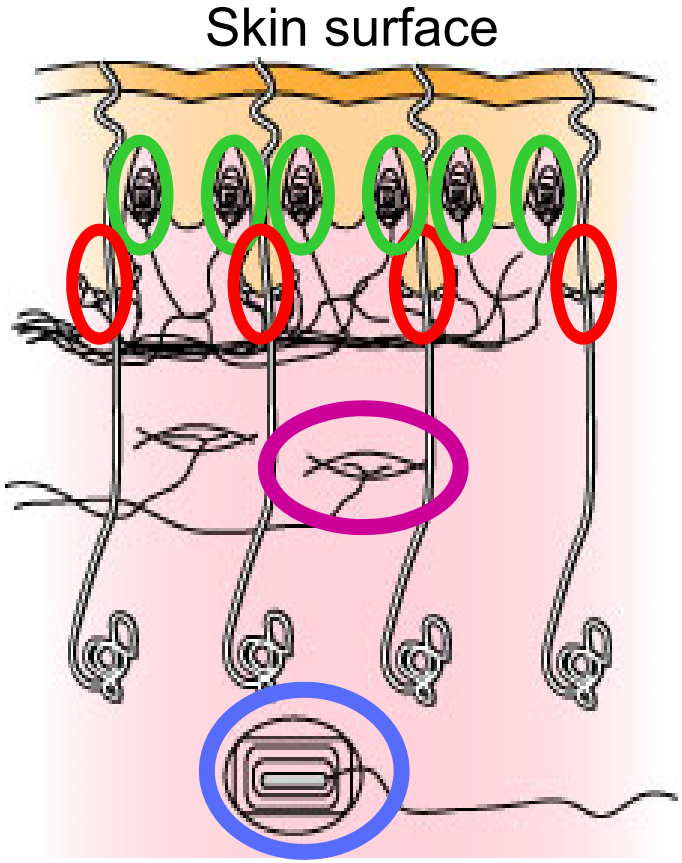
Stress is Concentrated at Merkel



Strain is Largest at Meissner

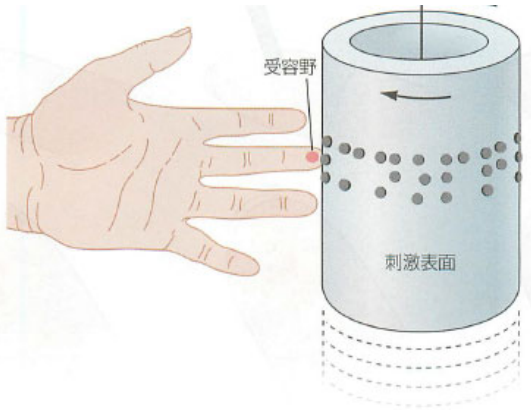
Gregory J. Gerling, “Fingerprint lines may not directly affect SA-I mechanoreceptor response,” Somatosensory and Motor Research 2008.

形状は主にMerkelによってコーディングされる
Shape is mainly coded by Merkel Cells

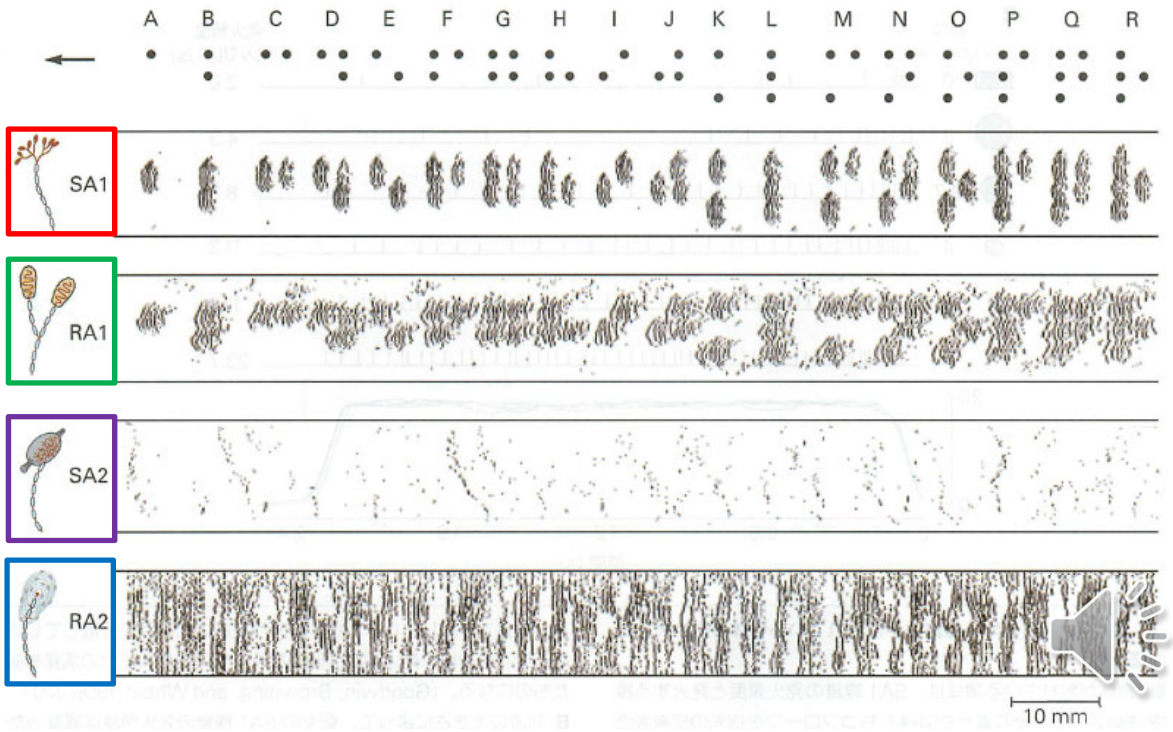


浅部／Shallow part
- マイスナー小体／MeissnerCorpuscle
- メルケル細胞／Merkel Cell

深部／Deep part
- ルフィニ終末／Ruffini Ending
- パチニ小体／Pacinian Corpuscle



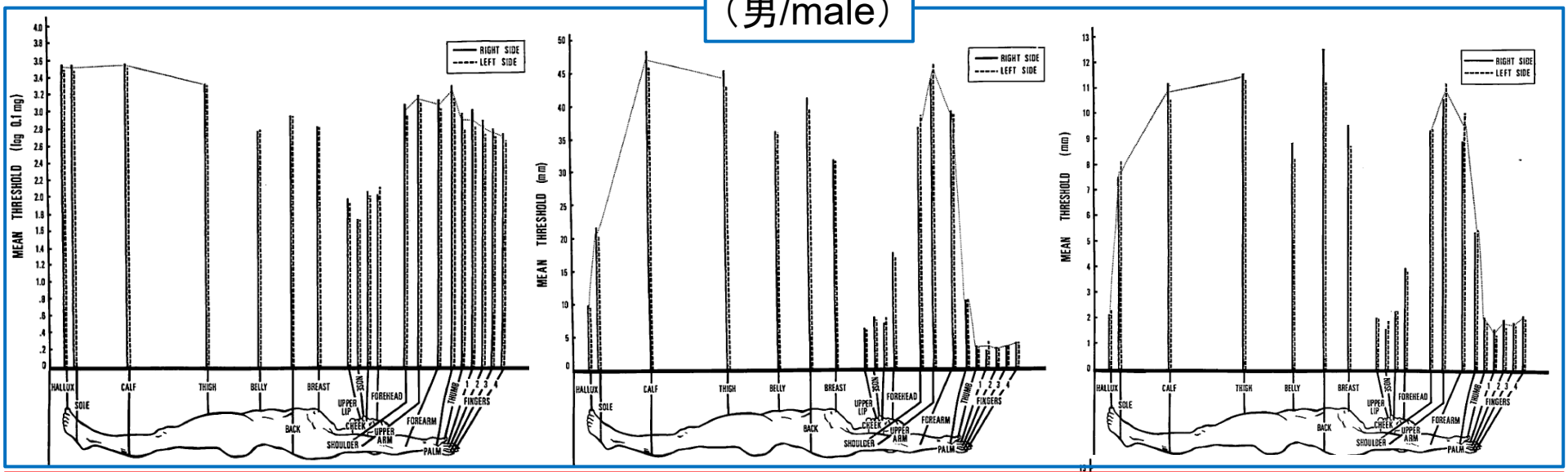
カンデル神経科学
(Principles of Neural Science)
https://www.medsi.co.jp/kandel/syousai/index.html

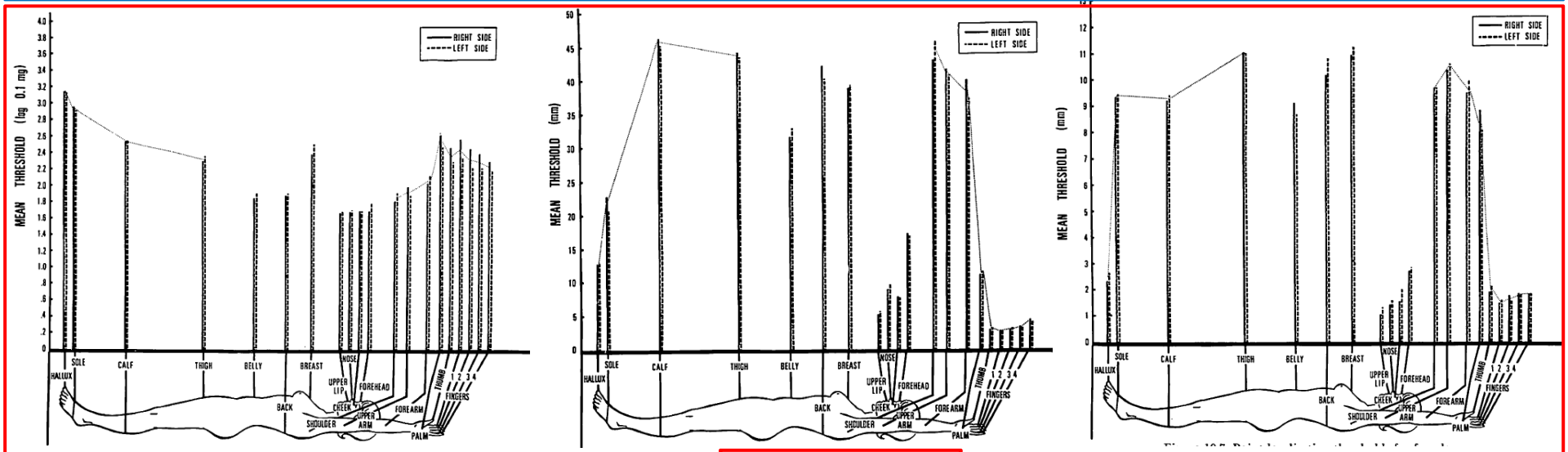


身体部位依存性

S. Weinstein, Intensive and Extensive Aspects of Tactile Sensitivity as a Function of Body Parts, Sex, and Laterality. In D. R. Kenshalo (Ed.), The skin senses, 1968.

（男/male）





（女/female）

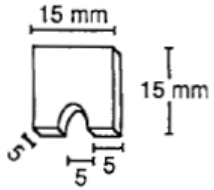
圧力知覚閾
Pressure threshold

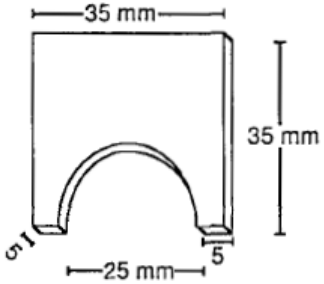
同時的な二点弁別閾
Two point discrimination

経時的な定位閾
Point localization

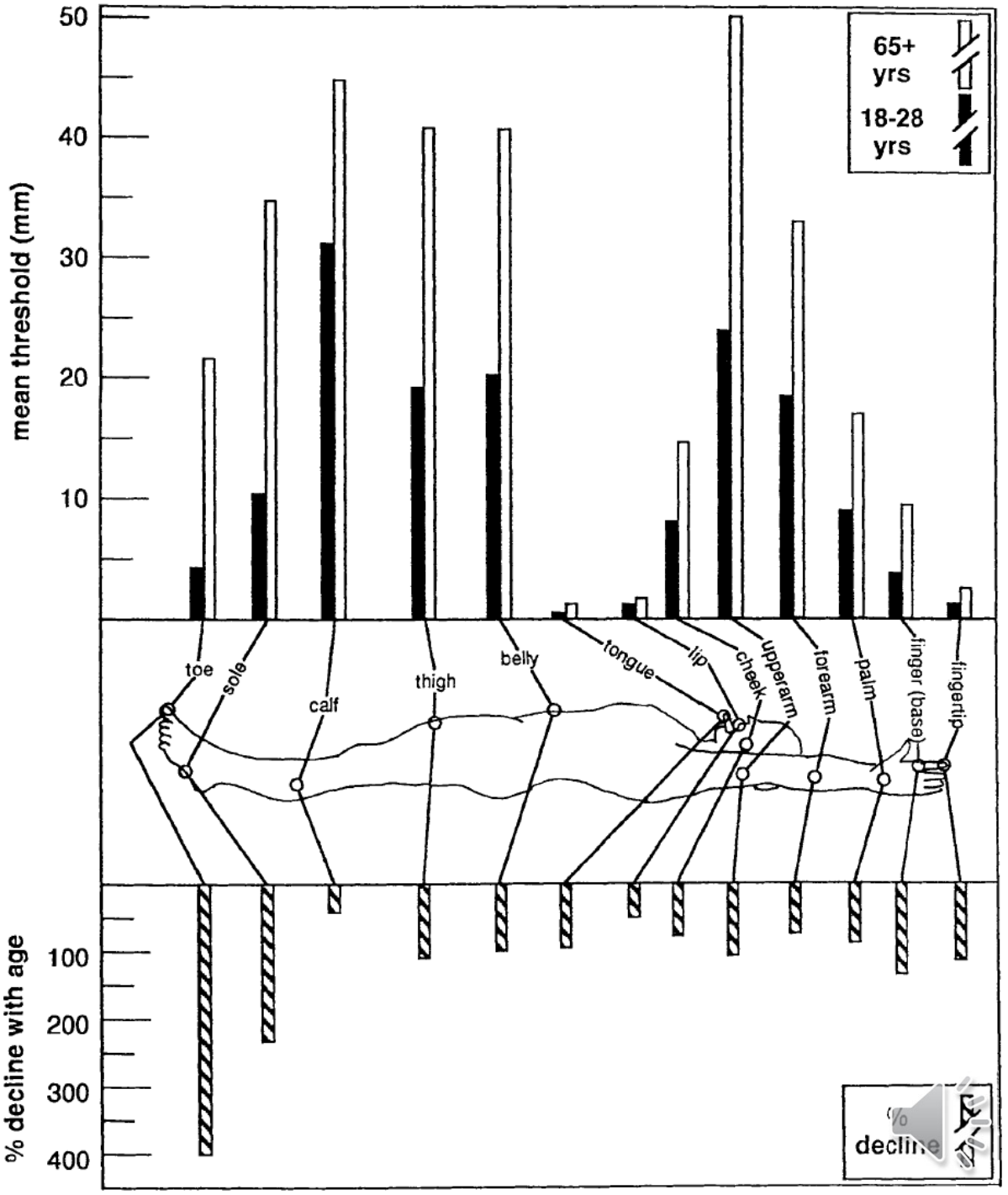
二点弁別域と加齢

Joseph C. Stevens & Kenneth K. Choo (1996) Spatial Acuity of the Body Surface over the Life Span, Somatosensory & Motor Research, 13:2, 153-166

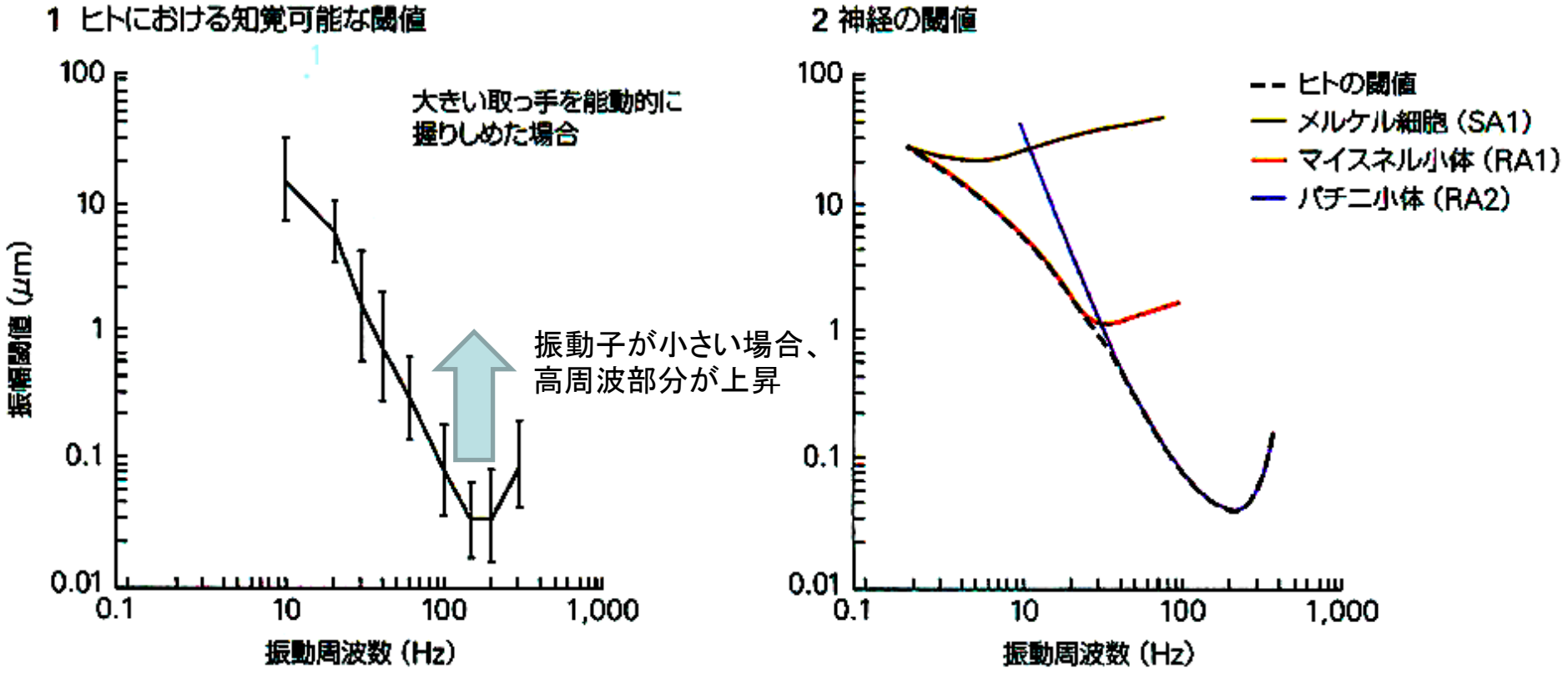




- 足裏の触覚の減退は著しい。
- 唇、ふくらはぎの減退は少ない（ただしふくらはぎは元々かなり悪い）
- 前腕、頬も減退がやや少ない。



周波数は受容器の活動比率でコーディングされる
Frequency is mainly coded by combination of receptor activities.

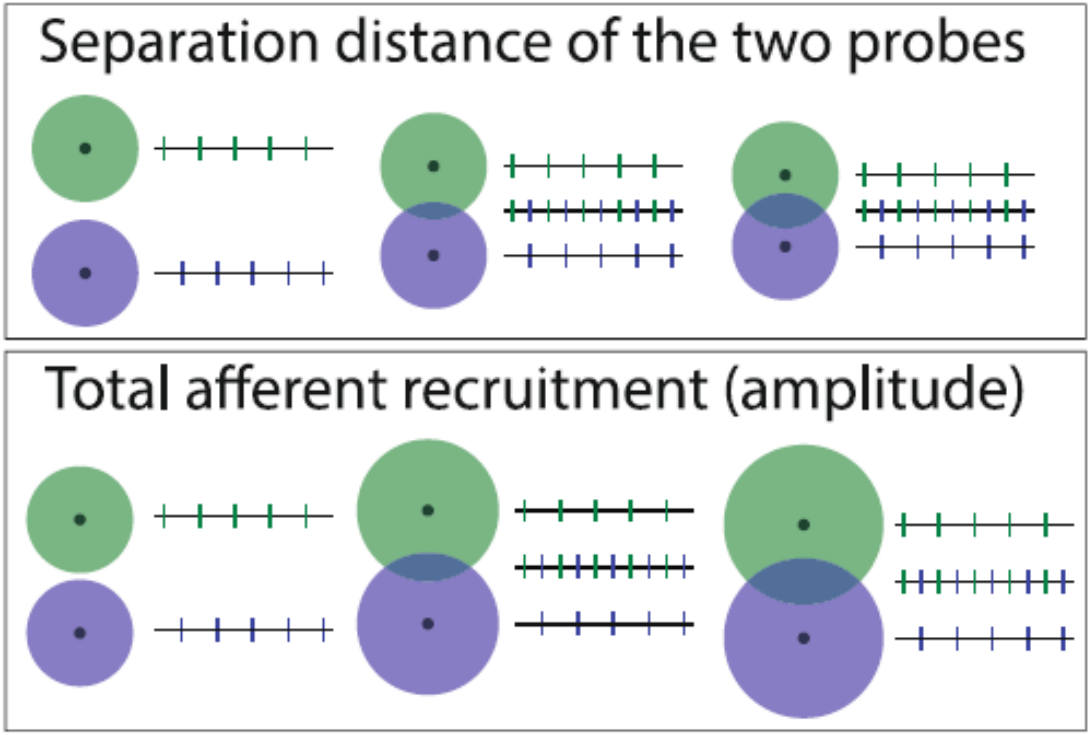


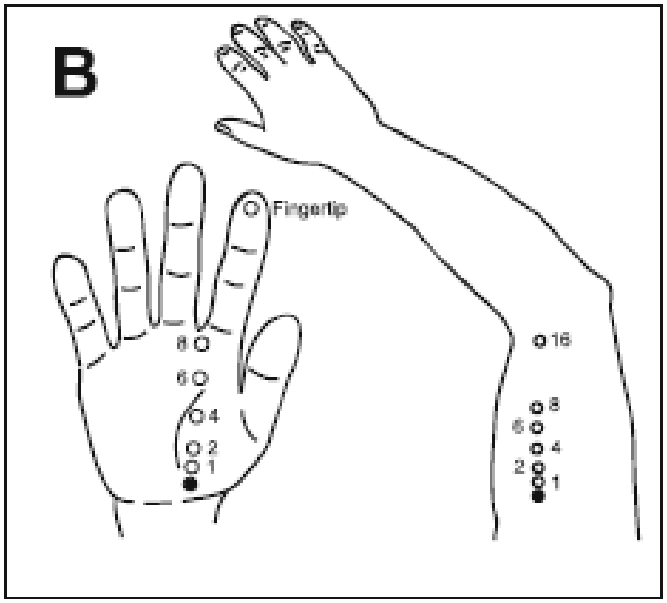
カンデル神経科学(Principles of Neural Science) https://www.medsi.co.jp/kandel/syousai/index.html

主にMeissnerとPacinianが関与。
ただし振動子が小さいとPaciniの「空間加算」効果が無くなり、高周波を感じなくなる
Vibration is coded by Meissner + Pacinian. If the vibrator size is small, high freq. threshold rises, ("spatial summation effect" of Pacinian corpuscle)

(EuroHaptics2016) Temporal integration of tactile inputs from multiple sites

Sarah McIntyre, Ingvars Birznieks, Robin Andersson, Gabriel Dicander, Paul Breen, Richard Vickery

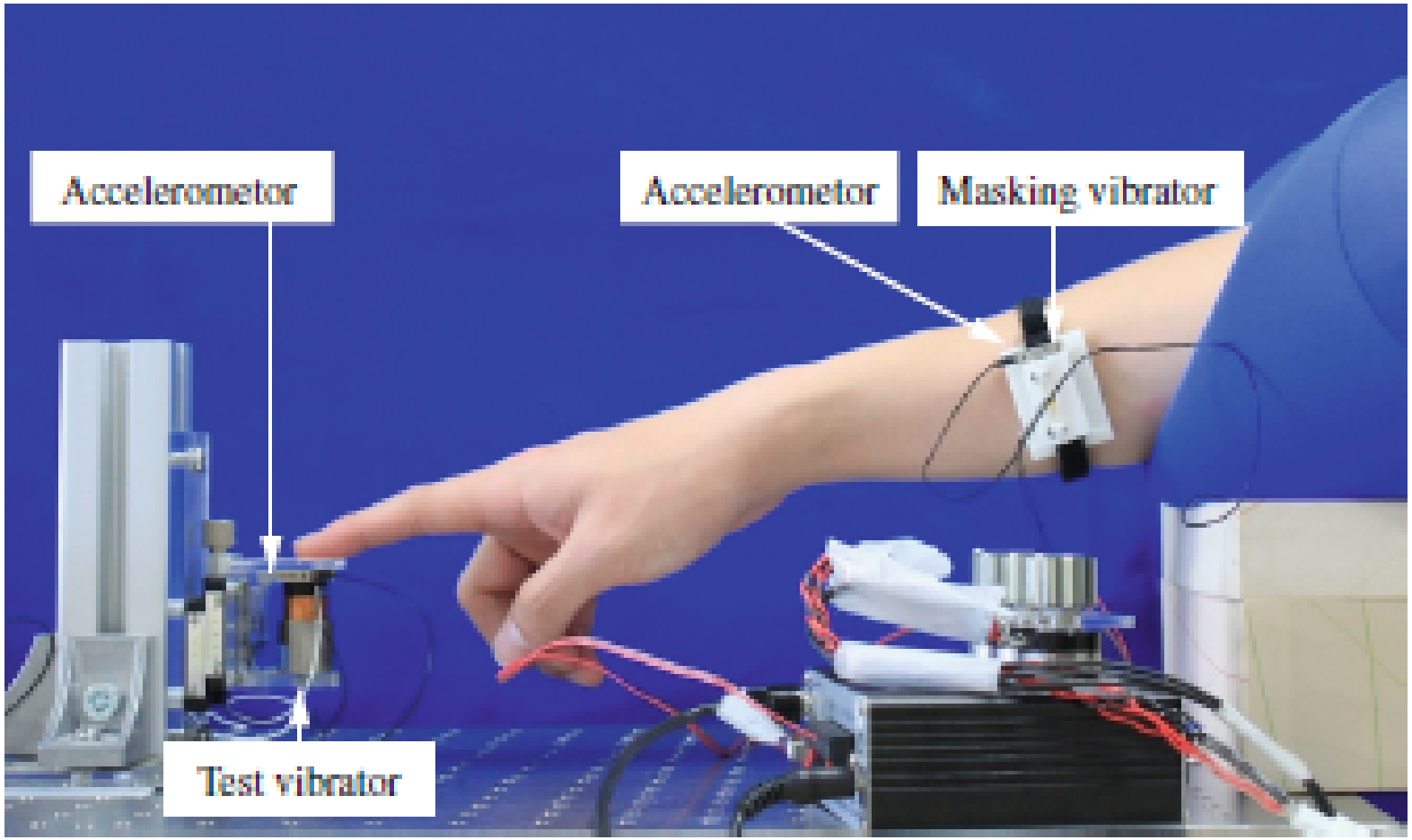




異なる二箇所に振動を与える．振動の周波数は同じで位相をずらす．これは脳にとっては例えば2倍の周波数に感じられないかという研究→非常に近い時は当然2倍近くに感じる．しかし腕の場合16cmくらい離れていても結構高い周波数に感じる．これは振幅を小さくしても同じなので、機械的に伝わったためとは考えにくい．

Simultaneously presenting vibration to two sites elicit “doubled” frequency feeling, although the positions are quite separated.

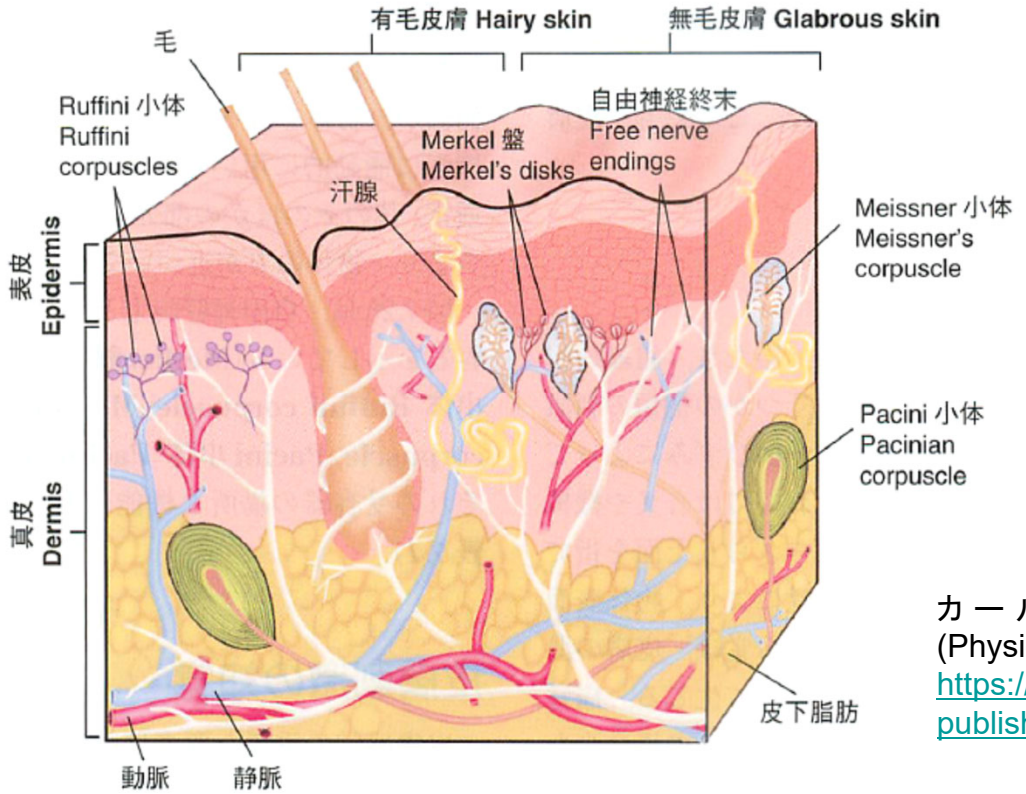
(EuroHaptics2016)Frequency-Specific Masking Effect by Vibrotactile Stimulation to the Forearm, Yoshihiro Tanaka, Shota Matsuoka, Wouter Bergmann Tiest, Astrid Kappers, Kouta Minamizawa, Akihito Sano



指先に閾値より少し上の振動を与えておき，腕にやや強い振動を与えると指先の感覚が完全に消えてしまう．異なる周波数ではこれは生じない．劇的に消えるので面白い．
Presentation of vibration to forearm dramatically “mask” vibration feeling at fingertip.

その他の触覚／Other cutaneous sensations

有毛部
Hairy part



無毛部
Glabrous part

カールソン神経科学テキスト
(Physiology of Behavior)
https://www.maruzen-publishing.co.jp/item/b294439.html

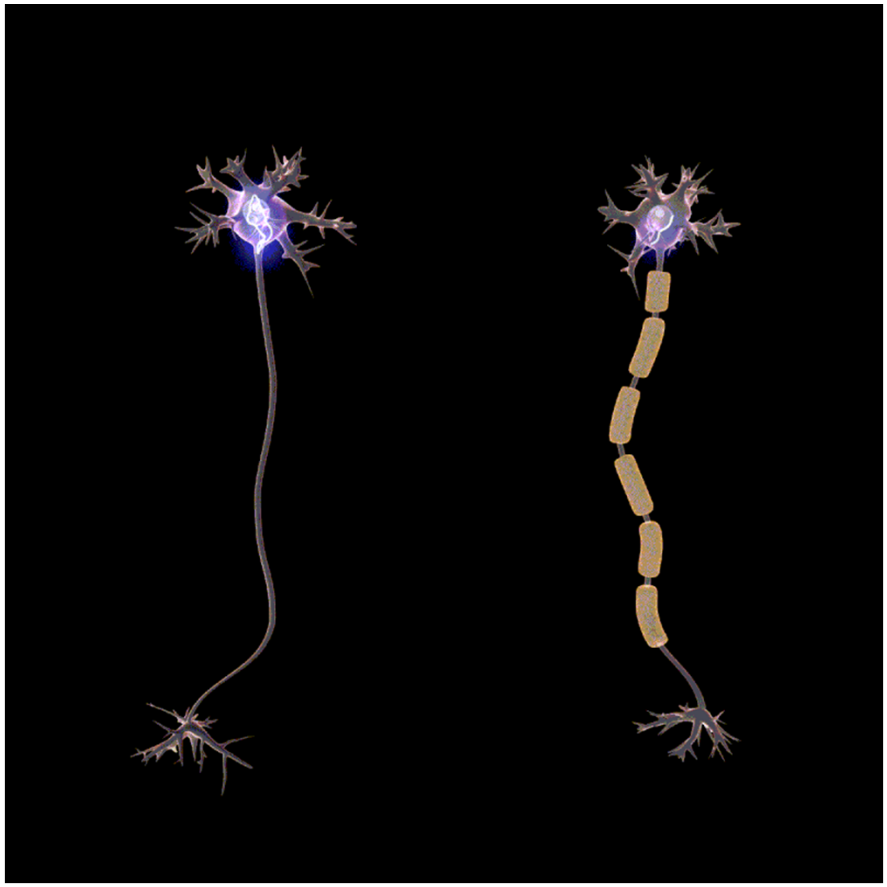
皮膚表面付近の自由神経終末　Free nerve ending

- 温度感覚：冷繊維と温繊維／Temperature sensation by two fibers.
- 痛覚：鋭痛と鈍痛はAγ繊維とC繊維が担当／Pain sensation by two fibers

有毛部／Hairy skin

- 毛包受容器／Follicle Receptor
  毛が曲がるときのみ活動（速度検出）。これに代わり，Meissner小体は無い。
  Activated by low frequency vibration, substituting Meissner corpuscle

C繊維？



Myelin (Wikipedia)
https://en.wikipedia.org/wiki/Myelin

機械受容器につながる多くの神経：Aβ繊維、一部Aγ繊維

- 高速に情報を伝えるMyelinatedな神経

C繊維：Unmyelinatedな神経．伝達速度が遅い．

- 温度感覚：Aγ繊維とC繊維
- 痛覚：Aγ繊維とC繊維（緊急の痛みと鈍痛）
- 無毛部のMeissner小体に入り込む繊維：数本C繊維が存在。
- 有毛部にも機械的変形に応答するC繊維が存在。情動に関与？

温度感覚と神経の種類/Temperature & nerve

侵害性冷覚

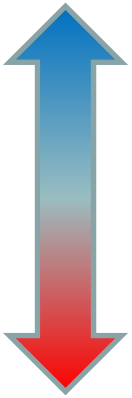
冷覚

温覚

侵害性温覚

Table 7–2 Sets of Afferents Sensitive to Temperature

Group	Axon	Threshold (°C)	Range (°C)
Noxious cold	C-fibers, 0.5–2.0 m/sec, rare	26–27	Down to tissue destruction
Cooling	A-delta, 13–15 m/sec, density 50–70 fibers/cm²	34	34–26
Warming	C-fibers, 0.5–2.0 m/sec, density 50–70 fibers/cm²	36	36–42
Noxious heat	(1) C-fibers, 0.2–2.0 m/sec	42	42–52
	(2) A-delta-I	42	42–52
Extreme heat	A-delta-II, rare	52	Up to tissue destruction

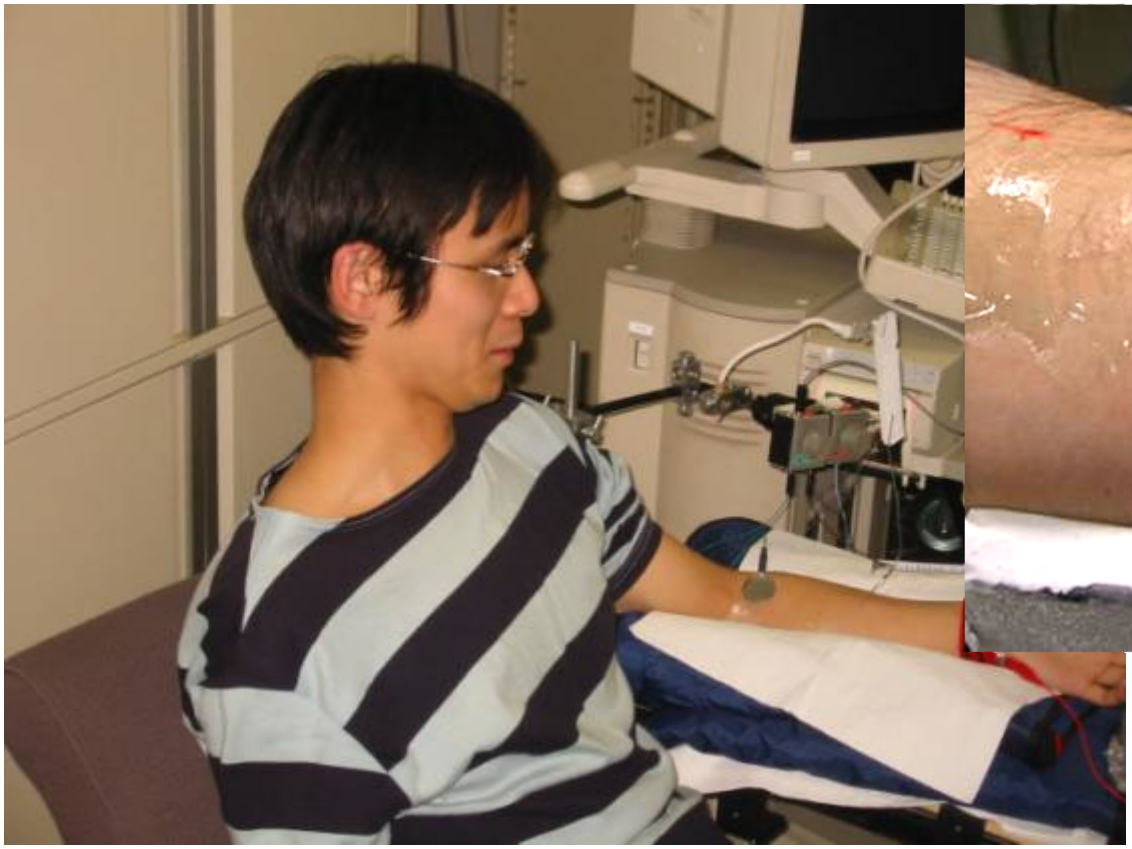


神経の種類と伝導速度：Aδ神経は13-15m/s，C繊維0.5-2m/s.
C繊維は圧倒的に遅い
温度感覚神経の伝達速度はなぜそれぞれ異なるのか？
おそらく可能な説明：

- 冷覚：「触った瞬間の温度変化」から，材質感を判定⇒素早いAδが必要
- 侵害性冷覚・温覚：「環境の温度」から，その場を離れるかどうかを判断⇒遅いC
- 侵害性温覚：熱い火，直射日光等を避ける⇒素早いAδ
- Moderate cool sensation is used for material identification, which requires fast response (Aδ). Noxious cold is environmental, and does not need to be quick. Noxious heat might be used to avoid sun?

（参考）水面知覚

どうやって調べる：神経活動
How we know?: nerve activity



By using needle, we can directly measure nerve activities. Vallbo, “Sensations evoked from the glabrous skin of the human hand by electrical stimulation of unitary mechanoseisitive afferents,” Brain Res., 1981.

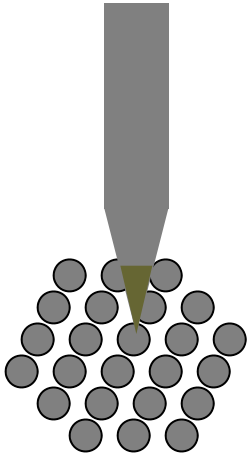
Procedure
(Medical Doctor's License Required)

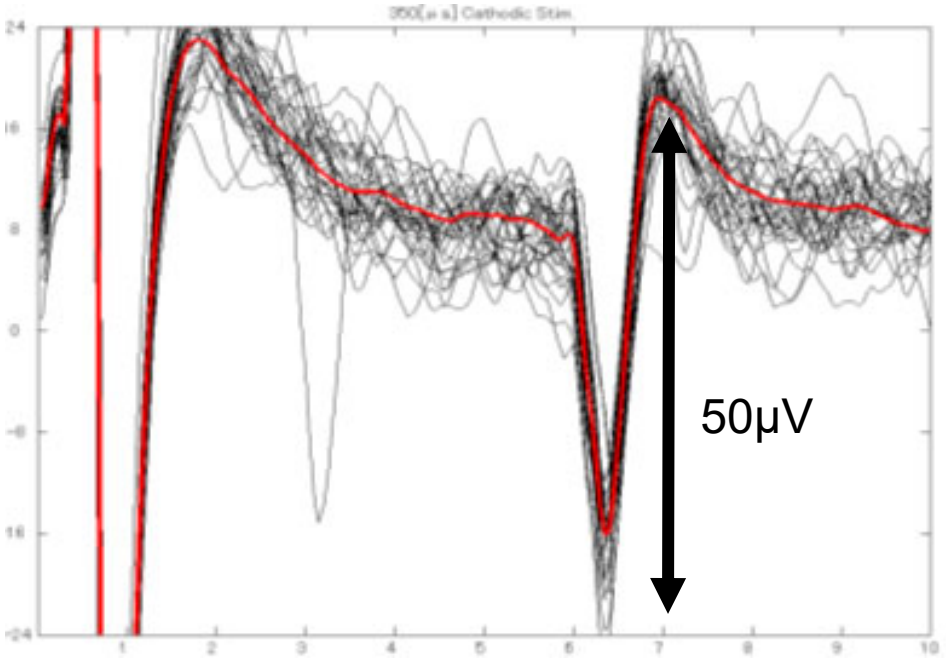
(0)See where the nerve bundle is. (by ultrasonography)

(1)Insert a needle (φ0.1mm), which is connected to Amp&Speaker

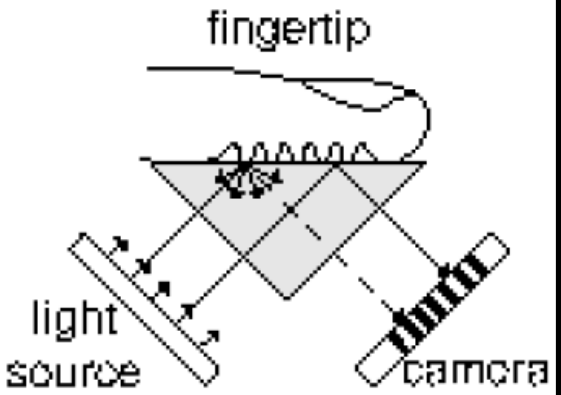
(2)Identify Location and Type of Receptor by the Sound.

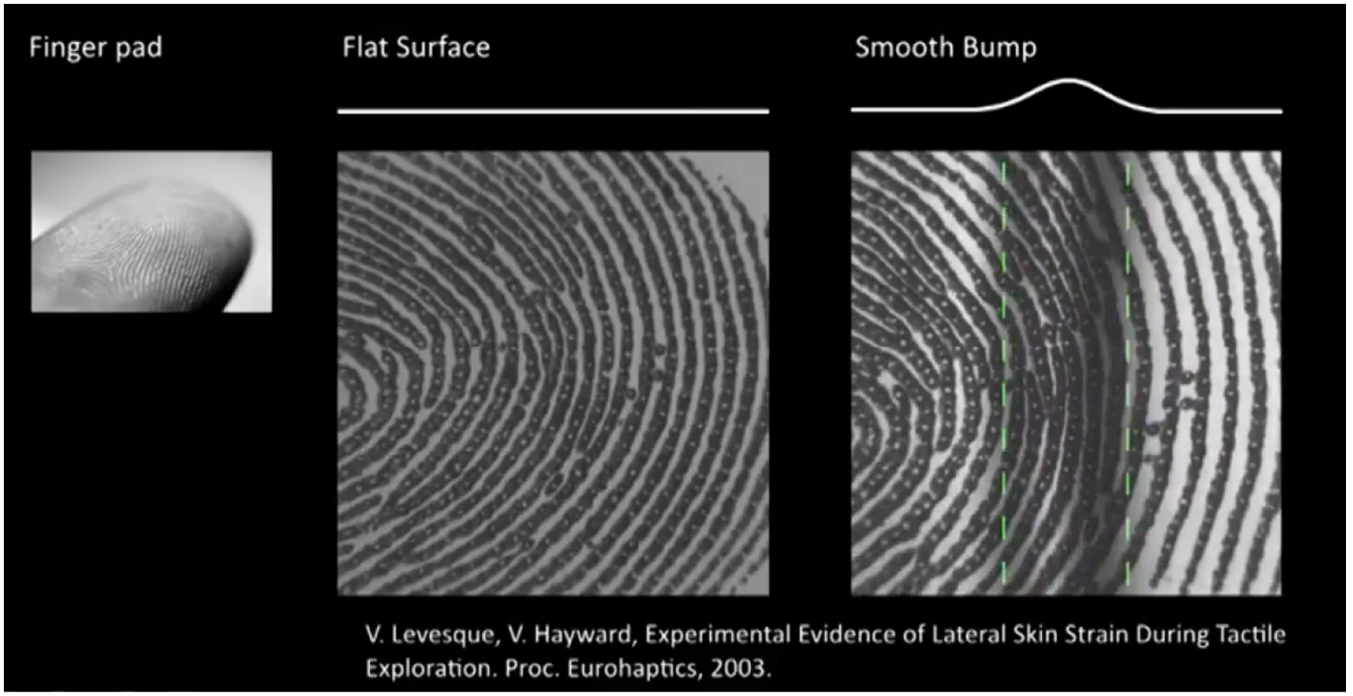
(3)Do Experiment on that Location.





どうやって調べる？：皮膚変形
How we know?: Skin recording



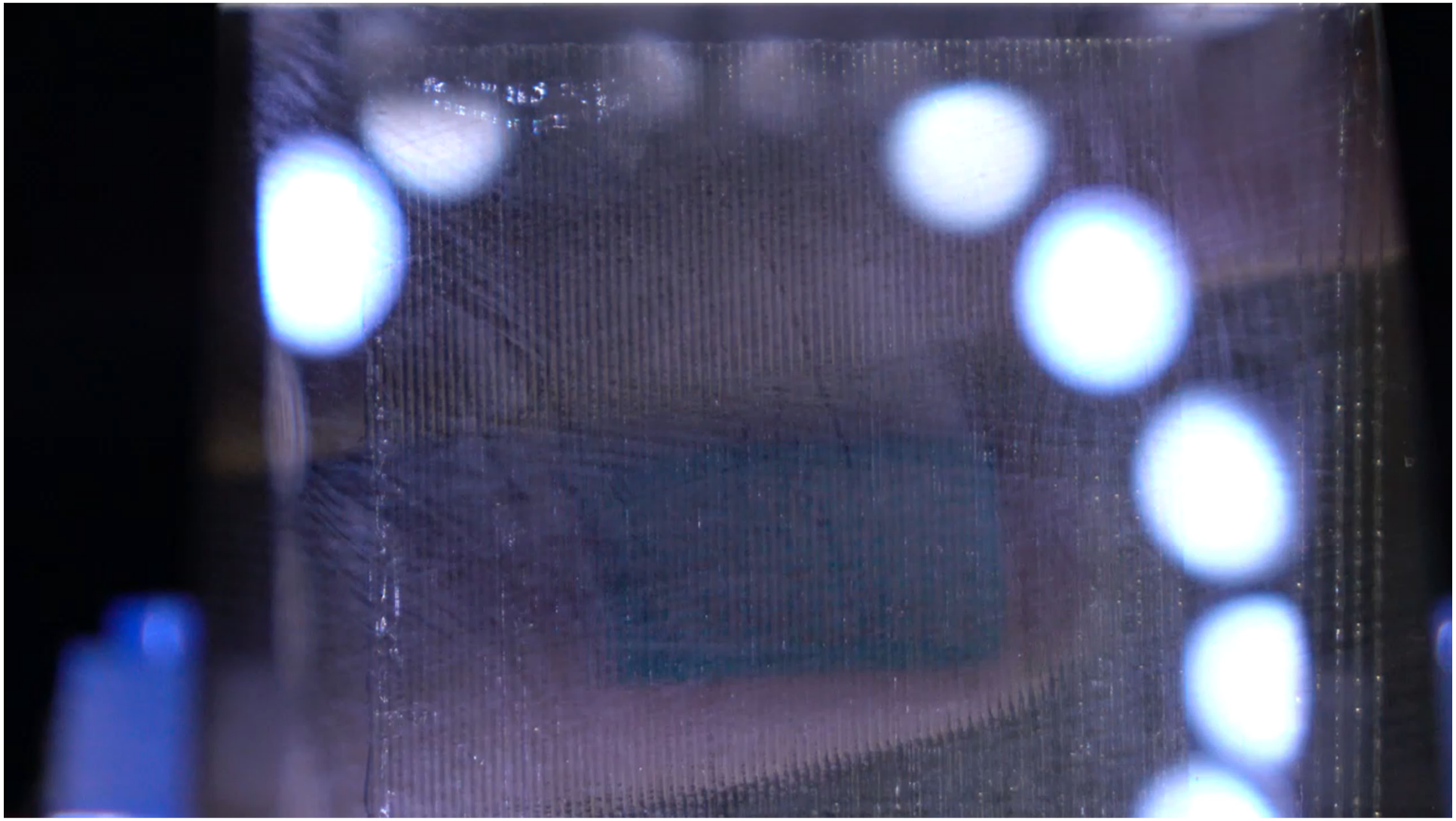


https://youtu.be/bdgmGrESe14?t=681

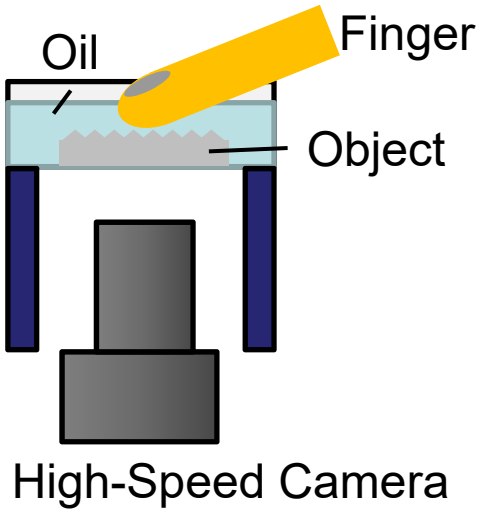
Levesque (2003) Experimental evidence of lateral skin strain during tactile exploration

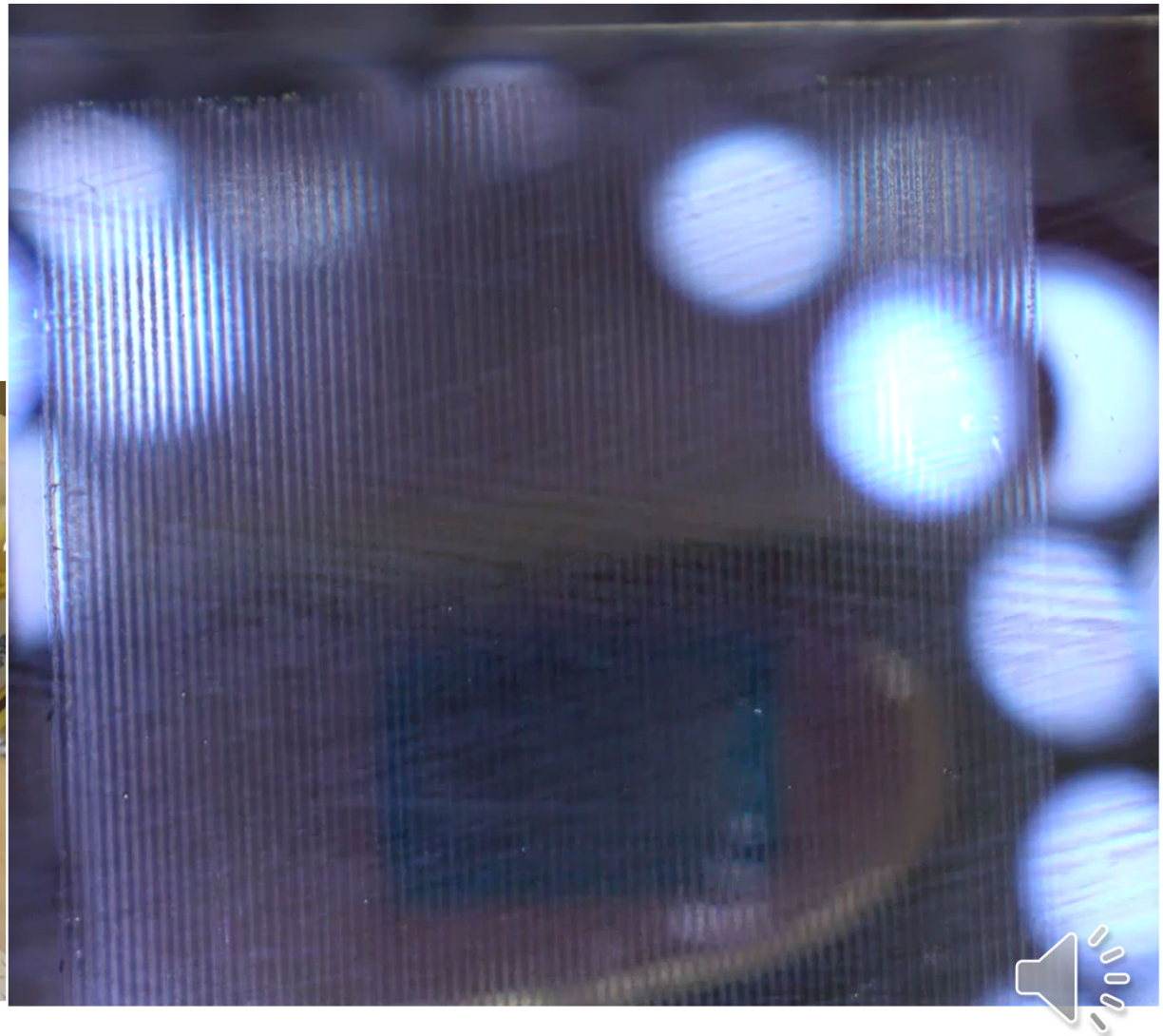
Optical observation only for flat or smooth surface.

When We Touch Rough Surface

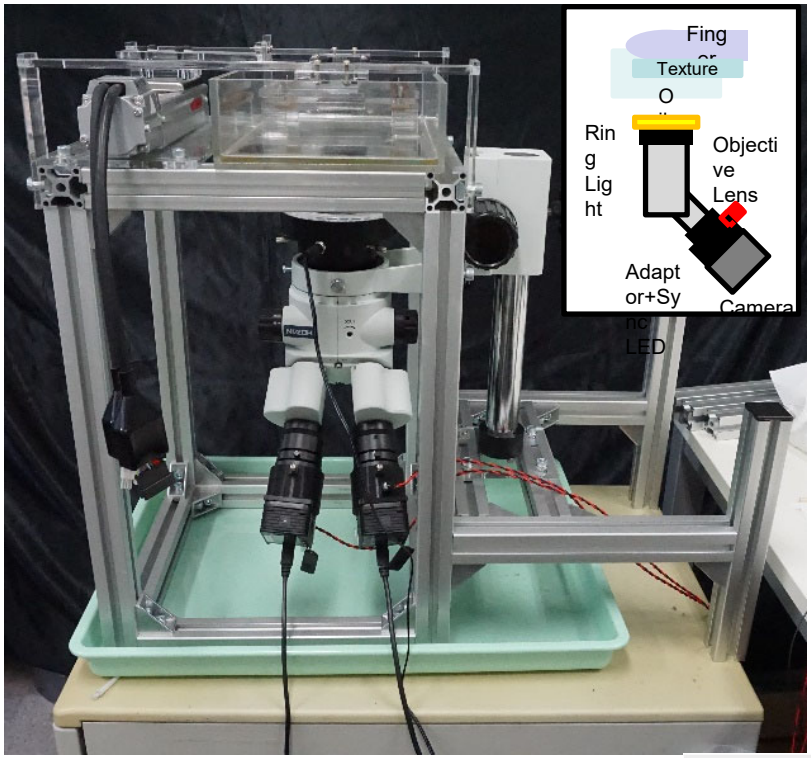


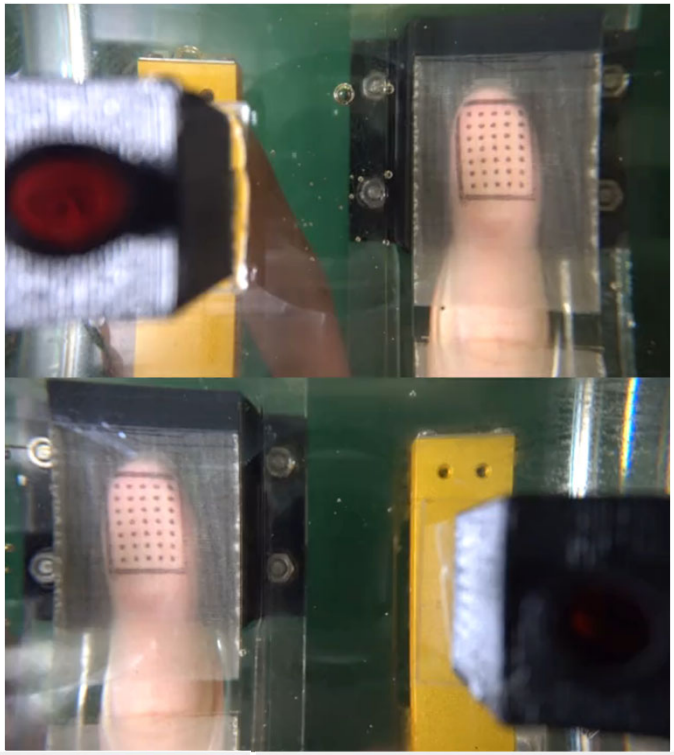
Make It Optically Transparent

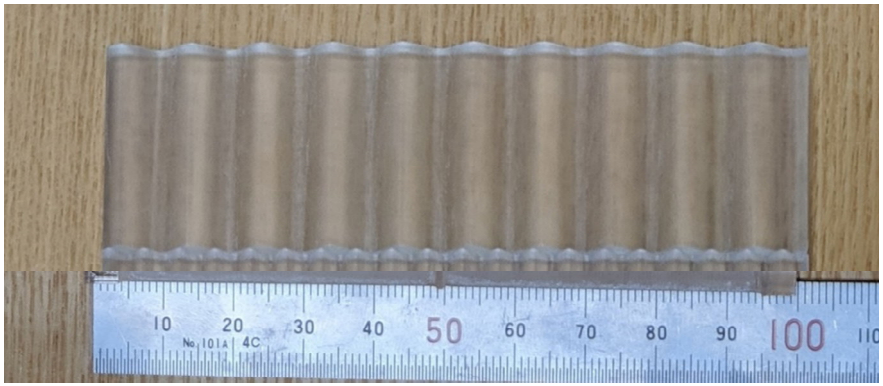


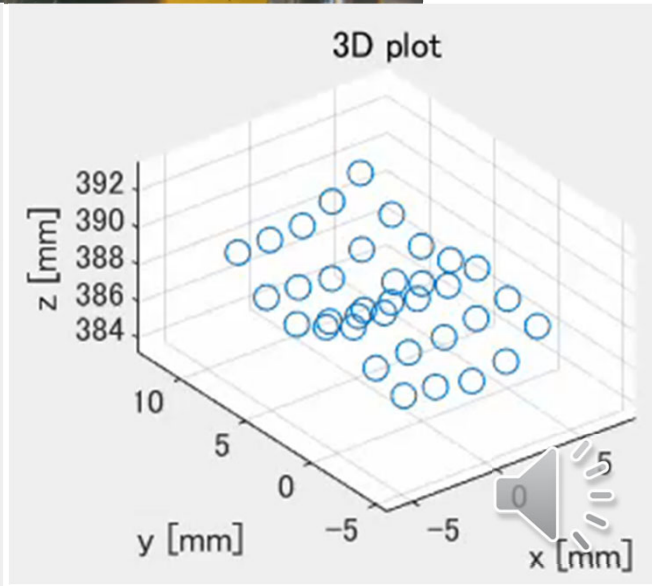


Skin Deformation on Textured Surface









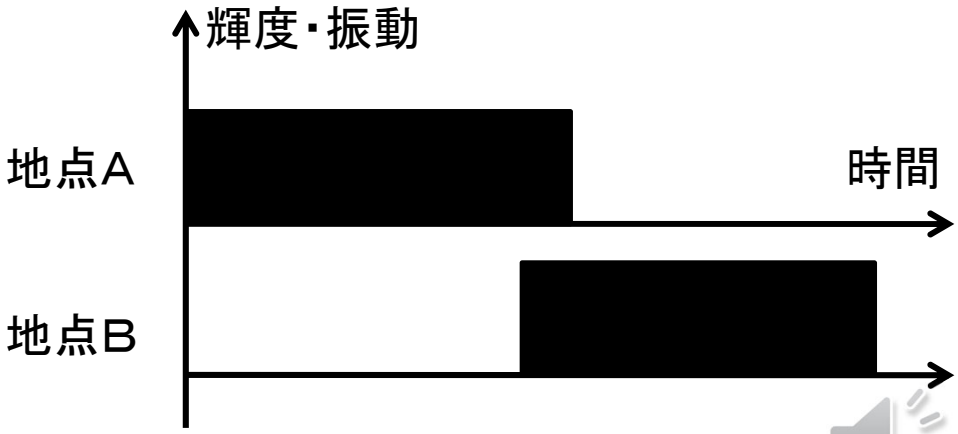
S.Tanaka, S. Kaneko,H. Kajimoto: Three-dimensional Measurement of Skin Displacement, Haptics Symposium 2020.

TODAY's TOPIC

1. Skin Sensation Mechanism
2. Tactile Illusion
3. Tactile Display

時空間能力の不完全さから生じる錯触(1):仮現運動

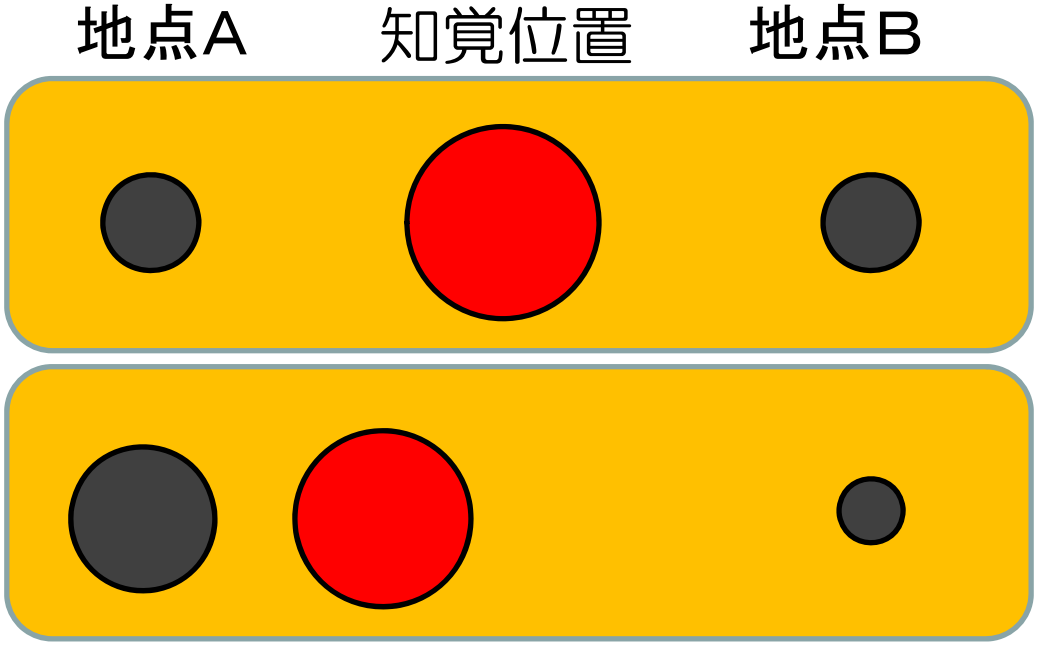
Illusion related to spatio-temporal interaction: Apparent motion



触覚の仮現運動では、時間的なオーバーラップが有る方が明瞭

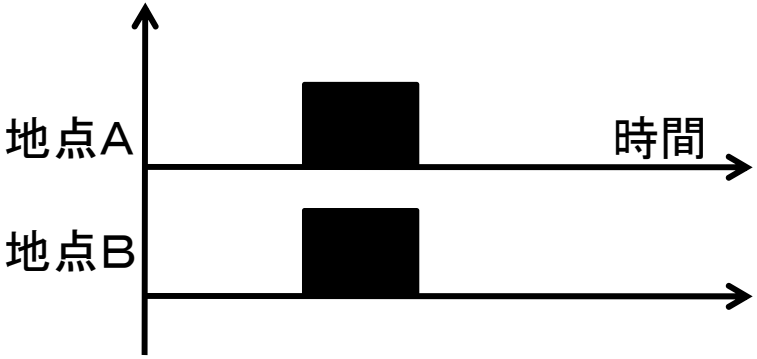
時空間能力の不完全さから生じる錯触(2):ファントムセンセーション

Illusion related to spatio-temporal interaction: Phantom Sensation (Funneling)

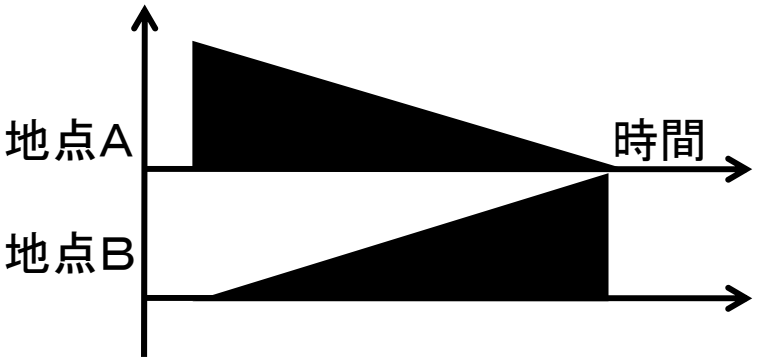


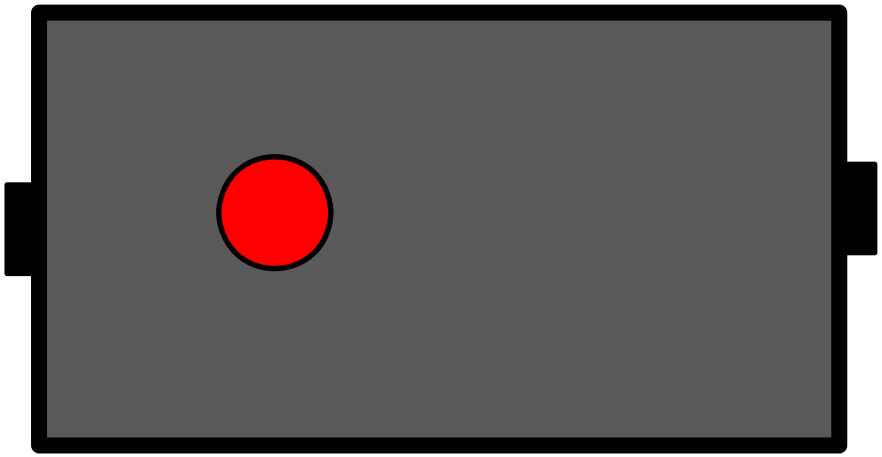
●特に短パルス刺激で強く発生
●複数刺激子の間に知覚
●位置は移動できる

●Generated by short pulses
●Image generated between stimulators
●Position can be controlled



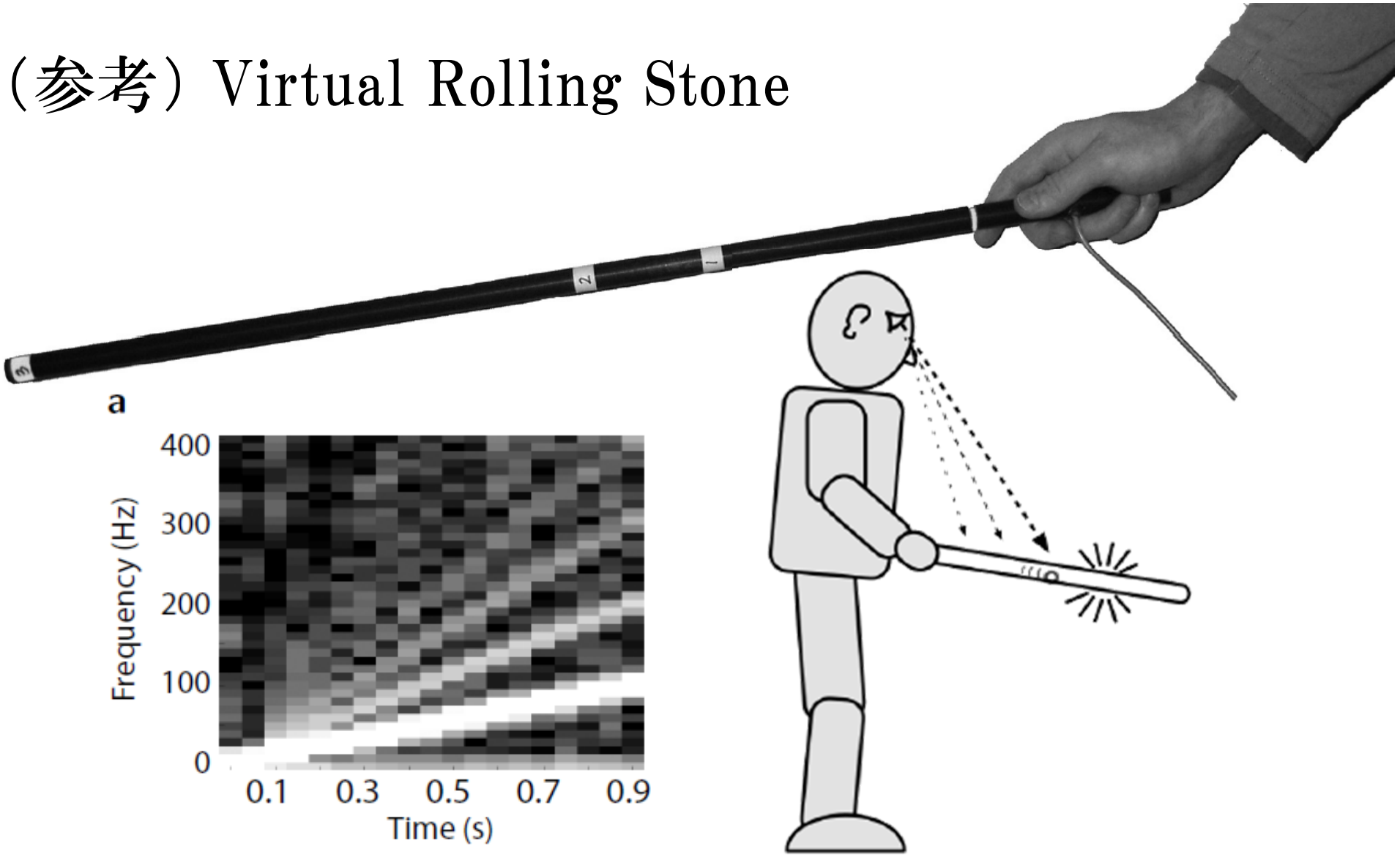
把持物体中のファントムセンセーション





- 持っている物体上に振動位置が定位する。
- 重心位置の移動によって滑らかに移動
- 仮現運動では不可能な連続的な動きを表現可能

（参考）Virtual Rolling Stone

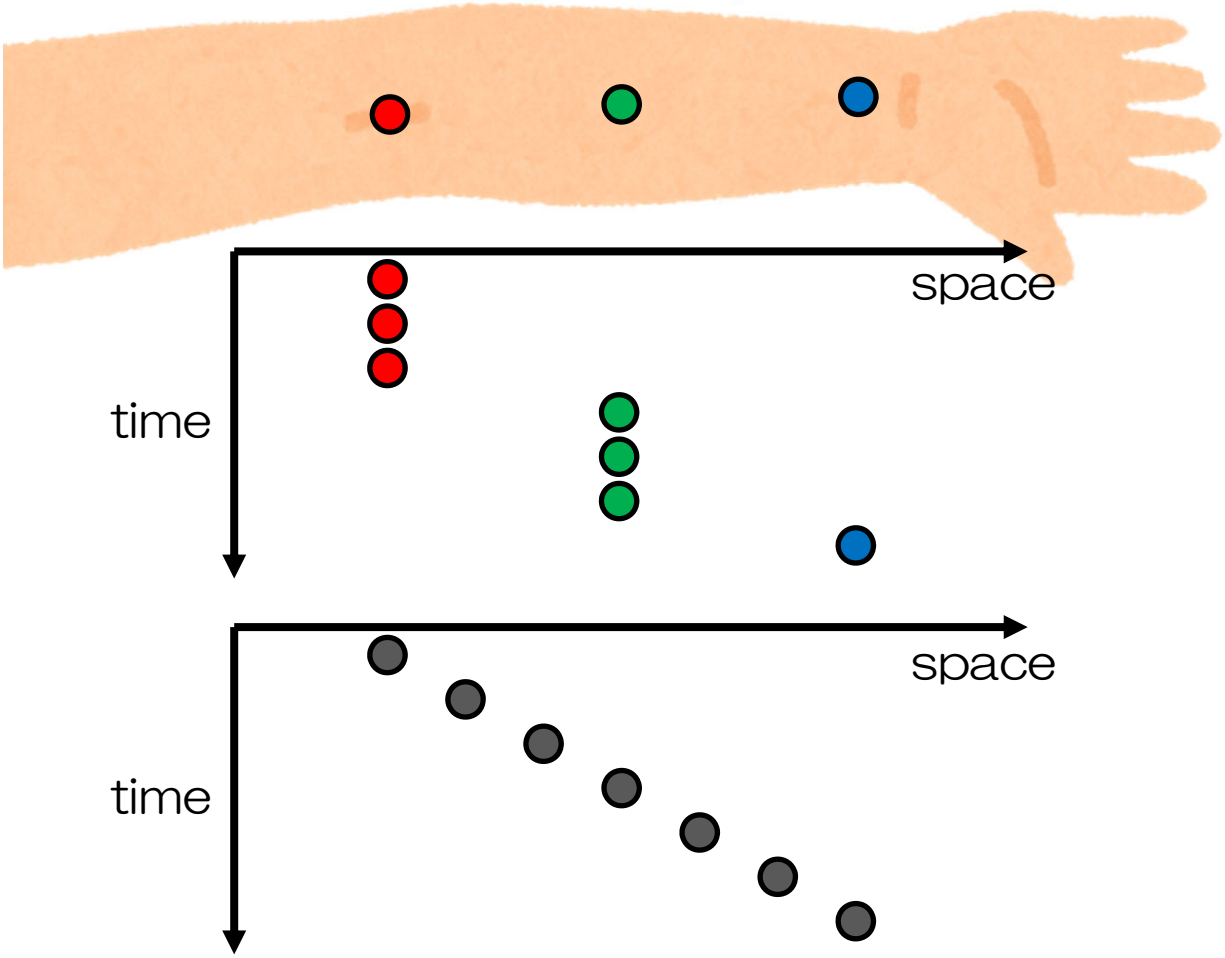


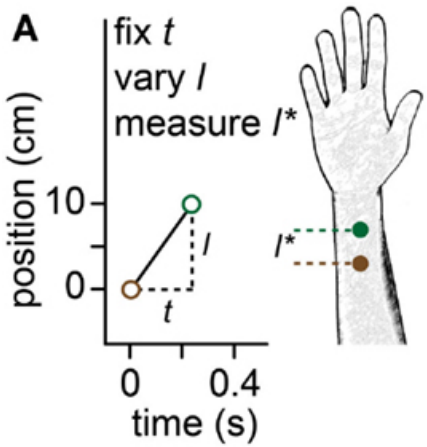
筒の中を転がっていく金属球をモデル化。転がる振動と衝突振動を振動子によって再生。ボールの衝突位置を把握でき、かつ非常にリアル。

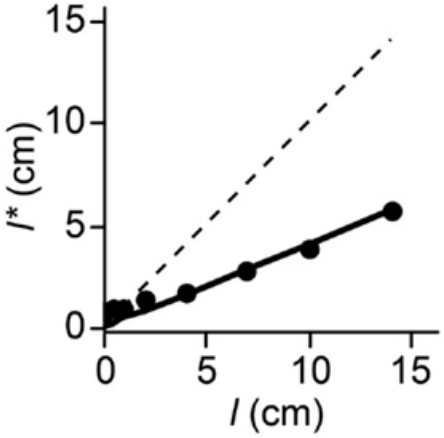
Yao, Hsin-Yun & Hayward, Vincent. (2006). An experiment on length perception with a virtual rolling stone. Proceedings of Eurohaptics.

時空間能力の不完全さから生じる錯触(3):跳躍運動

cutaneous saltation, rabbit





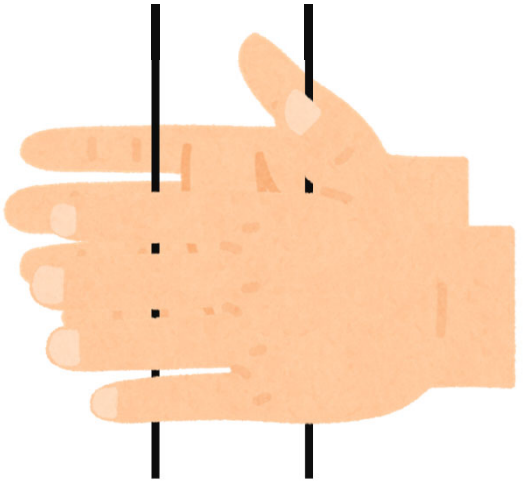


https://en.wikipedia.org/wiki/Cutaneous_rabbit_illusion

小数の場所(例えば3箇所)を複数回ずつ経時的に叩くと、連続的に移動しながら刺激されたように感じる(刺激間隔は300ms未満)
二点間の経時的な刺激で距離を実際よりも短く感じる現象と関連？

触感に関する錯触(1):ベルベットイリュージョン

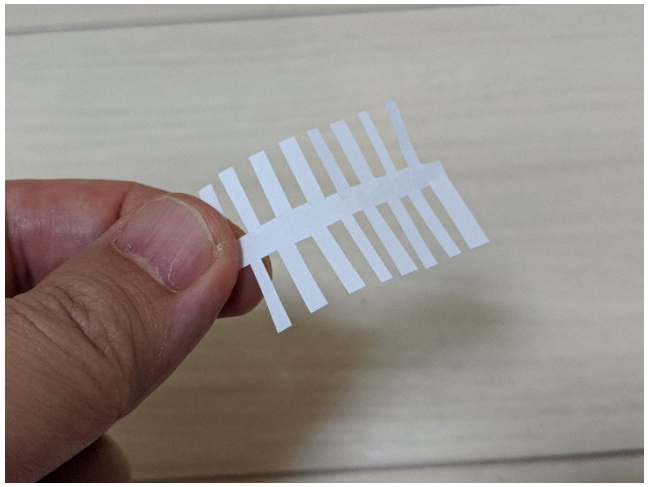
Illusion related to tactile feeling: Velvet Illusion

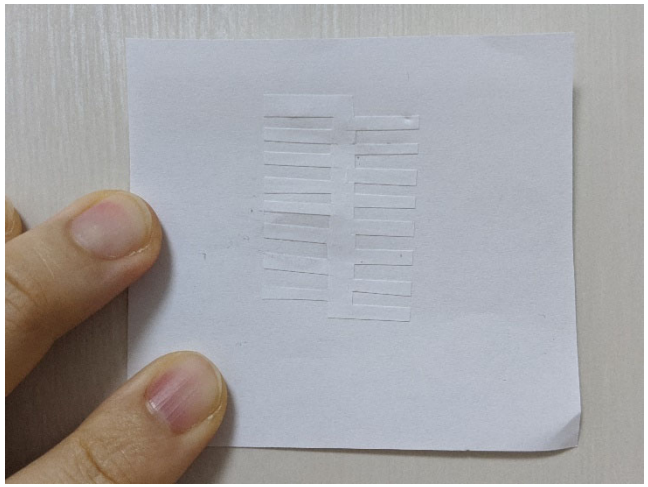


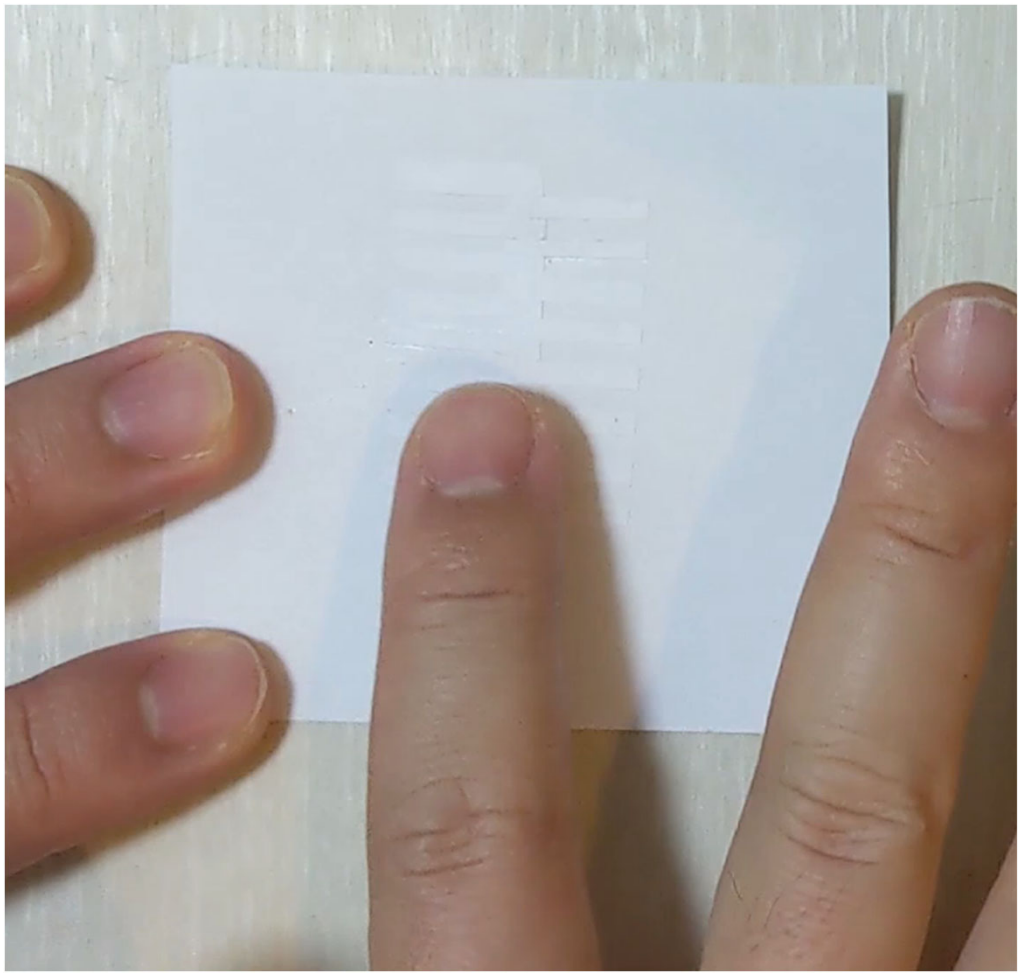
荒い網の目(テニスラケットなど)を両手で挟み,
前後に動かすと,モワッとしたベルベット感を生じる.(家で試しましょう)
細いワイヤ2本でも生じる。(2人で試しましょう)

Sandwiching coarse mesh of a net, such as tennis racket by two hands, and moves. Then, smooth surface like velvet is felt.

触感に関する錯触 Illusion related to tactile feeling (2): Fishbone錯覚







Nakatani, M., Howe, RD., and Tachi, S. Surface texture can bias tactile form perception. Exp Brain Res., Springer, 208(1), pp. 151-6, 2011. PMID: 20981539.

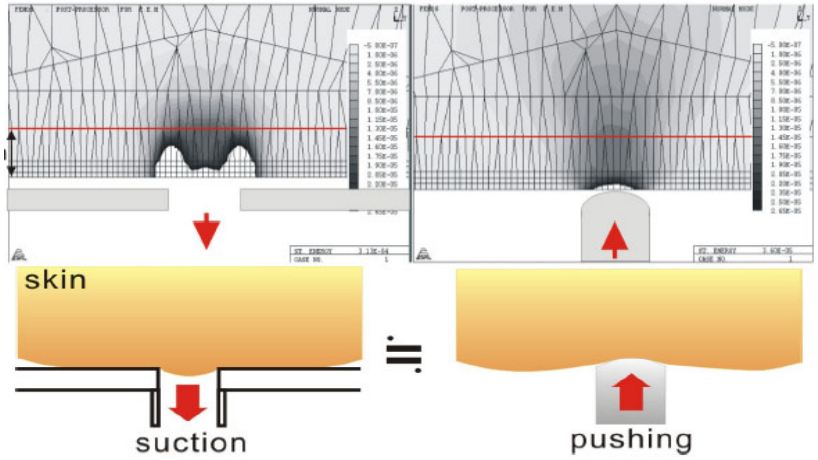
背骨状に切った紙を台紙に貼布。背骨中央部をなぞると、物理的には高いはずの中央部が周辺より凹んで感じる。（家で試しましょう）

物理的な凹凸ではなく受容器活動から凹凸を判断している。

触感に関する錯触(3): 吸引を圧迫と錯覚

Illusion related to tactile feeling: Air suction perceived as pressed.

Y. Makino, N. Asamura, H. Shinoda: A cutaneous feeling display using suction pressure. SICE Annu. Conf., 2003.



空気吸引による圧覚生成／Using air suction（家で試しましょう）

吸引と押下で，受容器位置に生じる歪エネルギーが同じ→人は区別できない。

実際の物理ではなく受容器活動で知覚することによって生じる齟齬現象。

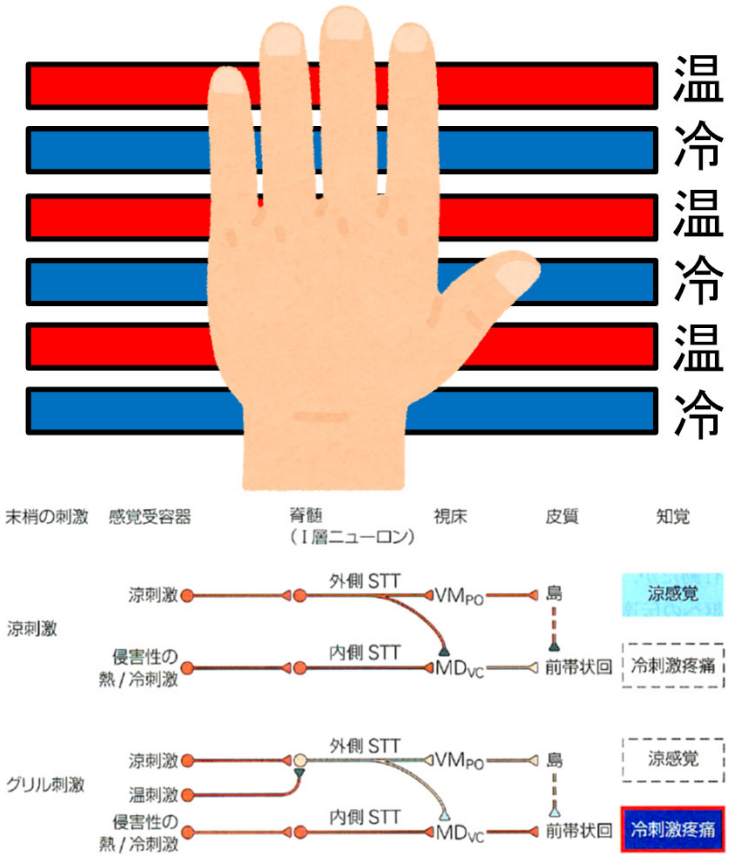
Suction and push produces the same strain energy, so human cannot distinguish.

温度関連錯覚 Temperature related illusion (1):Thermal Referral

人差し指と薬指を冷やしながら中指でものを触ると、中指で触れているものが冷たく感じる。温かい側でも生じる。（家で試しましょう）

Two cold stimuli generate illusory cold sensation at the middle.

温度関連錯覚 Temperature related illusion(2): Thermal Grill Illusion



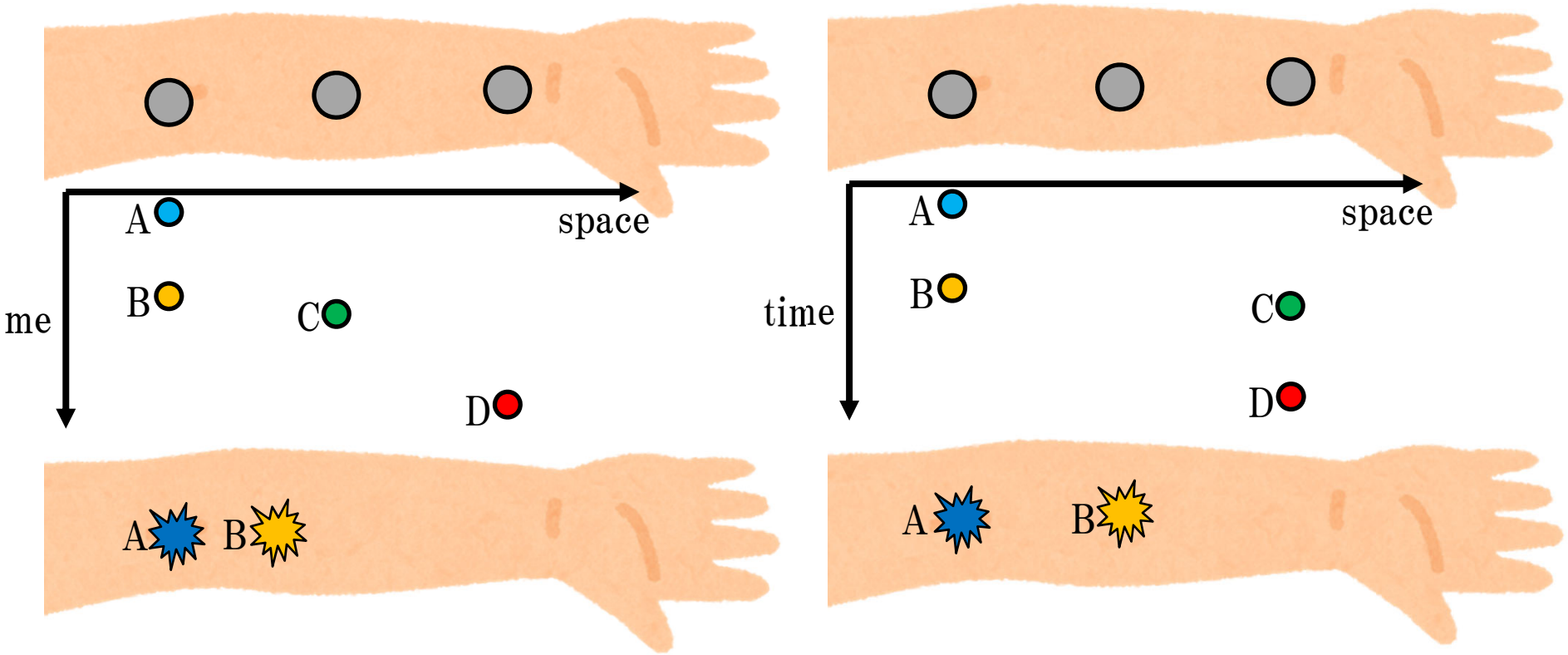
- 近距離の温＋冷同時提示で痛覚生起。（家で試しましょう）
- 通常、冷刺激は侵害性受容器も刺激するが、冷刺激によって痛みが抑制されて知覚しない。温刺激を加えるとこの抑制が外れ、痛みが知覚される、と説明される。
- Simultaneous presentation of warm + cold at close range to generate pain.
- Normally, cold stimulation simultaneously excites nociceptors, but it also suppresses pain pathway. The application of warm stimulus removes this suppression.

温度の交互提示による痒み抑制 / Itch relief by hot/cold stimuli

R. Watanabe, N. Saito, Y. Mori, T. Hachisu, M. Sato, S. Fukushima, H. Kajimoto: Development of Roller-Type Itch-Relief Device Employing Alternating Hot and Cold Stimuli, CHI 2013 (Ex-tended Abstracts), April27-May2, 2013, Paris, France.

温度の跳躍運動 /Thermal cutaneous rabbit

[HapticsSymposium2016] Space-Time Interactions and the Perceived Location of Cold Stimuli. Anshul Singhal, Lynette Jones

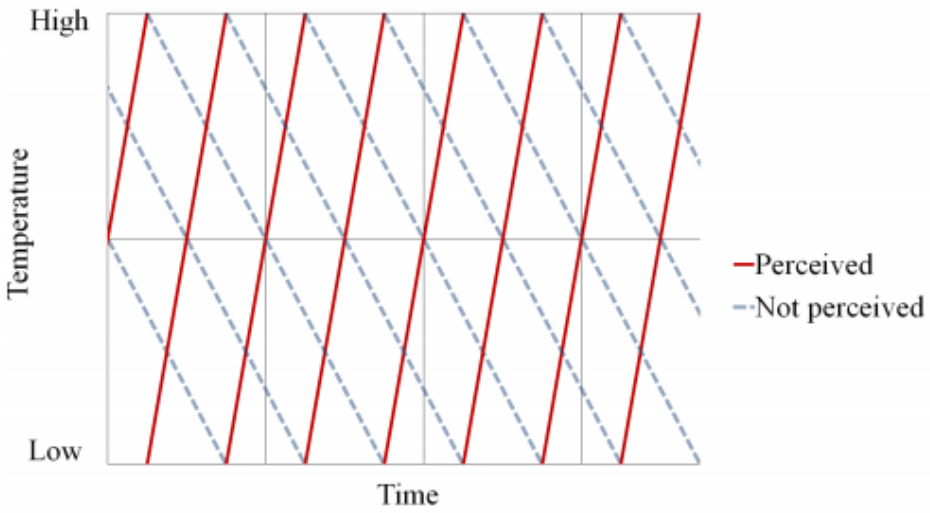


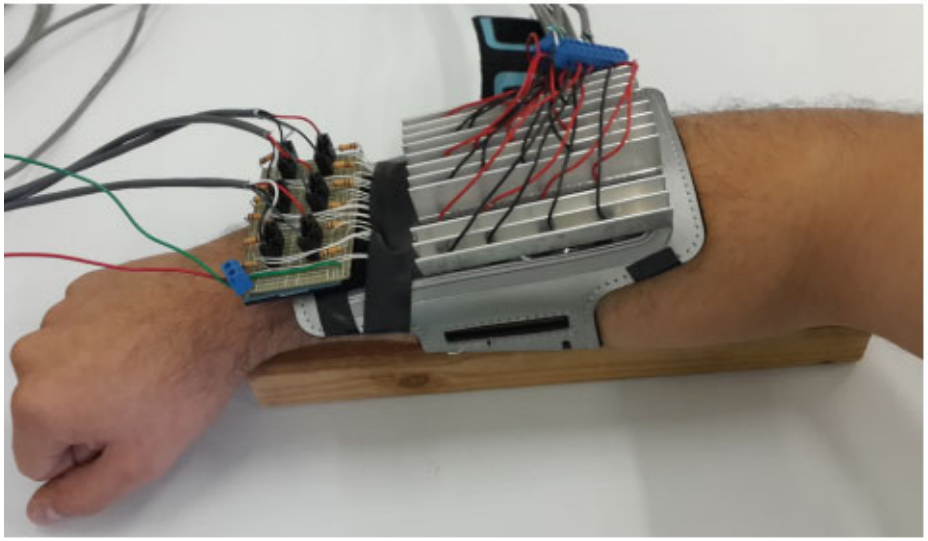
断続的に複数の冷覚を異なる場所に提示した時、途中の冷覚の知覚位置が提示タイミングに応じて変化。温度感覚においても時空間相互作用が有ることを示した。

Several cold sensations are presented intermittently at different locations. The perceived position of the cold sensation during the presentation is dependent on the timing of the presentation.

温度感覚の無限音階 Continuous heating

(WorldHaptics2017) Asymmetrically-Applied Hot and Cold Stimuli Gives Perception of Constant Heat. Ahmad Manasrah, Nathan Crane, Rasim Guldiken, Kyle B. Reed



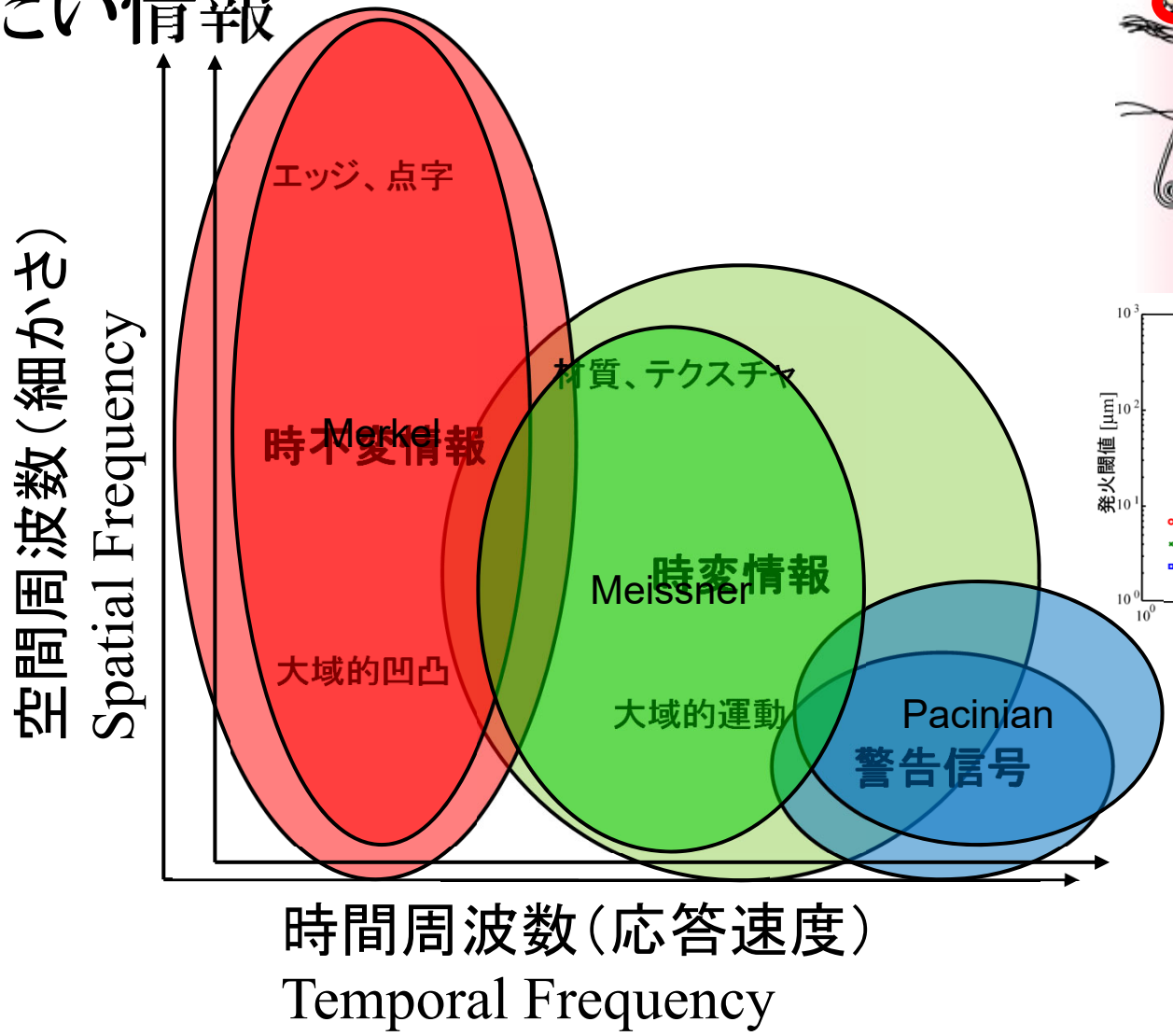


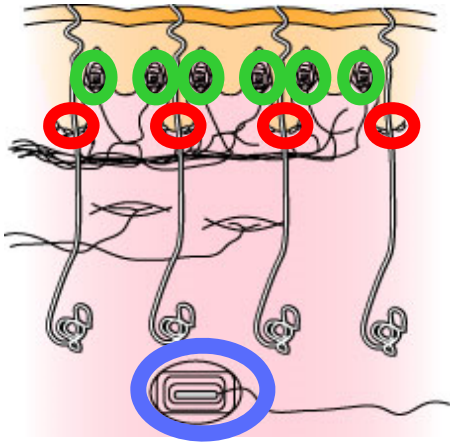
複数のペルチェ素子を、「温度急上昇となだらかな低下」で駆動すると、上昇側だけを知覚し、ある種の無限に上昇する温度感覚を知覚できる。

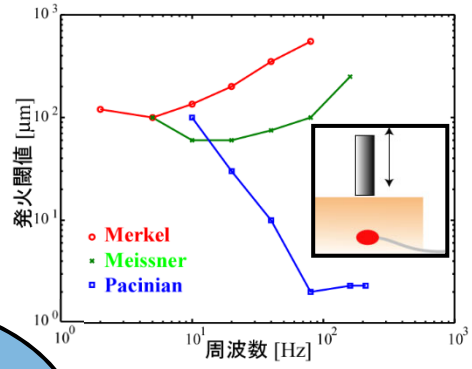
TODAY's TOPIC

1. Skin Sensation Mechanism
2. Tactile Illusion
3. Tactile Display

提示したい情報

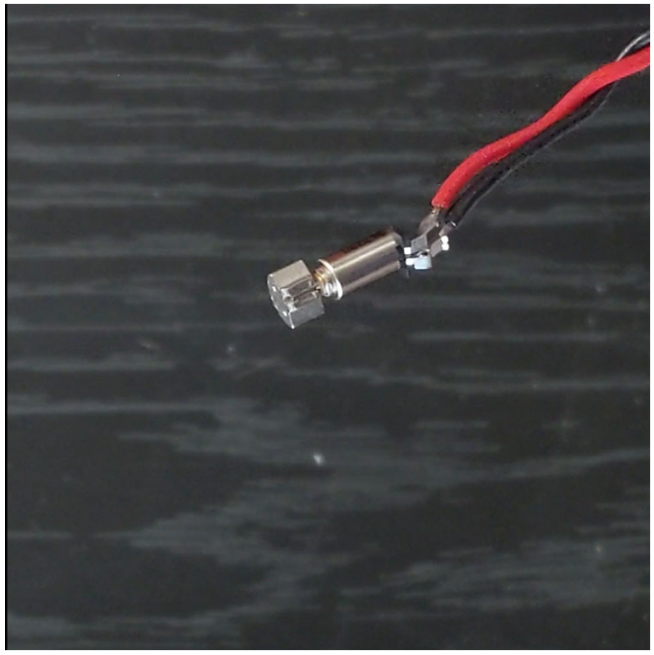


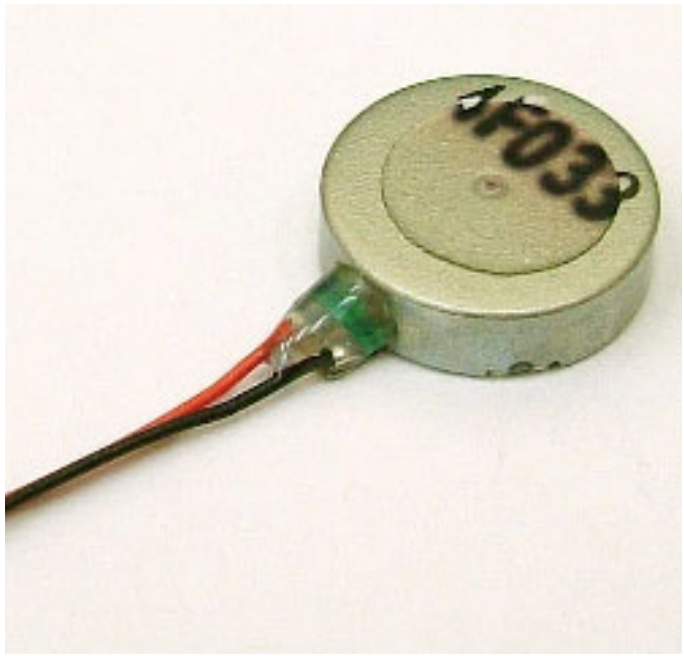


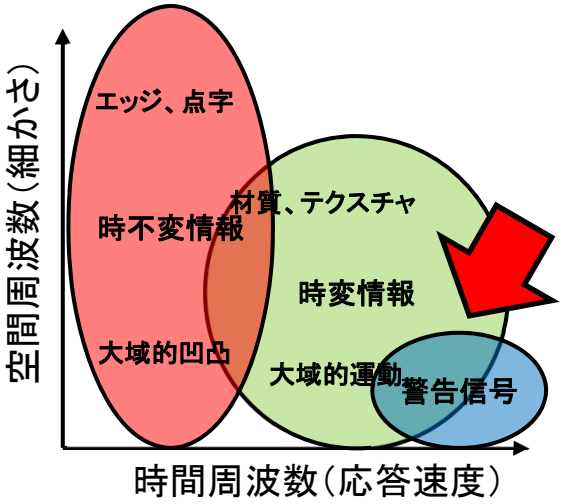


提示したい情報⇒必要なスペック
ハードウエアと密接な関係（すべての領域を提示できる手法は無い）

振動モータによる警告/Vibration Motor

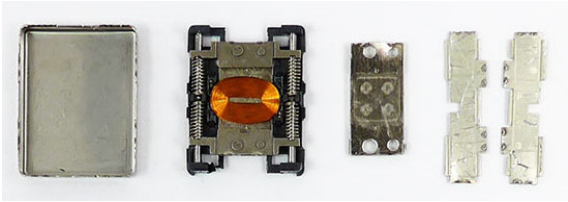


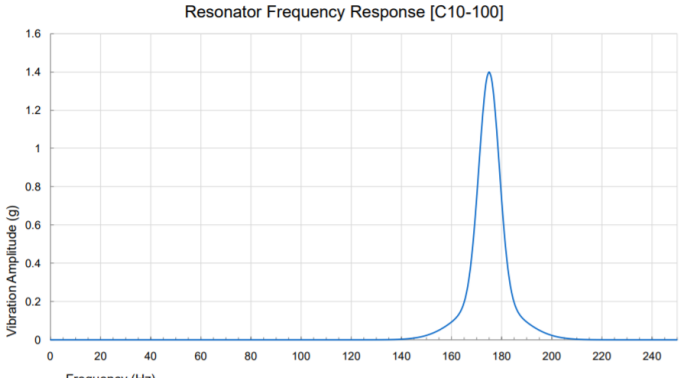


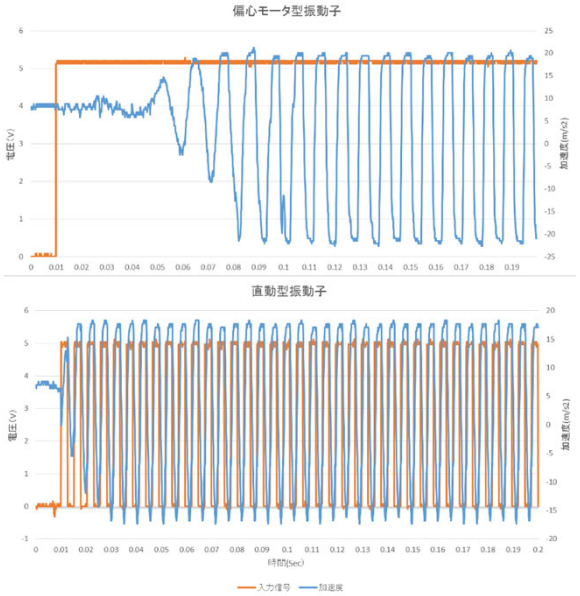


- モータ＋偏心おもり motor + eccentric mass
  - 電圧を変えると振動の周波数と振幅が同時に変更。Frequency & amplitude change according to applied voltage.
  - 材質、テクスチャの呈示には不向き。Not suitable for hi-fi tactile feeling.
  - 定格電圧でPacini小体の周波数領域で振動するように設計。Frequency at rated voltage is at the range of Pacinian corpuscles.
  - 警告信号、大域的運動に好適。Good for notification.

直動共振アクチュエータ/Linear Resonant Actuator







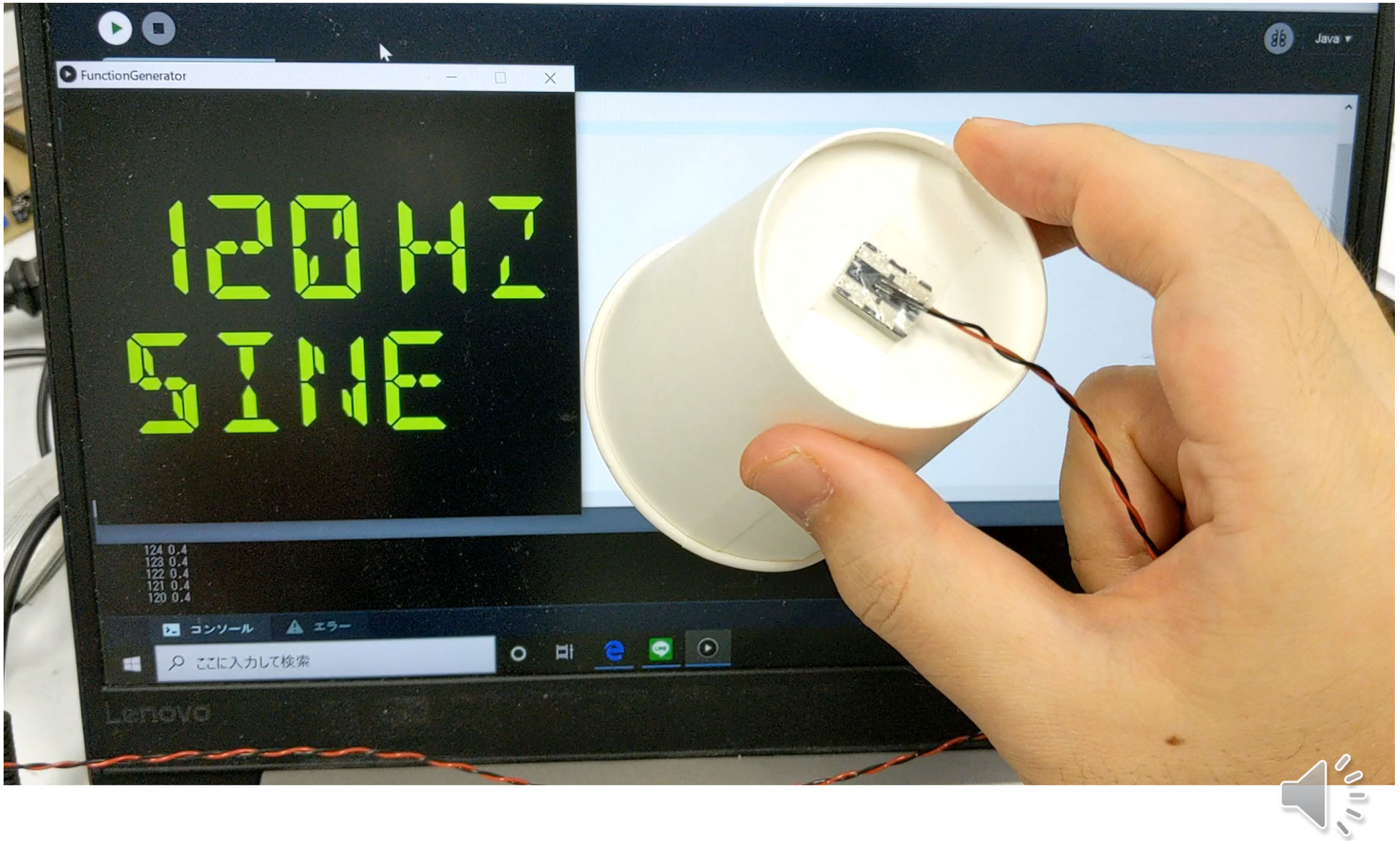
http://akizukidenshi.com/catalog/g/gP-06838/

https://www.precisionmicrodrives.com/product/c10-100-10mm-linear-resonant-actuator-4mm-type

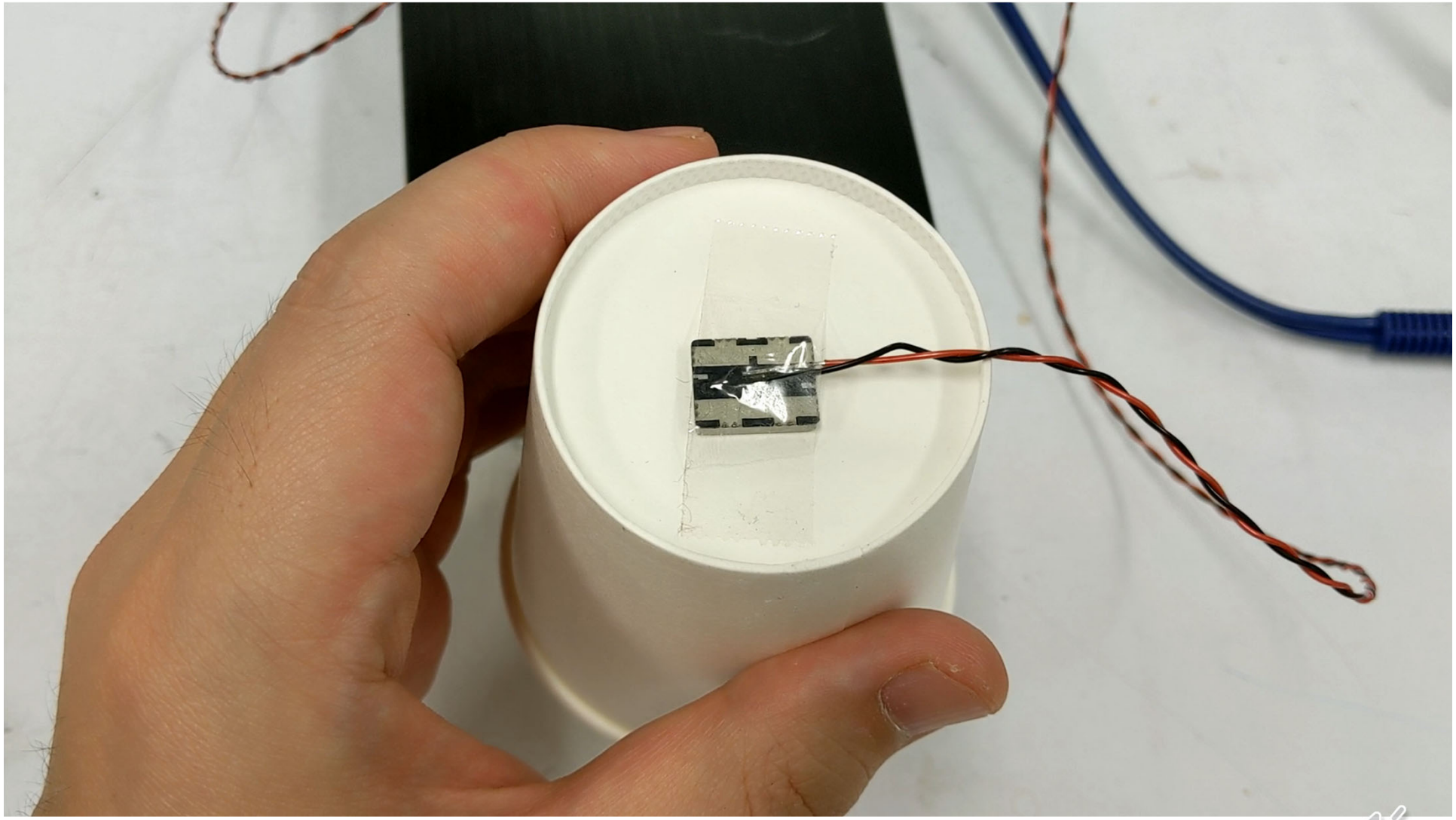
田辺他:多数の直動型振動子を用いた手全体への触覚提示が可能なグローブの開発,SICE-SI2014

- 偏心おもり:一定回転速度に達するまでの時間遅れ:80ms程度
- ボイスコイル振動子に共振特性をもたせたLinear Resonant Actuator:遅延10ms以下.
- 共振周波数150Hz～200Hz. Pacini領域を狙う
- 現在スマートフォン、スマートウオッチに内蔵

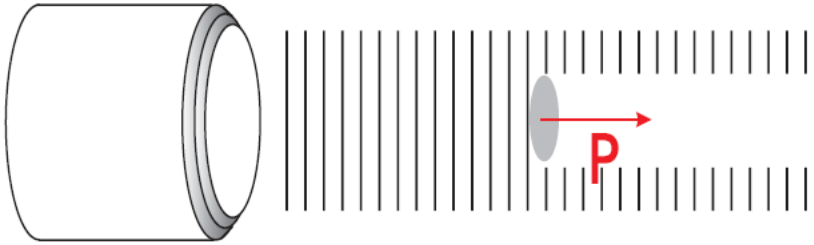
直動共振アクチュエータ/Linear Resonant Actuator

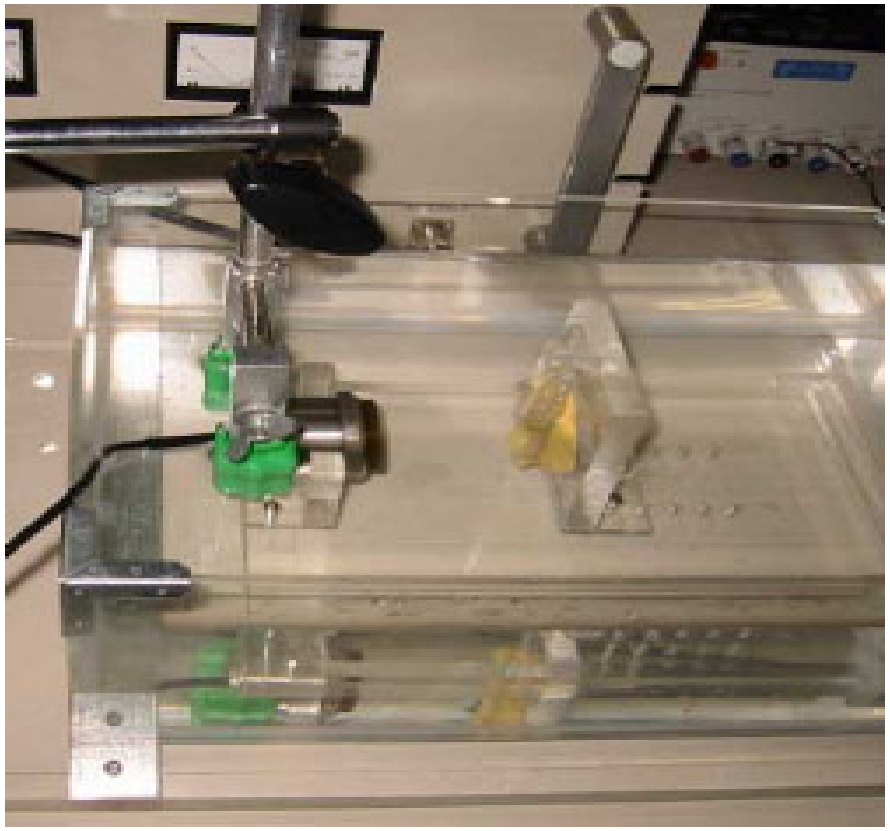


直動共振アクチュエータ/Linear Resonant Actuator



Actuator should disappear?

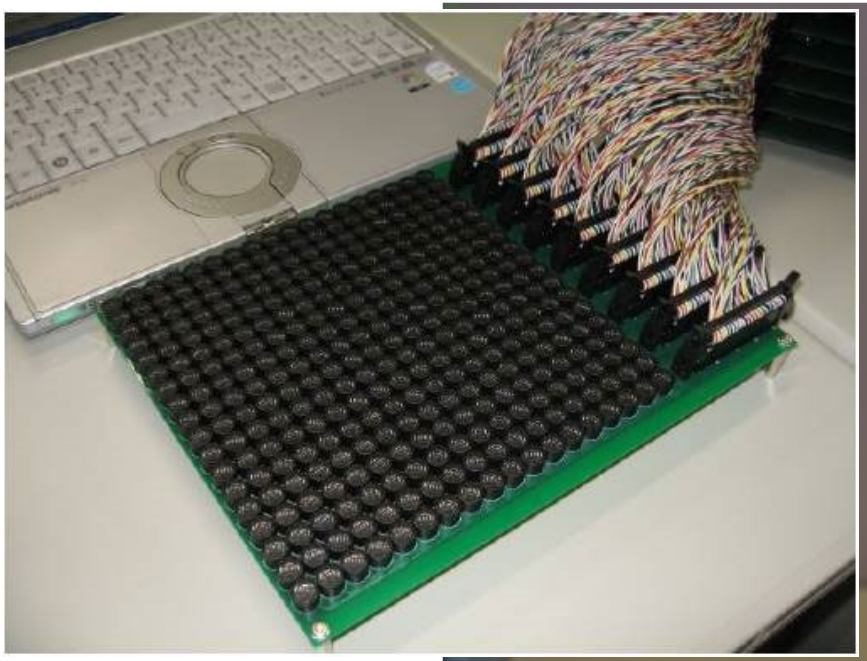


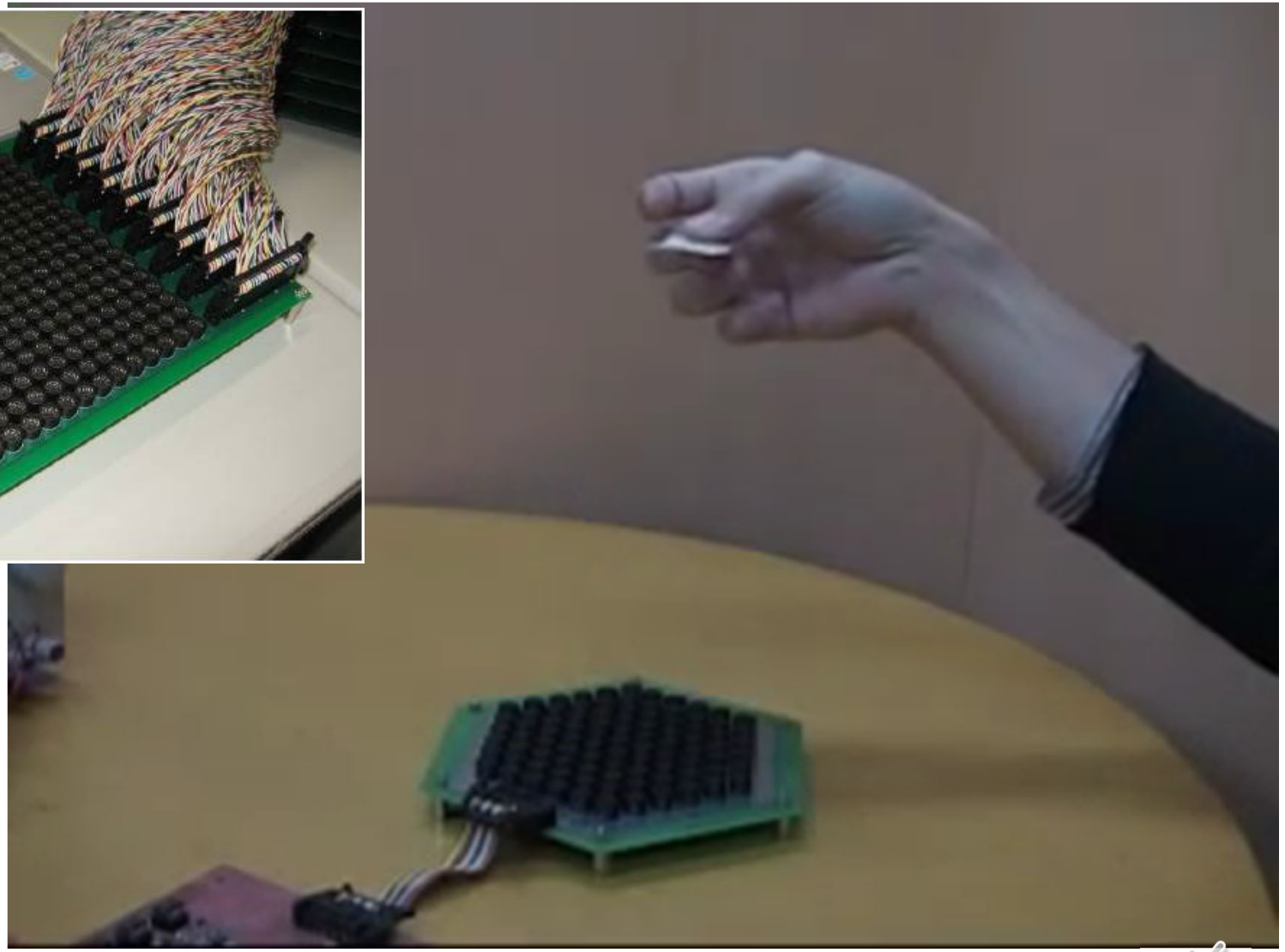


Ultrasound generates Static Pressure

Iwamoto, Maeda and Shinoda “Focused ultrasound for tactile feeling display,” In Proc. of ICAT2001.

空中超音波の収束による触覚提示
Airborne Ultrasound Tactile Display



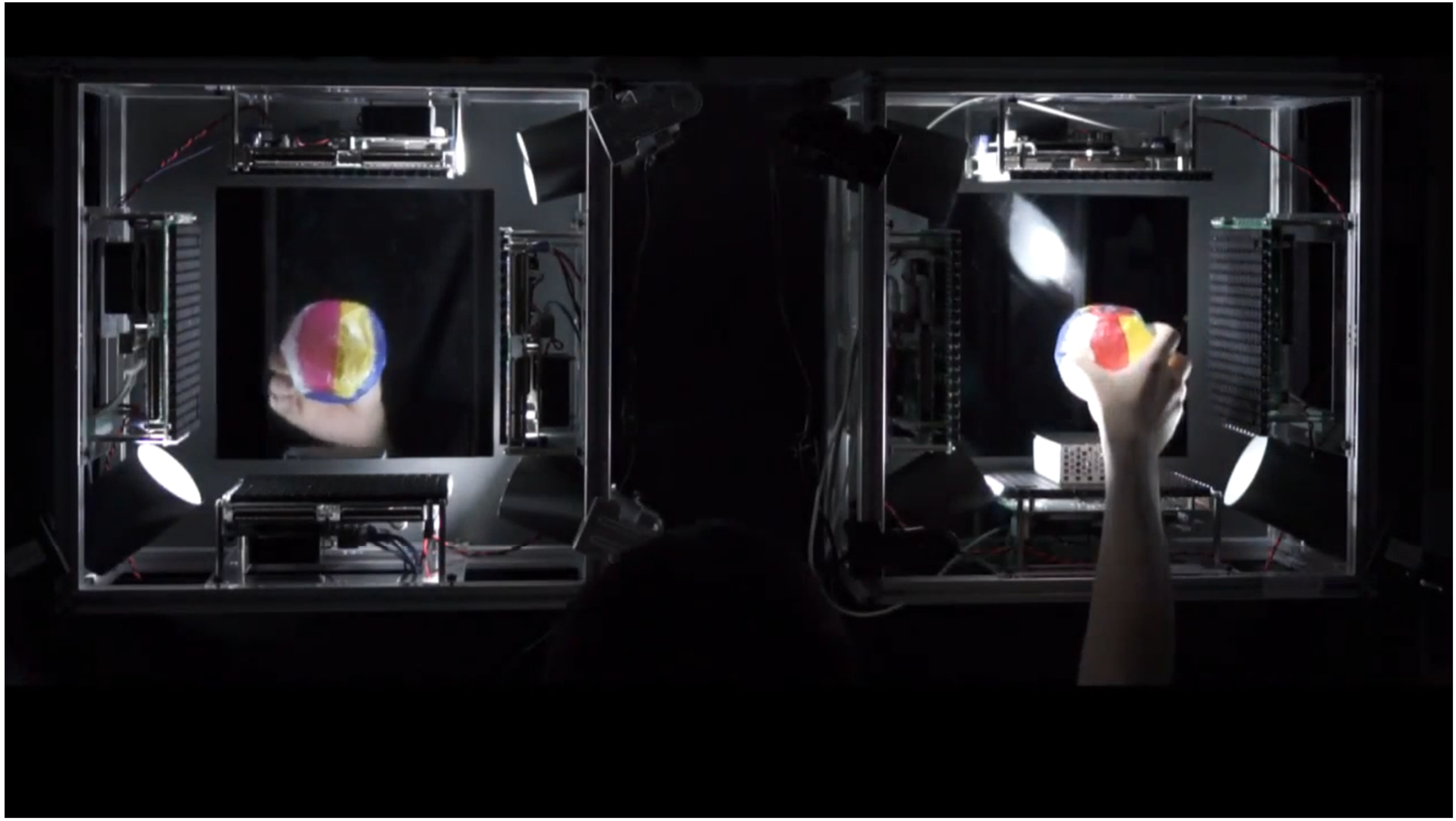


https://www.youtube.com/watch?v=hSf2-jm0SsQ

Hiroyuki Shinoda, Airborne Ultrasound Tactile Display. Journal of the Robotics Society of Japan, 2018

(CHI2016) HaptoClone (Haptic-Optical Clone) for Mutual Tele-Environment by Real-time 3D Image Transfer with Midair Force Feedback

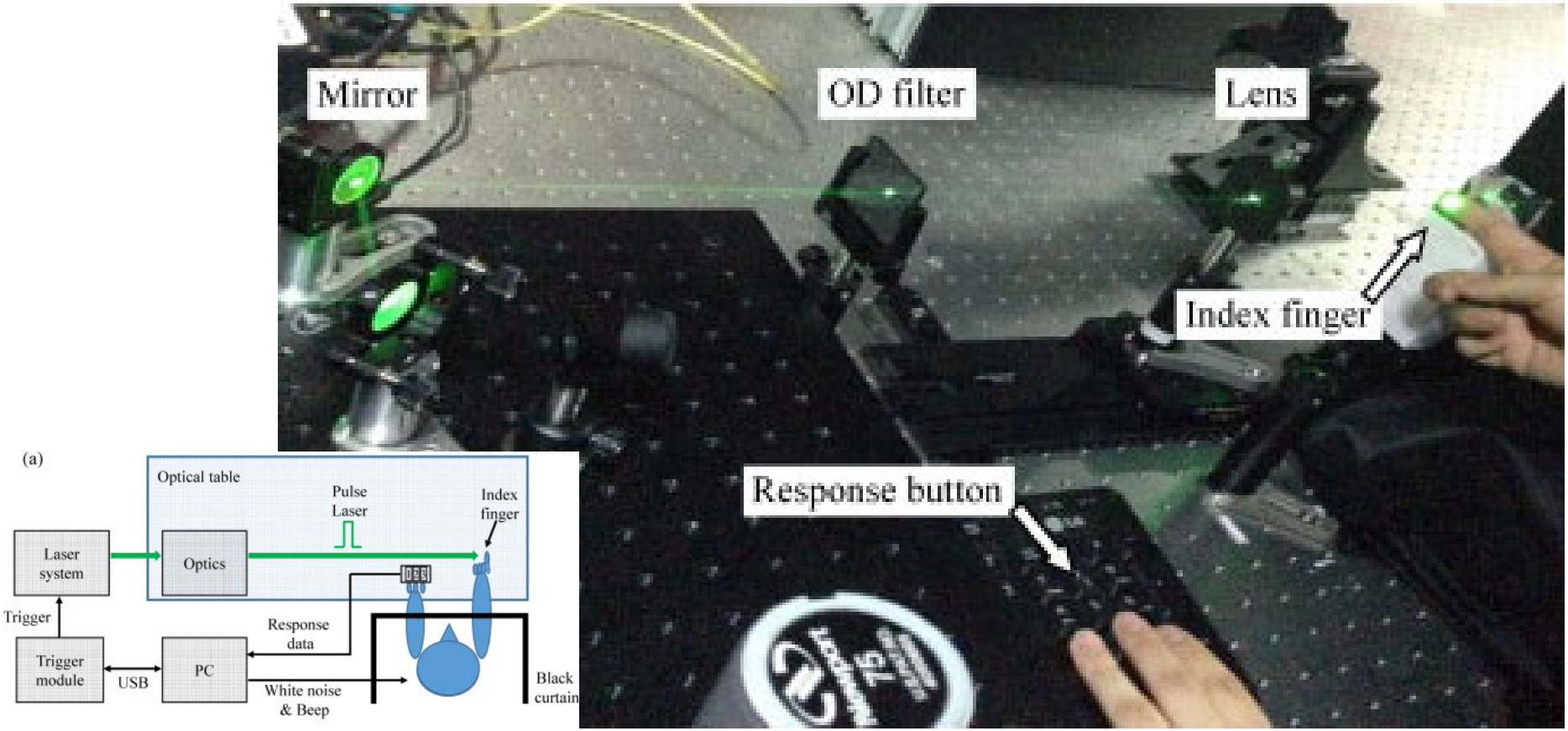
Yasutoshi Makino, Yoshikazu Furuyama, Seki Inoue, Hiroyuki Shinoda



https://www.youtube.com/watch?v=yxsgjqvSjQY

超音波触覚を用いた遠隔触覚.

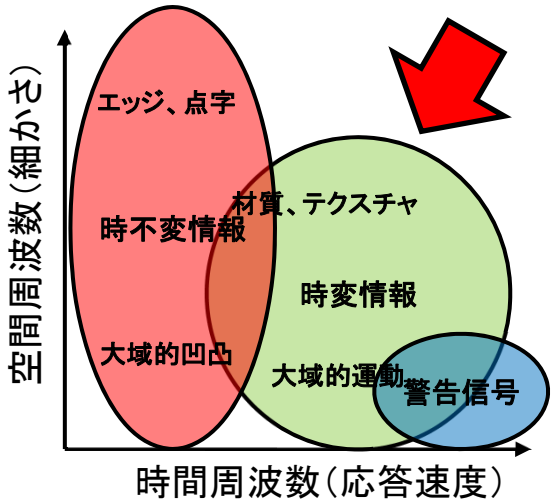
(WHC2015)レーザー光を用いた触覚提示

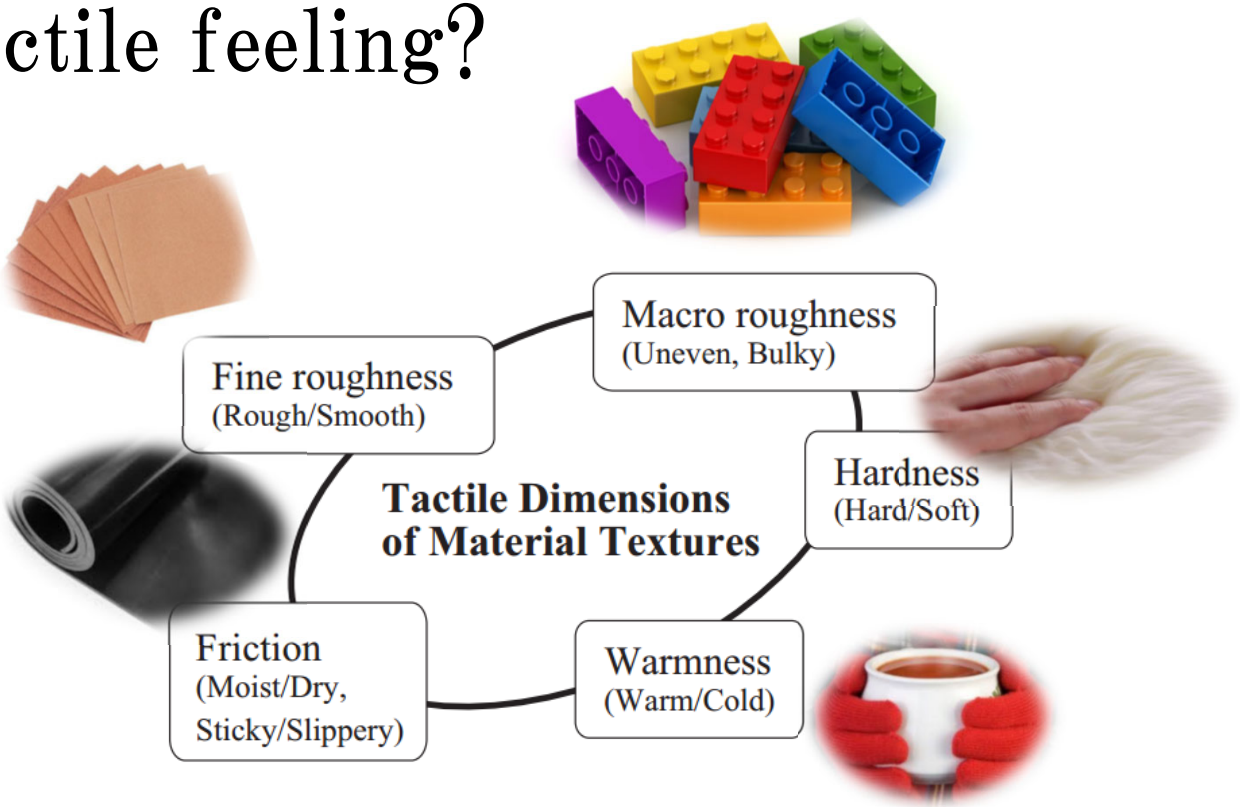


Mid-Air Tactile Stimulation Using Laser-Induced Thermoelastic Effects: The First Study for Indirect Radiation, WHC2015
Hyung-Sik Kim et al., "**Evaluation of the Possibility and Response Characteristics of Laser-induced Tactile Sensation**," *Neuroscience Letters*, Vol. 602, pp. 68-72, 2015.

超短時間の高エネルギーレーザー光を皮膚表面またはその上の弾性体に当てることでパルス状の衝撃波を生じ，触覚を提示できる．

「触感」を提示する
How to present tactile feeling?

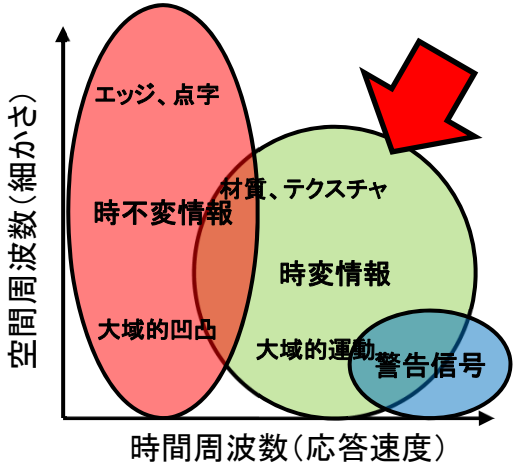


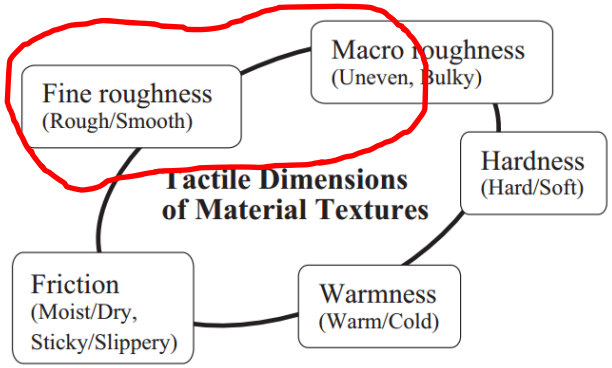


永野，岡本，山田：触覚的テクスチャの材質感次元構成に関する研究動向，TVRSJ2011

- 触感は大域的粗さ、細かな粗さ、硬柔、摩擦、温度、で構成される。
- 触感の記録・再現は遠隔触覚を実用レベルに上げうる。
- Tactile feeling is composed of macro/fine roughness, hardness, friction, and warmness.
- Record & replay of tactile feeling has big potential.

理想の振動子：スピーカ/ Audio speaker is ideal

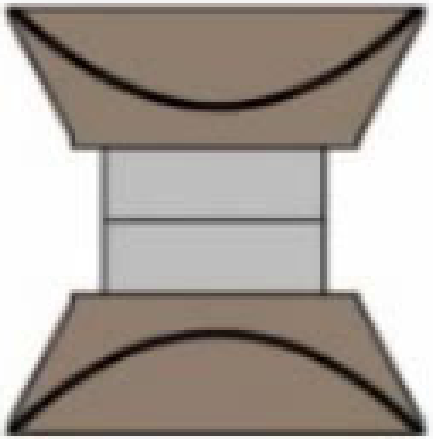




永野，岡本，山田：触覚的テクスチャの材質感次元構成に関する研究動向，TVRSJ2011

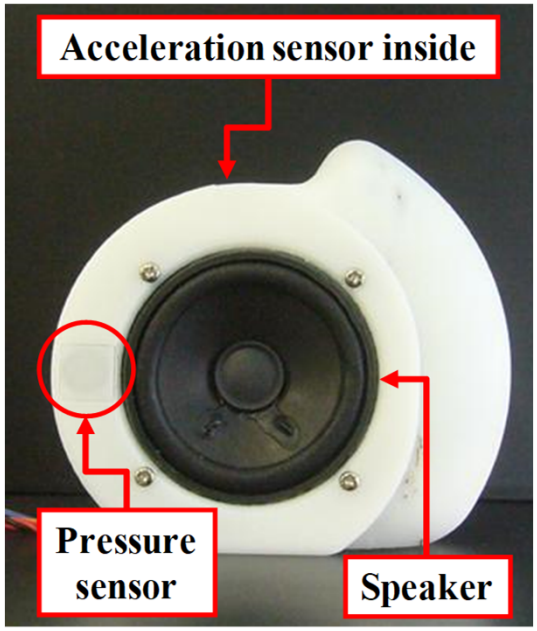
- 偏心モータ、LRAに対してエネルギー効率は落ちるものの、任意の周波数／振幅を実現。 Arbitrary frequency / amplitude can be replayed.
- 駆動系はほぼオーディオアンプ。 Audio system can be utilized.
- 比較的細かな粗さ感、主にPacini小体が捉える（が故に空間的な特徴のない）触感成分か、把持物体を介する（が故に空間的な特徴のない）触感成分が得意。

スピーカ⇒材質感の実現：生物感



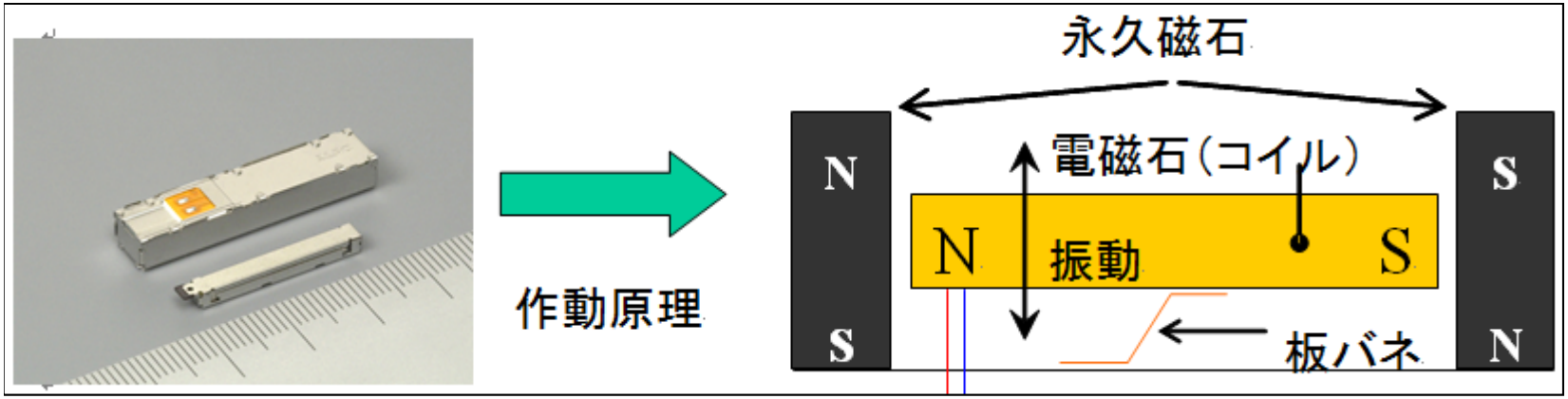
Users hold speakers with their hands and an elastic band around the speaker cone seals the air between the palm and the cone.

Y. Hashimoto A Novel Interface to Present Emotional Tactile Sensation to a Palm using Air Pressure, CHI2008



1Hz～2Hz程度の振動も提示できるため、例えば心拍も再現できる。スピーカを手で抑えると一種の空気圧駆動となり、本来的に「柔らかい」

スピーカ型アクチュエータの小型化
Miniatualizing speaker



ForceReactor構造

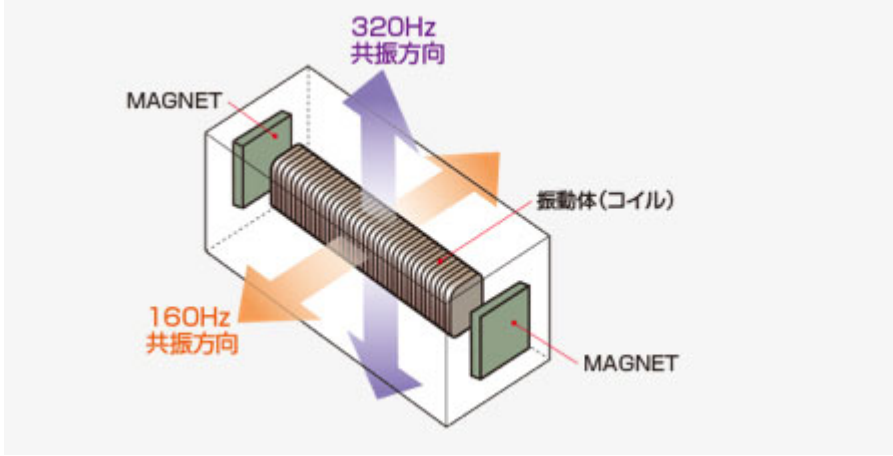
特に携帯電話用の振動子としていくつか開発された

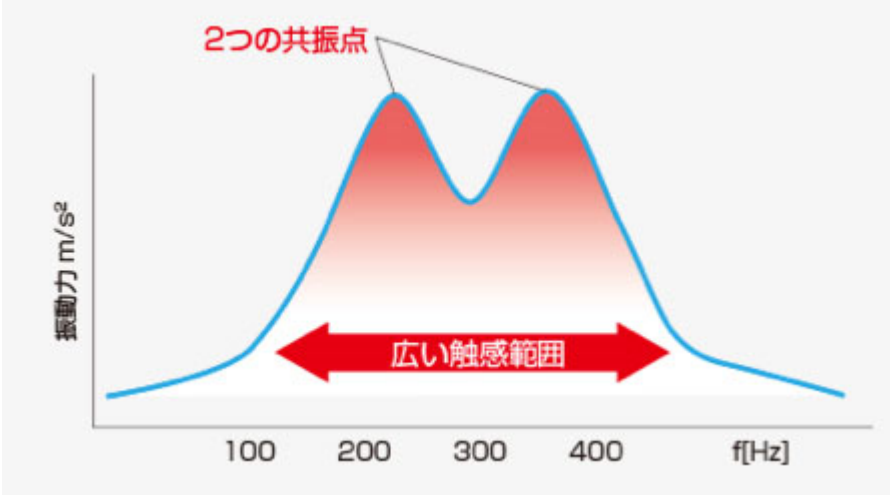
- 音声スピーカとの兼用を念頭においたもの
  - NECトーキン、マルチアクター（製造終了）
  - 並木精密宝石、振動スピーカ
- アクチュエータの形状を工夫したもの
  - AlpsAlpine: ForceReactor
- 触覚提示研究用として販売されているもの
  - Haptuator (Tactile Labs)

マルチアクター

Structure of HAPTIC Reactor by Alp Alpine

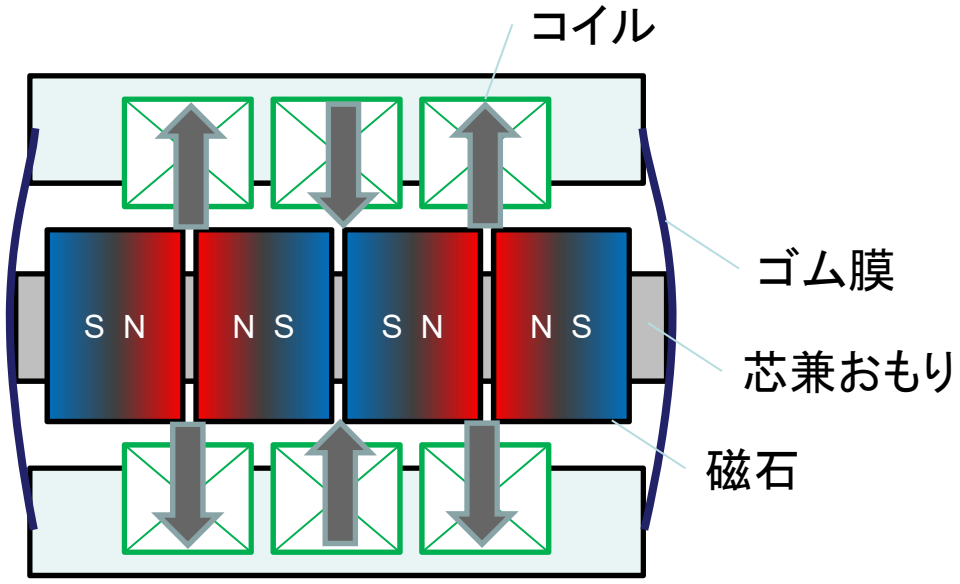
https://tech.alpsalpine.com/prod/e/html/haptic/

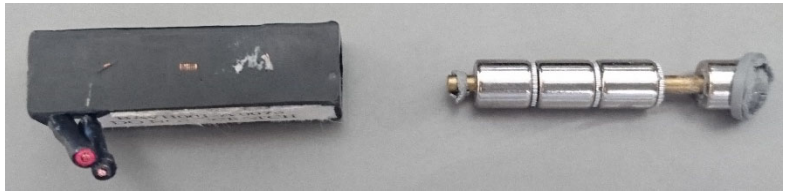




- 異なる軸に2つの共振点をもたせることで幅広い知覚が可能。
- Two resonant frequencies at different axes.
- LRAとスピーカ形アクチュエータの中間的位置。LRAと分類されることも。
- In between LRA and high-fi.

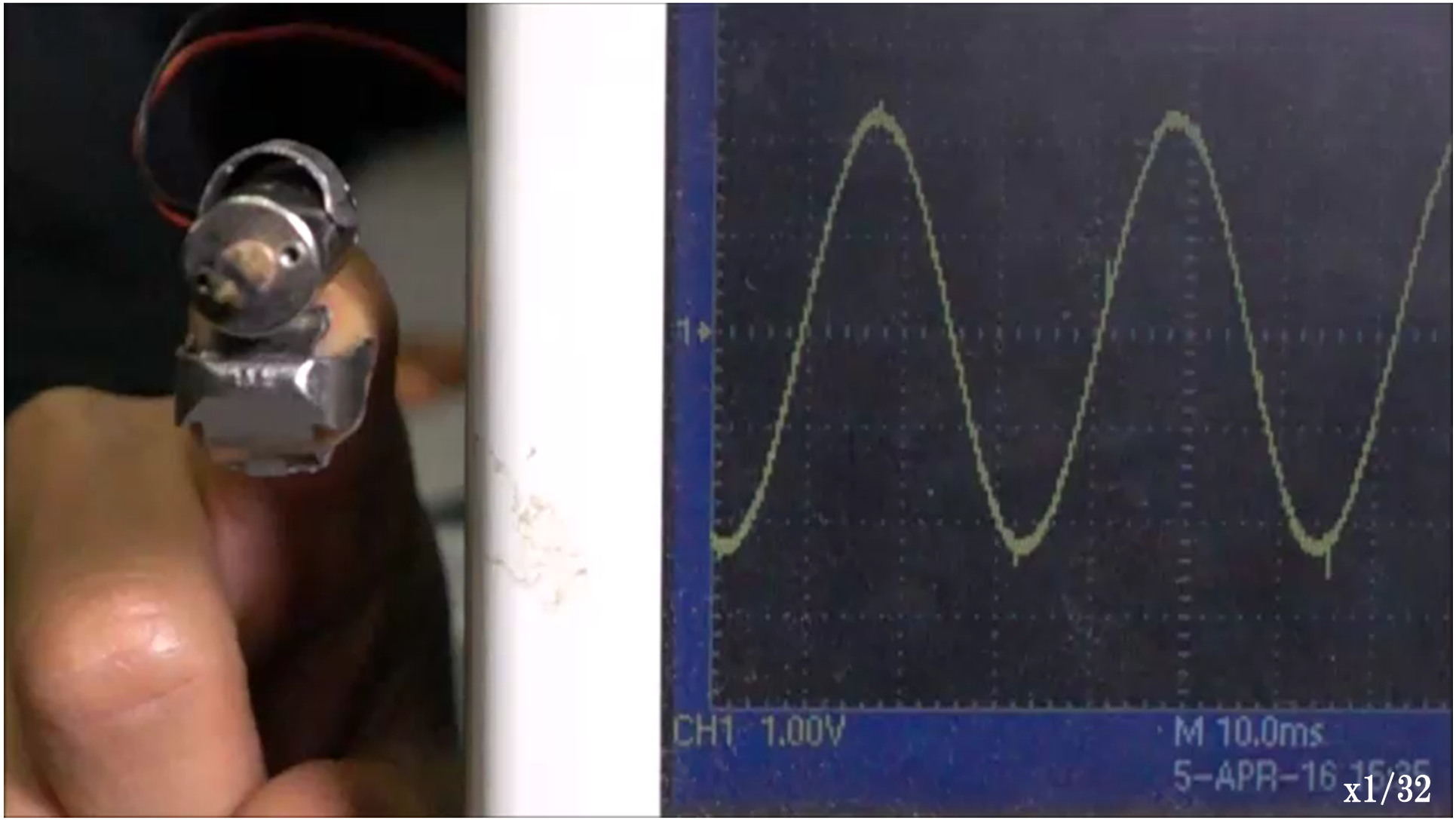
Structure of Haptuator mk2





- 磁束がコイルを貫通するために，磁石同士を逆極性で接続
- コイルの広い面積に効率よく磁束が貫通．
- 振動体として磁石＋芯を用い，コイルが筐体側にくるため，振動体の重量比が大きい．これは筐体に触れる触覚提示では重要．

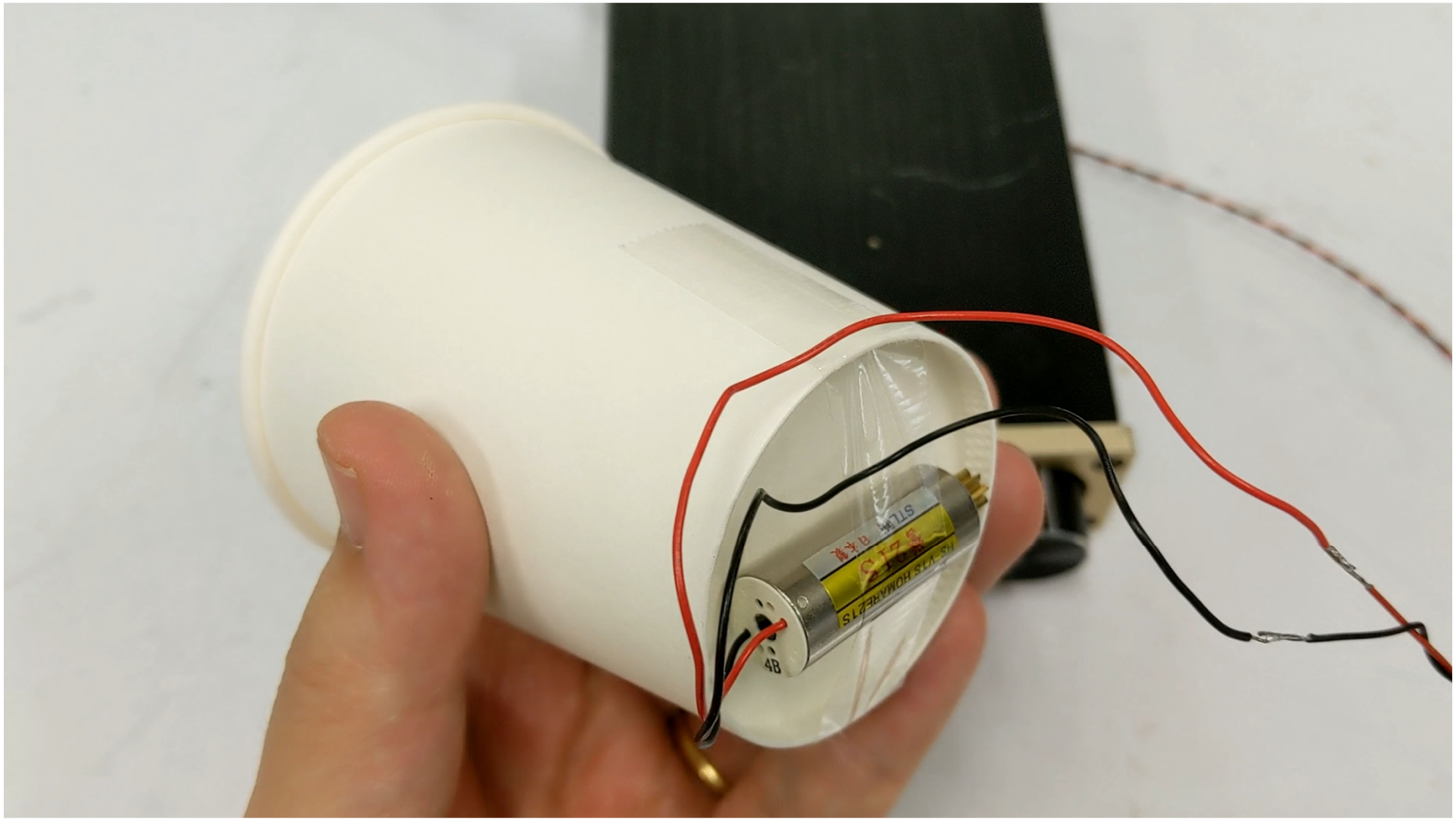
DCモータによる振動提示(1000fps)



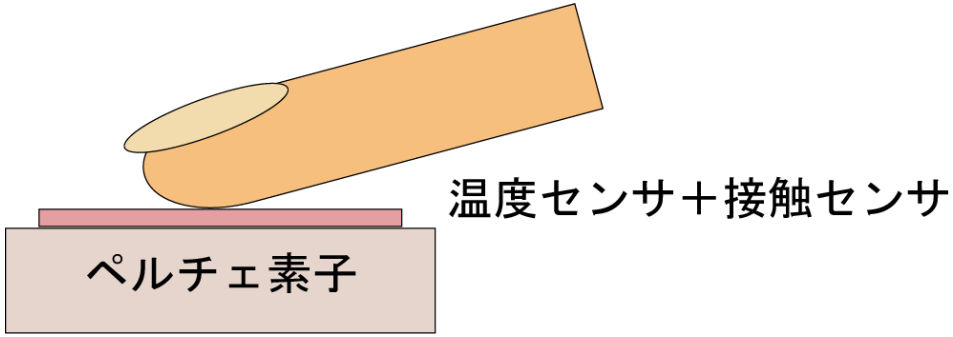
回転モータは偏心重りがなくとも高品位な触覚提示に利用できる。

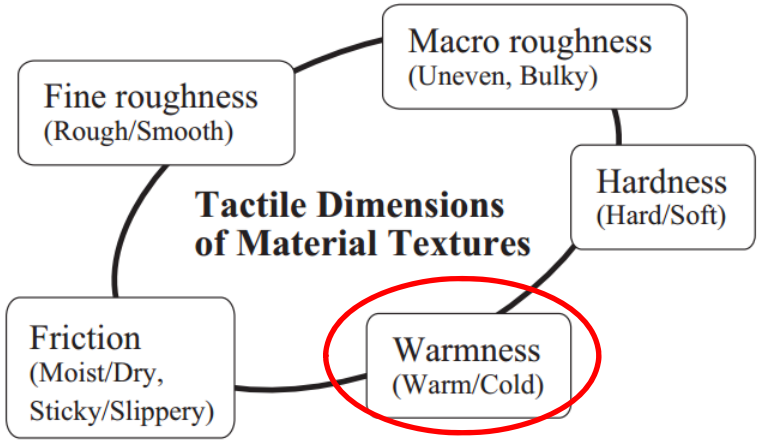
V. Yem, R. Okazaki and H. Kajimoto, "Vibrotactile and Pseudo Force Presentation using Motor Rotational Acceleration." Proc of IEEE HapticsSymposium, Philadelphia April 8-11th, pp. 47-51, 2016.

DCモータによる振動提示

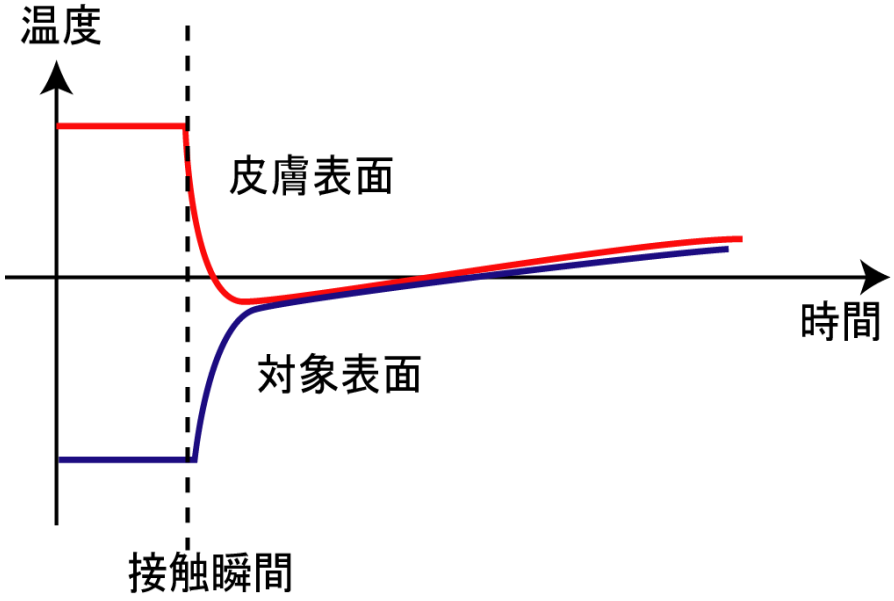


温度感覚ディスプレイ／Thermal Display





永野，岡本，山田：触覚的テクスチャの材質感次元構成に関する研究動向，TVRSJ2011

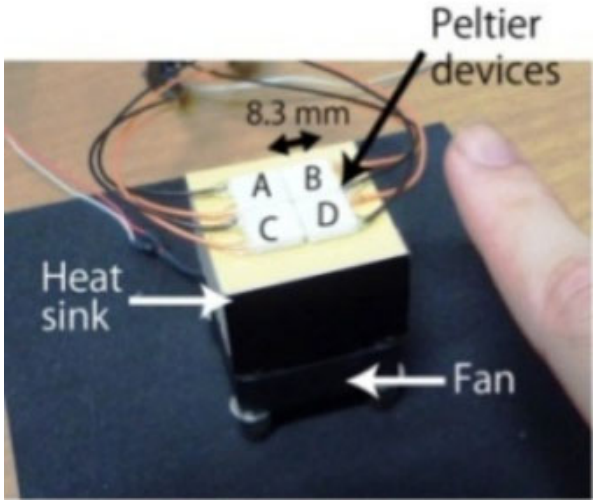


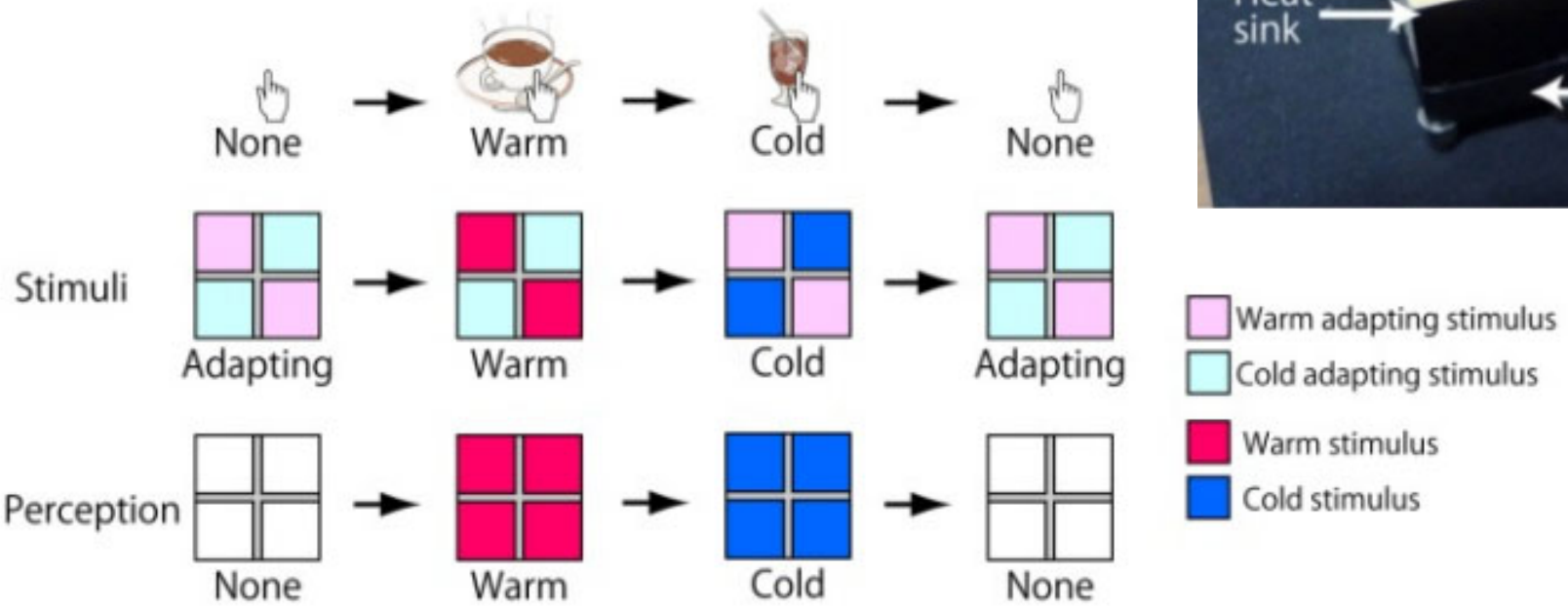
接触瞬間から2～3秒間の温度変化が
材質感推定の強力な手がかり

2 to 3s temperature change is the key to detect object property.
Peltier device with temperature sensor is used to reproduce the time course.

Yamamoto, “Control of Thermal Tactile Display Based on Prediction of Contact Temperature,” ICRA2004

温度の高速・効率的な提示
Quick & efficient temperature presentation



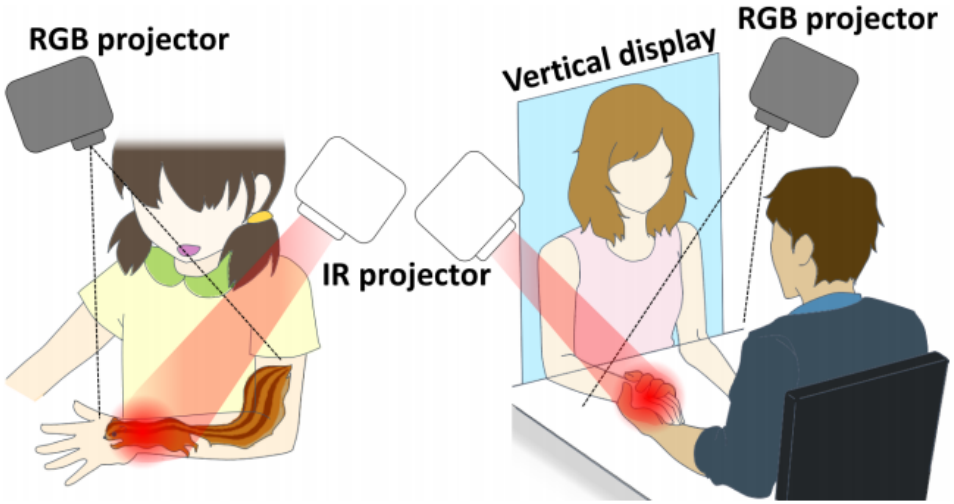


Katsunari Sato and Takashi Maeno: Presentation of Rapid Temperature Change using Spatially Divided Hot and Cold Stimuli, Journal of Robotics and Mechatronics, Vol.25, No.3, pp.497-505 (2013.6)

通常ペルチェ素子を用いて温／冷を提示。温冷提示を繰り返すと熱が溜まる悪循環。
温める素子と冷やす素子を分けることで効率化、かつ温度の高速な提示が可能。
温度そのものではなく変化成分のみを提示することでも効率化、高速化。

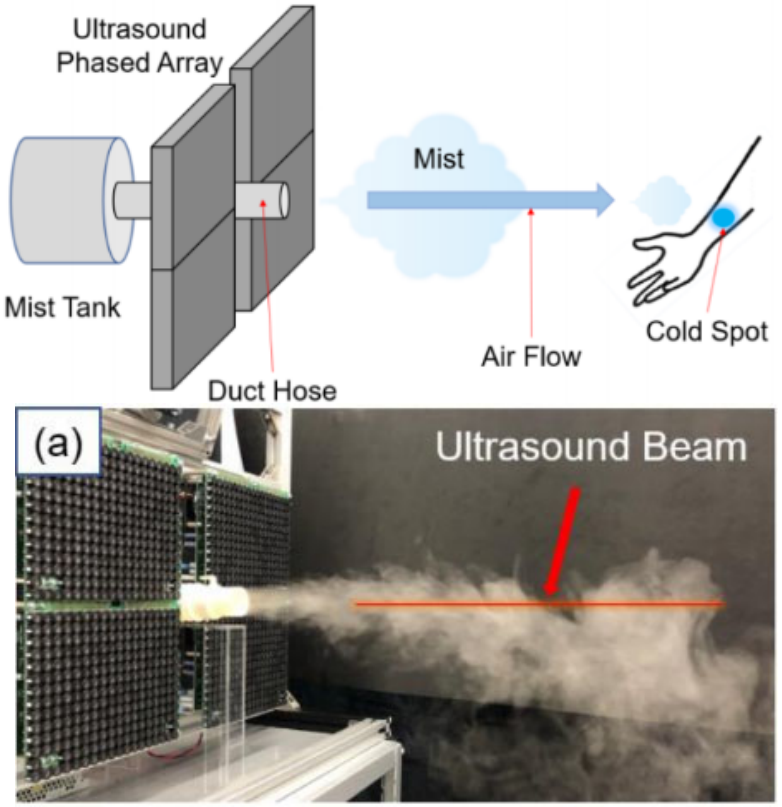
Peltier devices are often used to present hot and cold. If hot and cold presentation is repeated, heat accumulation occurs. This problem is solved by (1) separating the heating and cooling elements, and (2) presenting not the temperature itself, but only the components that change.

温度の非接触提示／Thermal Projection



Daisuke Iwai et al., Non-Contact Thermo-Visual Augmentation by IR-RGB Projection, 2019 IEEE TVCG

赤外プロジェクタで温度を投影する.
Project thermal sensation by IR projector.

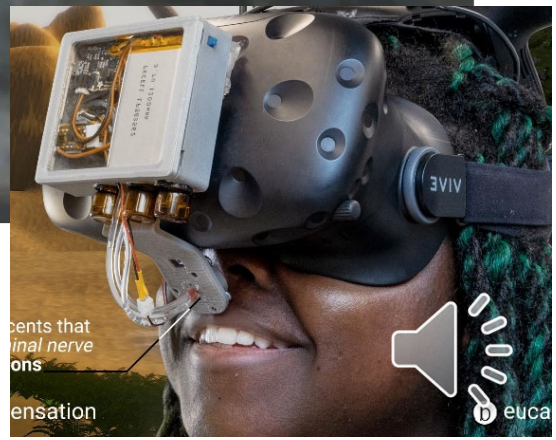


Mitsuru Nakajima, Yasutoshi Makino and Hiroyuki Shinoda, "Remote Cooling Sensation Presentation Controlling Mist in Midair," in Proc. 2020 IEEE/SICE International Symposium on System Integration, pp. 1238-1241, 2020.

空中超音波によるミストの搬送を用いて温度(冷覚)を提示。
Presenting cool sensation by mist conveyed by ultrasound.

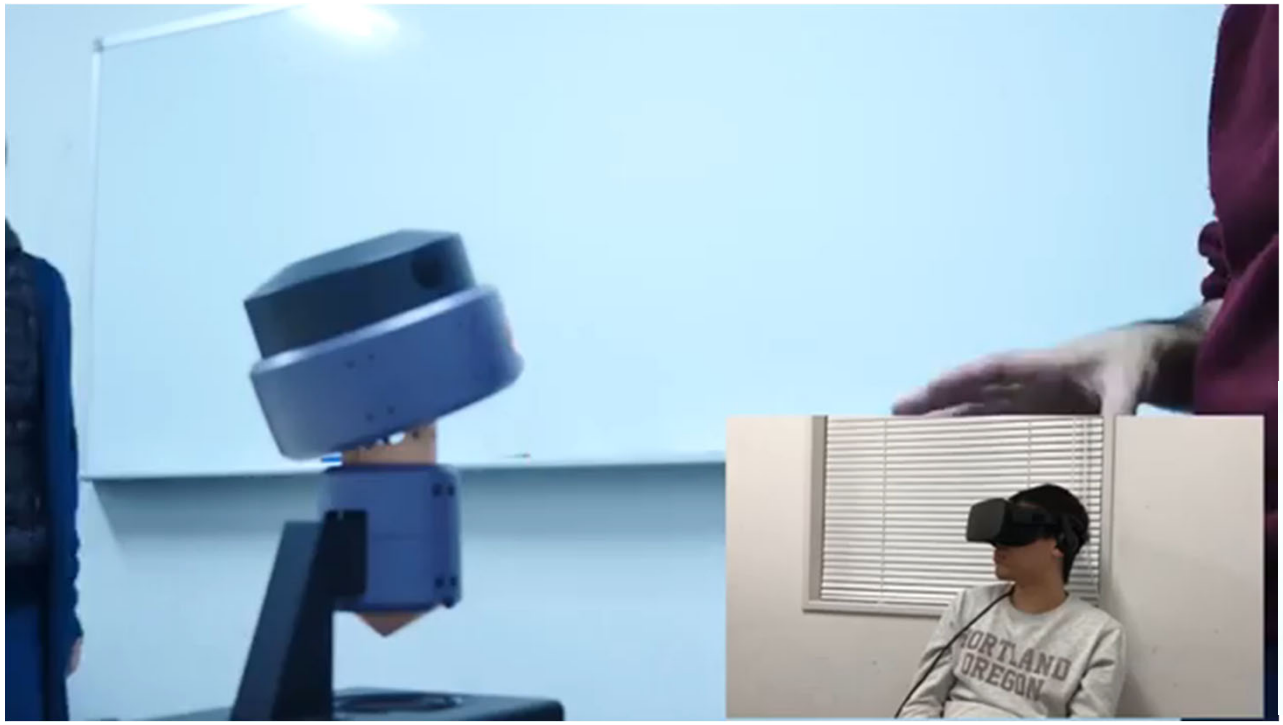
温度の化学的提示(CHI2020) Trigeminal-based Temperature Illusions

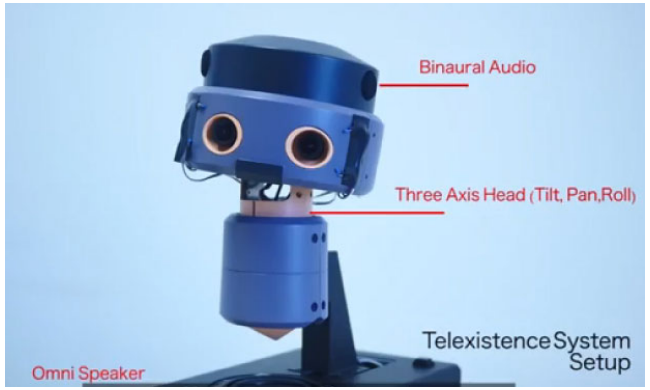
Jas Brooks;Steven Nagels;Pedro Lopes

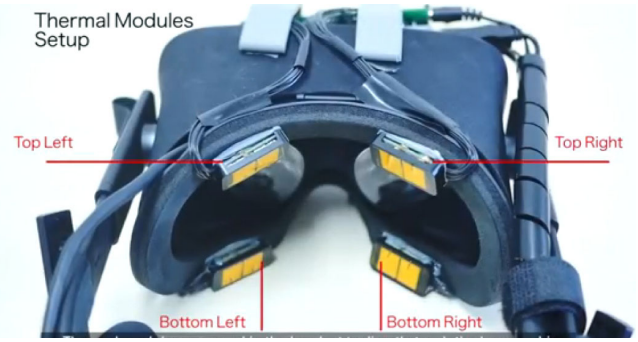


- https://www.youtube.com/watch?v=rEYslUk7bqk
- 温度提示にカプサイシンとオイカリプトールを使う。鼻に噴霧

(CHI2018) Ambient: Facial Thermal Feedback in Remotely Operated Applications
MHD Yamen Saraiji, Roshan Lalintha Peiris, Lichao Shen, Kouta Minamizawa, Susumu Tachi



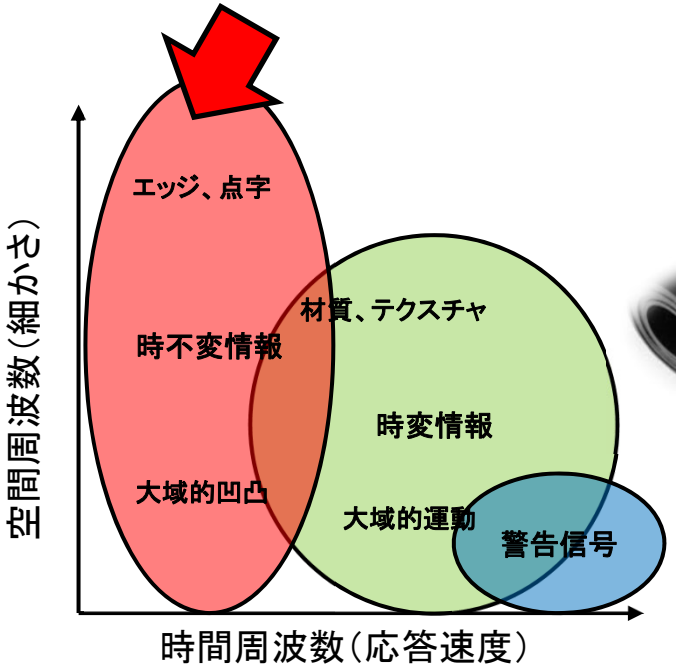


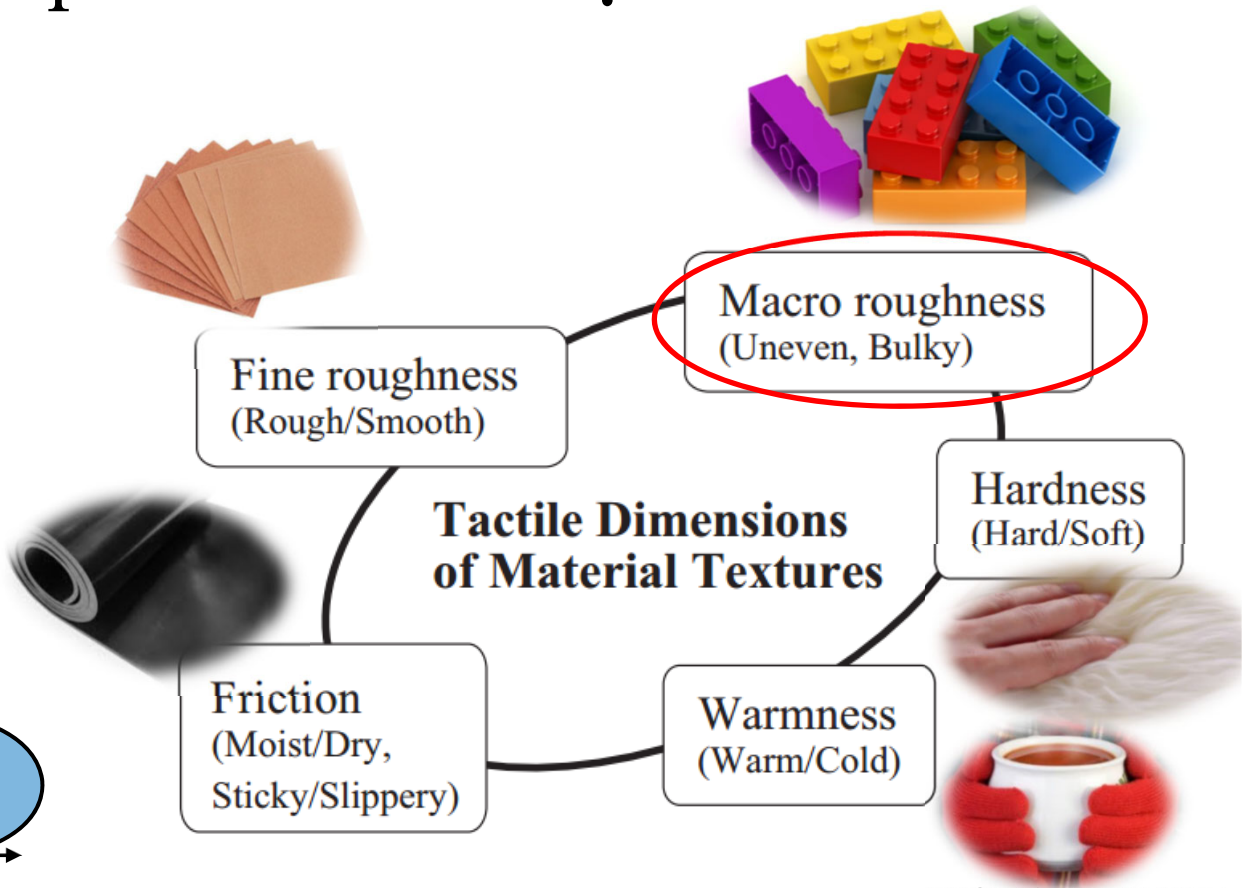


https://www.youtube.com/watch?v=Ewe2X663NNE

HMDの顔面接触部にペルチェ素子を貼布、顔周りの温度感覚を伝えるだけで雰囲気が伝わる
Presenting heat by Peltier device attached on HMD. Good for atmospheric transfer.

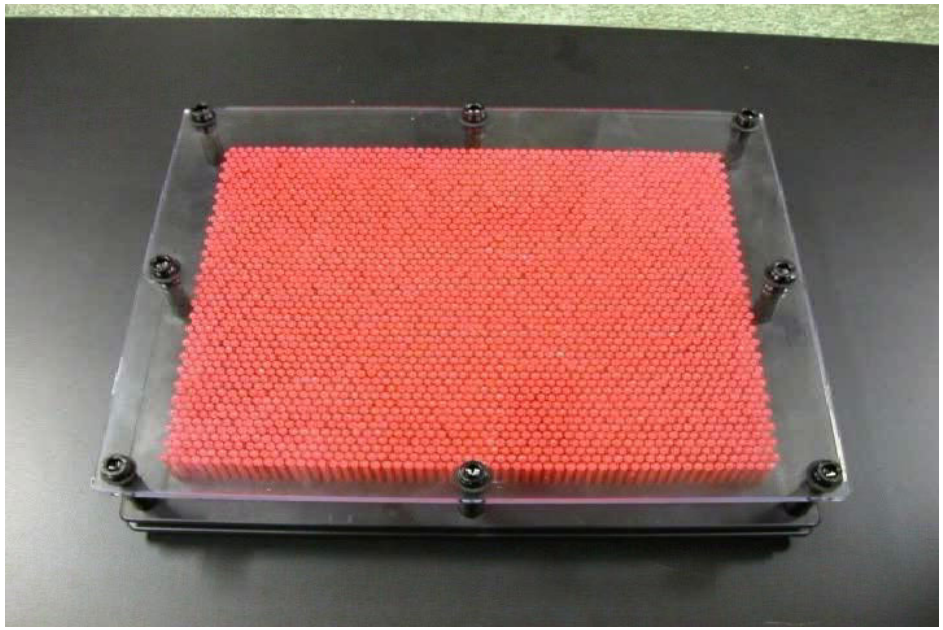
「形」を提示する
How to present shape information?

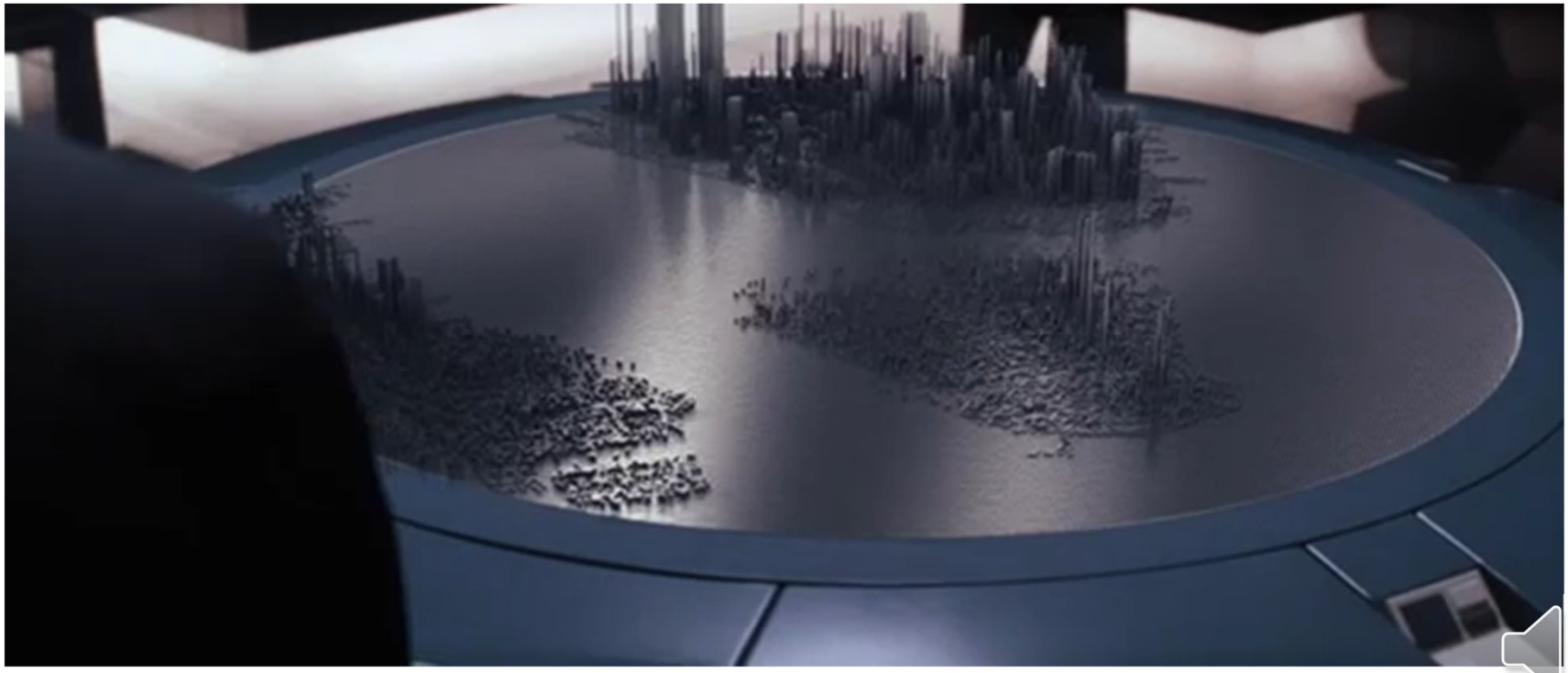




永野，岡本，山田：触覚的テクスチャの材質感次元構成に関する研究動向，TVRSJ2011

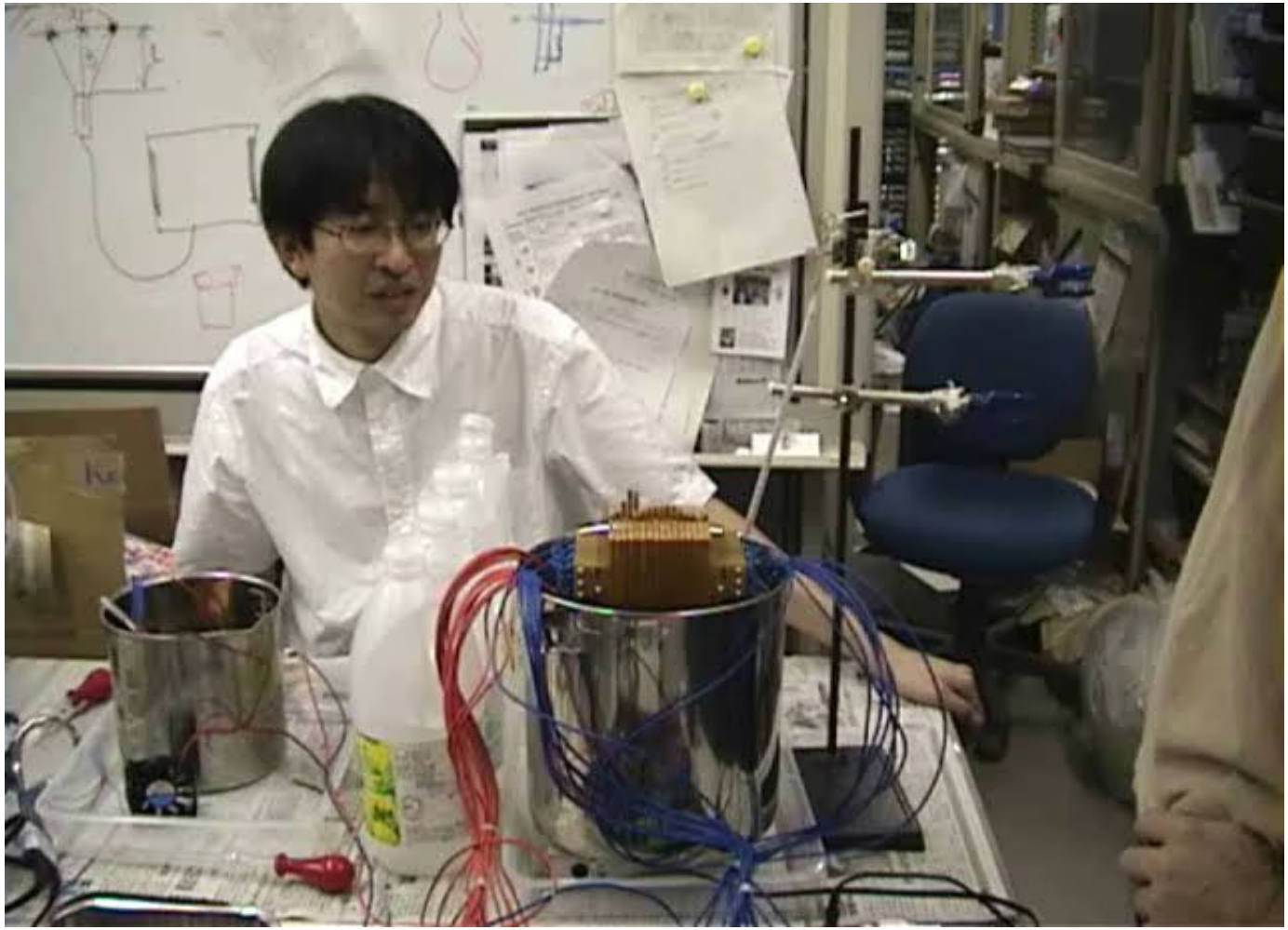
3D shape reconstruction

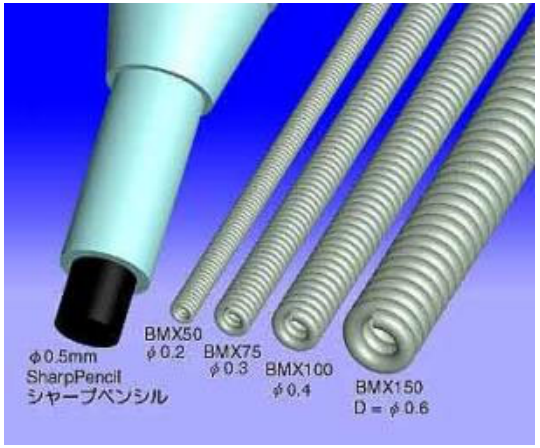


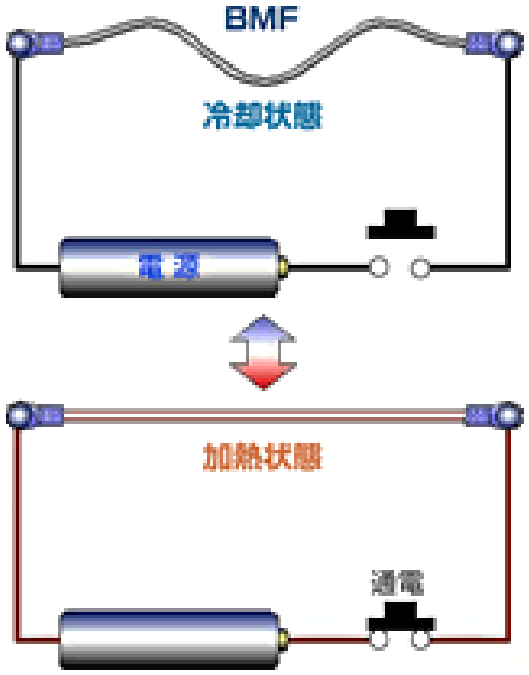


Xmen,2000 https://www.youtube.com/watch?v=55voa5Pee2M

PopUp(Nakatani et al, 2005)

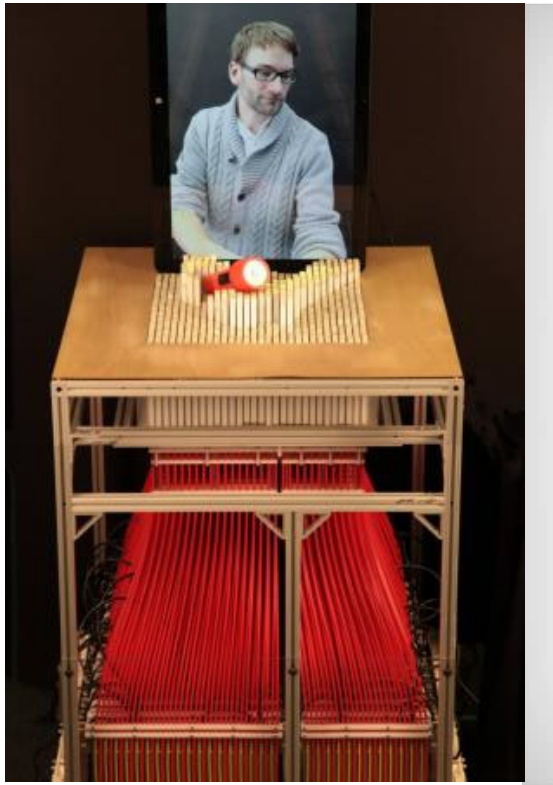




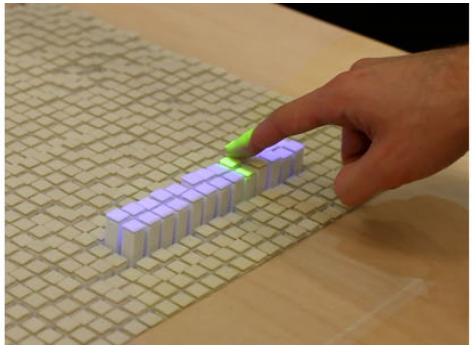
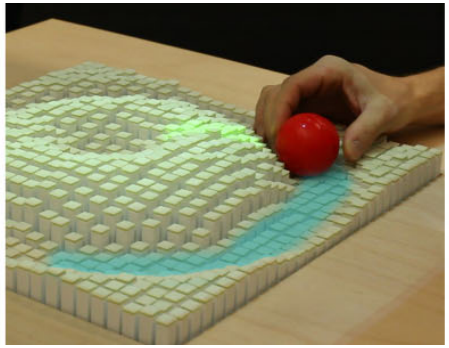
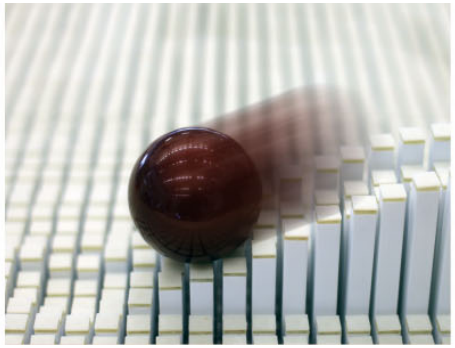
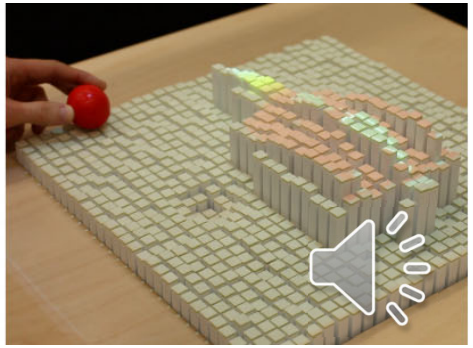


Coil-Type SMA（Shape Memory Alloy）
Extremely thin and large stroke

inFORM (Sean Follmer, 2013)

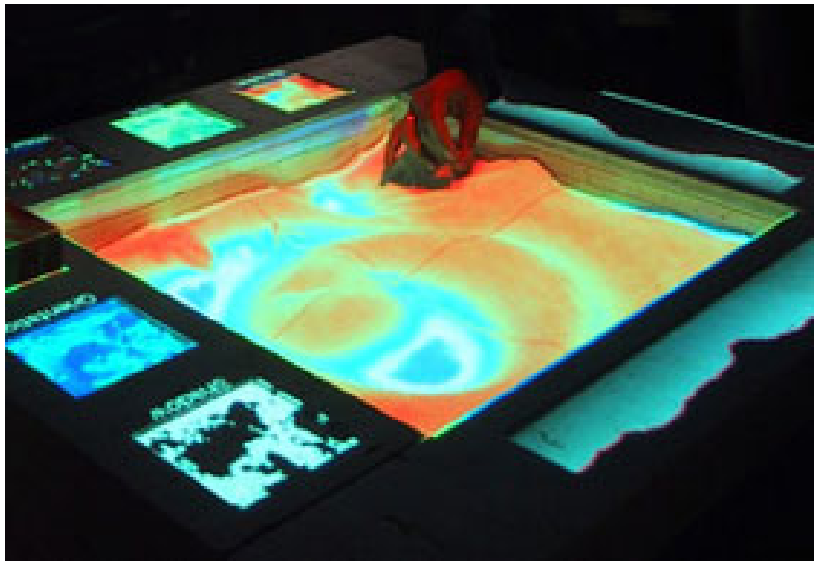


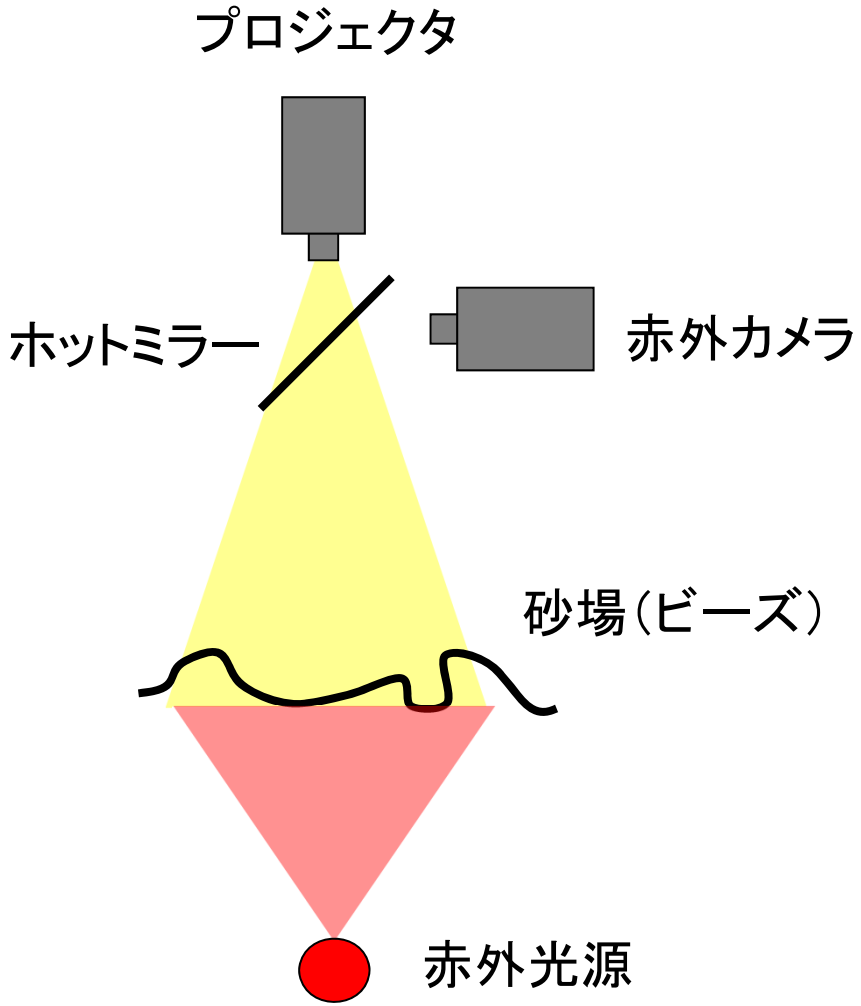
https://www.youtube.com/watch?v=5EkkTV51Pg0

Is Actuator really necessary?:SandScape

(Yao Wang et al., 2002)



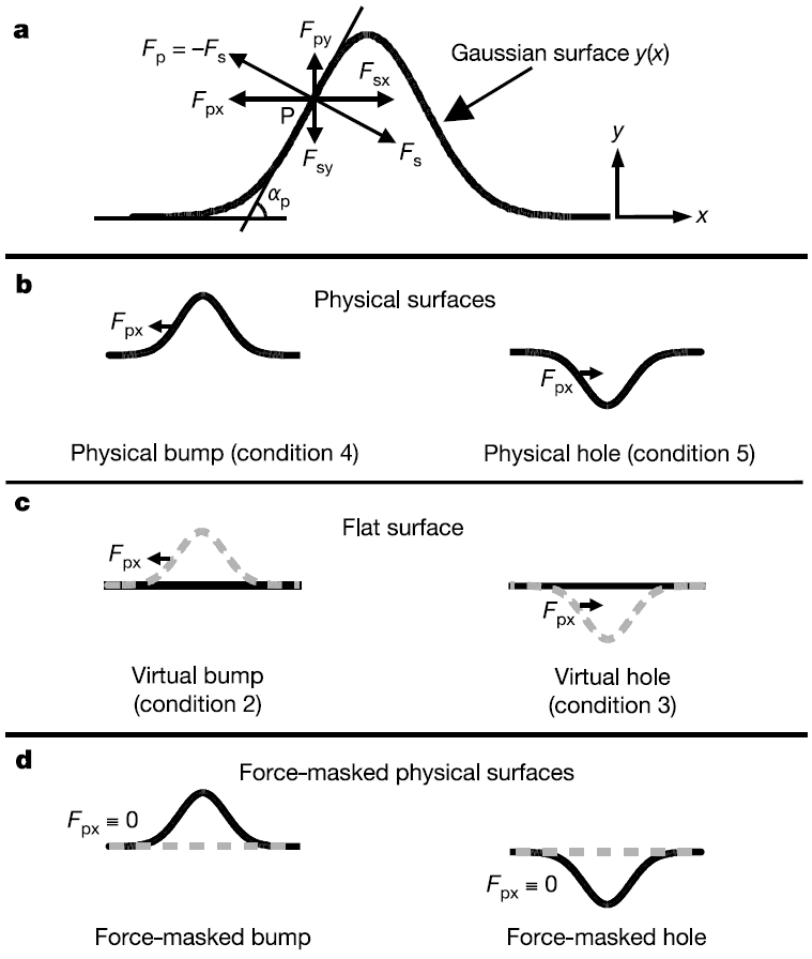


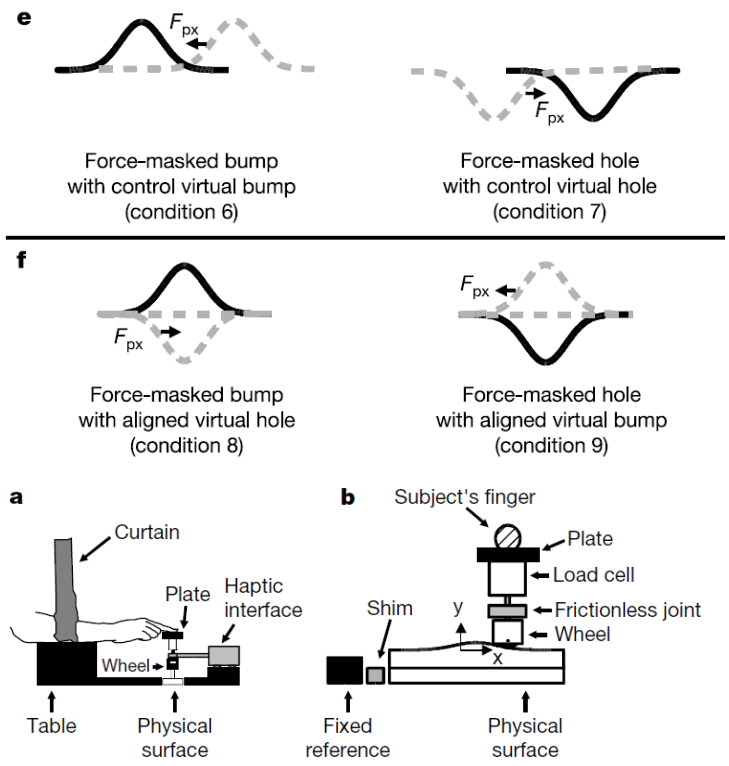
http://tangible.media.mit.edu/projects/sandscape/

SEGA　えーでるすなば（2015）

https://www.youtube.com/watch?v=lKR4BDuwZlU

凹凸感にとって重要なものは何か(1/2)
What is essential for bump sensation?

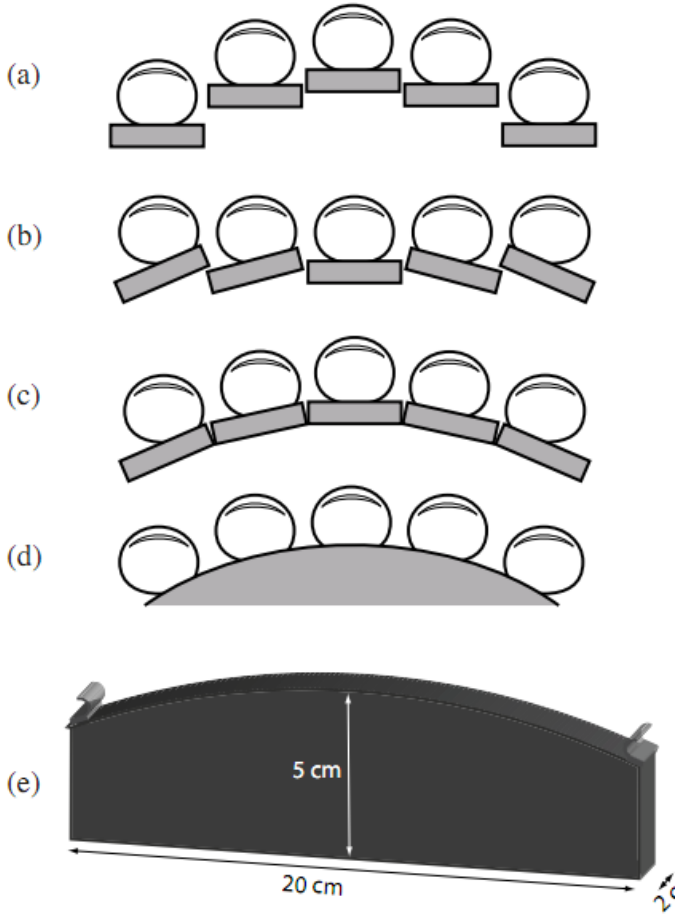


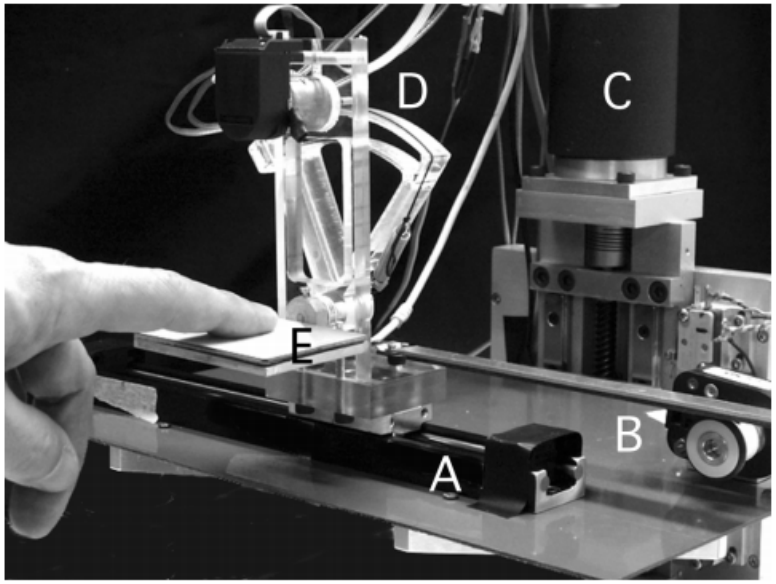


指なぞり時の凹凸⇒横方向の「力（ブレーキ）」と縦方向の「形状」という手がかり。
「形状」よりも「力」を優先して形状知覚をしている。

Gabriel Robles-De-La-Torre & Vincent Hayward: Force can overcome object geometry in the perception of shape through active touch Nature 2001.

凹凸感にとって重要なものは何か(2/2)
What is essential for bump sensation?





大域的な凹凸感の手がかり:
板の「傾き」＞＞板の高さ

Maarten W. A. Wijntjes, Akihiro Sato, Vincent Hayward, Astrid M. L. Kappers
Local Surface Orientation Dominates Haptic Curvature Discrimination, Trans. On Haptics, 2009.

モータによる水平力提示

http://www.youtube.com/watch?v=Prq9-uJSqSE

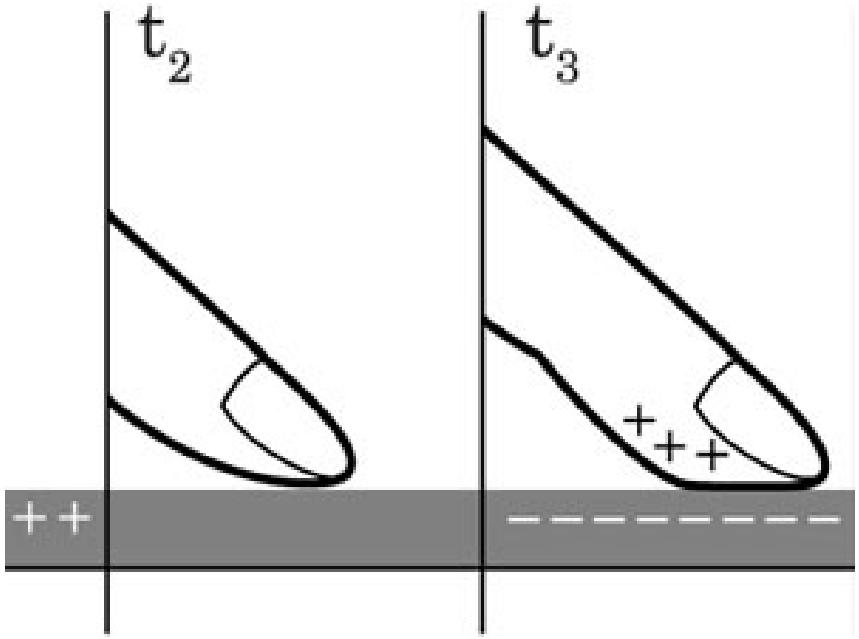
嵯峨他、剪断力を用いた2.5次元触覚ディスプレイにおける定量的凹凸感提示手法、VR学会大会2011

Passive type Horizontal Display
超音波振動による摩擦係数変化の利用
Controlling friction coefficient by ultrasonic vibration

- スクイーズ効果：高周波振動で摩擦係数が減少する
  Squeeze effect: friction is reduced by high freq. vibration
- 指位置計測と組み合わせ、摩擦係数の提示が可能
  Combined with pos. sensing, friction distribution is displayed.

- Nara et al., “Surface Acoustic Wave Tactile Display”, IEEE CG&A, 2001.
- Winfield et al., “*TPaD: Tactile Pattern Display Through Variable Friction Reduction*”, World Haptics Conf. 2007

Passive type Horizontal Display
高圧電極と皮膚の電気的吸引利用
Using adhesion between skin and electrode by high voltage



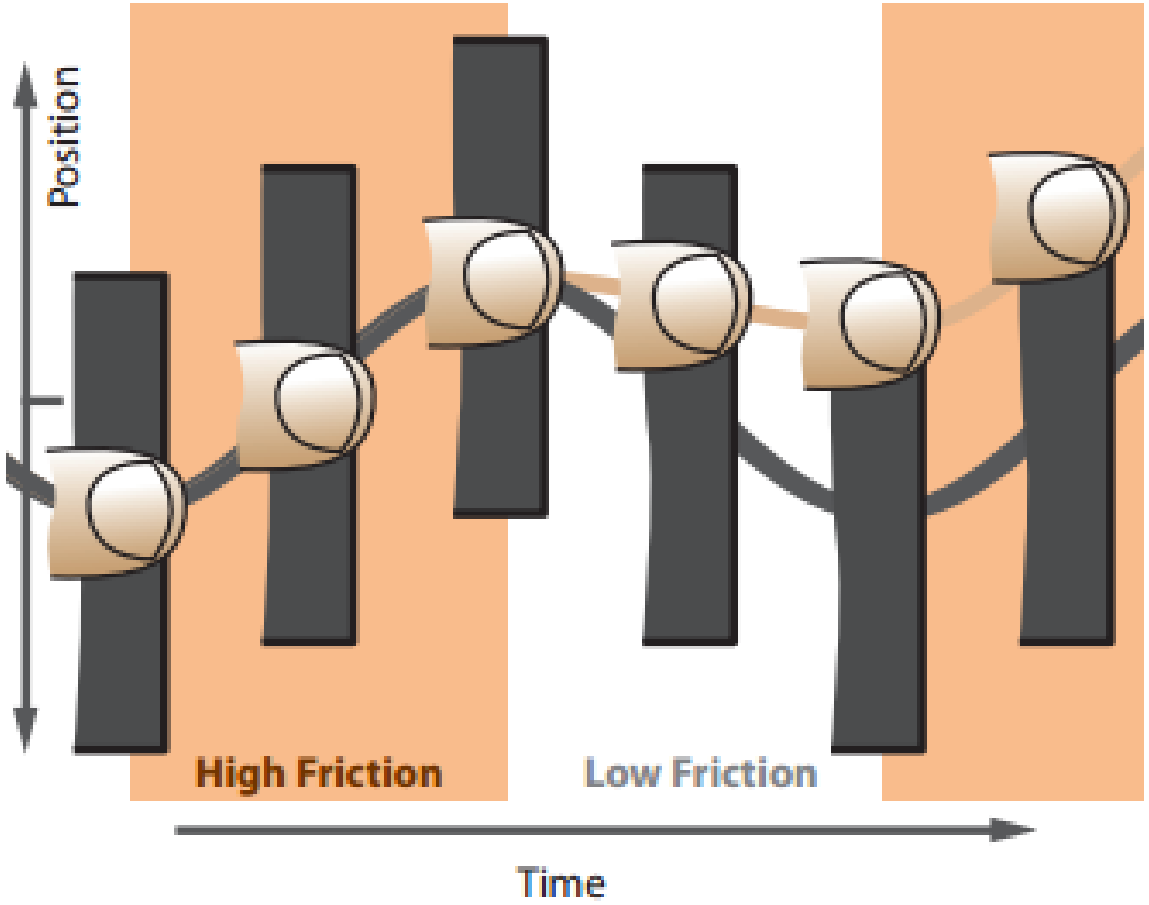
Kaczmarek et al., “Polarity Effect in Electrovibration for Tactile Display,” IEEE Trans. Biomedical Engineering,, 2006.

Olivier Bau et al., “TeslaTouch: Electrovibration for Touch Surfaces,” UIST2010

TeslaTouch (2010)

https://www.youtube.com/watch?v=3l3MDNZk-3I

[Haptics Symposium 2016] eShiver: Force Feedback on Fingertips through Oscillatory Motion of an Electroadhesive Surface
Joe Mullenbach, Michael Peshkin, Ed Colgate



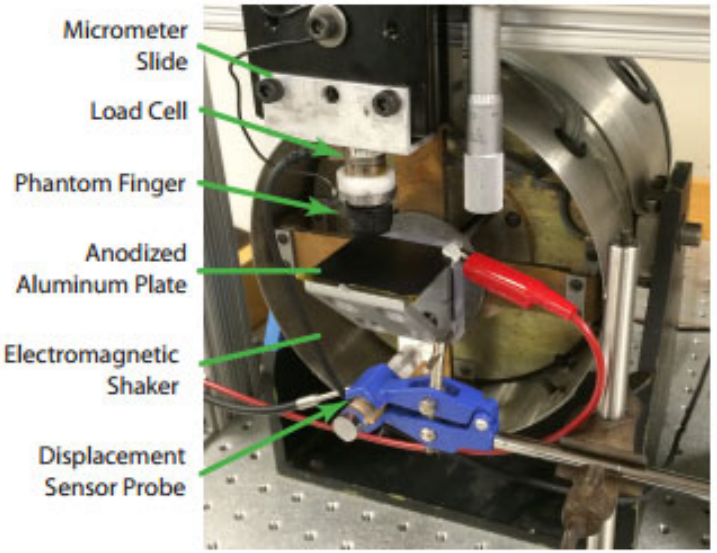
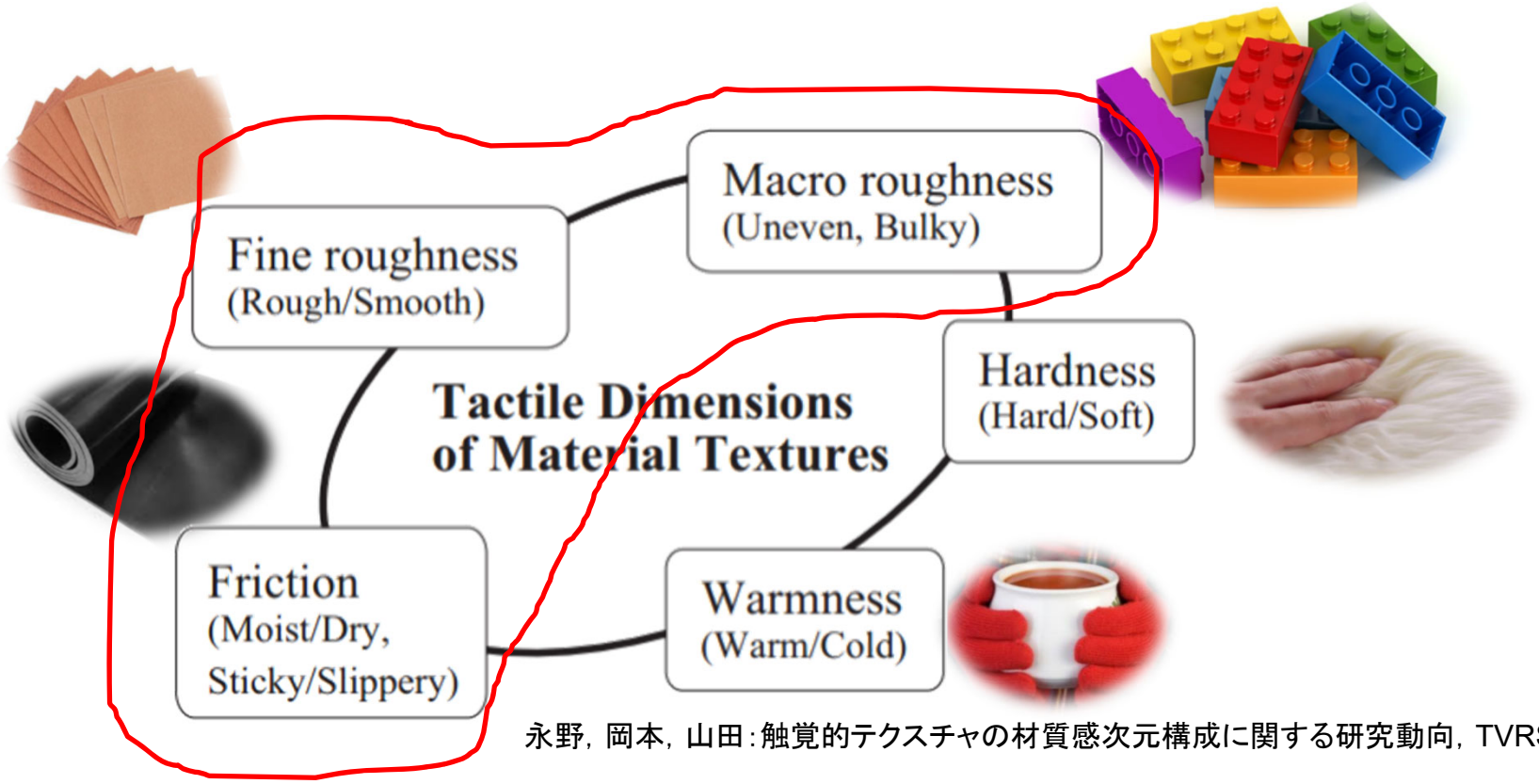


Fig. 4. eShiver Experimental Apparatus.

静電型の触覚ディスプレイを水平振動させ，振動と同期して摩擦係数を変化させることで，一方向に力を生じさせる．つまりタッチパネルでの力覚提示．

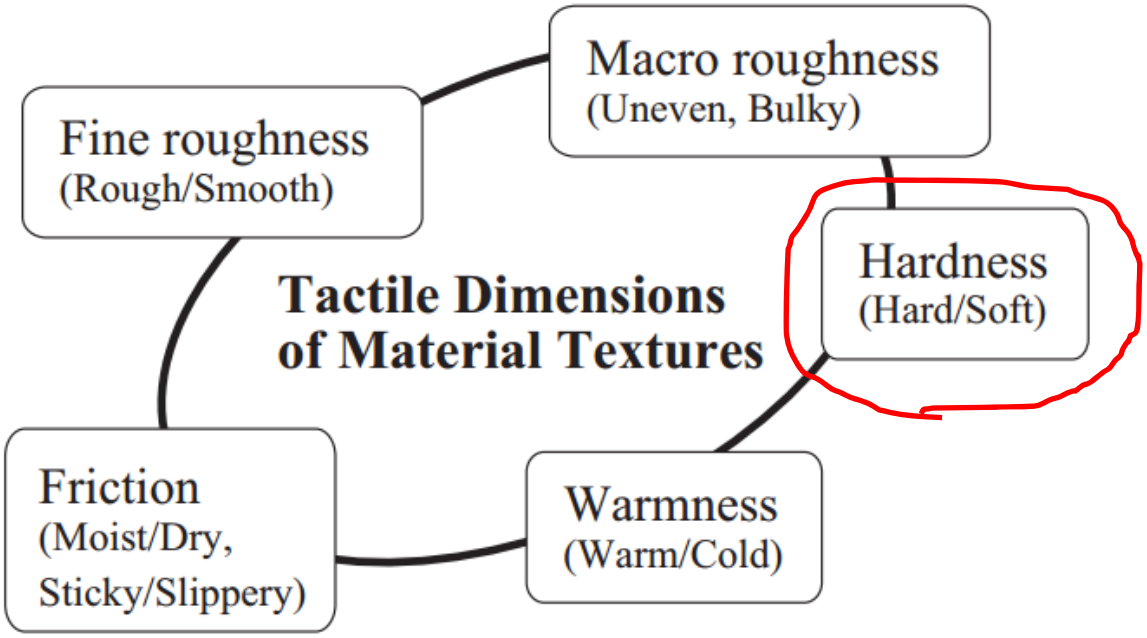
水平摩擦力提示によって得られた触感領域



永野，岡本，山田：触覚的テクスチャの材質感次元構成に関する研究動向，TVRSJ2011

形状情報のみならず，高速応答性をもたせることでStick-Slip感等の表面状態まで提示可能に

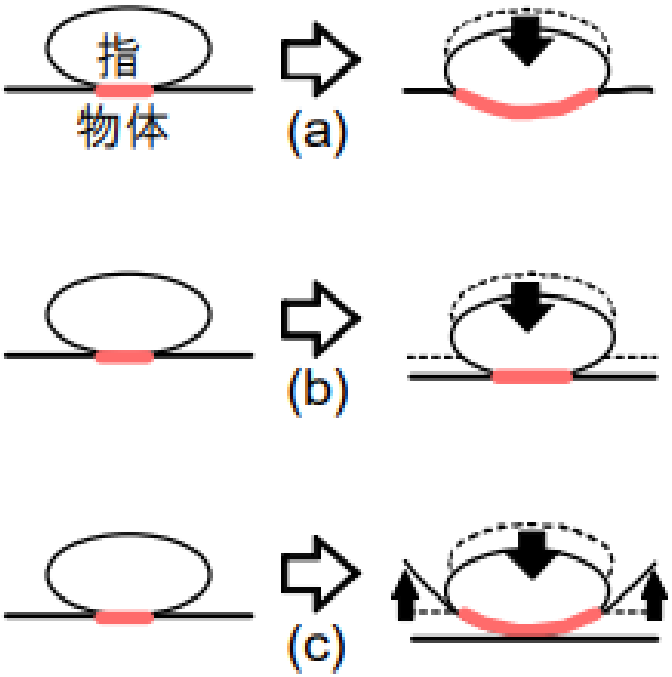
硬さ／柔らかさは皮膚感覚で表現できるか？



永野，岡本，山田：触覚的テクスチャの材質感次元構成に関する研究動向，TVRSJ2011

古典的には力覚提示装置でバネ／ダンパの挙動を模擬して表現

柔らかさの提示



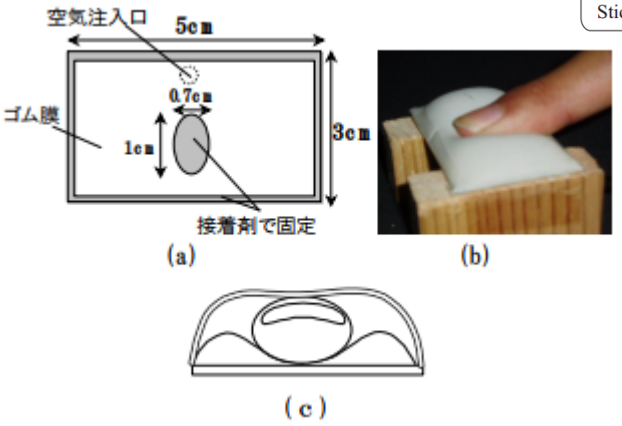
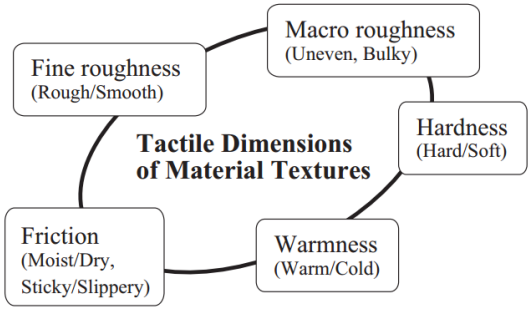
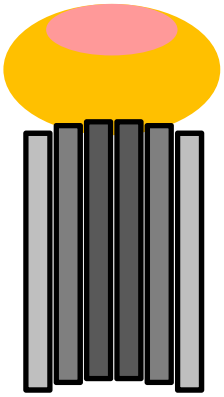


Figure 8: The prototype CASR display.



永野，岡本，山田：触覚的テクスチャの材質感次元構成に関する研究動向，TVRSJ2011

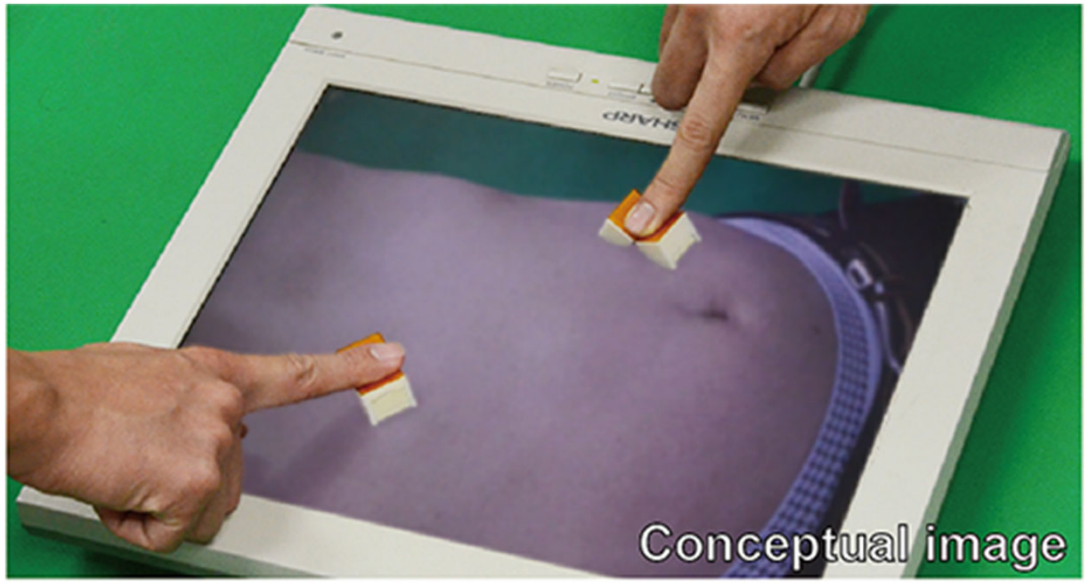


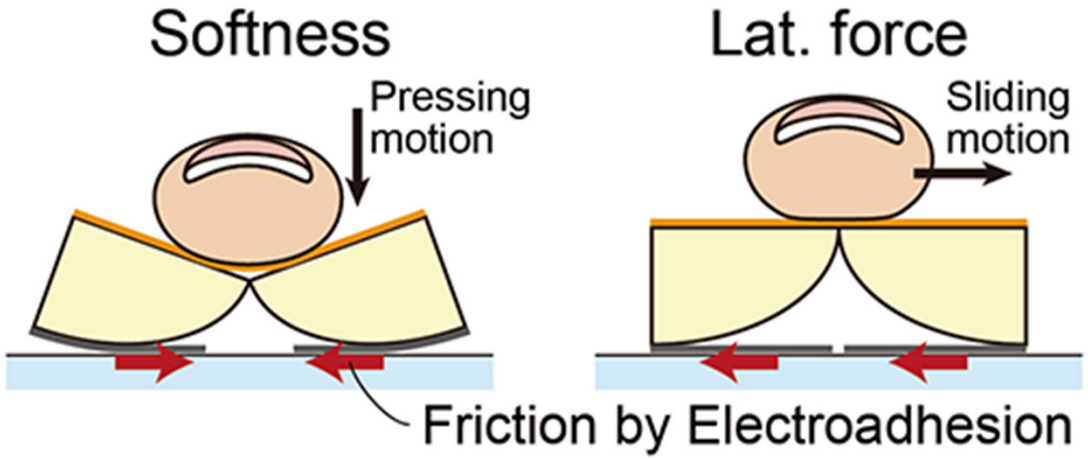
接触面積の変化を再現することで柔らかさを提示できる

- G. Ambrosi et al.:The role of contact area spread rate in haptic discrimination of softness, ICRA1999
- K. Fujita et al.: A new softness display interface by dynamic fingertip contact area control. SCI2001.
- M. Bianchi et al:A new fabric-based softness display, Haptics Symposium2010

[HapticsSympo2016] Extension of an Electrostatic Visuo-Haptic Display to Provide Softness Sensation

Taku Nakamura, Akio Yamamoto

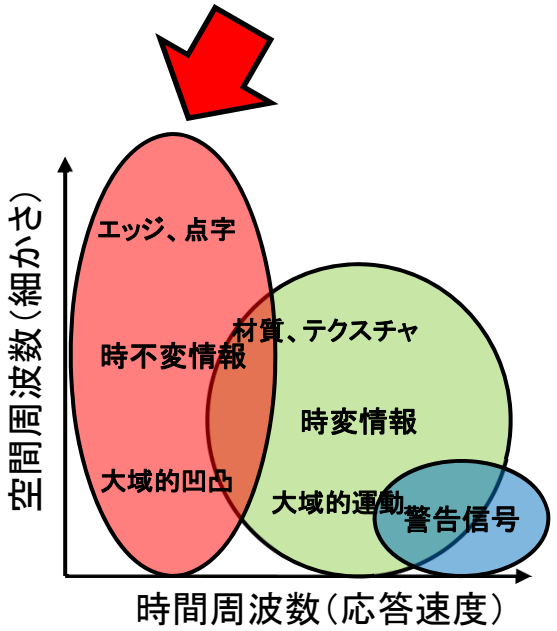




静電気型触力覚提示装置で柔らかさ感をなるべく簡単な機構で出す手法を考案

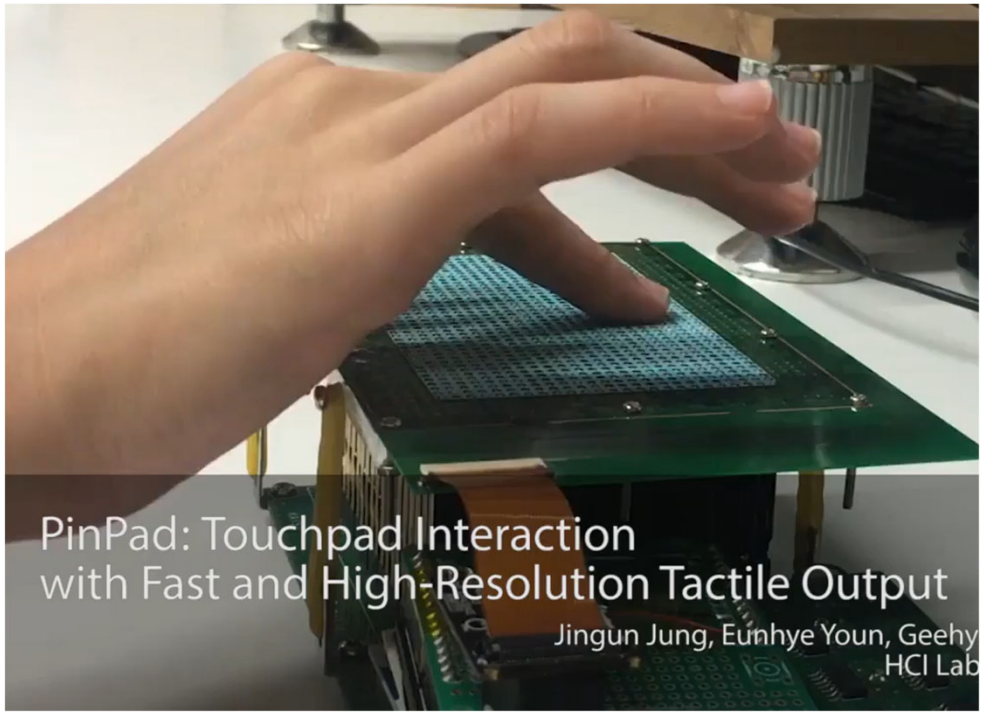
「形」をより細かく提示する

How to produce High-resolution Tactile display?

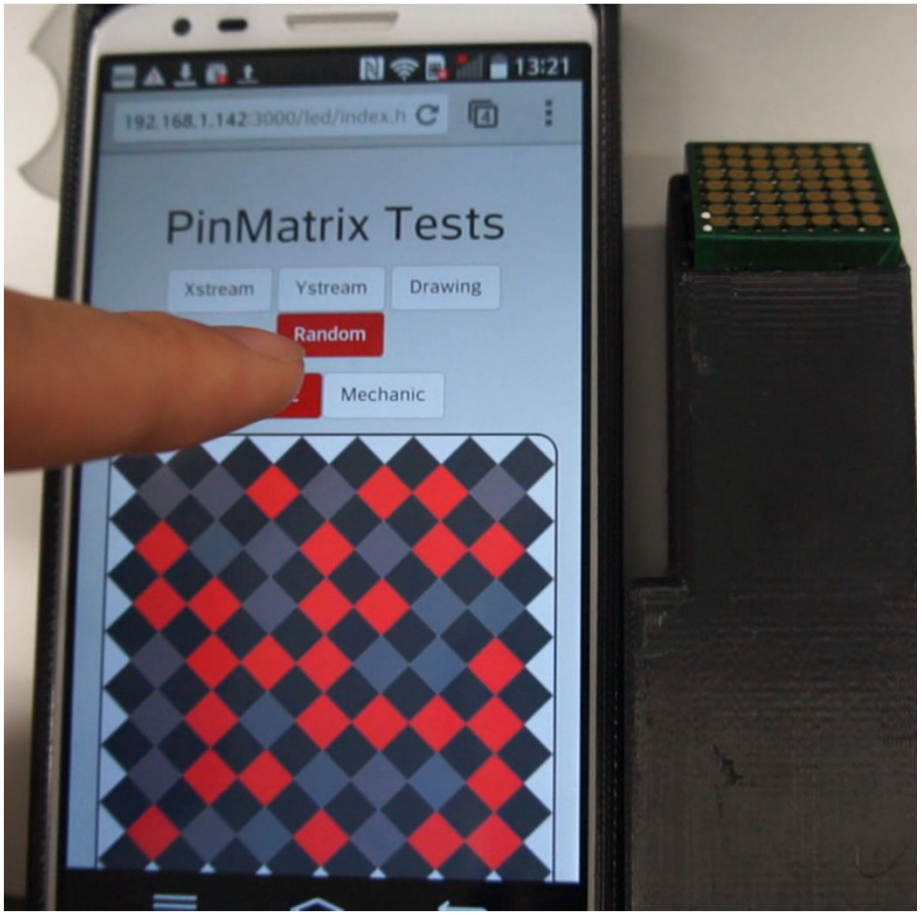


- これまで実はことごとく，「指一本全体」に対して触感を提示するもの．
- （意地悪に言うなら）高性能な力覚提示装置（PHANToM）で出せる感覚を，wearable化，portable化した，と見ることもできる．
- もし遠隔操縦を人が操るレベルで行うなら、指先皮膚の中の空間的な分布が提示できないといけない。
- Until here, most tactile displays are for “the whole finger”, but higher-resolution tactile information is required for precision tasks.

Pin matrix drive



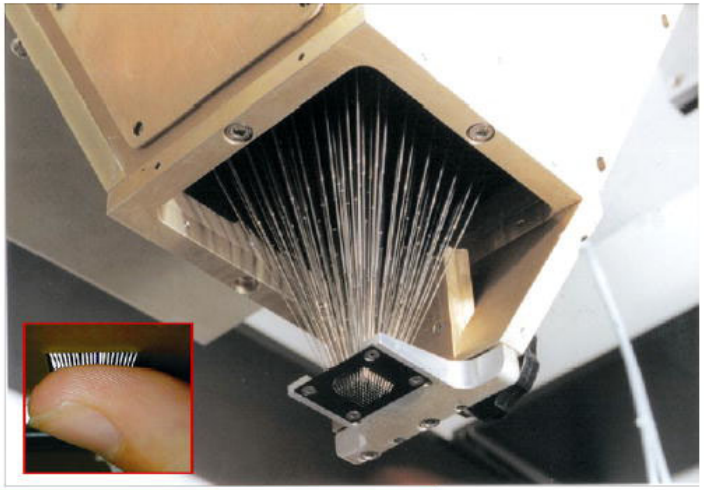
https://www.youtube.com/watch?v=B8UshkVpuAE
CHI2017 PinPad: Touchpad Interaction with Fast and High-Resolution Tactile Output, Jingun Jung, Eunhye Youn, Geehyuk Lee

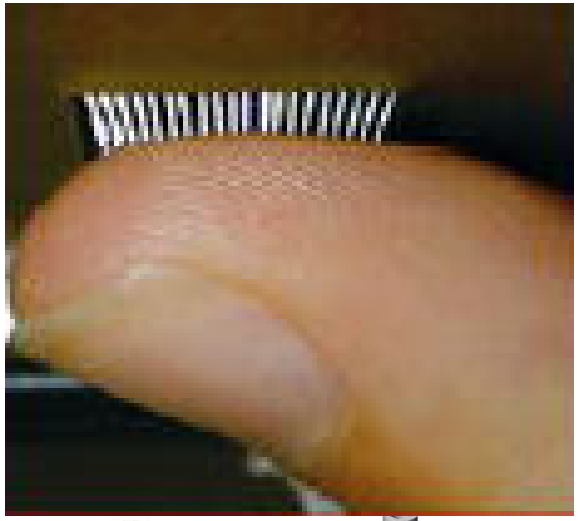


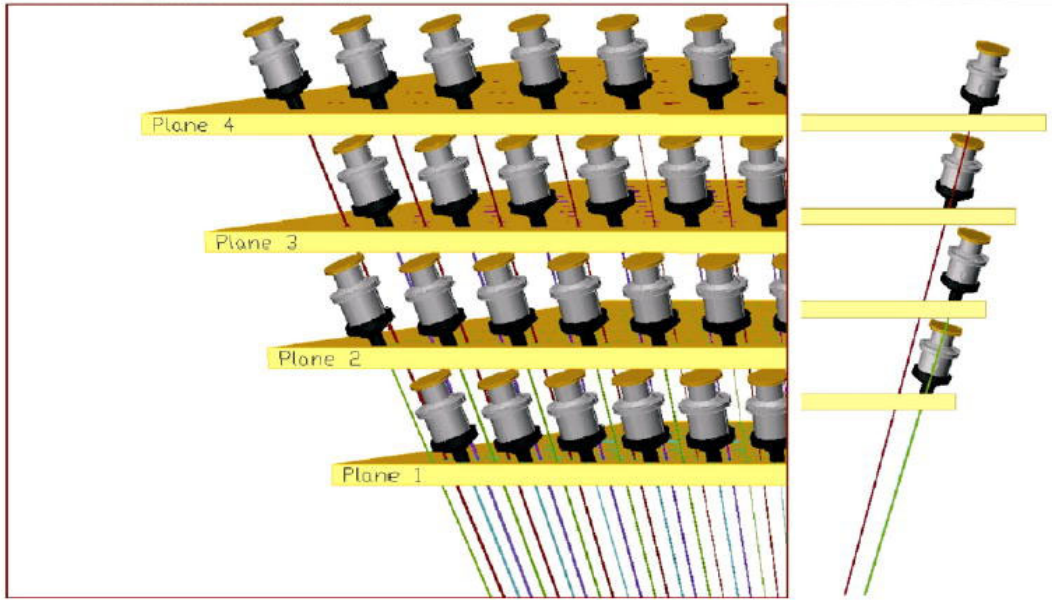
8x8ユニットの駆動（電気刺激との併用）
Sugarragchaa Khurelbaatar, Hiroyuki Kajimoto. Tactile display combining electrical and mechanical stimulation. EuroHaptics'16 WIP

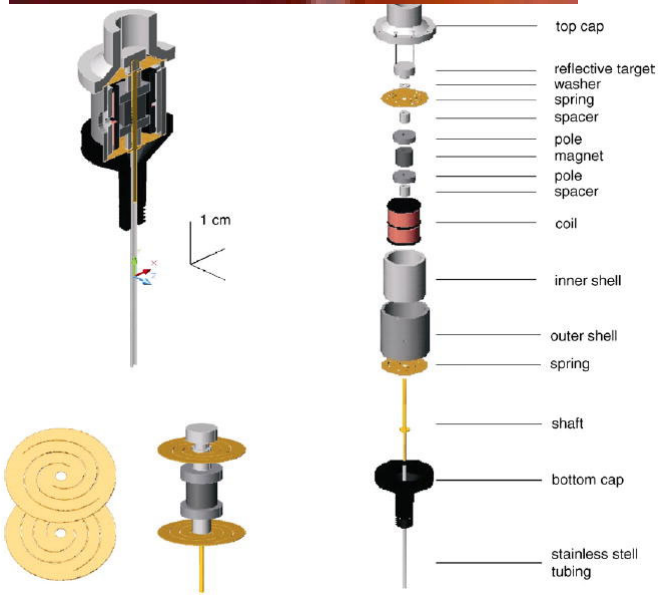
- 大量の高密度実装→アクチュエータの小ささ、安さが鍵
- Numerous, dense arrays→Actuator needs to be small and cheap

高解像度触覚ディスプレイ/High resolution tactile display





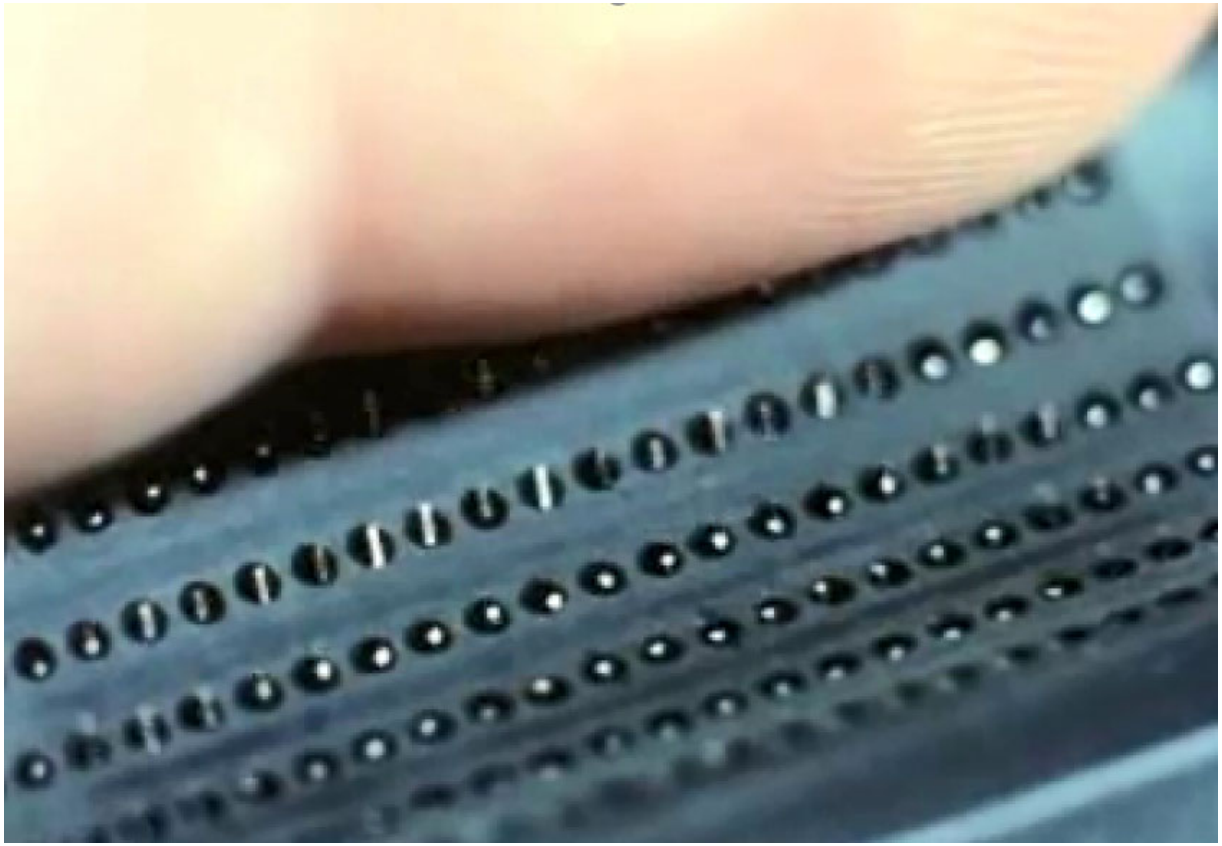




J.H. Killebrew et al., "A Dense Array Stimulator to Generate Arbitrary Spatio-Temporal Tactile Stimuli," *J. Neuroscience Methods*, vol. 161, pp. 62-74, 2007.

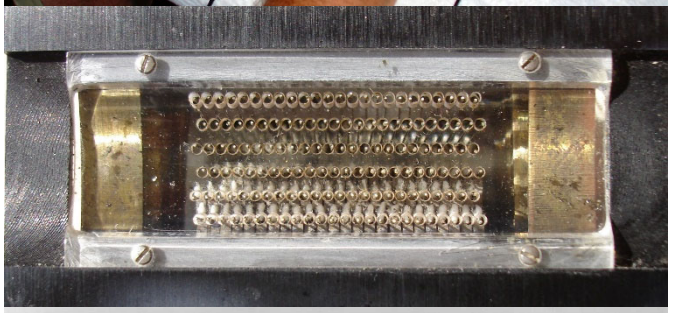
400ピン、特製のリニアアクチュエータ、DC～300Hz、0.5mm 間隔

オプタコン: 視触覚変換装置／
Optacon：Vision-Tactile Converter (1976)



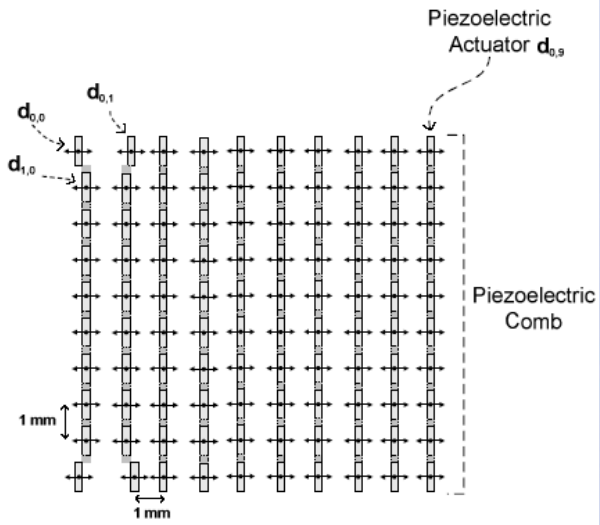
Braille Display (Optacon), Linville 1976

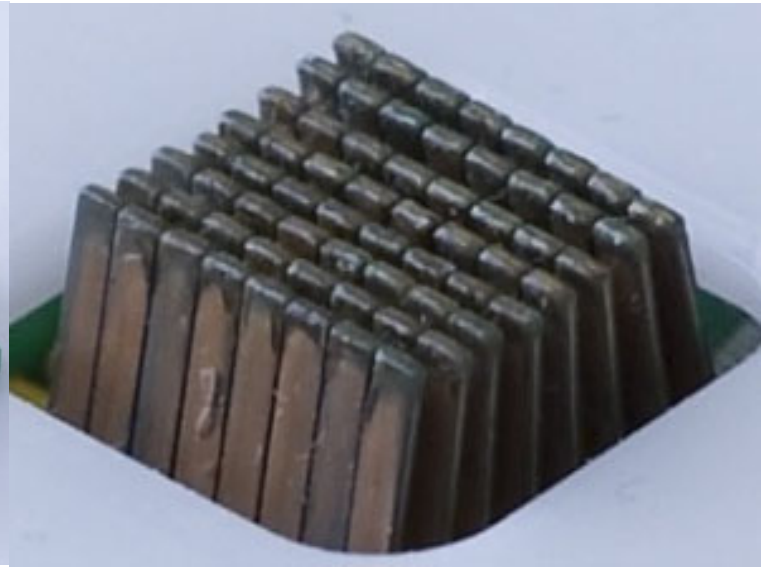
https://www.youtube.com/watch?v=ghsXhqu8FCY



https://en.wikipedia.org/wiki/Optacon

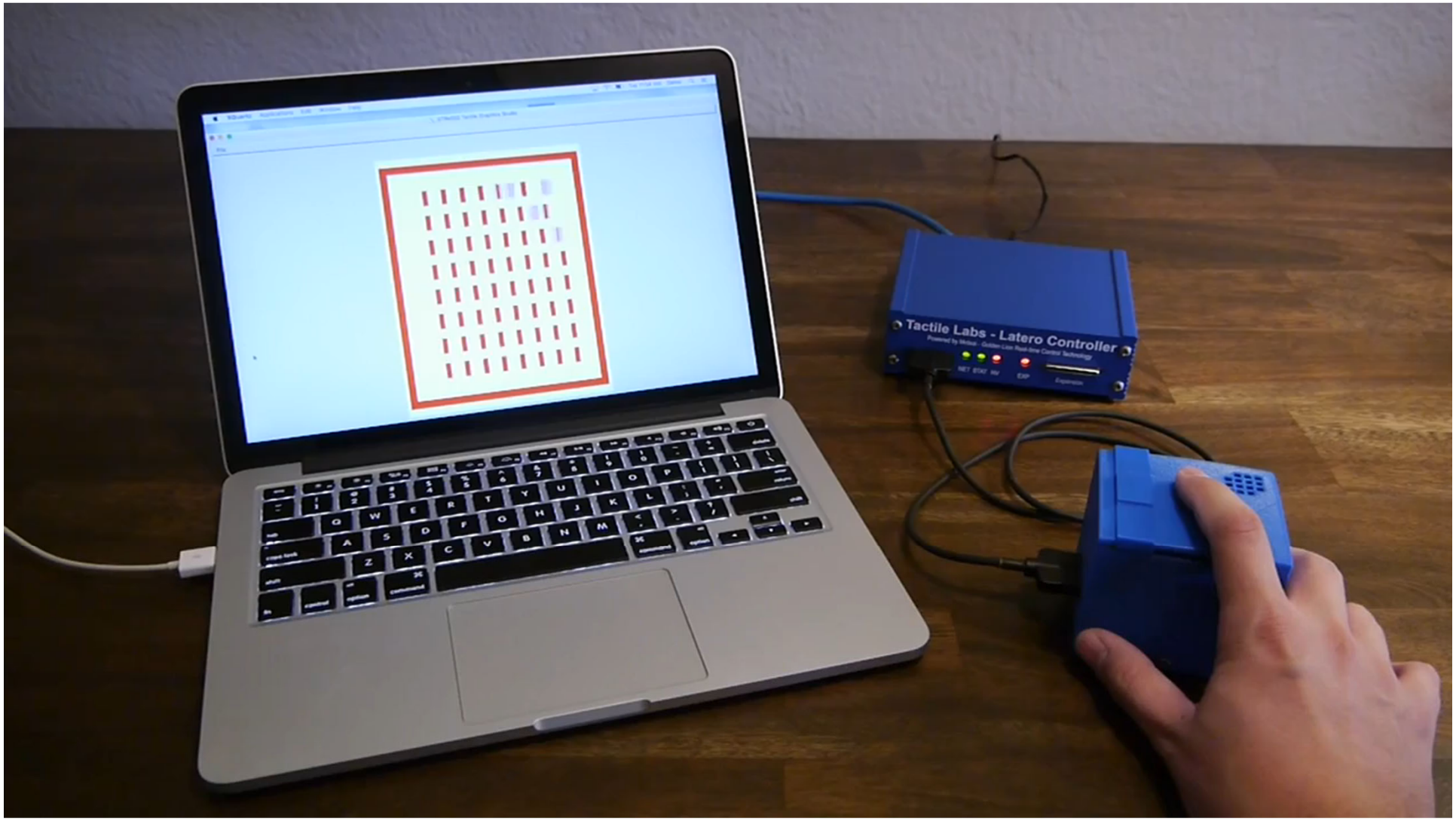
（おそらく今唯一）入手可能な高分解能，広帯域触覚ディスプレイ





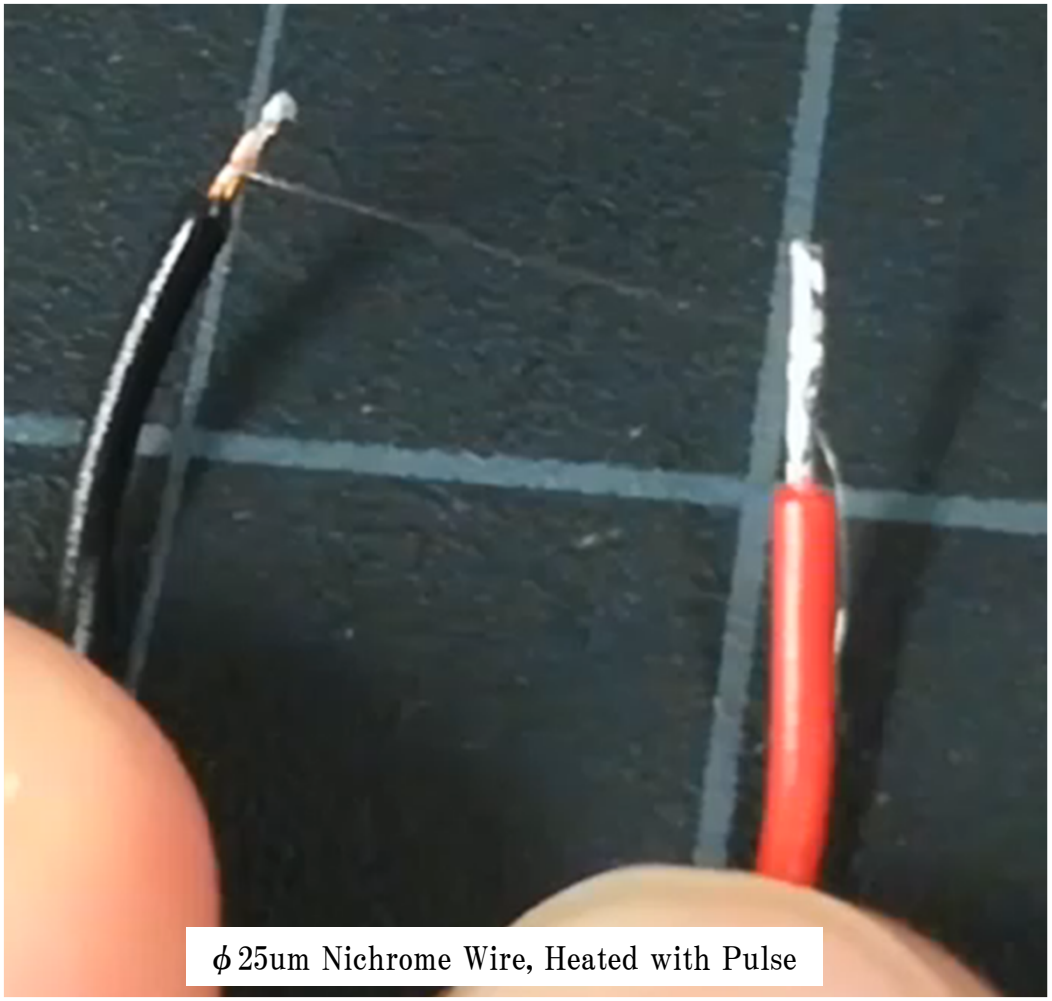
- 皮膚の水平駆動の重要性に着目して作成されたもの．
- 結果としてシンプルなピエゾアクチュエータの配置が可能となり，高密度化も可能に．
- Horizontal Vibration is achieved by piezo drive. High density and compact system is achieved by this simple structure.

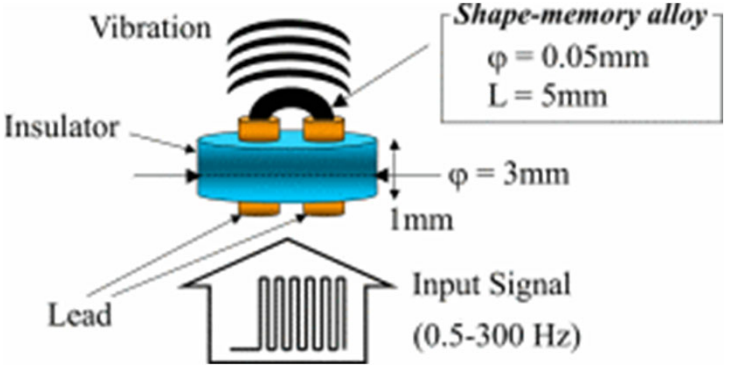
Hayward,”Tactile display device using distributed lateral skin stretch,” ASME, DSC, 2000.

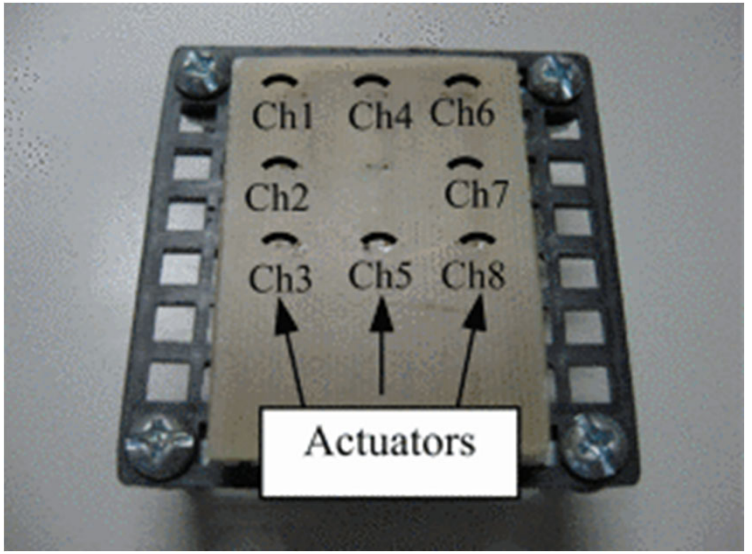


https://www.youtube.com/watch?v=AVsD1Gy0sHg

Simple Actuation by Heating Wire



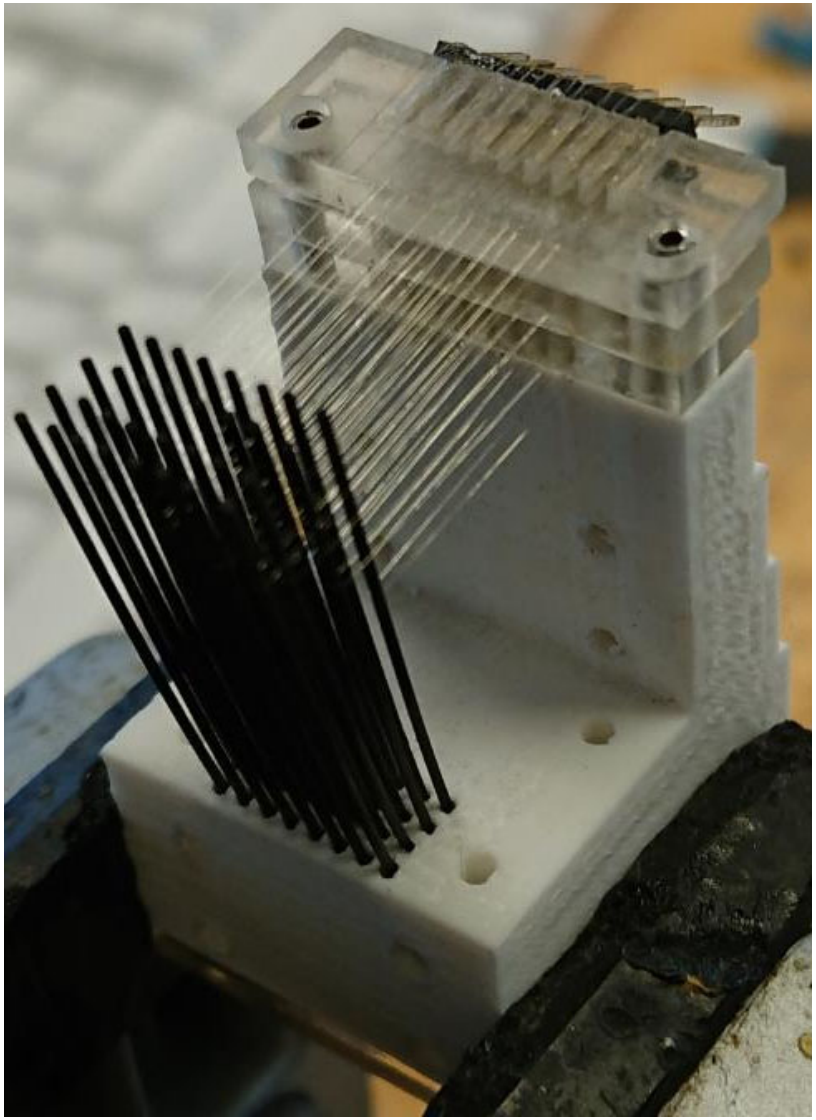




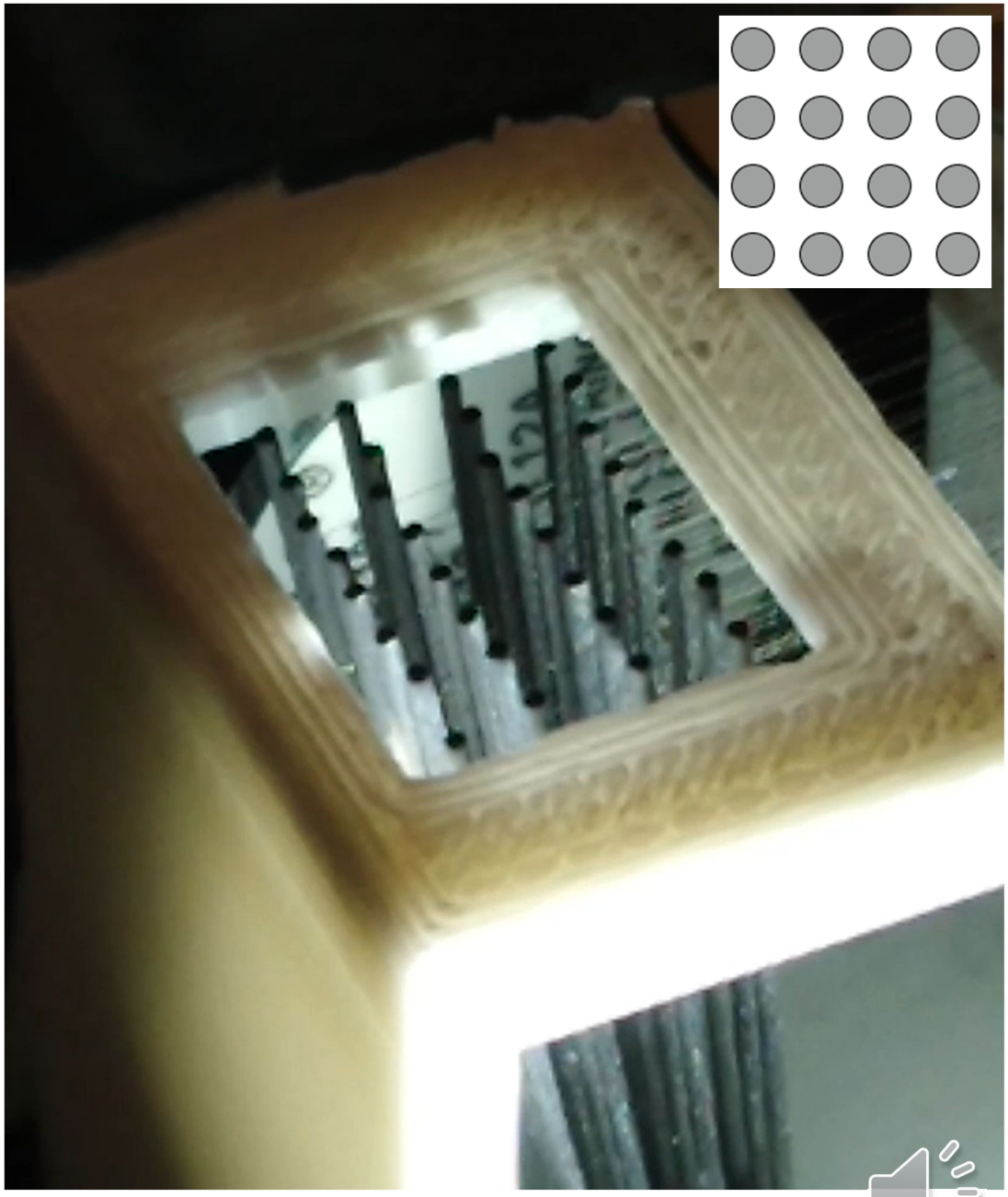
Fukuyama (2009) Tactile display using the vibration of SMA wires and the evaluation of perceived sensations

- Very thin Nichrome wire can be elongated by heating. Can also quickly shrink.
- Similar phenomenon observed by SMA wire, but not necessarily SMA.
- Heating phenomenon = Smaller the quicker. Good for small tactile display

2D Matrix

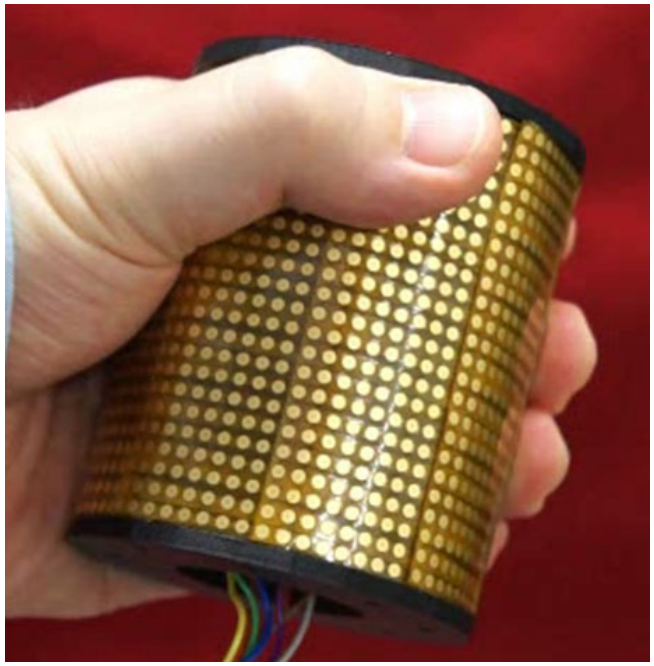


Hiroyuki Kajimoto, Lynette Jones: Wearable Tactile Display Based on Thermal Expansion of Nichrome Wire, IEEE Transaction on Haptics, pp.257-268, 2019.



8 by 4, 1.2mm interval. Up to 320 Hz vibration.

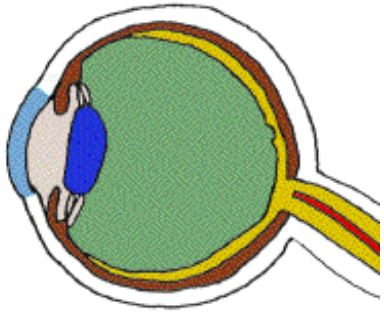
電気刺激：高時空間分解能，省スペース，低コスト/ Electrotactile display can be high-resolution at low cost

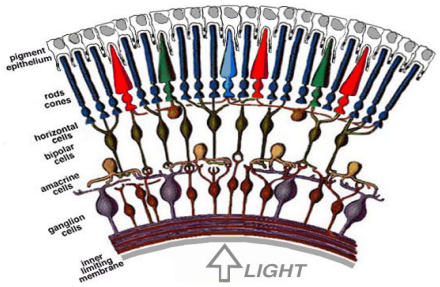


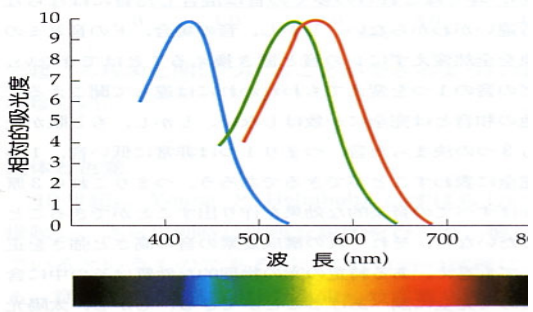
- でも電気といえばビリビリ．
- その理由は物理的相互作用による計算プロセス（皮膚が接触で変形して感覚受容器が活動）を飛ばして受容器活動を生じさせているため．
- 逆に言えば，電気刺激を自然な触感とするためには，物理的な相互作用をすべて理解，モデル化している必要があり，研究課題として魅力的．
- Small, robust, no mechanical resonance, no noise, low power.
- Yet, many consider *Electrical Shock* not appropriate for daily use.

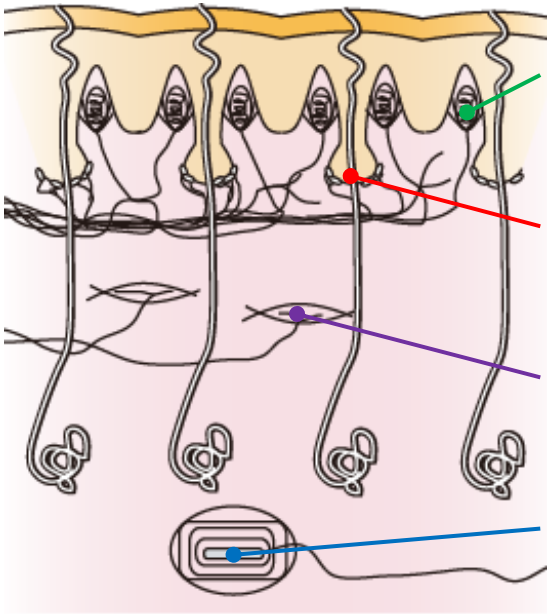
How to overcome *Electrical-Shock* impression, and achieve natural sensation?

Tactile Primary Color Approach







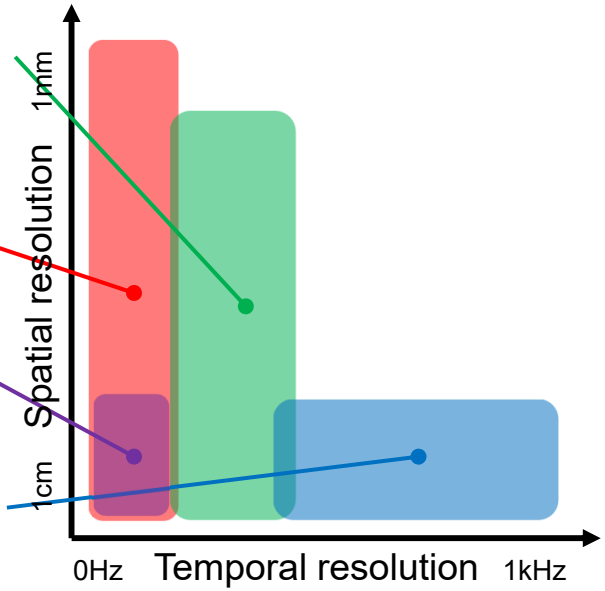


Meissner corpuscle
(low freq. vibration)

Merkel cell
(pressure)

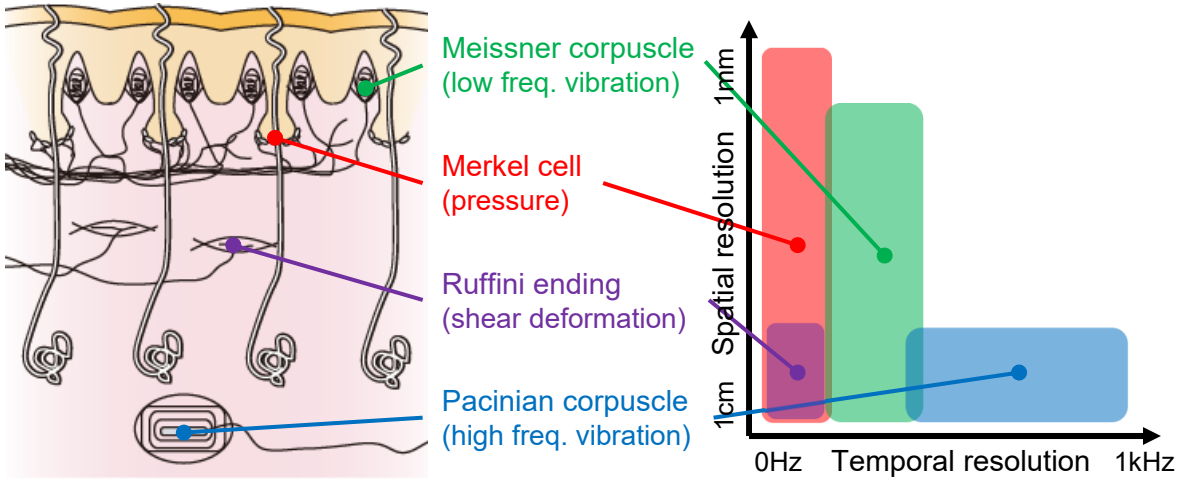
Ruffini ending
(shear deformation)

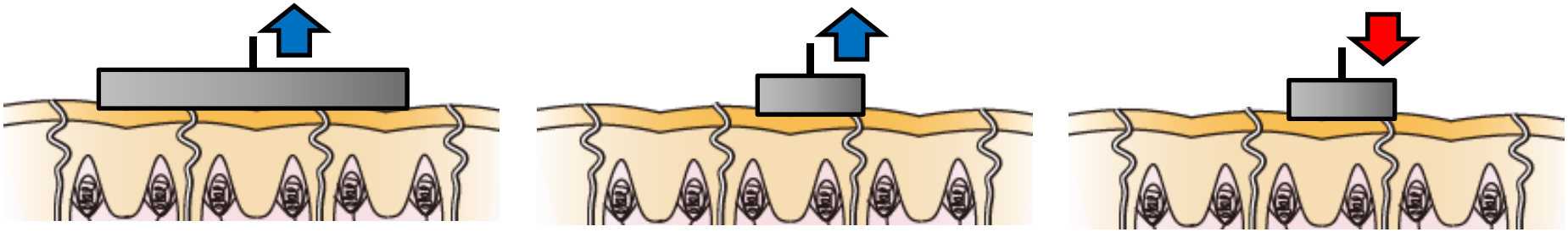
Pacinian corpuscle
(high freq. vibration)



In vision, primary colors (RGB) are related to receptors' characteristics.
If we selectively stimulate each type of receptors, we can use them as primary colors.

電気刺激は，その極性（陽極，陰極）を替えることで，浅部受容器を（ある程度）選択刺激できる
Selective stimulation is possible by changing polarity



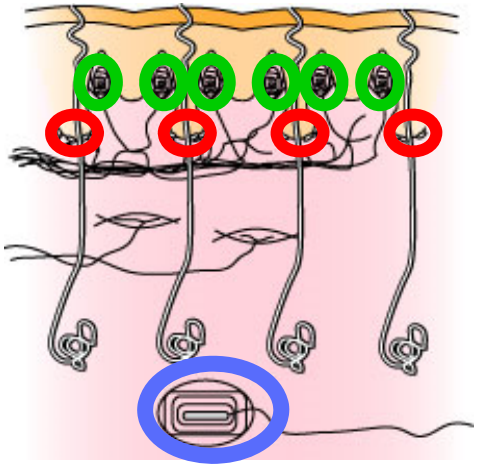


- **Large** electrode can stimulate deeper nerves -> Vibration sensation
- **Small** electrode with **cathode** can stimulate Merkel -> Pressure sensation
- **Small** electrode with **anode** can stimulate Meissner -> Texture sensation

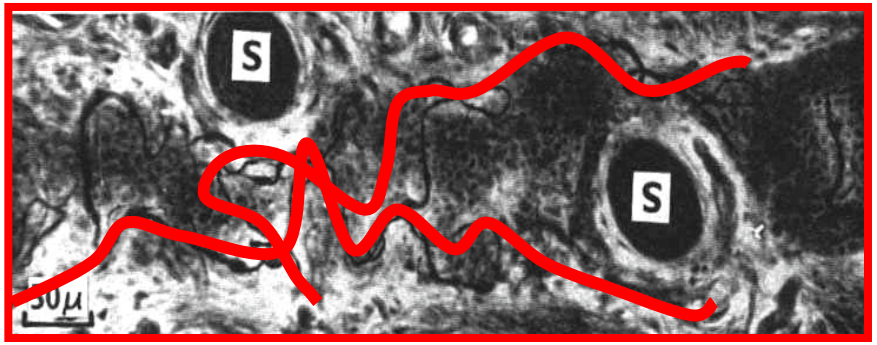
- Kajimoto et al: Tactile Feeling Display using Functional Electrical Stimulation, ICAT'99
- V. Yem et al: Comparative Evaluation of Tactile Sensation by Electrical and Mechanical Stimulation. IEEE Trans. Haptics 2017.

原因：浅部における軸索の走行？

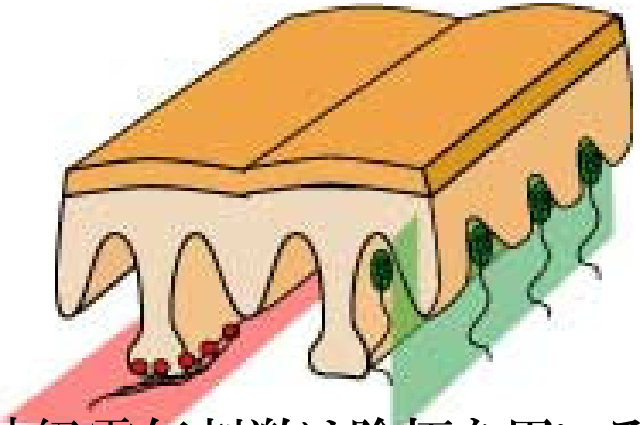
Possible reason: nerve pathway and boundary conditions?

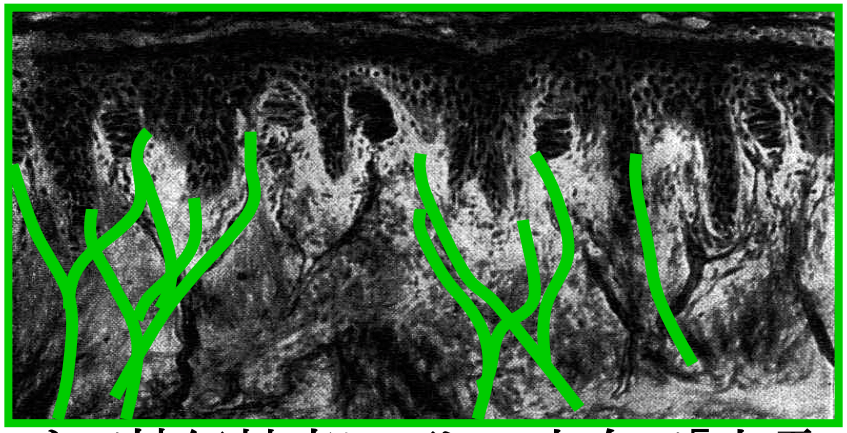


Merkel：皮膚水平に走行



Meissner：皮膚垂直に走行

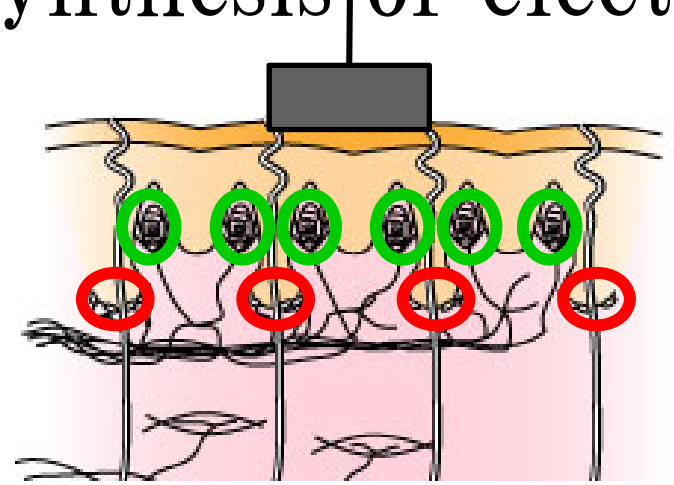


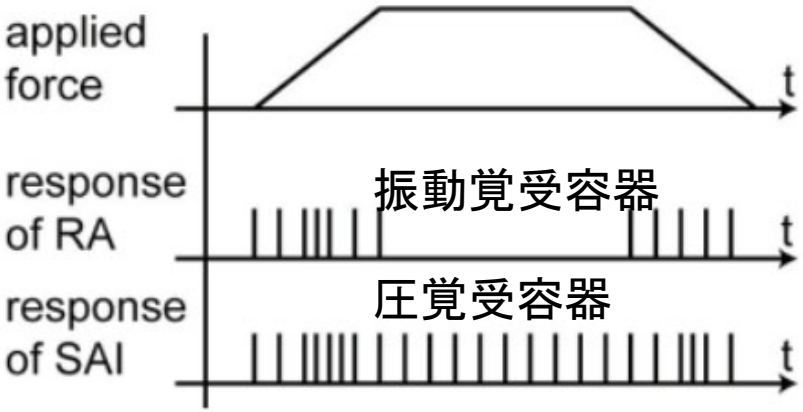


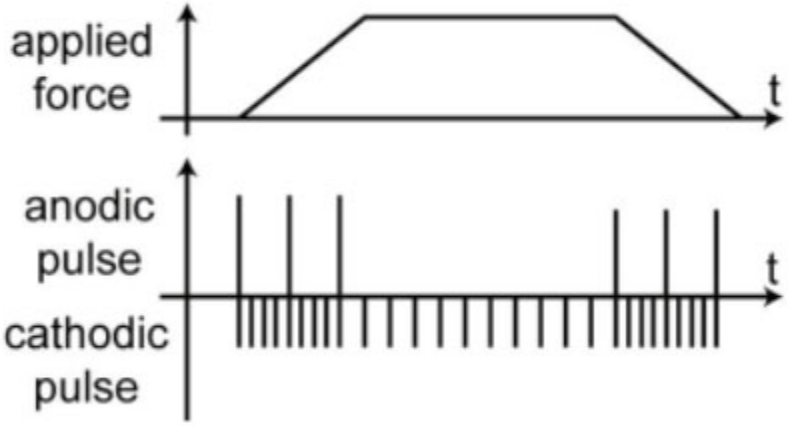
通常の神経電気刺激は陰極を用いることで神経軸索に正しい方向で「充電」されるが，
指先末梢の神経は受容器ごとに走行、電気的境界条件に特徴がある。

Although normal electrical stimulation uses a cathode to "charge" the nerve axons, the peripheral nerves of the fingertips are characterized by pathways and electrical boundary conditions of each receptor.

原色の組み合わせによる感覚合成
Synthesis of electrotactile stimulation







陽極刺激による振動覚受容器への刺激

陰極刺激による圧覚受容器への刺激

刺激モードの組み合わせにより自然な触覚を合成

Sato et al.: Design of Electrotactile Stimulation to Represnt Distribution of Force Vectors, IEEE Haptics Symposium 2010

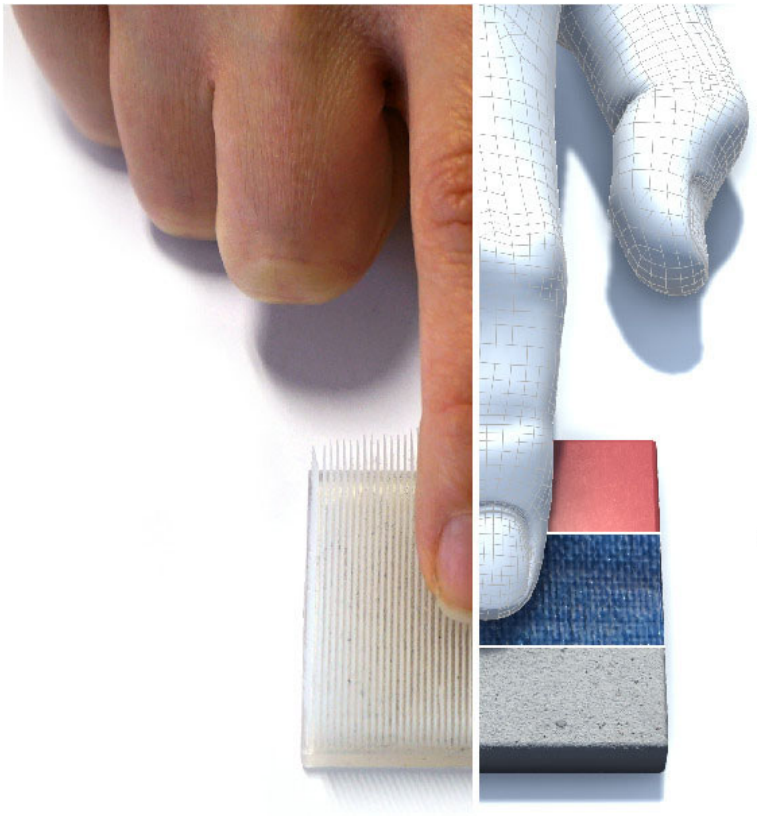
現実的アプローチ：実物を使う

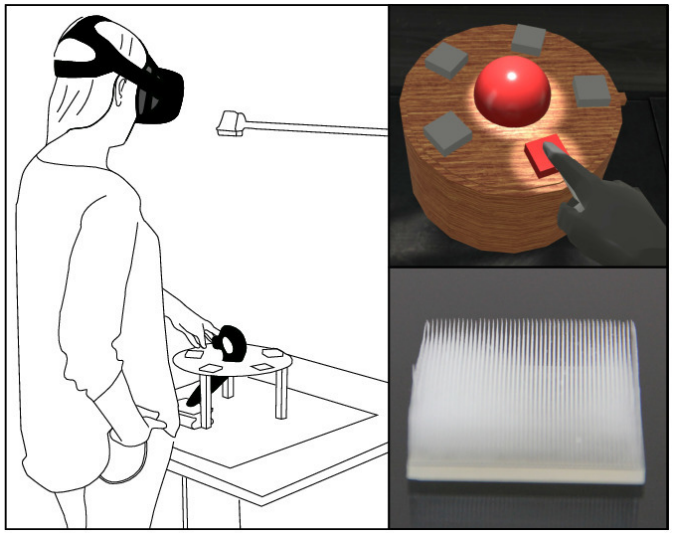
(CHI2018) Haptic Revolver: Touch, Shear, Texture, and Shape Rendering on a Reconfigurable Virtual Reality Controller, Eric Whitmire, Hrvoje Benko, Christian Holz, Eyal Ofek, Mike Sinclair

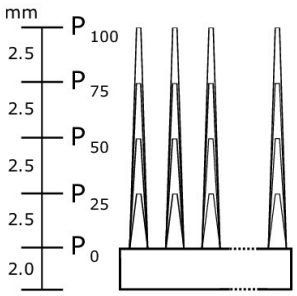
- 遭遇型触覚提示の一種 https://www.youtube.com/watch?v=kp01cDU
- 実物を使うことでリアルな触感を提示。

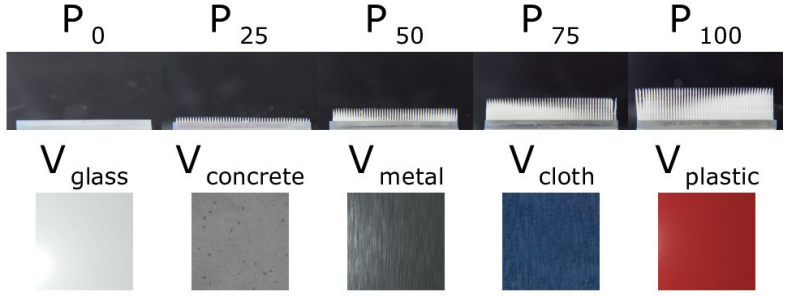
現実的アプローチ：実物を使う

(CHI2019) Enhancing Texture Perception in Virtual Reality Using 3D-Printed Hair Structures, Donald Degraen André Zenner Antonio Krüger









- 多数の布テクスチャの感触を，限られた本物のテクスチャ＋VR視覚で実現．

小テスト／Mini Test 次回開始まで

以下の全てに100字以内程度で解答せよ／Answer all questions within 50 words

1. メルケル細胞の役割について説明せよ Explain role of Merkel cell
2. マイスナー小体の役割について説明せよ Explain role of Meissner corpuscle.
3. パチニ小体の役割について説明せよ Explain role of Pacini corpuscle.
4. ルフィニ終末の役割について説明せよ Explain role of Ruffini ending
5. 温度感覚の仕組みについて説明せよ Explain mechanism of thermal sensation.
6. 触覚の仮現運動について説明せよ Explain tactile apparent motion
7. 触覚の跳躍現象について説明せよ Explain cutaneous rabbit.
8. ファントムセンセーションについて説明せよ Explain Phantom Sensation
9. ベルベットイリュージョンについて説明せよ Explain velvet illusion
10. サーマルリファレルについて説明せよ Explain thermal referrel
11. サーマルグリルイリュージョンについて説明せよ Explain thermal grill illusion
12. 触感の5要素について説明せよ Explain five dimension of tactile feeling