Remote Haptic Telepresence and Telemanipulation with Robotic Exoskeletons

Antonio Frisoli

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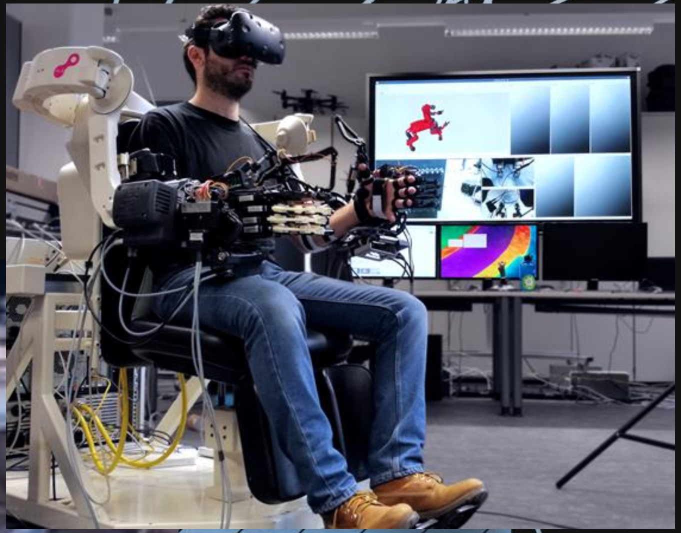
ISTITUTO DI INTELLIGENZA MECCANICA

Sant'Anna Scuola Universitaria Superiore Pisa

HRI Human Robot Interaction

SANT'ANNA SCHOOL OF ADVANCED STUDIES PISA



THE Tuscany Health Ecosystem

Finanziato dall'Unione europea NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

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HRI Human Robot Interaction @

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THE Tuscany Health Ecosystem

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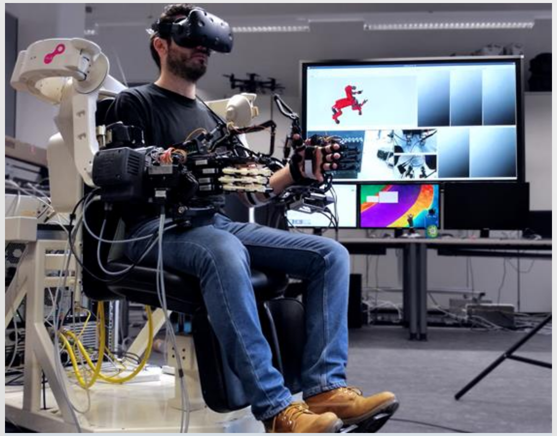
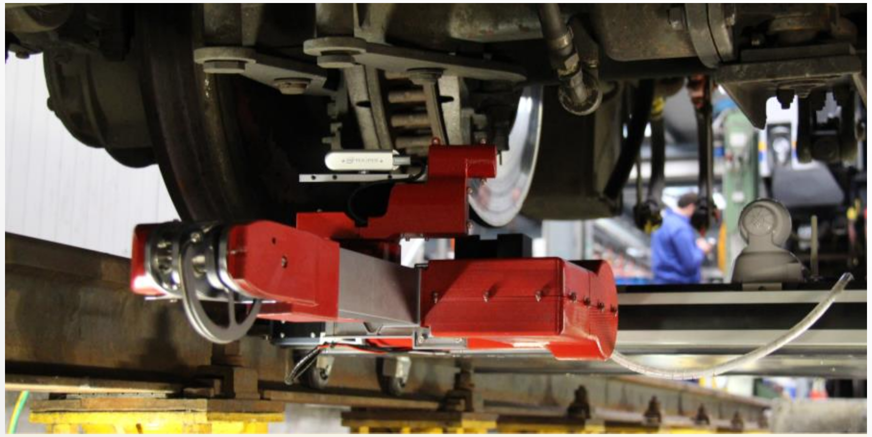
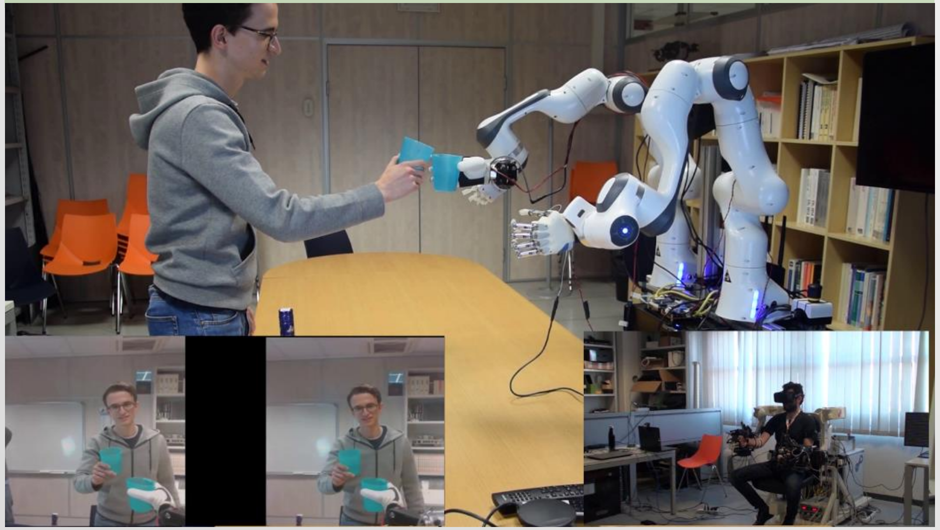


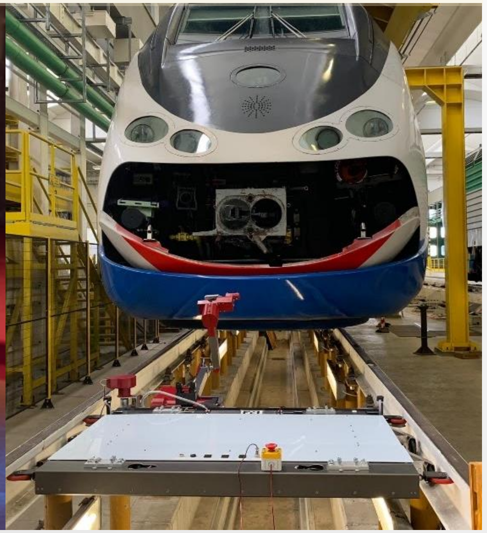


Wearable Robotics

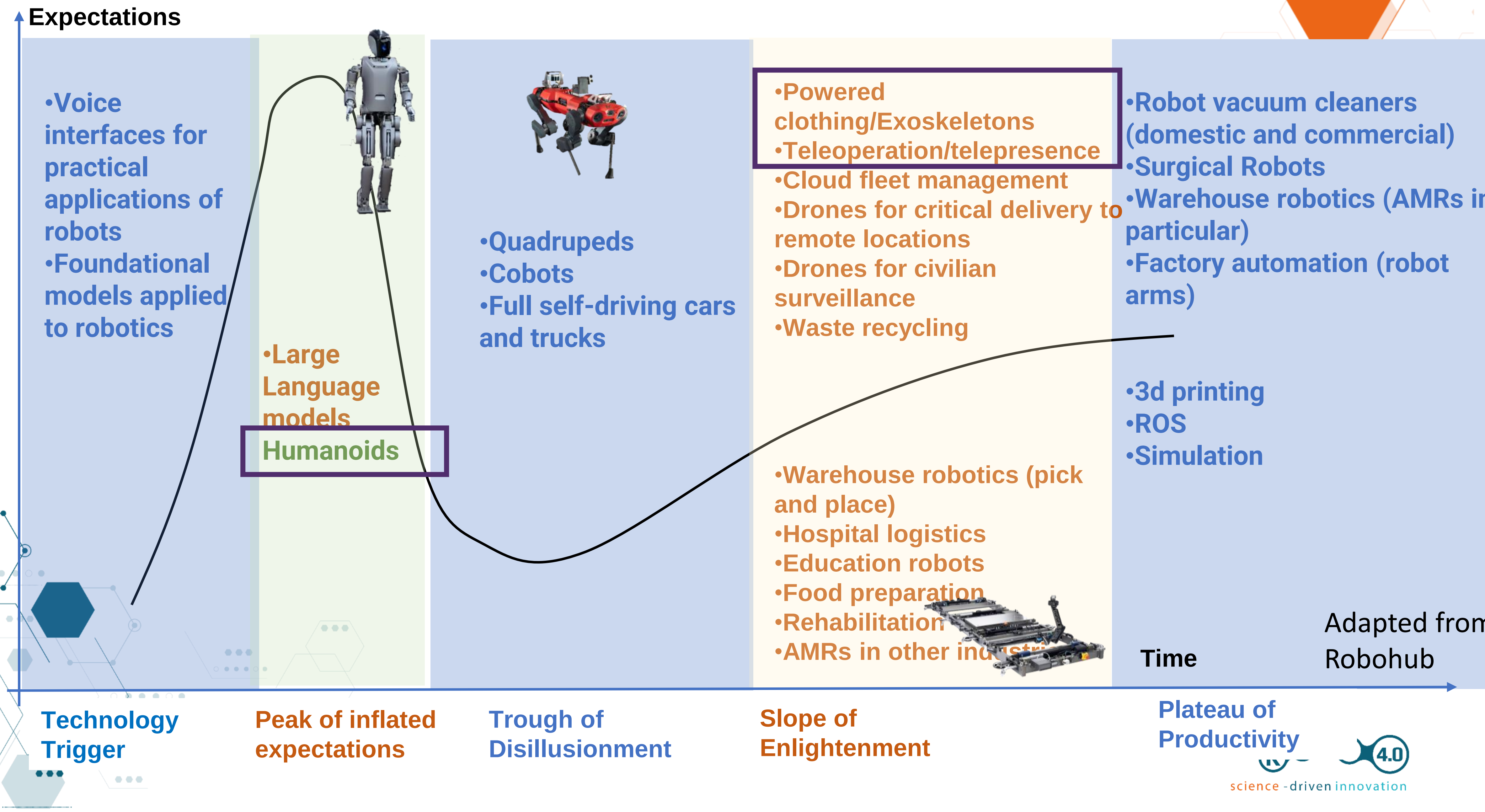
Telerobotics and Collaborative Robotics

Mobile and Inspection Robotics





The Hype Cycle in robotics

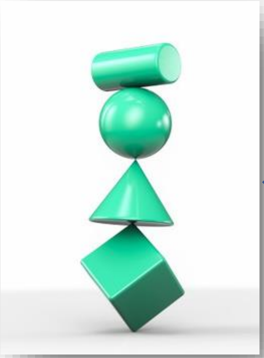


Exoskeleton as haptic interface for Telepresence/Teleoperation

Current challenges in telerobotics

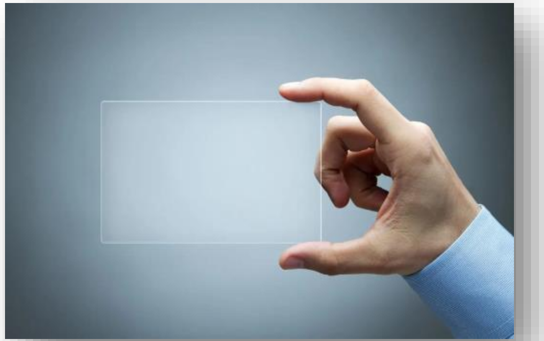
- Restitution of high fidelity haptic feedback
- Dexterous manipulation
- Remote context aware of environment
- Haptic stability and transparency in bilateral teleoperation

Stability and Transparency



STABILITY

COMPETITING TARGETS



TRANSPARENCY

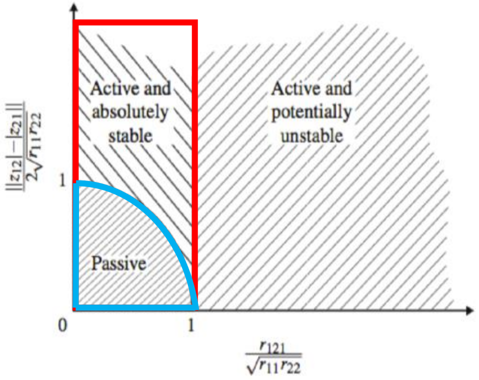
HUMAN ⇄ HAPTIC INTERFACE ⇄ COMMUNICATION CHANNEL ⇄ REMOTE AVATAR ⇄ REMOTE ENVIRONMENT

REQUIRES STABILIZATION METHODS DUE

- Discretization (Quantization, Sampling)
- Time-Delay (constant or variable)

PASSIVITY BASED APPROACHES:

- Scattering theory (Anderson et al. 1989)
- Wave variables (Niemeyer et al. 1991)
- TDPA (Hannaford, Ryu et al. 2002)



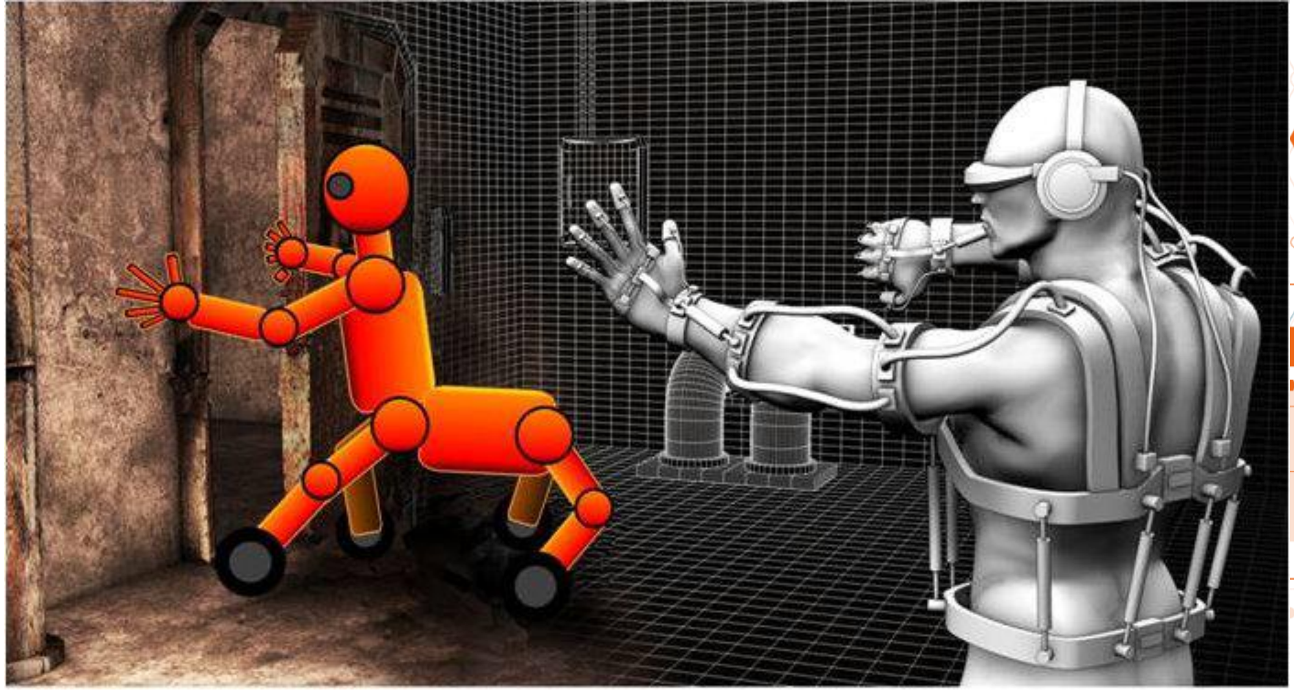
PASSIVITY → $E(t) \geq 0 \ \forall t \geq 0$

$\Downarrow \ \not\Uparrow$

STABILITY

Moreover:

- Easy to be verified in network blocks
- A composition of passive network blocks is still passive



Hand teleoperation control

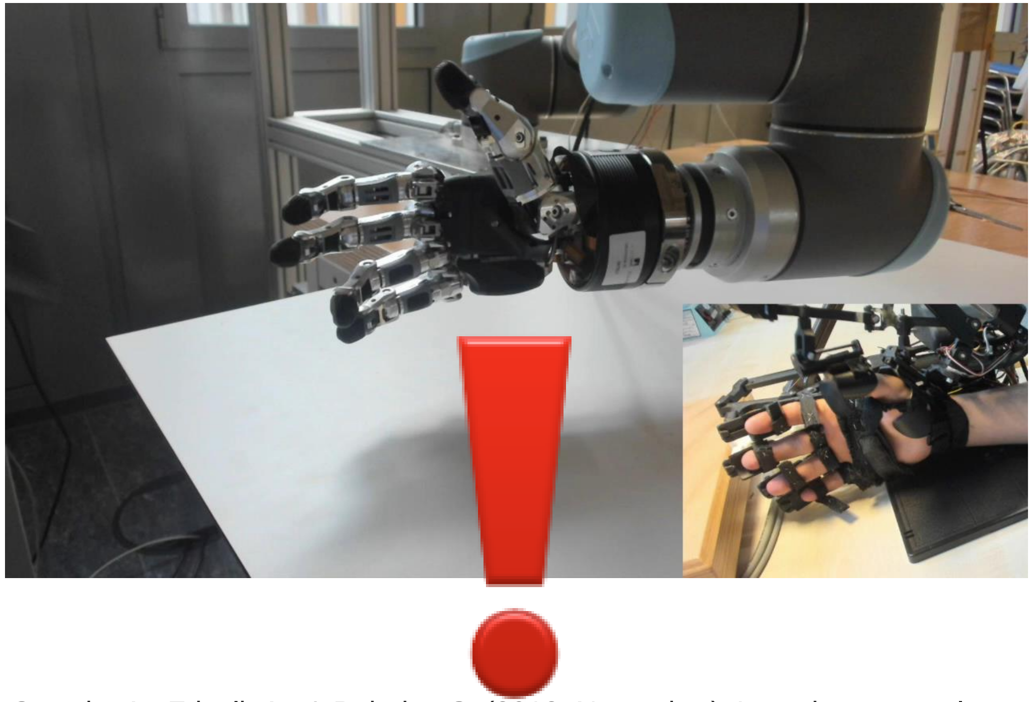
ARTES 4.0
science -driven innovation

Kinematic Mapping

BACKWARD
from Schunk Hand motor currents to exoskeleton force commands

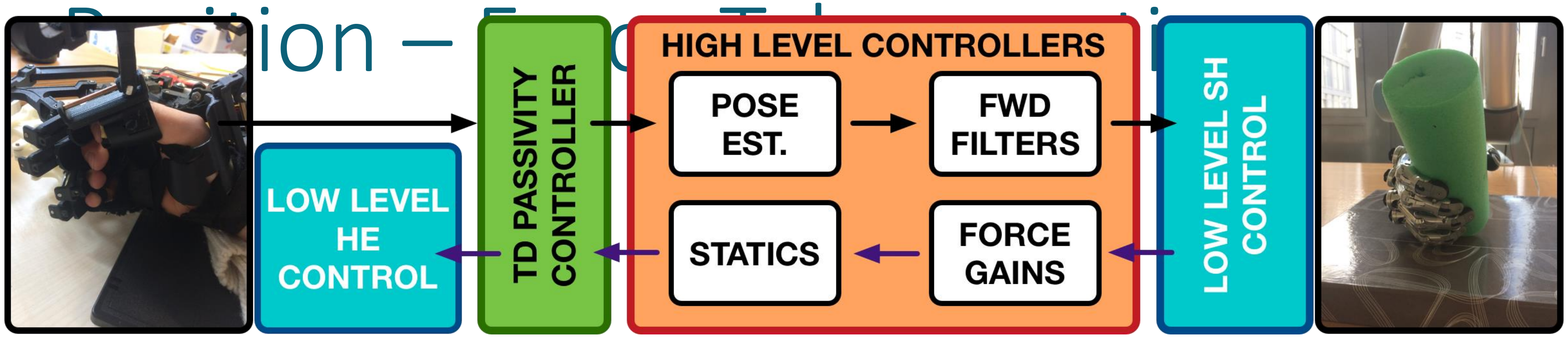
FORWARD
from operator joint angles to Schunk Hand position commands

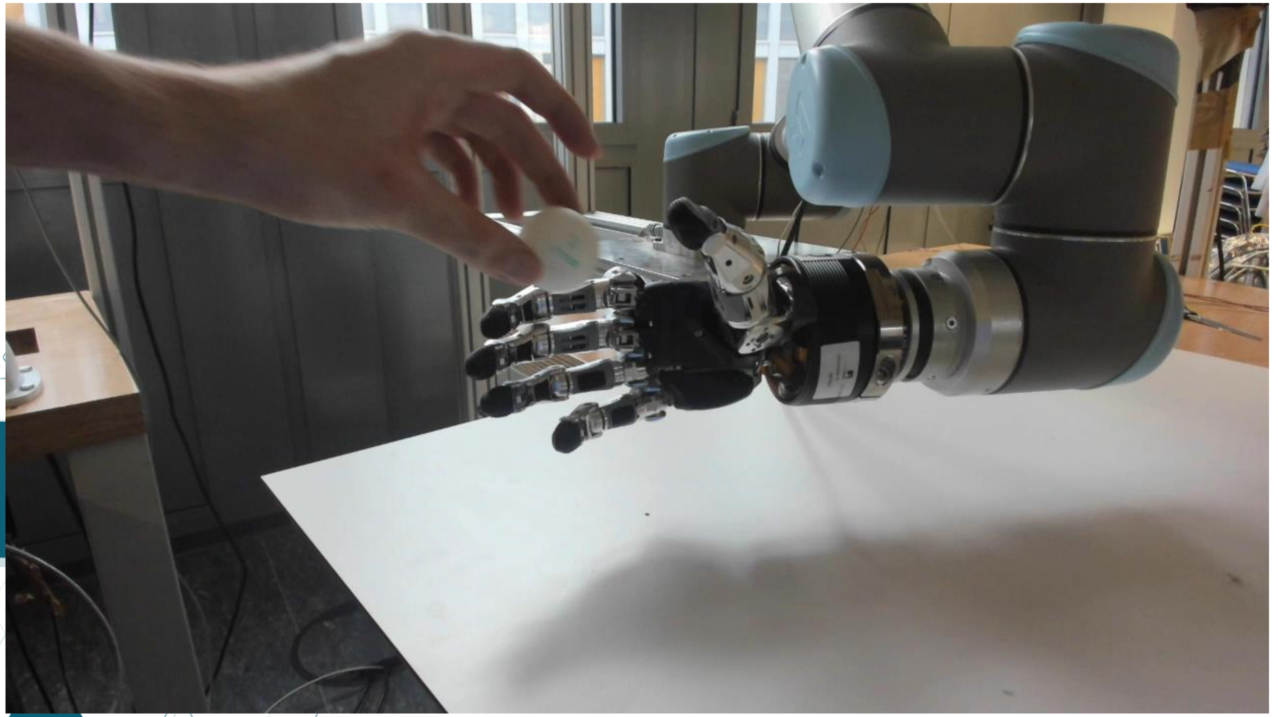
Unknown Schunk Hand dynamic model

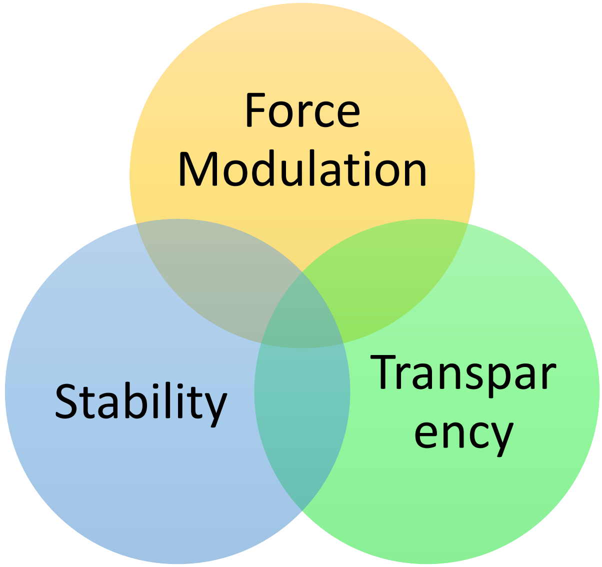


No complete kinematic simmetry

Rodriguez, D., Di Guardo, A., Frisoli, A., & Behnke, S. (2018, November). Learning postural synergies for categorical grasping through shape space registration. In *2018 IEEE-RAS 18th International Conference on Humanoid Robots (Humanoids)* (pp. 270-276). IEEE.







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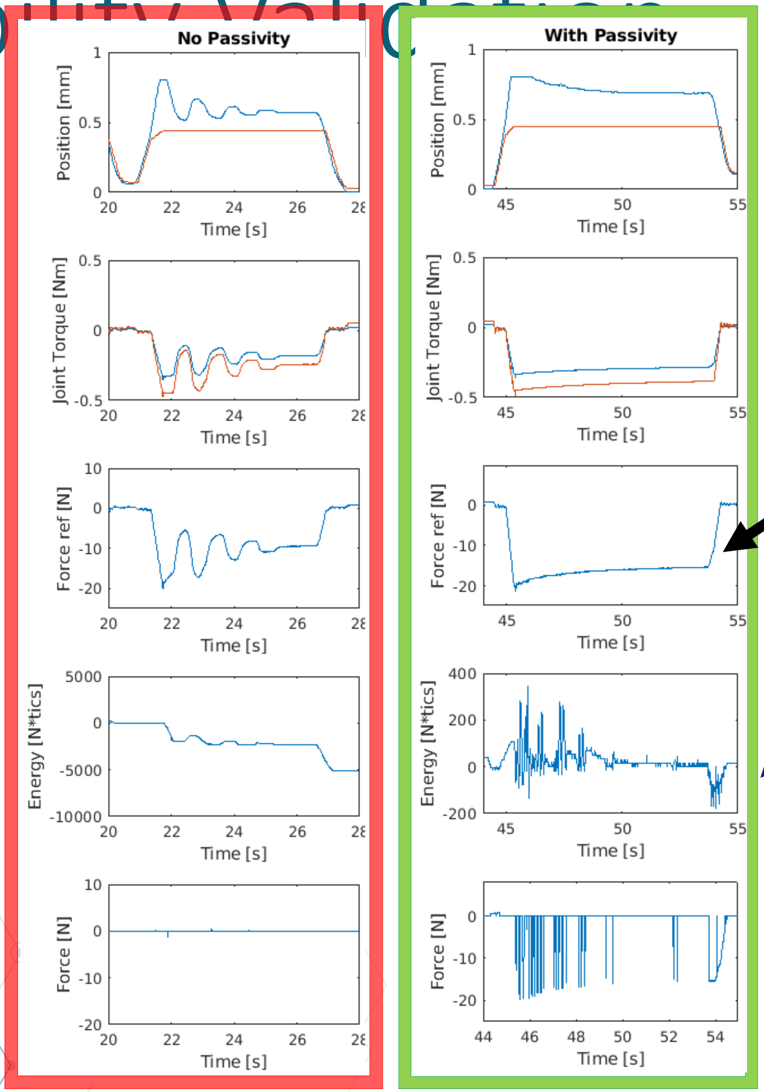
Stability Validation

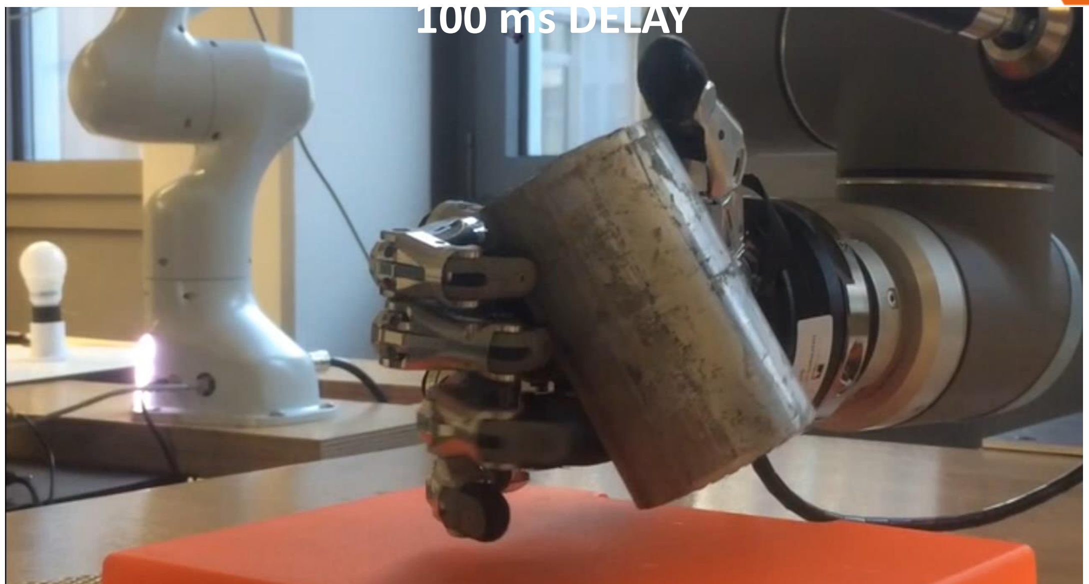


In case of energy generation, only the master seems to obscillate…

…but looking at motor currents the instability is evident!

Time domain passivation stabilize the system

When the energy becomes negative, time domain passivator activated and the energy generated is dissipated



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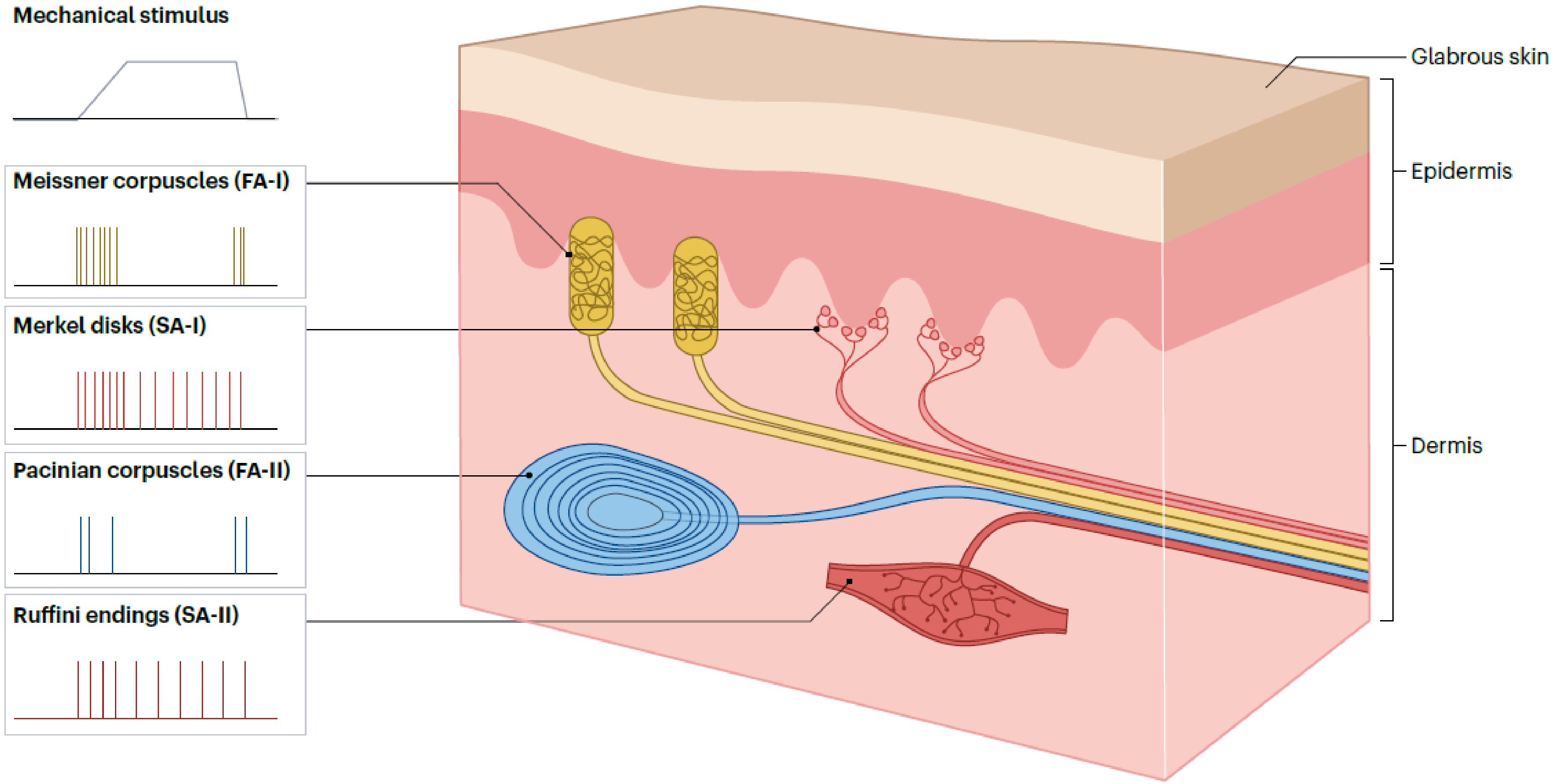
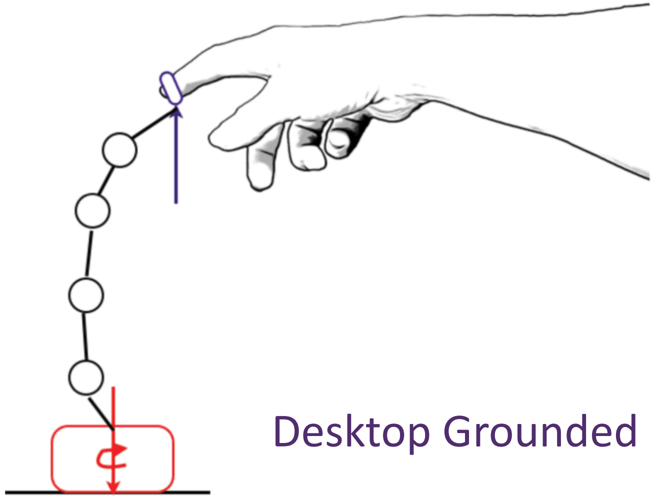
Sensory principles for artificial skin transduction

The creation of haptic sensation directly at the hands relies on eliciting mechanoreceptors that emulate the stimuli encountered during interactions with real physical object surfaces

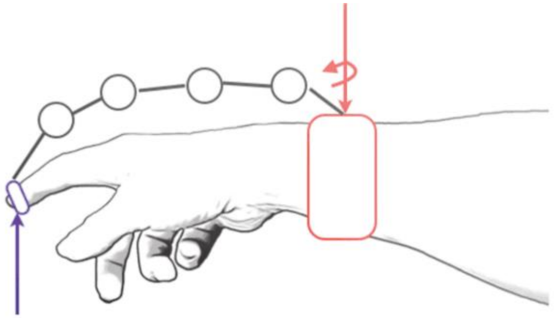
This recreation is fundamental for evoking a sense of richness in haptics, as it involves the activation of four main types of mechanoreceptors. These receptors - differ in their response characteristics concerning adaptation rates, receptor field sizes, and temporal and spatial sensitivities



Classification based on wearability



Desktop Grounded



Hand Grounded

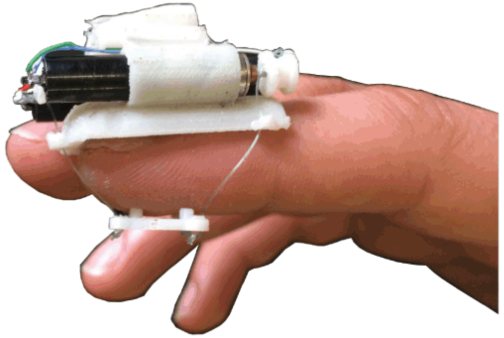
Fingertip Devices

With Domenico Prattichizzo

(a) Grounded haptics
(e.g., Phantom Premium)

Courtesy of SIRS labs UNISI

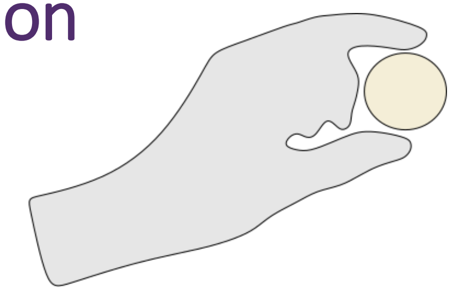
(b) Exoskeletons
(e.g., CyberGrasp)

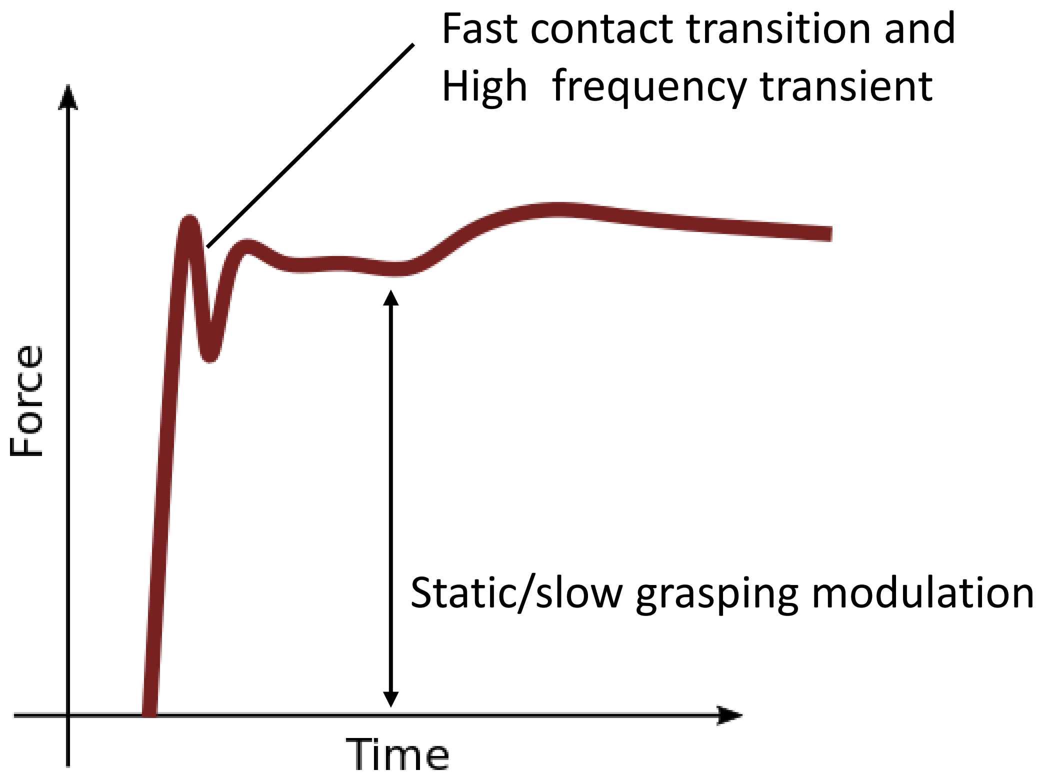


(c) Fingertip devices
(e.g., 3-DoF cable-driven device [5])

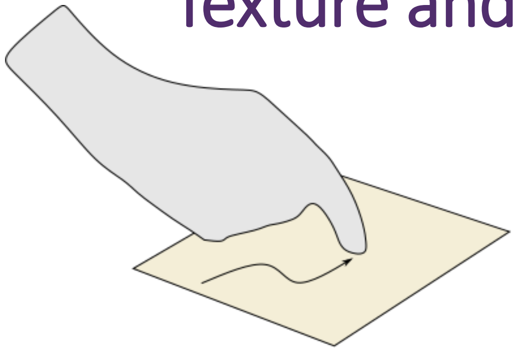
Pacchierotti, C., Sinclair, S., Solazzi, M., Frisoli, A., Hayward, V., & Prattichizzo, D. (2017). Wearable haptic systems for the fingertip and the hand: taxonomy, review, and perspectives. *IEEE transactions on haptics*, *10*(4), 580-600.

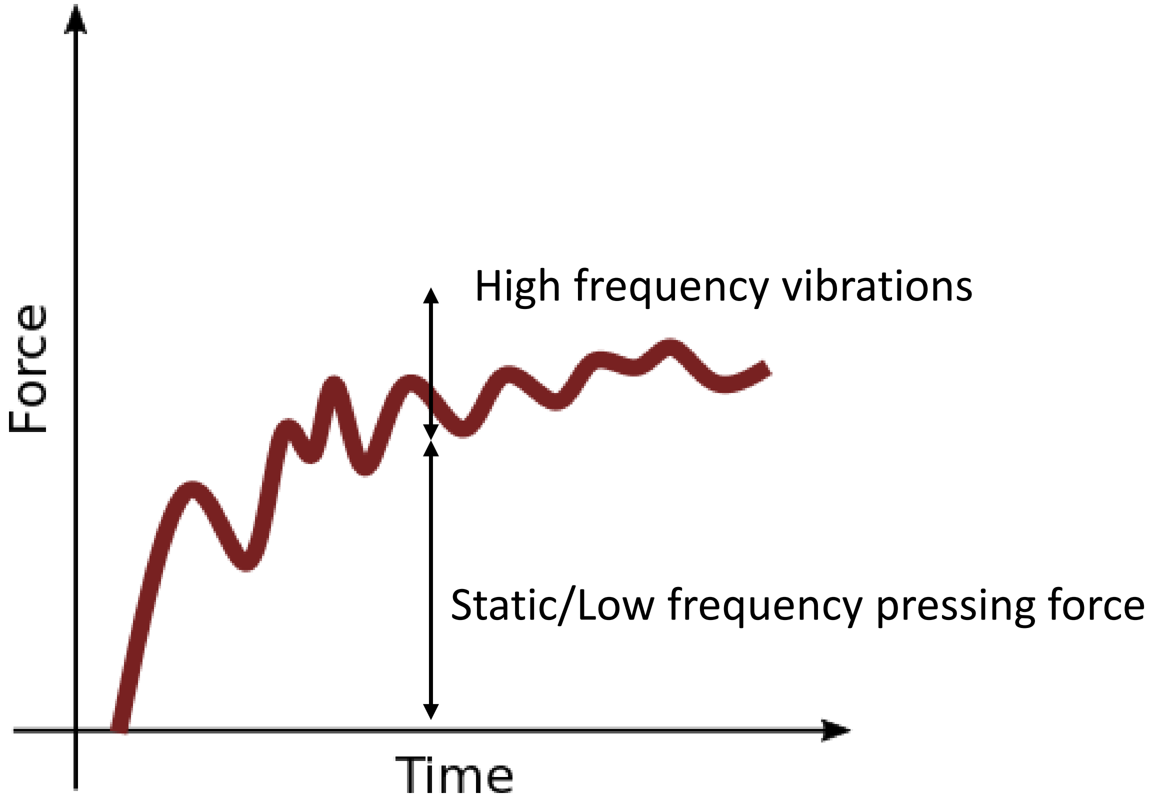
Contact transition and grasping force modulation





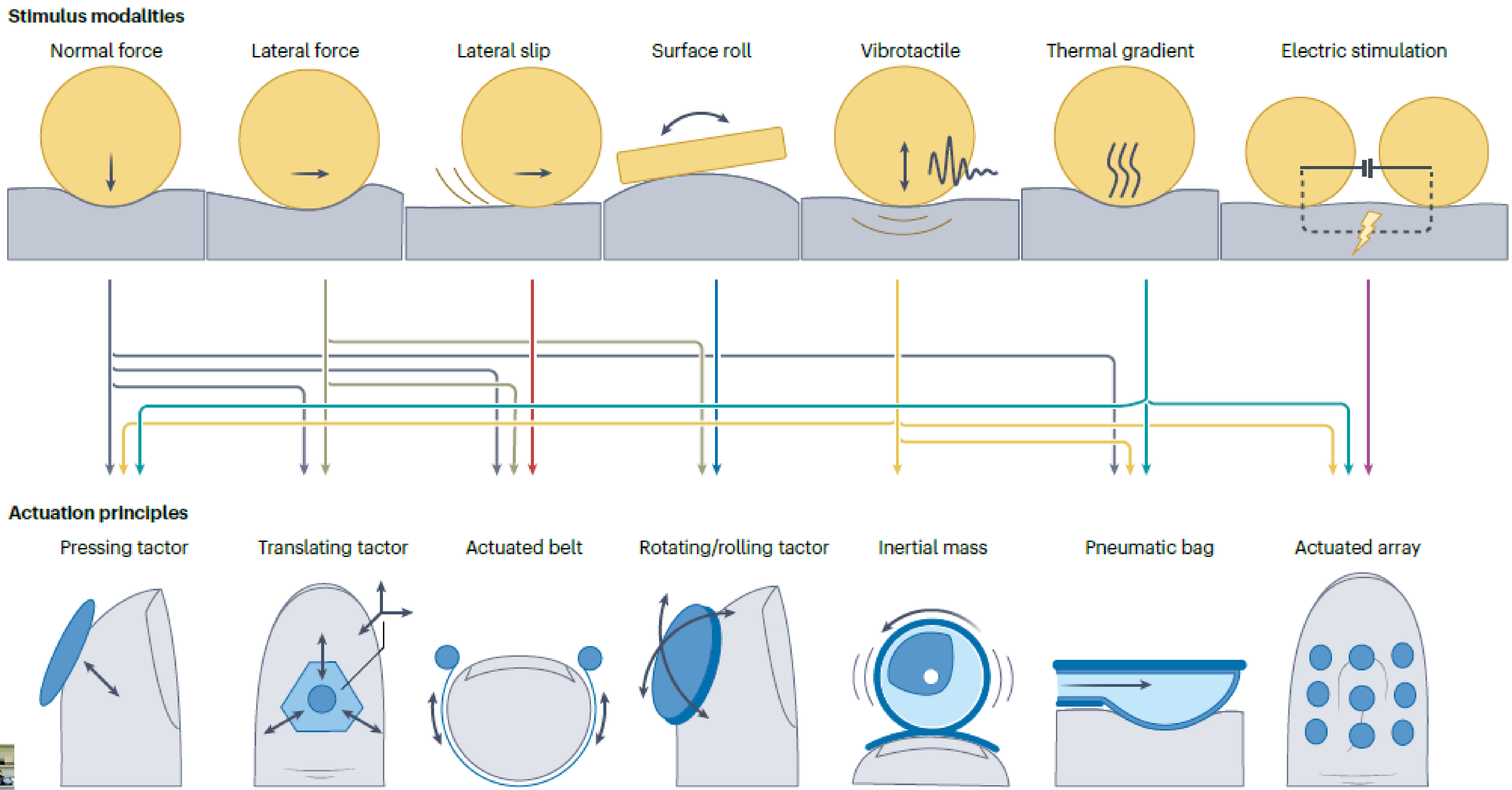
Texture and slip rendering





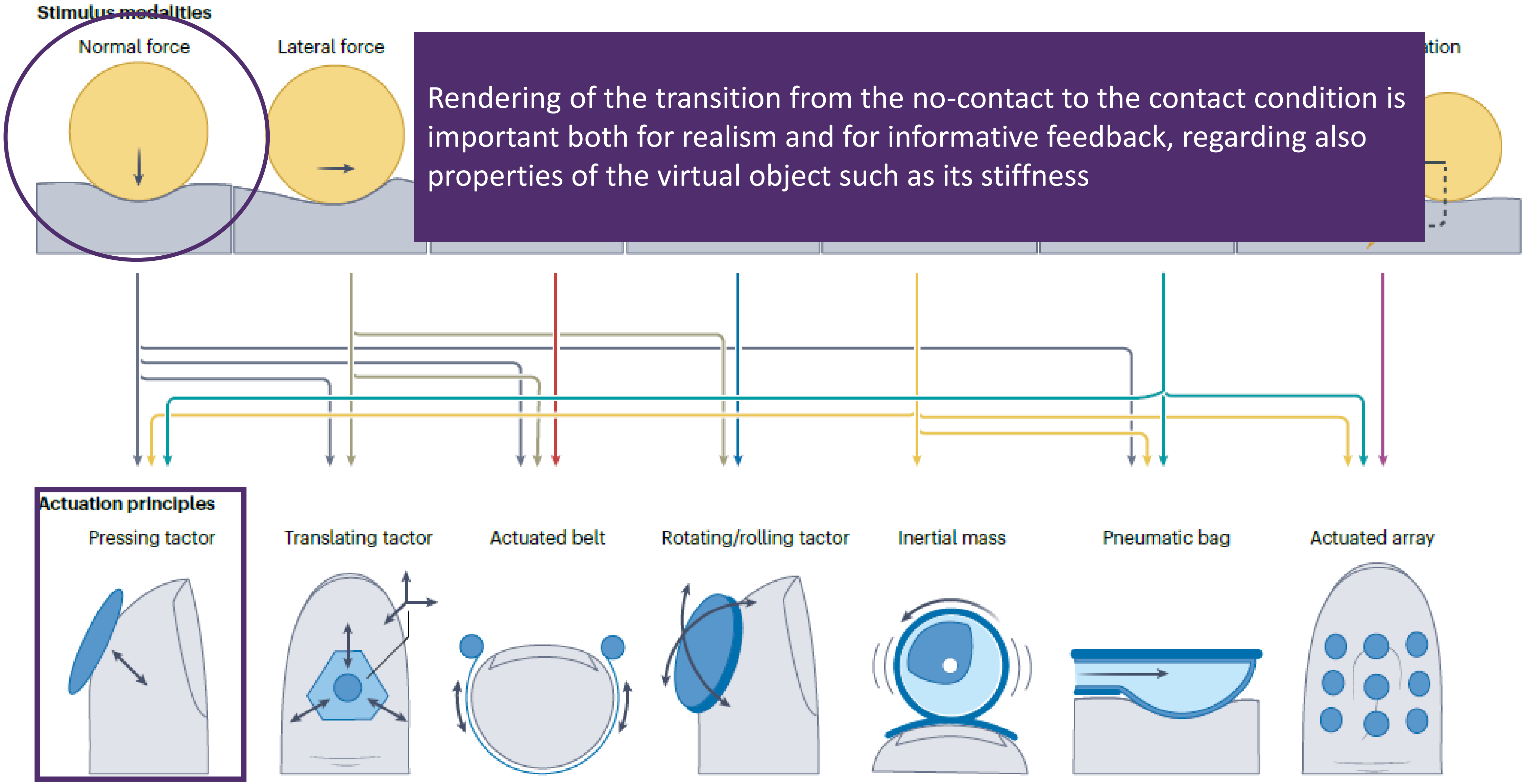
Principles for artificial haptics recreation

Antonio Frisoli



Art-graphic by Daniele Leonardis

Principles for artificial haptics recreation



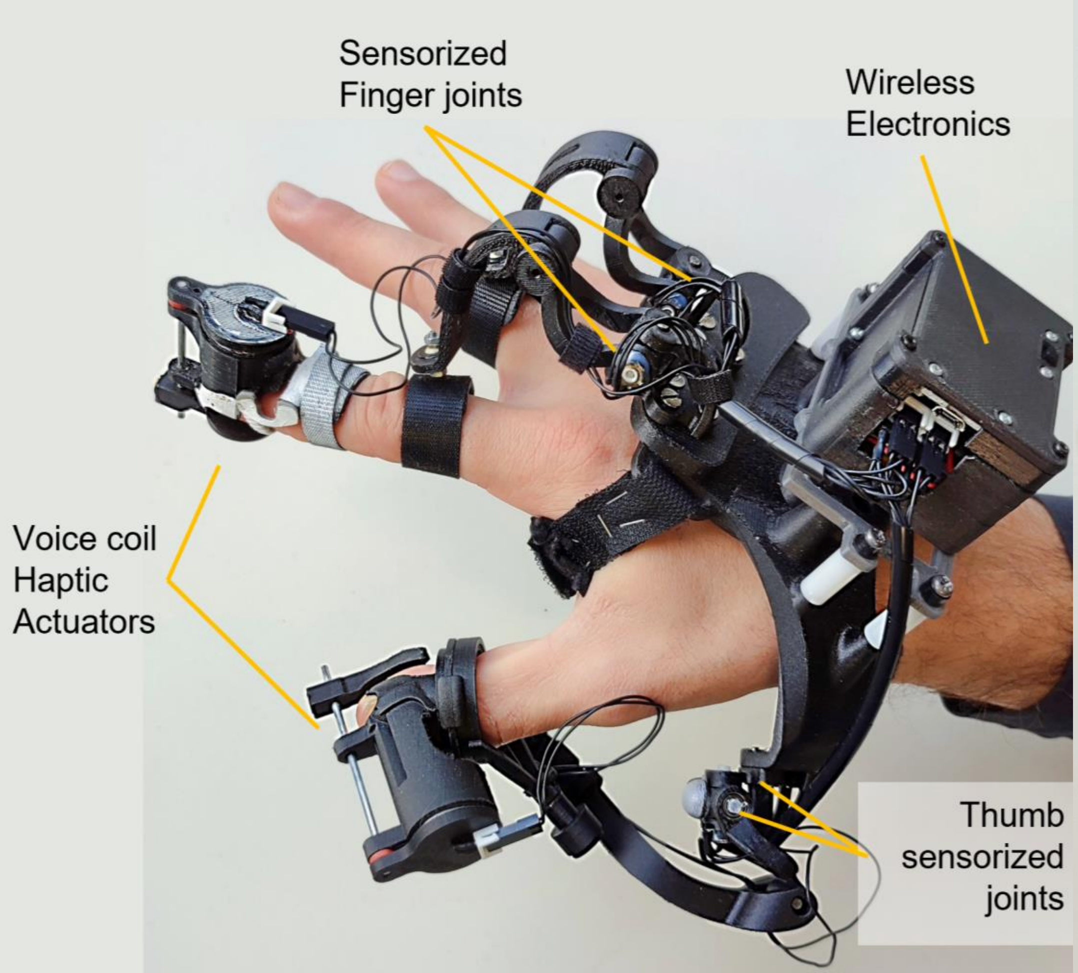
Frisoli, Leonardis, Nature Reviews in Electrical Engineering (2024)

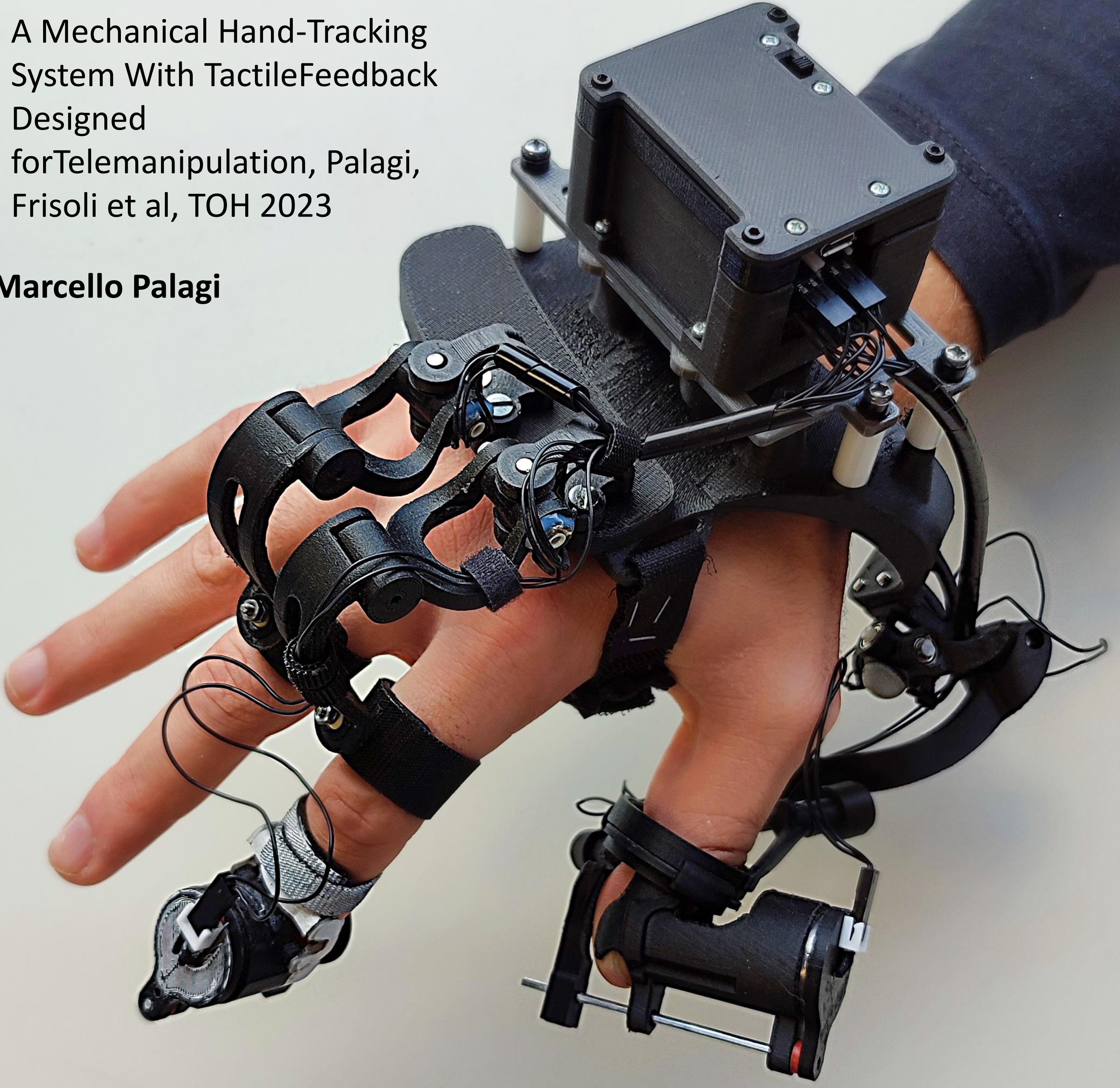

IEEE
IEEE ROBOTICS AND AUTOMATION SOCIETY
Technical Committee for Telerobotics
Best Paper Award
is hereby presented to
MARCELLO PALAGI
For the paper co-authored with G. Santamato, D. Chiaradia, M. Gabardi, S. Marcheschi, M. Sollazi, A. Firosoli, and D. Leonardis, entitled
"A Mechanical Hand-Tracking System with Tactile Feedback Designed for Telemanipulation"
as published in the IEEE Transactions on Haptics; vol. 16, no. 4, pp. 594 - 601, Oct-Dec 2023
April 2024
Signature
Keyvan Hashtrudi-Zaad
IEEE RAS TCT Co-Chair
Signature
Claudio Pacchierotti
IEEE RAS TCT Co-Chair

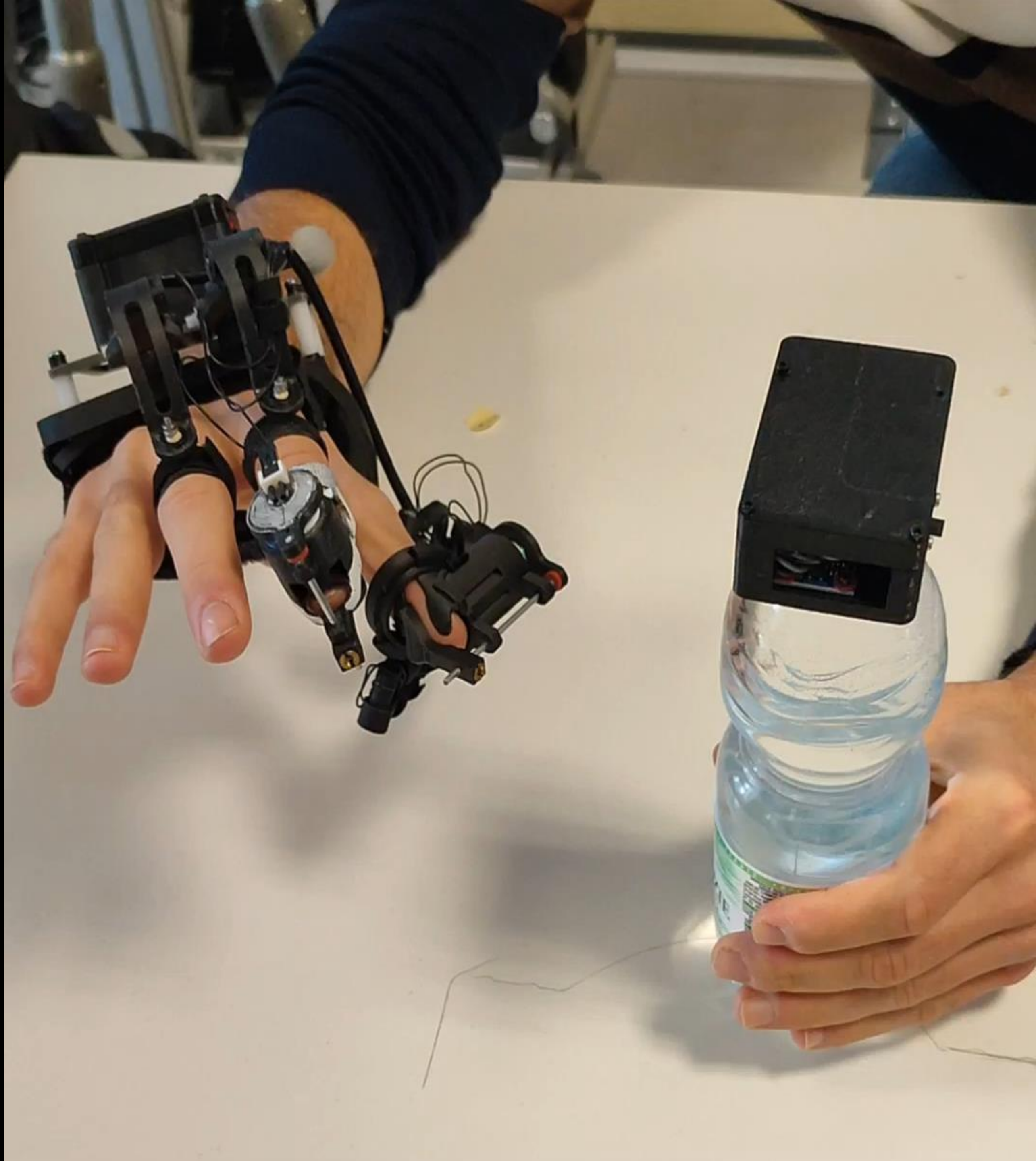
IEEE WORLD HAPTICS 2023

A Mechanical Hand-Tracking System With TactileFeedback Designed forTelemanipulation, Palagi, Frisoli et al, TOH 2023

With Marcello Palagi



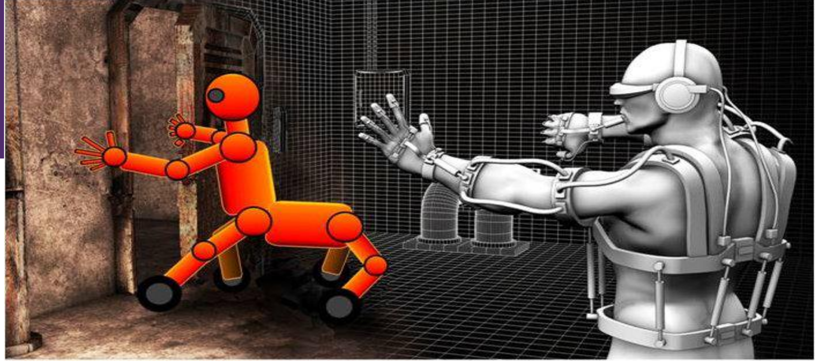


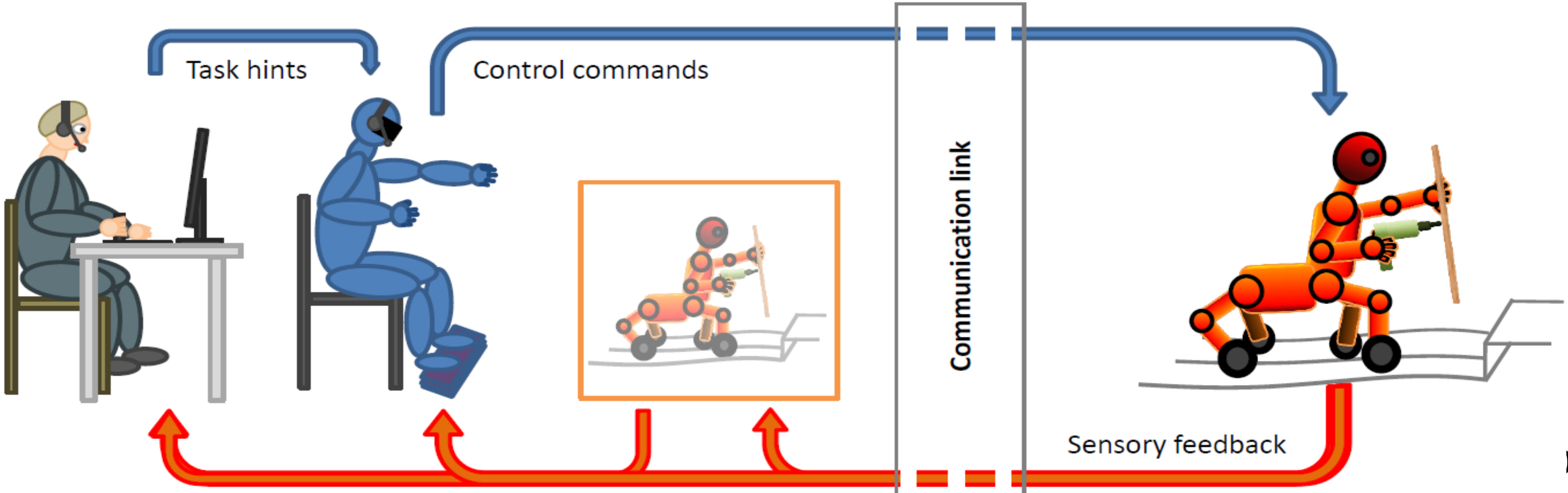
Teleoperation with haptic feedback

The CENTAURO Project

The CENTAURO project Approach



- Hybrid wheeled-legged base => Flexible locomotion
- Anthropomorphic upper body => Dexterous manipulation
- Telepresence suit => Situation awareness, intuitive control
- Predictive robot-environment model => Action planning
- Sup
  tear



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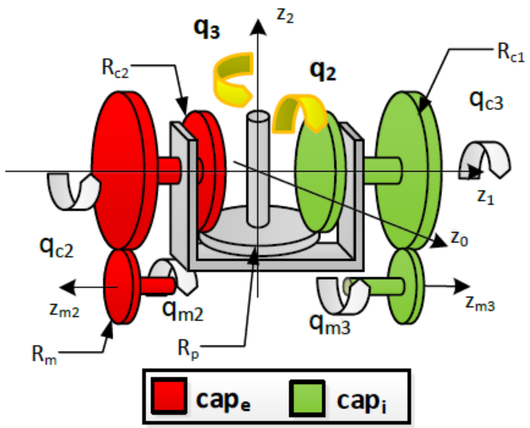
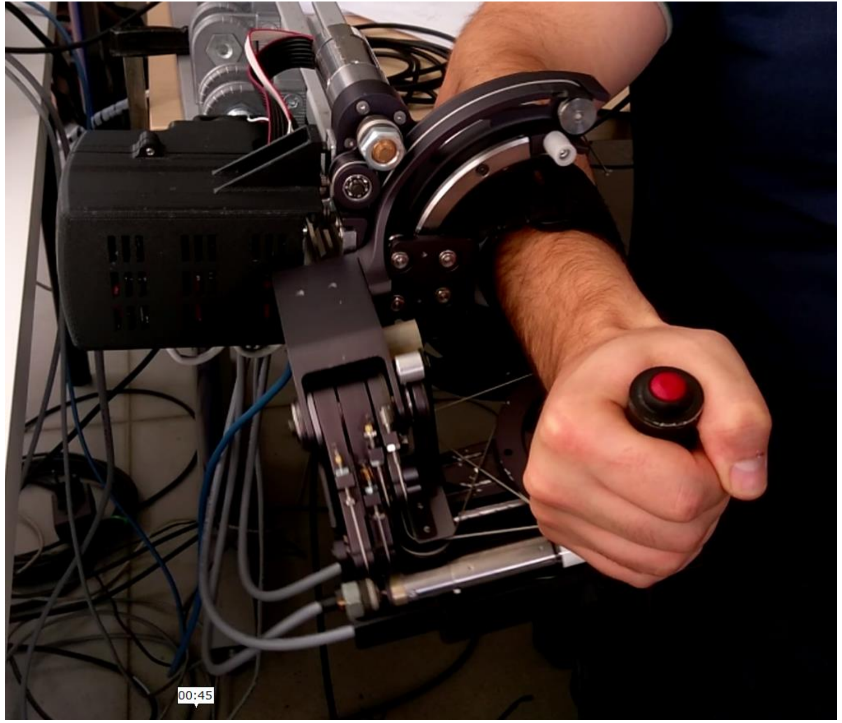
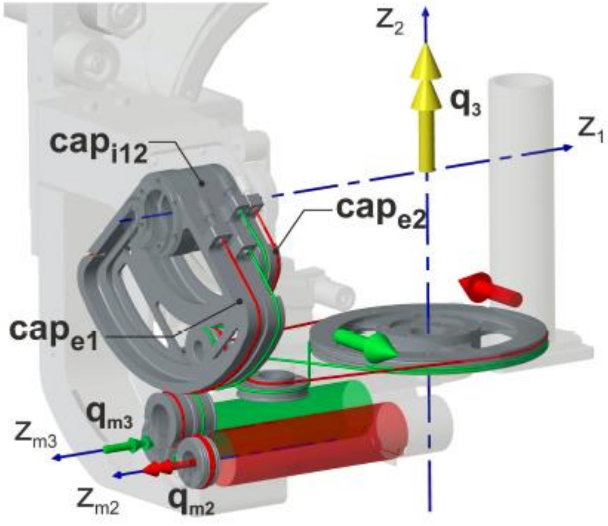
Visual Feedback
Hand exoskeleton
Upper limb exos
Pedals

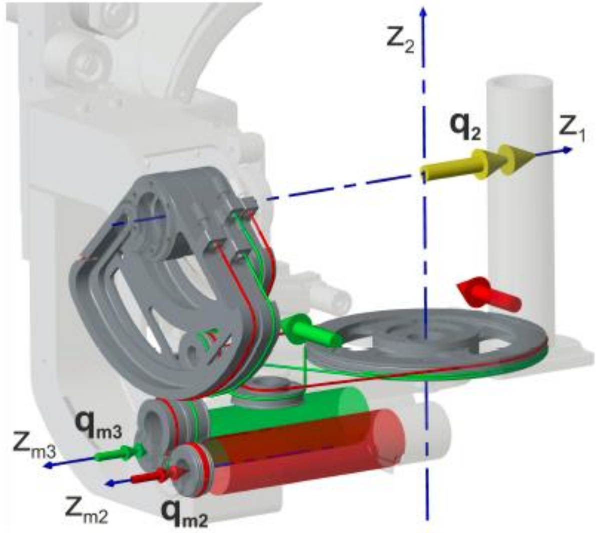
WRES: Differential kinematics

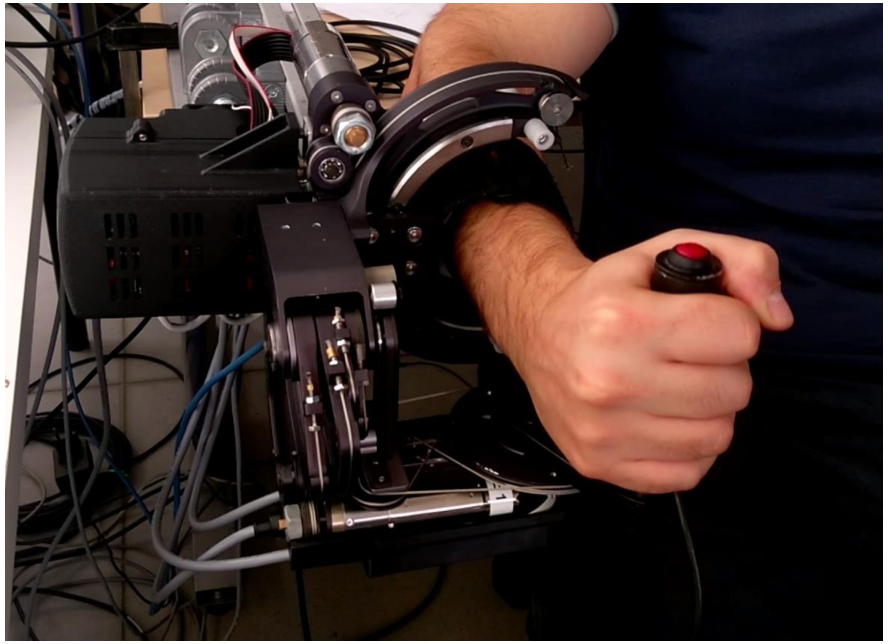


- Low weight
- Optimal mass distribution
- High torque/mass ratio









Buongiorno, Domenico, et al. "WRES: a novel 3 DoF WRist ExoSkeleton with tendon-driven differential transmission for neuro-rehabilitation and teleoperation." *IEEE Robotics and Automation Letters* 3.3 (2018): 2152-2159.

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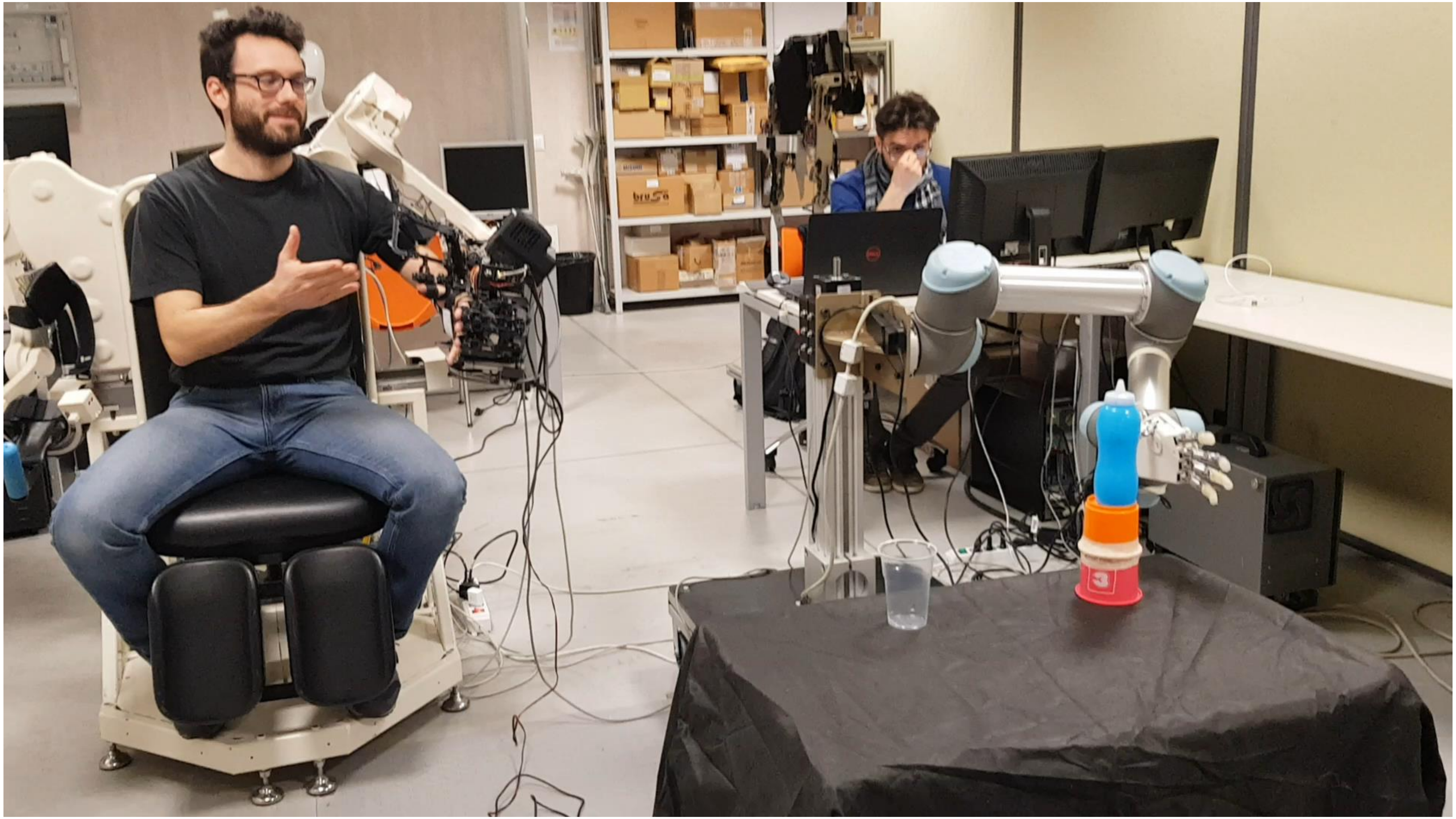
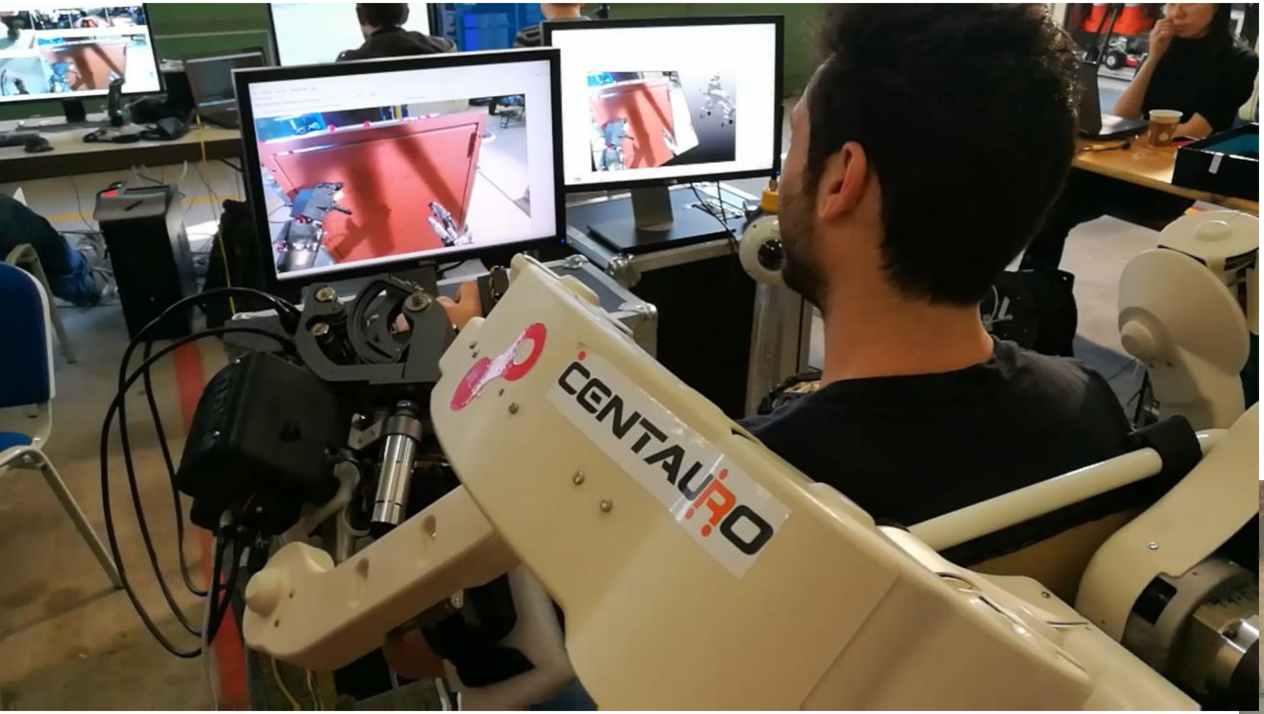
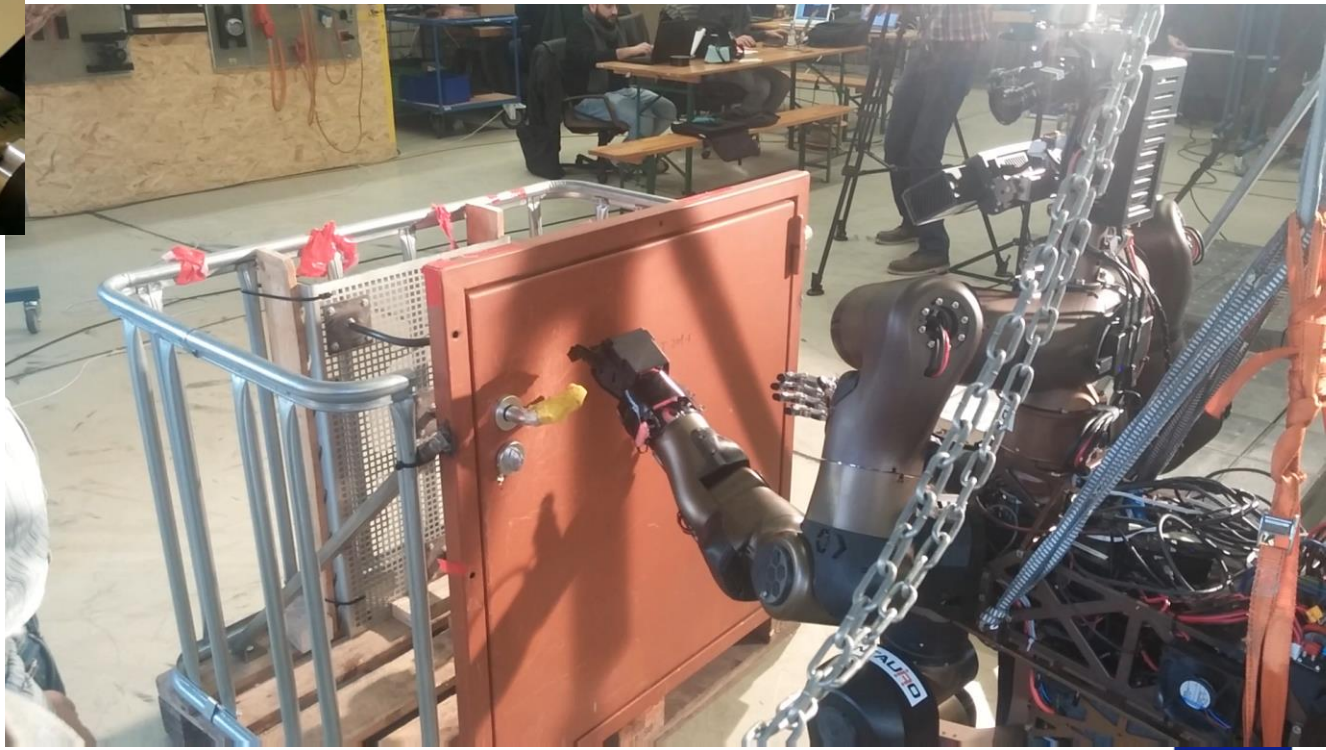


Teleoperation in 1st evaluation camp

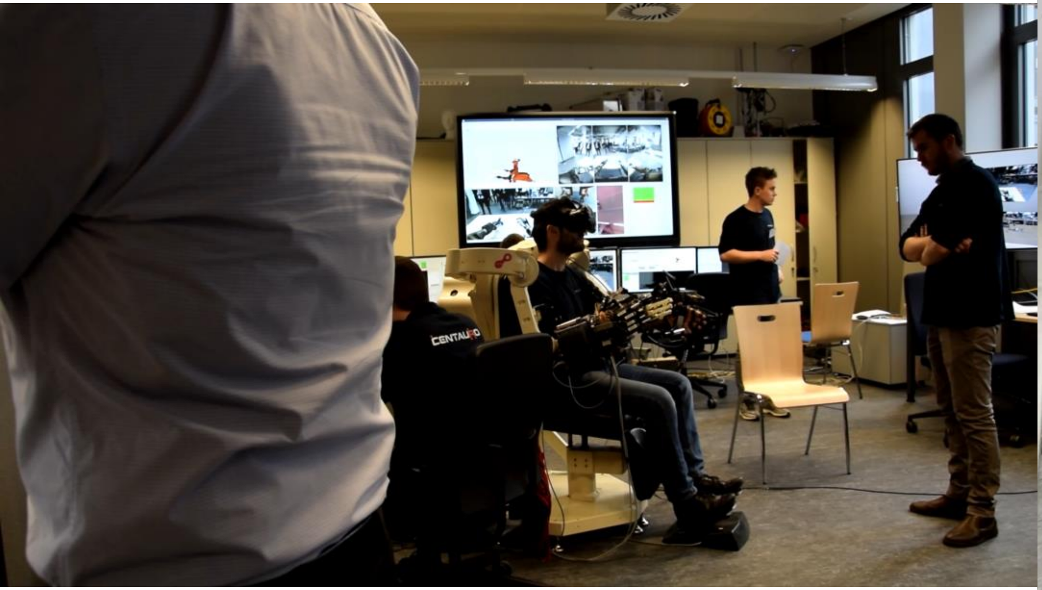


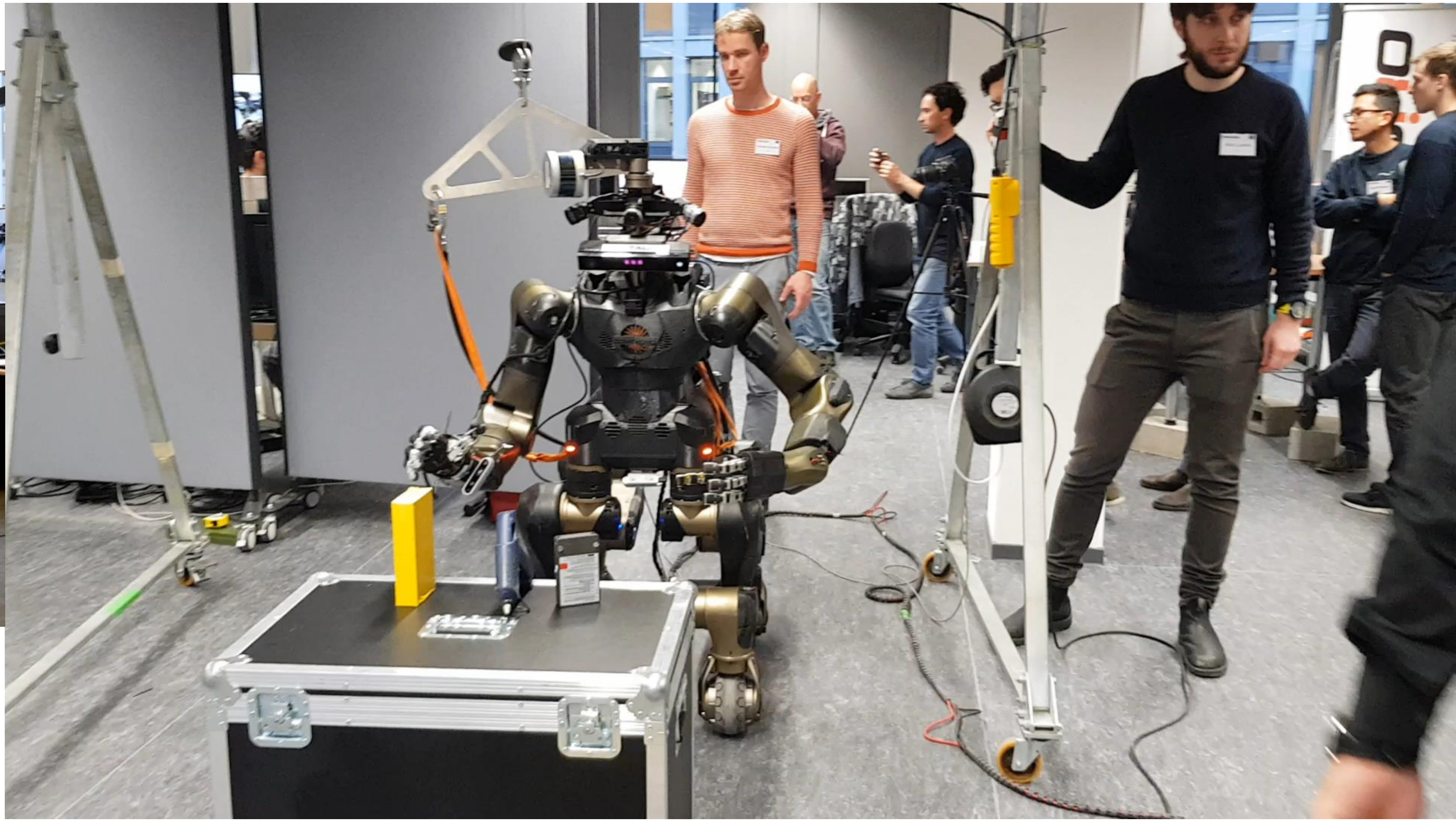


CENTAURO


CENTAURO

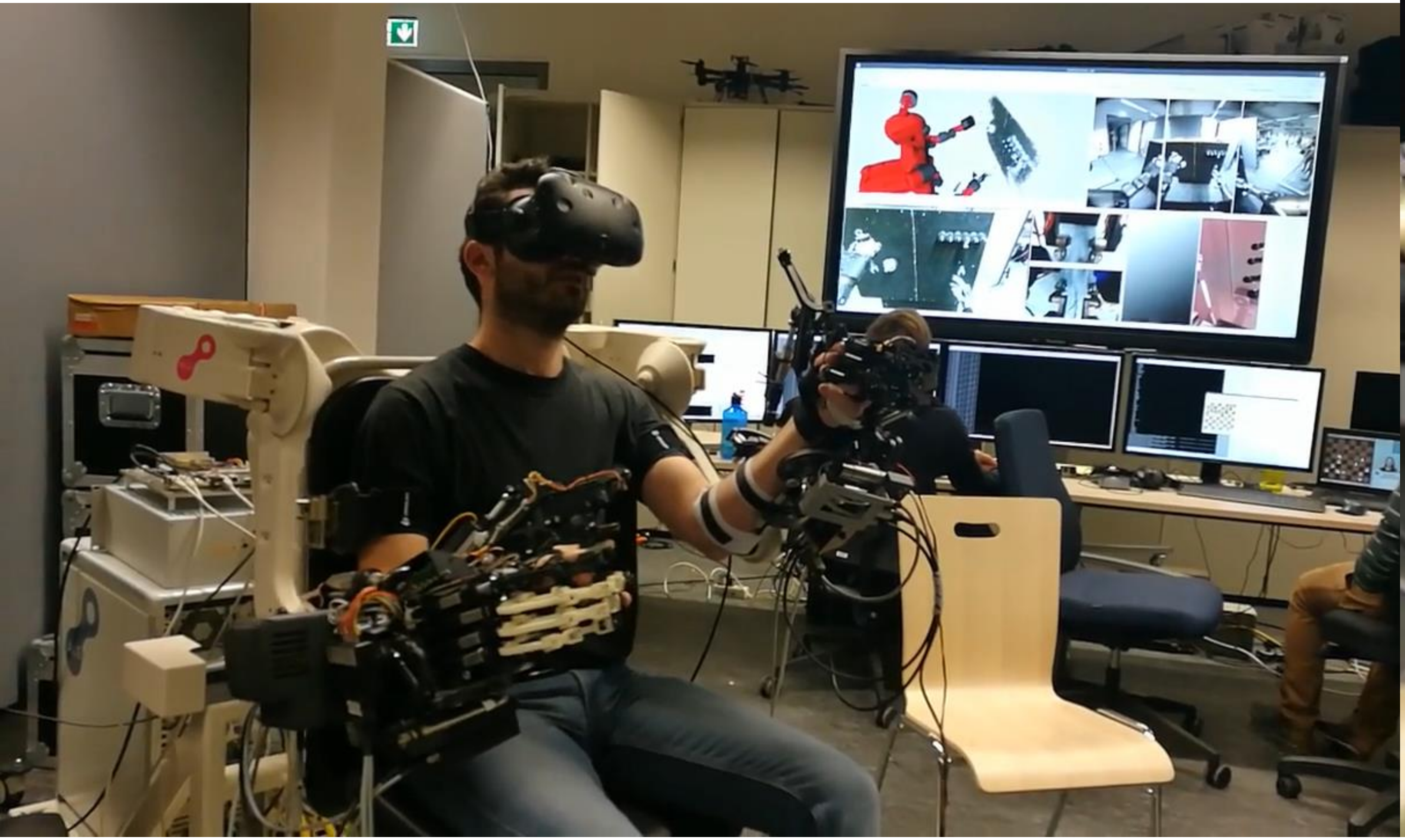
Manipulation with Schunk Hand

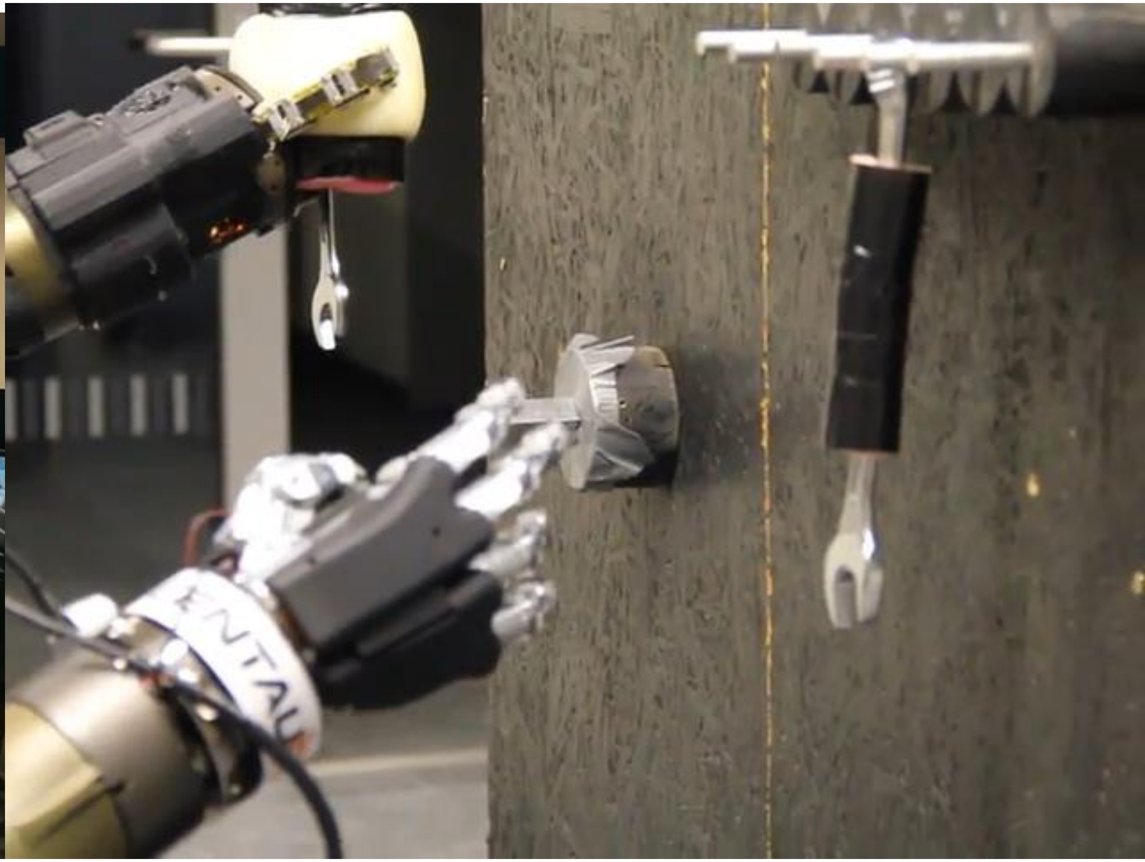




Klamt, Tobias, et al. "Remote mobile manipulation with the centauro robot: Full-body telepresence and autonomous operator assistance." *Journal of Field Robotics* 37.5 (2020): 889-919.

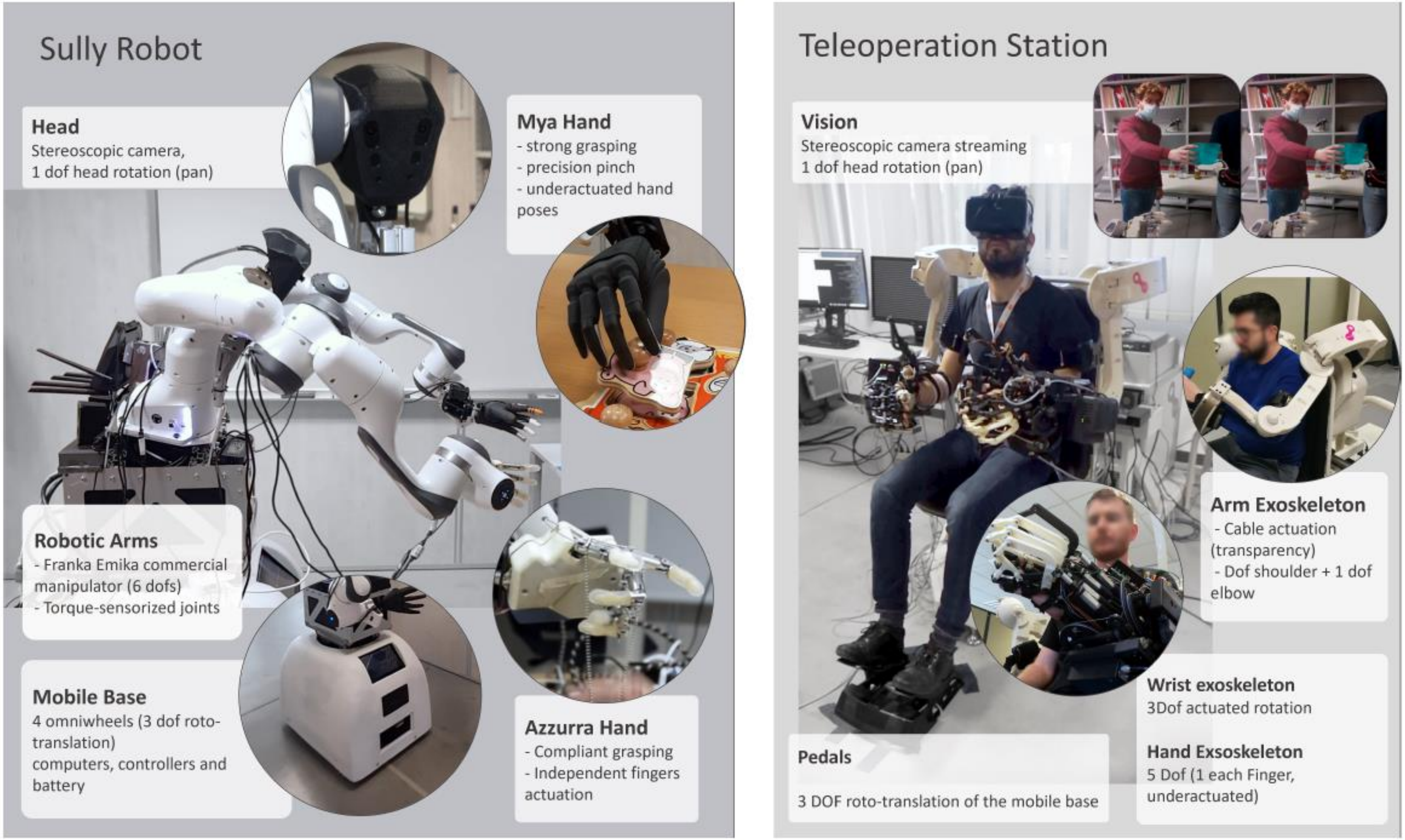
Exoskeleton as Operator Station



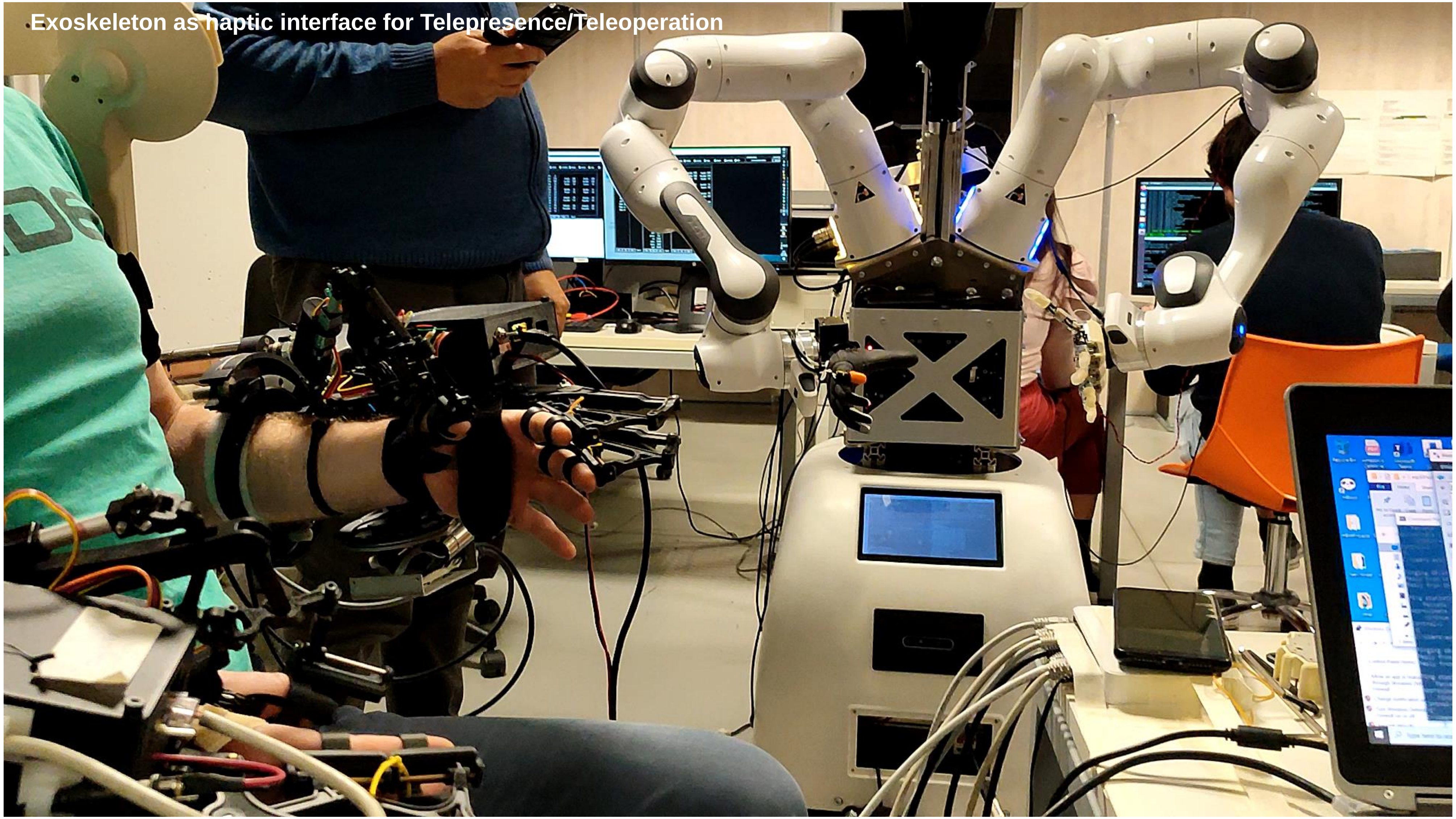


Klamt, Tobias, et al. "Remote mobile manipulation with the centauro robot: Full-body telepresence and autonomous operator assistance." *Journal of Field Robotics* 37.5 (2020): 889-919.

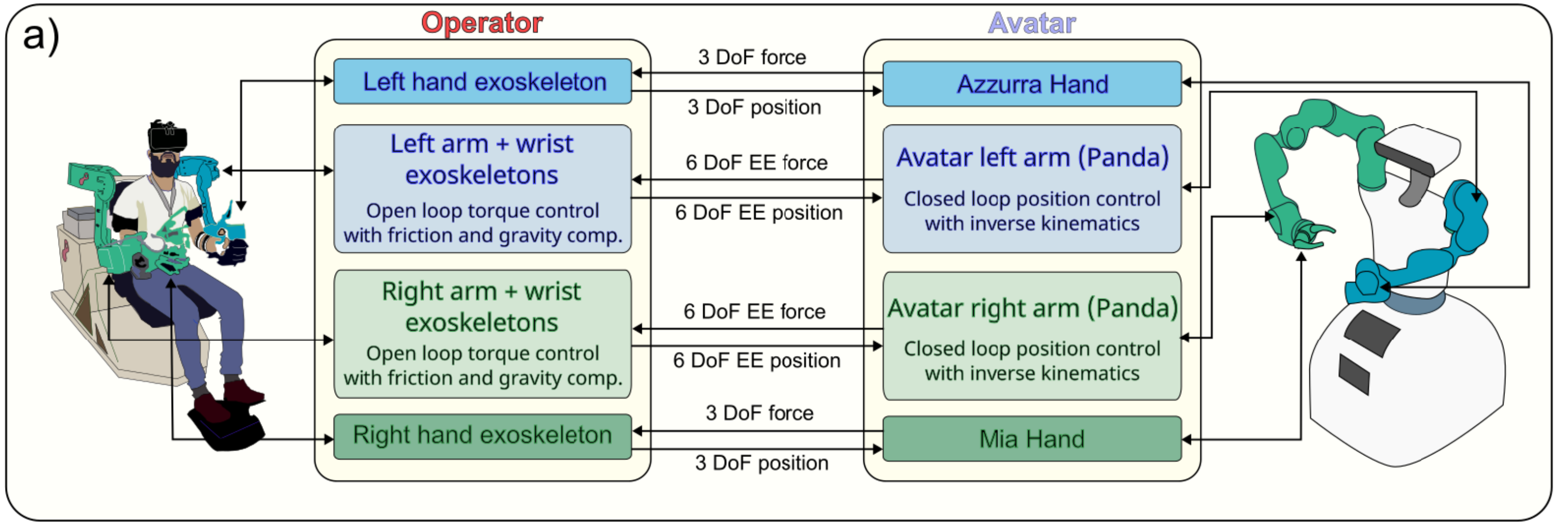
The AVATAR ANA X_Prize

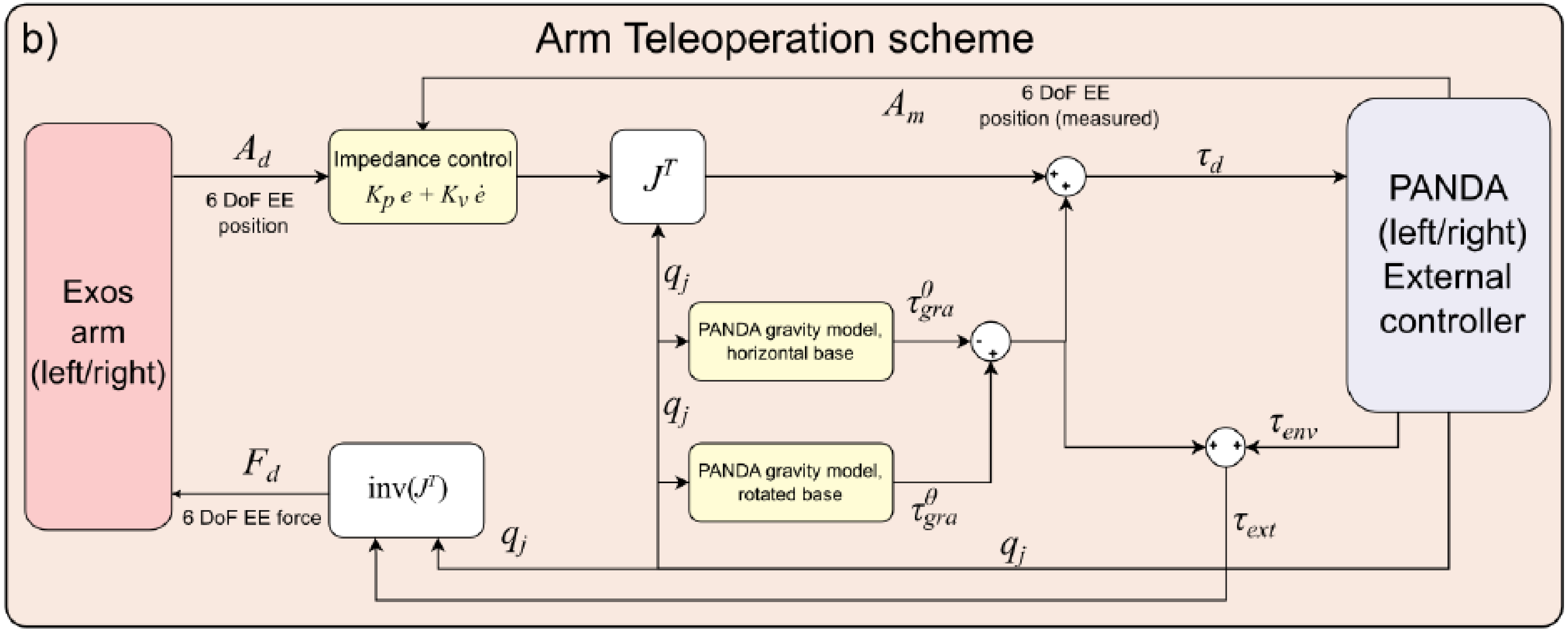

Sully Robot
Head
Stereoscopic camera,
1 dof head rotation (pan)
Mya Hand
- strong grasping
- precision pinch
- underactuated hand poses
Robotic Arms
- Franka Emika commercial manipulator (6 dofs)
- Torque-sensorized joints
Mobile Base
4 omniwheels (3 dof roto-translation)
computers, controllers and battery
Azzurra Hand
- Compliant grasping
- Independent fingers actuation
Teleoperation Station
Vision
Stereoscopic camera streaming
1 dof head rotation (pan)
Arm Exoskeleton
- Cable actuation (transparency)
- Dof shoulder + 1 dof elbow
Wrist exoskeleton
3Dof actuated rotation
Hand Exsoskeleton
5 Dof (1 each Finger, underactuated)
Pedals
3 DOF roto-translation of the mobile base

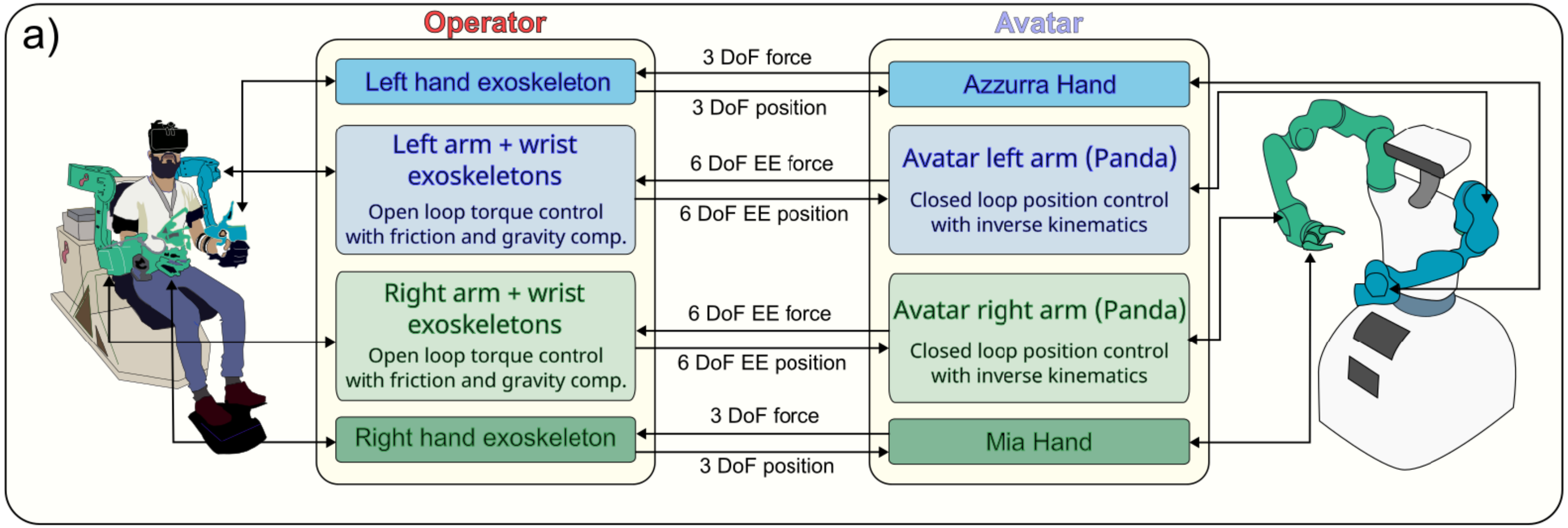
Exoskeleton as haptic interface for Telepresence/Teleoperation



Santamato, G., Leonardis, D., Marcheschi, S., D'Avella, S., Bagneschi, T., Camardella, C., ... & Frisoli, A. (2024). Anywhere is possible: An Avatar Platform for Social Telepresence with Full Perception of Physical Interaction. *IEEE Access*.


a)
Operator
Avatar
Left hand exoskeleton
Left arm + wrist exoskeletons
Open loop torque control with friction and gravity comp.
Right arm + wrist exoskeletons
Open loop torque control with friction and gravity comp.
Right hand exoskeleton
3 DoF force
3 DoF position
6 DoF EE force
6 DoF EE position
6 DoF EE force
6 DoF EE position
3 DoF force
3 DoF position
Azzurra Hand
Avatar left arm (Panda)
Closed loop position control with inverse kinematics
Avatar right arm (Panda)
Closed loop position control with inverse kinematics
Mia Hand


b)
Arm Teleoperation scheme
Exos arm (left/right)
A_d
6 DoF EE position
Impedance control
$K_p e + K_v \dot{e}$
J^T
A_m
6 DoF EE position (measured)
τ_d
PANDA (left/right) External controller
q_j
PANDA gravity model, horizontal base
τ^0_{gra}
q_j
PANDA gravity model, rotated base
τ^θ_{gra}
τ_{env}
τ_{ext}
F_d
inv(J^T)
6 DoF EE force
q_j
q_j



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Left arm + wrist exoskeletons
Open loop torque control with friction and gravity comp.
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Right hand exoskeleton
3 DoF force
3 DoF position
6 DoF EE force
6 DoF EE position
6 DoF EE force
6 DoF EE position
3 DoF force
3 DoF position
Azzurra Hand
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Closed loop position control with inverse kinematics
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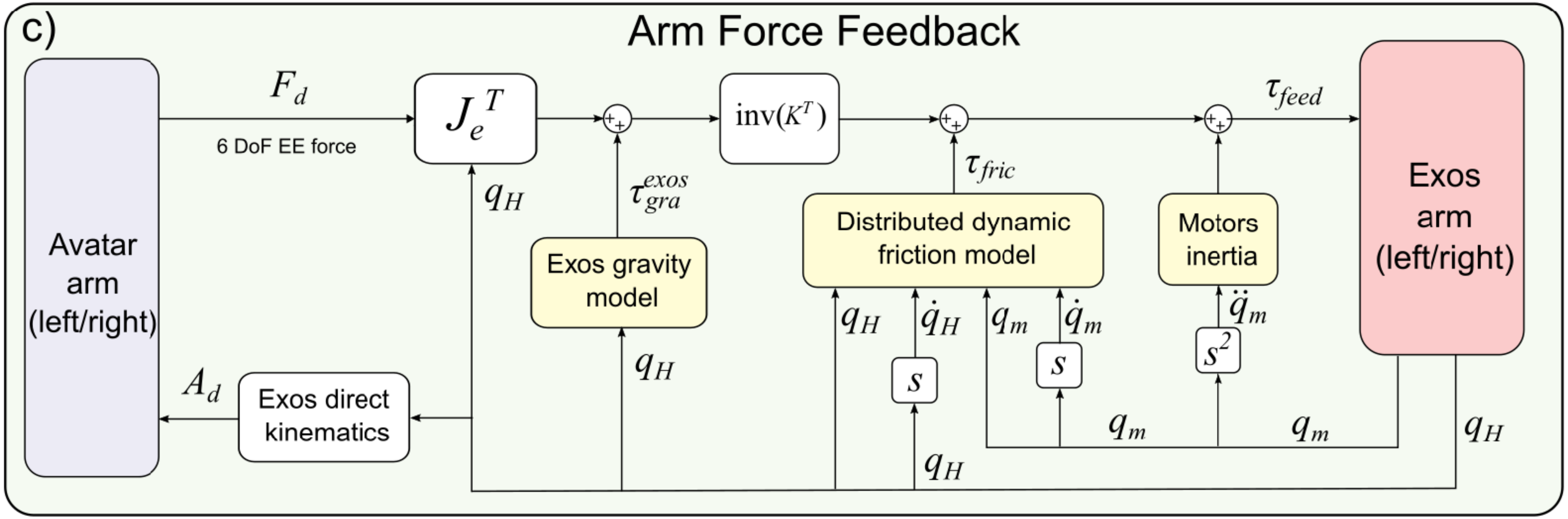


c)
Arm Force Feedback
Avatar arm (left/right)
F_d
6 DoF EE force
J_e^T
q_H
τ_{gra}^{exos}
Exos gravity model
q_H
inv(K^T)
τ_{fric}
Distributed dynamic friction model
q_H
$\dot{q}_H$
q_m
$\dot{q}_m$
s
s
Motors inertia
$\ddot{q}_m$
s^2
τ_{feed}
Exos arm (left/right)
q_m
q_m
q_H
q_H
A_d
Exos direct kinematics

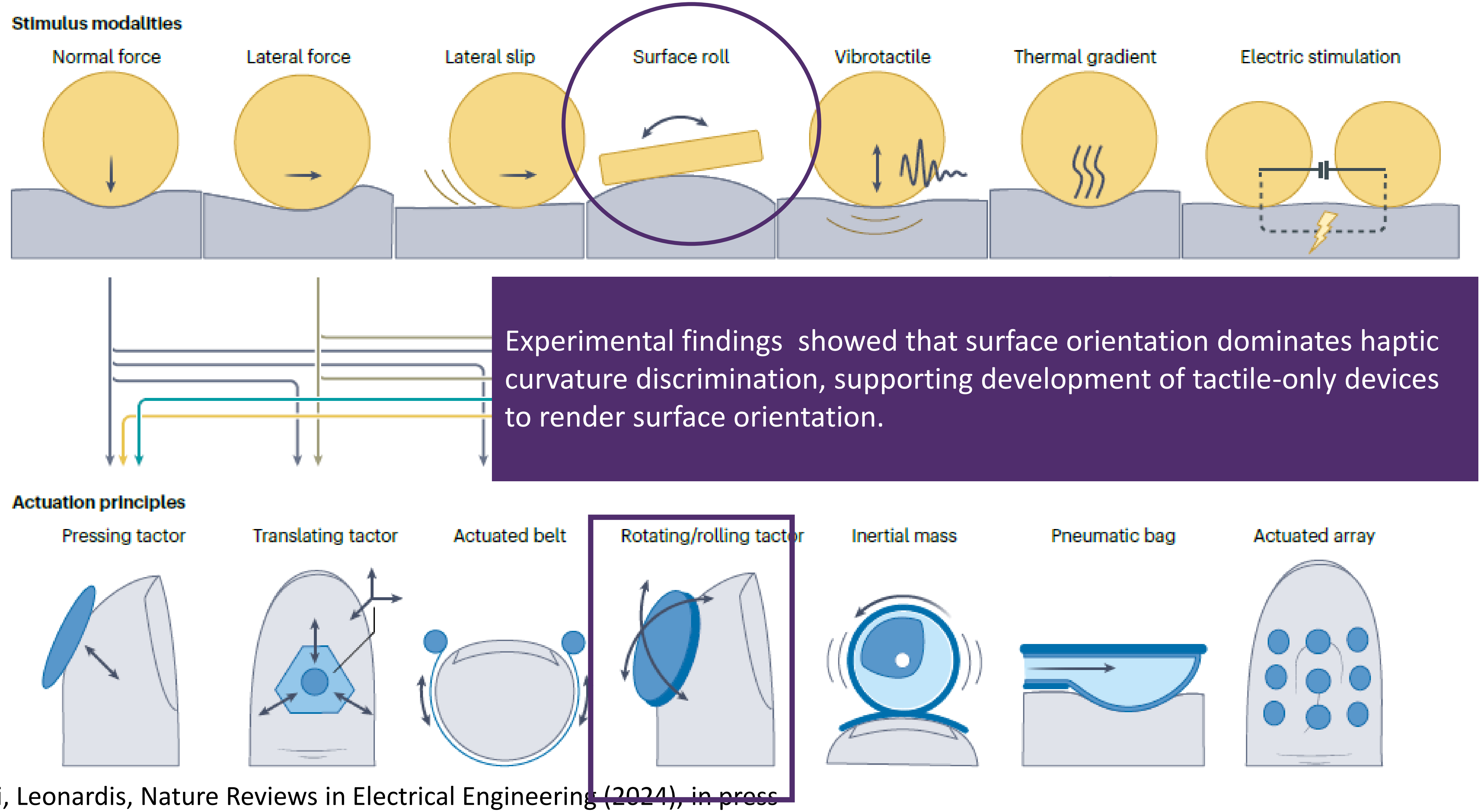
Task example – Magic trick with remote friend

Recipient Room

Operator Room

Santamato, G., Leonardis, D., Marcheschi, S., D'Avella, S., Bagneschi, T., Camardella, C., ... & Frisoli, A. (2024). Anywhere is possible: An Avatar Platform for Social Telepresence with Full Perception of Physical Interaction. *IEEE Access*.

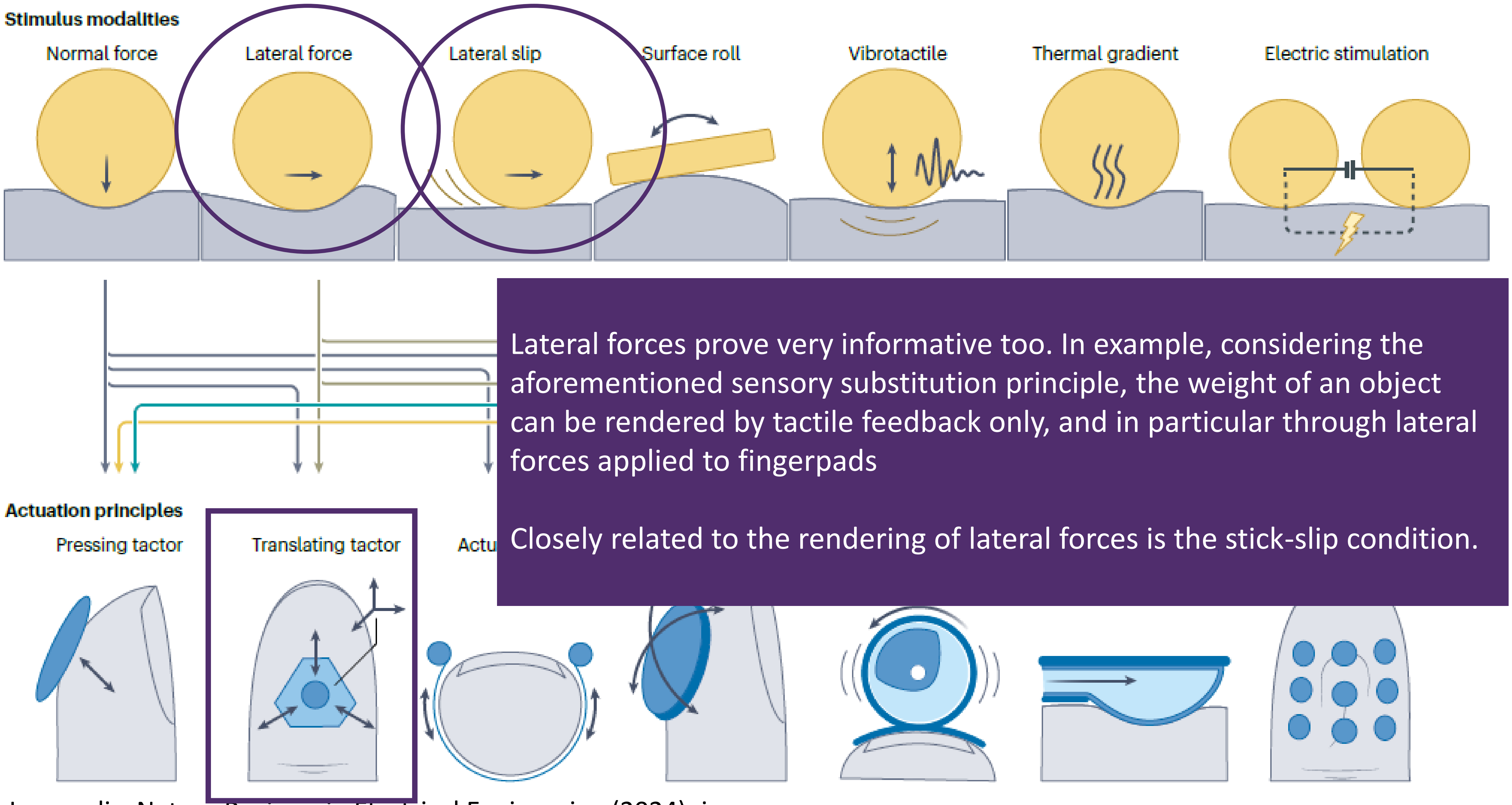
Principles for artificial haptics recreation



Experimental findings showed that surface orientation dominates haptic curvature discrimination, supporting development of tactile-only devices to render surface orientation.

Frisoli, Leonardis, Nature Reviews in Electrical Engineering (2024), in press

Principles for artificial haptics recreation

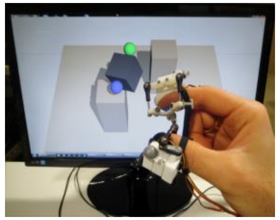


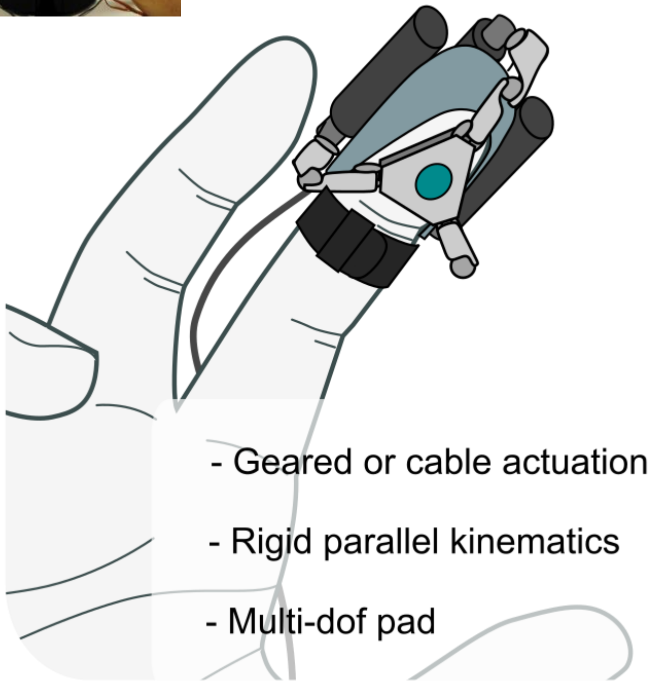
Lateral forces prove very informative too. In example, considering the aforementioned sensory substitution principle, the weight of an object can be rendered by tactile feedback only, and in particular through lateral forces applied to fingerpads

Closely related to the rendering of lateral forces is the stick-slip condition.

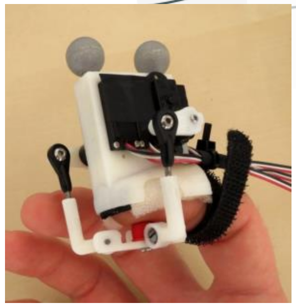
Frisoli, Leonardis, Nature Reviews in Electrical Engineering (2024), in press

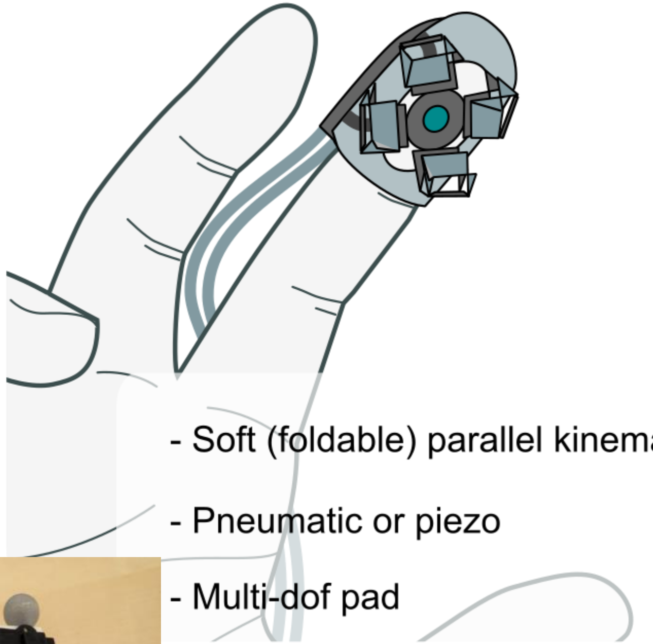
Evolution from rigid to soft multimodal wearable haptics



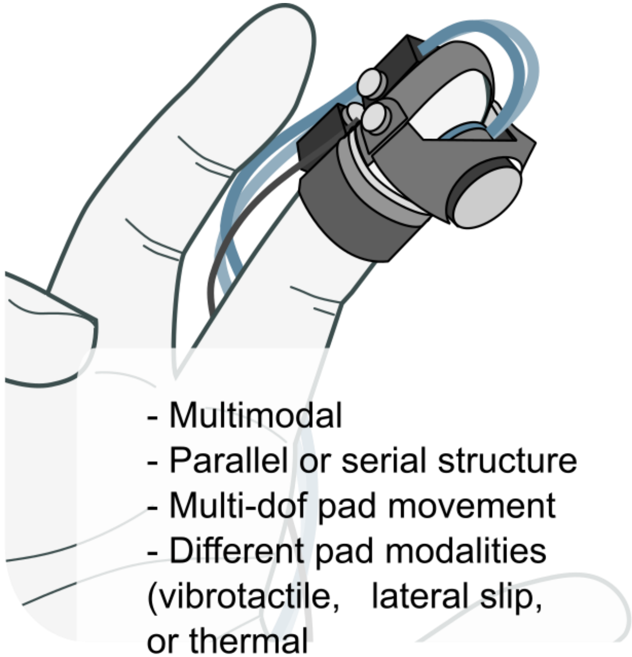


- Geared or cable actuation
- Rigid parallel kinematics
- Multi-dof pad





- Soft (foldable) parallel kinematics
- Pneumatic or piezo
- Multi-dof pad

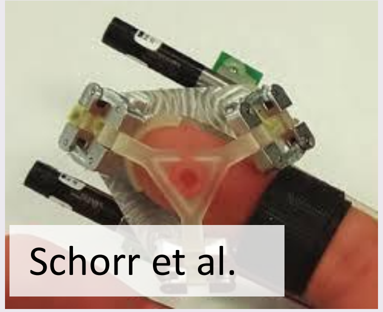


- Multimodal
- Parallel or serial structure
- Multi-dof pad movement
- Different pad modalities (vibrotactile, lateral slip, or thermal

Miniature Actuators in Fingertip Haptic Devices

The forefront of wearable haptics research has been characterized by advancements in actuation mechanisms. It emerges a sustained interest in developing soft and stretchable haptic actuators, striving to increase wearability and comfort for the user

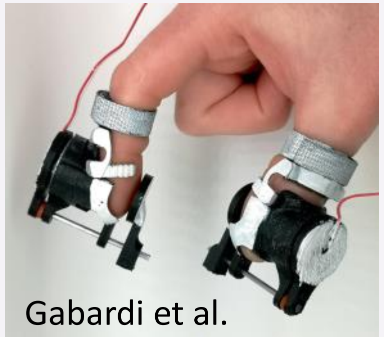
Micro gearmotors: high output force, yet noise and low-bandwidth


Schorr et al.

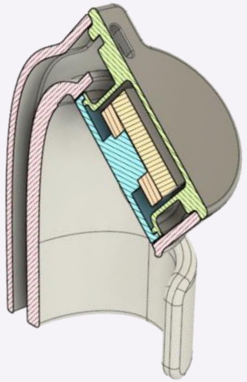

Tao et al.


Chinello et al.

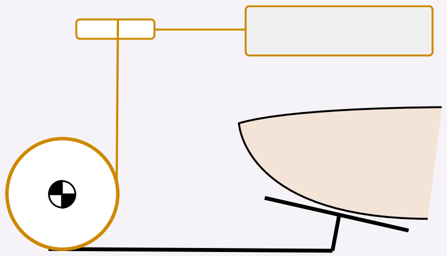
Linear Voice Coil: wide bandwidth, low maximum force

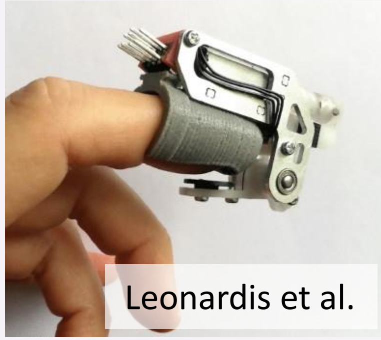

Gabardi et al.


Camardella et al.



Wire transmission: difficult routing and preload in miniature mechanisms

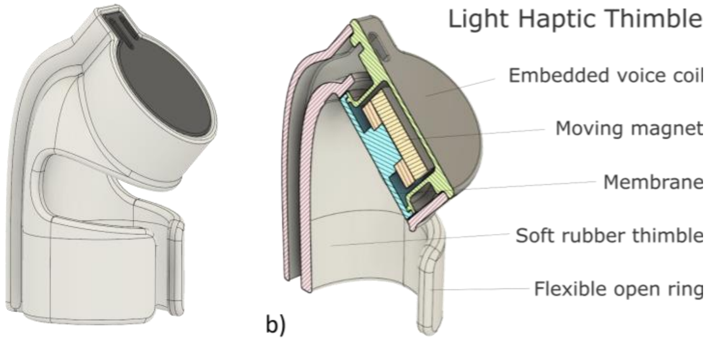



Leonardis et al.

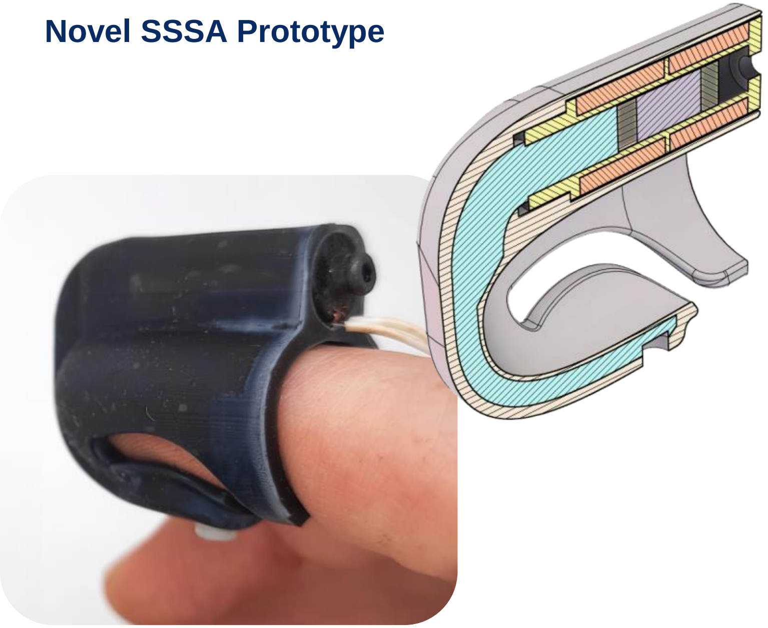

Pacchierotti et al.

Haptic feedback at fingertips

SSSA Prototype (tested in Children Neurorheabilitation)



Novel SSSA Prototype



Ferrofluid miniature hydraulic actuator,
Better rendering, long-term reliability to be solved

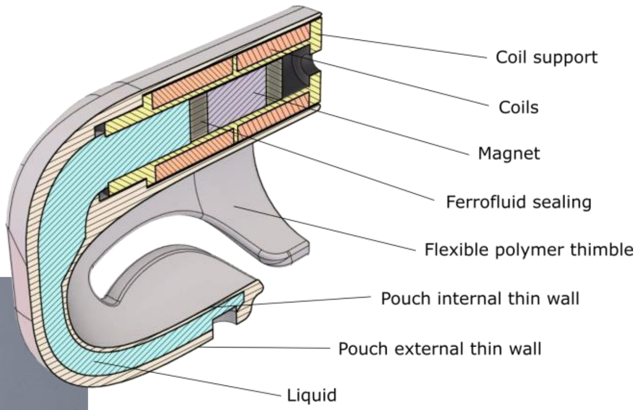
Prototypes developed by SSSA:
Targeted at high wearability and wide-bandwidth modulation (no vibration inertial motors!)

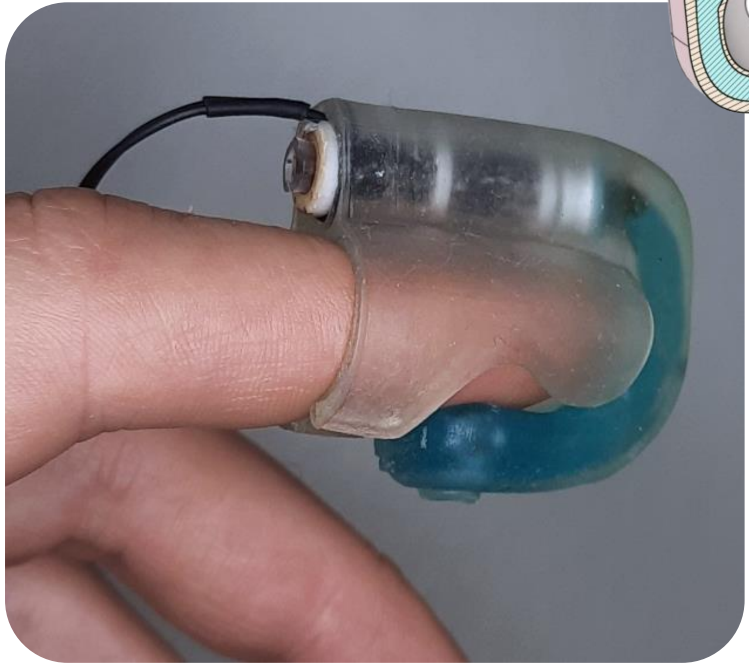
Leonardis, Daniele, Domenico Chiaradia, and Antonio Frisoli. "A Miniature Direct-Drive Hydraulic Actuator for Wearable Haptic Devices based on Ferrofluid Magnetohydrodynamic Levitation." *2023 IEEE World Haptics Conference (WHC)*. IEEE, 2023.

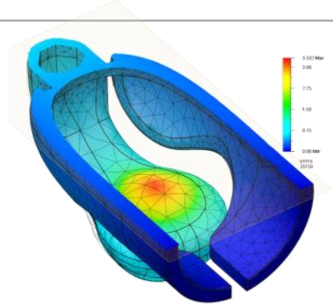
Direct-drive hydraulic actuator

Miniature hydraulic actuator

- Device embedded, no tethering
- Soft finger interface
- Better transmission of signals
- Potential of more complex shapes

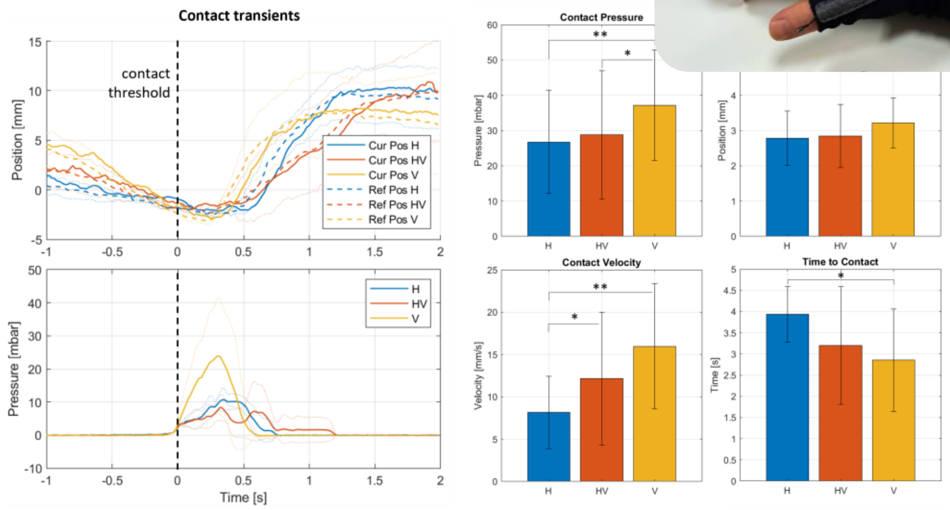






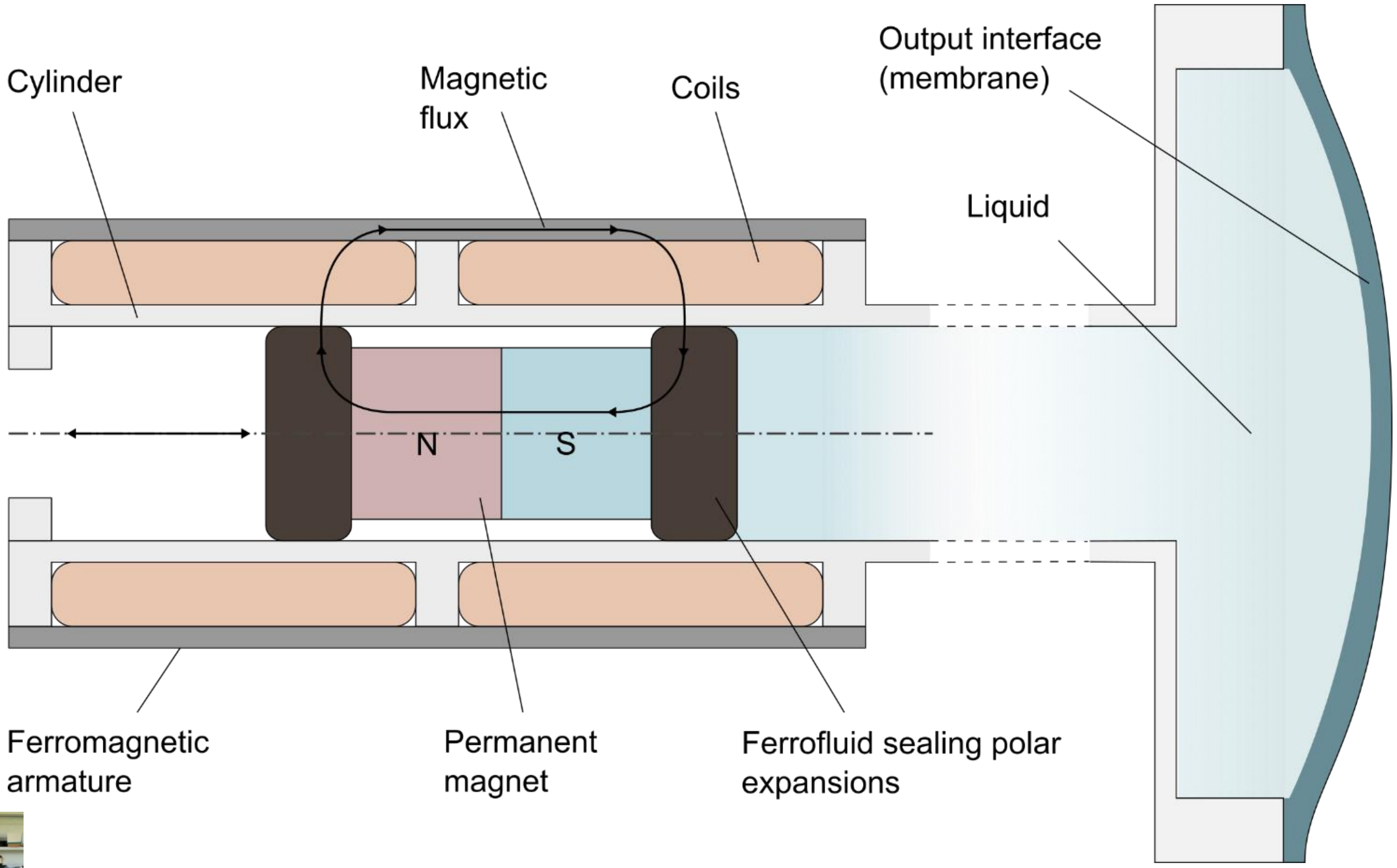
Novel prototype with different resin and coil materials
(aiming at improving long-term reliability)

Characterization and rendering experiments measuring higher force modulation control in virtual/teleoperated settings



Leonardis, Daniele, Domenico Chiaradia, and Antonio Frisoli. "A Miniature Direct-Drive Hydraulic Actuator for Wearable Haptic Devices based on Ferrofluid Magnetohydrodynamic Levitation." *2023 IEEE World Haptics Conference (WHC)*. IEEE, 2023.

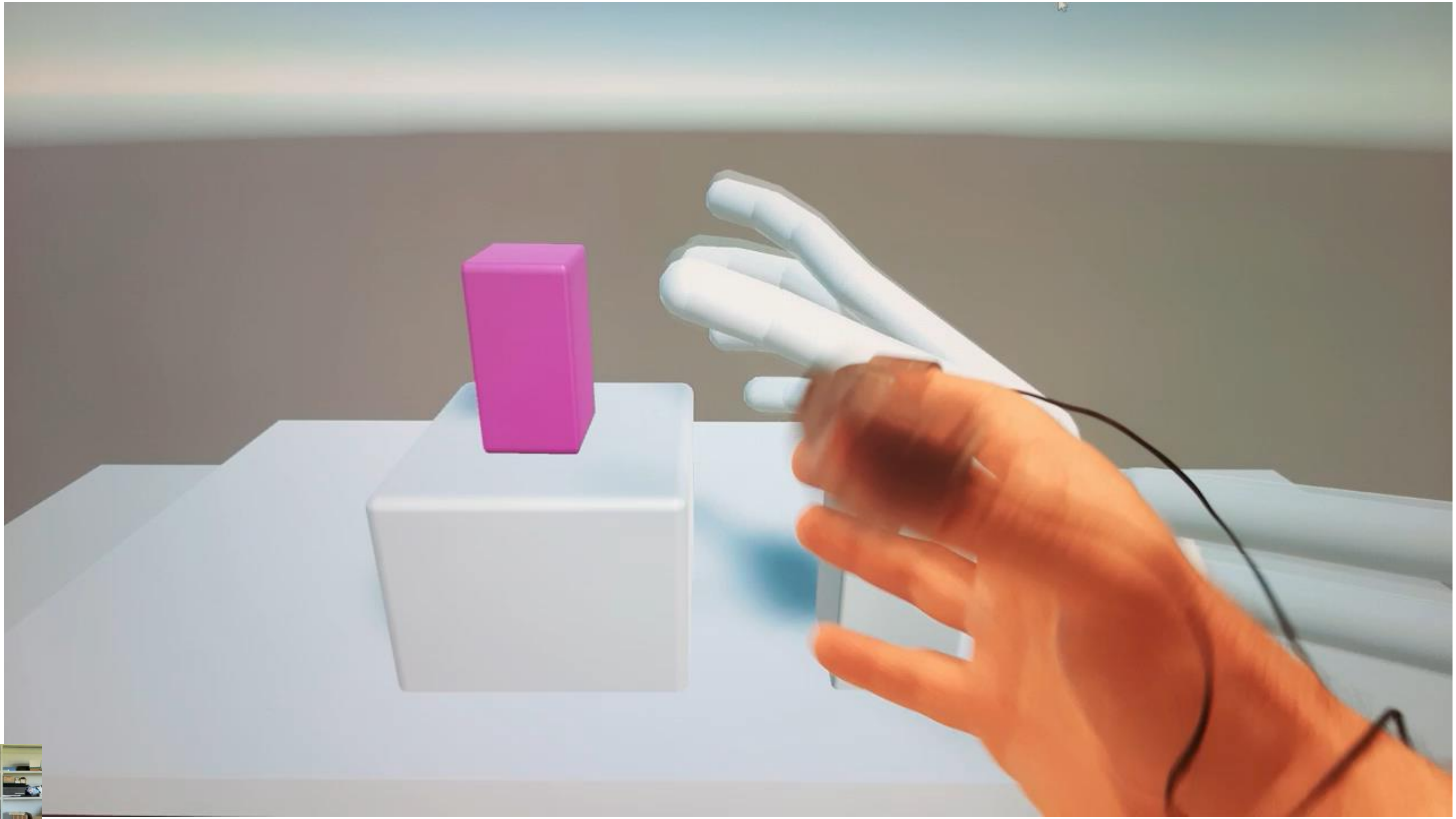
Ferrofluid sealing as part of the linear actuator



Magnet with ferrofluidic polar expansions

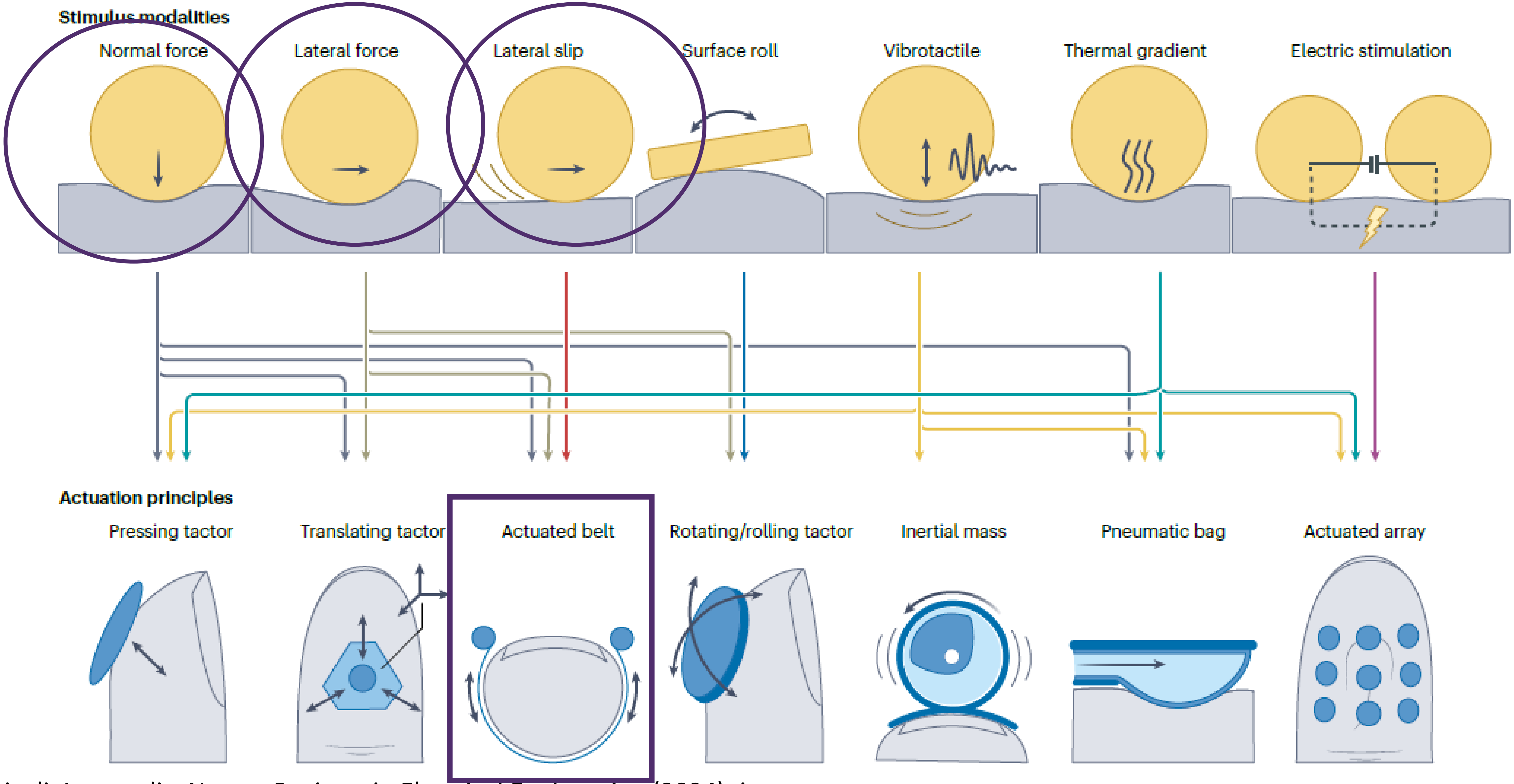
Implemented actuator (without iron armature)

With Daniele Leonardis



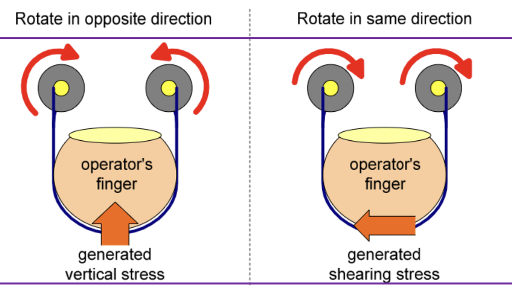
With Daniele Leonardis

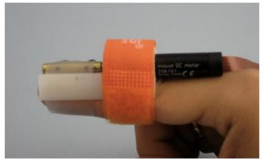
Principles for artificial haptics recreation



Frisoli, Leonardis, Nature Reviews in Electrical Engineering (2024), in press

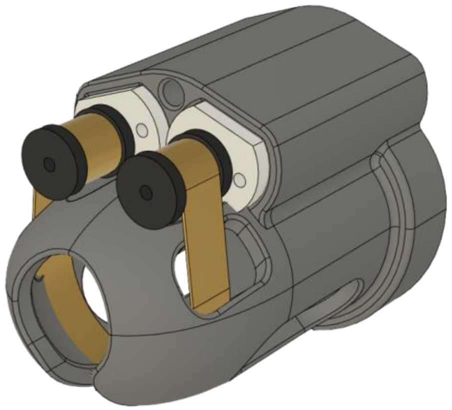
Belt-Driven direct-drive thimble



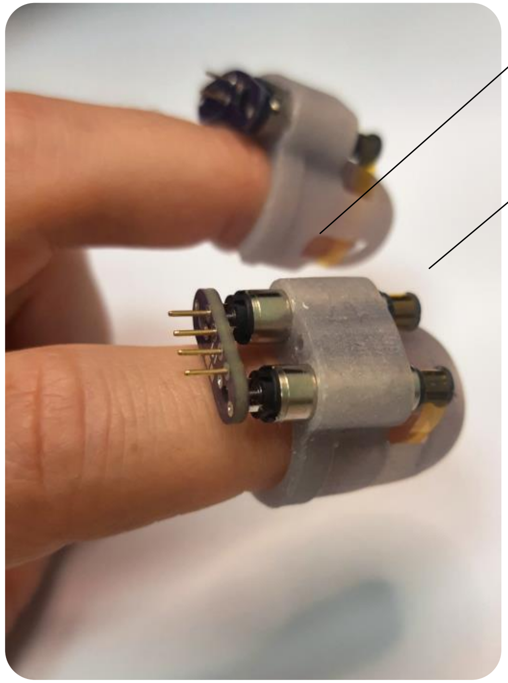


- Gravity Grapper was the 1st seminal work by Kouta Minimizawa

- Soft thimble, 3D printed, commercial miniature DC motors
- Shape and actuation method adaptable to large finger-dimensions range
- Robust, suitable for extensive use in rehabilitation



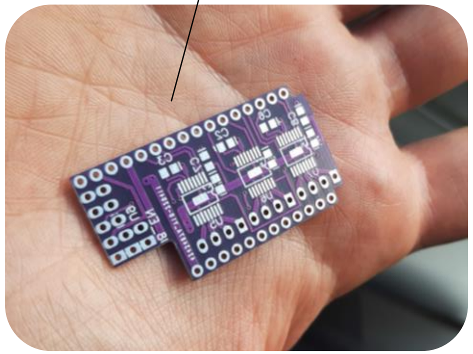
Improvements



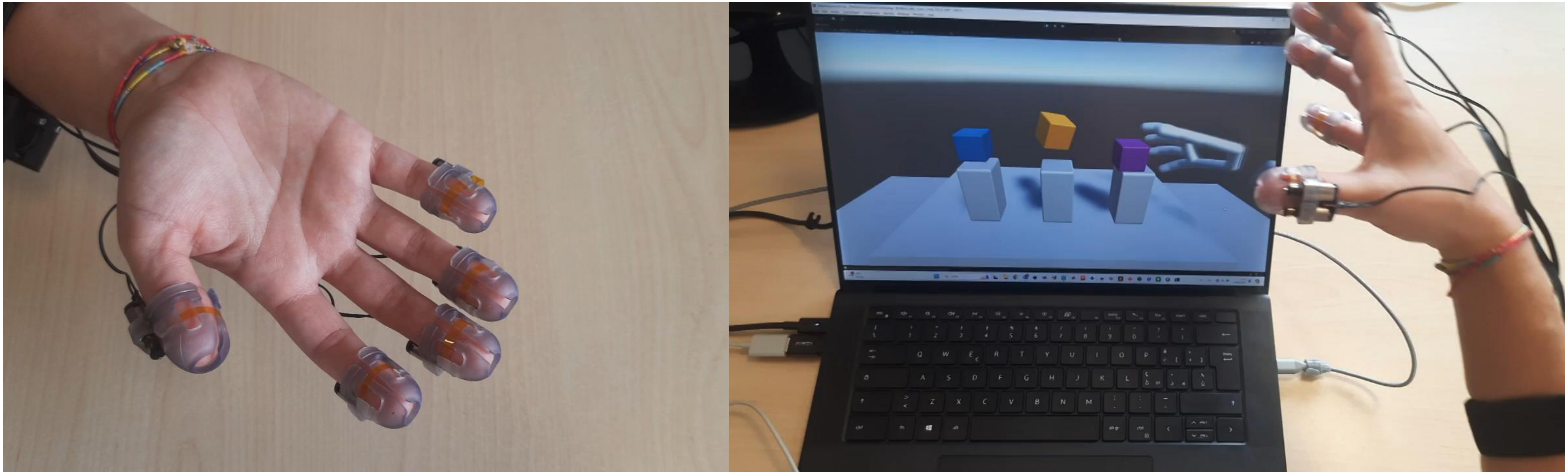
Novel miniature actuators (low-friction, precision ball bearings)

Colours compliant to IR vision-based tracking

Hand dorsum Integrated electronics for multi-finger configuration (5 actuators)



Minamizawa, Kouta, et al. "Gravity grabber: wearable haptic display to present virtual mass sensation." *ACM SIGGRAPH 2007 emerging*



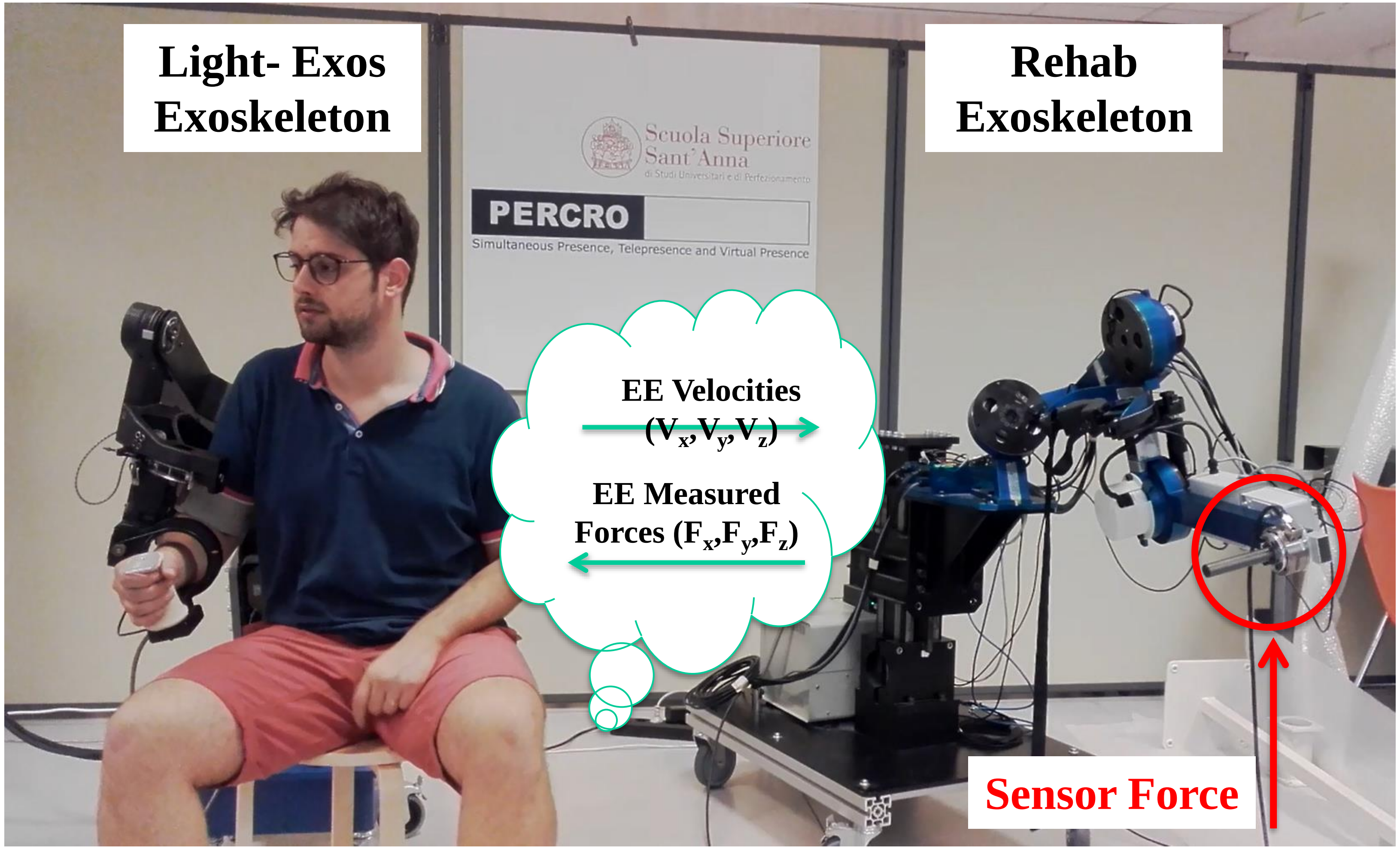
With Daniele Leonardis

Null Space Exploration for Enhanced Transparency Dissipation in rTDPA-based Teleoperation

INSTITUTE
OF MECHANICAL
INTELLIGENCE

Sant'Anna
Scuola Universitaria Superiore Pisa

Experimental Setup



Exoskeleton-based bilateral teleoperation of an asymmetrical master-slave system with a time Domain passivity approach

Domenico Buongiorno, Domenico Chiaradia, Massimiliano Solazzi and Antonio Frisoli

Scuola Superiore Sant’Anna, TeCIP Institute, PERCRO Laboratory, Pisa, Italy

Teleoperation Stability and Transparency Issues

• In teleoperation, achieving stability and transparency is crucial, but time delays cause instability.
• The Time-Domain Passivity Approach (TDPA) ensures stability but degrades transparency by introducing drift and jitter.

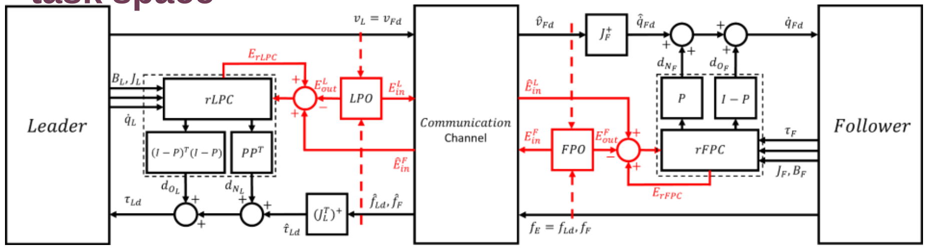
A proposed solution is rTDPA (Porcini et al., 2022)

The redundant TDPA (rTDPA) uses null space to dissipate energy and minimize transparency loss.

LBR iiwa - Kinematic Redundancy, KUKA - Robots & Automation,
https://www.youtube.com/watch?v=sZYBC8Lrmdo

- **Prioritize dissipation in Jacobian null-space**
- **Residual energy (if any) dissipated in the task space**

→ **THE TASK SPACE IS MINIMALLY INFLUENCED BY THE DISSIPATING ACTION**



However, rTDPA limitations like <u>suboptimal use of null space</u> lead to configuration issues.

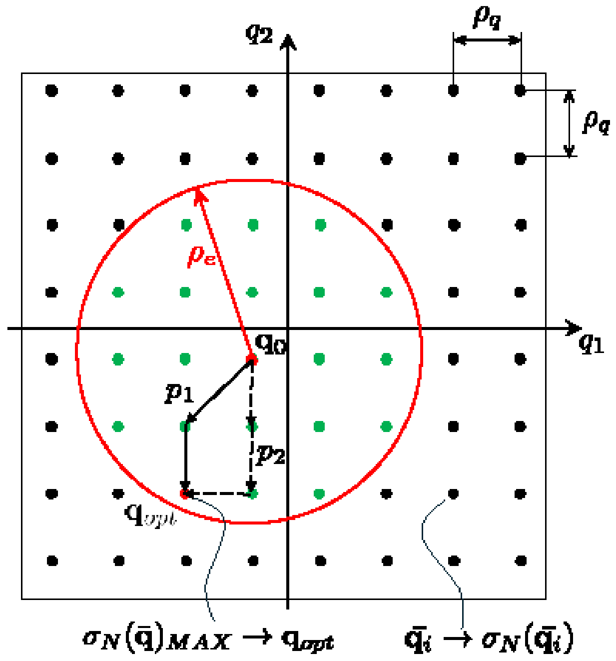
NrTDPA: Philosophy and Nullability Index

Nullability Index is defined as a measure of the robot's ability to manipulate in its null space, enhancing dissipation.

$$\sigma_N(q) = \frac{\sigma_{min}(P)}{\sigma_{MAX}(P)}$$

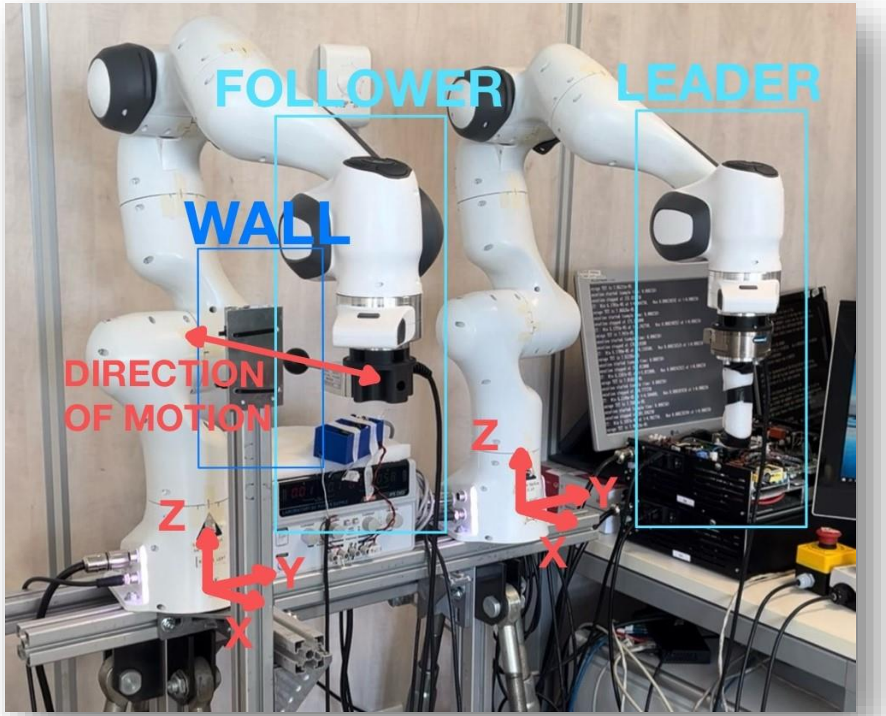
NrTDPA enhances rTDPA by maximizing the efficiency of energy dissipation in the null space. Thus, **the dissipation vector is defined to maximize the nullability index**.

- Joint space is explored computing Nullability index of each state
- An optimal path to maximize a cumulative Nullability index is identified
- The dissipation vector is oriented along this path



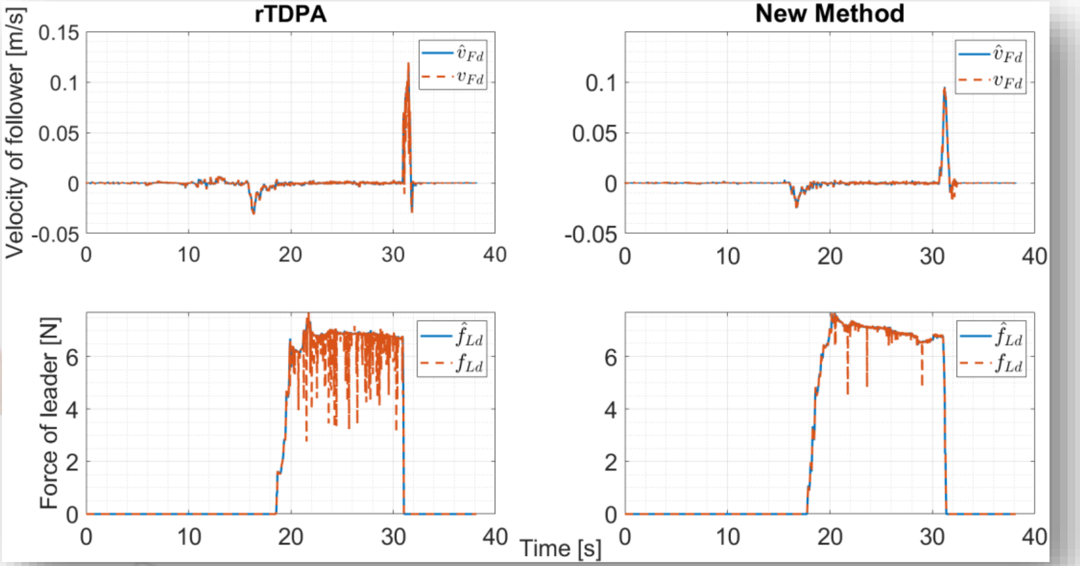
Experimental Setup and Procedure

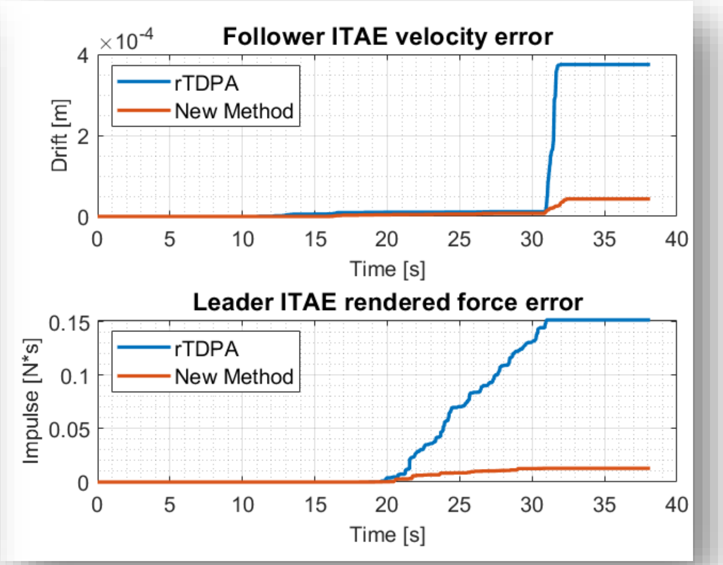
- The experiment used two Franka Emika Panda robots (leader and follower) with a 50 ms time delay.
- The follower tracked the leader's motion, interacting with a stiff wall, simulating real-world contact with time delay.



Results: ITAE and Velocity/Force Comparison

The experiment compared rTDPA and NrTDPA in terms of drift and force jitter.





- NrTDPA shows a significant improvement in transparency with lower drift and force jittering.
- ITAE results demonstrate a nearly one order of magnitude reduction in errors compared to rTDPA.

Towards a remote ultrasound diagnostic system

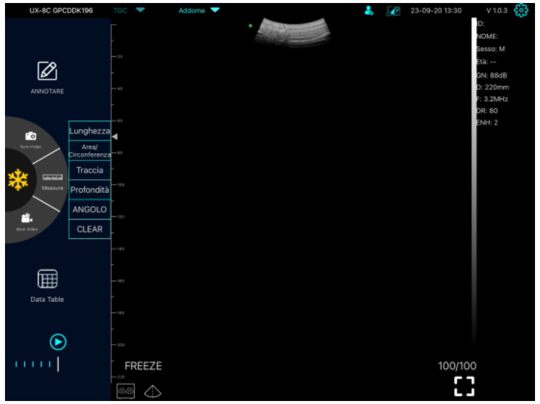
ISTITUTO DI INTELLIGENZA MECCANICA
Sant'Anna Scuola Universitaria Superiore Pisa

Overcoming existing solutions

- ✗ The mat in the doctor-site workstation does not allow you to manage the third dimension
- ✗ Difficulty distributing the gel and ensuring uniform contact of the transducer with the skin
- ✗ **Insufficient two-dimensional view from cameras**

Bilateral architecture

- ✓ Management of the third dimension and orientations through the haptic interface
- ✓ **Good gel distribution enabled by the use of the haptic interface**
- ✓ **Ongoing development of an optimal vision system**



Interfaccia aptica provvisiora + **sonda fittizia**

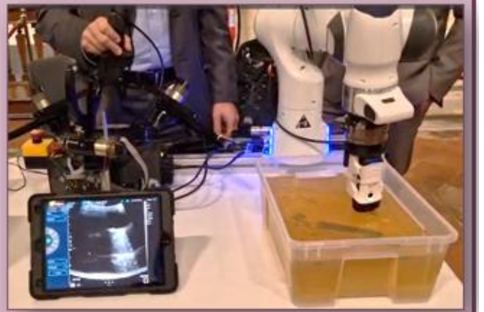
→

Integrazione dei componenti con **cobot** provvisorio

→

Integrazione con **Sonda wireless** + **tablet** per echo

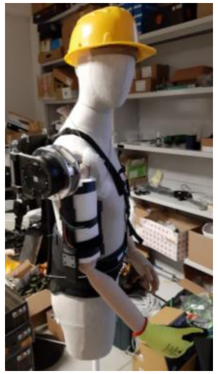
→



Architettura attuale

TRL 4

Human-Robot Interaction Group



thank you!

email: a.frisoli@santannapisa.it