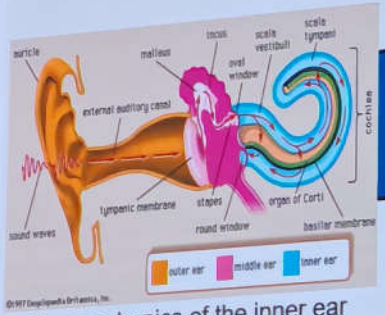
From understanding of AUDITION and VISION SENSES to biomedical and consumer applications



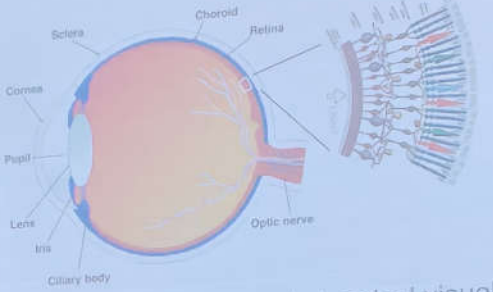
The mechanics of the inner ear

Georg von Békésy
Nobel laureate 1961

~20 kHz max audible frequency

Nyquist criteria

~44 kHz sampling frequency

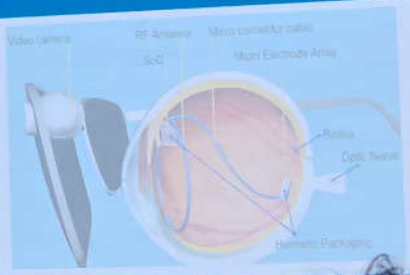


Primary physiological and chemical visual processes in the eye
Haldan Hartline, George Wald, Ragnar Granit
Nobel laureates 1967

Information processing in the visual system
David H. Hubel and Torsten N. Wiesel
Nobel laureates 1980

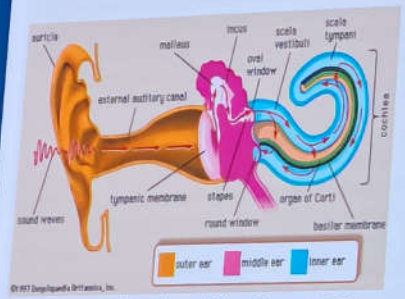
MP3 AUDIO

JPEG



Most diffused and advanced consumer and medical devices ground on science-technology synergies

From understanding of AUDITION and VISION SENSES to biomedical and consumer applications

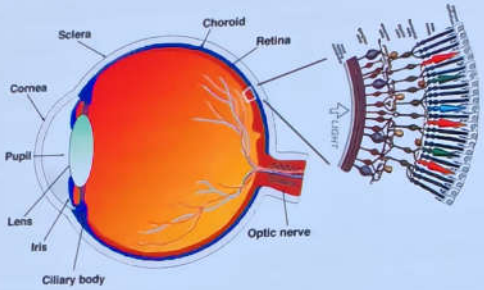


The mechanics of the inner ear

Georg von Békésy
Nobel laureate 1961

Dioptrics of the eye

Allvar Gullstrand
Nobel laureate 1911



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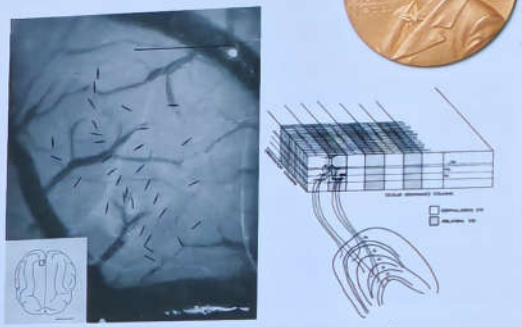

Information processing in the visual system

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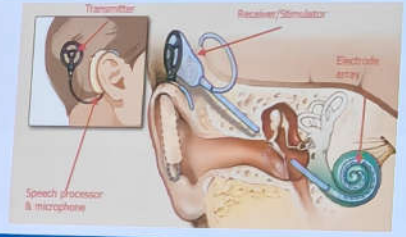
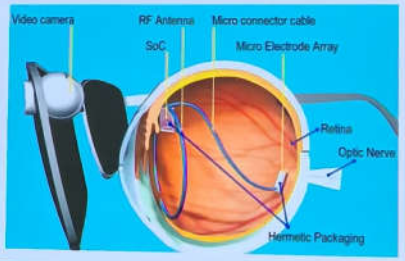
Nobel laureates 1980





Most diffused and advanced consumer and medical devices ground on science-technology synergies

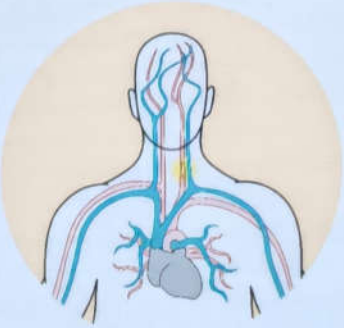
This is the ERA of physical human-machine interaction

Collaborative Robots

Robots need a sense of touch to interact physically with humans and the environment

Wearable Robots

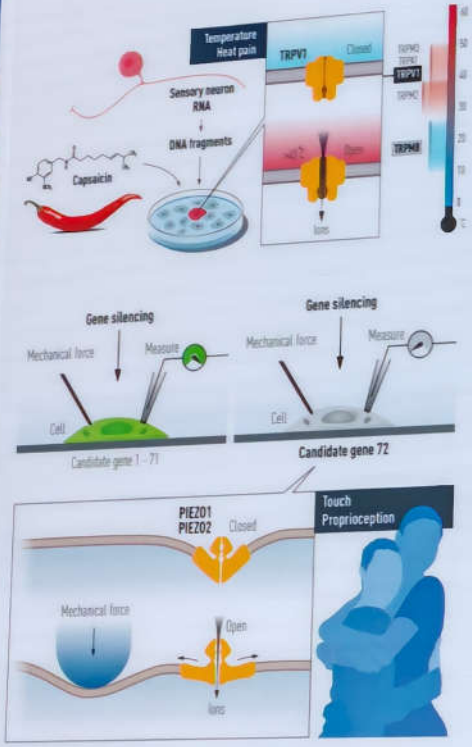
Implantable Robots

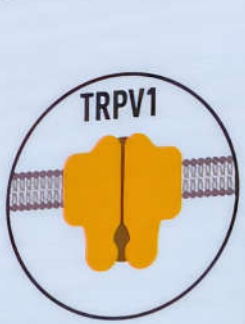


Surgical Robots

Neuro-Robotic Touch Laboratory, The Biorobotics Institute
Sant'Anna School of Advanced Studies, Pisa, Italy (calogero.od tannapisa.it)

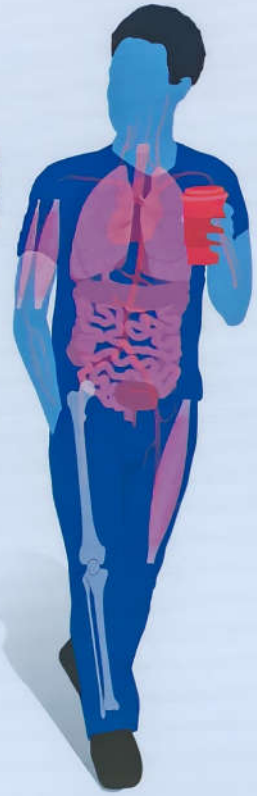
Tactile sensing to enable interaction abilities





Temperature
Heat pain

Core body temperature
Inflammatory pain
Neuropathic pain
Visceral pain
Protective reflexes



Touch
Proprioception

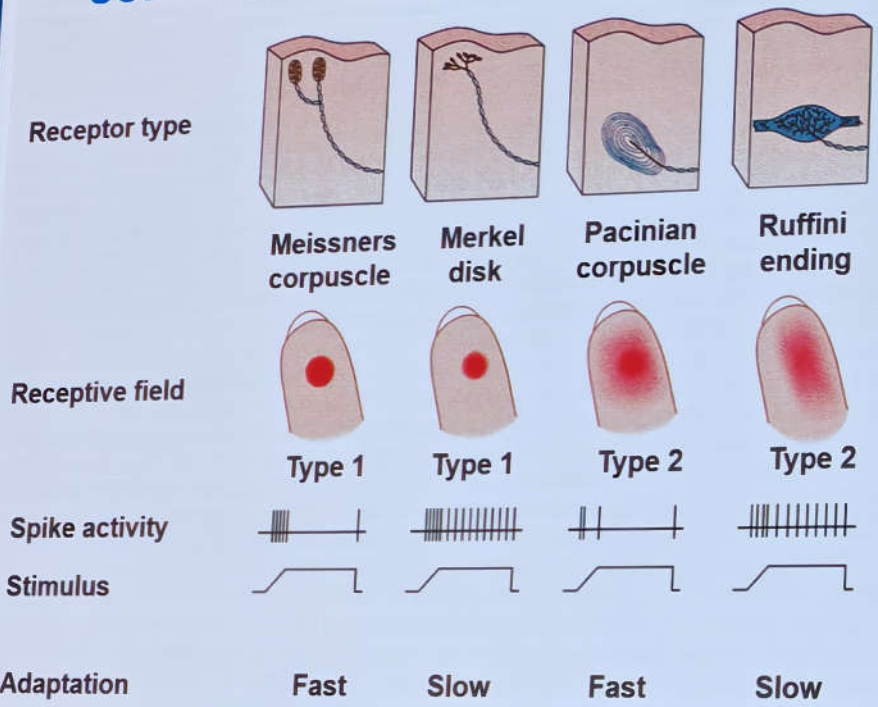
Mechanical pain
Urination
Respiration
Blood pressure
Skeletal remodeling

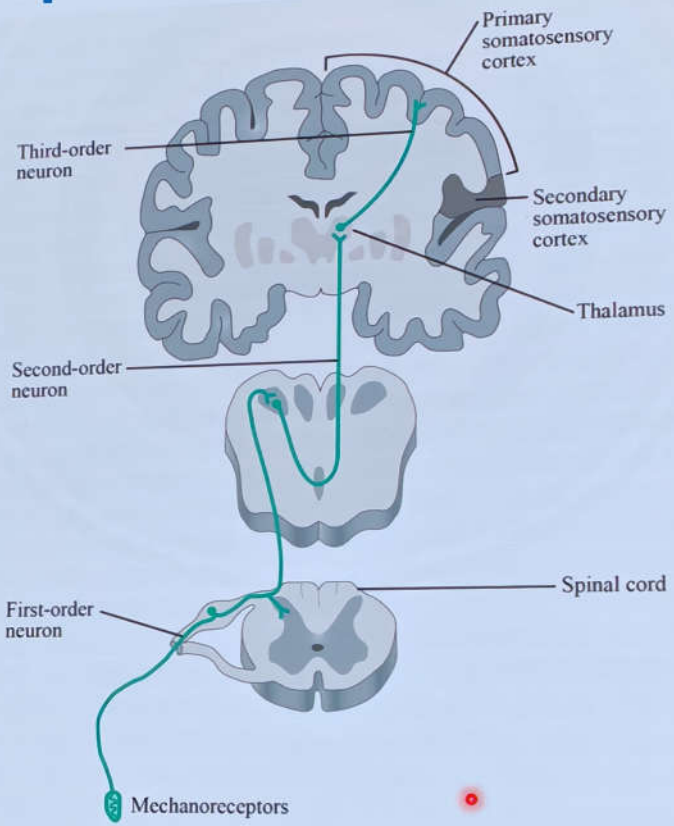
David Julius

Ardem Patapoutian

The 2021 Nobel Prize in Physiology or Medicine jointly awarded [illegible]id Julius and Ardem Patapoutian for their discoveries of receptors for temperature and touch (source [illegible]belprize.org)

Human tactile receptors: spatial and temporal encoding and somatosensory connectome





Source: Pearson Education

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Neuroscientific Quest
Investigation of human somatosensation

Biorobotic Engineering
Artificial model of human touch

Science-Engineering loop

Bionic Applications
Touch restoration in amputees

Neuromorphic Touch
Spike-based encoding

Applications in Industry 4.0 & Safety at Work
Collaborative robots and workwear

Applications in BioRobotics & Healthcare Sensors
Colonoscopes, wearable/implantable sensors for cardiorespiratory monitoring

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Functional mimicry of Ruffini receptors with fibre Bragg gratings and deep neural networks enables a bio-inspired large-area tactile-sensitive skin

Luca Massari, Giulia Fransvea, Jessica D'Abbraccio, Mariangela Filosa, Giuseppe Terruso, Andrea Aliperta, Giacomo D'Alesio, Martina Zaltieri, Emiliano Schena, Eduardo Palermo, Edoardo Sinibaldi and Calogero Maria Oddo

www.nature.com/natmachintell / May 2022 Vol 4 No 5

nature machine intelligence

Tactile sensing in robotic skin

Neuro-Robotic Touch Laboratory, The Biorobotics Institute / Department of Excellence in Robotics & AI
Interdisciplinary Research Centre Health Science / Sant'Anna School of Advanced Studies, Pisa, Italy
Principal Investigator: Prof. Calogero Maria Oddo (calogero.oddo@santanna


Neuroscientific Quest
Investigation of human somatosensation
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Bionic Applications
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Spike-based encoding
Applications in Industry 4.0 & Safety at Work
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Colonoscopes, wearable/implantable sensors for cardiorespiratory monitoring
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Tactile sensing in robotic skin
for Bionic Prostheses
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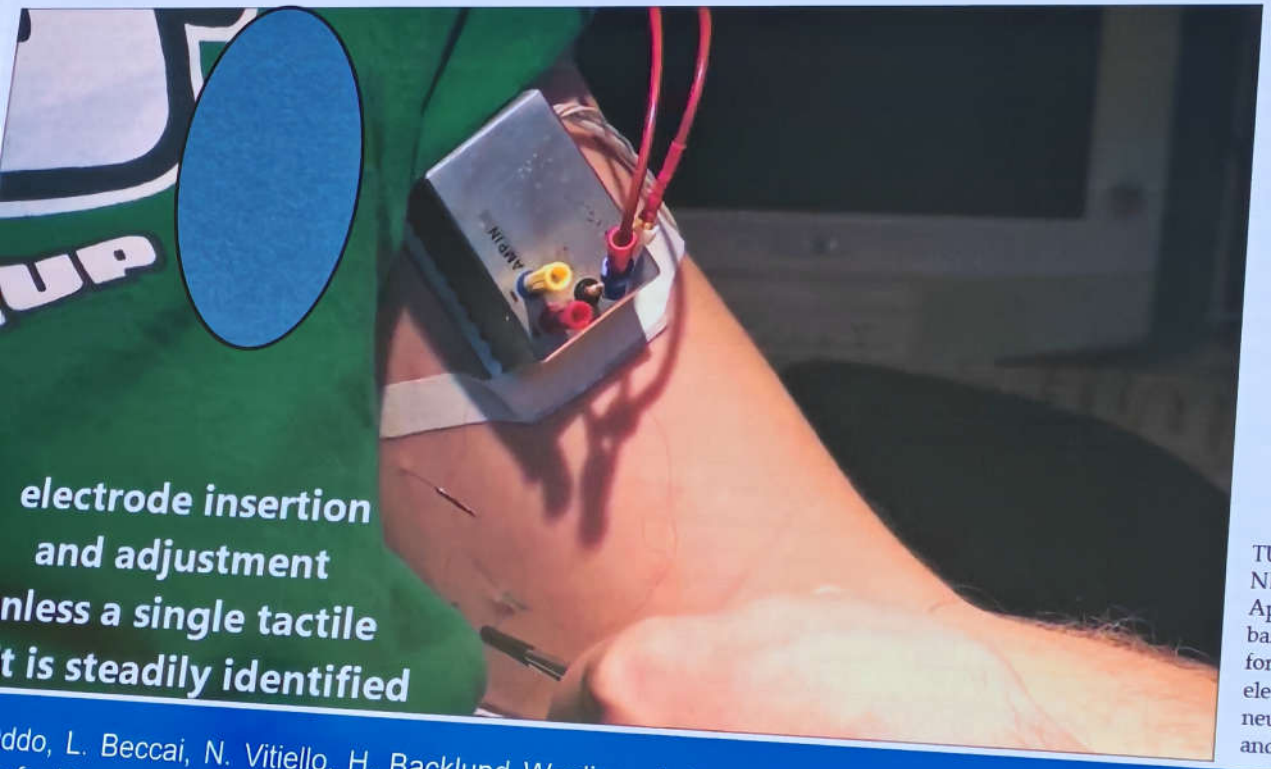
The microneurographic technique to investigate the human somatosensory system



J. Wessberg

S. Ballanti

G. D'Alesio

TUNE BEAM - TUscany NEtwork for BioElectronic Approaches in Medicine: AI-based predictive algorithms for fine-tuning of electroceutics treatments in neurological, cardiovascular and endocrinological diseases

TUNE

BEAM

ddo, L. Beccai, N. Vitiello, H. Backlund Wasling, J. Wessberg, M.C. C zza (2011). "A Mechatronic
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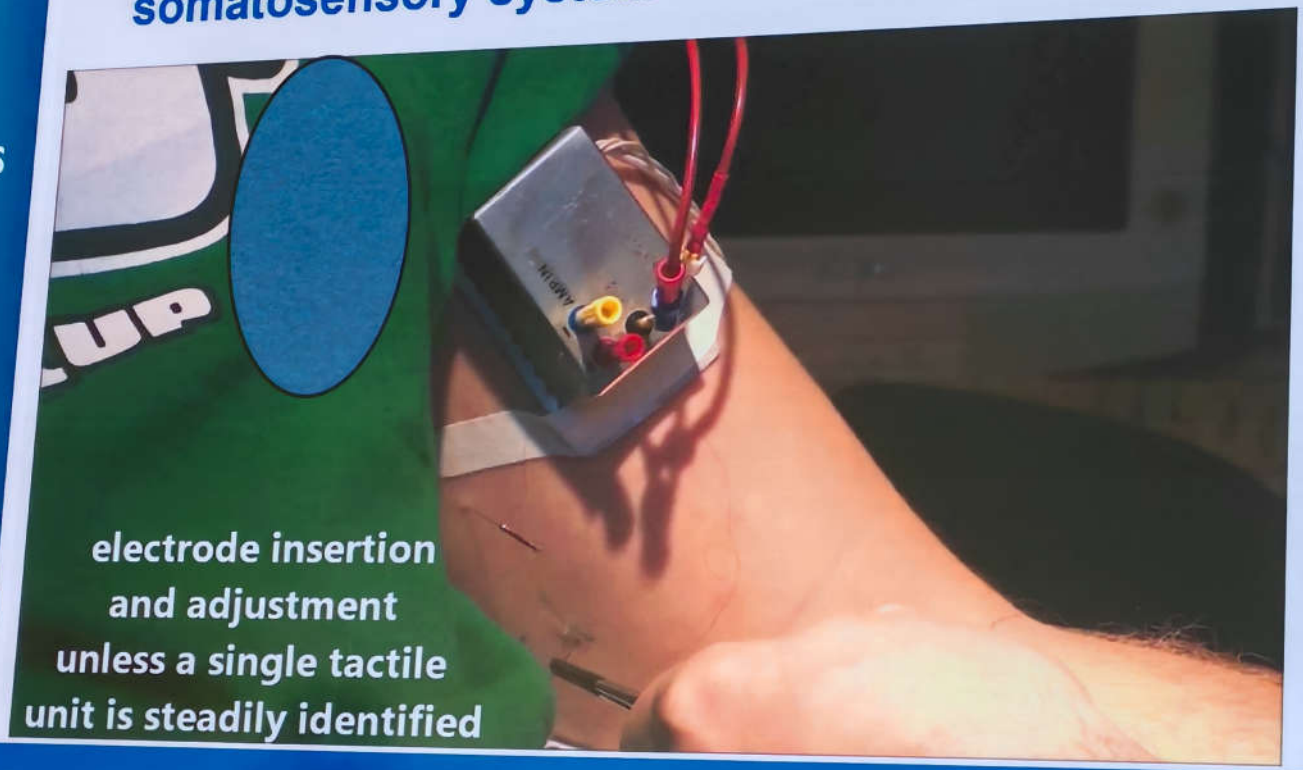
The microneurographic technique to investigate the human somatosensory system



J. Wessberg

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TUNE BEAM - TUscany NEtwork for BioElectronic Approaches in Medicine: AI-based predictive algorithms for fine-tuning of electroceutics treatments in neurological, cardiovascular and endocrinological diseases

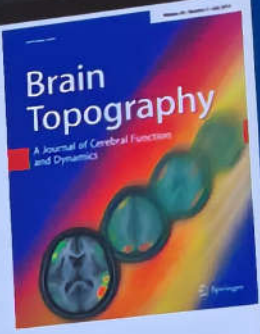
TUNE BEAM

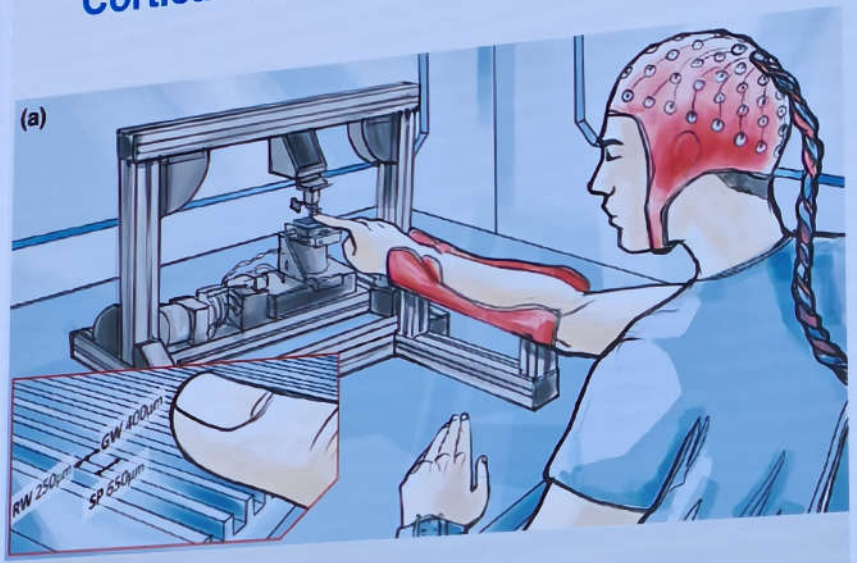
C.M. Oddo, L. Beccai, N. Vitiello, H. Backlund Wasling, J. Wessberg, M.C. C[illegible]zza (2011). "A Mechatronic Platform for Human Touch Studies." Mechatronics, 21, pp. 604-613.

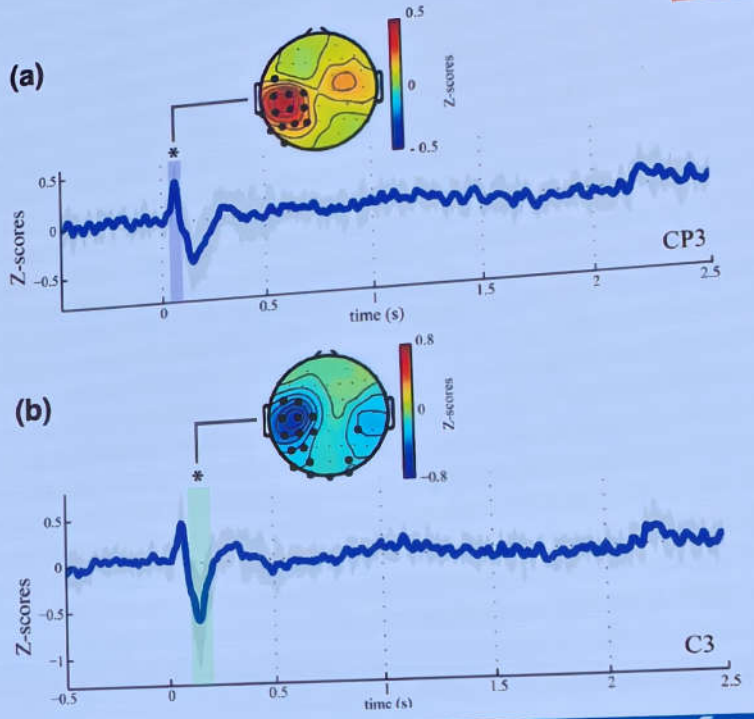
Cortical Responses to Touch Experience



F. Artoni C. Genna S. Micera







C. Genna, C. M. Oddo, C. Fanciullacci, C. Chisari, H. Jorntell, F. Artoni and S. Micera (2017). "Spatiotemporal Dynamics of the Cortical Responses Induced by a Prolonged Tactile Stimulation of the Human Fingertips." Brain Topography 30(4): 473-485.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nature conferences
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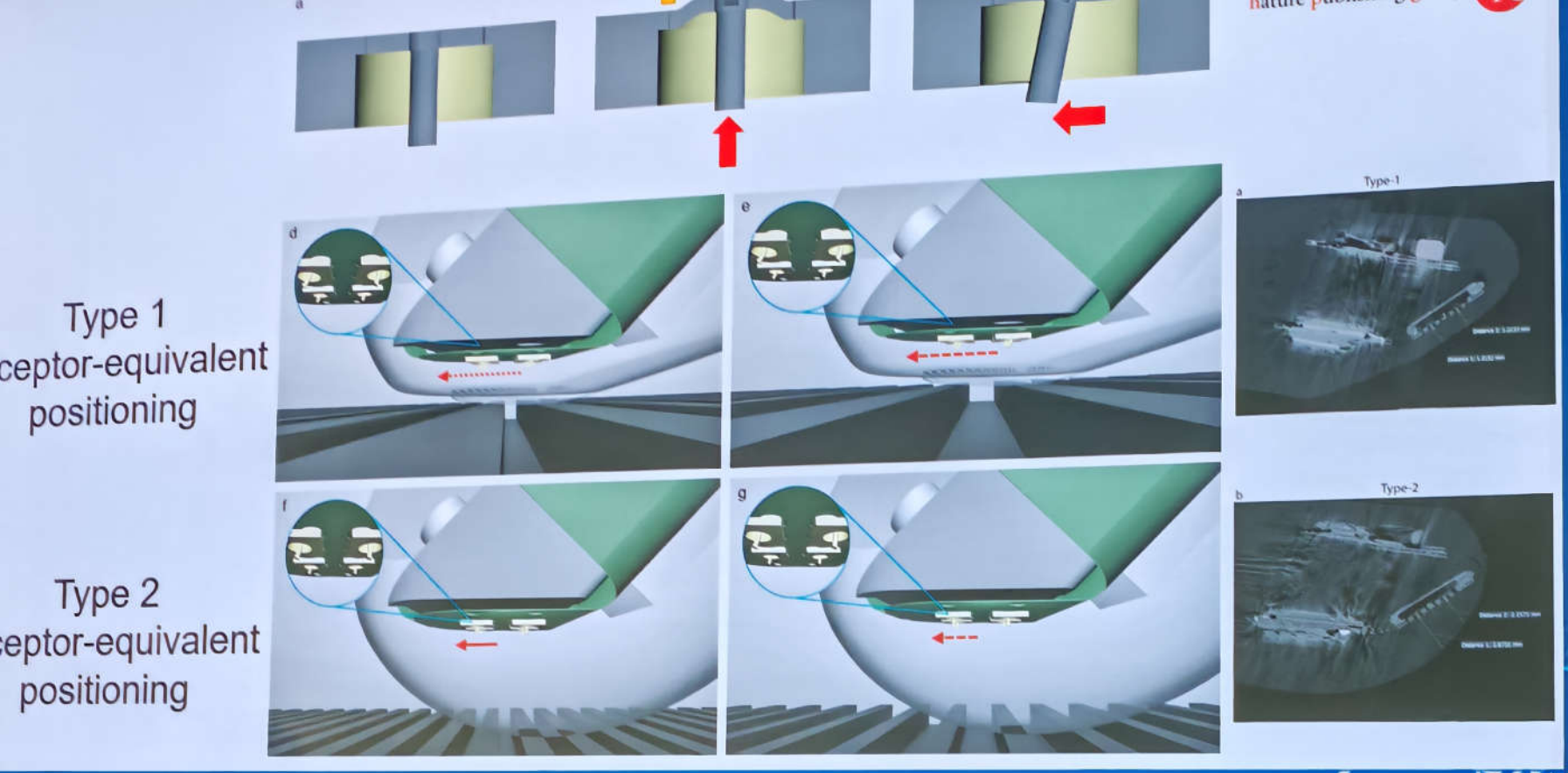

Mazzoni, C. M. Oddo, … S. Micera (2020). "Morphological Neural … utation Restores
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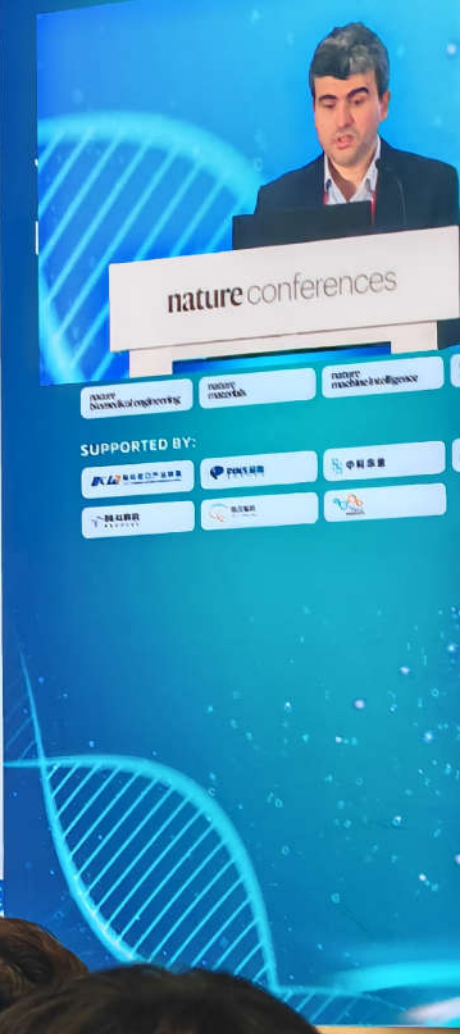


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Type 1 receptor-equivalent positioning
Type 2 receptor-equivalent positioning
Type-1
Type-2
A. Mazzoni, C. M. Oddo, … S. Micera (2020). "Morphological Neural
tation Restores Discrimination of Naturalistic Textures in Trans-radial Amputees." Scienti
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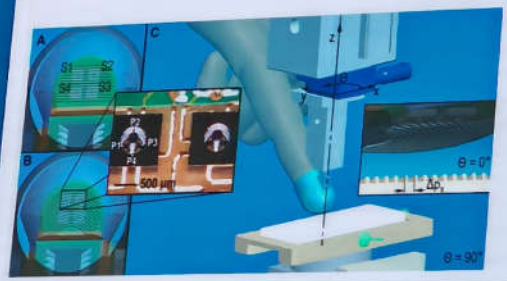
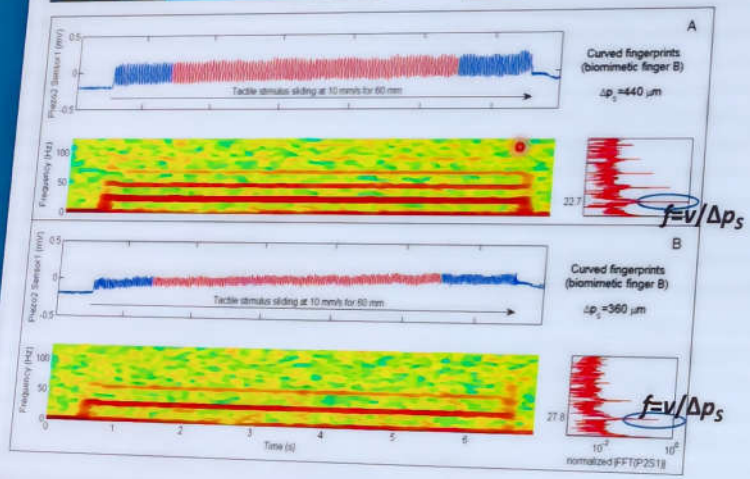
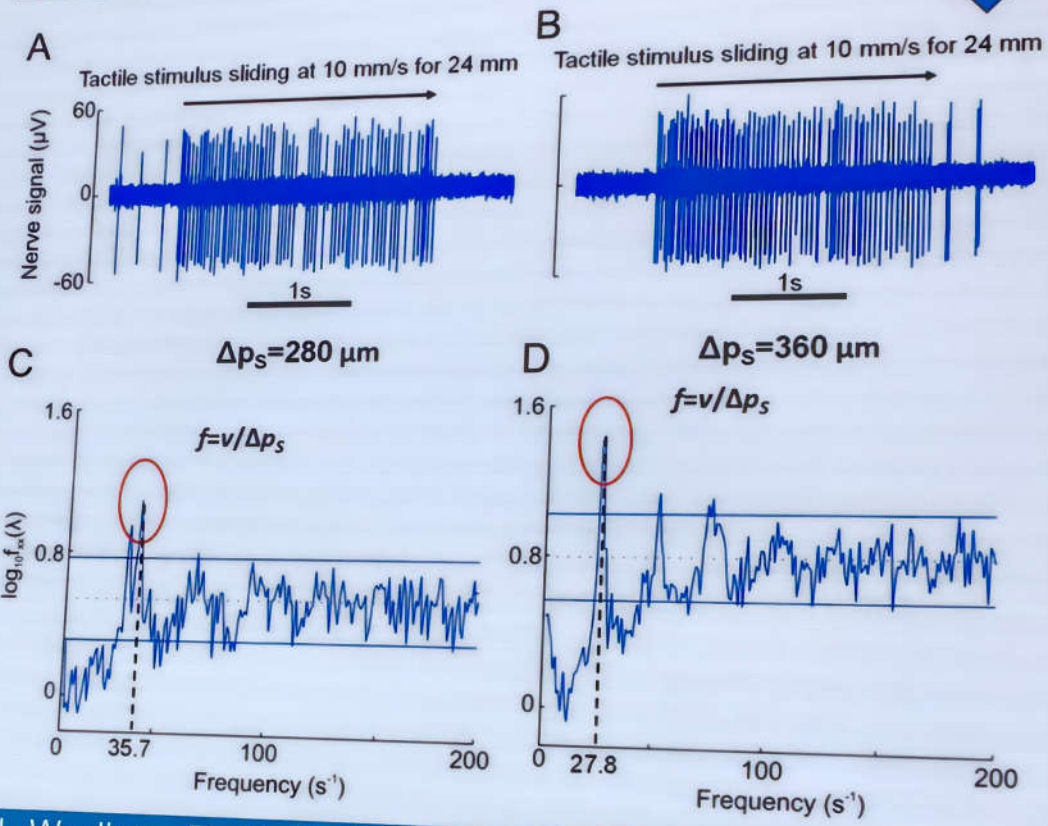
Towards Neuromorphic Touch



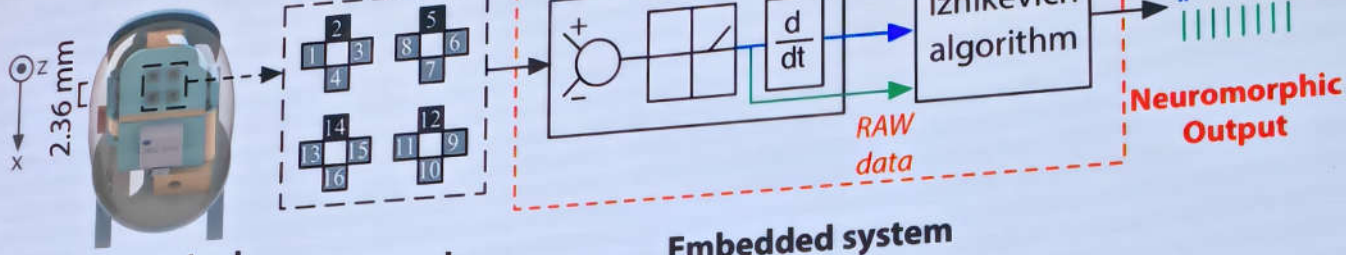
J. Wessberg



Comparison of outputs of artificial tactile sensors with human touch (via microneurography)



C.M. Oddo, L. Beccai, J. Wessberg, H. Backlund Wasling, F. Ma[illegible]li, M.C. Carrozza. "Roughness Encoding in Human and Biomimetic Artificial Touch: Sp[illegible]oral Frequency Modulation and Structural Anisotropy of Fingerprints." 2011



Bio-inspired tactile sensor **16 Channels** **Embedded system**

$$\frac{dv}{dt} = Av^2 + Bv + C - u + \frac{I_{input}}{C_m} \qquad (I_{input})_i = \begin{cases} \frac{X_i}{R} \\ \frac{T}{R}\frac{dX_i}{dt} \end{cases}$$

Adapted Izhikevich model

Fitted over microneurography data

$$\frac{du}{dt} = a(bv - u)$$

$$\forall t : v \geq vth \quad v \leftarrow c \quad u \leftarrow u + d$$

Possibility to mimic different receptor types (e.g., Merkel, Meissner)

C.M. Oddo*, S. Raspopovic*, F. Artoni, A. Mazzoni, G. Spigler, F. Petrini, F. Giambattistelli, F. Vecch… Miraglia, L. Zollo, G. Di Pino, D. Camboni, M.C. Carrozza, E. Guglielmelli, P.M. Rossini, U. Faraguna, S. Micera.

Intraneural stimulation elicits discrimination of textural features by artificial fingertips in int… …tee humans. *eLife 2016*


Neuromorphic Touch
Bio-inspired tactile sensor
16 Channels
Signal processing
FPGA
Izhikevich algorithm
Neuromorphic computation
Embedded system
Neuromorphic Output
TextileUX
Textile Blue
Textile White
DC
Velvet
BioSkin
Latex
Wii
Paper
Glass
A. Mazzoni
U.B. Rongala
H. Jörntell
Time (s)
Neuro-inspired tactile features representation
Sant'Anna
LUND
U.B. Rongala, A. Mazzoni, C.M. Oddo (2017). "Neuromorphic Artificial Touch
Textures." IEEE Transactions on Neural Networks and Learning Systems 28(
29.
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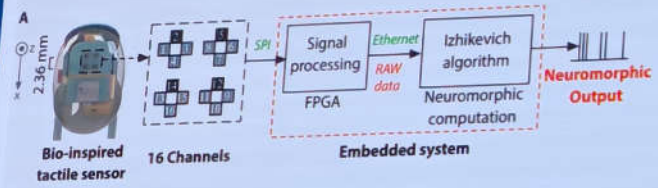
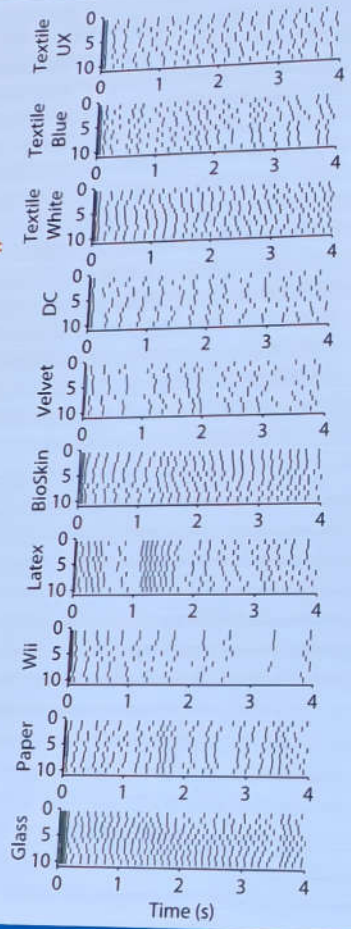
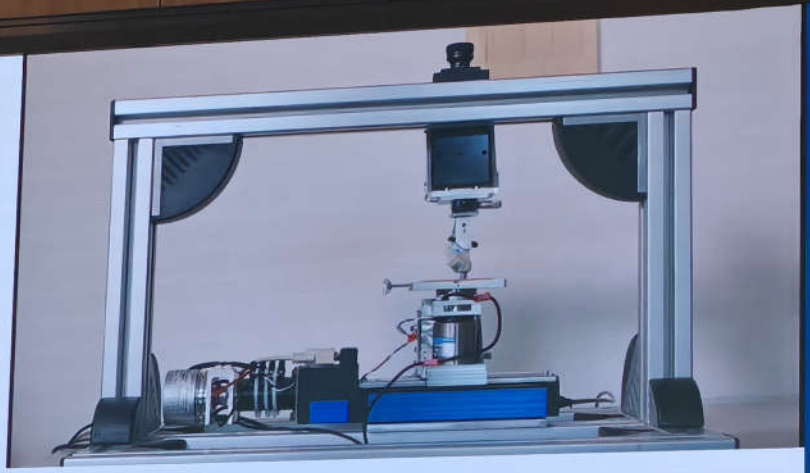
Neuromorphic Touch







Neuro-inspired tactile features representation

A neuronal learning model based on cellular dynamics, to create better understanding of the brain *and* to develop efficient artificial intelligent systems.

Motor babbling in the infant provides the brain with an enormous amount of sensory information.

Cuneate nucleus neurons process the tactile information before they enter the higher level brain networks.

The biological neuronal circuitry architecture was found to learn sets of correlated sensors, preparing the brain for new future experiences.

A neuronal model of synaptic learning was developed based on intracellular dynamics from cuneate neurons *in vivo* recordings.

A generalized learning evolved across the population of cuneate neurons that were capable of identifying a very large set of textures and shapes.

A bionic fingertip was used to mimic the biological sensors in the skin by generating spiking sensory responses encoding touch of a limited set of textures and shapes.

Sant'Anna Scuola Universitaria Superiore Pisa

LUND UNIVERSITY

U.B. Rongala, A. Mazzoni, C.M. Oddo (2017). "Neuromorphic Artificial Touch for ...gorization of Naturalistic Textures." IEEE Transactions on Neural Networks and Learning Systems 28(4)

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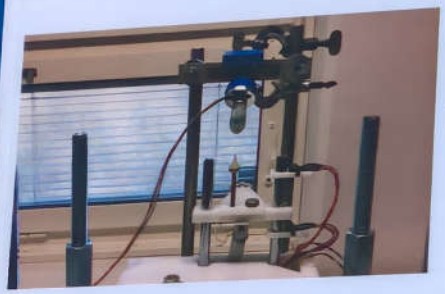
Investigation of touch encoding in brain somatosensory cortex

Description of the taxonomy of neurons in the somatosensory cortex



H. Jörntell

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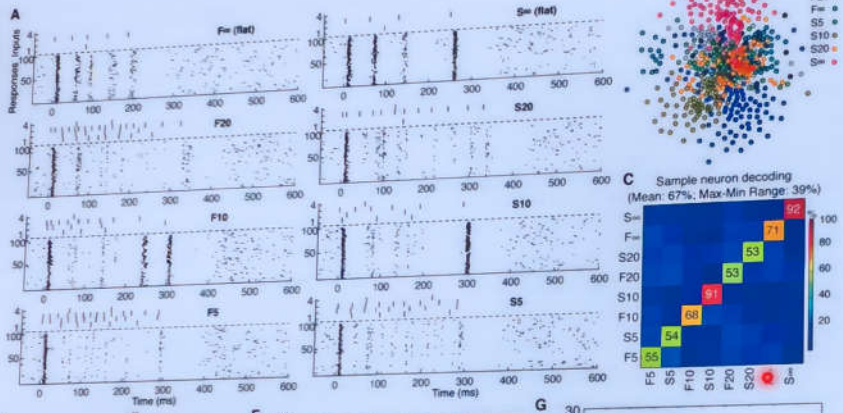
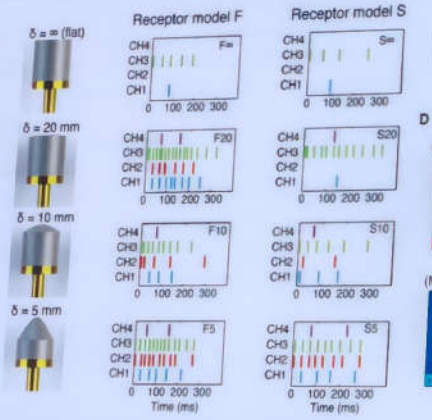
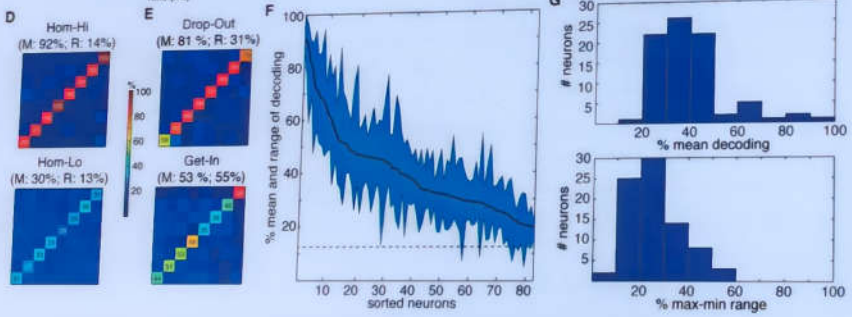
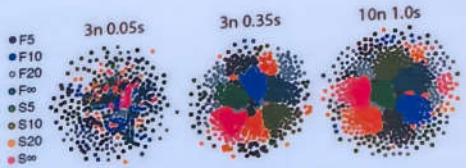
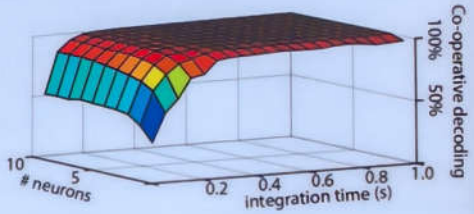
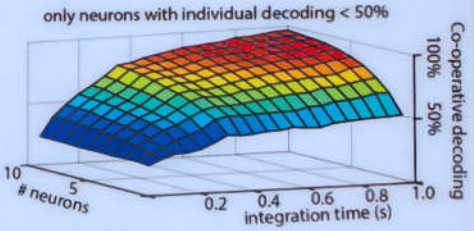












C. M. Oddo, A. Mazzoni, A. Spanne, J. M. Enander, H. Mogensen, F. Bengtsson, D. Camboni, S. Micera and H. Jörntell (2017). "Artificial spatiotemporal touch inputs reveal complem decoding in neocortical neurons." Scientific Reports 8: 45898.

Feeling Texture with Bionic Touch


S. Raspopovic

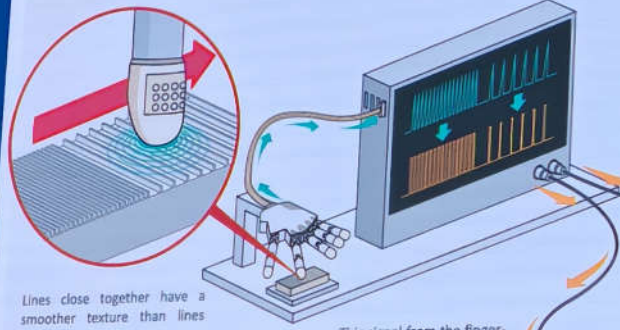

S. Micera


A. Mazzoni

Sensors in the fingertip generate an electrical signal by moving across the textured surface.

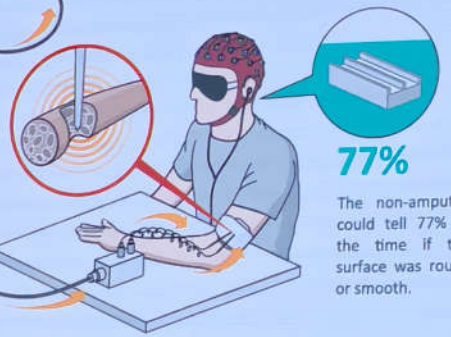
96%

The amputee could tell 96% of the time if the surface was rough or smooth.



Lines close together have a smoother texture than lines that are farther apart.

This signal from the fingertip is translated into a series of electrical spikes, imitating the language of the nervous system, then delivered to the nerves.



77%

The non-amputee could tell 77% of the time if the surface was rough or smooth.


P.M. Rossini


U. Faraguna

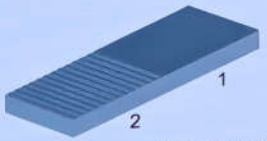

F. Artoni

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

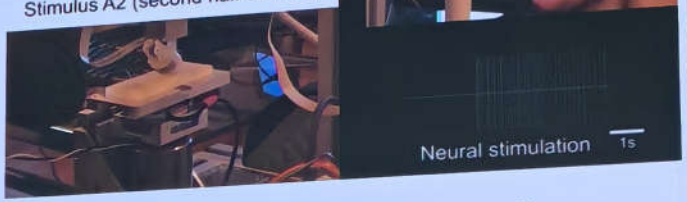
Sant'Anna School of Advanced Studies – Pisa

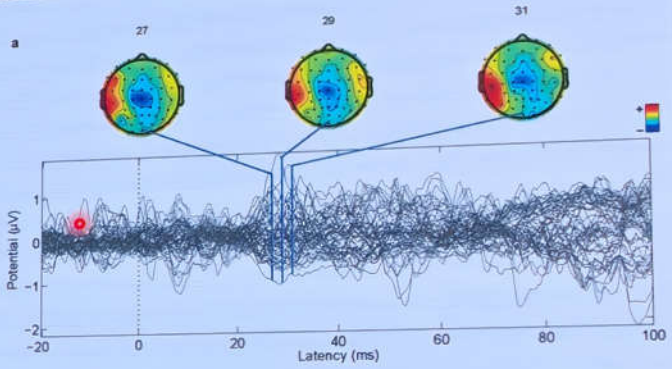
eLIFE

Does the bionic fingertip really resemble the feeling of touch from a real finger ? Brain scans collected by an EEG cap placed on the subject's head revealed that activated regions in the brain were analogous.



Stimulus A2 (second half coarser)





C. M. Oddo et al. (2016). "Intraneural stimulation elicits discriminati textural features by artificial fingertip in intact and amputee humans." eLife, 5, e09148.

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Morphological Neural Computation Restores Discrimination of Naturalistic Textures in Trans-radial Amputees

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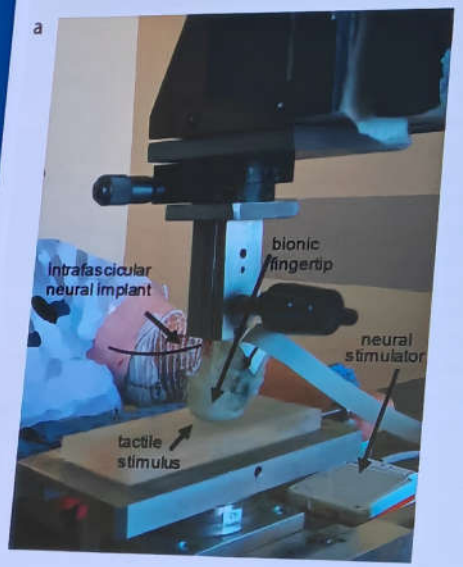
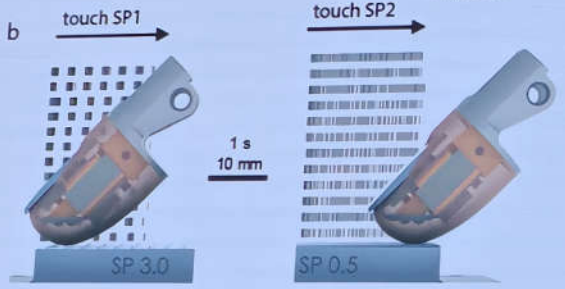
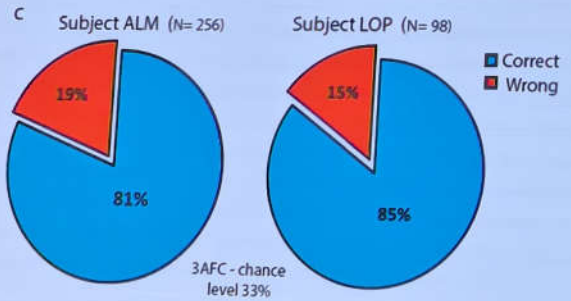
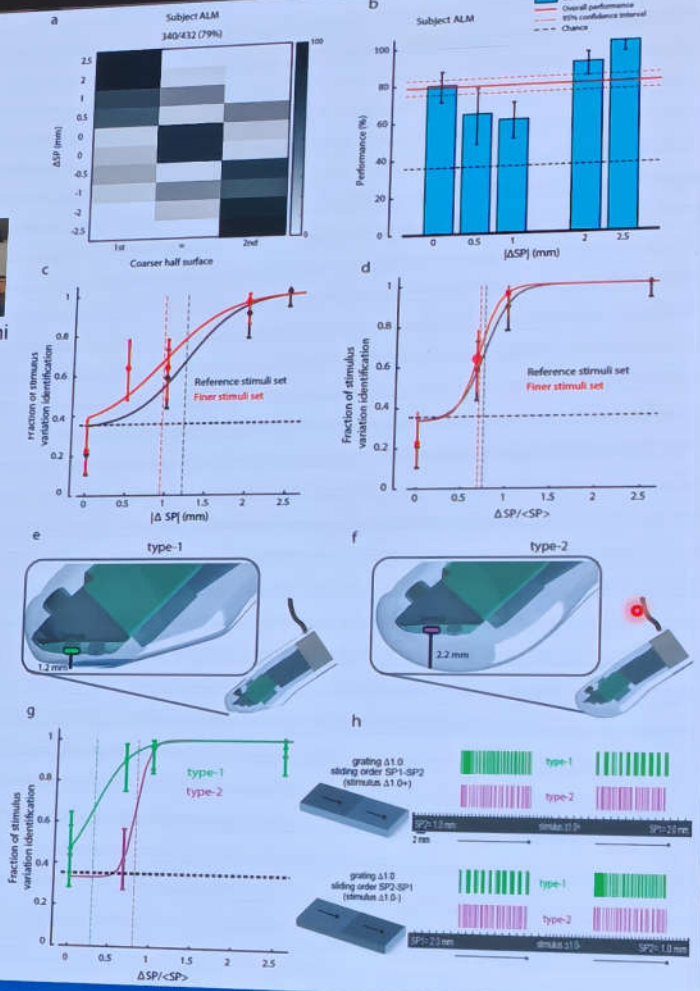
S. Micera A. Mazzoni

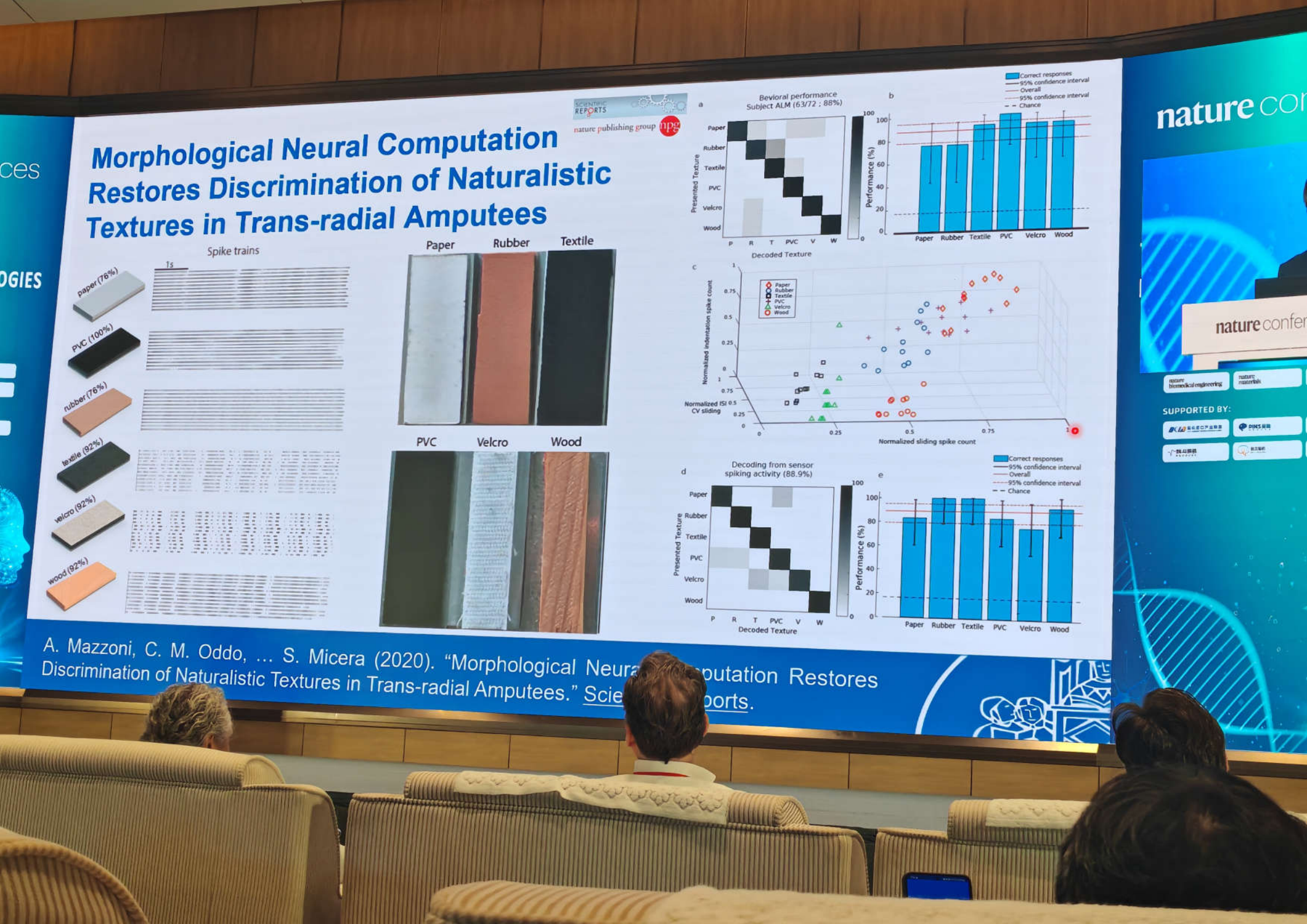








A. Mazzoni, C. M. Oddo, … S. Micera (2020). "Morphological Neural C utation Restores Discrimination of Naturalistic Textures in Trans-radial Amputees." Scienti ts.


Morphological Neural Computation Restores Discrimination of Naturalistic Textures in Trans-radial Amputees
SCIENTIFIC REPORTS
nature publishing group npg
Spike trains
1s
paper (76%)
PVC (100%)
rubber (76%)
textile (92%)
velcro (92%)
wood (92%)
Paper
Rubber
Textile
PVC
Velcro
Wood
a
Bevioral performance
Subject ALM (63/72 ; 88%)
Presented Texture
Decoded Texture
P R T PVC V W
b
Correct responses
95% confidence interval
Overall
95% confidence interval
Chance
Performance (%)
c
Normalized indentation spike count
Normalized ISI CV sliding
Normalized sliding spike count
d
Decoding from sensor spiking activity (88.9%)
e
A. Mazzoni, C. M. Oddo, … S. Micera (2020). "Morphological Neural Computation Restores Discrimination of Naturalistic Textures in Trans-radial Amputees." Scientific Reports.
nature conf
SUPPORTED BY:

How this can be applied to ICT applications?

Data compression

6 kBytes for 4s of data with traditional representation based on constant sampling frequency

16 Bytes for same data represented in neuromorphic event-driven manner

Neuromorphic event-driven representation brings all [illegible] information but without with a **tremendous scale-down of data**

Gesture-based control in telepresence with neuromorphic haptic feedback for the metaverse (operator in Italy, robot in Serbia)

In collaboration with Prof. Petar Petrovic, University of Belgrade

Farnesina
Ministero degli Affari Esteri
e della Cooperazione Internazionale

Towards multisensory telepresence in t etaverse

nature co

nature co

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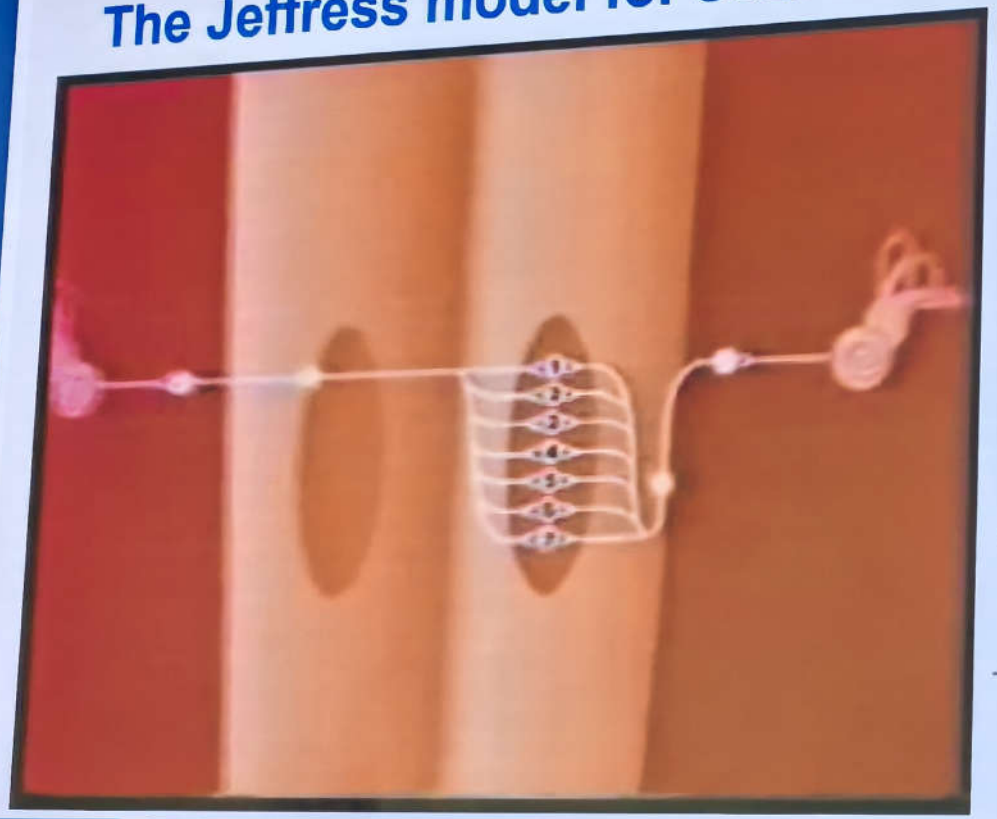
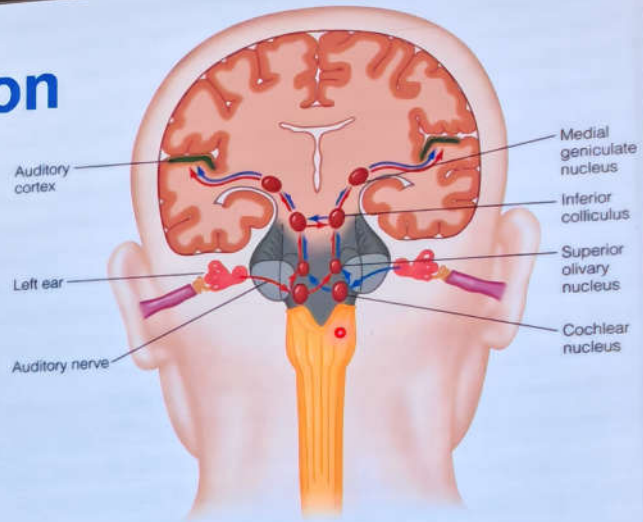
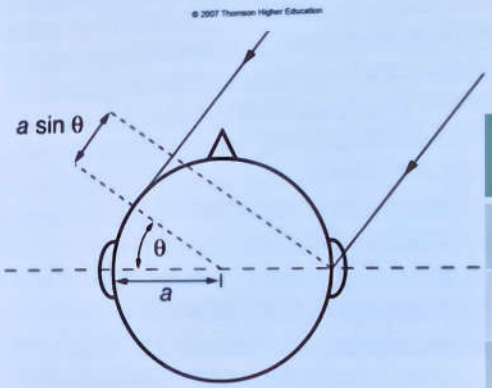
The Jeffress model for sound localization





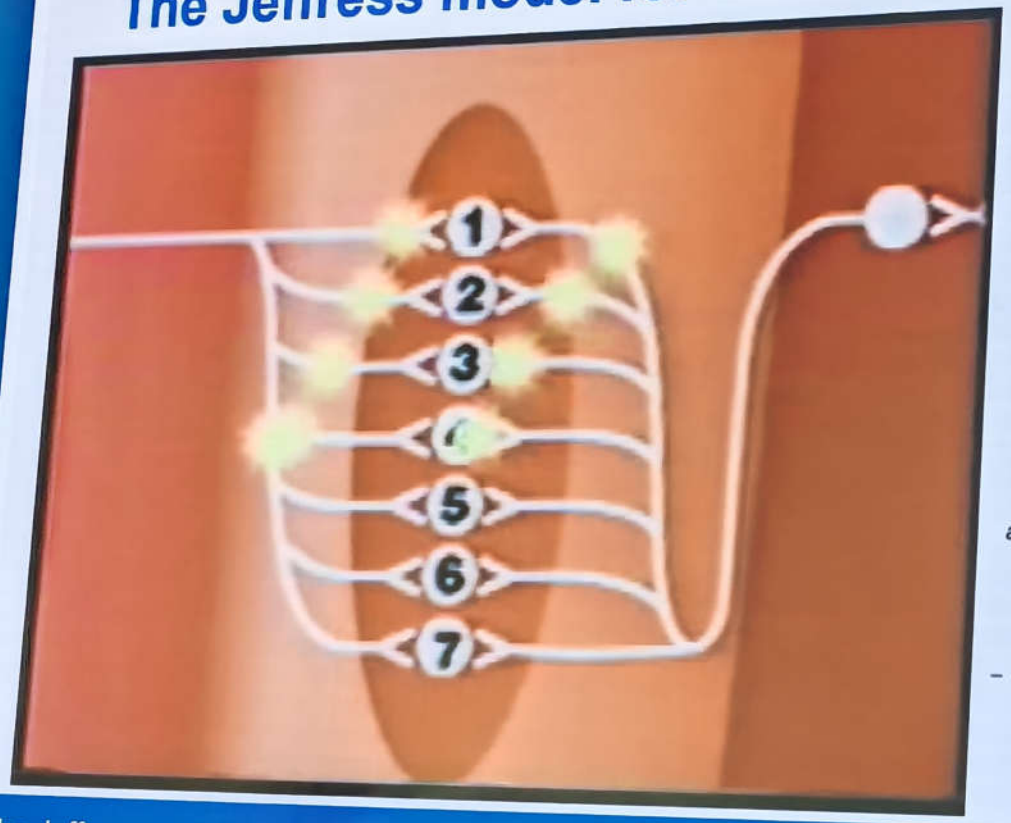


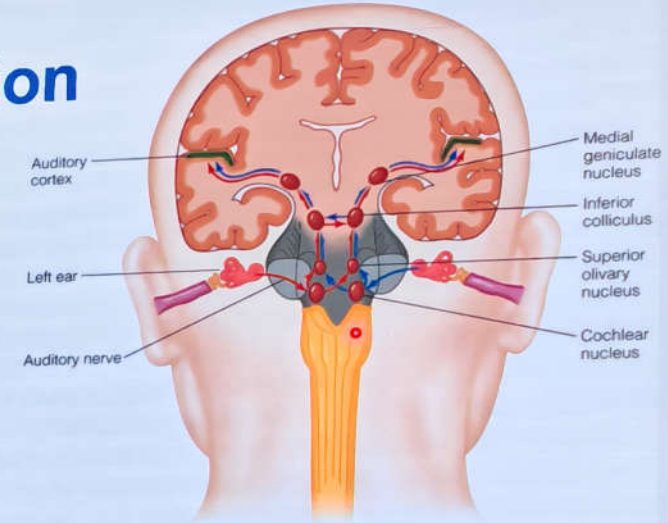
$$\tau = \left(a/c\right) 2 \sin\theta$$

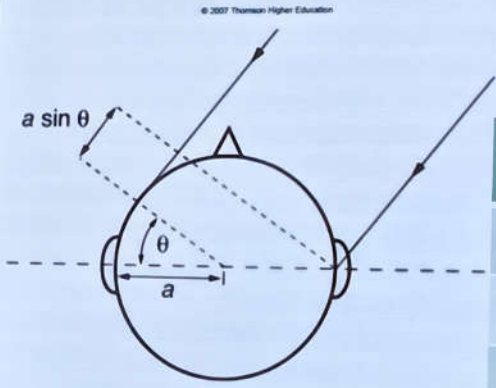
θ	τ
0°	0 μs
10°	100 μs
90°	580 μs

The Jeffress m[illegible]ased on coincidence detection of firing in the superi[illegible]y nucleus.
https://auditor[illegible]ence.com/topics/jeffress-model-animation

The Jeffress model for sound localization







$$\tau = \left(a/c\right) 2\sin\theta$$

θ	τ
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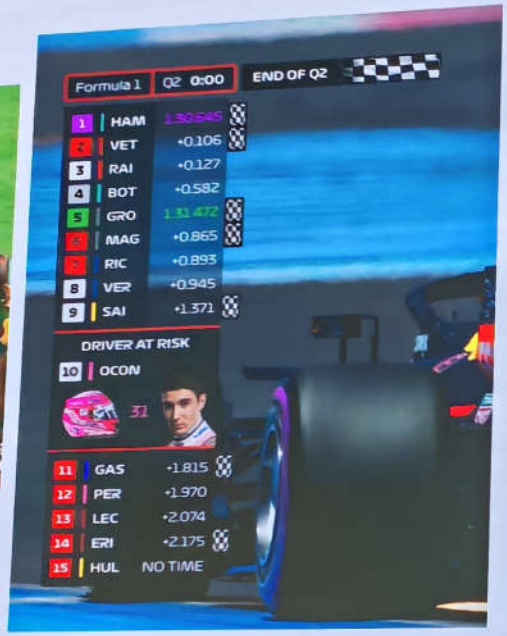
10°	100 μs
90°	580 μs

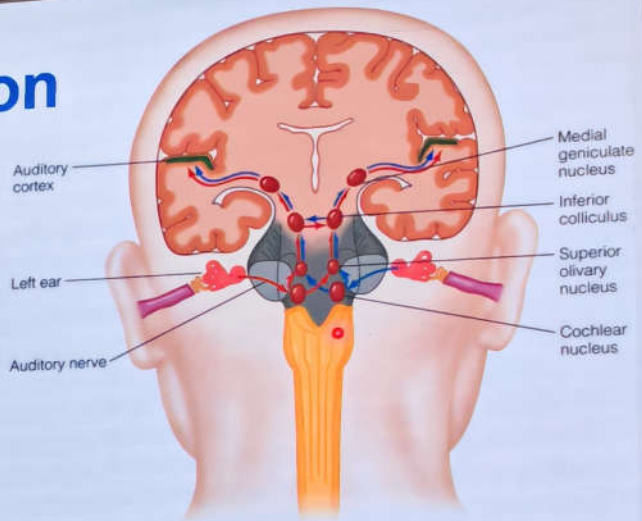
The Jeffress model is based on coincidence detection of firing in the superior nucleus.
https://auditoryneuroscience.com/topics/jeffress-model-animation

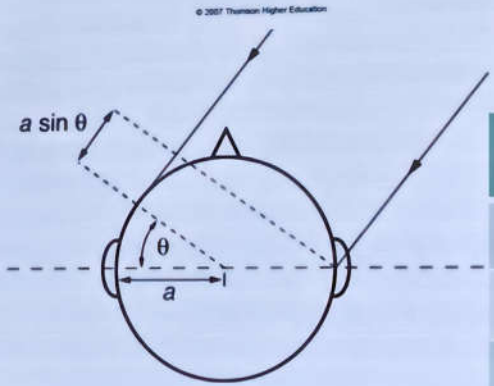
The Jeffress model for sound localization

cs resolution!



ms resolution!!





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10°	100 μs
90°	580 μs

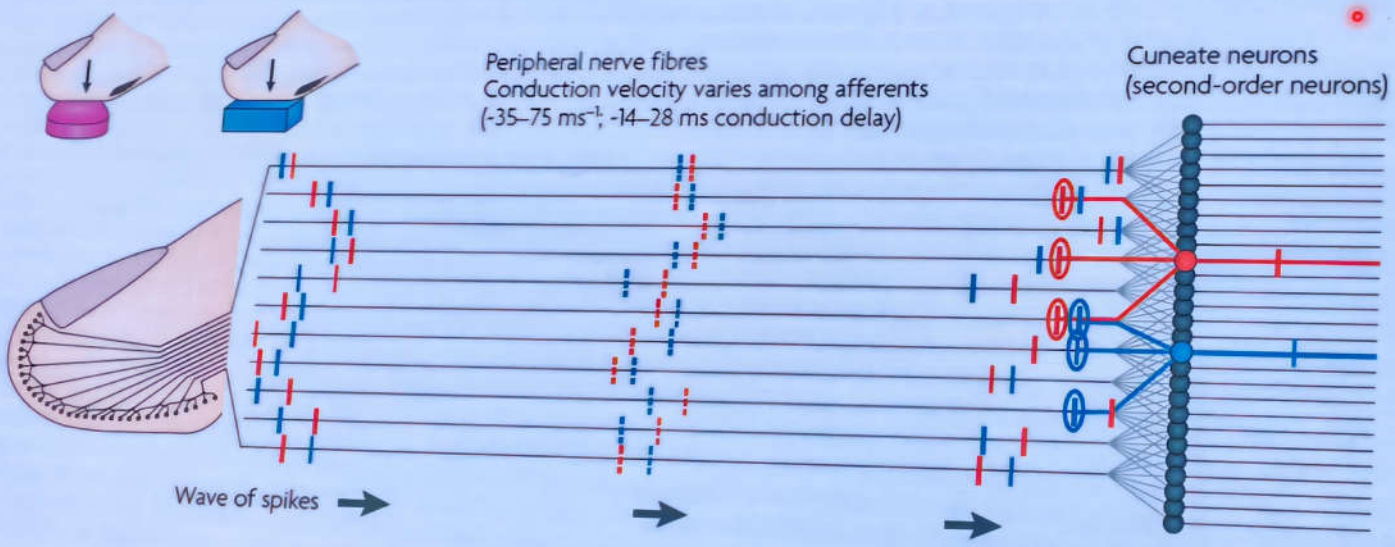
The Jeffress model is based on coincidence detection of firing in the superior [illegible] nucleus.
https://auditoryneuroscience.com/topics/jeffress-model-animation

2009

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

NATURE REVIEWS | NEUROSCIENCE

Roland S. Johansson* and J. Randall Flanagan‡



Computation "via wiring"

Distributed memory by means of differentiated delays along the afferent neural p

Neuromorphol computation

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April 10, 2024 - April 12, 2024

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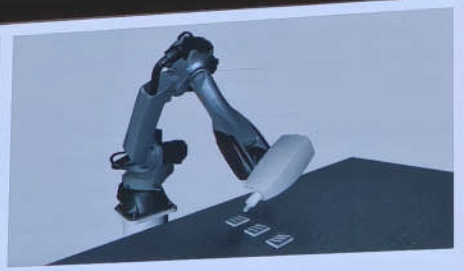
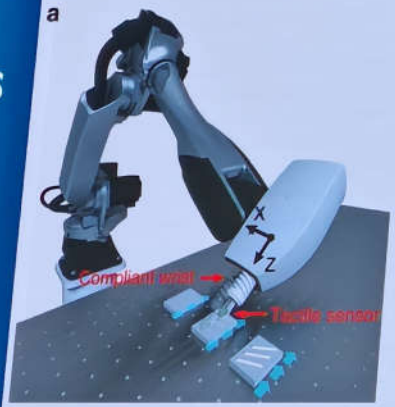
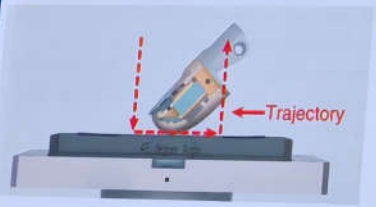
Cuneate-based model for Neuromorphic Artificial Touch

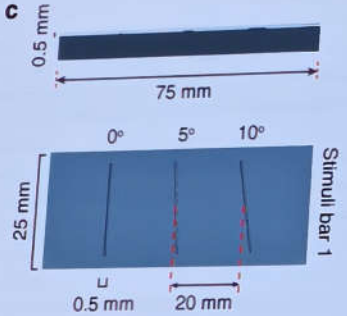


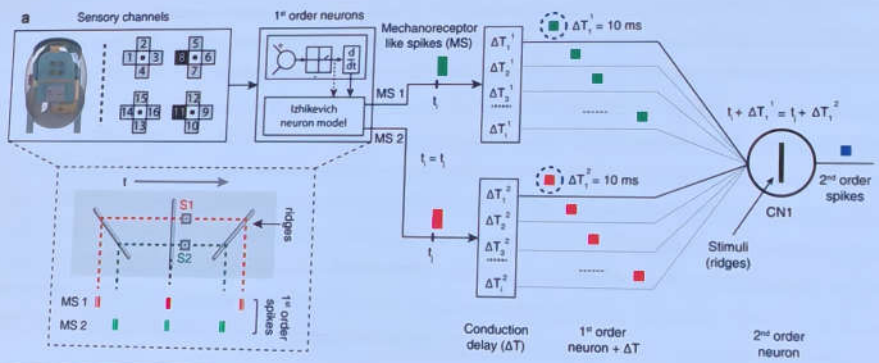
Tactile Decoding of Edge Orientation With Artificial Cuneate Neurons in Dynamic Conditions

Udaya Bhaskar Rongala[1,2], Alberto Mazzoni[1], Marcello Chiurazzi[1], Domenico Camboni[1], Mario Milazzo[1], Luca Massari[1,2], Gastone Ciuti[1], Stefano Roccella[1], Paolo Dario[1] and Calogero Maria Oddo[1*]*

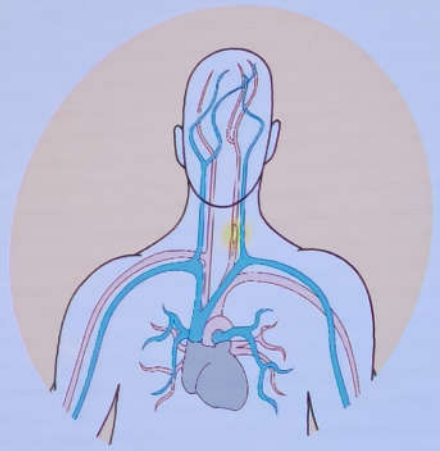






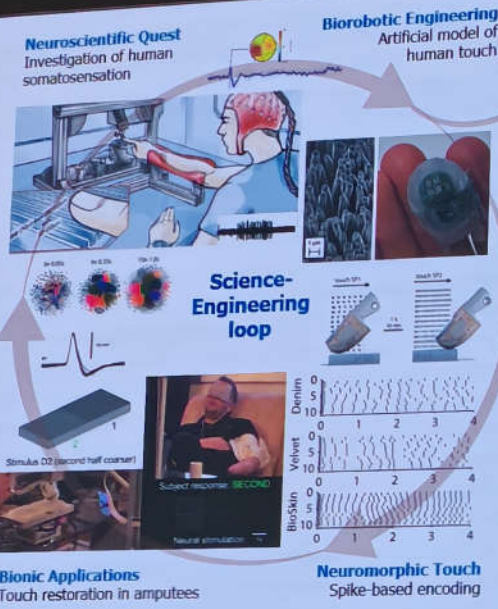


Computation via architecture, not via softwa ocessing!



Neuroscientific Quest
Investigation of human somatosensation

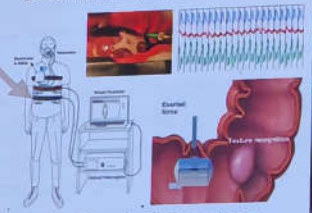
Biorobotic Engineering
Artificial model of human touch



Bionic Applications
Touch restoration in amputees

Neuromorphic Touch
Spike-based encoding

Applications in Industry 4.0 & Safety at Work
Collaborative robots and workwear



Applications in BioRobotics & Healthcare Sensors
Colonoscopes, wearable/implantable sensors for cardiorespiratory monitoring

for Collaborative-Medical Robotics & Healthcare

TOUCH SCIENCE AND ENGINEERING

Multisensory platform and AI methods for histological analyses in the metaverse

2.2 M€ secured for PoCs targeting start-up foundation

Finanziato dall'Unione europea NextGenerationEU

IMEROS 4.0 INTEGRATED MEDICAL-ROBOTIC SOLUTIONS

RoboIT Il Polo Nazionale di Trasferimento Tecnologico della Robotica

Framework for digital pathology to innovate traditional procedures

F. Auletta

Traditional procedure

Touch

Vision

Manual palpation

Identification of the area to sample

Tissue severing and preparation

Novel procedure

Touch

Ultrasound

Vision

Robotic analysis

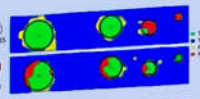
Local or remote identification of the area to sample

Sample elaboration

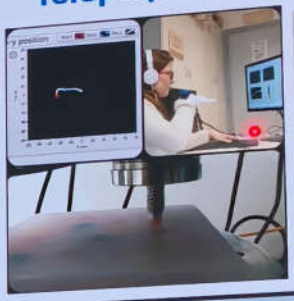
Medical report and feedback

Additional data and feedback

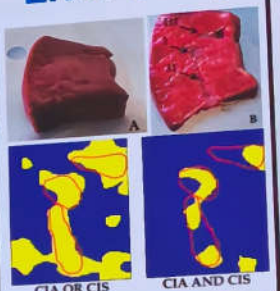
Phantom study



Telepalpation



Liver study



Regione Toscana

FAS Fondo Aree Sottoutilizzate 2007-2013

JUMP

Joint Universities programM for Poc

Sant'Anna Scuola Normale Superiore

Università degli Studi di Palermo

Initiative by: cdp

Together with: pariter partners

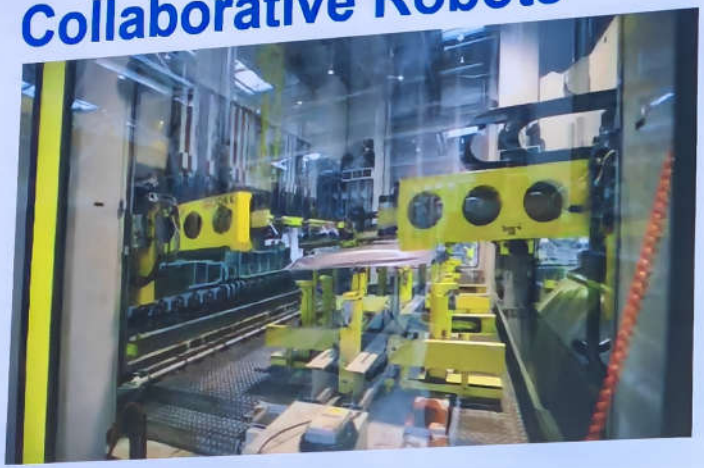
Scientific Promoters: iit, Sant'Anna, Università di Verona, Università degli Studi di Napoli Federico II

Institutional Partner: Filse

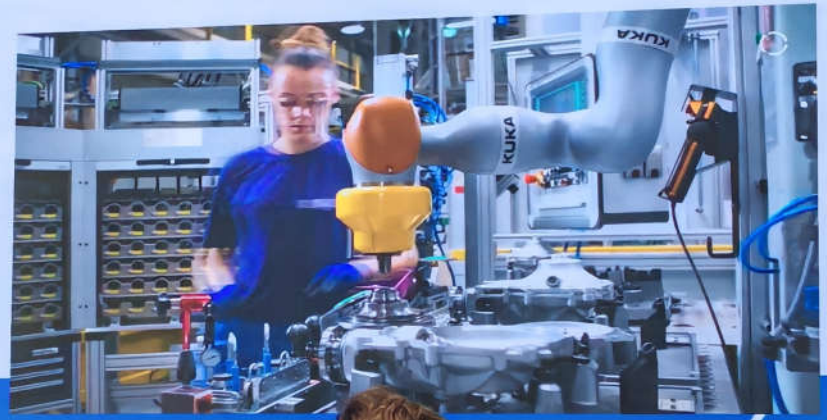
Corporate Partner: Leonardo

cdp Nazionale Tecnologico

Collaborative Robots

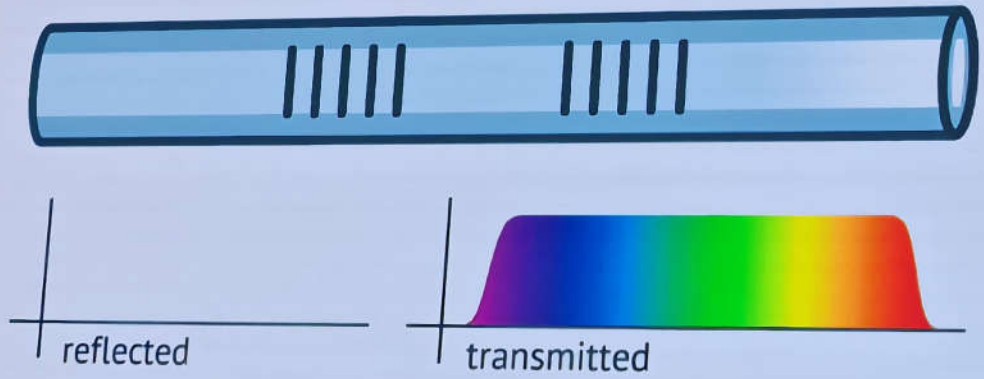


Past robots used to operate inside closed **cages** and kept **separated** from workers, namely within different areas. **Future** collaborative robots, instead, will share **common spaces** with workers, the robot will become a **work-mate** and will not be anymore a potential replacement.



Future: Collaborative Robots

Fiber Bragg Grating sensors



- Low wiring encumbrance
- Immunity to EM
- High sensitivity
- Multiplexing

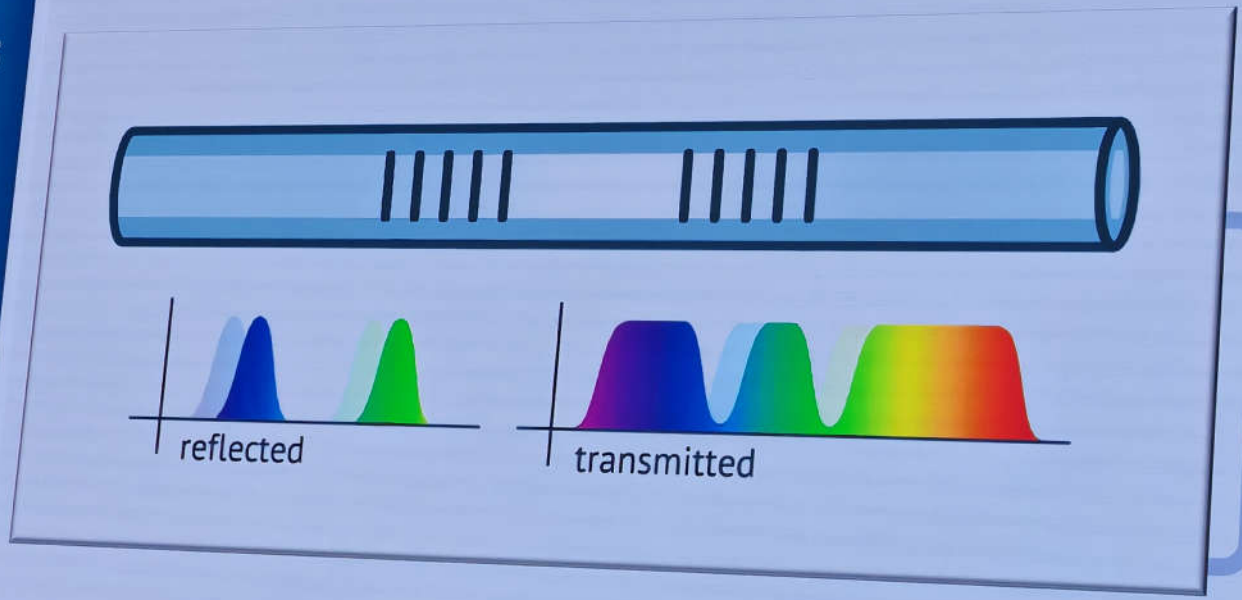
Animation source: https://fiseq...m/fbg-sensors/

re conferences

henzhen, China

MATIVE TECHNOLOGIES
DENGINEERING

Fiber Bragg Grating sensors



Low wiring encumbrance

Immunity to EM

High sensitivity

Multiplexing

Animation source: https://fisens.com/fbg-sensors/

202

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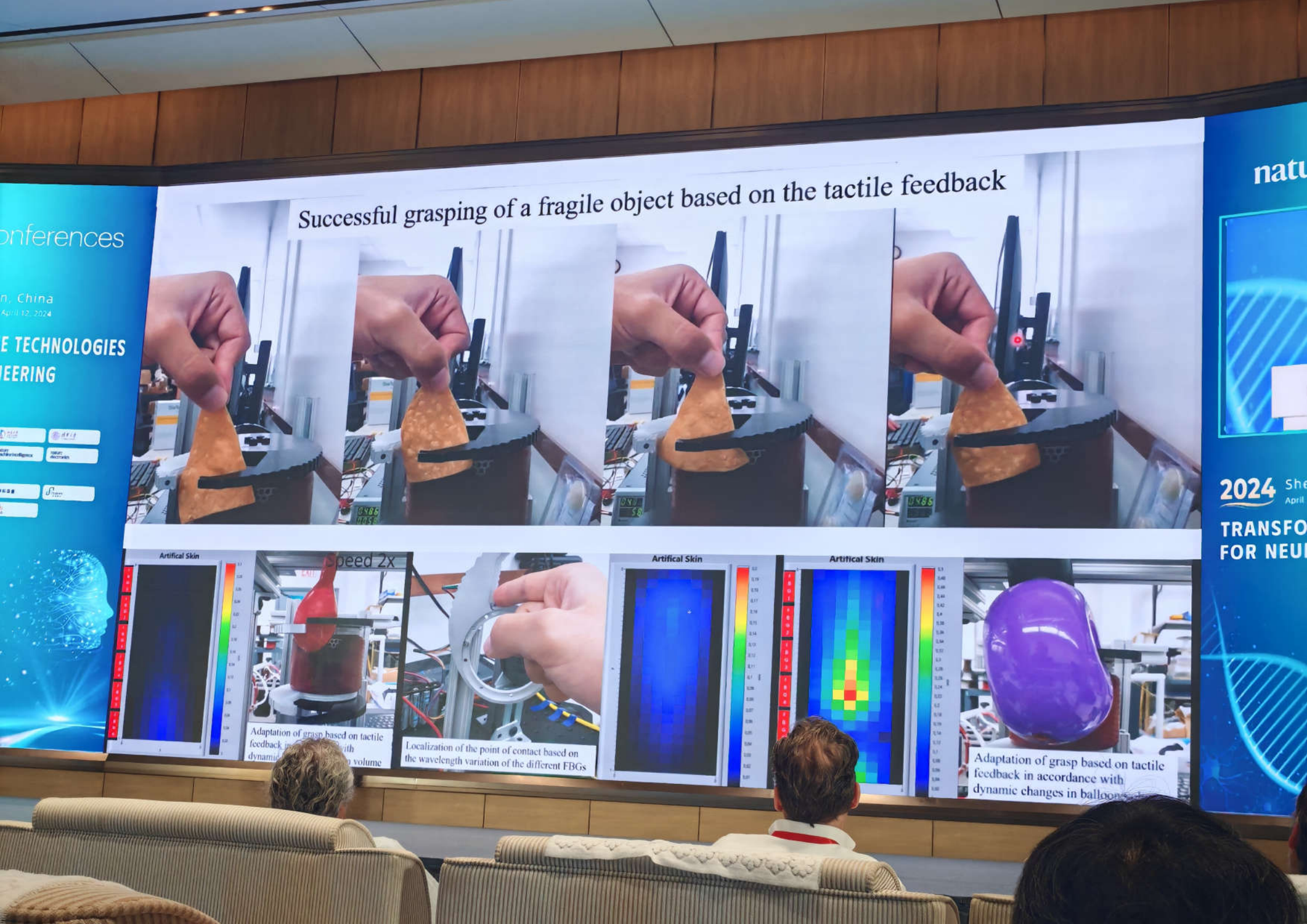
FOR


Successful grasping of a fragile object based on the tactile feedback
Artifical Skin
Speed 2x
Adaptation of grasp based on tactile feedback
Localization of the point of contact based on the wavelength variation of the different FBGs
Artifical Skin
Artifical Skin
Adaptation of grasp based on tactile feedback in accordance with dynamic changes in balloon
onferences
n, China
E TECHNOLOGIES
IEERING
2024
TRANSFO
FOR NEU

The Artificial Skin

M. Filosa

EINST4INE

TUNE

BEAM

nature machine intelligence

ARTICLES

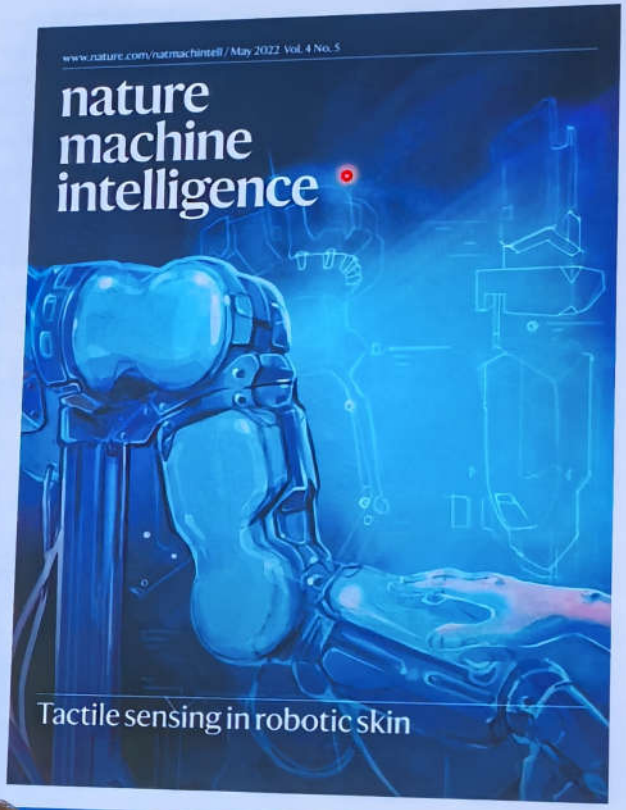
https://doi.org/10.1038/s42256-022-00487-3

Check for updates

OPEN

Functional mimicry of Ruffini receptors with fibre Bragg gratings and deep neural networks enables a bio-inspired large-area tactile-sensitive skin

Luca Massari[1,2,3,8], Giulia Fransvea[1,2,4,5,8], Jessica D'Abbraccio[1,2], Mariangela Filosa[1,2,3], Giuseppe Terruso[1,2,3], Andrea Aliperta[1,2,5], Giacomo D'Alesio[1,2], Martina Zaltieri[1,2,3,4,6], Emiliano Schena[6], Eduardo Palermo[4], Edoardo Sinibaldi[7]✉ and Calogero Maria Oddo[1,2]✉



Massari, L., Fransvea, G., D'Abbraccio, J., Filosa, M., Terruso, G., Aliperta, A., ... & Oddo, C. M. (20 tional mimicry of Ruffini receptors with Fiber Bragg Gratings and Deep Neural Networks enables a bio-inspired large e sensitive skin. Nature Machine Intelli 22

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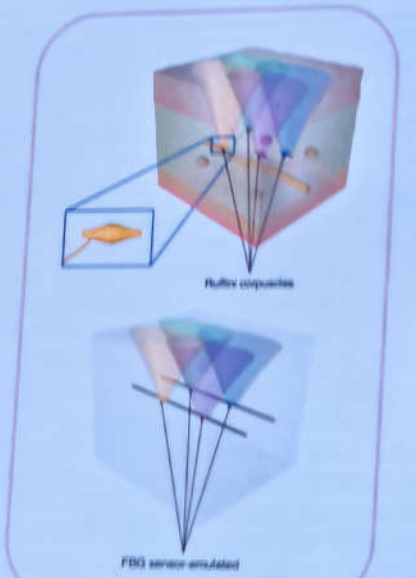
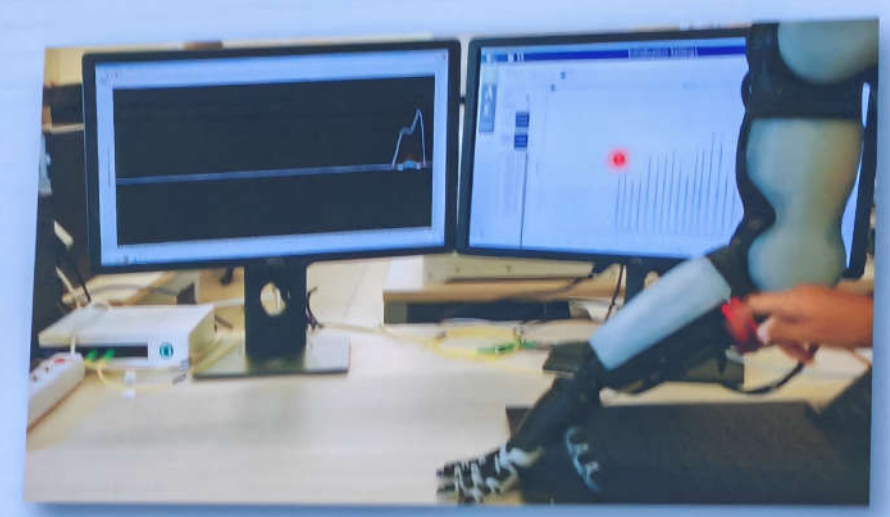
Functional mimicry of Ruffini receptors with Fiber Bragg Gratings





Distributed Sensors

Soft One/few wire/s

Large Area Lightweight

ri, L., Fransvea, G., D'Abbraccio, J., Filosa, M., Terruso, G., Aliperta, A., ... & Oddo, C. M. (20 ional mimicry of
receptors with Fiber B atings and Deep Neural Networks enables a bio-inspired large e sensitive skin.
Machine Intelligenc

nature conferen

2024 Shenzhen, China

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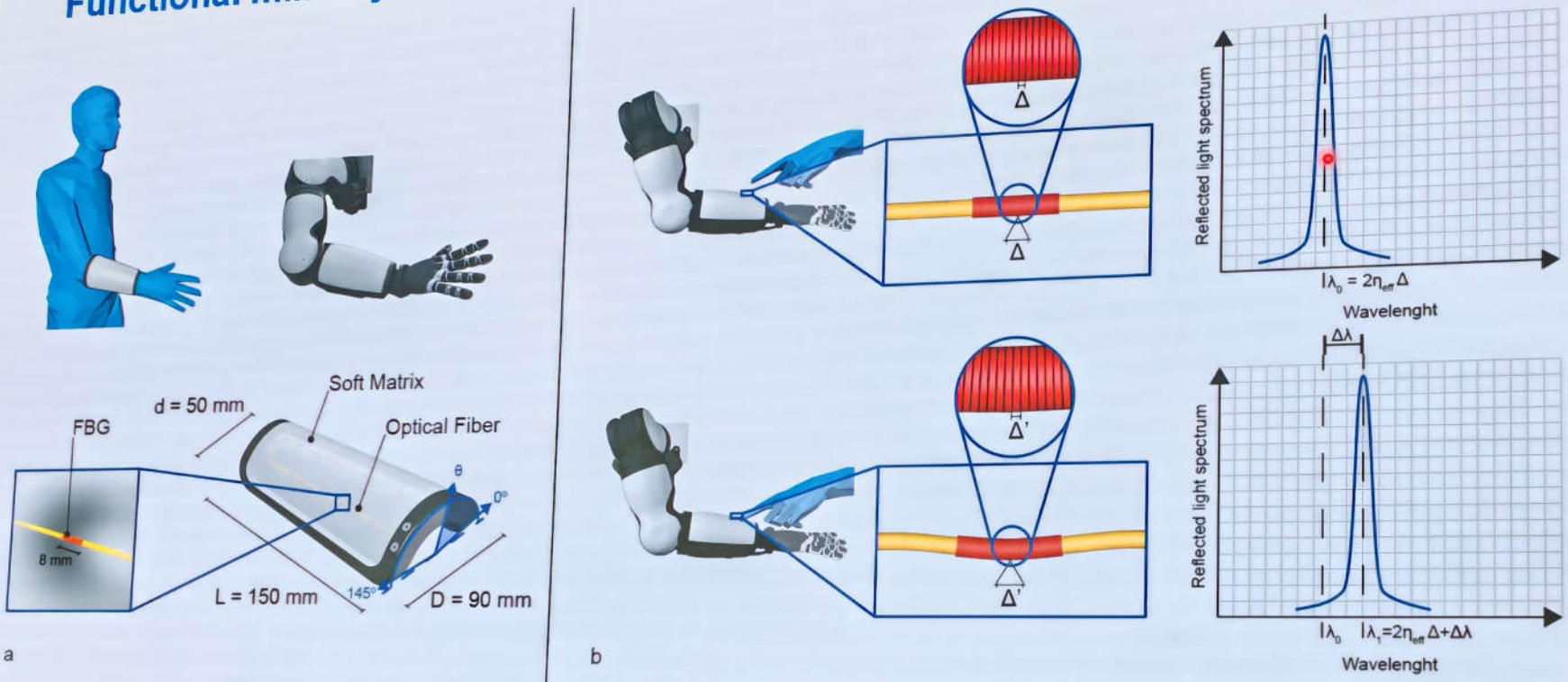
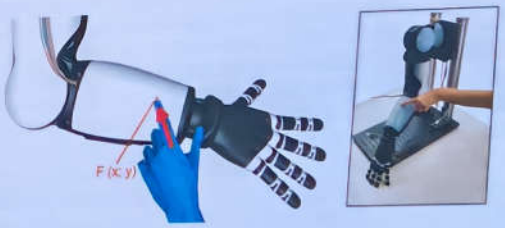
Functional mimicry of Ruffini receptors with Fiber Bragg Gratings

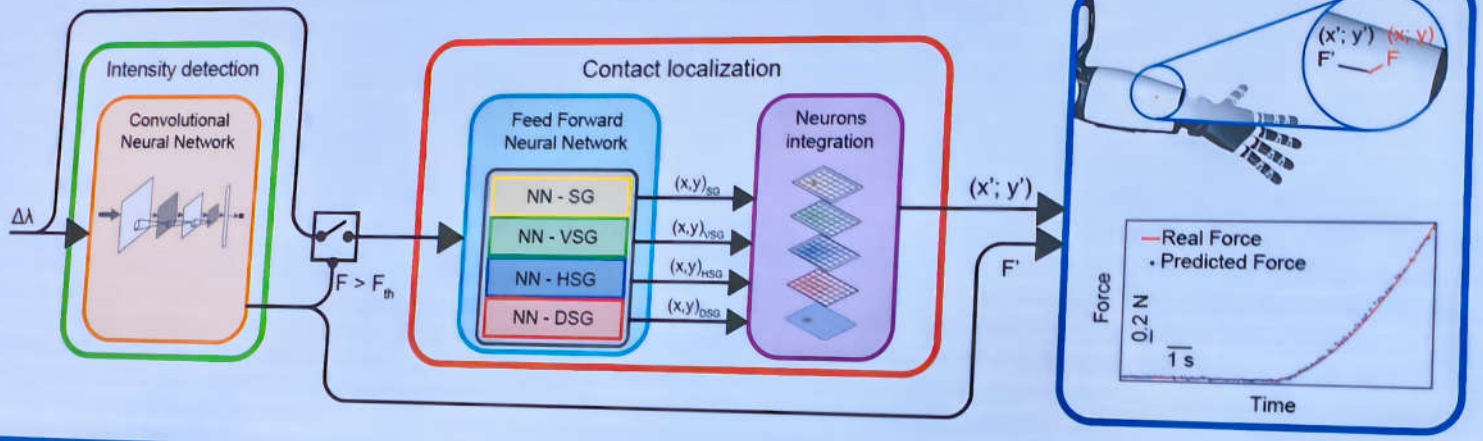


Massari, L., Fransvea, G., D'Abbraccio, J., Filosa, M., Terruso, G., Aliperta, A., ... & Oddo, C. M. (20 tional mimicry of Ruffini receptors with Fiber Bragg Gratings and Deep Neural Networks enables a bio-inspired larg le sensitive skin. Nature Machine Intelligence 2022

Functional mimicry of Ruffini receptors with Fiber Bragg Gratings
Large area force sensing and contact location: AI model



Touch-based decoding of the applied force and contact localization



Massari, L., Fransvea, G., D'Abbraccio, J., Filosa, M., Terruso, G., Aliperta, A., ... & Oddo, C. M. (20 tional mimicry of Ruffini receptors with Fiber Bragg Gratings and Deep Neural Networks enables a bio-inspired larg le sensitive skin. Nature Machine Intelligen

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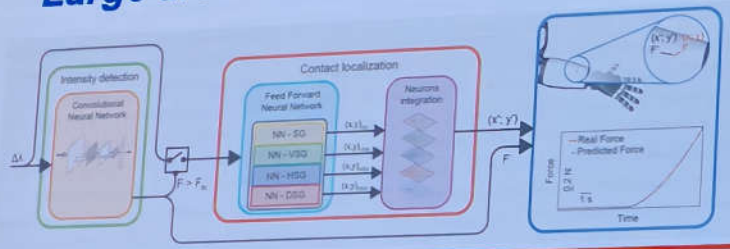
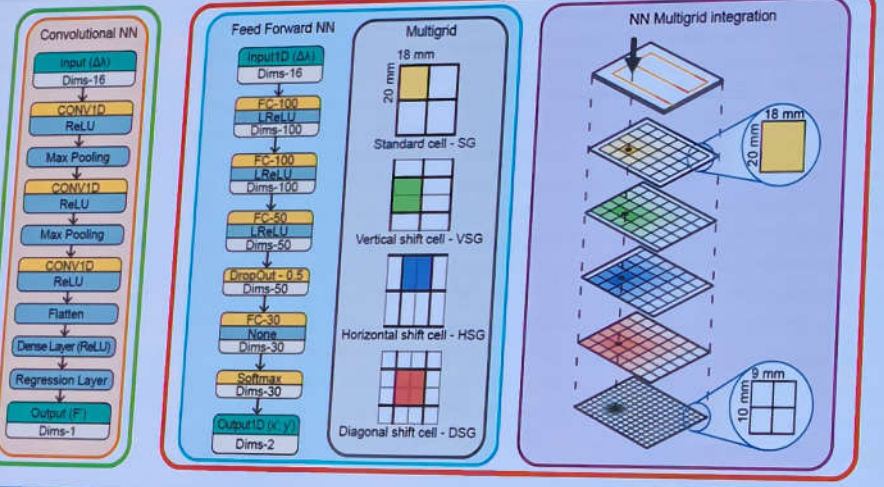
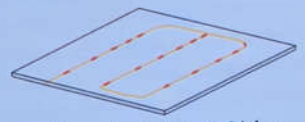
Functional mimicry of Ruffini receptors with Fiber Bragg Gratings
Large area force sensing and contact location: AI model

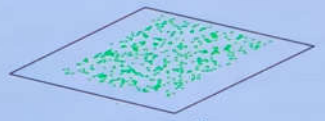




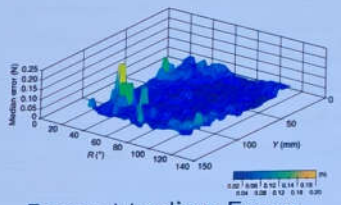
RESULTS



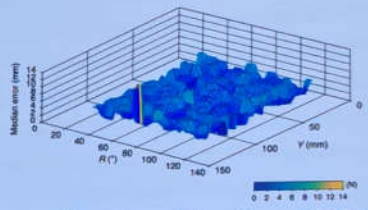
Flatten Artificial Skin



Indentations



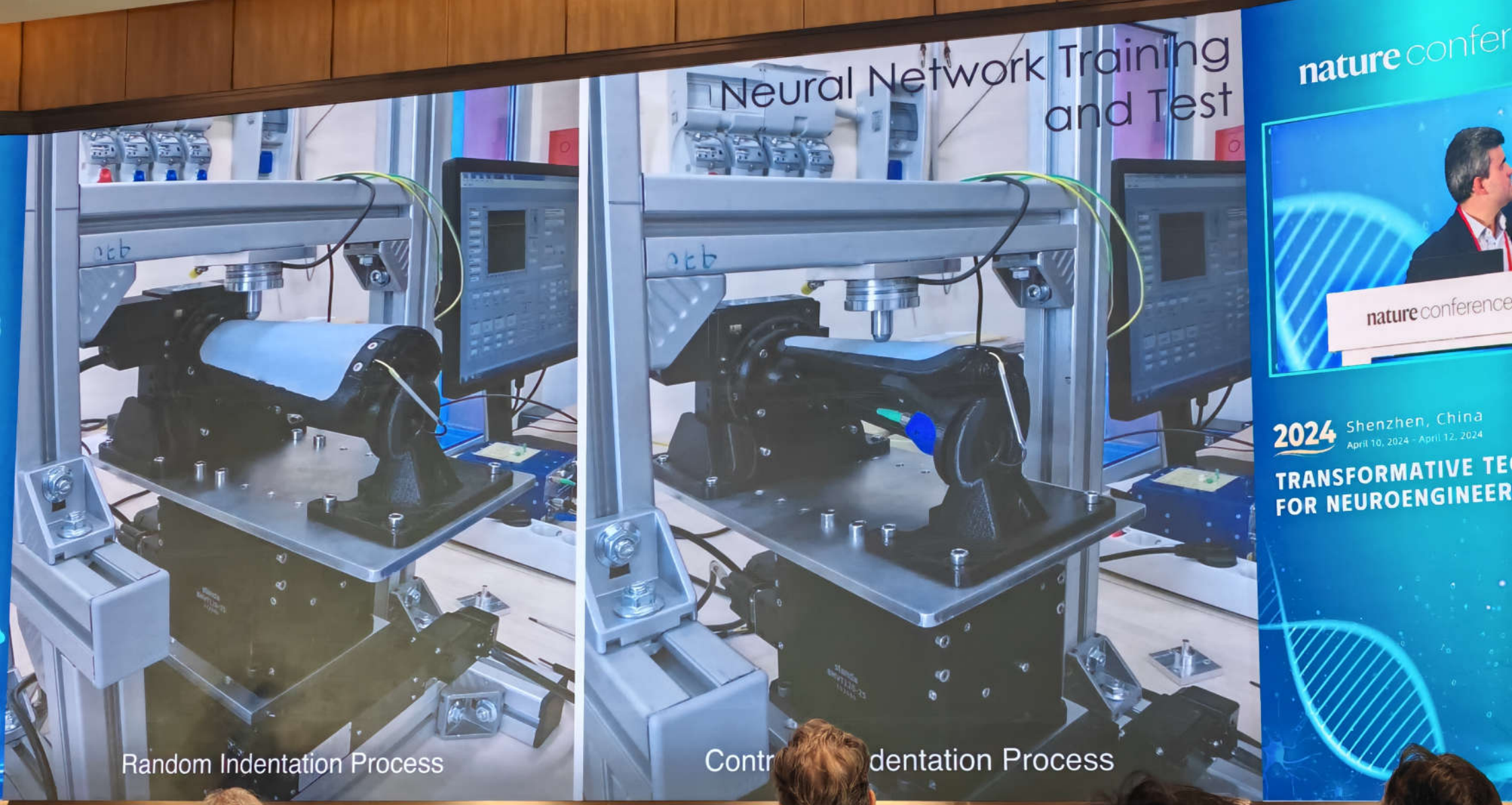
Force Median Errors



Localization Median Errors

Task		Error	
		Median	IQR
Intensity detection	NN - CNN	35 mN	56 mN
Contact localization	NN - SG	12.6 mm	7.5 mm
	NN - VSG	8.4 mm	4.6 mm
	NN - HSG	10.8 mm	8.9 mm
	NN - DSG	6.1 mm	4.2 mm
	Neuron integration	3.2 mm	2.3 mm

Massari, L., Fransvea, G., D'Abbraccio, J., Filosa, M., Terruso, G., Aliperta, A., ... & Oddo, C. M. (202 ctional mimicry of Ruffini receptors with Fiber Bragg Gratings and Deep Neural Networks enables a bio-inspired larg le sensitive skin. Nature Machine Intelligence 2022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Random Indentation Process
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LOAD CELL
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ARTIFICIAL SKIN
MECHATRONIC PLATFORM
Predicted signal
Real Signal
Y [mm]
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controlled indentations
Predicted signal
Real Signal
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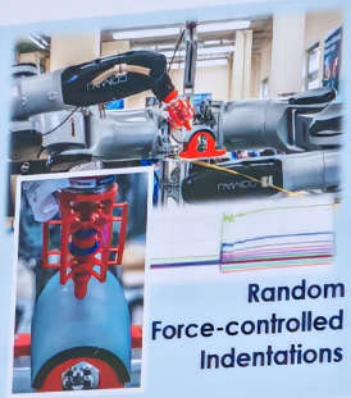
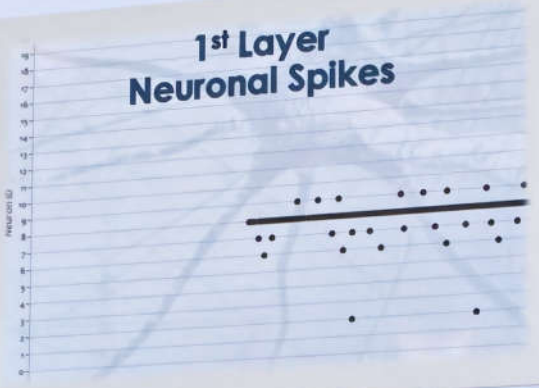
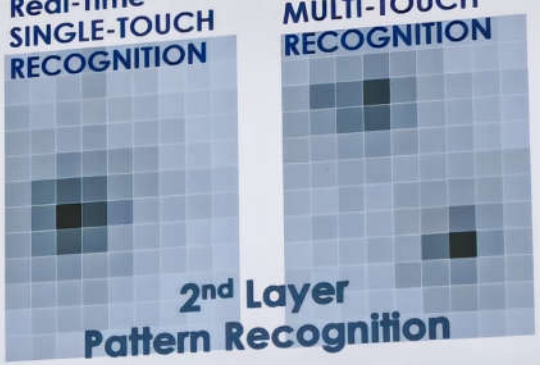
Ongoing: Cuneate-based Decoding for Neuromorphic Large-Area Touch Sensing

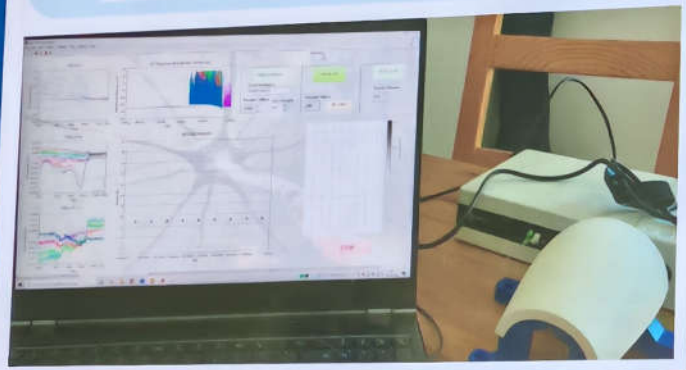
M. Filosa

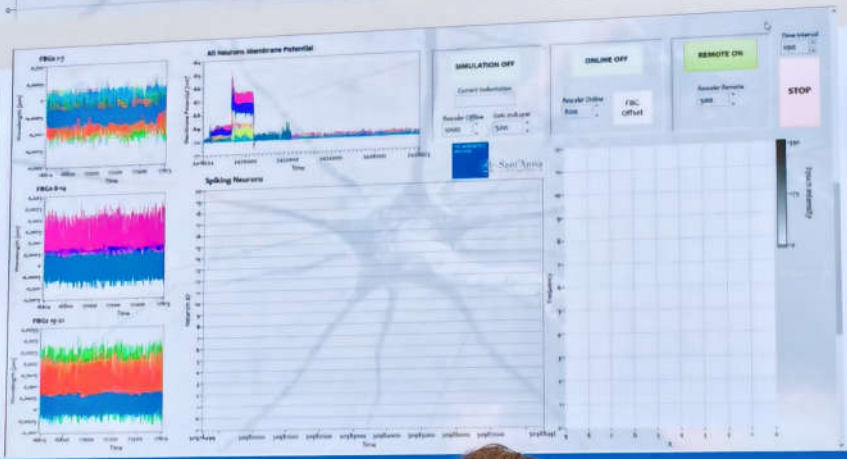


Random
Force-controlled
Indentations

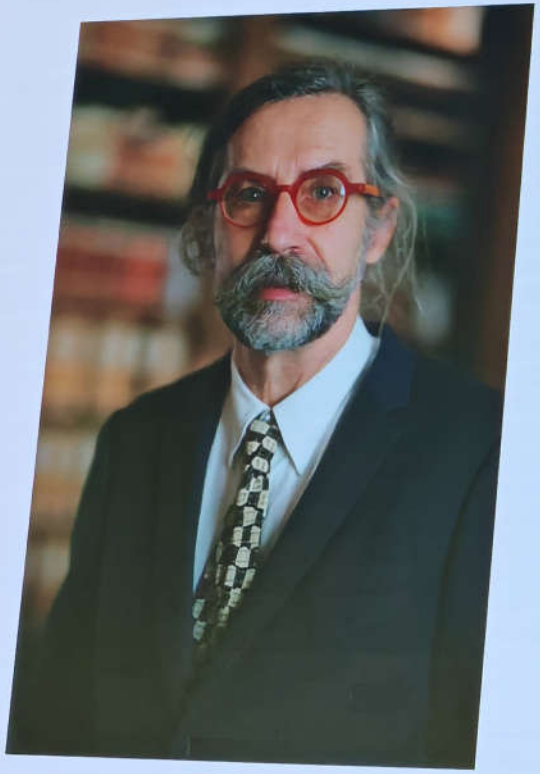








M. Filosa et al., Live demo at IEEE Sensors Conference
Unpublished results



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