POLITECNICO
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Hierarchical Control for Optimal Human-Robot Collaboration

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HUMAN-ROBOT INTERFACES AND INTERACTION

Context & Motivations

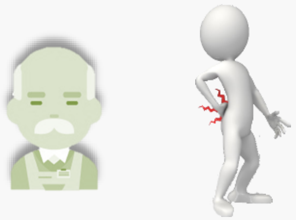
CONTEXT

Industrial Environment

Demanding physical tasks

OPEN ISSUES

Work-related MusculoSkeletal Disorders (MSDs)



Ageing industrial workforce

IMPACTS

Over 44 Million workers suffer from MSD in EU

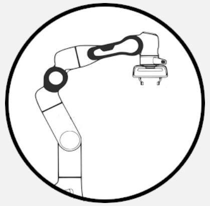
- Economical losses
- Production halts
- Less specialized workforce

OBJECTIVE

- Prioritise **human ergonomics** without compromising **productivity**
- Reduce work-related **MSDs**

OBJECTIVES: Enhance robot autonomy to improve HRI | Formulate Multi-Tasking robot behavior

Hierarchical Control for HRC



→ **A-HQP**

→ **Ergo-Aware A-HQP**

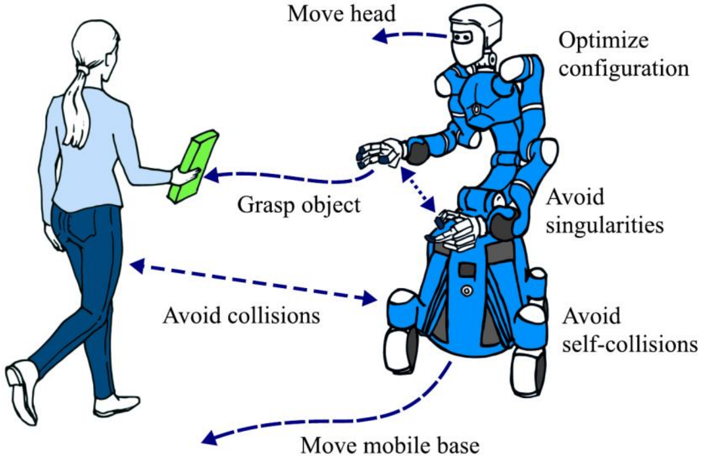
→ **Perception-Aware A-HQP**

Multi-Tasking in Human-Robot Collaboration

OBJECTIVES

Optimize multiple **human-related parameters**, e.g.: **human ergonomics** and **preference.**

Manage their **coexistence**, **prioritizing** some with respect to others.

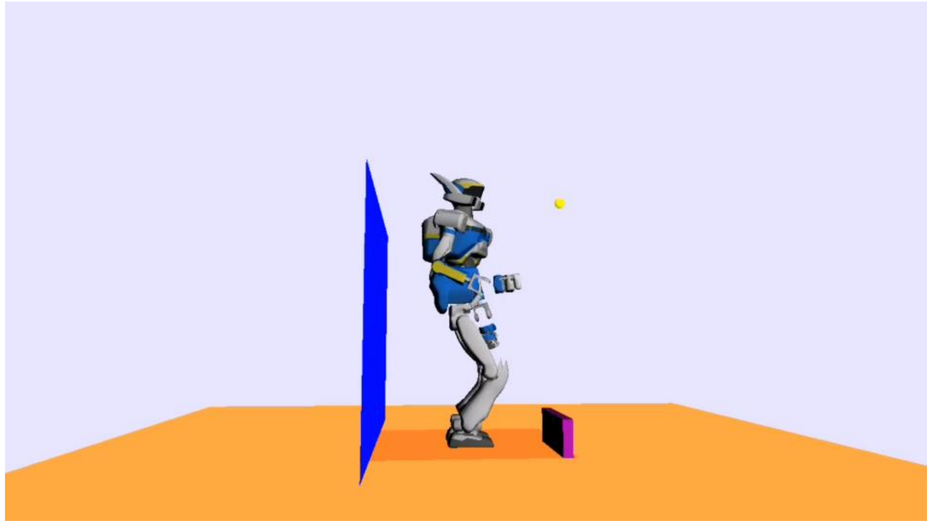


A.Dietrich, C. Ott, "Hierarchical Impedance-Based Tracking Control of Kinematically Redundant Robots“ (2019)

METHODS

Hierarchical Control & multi-tasking

(e.g. reach goal pose avoiding collision and keeping upright posture).
(Escande A. et al., 2014)



Escande, A. et al. “Hierarchical quadratic programming: Fast online humanoid-robot motion generation” (2014)

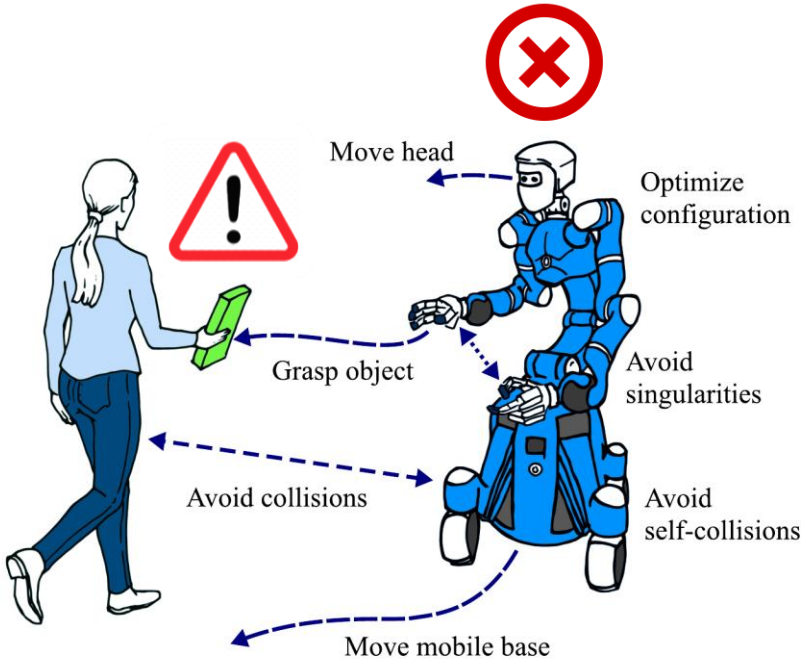
SoA and Current Limitations

Human-aware SoA & Limitations

- **Human Ergonomics** optimized at planning level only, with cumbersome kinematics models and low **real-time** feasibility (K. Otani et al., 2018; P. Tsarouchi et al., 2016).
- No **coexistence** of Human and Robot parameters, nor **prioritization** between each other.

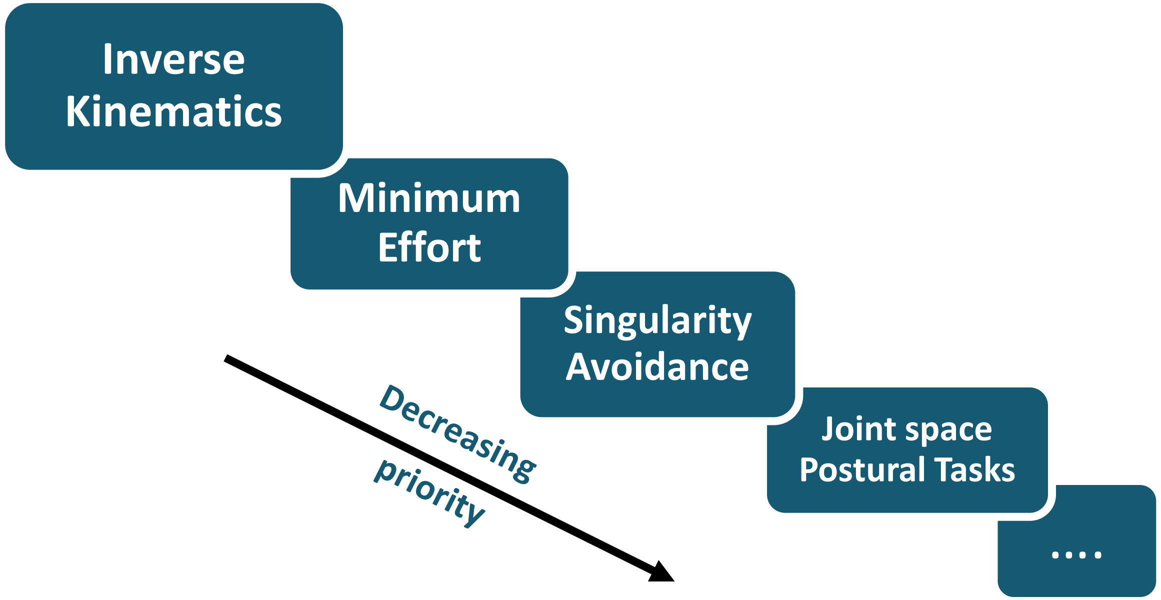
Hierarchical Control Limitations

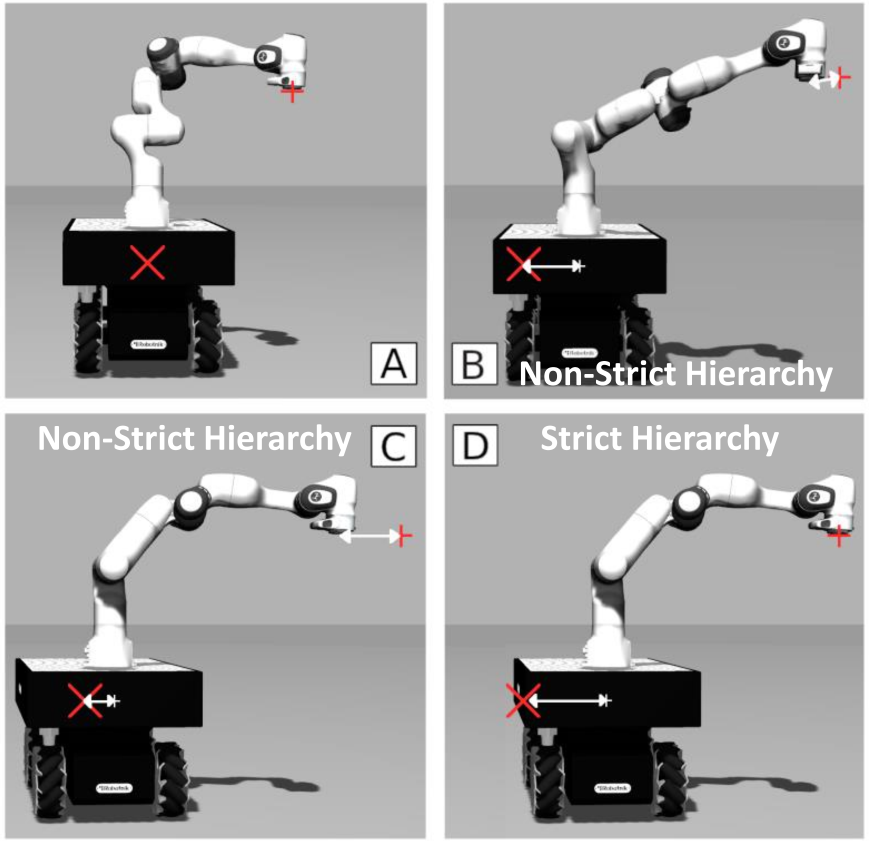
- Often used for highly redundant robots, but never accounts for **HRC.**
- Do not include **human** parameters such as: **Ergonomics**, **Preference** or **Intention.**
- Abstraction layer generated from **plan-control** separation.



Hierarchical Quadratic Programming: SoA

A **strict hierarchy** allows the definition of multiple **non-conflicting tasks**





Strict VS Non-Strict 2-layered hierarchy comparison. (A): both tasks for EE and base are feasible. (B-C-D): not simultaneously feasible tasks.

Hierarchical Quadratic Programming: SoA

QP Problem

$$\begin{aligned}
\min_{\chi} \ & \frac{1}{2}\|\boldsymbol{A}_k \chi - \boldsymbol{b}_k\|^2 \\
s.t. \ & \boldsymbol{C}_1 \chi \leq \boldsymbol{d}_1 \\
& \vdots \\
& \boldsymbol{C}_k \chi \leq \boldsymbol{d}_k \\
& \boldsymbol{E}_1 \chi = \boldsymbol{f}_1 \\
& \vdots \\
& \boldsymbol{E}_k \chi = \boldsymbol{f}_k
\end{aligned}$$

Stack of Tasks

QP Problem

QP Problem

QP Problem

QP Problem

Optimality condition between layers

$$A_{k-1}\ \chi_k = A_{k-1}\ \chi_{k-1}{}^*$$

HQP

Nested QP problems

Robot Autonomy for Reduced Human Injuries

Impact-Related Tasks and Human Injuries

The Issue

High **impact forces** generated by the human

Objective

Avoid **human injury** and potential **robot damage**

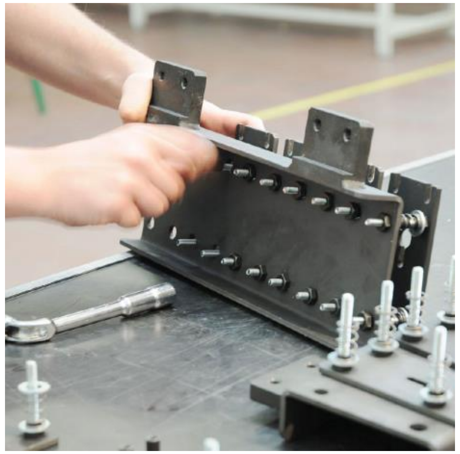
Requirement

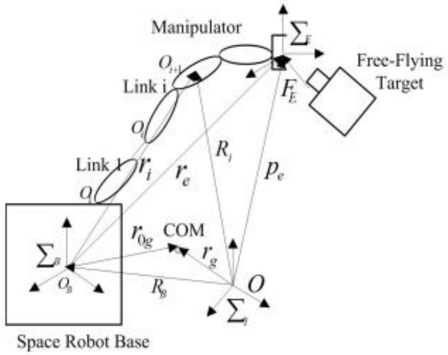
Generate a **specific** and consistent **impact force**

HAMMERING

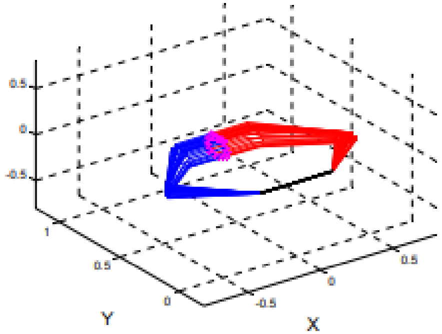
DEBURRING

ASSEMBLY

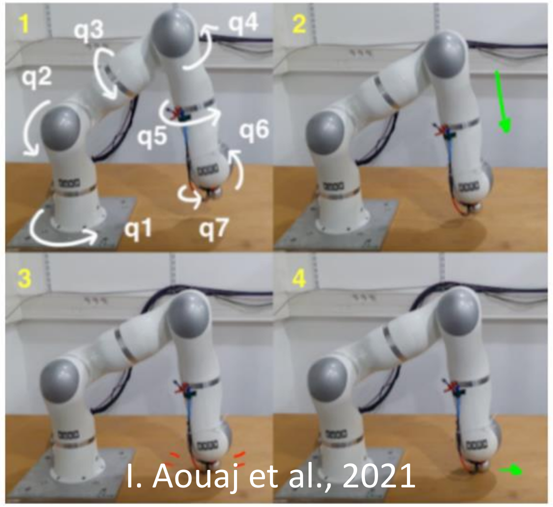




P. Huang et al., 2006



J. Y. Choi et al., 2008



I. Aouaj et al., 2021

Impact-Related Tasks and Human Injuries

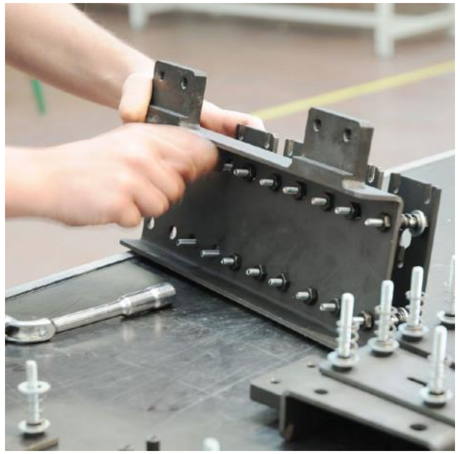
State-of-the-art

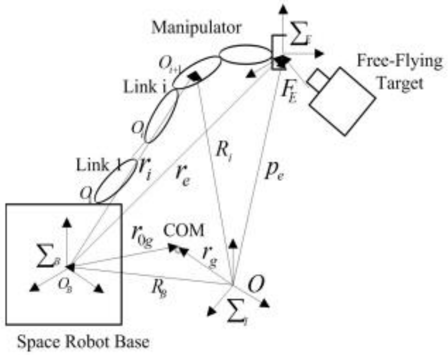
- Simulation-based
- No optimization
- No hierarchical behavior

HAMMERING

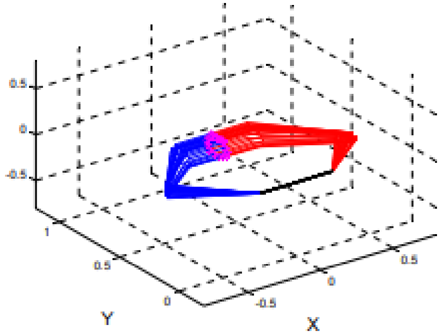
DEBURRING

ASSEMBLY

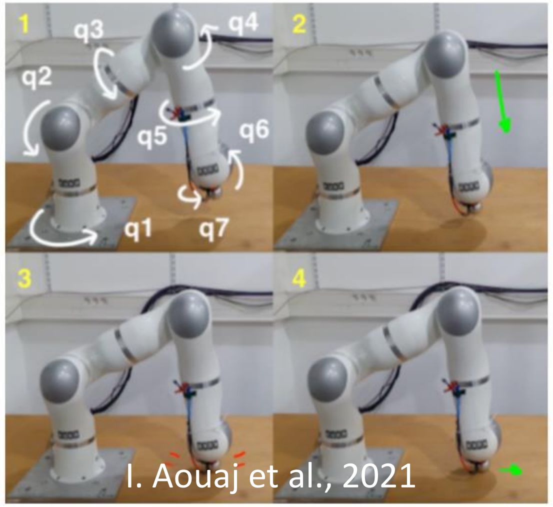




P. Huang et al., 2006



J. Y. Choi et al., 2008



I. Aouaj et al., 2021

Stack of Tasks

PRIORITIES

1 — **Inverse Kinematics**

$$\min_{\dot{\boldsymbol{q}}} ||\boldsymbol{J}\dot{\boldsymbol{q}} - \dot{\boldsymbol{x}}||^2$$

2 — **Impact Model**

$$\hat{\boldsymbol{F}} \propto \frac{1}{\boldsymbol{J}(\boldsymbol{q})\,\boldsymbol{M}(\boldsymbol{q})^{-1}\,\boldsymbol{J}(\boldsymbol{q})^{T}}$$

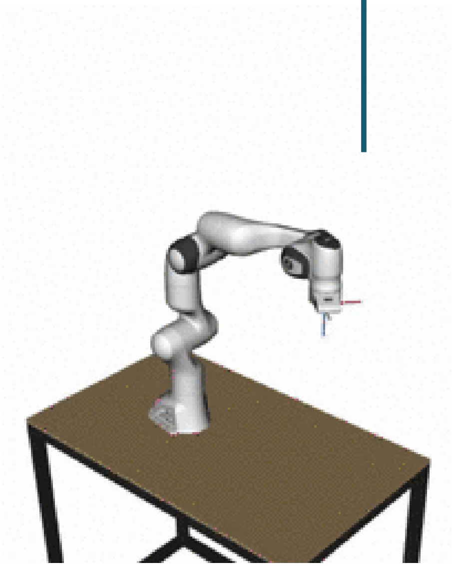
Impact Force

Dynamic Impact Measure (DIM)

$$w_{f_d}(\boldsymbol{q}) := \sqrt{\det\left(\boldsymbol{J}^{+}(\boldsymbol{q})^{T}\,\boldsymbol{M}(\boldsymbol{q})\,\boldsymbol{M}(\boldsymbol{q})^{T}\,\boldsymbol{J}^{+}(\boldsymbol{q})\right)}$$

Added to HQP as:

$$\min_{\boldsymbol{q}} \; -w_{f_d}(\boldsymbol{q})$$



Related publication:

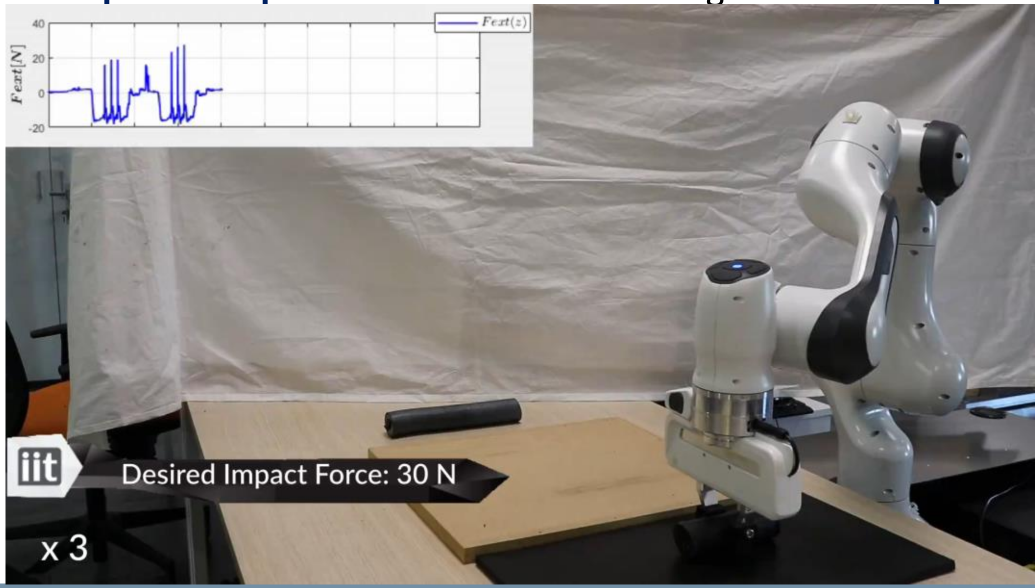
F. Tassi, S. Gholami, S. Giudice and A. Ajoudani, *"Impact Planning and Pre-configuration based on Hierarchical Quadratic Programming,"* 2022 International Conference on Robotics and Automation (ICRA), 2022.

Deburring Task

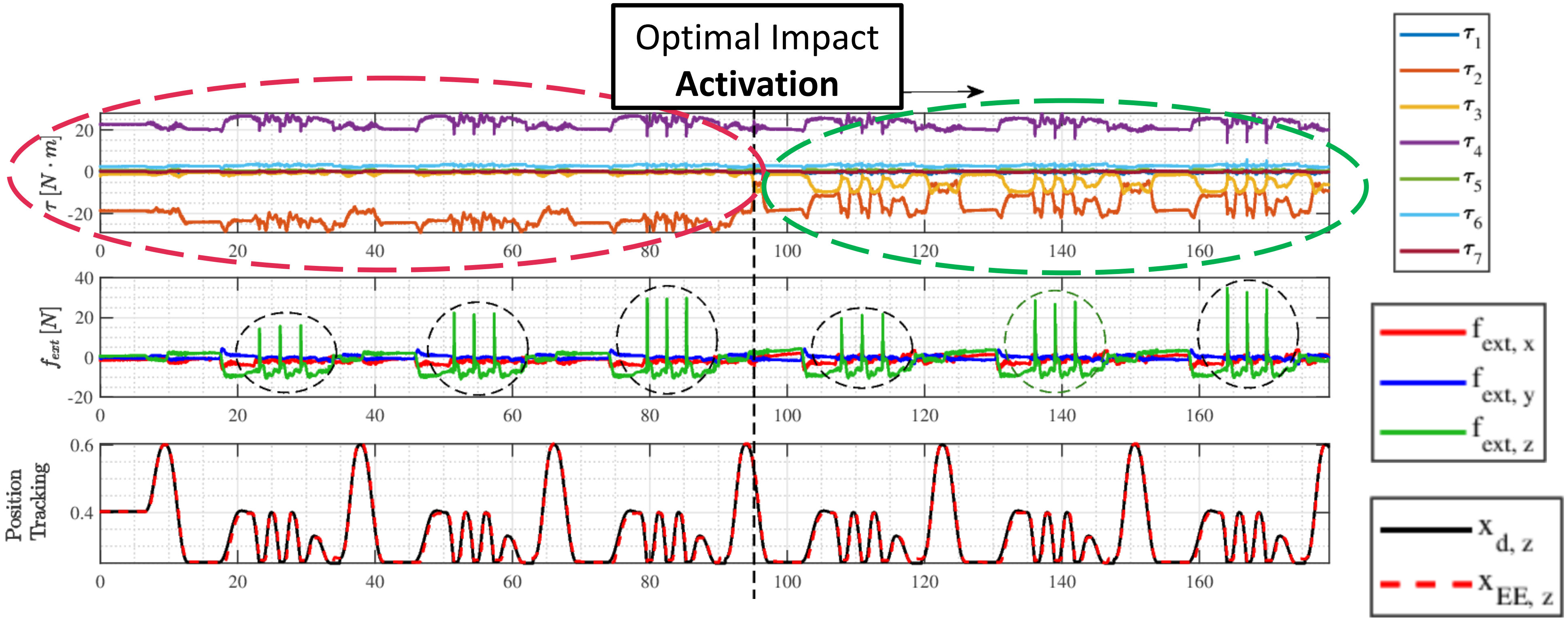
(excess material removal)

GOAL

Generate **specific impact forces** while minimizing **internal torques**



Deburring Task

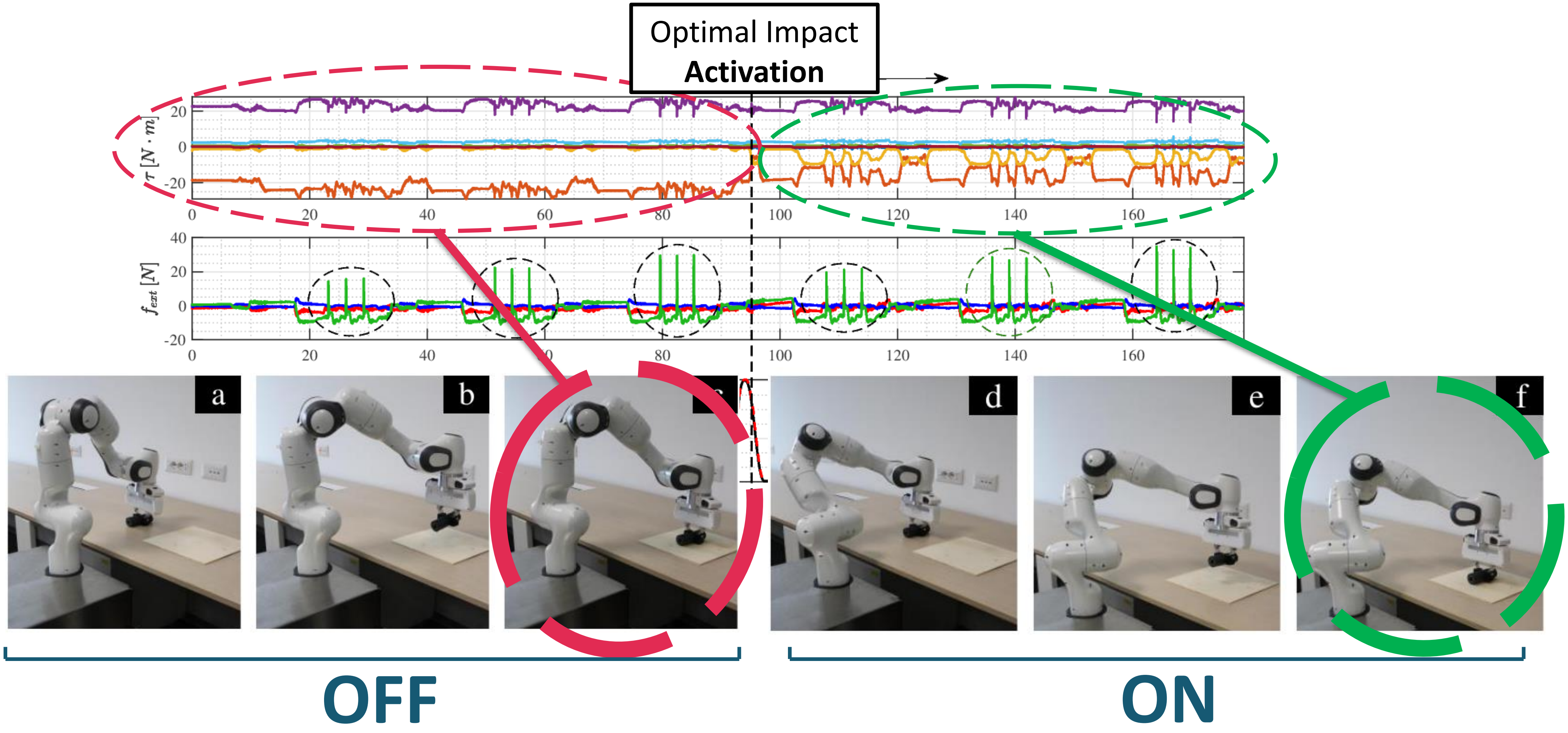


Impact Forces
Accurate and consistent

Robot Torques
optimal internal redistribution & peak reduction

End-Effector
accurate position/velocity tracking

Deburring Task



Far-Proximity
Human-Robot Interaction

Teleoperation: State-of-the-Art

Leader System

SpaceMouse Compact
3Dconnexion

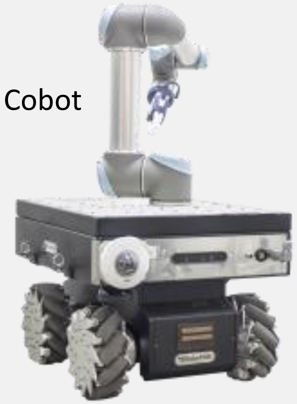
Phantom Omni Haptic Device
SensAble Tecnologies

Motion Capture System & VR
Image courtesy of GITAI

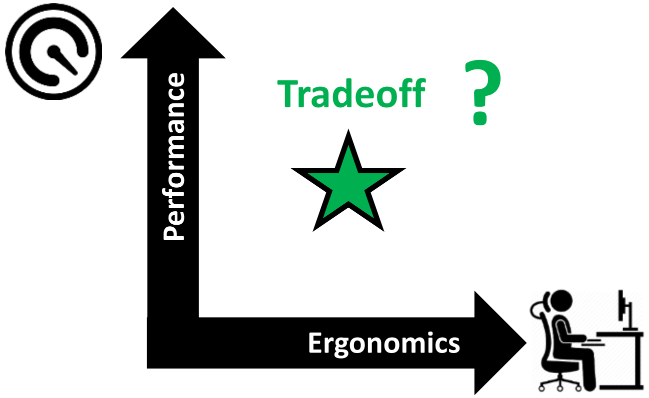
Control Pad Device
PlayStation 4 controller

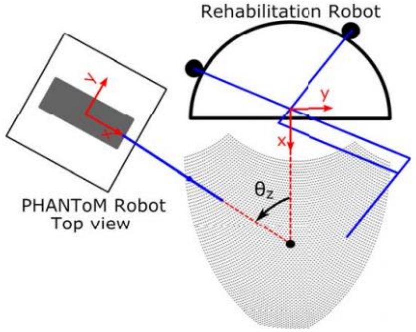
Follower System

Cobot

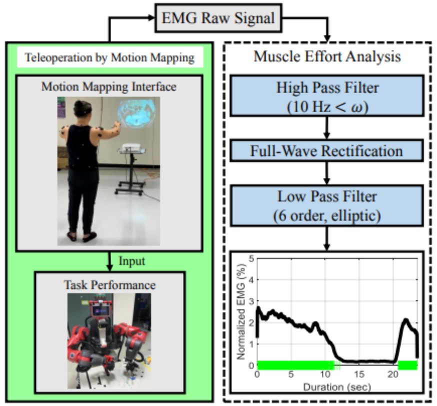


Current issues

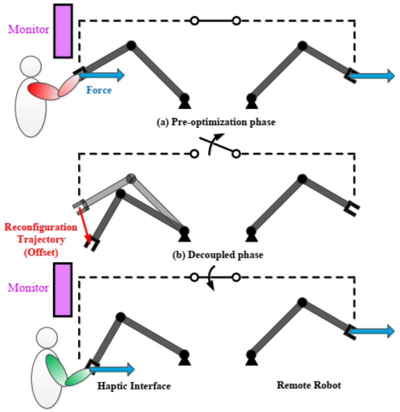




Torabi et al., ISMR 2018 *Manipulability*



Lin et al., ICRA 2020 *Shared-Autonomy*



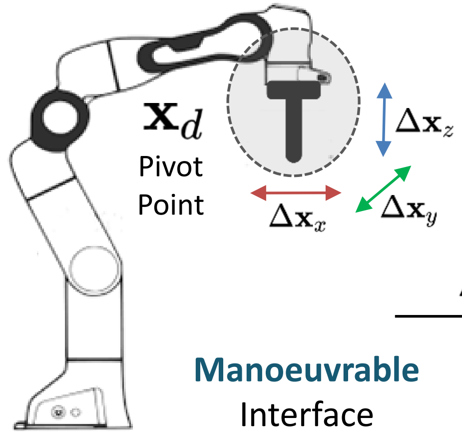
Peternel et al., BioRob 2020
Robot Posture Optimisation

Manoeuvrable + Ergonomic Interfaces

Far-proximity

Leader

Impedance Control



Manoeuvrable Interface

+

Ergonomic Interface

$\Delta\mathbf{x}$ →

Follower

VELOCITY PLANNER

$$\mathbf{v}_x = \frac{\Delta\mathbf{x}_x}{X_{max}}$$

$$\mathbf{v}_y = \frac{\Delta\mathbf{x}_y}{Y_{max}}$$

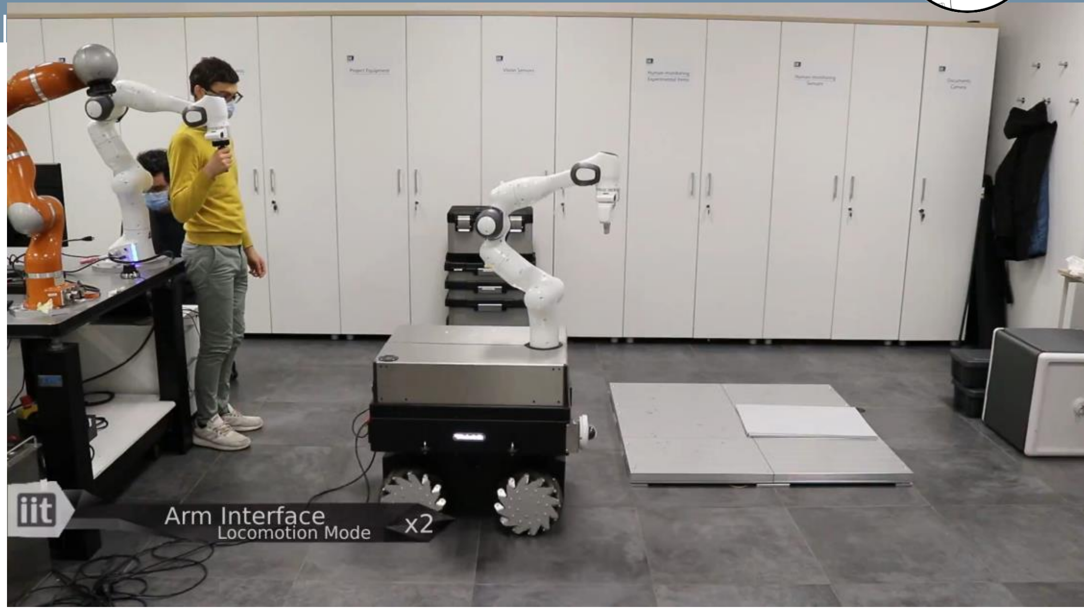
$$\omega_z = \frac{\Delta\mathbf{x}_z}{Z_{max}}$$

↓

Hierarchical Control

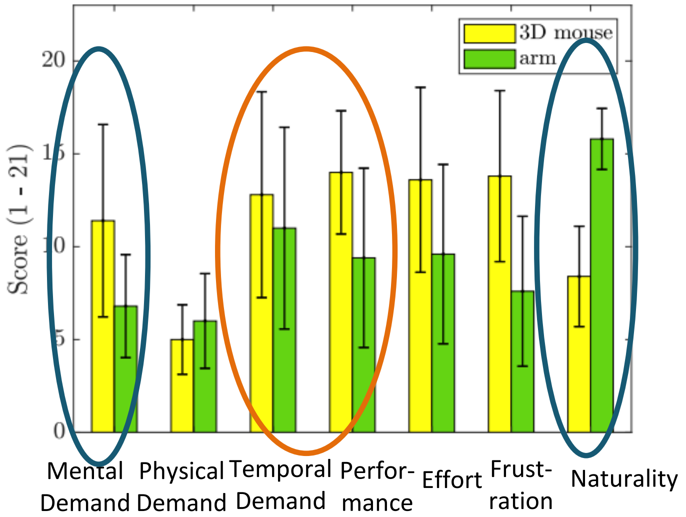
STACK OF TASKS

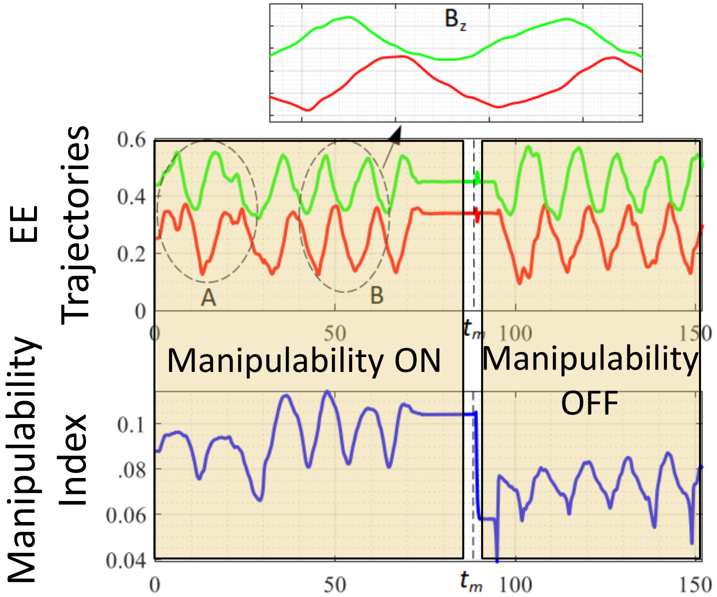
1. Robot Kinematics
2. Manipulability Optimization



Related publication: **F. Tassi**, S. Gholami, E. De Momi and A. Ajoudani, *"A Reconfigurable Interface for Ergonomic and Dynamic Tele-Locomanipulation,"* 2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2021, pp. 4260-4267.

NASA-TLX
(5 participants)



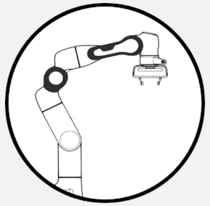


OBJECTIVES:

No dependency from fixed motion planning

Autonomous Adaptive Compliance

Hierarchical Control for HRC



→

A-HQP

→

Ergo-Aware A-HQP

→

Perception-Aware A-HQP

Human-Robot Interaction

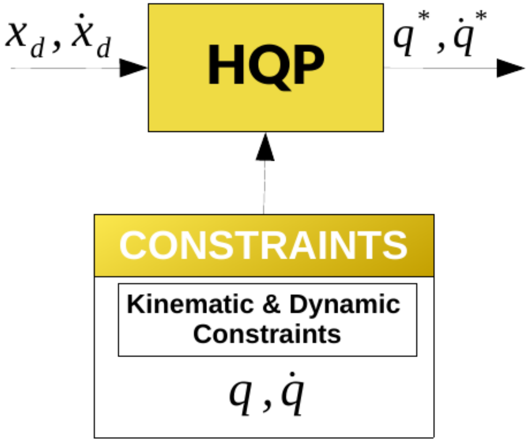
Human-Robot Physical Interaction	→	**GOAL** Prioritize HRI over robot precision	→	**HOW** • Adaptive compliance (@ control level) • Input shaping (@ planning level)

OBJECTIVES

1. Avoid dependency from fixed motion plan

2. ***Adaptive Compliance*** thanks to **intrinsic** input shaping (**no switches**):
   - Impedance-like behavior under **external forces**
   - Admittance-like behavior under **human forces**

→ Hybrid **impedance-admittance** behavior



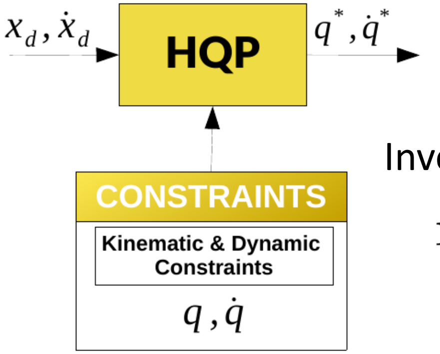
HQP

Inverse Kinematics problem

$$\min_{\dot{\boldsymbol{q}}} ||\boldsymbol{J}\dot{\boldsymbol{q}} - \dot{\boldsymbol{x}}||^2$$

Joint Velocities

Augmented HQP (A-HQP)



HQP

Inverse Kinematics problem

$$\min_{\dot{q}} ||J\dot{q} - \dot{x}||^2$$

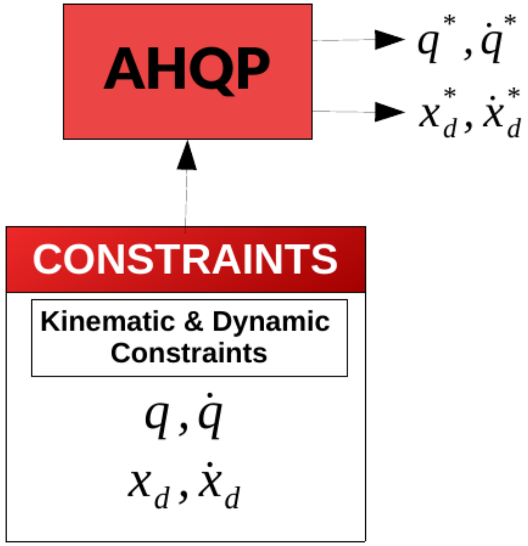
A-HQP

State augmentation

$$\chi = \begin{bmatrix} \dot{q} \\ \dot{x}_d \end{bmatrix}$$

Joint Velocities

Cartesian Velocities



- **Desired Cartesian trajectory x_d** is no longer an input, but becomes part of the optimization variable
- **No** higher level **trajectory generation**

Stack of Tasks

A-HQP

1 **Desired trajectory generation**

Optimization variable — Target Pose

$$\min_{\chi} ||x_d - x_t||^2$$

$$\chi = \begin{bmatrix} \dot{q} \\ \dot{x}_d \end{bmatrix}$$

AHQP → $q^*, \dot{q}^*$; $x_d^*, \dot{x}_d^*$

CONSTRAINTS

Kinematic & Dynamic Constraints

$q, \dot{q}$

$x_d, \dot{x}_d$

2 **Closed-Loop Inverse Kinematics (CLIK)**

$$\min_{\chi} ||J\dot{q} - \dot{x}||^2$$

Robot joints

Closed loop on End-effector Cartesian error

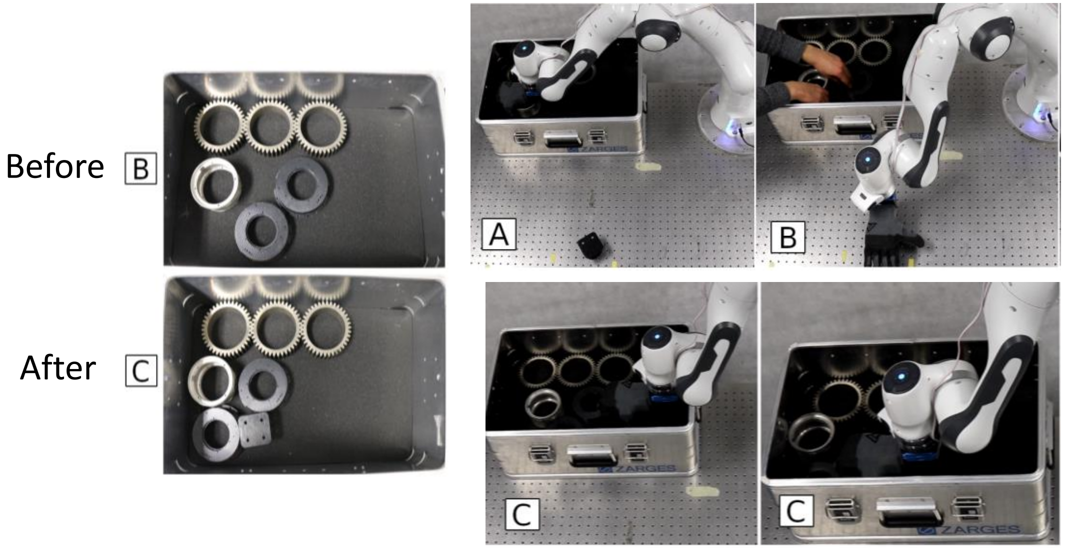
$$\min_{\chi} ||J\dot{q} - (\dot{x}_d + K_p(x_d - x_a))||^2$$

Measured pose

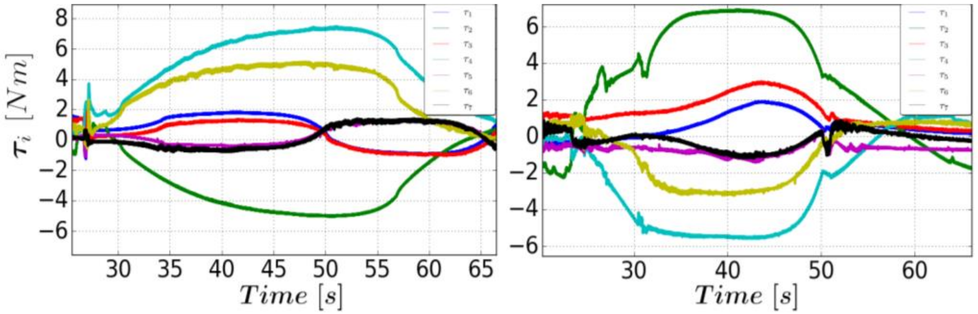
- **Optimal trajectory x_d** generated online based on constraints
- **Optimal reference shaping** → **Better Adaptive Compliance**

Collaborative Box-Filling using AHQP Adaptive Framework

A-HQP



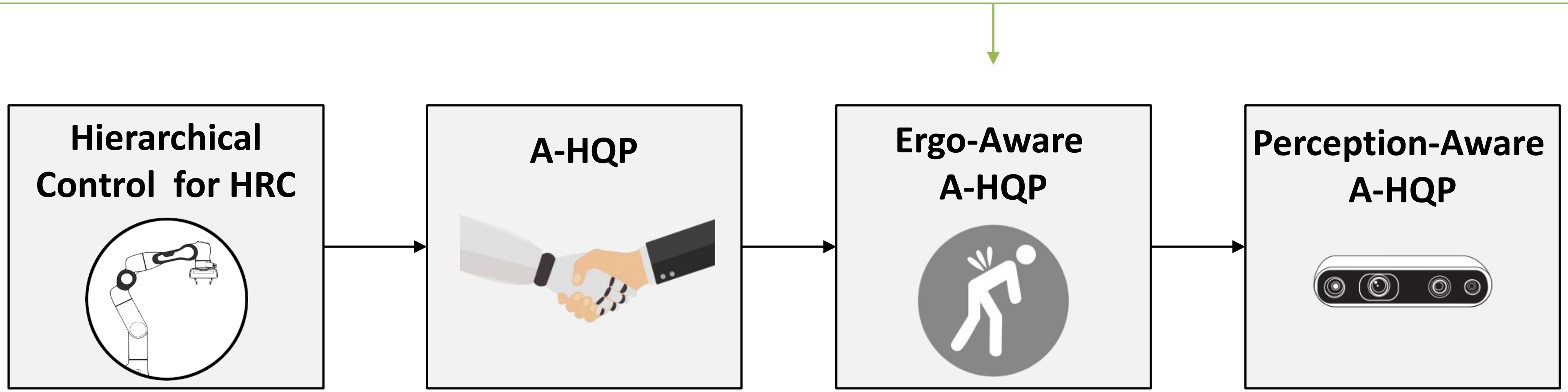
Robot torques adaptation during human intervention



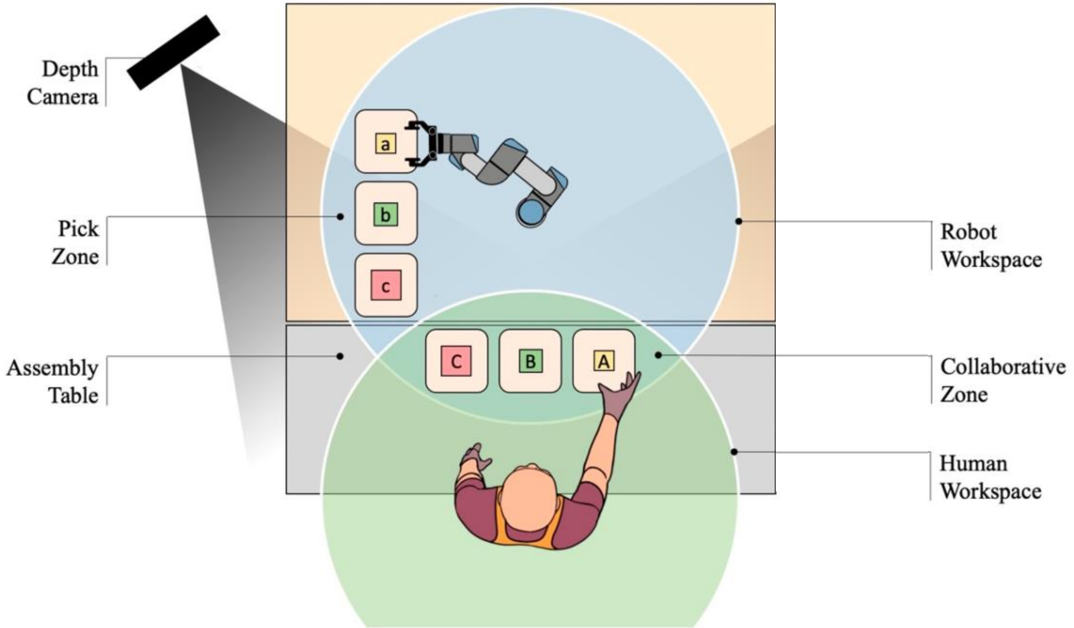
Related publication:

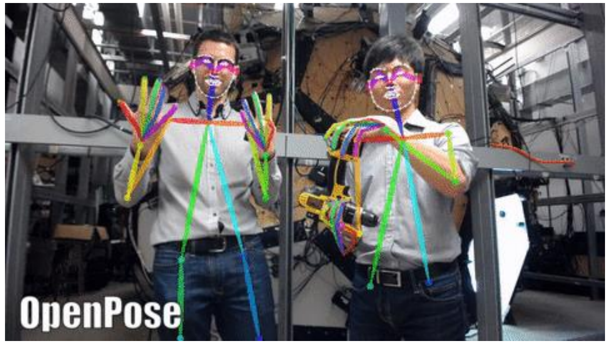
F. Tassi, E. De Momi and A. Ajoudani, "*Augmented Hierarchical Quadratic Programming for Adaptive Compliance Robot Control,*" 2021 IEEE International Conference on Robotics and Automation (ICRA), 2021, pp. 3568-3574.

OBJECTIVES: Prioritize Human vs Robot — Optimize Ergonomics hierarchically



Human Ergonomics Cartesian Mapping





https://github.com/CMU-Perceptual-Computing-Lab/openpose

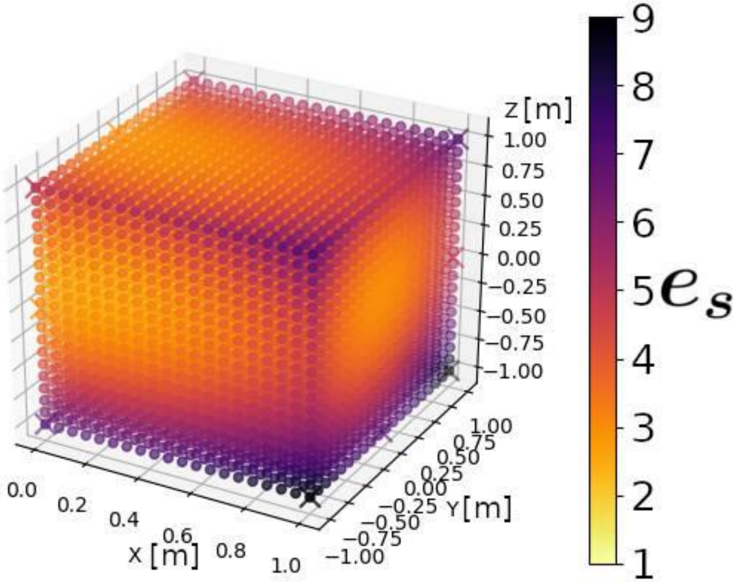
Creation of a Cartesian-based Ergonomics Map:

1. Acquisitions with OpenPose skeletal tracking for human reaching multiple points **inside the workspace**
2. **REBA** score calculation for each point
3. **Mapping** of the scores through **Cartesian** interpolation

REBA score

Ergo Plus: A Step-by-Step Guide to the REBA Assessment Tool
https://ergo-plus.com/reba-assessment-tool-guide/

Human Ergonomics Cartesian Mapping



Cartesian map of the REBA ergonomics score $\mathbf{e_s}$ for human's hand position. A higher score indicates a less ergonomic posture (1 being safe, while 9+ highly risky).

Ergonomics score ⇒ **As Cartesian function**

$$E_s = f(\boldsymbol{q_h})$$

Human joints

$$e_s = f(\boldsymbol{x_d})$$

Robot End-Effector (EE) pose

Human Ergonomics as QP function

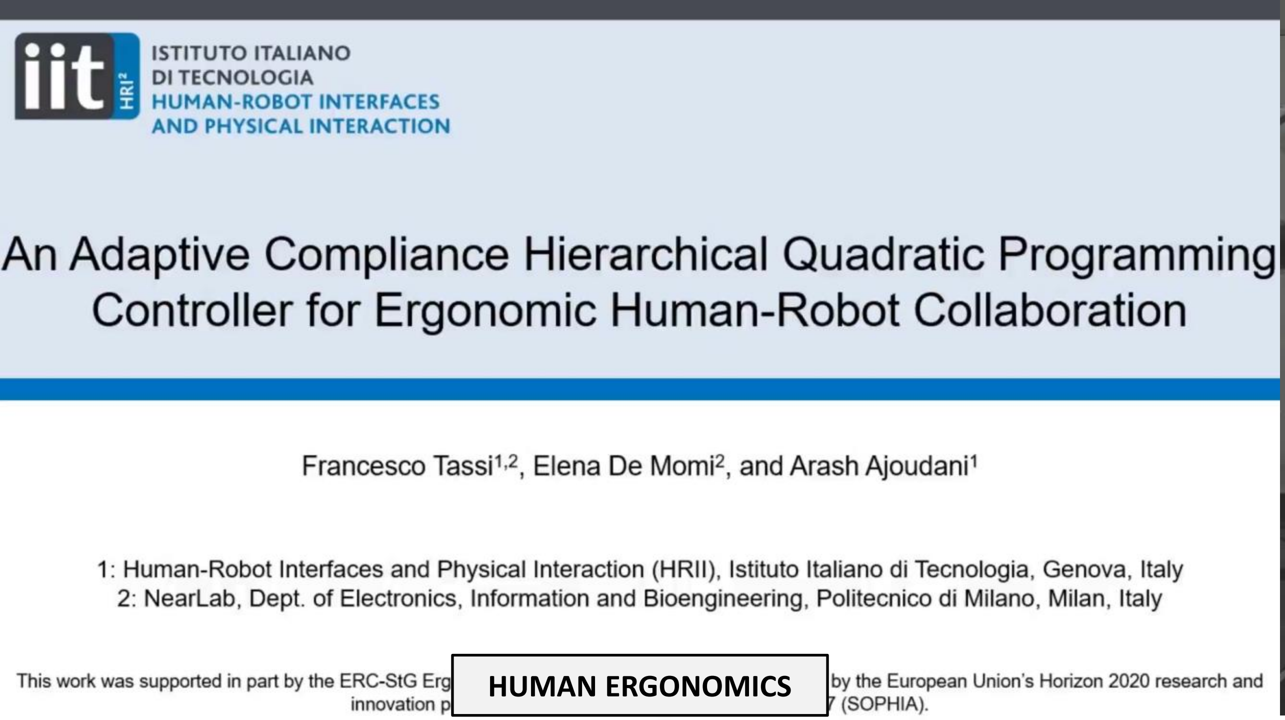
$$f(\boldsymbol{x_d}) = \frac{1}{2}\boldsymbol{x_d}^T \boldsymbol{H} \boldsymbol{x_d} + \boldsymbol{g}^T \boldsymbol{x_d}$$

Obtained from the mapping and passed to the HQP online

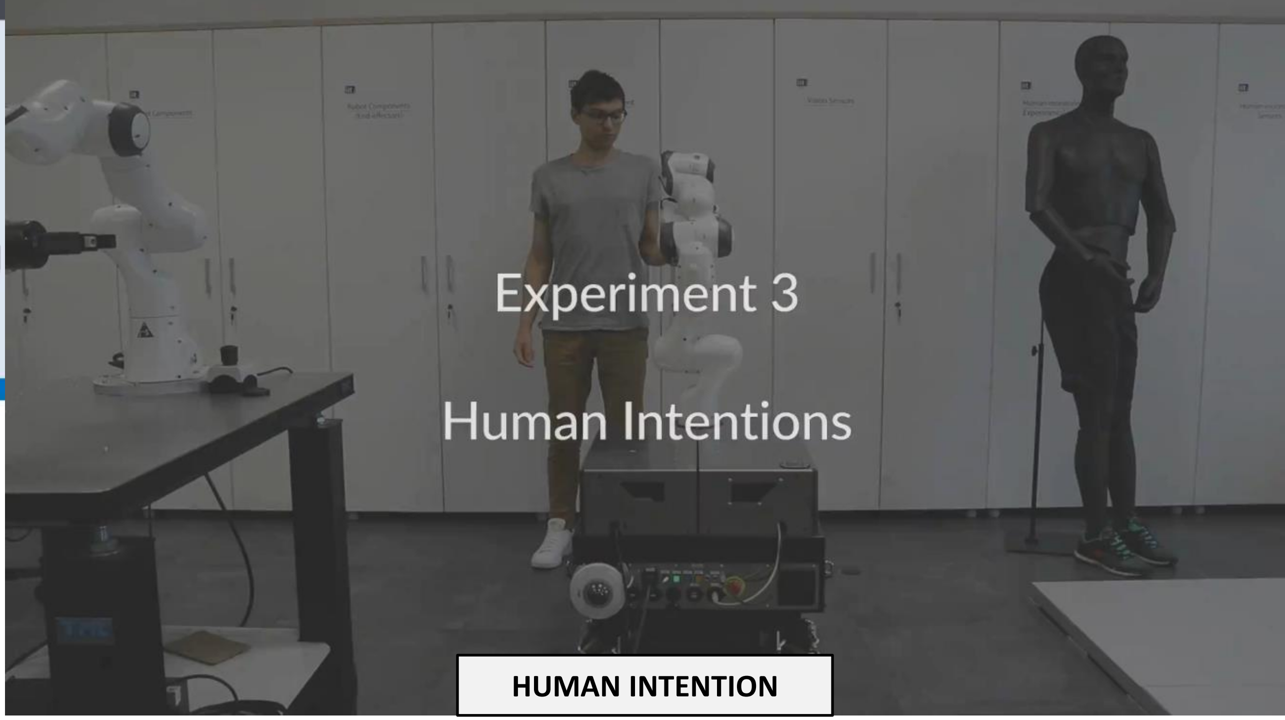
Max Ergonomics as HQP function

Can be added to the hierarchical **Stack of Tasks**.

$$\min_{\dot{\boldsymbol{q}}, \dot{\boldsymbol{x}}_{\boldsymbol{d}}} e_s = \min_{\dot{\boldsymbol{q}}, \dot{\boldsymbol{x}}_{\boldsymbol{d}}} f(\dot{\boldsymbol{x}}_{\boldsymbol{d}})$$

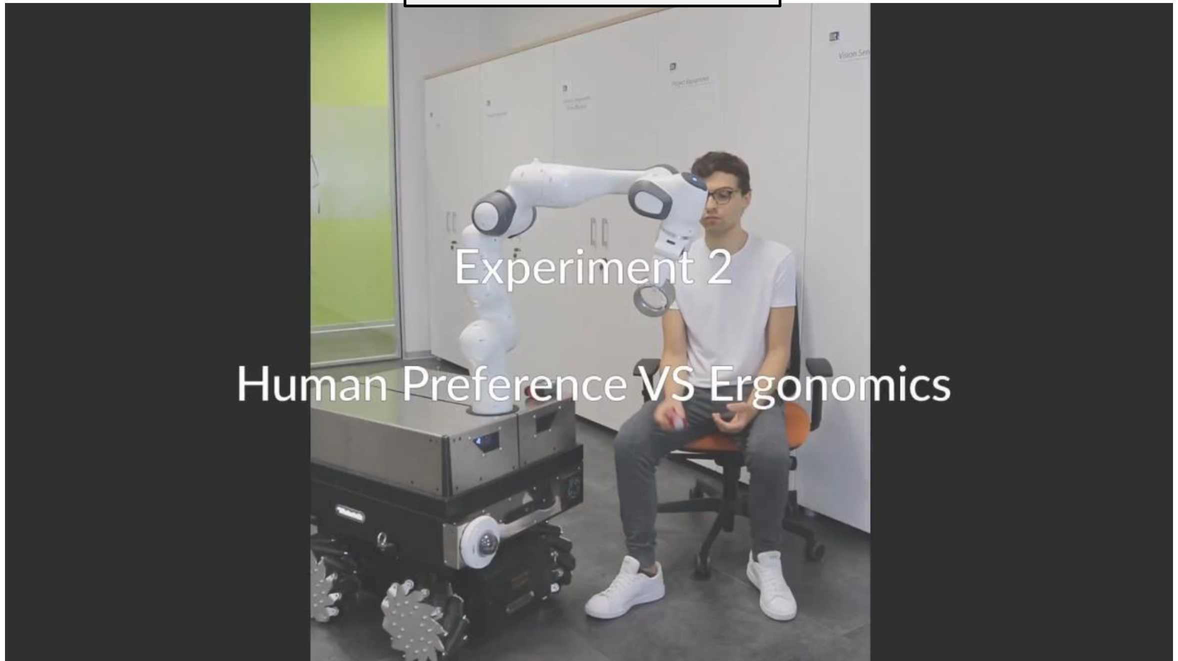


HUMAN ERGONOMICS



HUMAN INTENTION

HUMAN PREFERENCE

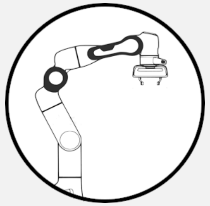


Related publication:

F. Tassi, E. De Momi, A. Ajoudani, "*An adaptive compliance Hierarchical Quadratic Programming controller for ergonomic human–robot collaboration,*" Robotics and Computer-Integrated Manufacturing, Volume 78, 2022, 102381.

OBJECTIVES: Perceive human actions | Enable *In-Movement* Interaction

Hierarchical Control for HRC

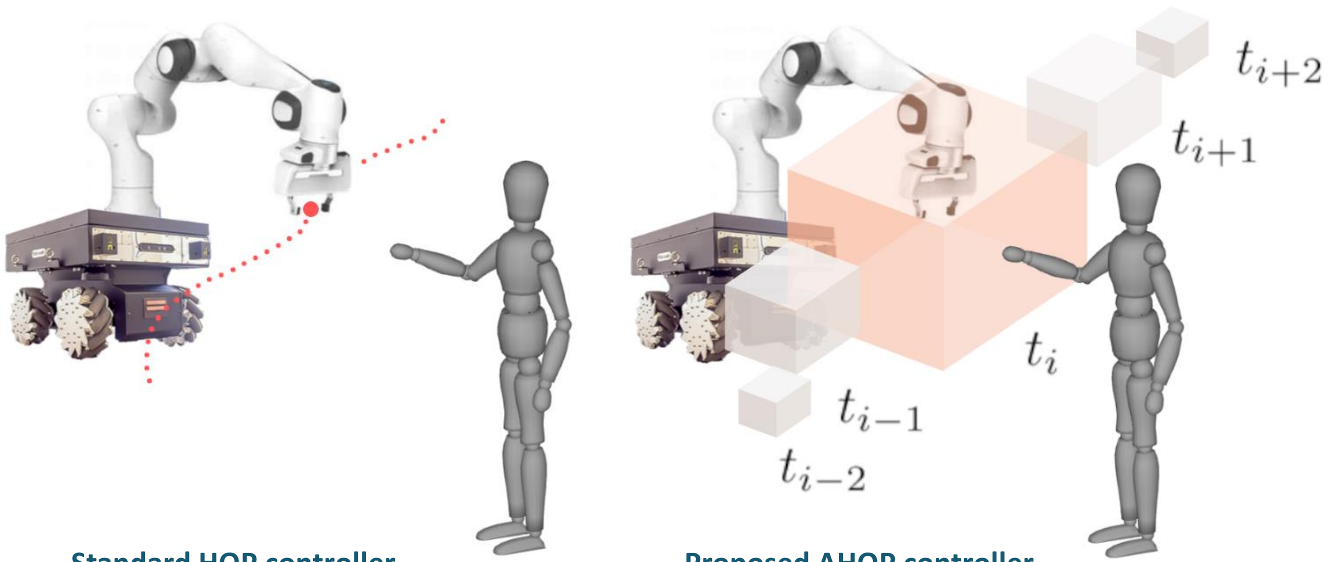


A-HQP

Ergo-Aware A-HQP

Perception-Aware A-HQP

In-Movement Human-Robot Interaction



Standard HQP controller

Proposed AHQP controller

SoA controllers (left)

Human adapts to robot trajectory dictated by motion planning

Proposed AHQP controller (right)

- **H**uman-**R**obot **S**hared **W**orkspace (**HRSW**), at time instant t_i enables **interaction during movement**
- Inside HRSW, the robot identifies the optimal pose based on the hierarchy of tasks.
- **Robot adapts** to the **human** and not vice versa.

Human-Robot Shared Workspace (HRSW)

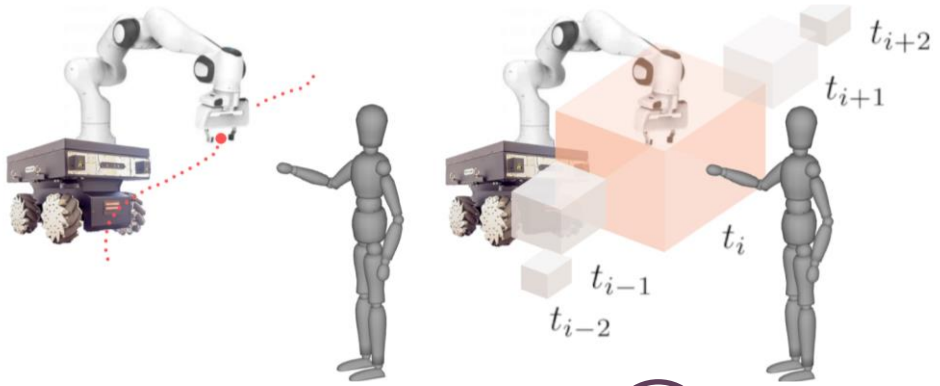
$$\min_{\mathcal{X}, \boldsymbol{s}} \frac{1}{2} \|\boldsymbol{s}\|^2$$

Slack variable

$$s.t.\ \boldsymbol{x}_{\boldsymbol{d}_{min}} - \boldsymbol{s} \leq \boldsymbol{x}_{\boldsymbol{d}} \leq \boldsymbol{x}_{\boldsymbol{d}_{max}} + \boldsymbol{s}$$

Cartesian constraint on EE pose to define the shared workspace

Stack of Tasks (SoT)



1 **Human-Robot Shared Workspace (HRSW)**

$$\min_{\chi, \boldsymbol{s}} \frac{1}{2}||\boldsymbol{s}||^2$$

$$s.t.\ \boldsymbol{x}_{\boldsymbol{d}_{min}} - \boldsymbol{s} \leq \boldsymbol{x}_{\boldsymbol{d}} \leq \boldsymbol{x}_{\boldsymbol{d}_{max}} + \boldsymbol{s}$$

→ Slack variable

→ Cartesian constraint on EE pose to define the shared workspace

2 **Optimal Ergonomics**

$$\min_{\dot{\boldsymbol{q}}, \dot{\boldsymbol{x}}_{\boldsymbol{d}}} e_s = \min_{\dot{\boldsymbol{q}}, \dot{\boldsymbol{x}}_{\boldsymbol{d}}} f(\dot{\boldsymbol{x}}_{\boldsymbol{d}})$$

→ Ergonomics Score (REBA) minimization

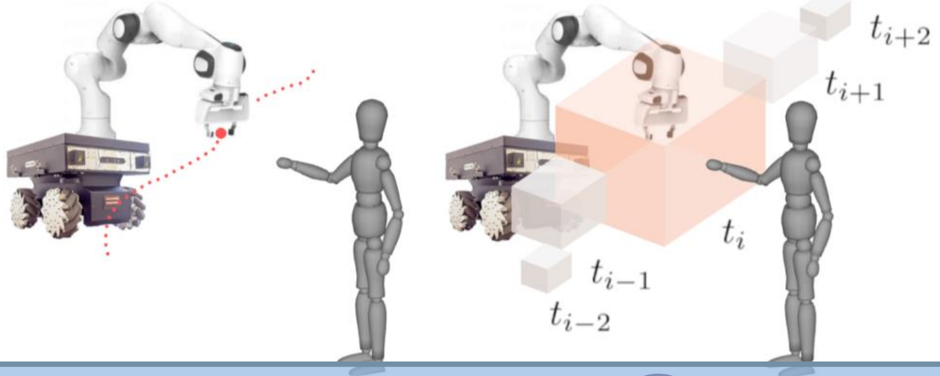
3 **Closed-Loop Inverse Kinematics (CLIK)**

$$\min_{\dot{\boldsymbol{q}}} ||\boldsymbol{J}\dot{\boldsymbol{q}} - (\dot{\boldsymbol{x}}_d + \boldsymbol{K}_{\boldsymbol{p}}(\boldsymbol{x}_d - \boldsymbol{x}_a))||^2$$

Robot joints

→ Trajectory tracking: desired $\boldsymbol{x}_{\boldsymbol{d}}$ vs actual $\boldsymbol{x}_{\boldsymbol{a}}$ EE pose

Stack of Tasks (SoT)



1 **Human-Robot Shared Workspace (HRSW)**

$$\min_{\chi, s} \frac{1}{2} ||s||^2$$ → Slack variable

$$s.t.\ x_{d_{min}} - s \leq x_d \leq x_{d_{max}} + s$$ → Cartesian constraint on EE pose to define the shared workspace

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$$\min_{\dot{q}, \dot{x}_d} e_s = \min_{\dot{q}, \dot{x}_d} f(\dot{x}_d)$$ → Ergonomics Score (REBA) minimization

HUMAN

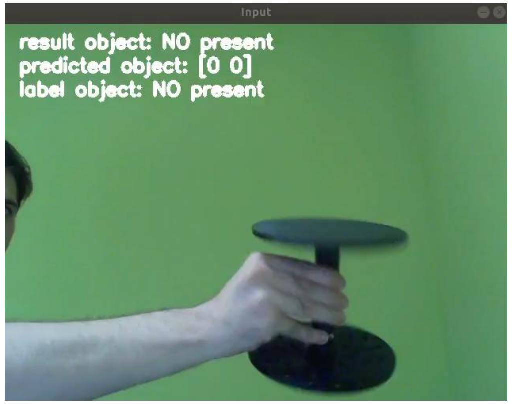
3 **Closed-Loop Inverse Kinematics (CLIK)**

$$\min_{\dot{q}} ||J\dot{q} - (\dot{x}_d + K_p(x_d - x_a))||^2$$ → Trajectory tracking: desired x_d vs actual x_a EE pose

Robot joints

ROBOT

Perception-Aware HQP



Objective

Obtain a Perception-Aware Ergonomic Controller, to include Human Actions recognition

How to

Addition of **3 new modules**:

3D Human Tracking:

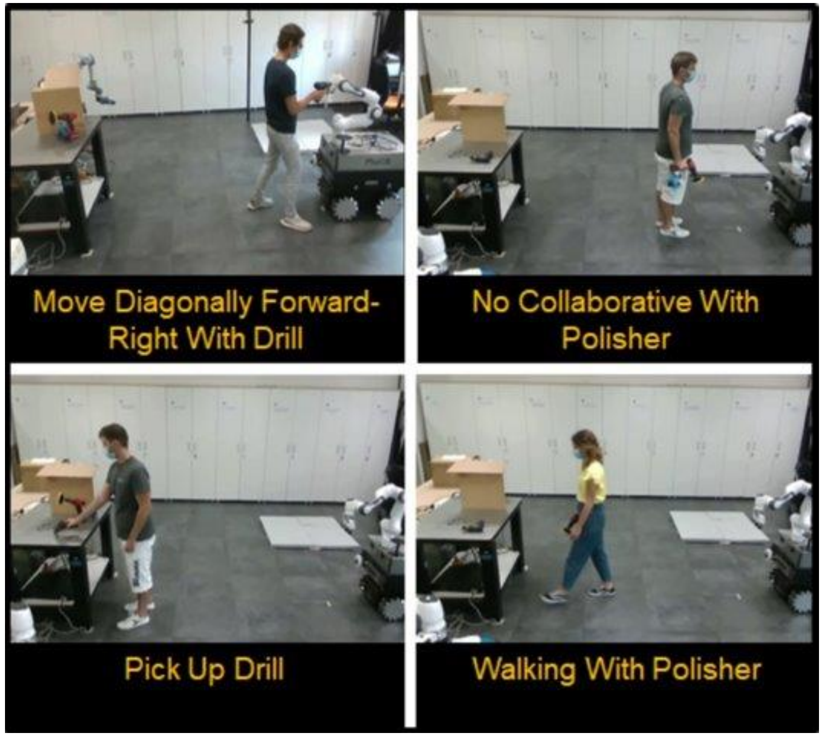
- Online update of the **ergonomic map** based on **human's position**.

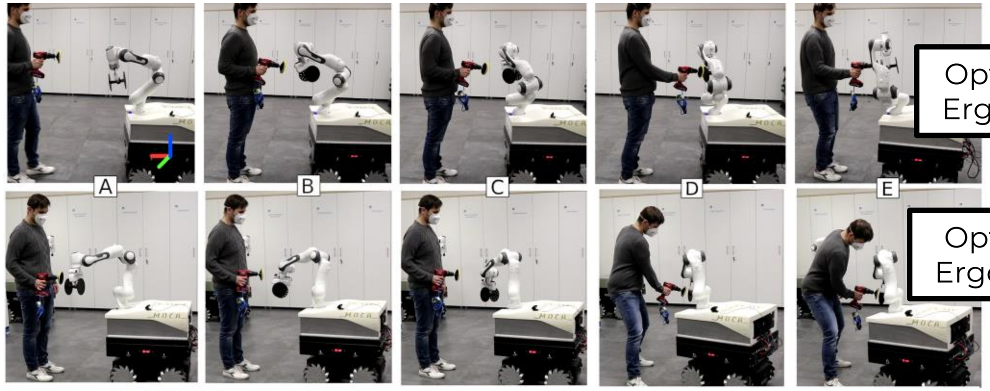
Image Classification:

- Identification of the workpiece orientation for **human's intention** estimation.

Action Recognition:

- Online **human action recognition** for the AHQP constraints definition phase.



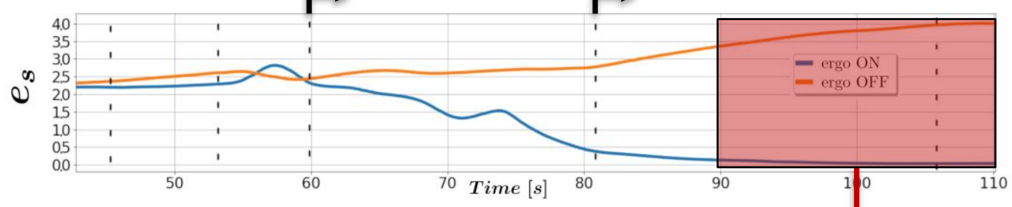


Optimal Ergo **ON**

Optimal Ergo **OFF**

Optimal Ergonomics activation

Human-Robot Interaction



Large ergonomics score difference between **Ergo ON** and **OFF**

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HUMAN-ROBOT INTERFACES AND PHYSICAL INTERACTION

Sociable and Ergonomic Human-Robot Collaboration through Action Recognition and Augmented Hierarchical Quadratic Programming

Francesco Tassi[1,2], Francesco Iodice[1,2], Elena De Momi[2], and Arash Ajoudani[1]

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2: NearLab, Dept. of Electronics, Information and Bioengineering, Politecnico di Milano, Milan, Italy

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Optimal Ergonomics

ON vs OFF

- Ergonomics score e_s is minimized during HRI
- Large postural improvement as task progresses

Subjective Results

Perception-aware

Subjective questionnaires

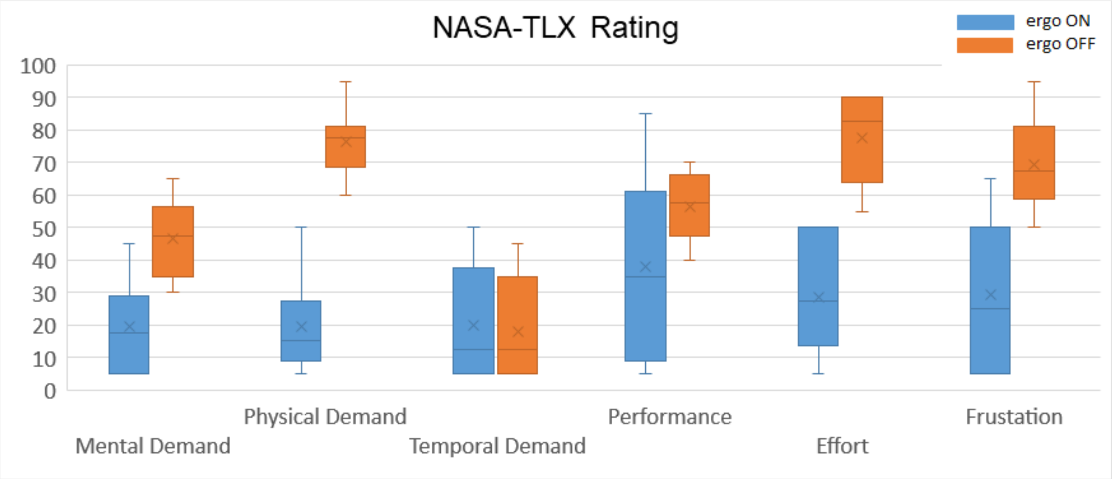
10 subjects

(~30% females based on [1])

[1] *"The Industry Gender Gap Women and Work in the Fourth Industrial Revolution"*, 2016, World Economic Forum, Geneva, Switzerland.

- **Reduced** mental and physical **workloads**
- **High** execution **responsiveness**
- **Lower effort** and **stress** levels
- **Ease of use** when controlling the robot

NASA-TLX questionnaire outcomes on HRC task for 10 subjects



Average and peak ergonomic scores for each subject for each experiment

		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Exp 1	e_{ava} reduction $[\%]$	73	75	70	68	70	72	75	71	77	76
Exp 2	e_{avg} reduction $[\%]$	64	58	68	70	74	63	68	72	67	70

~70% Ergonomics score improvement

Related publication: **F. Tassi**, F. Iodice, E. De Momi and A. Ajoudani, "*Sociable and Ergonomic Human-Robot Collaboration through Action Recognition and Augmented Hierarchical Quadratic Programming,*" 2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2022.

Conclusions

1. Augmented-HQP

OBJECTIVES		CONTRIBUTIONS
Higher Robot Autonomy	→	**No fixed motion planning**
Increased HRC Safety	→	**Adaptive compliance** for safer HRI

A-HQP → **Ergo-Aware A-HQP**

2. Ergonomics-Aware AHQP

OBJECTIVES

Prioritize Human vs Robot

CONTRIBUTIONS

- **Creation of Ergonomics Map** in HQP
- **Human Preference vs Optimal Ergonomics**

Conclusions

	OBJECTIVES	CONTRIBUTIONS
3. Perception-Aware AHQP	**Enable *In-Movement* Interaction**	• **Human actions** and **intention** recognition • ***In-Movement* Interaction** with optimal ergonomics

Limitations & Future Developments

Further studies on **human behaviour** for understanding **human intentions**, to anticipate human and autonomously adapt Stack of Tasks.

⇩

Autonomous adaptation to real-word scenarios

Ergonomic Teleoperation on both leader and follower robots

⇩

Exploitable in surgical teleoperation and rehabilitation

Thanks to the HRII Lab

EU Projects

- H2020 SOPHIA
- Ergo-Lean

Thank you for your attention.

Scientific Activity

Publications

Journals

- **F. Tassi**, E. De Momi, A. Ajoudani, "An adaptive compliance Hierarchical Quadratic Programming controller for ergonomic human–robot collaboration," Robotics and Computer-Integrated Manufacturing, Volume 78, 2022, 102381.
- **F. Tassi**, and A. Ajoudani, "Multi-Modal and Adaptive Control of Human-Robot Interaction through Hierarchical Quadratic Programming," 2023. (Under review)
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Conferences

- **F. Tassi**, F. Iodice. E. De Momi, and A. Ajoudani "Sociable and Ergonomic Human-Robot Collaboration through Action Recognition and Augmented Hierarchical Quadratic Programming," *2022 International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2022.
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- **F. Tassi**, S. Gholami, S. Giudice, and A. Ajoudani, "Impact Planning and Pre-configuration based on Hierarchical Quadratic Programming", *2022 International Conference on Robotics and Automation (ICRA)*. IEEE, 2022.
- Z. Liao**, F. Tassi**, C. Gong, M. Leonori, F.Zhao, G. Jiang, and A. Ajoudani, "Simultaneously Learning of Motion, Stiffness, and Force from Human Demonstration based on Riemannian DMP and QP Optimization," 2023 IEEE Transactions on Automation Science and Engineering. (Under review)
- J. Zhao, G.J. Lahr, **F. Tassi**, A. Santopaolo, E. De Momi, and A. Ajoudani "Impact-Friendly Object Catching at Non-Zero Velocity based on Hybrid Optimization and Learning," *2022 International Conference on Robotics and Automation (ICRA)*. IEEE, 2022 (Submitted)