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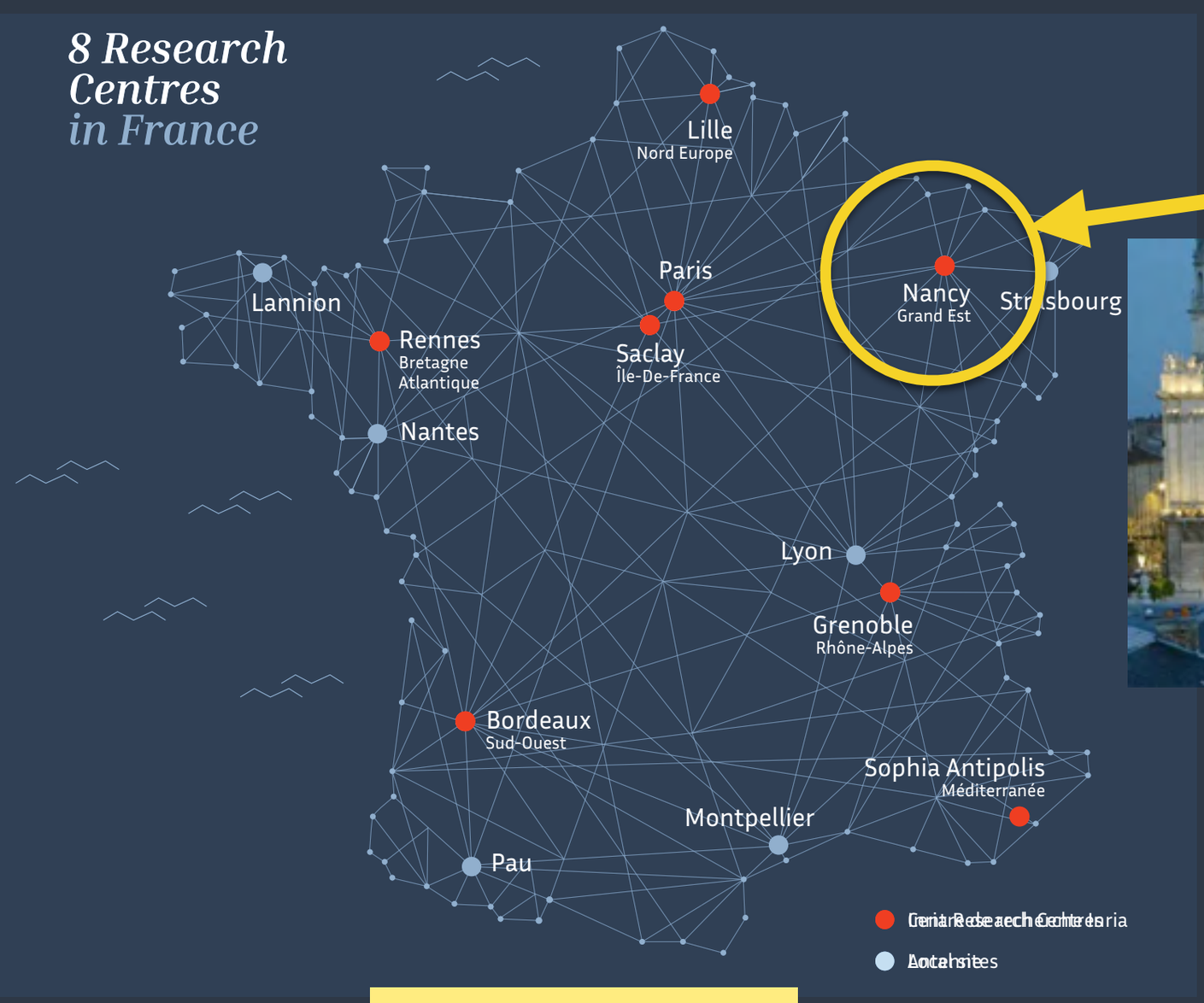
Teleoperation for Human-humanoid Collaboration

Humanoids 2019 WS on Humanoid Teleoperation

Horizon 2020
European Union funding
for Research & Innovation



Inria Nancy / Loria
Team Larsen

European Commission | Horizon 2020 European Union funding for Research & Innovation

erc European Research Council

smart apartment

Pepper

Tiago

Franka

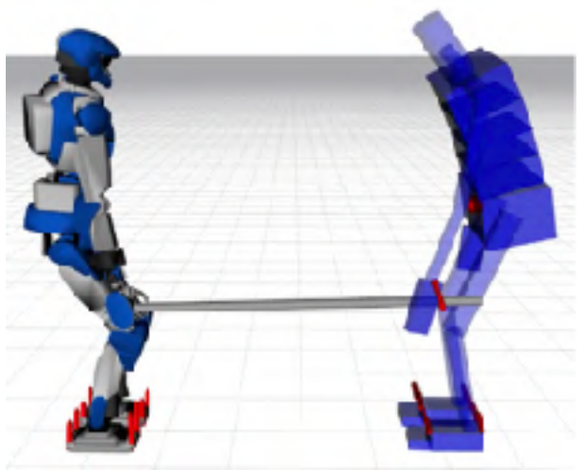
arena

iCubNancy01

Talos

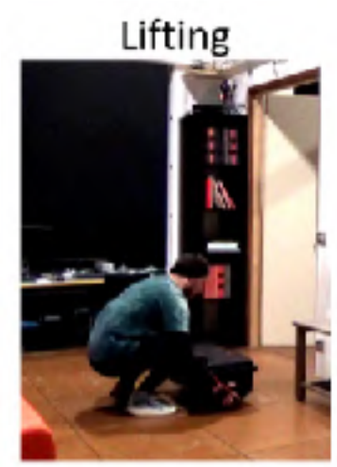
Human-human collaboration

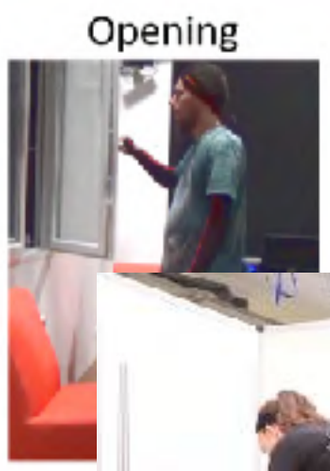
Can we reach a similar level of seamless collaboration with robots?



Problems in human-robot collaboration

Perceive the human, the environment

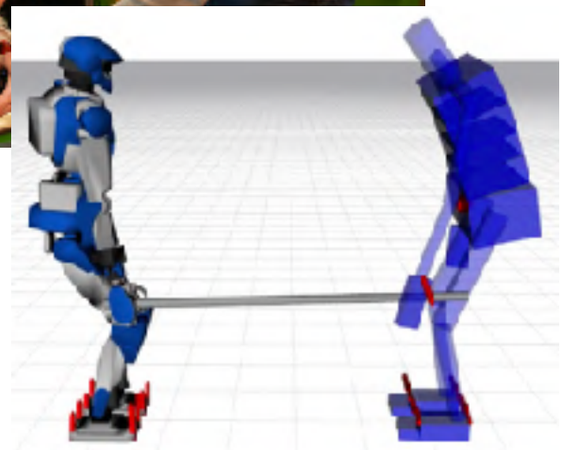




Recognize context & action

Predict what is the intention of the human during interaction

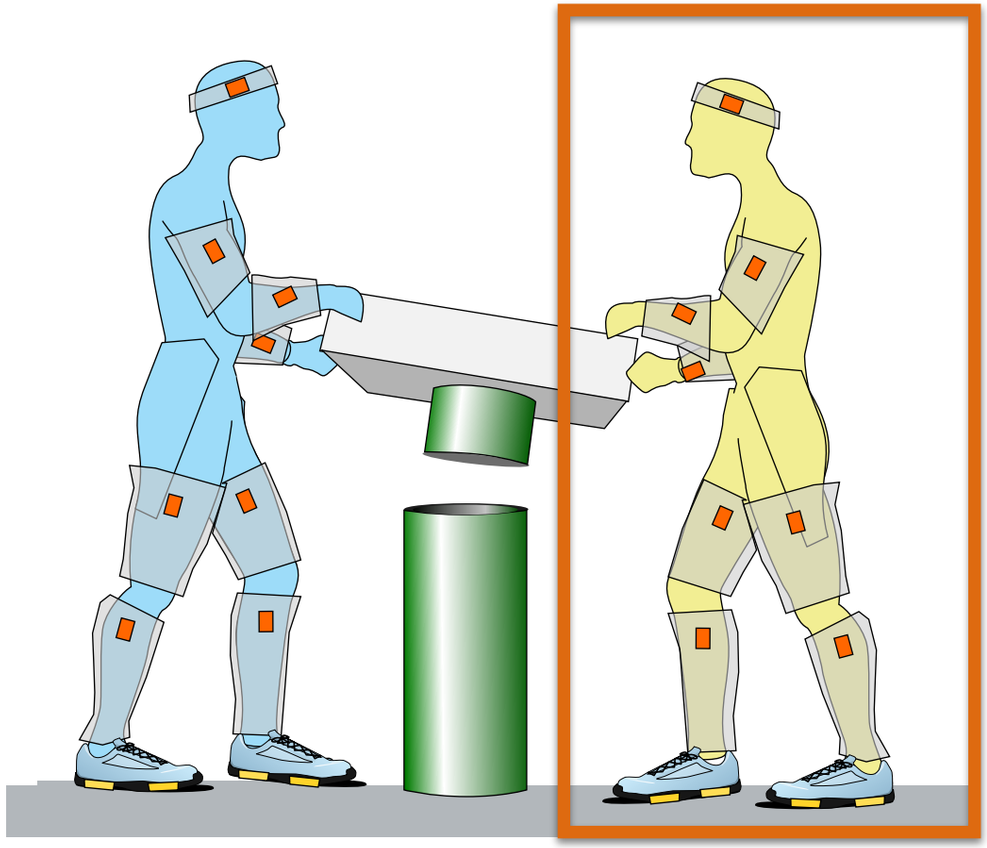
Perceive and control the contact forces (pHRI level 0)

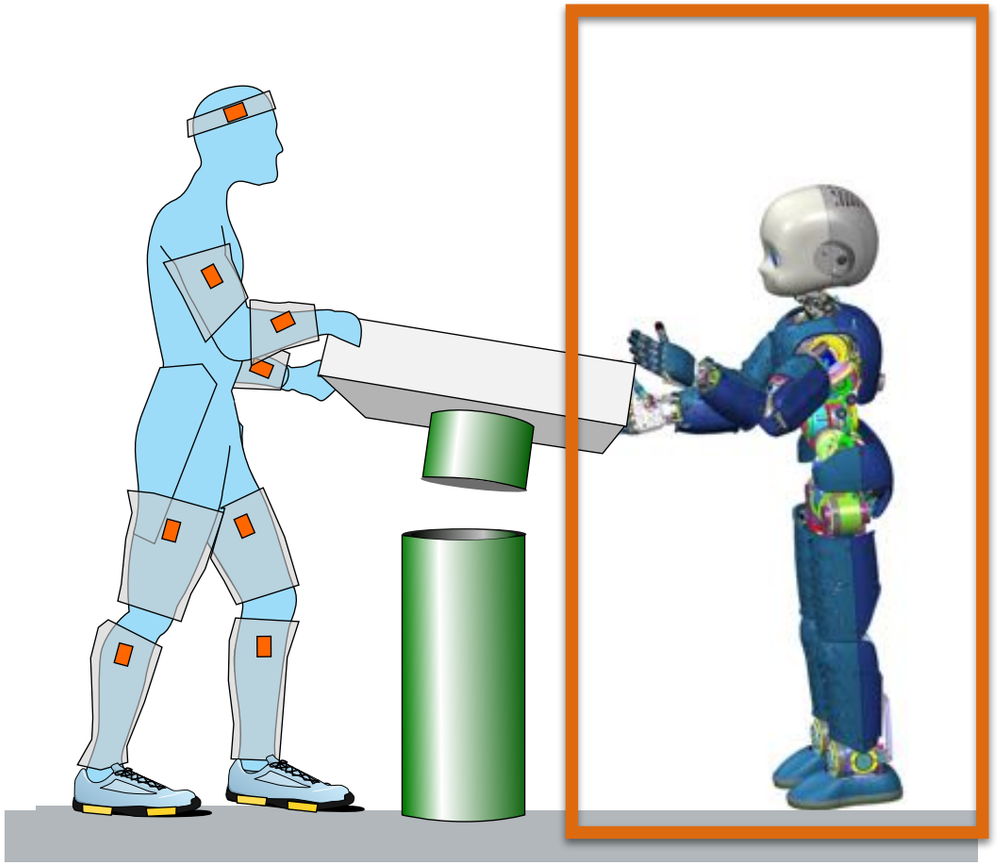


Take into account the human in the controller (pHRI level ++)

Lyubova et al, AURO 2016
Malaisé et al, ACHI 2018
Dermy et al, Front Rob&AI 2017
Ivaldi et al, IJSR 2016
Romano et al, RAL 2018 + Otani et al, ICRA 2018

Transfer paradigm: from humans to humanoids





Can we synthesize whole-body collaborative primitives exploiting human demonstrations?

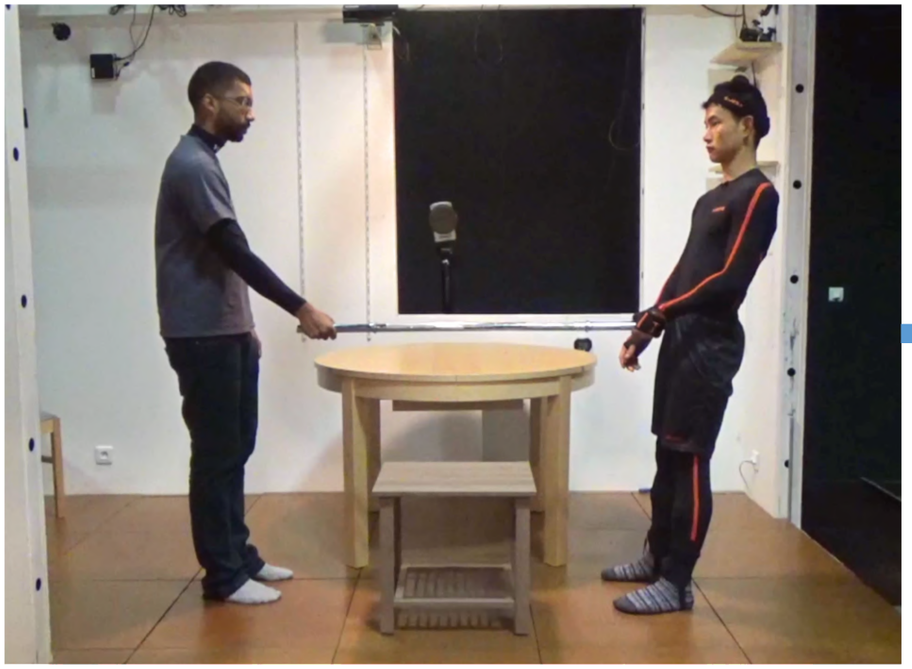
Transfer paradigm: from humans to humanoids

Yes! We can use demonstrations from the human operator.

Tele-operation/retargeting is the whole-body kinesthetic teaching!

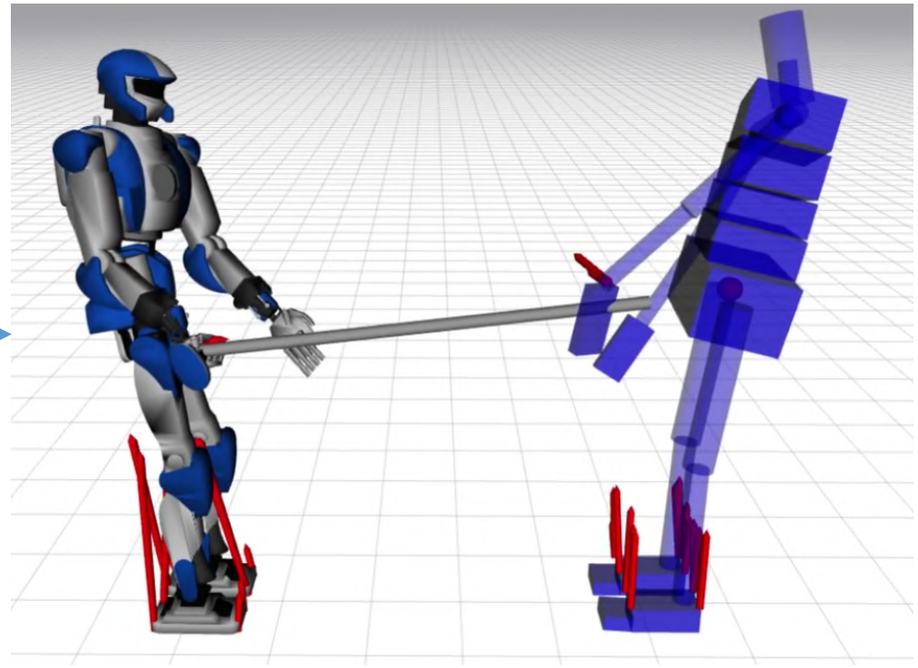
Human-aware pHRI

- Take into account the entire human dynamics in a multi-task QP controller for collaborative manipulations
- Joint level controller for the robot, but capable of reacting to the human



Human collaborator (to be replaced by robot)

Recorded human

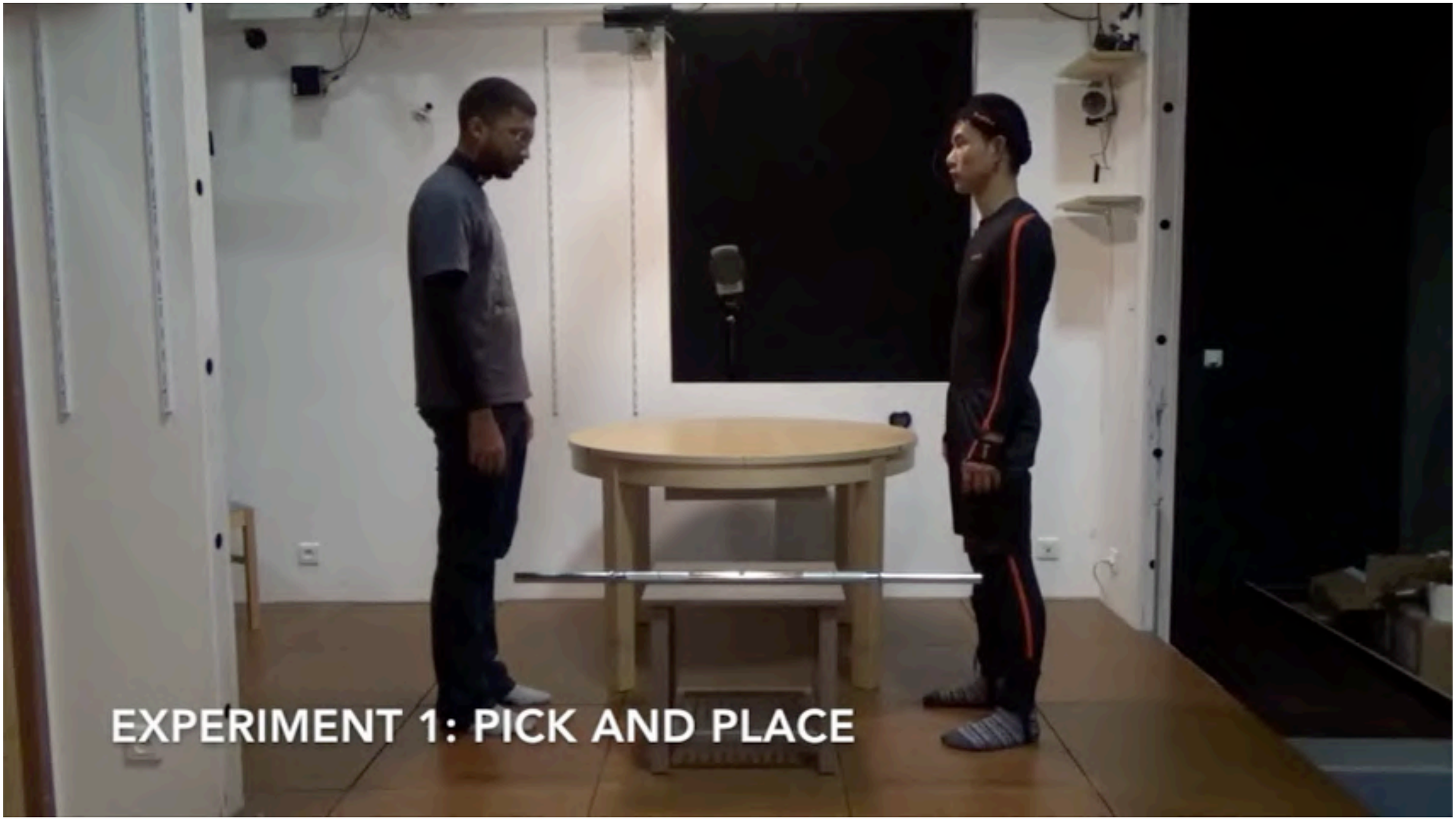


Robot collaborator

Simulated human

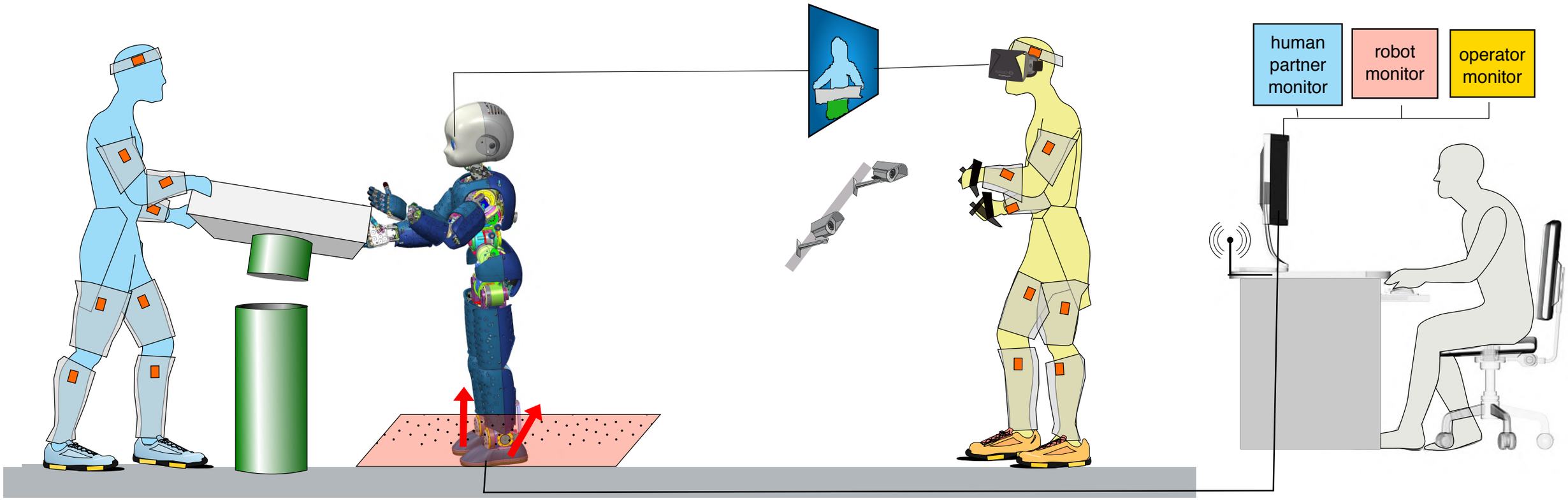
K. Otani, K. Bouyarmane, S. Ivaldi (2018) ICRA

Demonstrating collaborative behaviors



K. Otani, K. Bouyarmane, S. Ivaldi (2018) ICRA

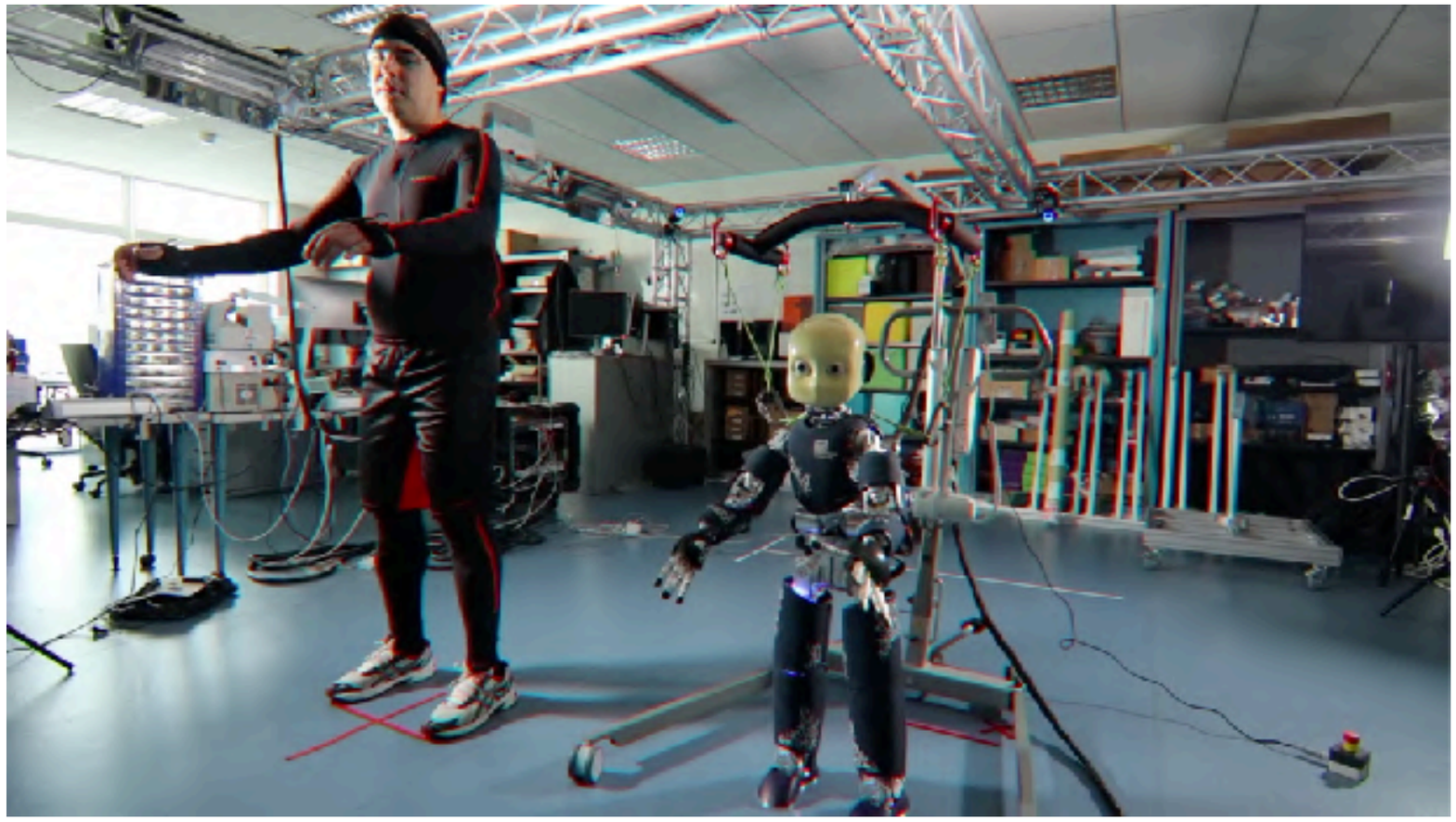
Transfer paradigm: from humans to robots



Different forms of teleoperation

Operator:
Motion retargeting

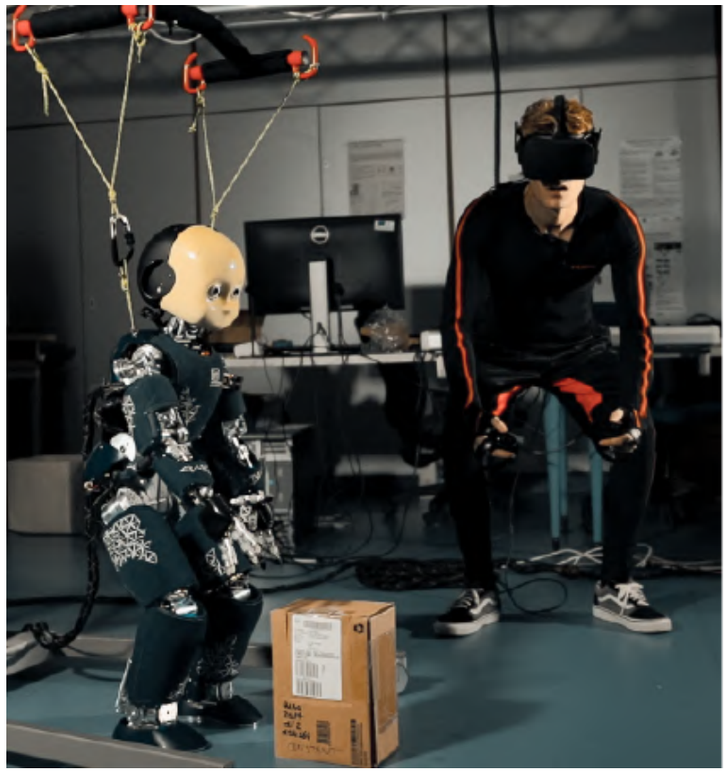
Penco et al. (2018) HUMANOIDS



Ground control:
Teleoperation with
shared control

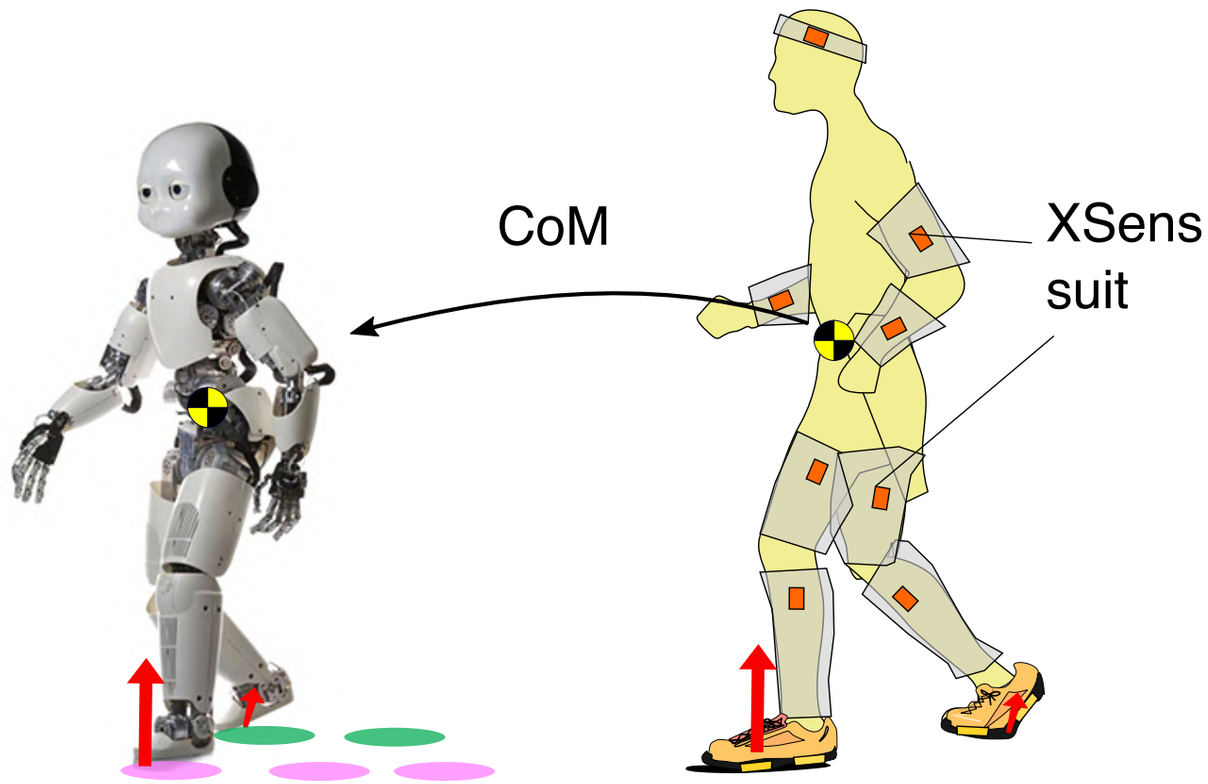
Ivaldi et al. (2016) IJSR

Some problems in “human to humanoids”



1) Human-aware control with demonstrations of complex whole-body behaviors for collaboration, which considers the unfeasible
   ➟ Teleoperation with robust retargeting that filters commands
2) The teleoperator may do something off the script!
   ➟ We need to optimize the controller’s parameters to be robust and “generic” so we can execute any teleoperate movement
3) The teleoperated movement may not be optimal for the robot
   ➟We need to re-optimize the motion for the robot dynamics

I) teleoperation with a robust retargeting strategy



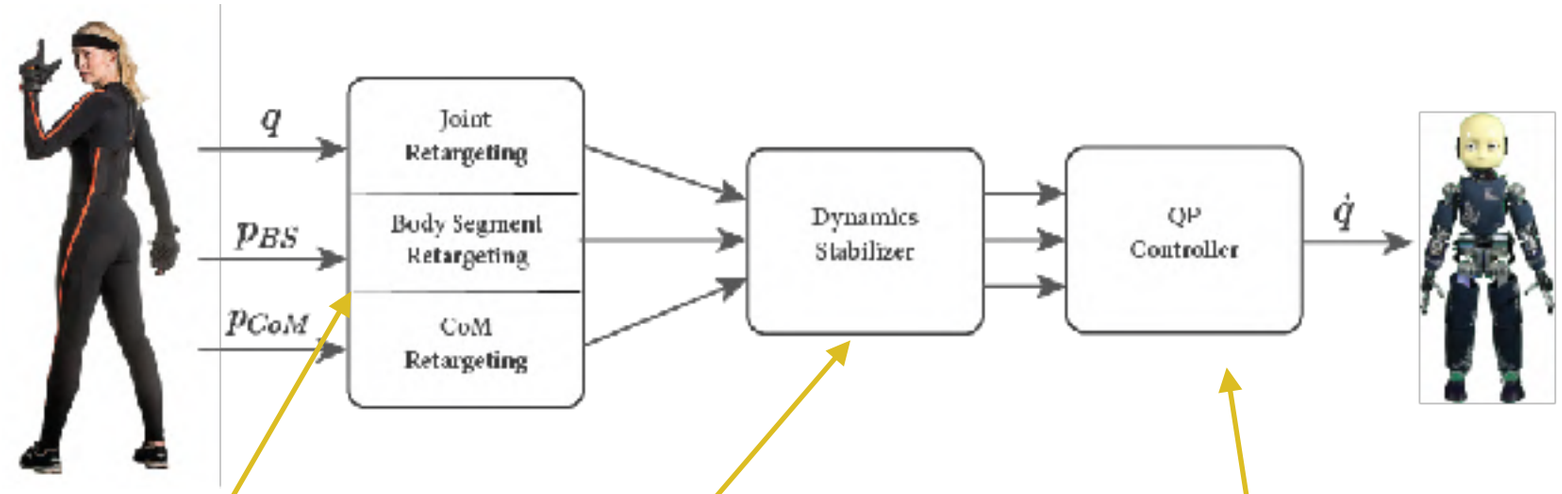
How do we retarget
human motions in real-time to enable
robust teleoperation?

1) teleoperation with a robust retargeting strategy

Retargeting in a robust way for tele-operation

Penco et al. (2018) HUMANOIDS

1) teleoperation with a robust retargeting strategy



$$\min_{x} \; || Ax - b ||^2_W \quad s.t. \quad l \leq Cx \leq u$$

$$stack = (lFoot + rFoot + head_{sub})/$$
$$(com_{sub} + base_{sub} + torso_{sub} + lArm_{sub} + rArm_{sub});$$

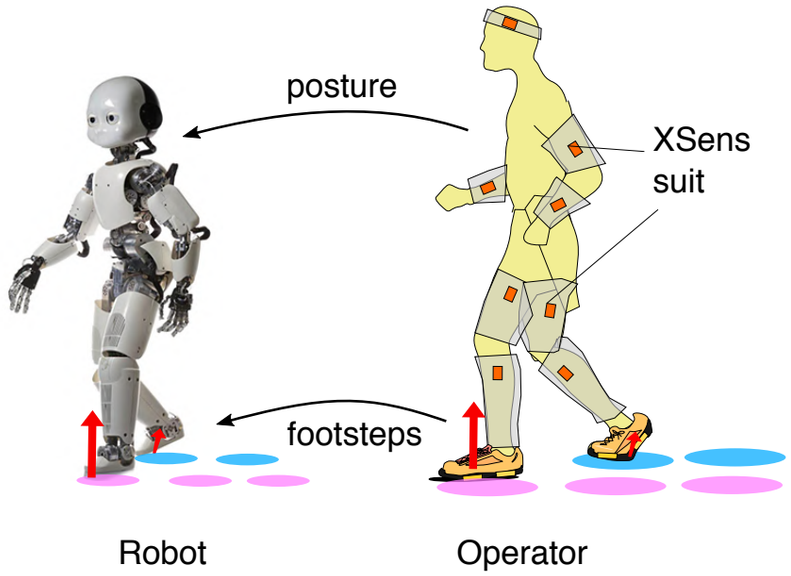
Multi-task QP controller with strict priorities (OpenSoT)

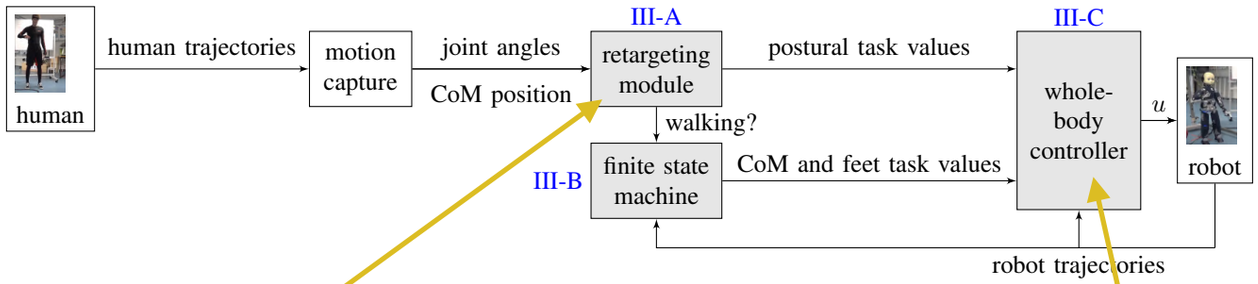
$$\begin{aligned} \min_{p_{ZMP}} \quad & (\dot{p}^{des}_{CoM} - \dot{p}_{CoM})^T R \, (\dot{p}^{des}_{CoM} - \dot{p}_{CoM}) \\ \text{s.t.} \quad & \dot{p}_{CoM} = \dot{p}^{t-1}_{CoM} + \frac{Tg}{h^{t-1}}(p_{CoM} - p_{ZMP}) \\ & lb_{SP} < p_{ZMP} < ub_{SP} \end{aligned}$$

ZMP correction

Penco et al. (2018) HUMANOIDS

Retargeting footsteps: not a good idea

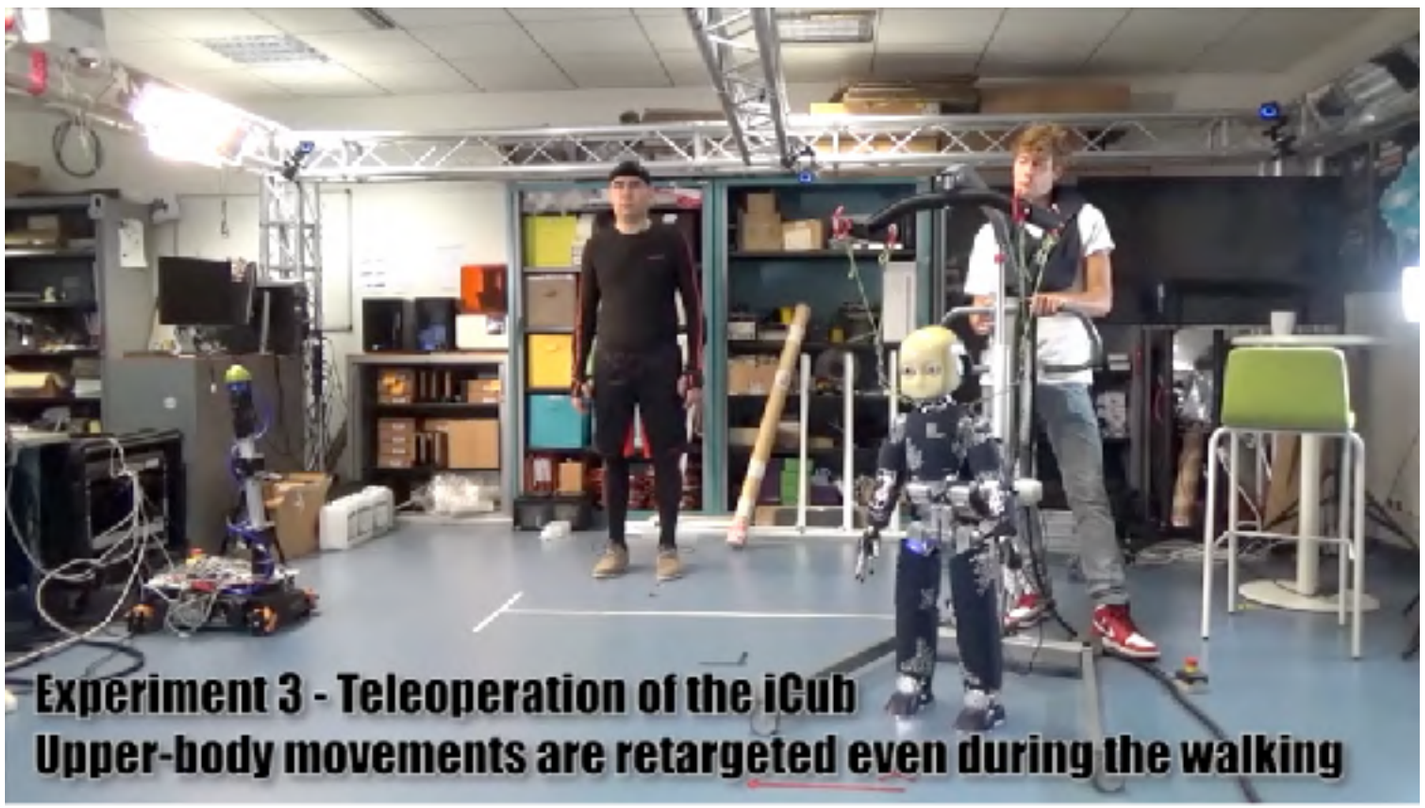




Footstep retargeting

$$x_{foot_R} = o_{footstep}(x_{foot_{max_R}} - x_{foot_{min_R}}) + x_{foot_{min_R}}$$

$$o_{footstep} = \frac{(x_{foot_H} - x_{foot_{min_H}})}{(x_{foot_{max_H}} - x_{foot_{min_H}})}$$



Whole-body QP controller (switching tasks depending on the FSM)

$$u^* = \arg\min_u \ \frac{1}{2} \sum_{X_{null}} w_{X_{null}} E_{X_{null}}$$

$$\text{s. t.} \ \ \underline{s} < Au < \overline{s}$$

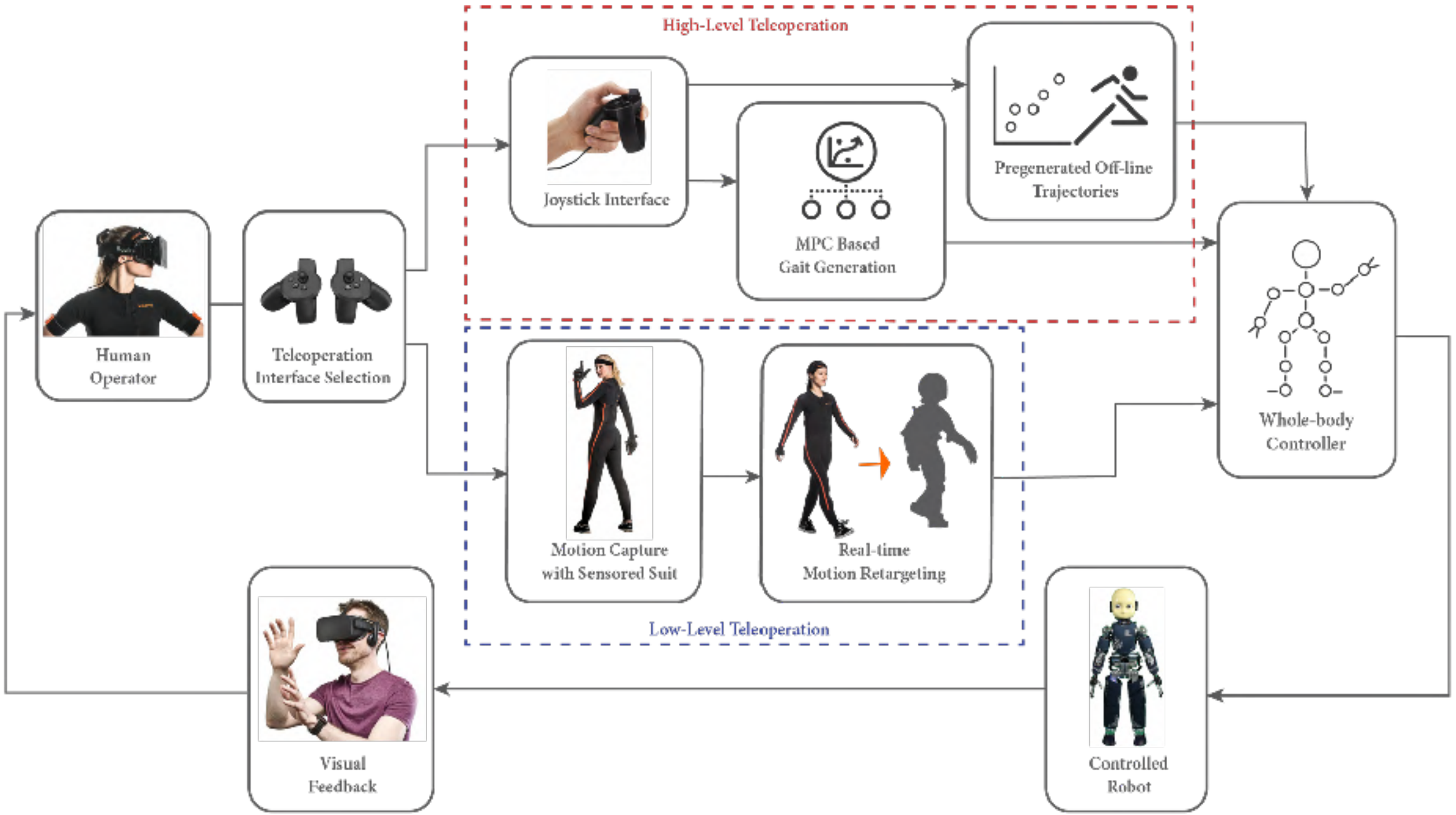
$$\dot{\underline{s}} < u < \dot{\overline{s}}$$

$$u = \arg\min_u \ \frac{1}{2} \sum_X w_X E_X$$

- Stance foot pose ${}^{stance}T_{\mathcal{B}} \in SE(3)$
- Swing foot pose ${}^{swing}T_{\mathcal{B}} \in SE(3)$
- CoM ground projection position $p_{CoM} \in \mathbb{R}^2$
- Waist height $z_{waist} \in \mathbb{R}$ and orientation ${}^{waist}R_{\mathcal{B}} \in SO(3)$
- Neck orientation ${}^{neck}R_{\mathcal{B}} \in SO(3)$
- Upper-body joint positions $s_{up} \in \mathbb{R}^{n_{up}}$

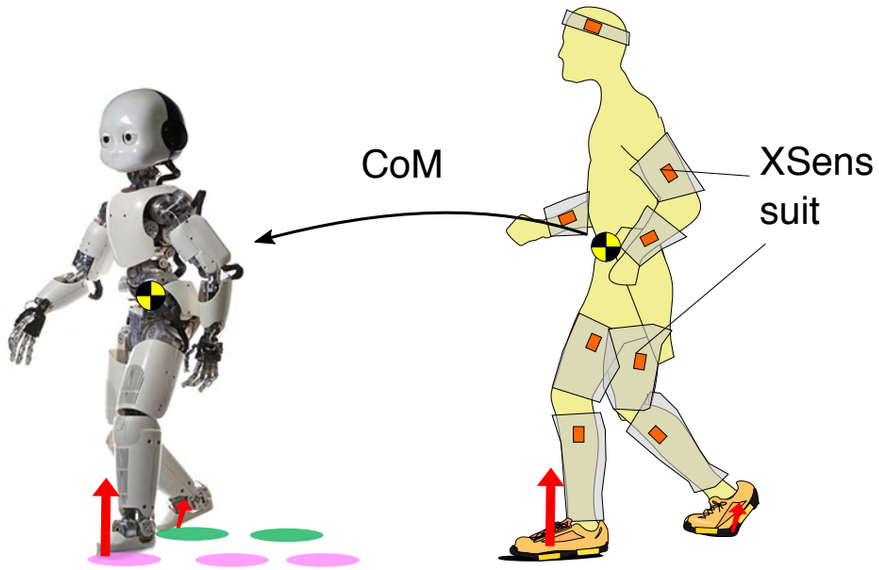
=> the result is not good, delay in correspondance

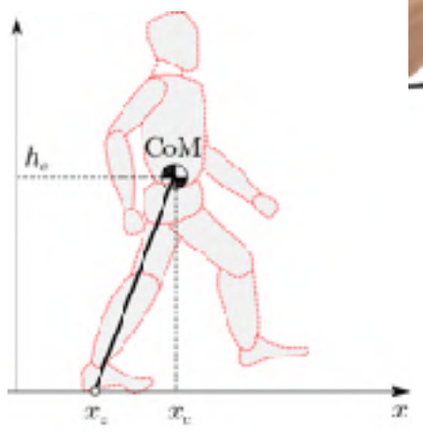
Teleoperating with walking

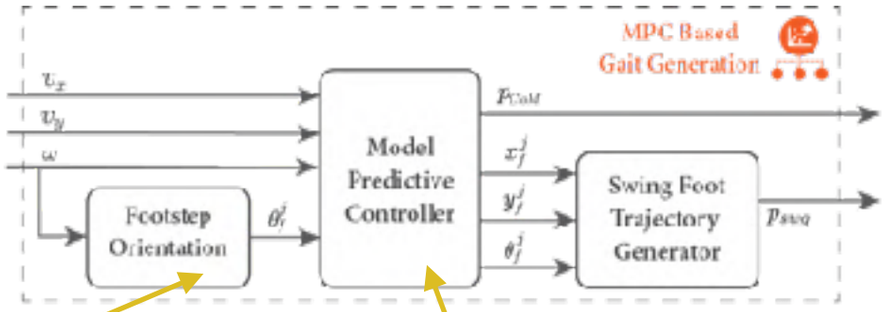


Penco et al. accepted at RAM 2019

Teleoperating with walking

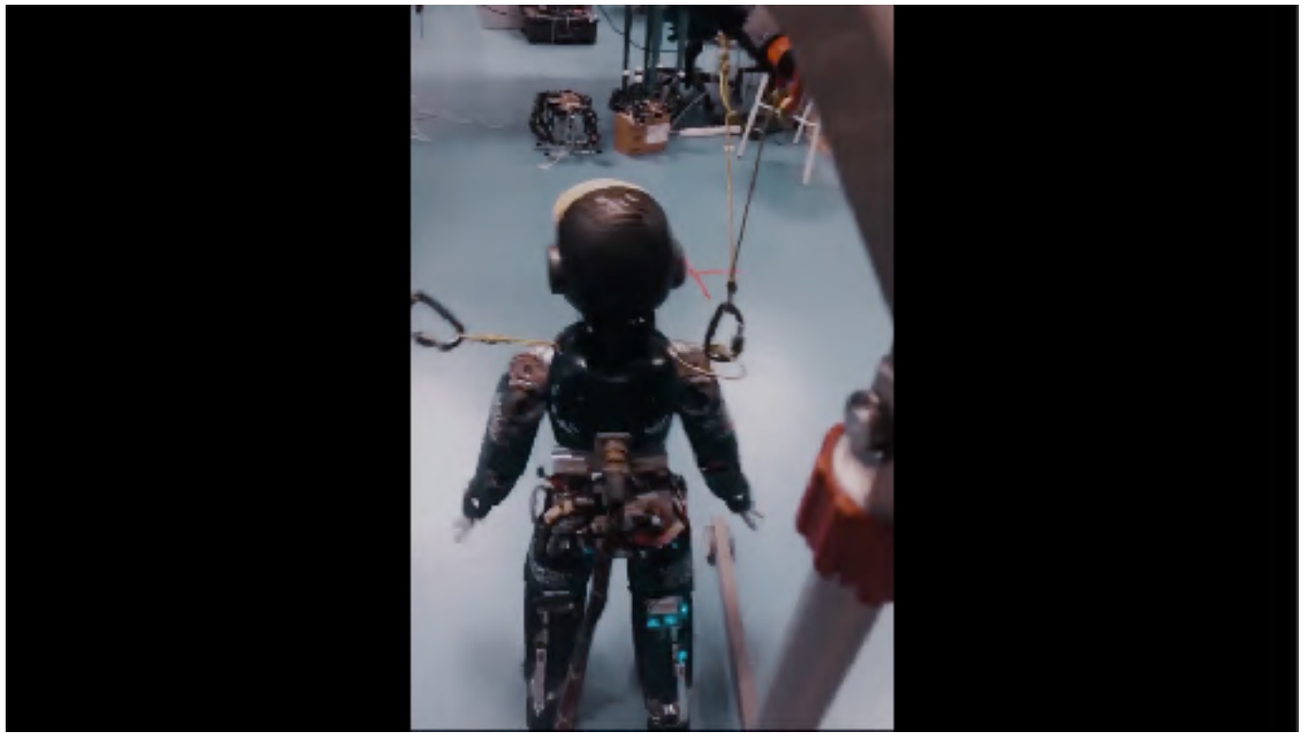




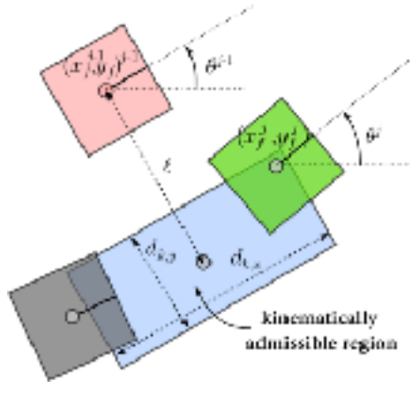


1st QP problem
generate candidate footstep orientation

2nd QP problem
generate CoM trajectory and footstep positions with a MPC formulation, under constraints:
- balance (ZMP inside support polygon)
- stability (CoM not diverging w.r.t. ZMP)
- footstep kinematically feasible

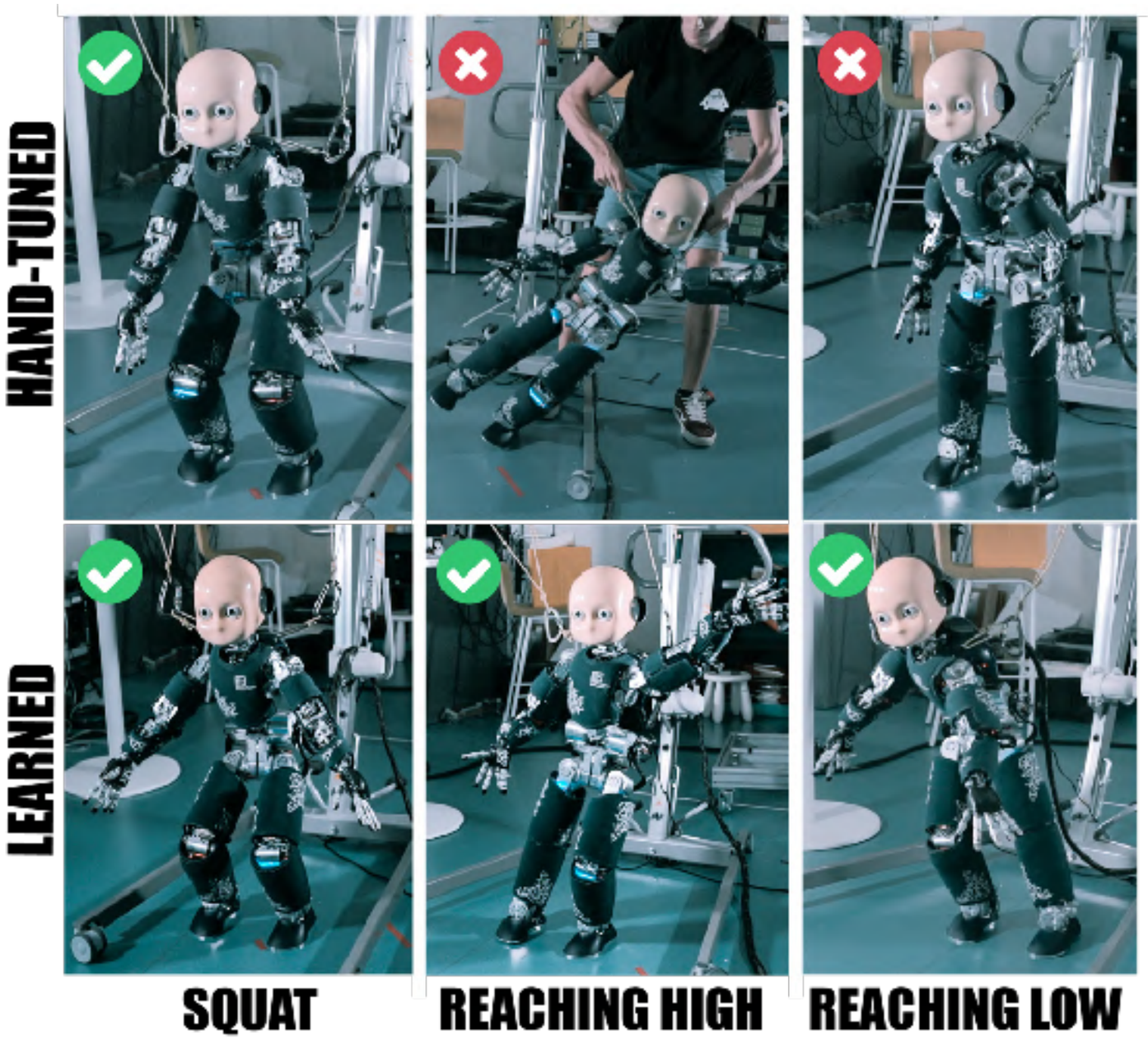


=> better result! The robot walks in its own way



Penco et al. accepted at RAM 2019

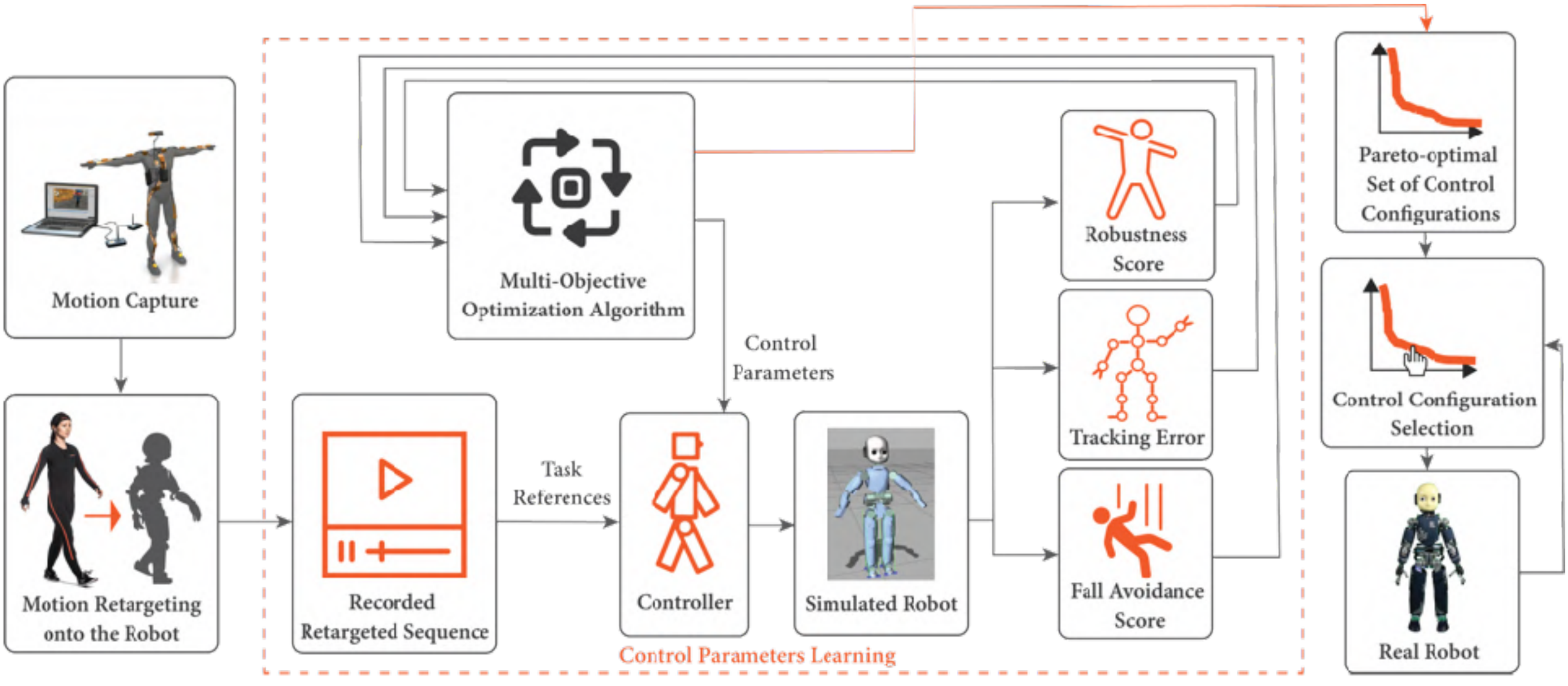
2) auto-tuning the controller for teleoperation



Can we make sure that the robot controller
can execute in principle any
retargeted human motion in real-time?

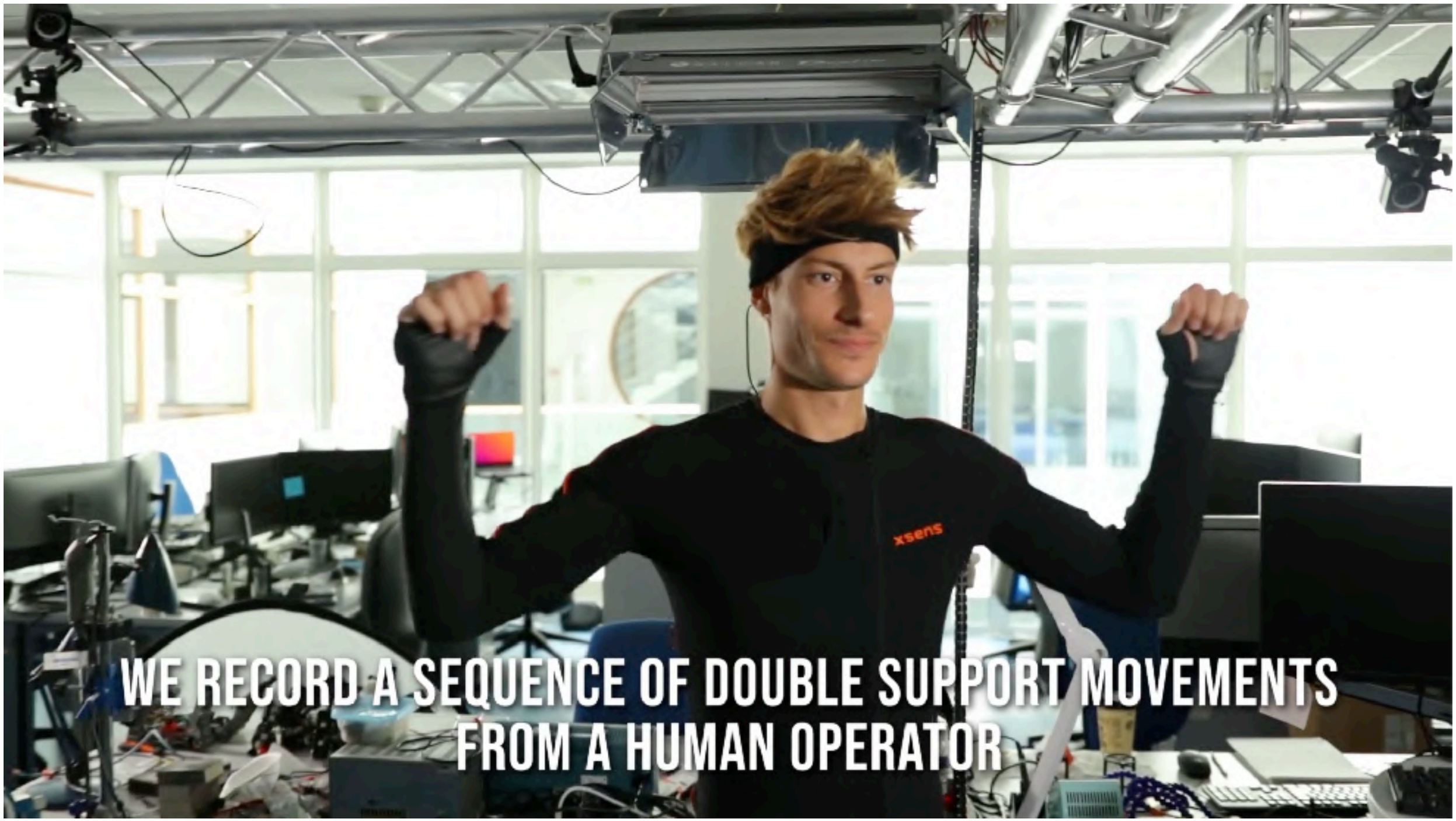
2) auto-tuning the controller for teleoperation

Learning the control structure and the parameters that enable the robot to perform a variety of motions



Penco et al. - under review

2) auto-tuning the controller for teleoperation



Penco et al. - under review

2) auto-tuning the controller for teleoperation

We define a generic stack of tasks with multiple levels

$$\mathcal{S} = (w_1\mathcal{T}_1 + ... + w_i\mathcal{T}_i)/$$
$$\vdots$$
$$(w_j\mathcal{T}_j + ... + w_n\mathcal{T}_m);$$

Each level is a weighted combination of all the possible tasks.

$$\mathcal{S}_i = (w_{lf}\mathcal{T}_{lf} + w_{rf}\mathcal{T}_{rf} + w_{com}\mathcal{T}_{com} + \\ + w_{wo}\mathcal{T}_{wo} + w_{wh}\mathcal{T}_{wh} + w_h\mathcal{T}_h + w_c\mathcal{T}_c + \\ + w_n\mathcal{T}_n + w_t\mathcal{T}_t + w_{la}\mathcal{T}_{la} + \\ + w_{ra}\mathcal{T}_{ra} + w_{ll}\mathcal{T}_{ll} + w_{rl}\mathcal{T}_{rl}).$$

Tasks			
Joint Space	Symbol	Cartesian Space	Symbol
neck	$\mathcal{T}_n$	*com*	$\mathcal{T}_{com}$
torso	$\mathcal{T}_t$	*waist orientation*	$\mathcal{T}_{wo}$
left arm	$\mathcal{T}_{la}$	*waist height*	$\mathcal{T}_{wh}$
right arm	$\mathcal{T}_{ra}$	*chest*	$\mathcal{T}_c$
left leg	$\mathcal{T}_{ll}$	*head*	$\mathcal{T}_h$
right leg	$\mathcal{T}_{rl}$	*left foot*	$\mathcal{T}_{lf}$
		right foot	$\mathcal{T}_{rf}$

Three levels ➟ task selectors

$$\mathcal{S} = (\mathcal{S}_1)/ \\ (\mathcal{S}_2)/ \\ (\mathcal{S}_3);$$

$$\begin{cases} \mathcal{T}_k \subseteq \mathcal{S}_1 & if\ (0 \leq l_k \leq 0.25) \\ \mathcal{T}_k \subseteq \mathcal{S}_2 & if\ (0.25 < l_k \leq 0.5) \\ \mathcal{T}_k \subseteq \mathcal{S}_3 & if\ (0.5 < l_k \leq 0.75) \\ \mathcal{T}_k\ deactivated & if\ (0.75 < l_k \leq 1) \end{cases}$$

2) auto-tuning the controller for teleoperation

Two controller configurations

$$\overline{\mathcal{S}}_{C1} = (w_f(\mathcal{T}_{lf} + \mathcal{T}_{rf}) + w_h\mathcal{T}_h)/ (w_{cxy}\mathcal{T}_{cxy} + w_{cz}\mathcal{T}_{cz} + w_t\mathcal{T}_t + + w_{wo}\mathcal{T}_{wo} + w_{ha}(\mathcal{T}_{lh} + \mathcal{T}_{rh}))/ (w_{la}(\mathcal{T}_{lla} + \mathcal{T}_{rla}));$$

Tasks			
Joint Space	Symbol	Cartesian Space	Symbol
torso	$\mathcal{T}_t$	*com (x,y)*	$\mathcal{T}_{cxy}$
left lower arm	$\mathcal{T}_{lla}$	*com height*	$\mathcal{T}_{cz}$
right lower arm	$\mathcal{T}_{rla}$	*waist orientation*	$\mathcal{T}_{wo}$
neck	$\mathcal{T}_n$	*left foot pose*	$\mathcal{T}_{lf}$
		right foot pose	$\mathcal{T}_{rf}$
		left hand position	$\mathcal{T}_{lh}$
		right hand position	$\mathcal{T}_{rh}$
		head orientation	$\mathcal{T}_h$

$$\overline{\mathcal{S}}_{C2} = (w_f(\mathcal{T}_{lf} + \mathcal{T}_{rf}) + w_o\mathcal{T}_{wo} + w_n\mathcal{T}_n)/ (w_{cxy}\mathcal{T}_{cxy} + w_{wh}\mathcal{T}_{wh} + w_t\mathcal{T}_t + w_a(\mathcal{T}_{la} + \mathcal{T}_{ra}))/ (w_c\mathcal{T}_c);$$

Tasks			
Joint Space	Symbol	Cartesian Space	Symbol
neck	$\mathcal{T}_n$	*com (x,y)*	$\mathcal{T}_{cxy}$
torso	$\mathcal{T}_t$	*waist orientation*	$\mathcal{T}_{wo}$
left arm	$\mathcal{T}_{la}$	*waist height*	$\mathcal{T}_{wh}$
right arm	$\mathcal{T}_{ra}$	*chest orientation*	$\mathcal{T}_c$
left leg	$\mathcal{T}_{ll}$	*head orientation*	$\mathcal{T}_h$
right leg	$\mathcal{T}_{rl}$	*left foot pose*	$\mathcal{T}_{lf}$
		right foot pose	$\mathcal{T}_{rf}$

2) auto-tuning the controller for teleoperation

Control Parameters (28)			
Task	SPW (10)	HLS (10)	CG (8)
$\mathcal{T}_{lf}$	w_f	l_f	$\lambda_{feet}, \sigma_{feet}$
$\mathcal{T}_{rf}$	w_f	l_f	$\lambda_{feet}, \sigma_{feet}$
$\mathcal{T}_{com}$	w_{com}	l_{com}	λ_{com}
$\mathcal{T}_{wo}$	w_{wo}	l_{wo}	σ_{waist}
$\mathcal{T}_{wh}$	w_{wh}	l_{wh}	λ_{waist}
$\mathcal{T}_{h}$	w_{h}	l_{h}	σ_{head}
$\mathcal{T}_{c}$	w_{c}	l_{c}	σ_{chest}
$\mathcal{T}_{n}$	w_{n}	l_{n}	$\mu_{posture}$
$\mathcal{T}_{t}$	w_{t}	l_{t}	$\mu_{posture}$
$\mathcal{T}_{la}$	w_{a}	l_{a}	$\mu_{posture}$
$\mathcal{T}_{ra}$	w_{a}	l_{a}	$\mu_{posture}$
$\mathcal{T}_{ll}$	w_{l}	l_{l}	$\mu_{posture}$
$\mathcal{T}_{rl}$	w_{l}	l_{l}	$\mu_{posture}$

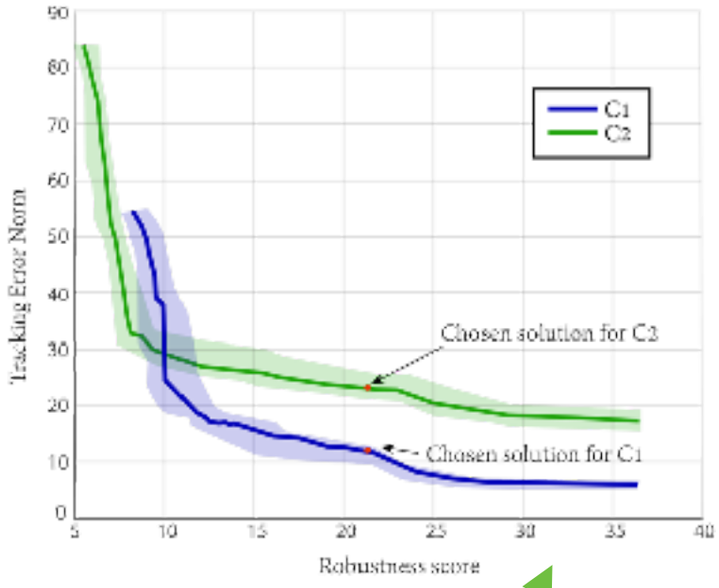
Priority Weight

Level Selector

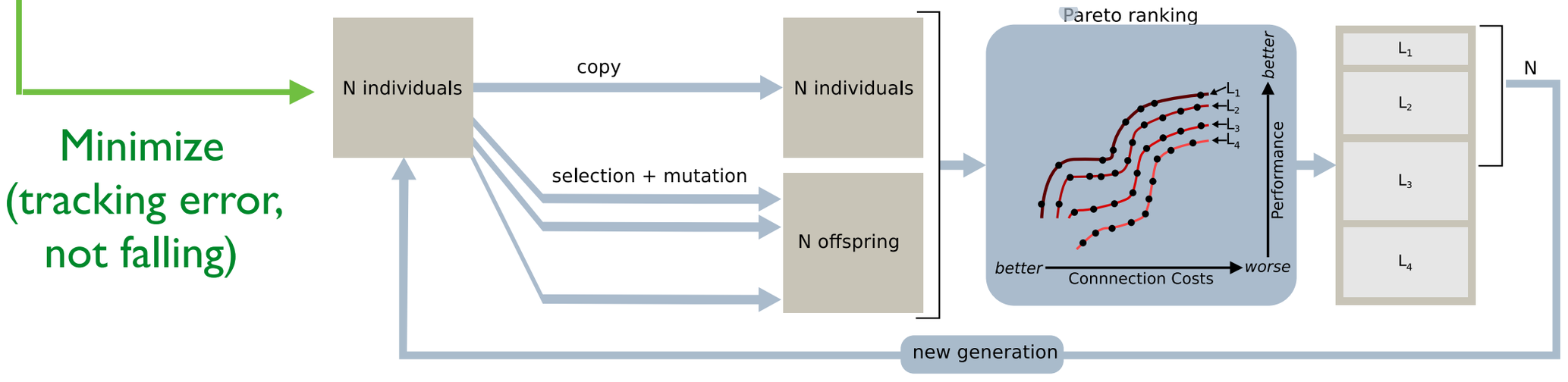
Convergence Gains

Minimize $(f_1(\boldsymbol{x}), -f_2(\boldsymbol{x}), f_3(\boldsymbol{x}))$

Minimize $(f_1(\mathbf{x}), -f_2(\mathbf{x}))$



Minimize (tracking error, not falling)



NSGA-II

2) auto-tuning the controller for teleoperation

Soft Priority Weights

C1			C2		
SFW	Median	IQR	SFW	Median	IQR
w_{ha}	0.639	0.2131	w_a	0.8406	0.296
w_f	0.5357	0.1786	w_f	0.5835	0.2144
w_{cxy}	0.8368	0.1941	w_{cxy}	0.9519	0.1984
w_{wo}	0.8674	0.4832	w_{wo}	0.1613	0.2337
w_h	0.3343	0.3101	w_h	0.5357	0.2465
w_n	0.3256	0.2893	w_n	0.406	0.2419
w_t	0.9258	0.245	w_t	0.0656	0.2138
w_{la}	0.3599	0.3133	w_l	0.1145	0.3756
w_{cz}	0.7684	0.2191	w_{wh}	0.1879	0.1785
			w_c	0.9902	0.091

Convergence Gains

C1			C2		
CG	Median	IQR	CG	Median	IQR
λ_{hand}	0.0191	0.033	λ_{waist}	0.5491	0.3791
λ_{feet}	0.0577	0.064	λ_{feet}	0.2486	0.0983
σ_{feet}	0.0051	0.0059	σ_{feet}	0.0983	0.1231
λ_{com}	0.4426	0.1664	λ_{com}	0.5911	0.1946
σ_{waist}	0.0591	0.042	σ_{waist}	0.0652	0.0472
σ_{head}	0.0796	0.0234	σ_{head}	0.2778	0.2560
$\mu_{posture}$	0.5605	0.2145	$\mu_{posture}$	0.5162	0.0821
			σ_{chest}	0.6052	0.4009

2) auto-tuning the controller for teleoperation

Task selectors

C1				C2			
Task	$\mathcal{S}_1$	$\mathcal{S}_2$	$\mathcal{S}_3$	Task	$\mathcal{S}_1$	$\mathcal{S}_2$	$\mathcal{S}_3$
$\mathcal{T}_{lh},\ \mathcal{T}_{rh}$	2	**18**	0	$\mathcal{T}_{la},\ \mathcal{T}_{ra}$	3	**17**	0
$\mathcal{T}_{lf},\ \mathcal{T}_{rf}$	**18**	2	0	$\mathcal{T}_{lf},\ \mathcal{T}_{rf}$	**19**	1	0
$\mathcal{T}_{cxy}$	4	**16**	0	$\mathcal{T}_{cxy}$	3	**17**	0
$\mathcal{T}_{wo}$	6	**8**	0	$\mathcal{T}_{wo}$	6	**14**	0
$\mathcal{T}_h$	**11**	0	1	$\mathcal{T}_h$	6	1	0
$\mathcal{T}_n$	9	1	1	$\mathcal{T}_n$	**9**	4	0
$\mathcal{T}_t$	3	**17**	0	$\mathcal{T}_t$	1	**17**	2
$\mathcal{T}_{lla},\ \mathcal{T}_{rla}$	1	3	**16**	$\mathcal{T}_{ll},\ \mathcal{T}_{rl}$	0	0	5
$\mathcal{T}_{cz}$	4	**16**	0	$\mathcal{T}_{wh}$	3	**17**	0
				$\mathcal{T}_c$	0	1	**9**

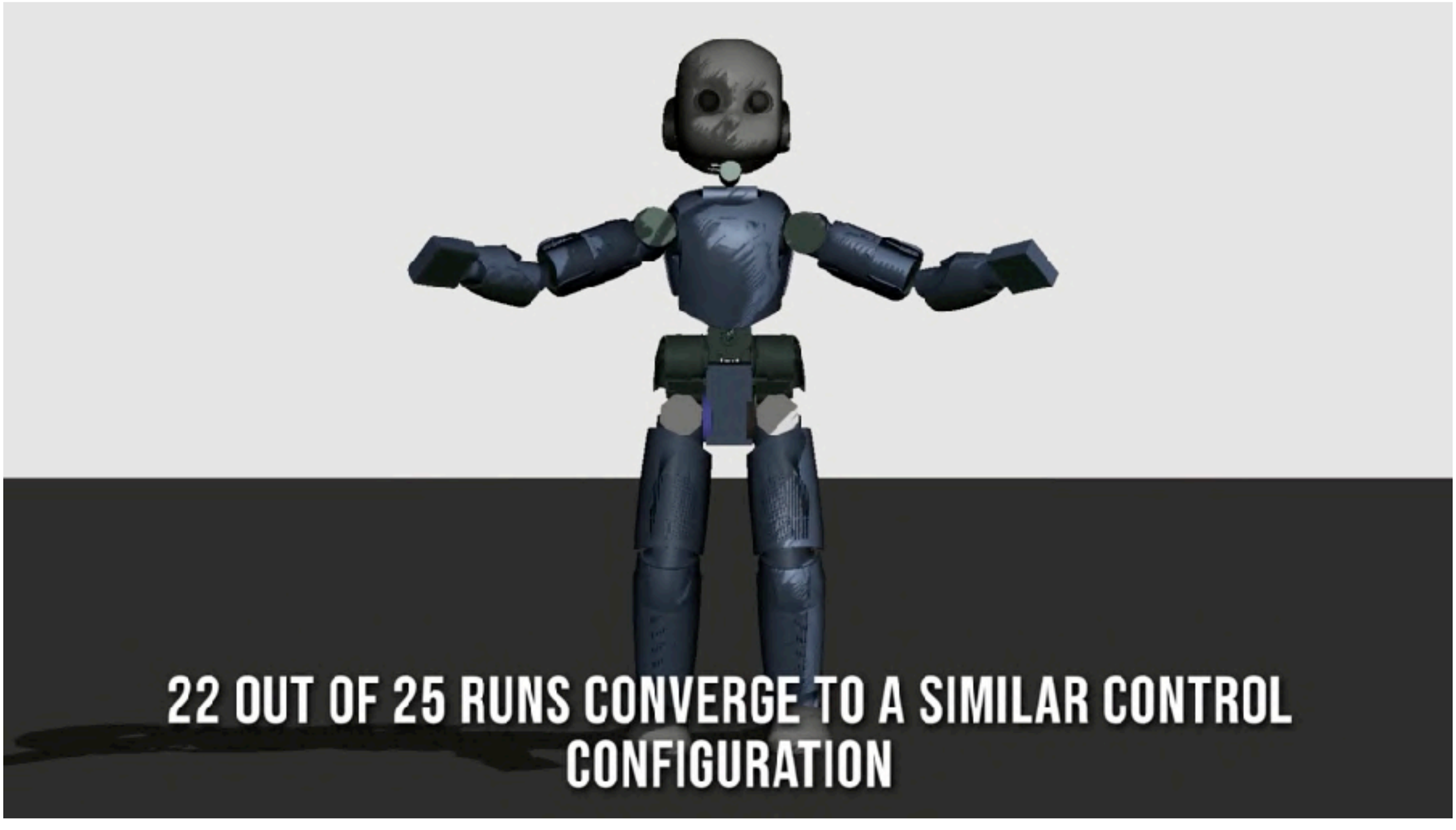
High priority — Left foot, Right foot, Head

Medium priority — Left hand, Right hand, CoM, Waist, Torso

Low priority — Arms, Chest

2) auto-tuning the controller for teleoperation

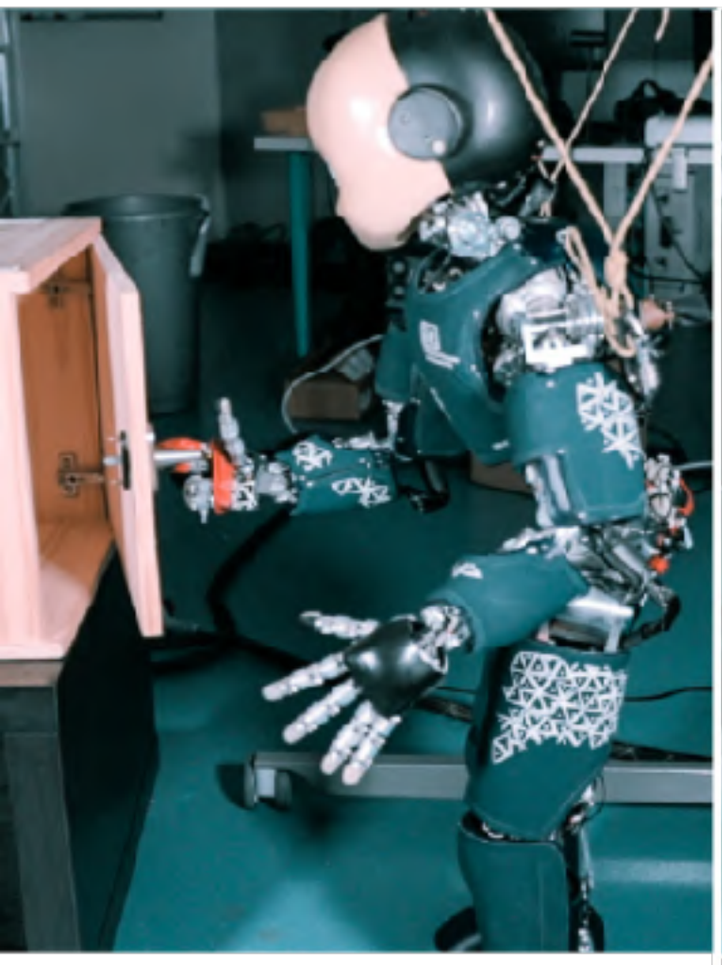
Learning the control structure and the parameters that enable the robot to perform a variety of motions



Penco et al. - under review

2) auto-tuning the controller for teleoperation

The best solution enables the robot to do more tasks that are not in its training sequences and that are shown on-line by the teleoperator!



OPENING DOOR

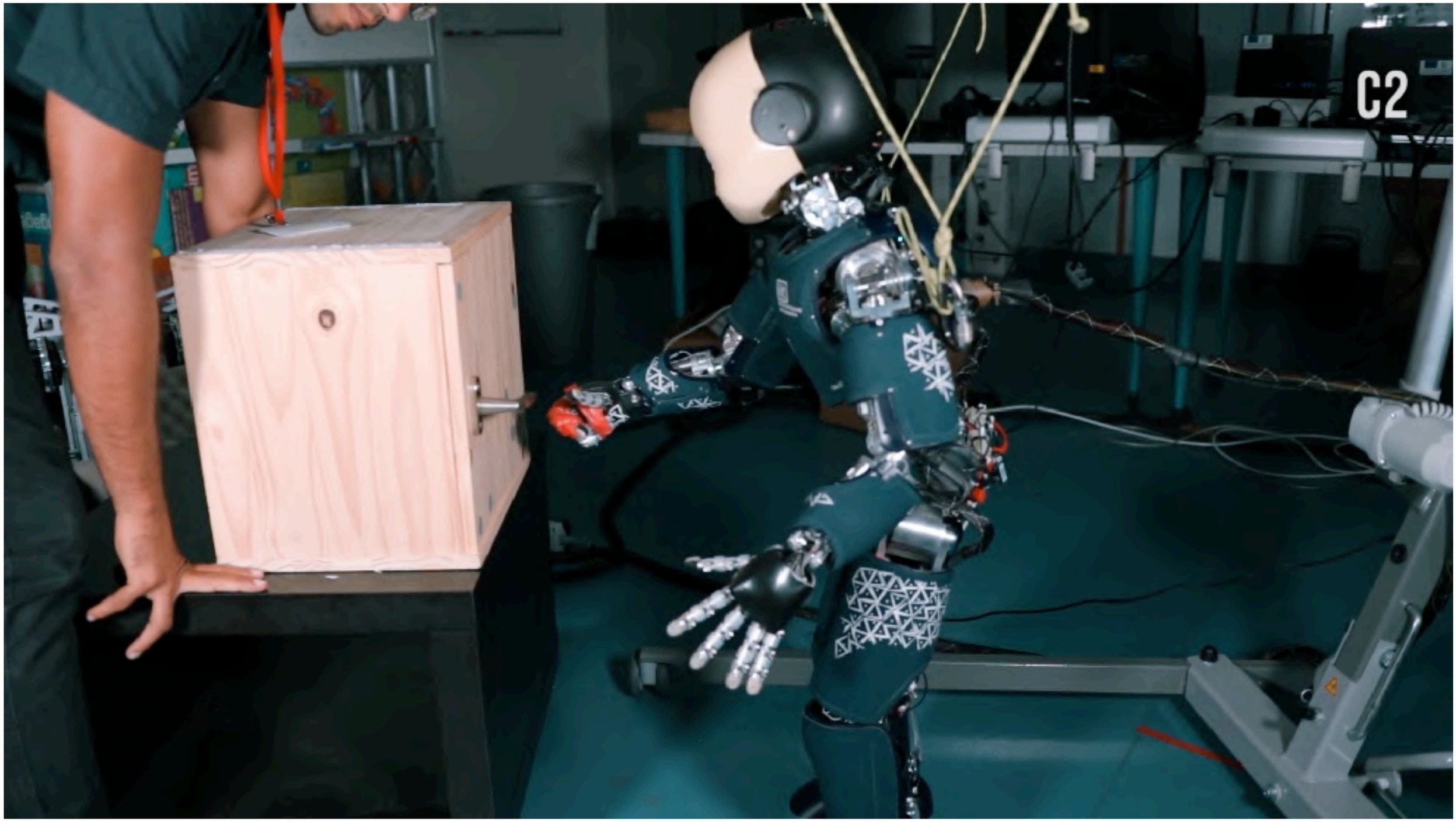
HITTING BALL

DANCING

PICKING-UP BOX

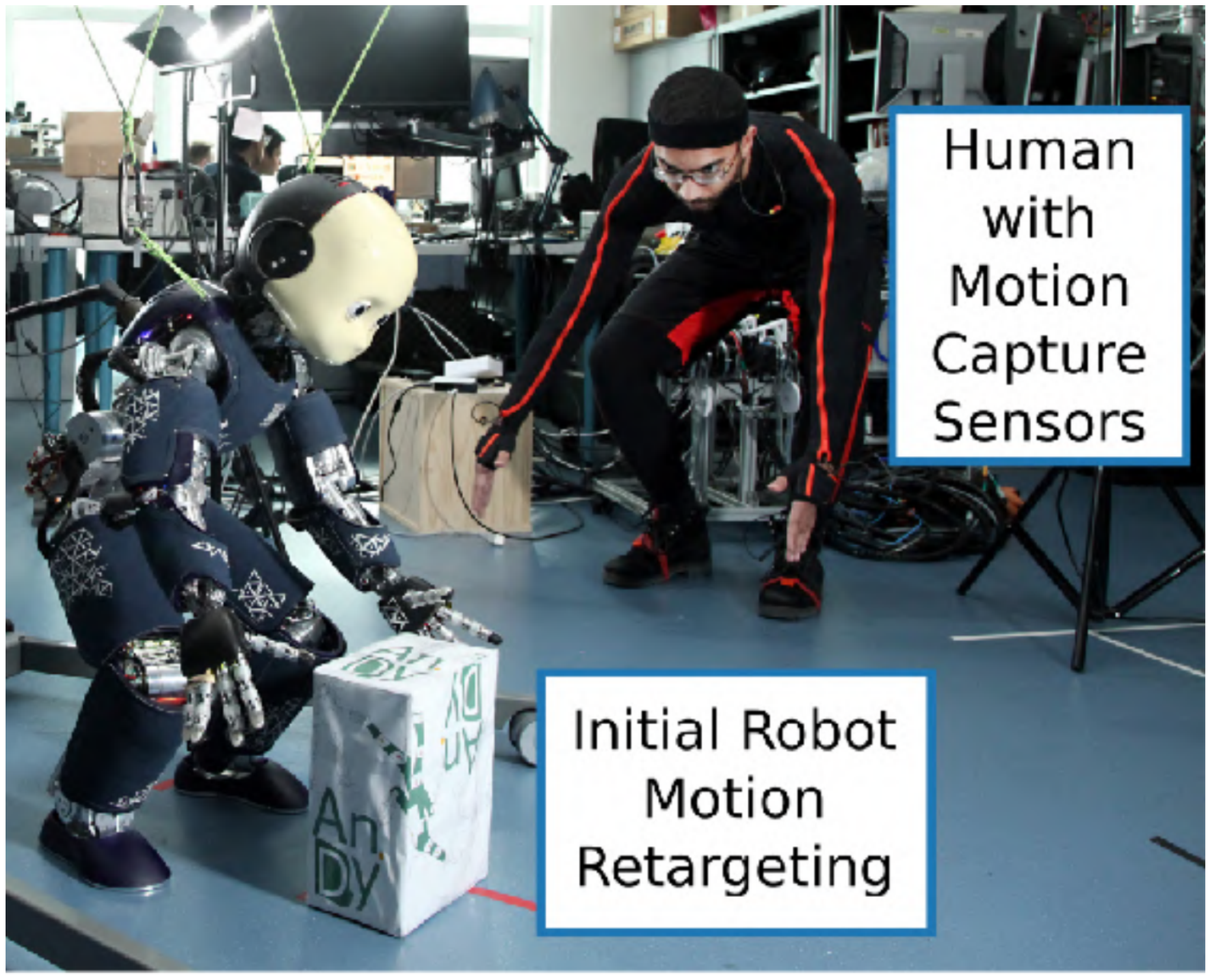
Penco et al. - under review

2) auto-tuning the controller for teleoperation



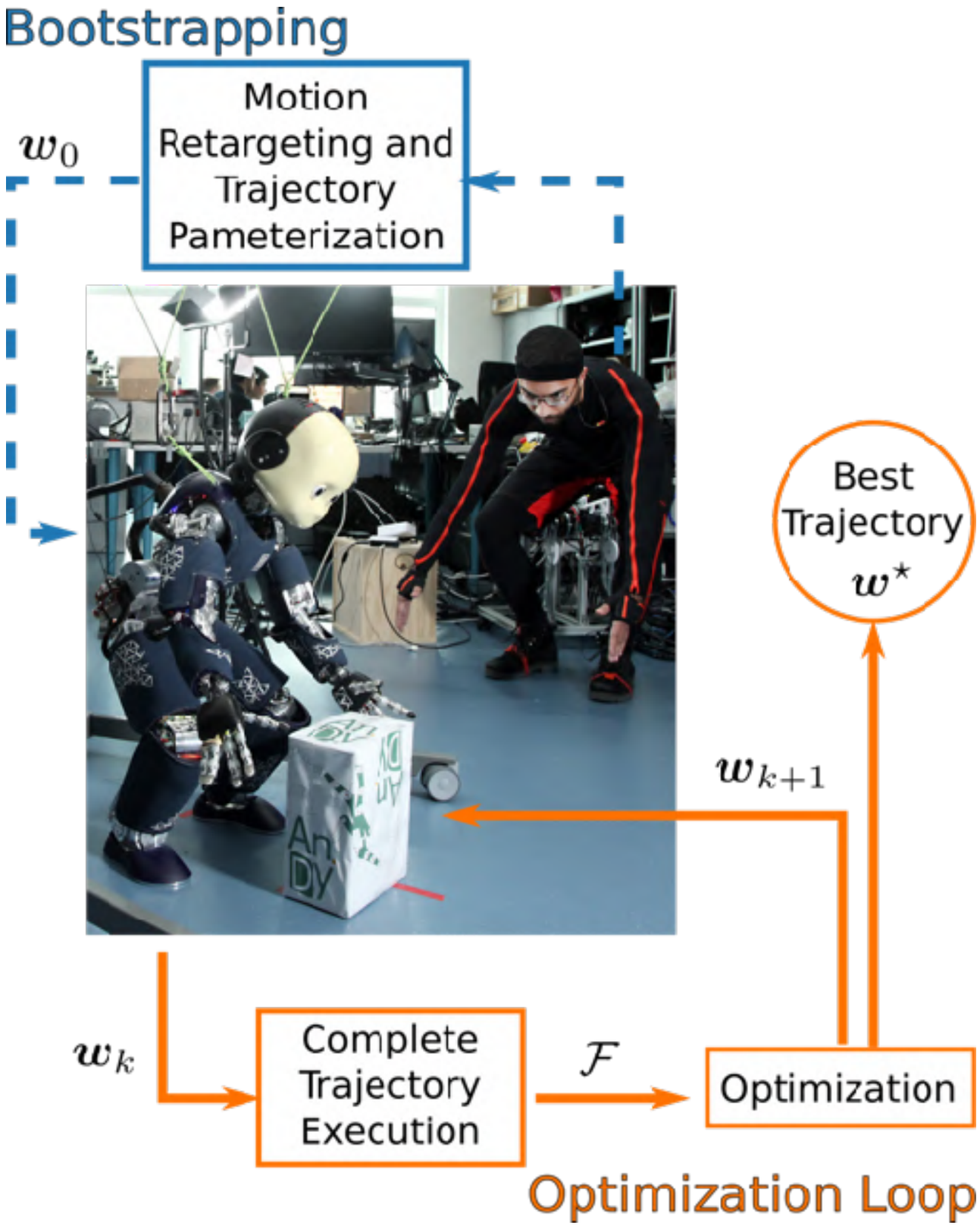
Penco et al. - under review

3) optimization of the demonstrated motions



How to ensure that the teleoperate motions are "optimal" for the robot's dynamics w.r.t. the task?

3) optimization of the demonstrated motions



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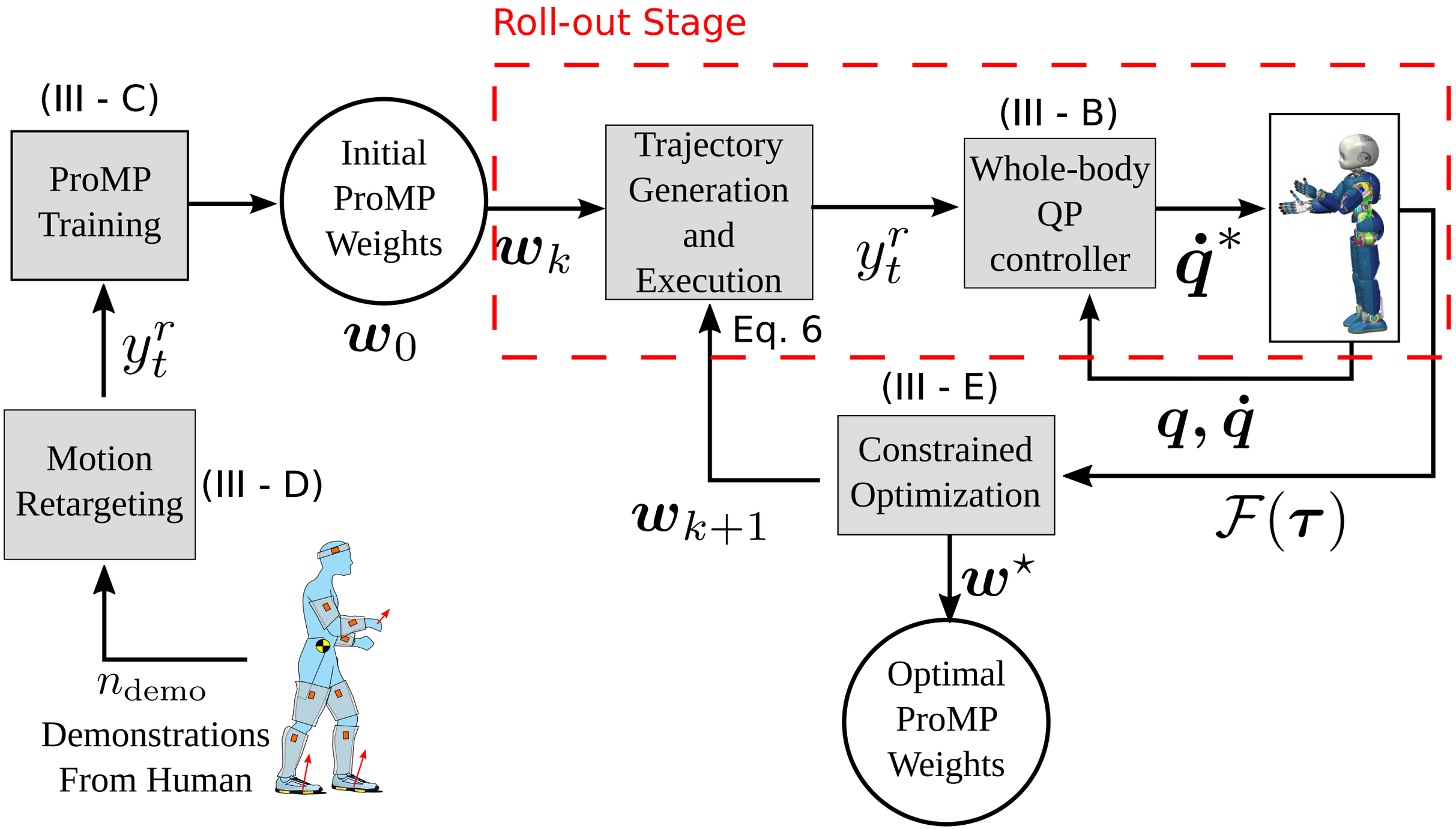
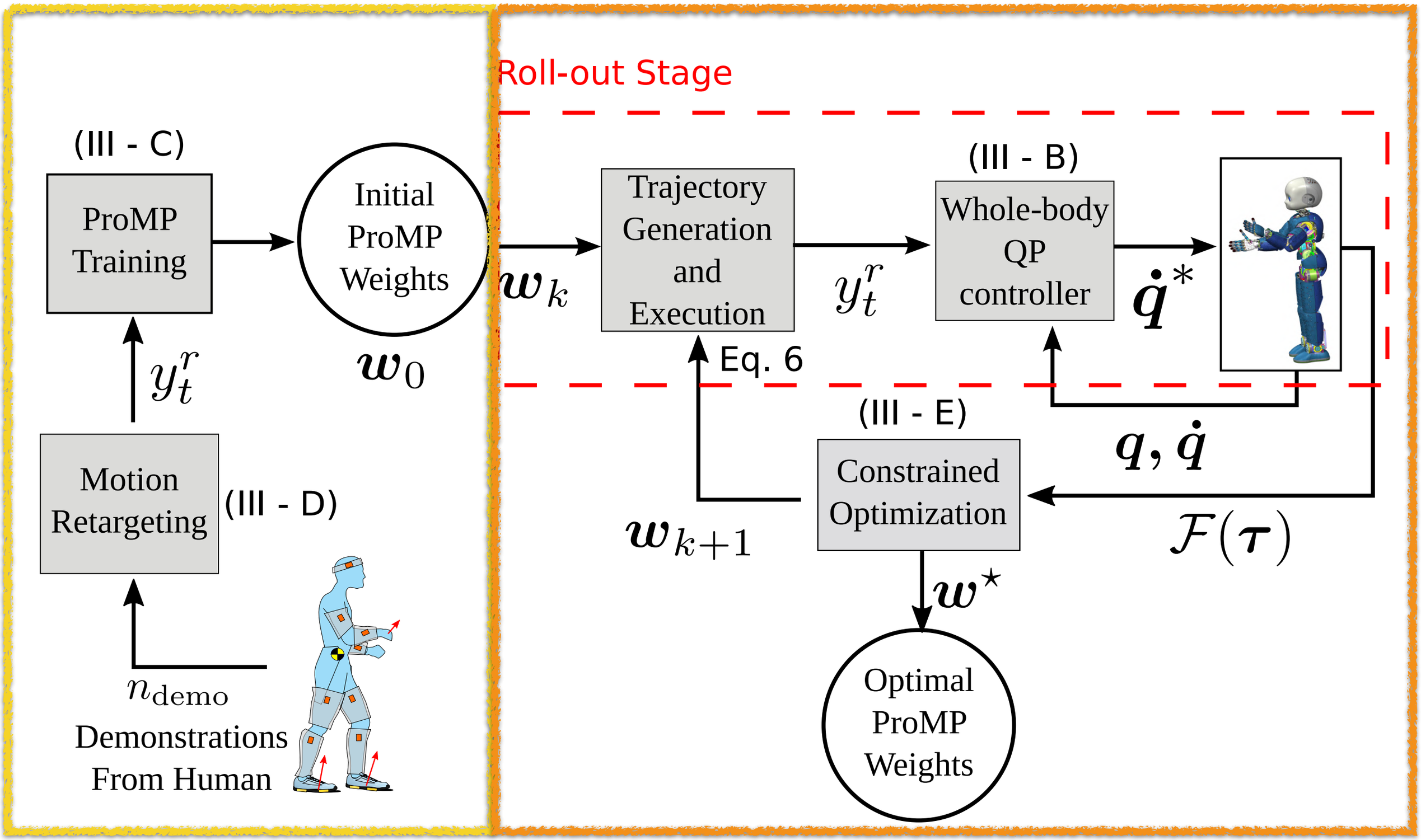


Gomes et al., HUMANOIDS 2019

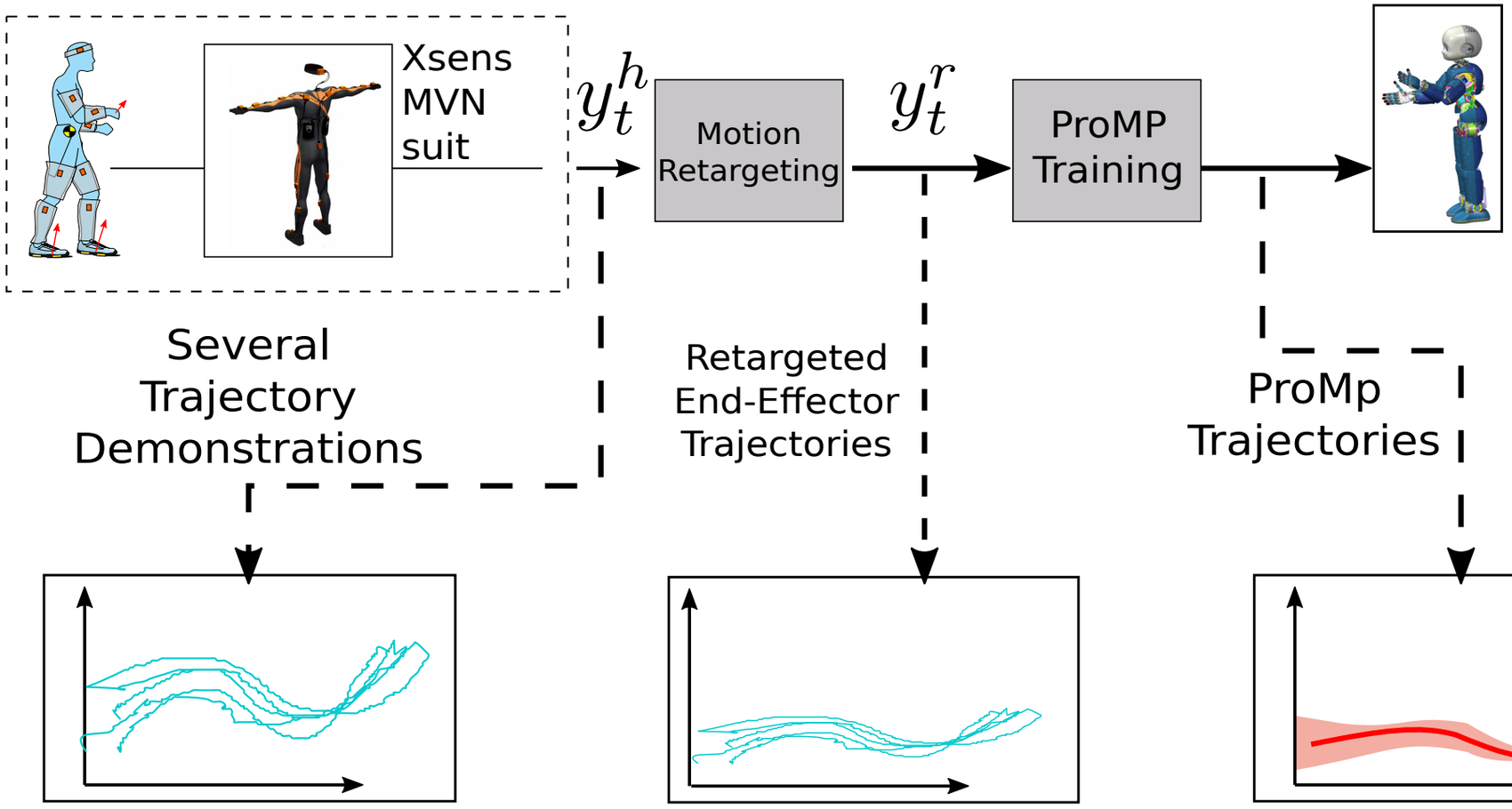
3) optimization of the demonstrated motions

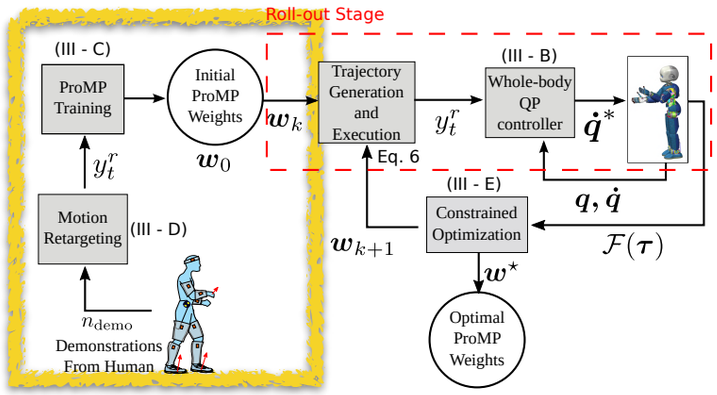


STEP 1

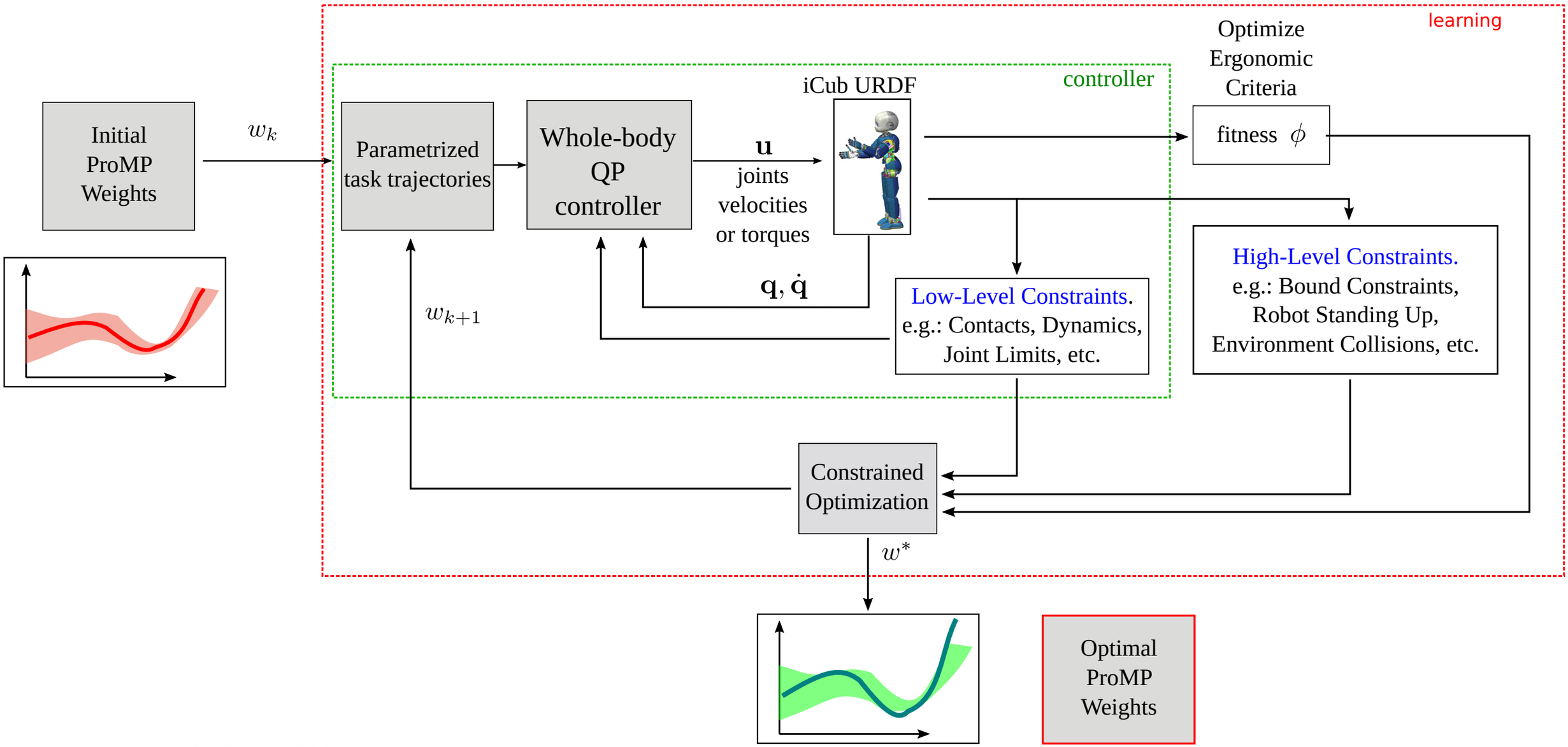
STEP 2

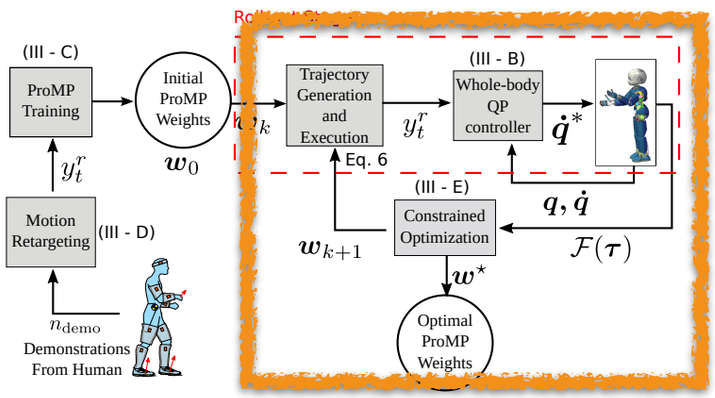
3) optimization of the demonstrated motions





3) optimization of the demonstrated motions





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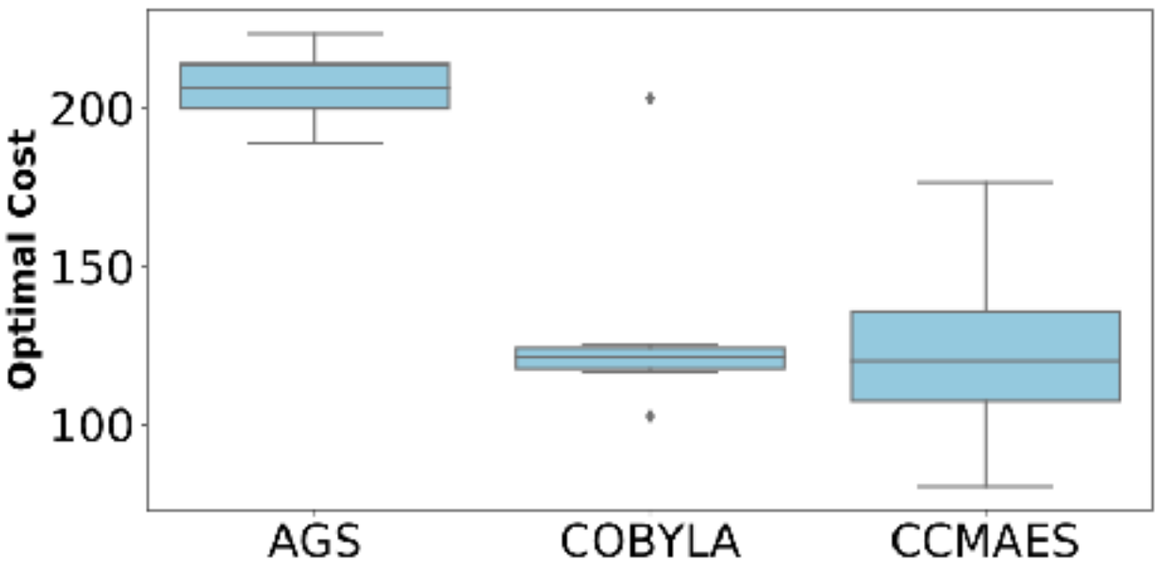
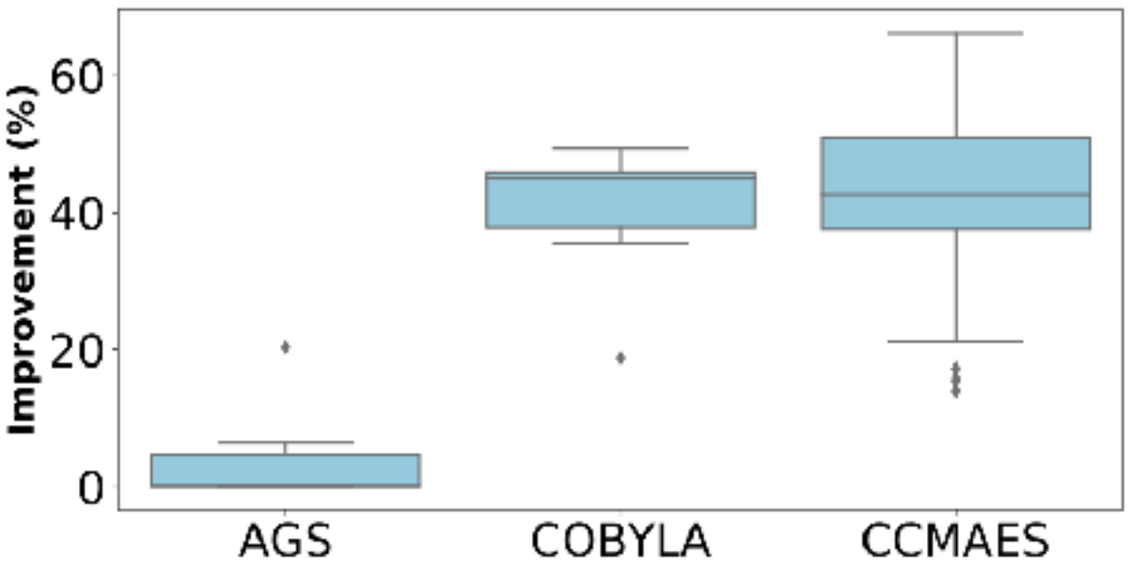
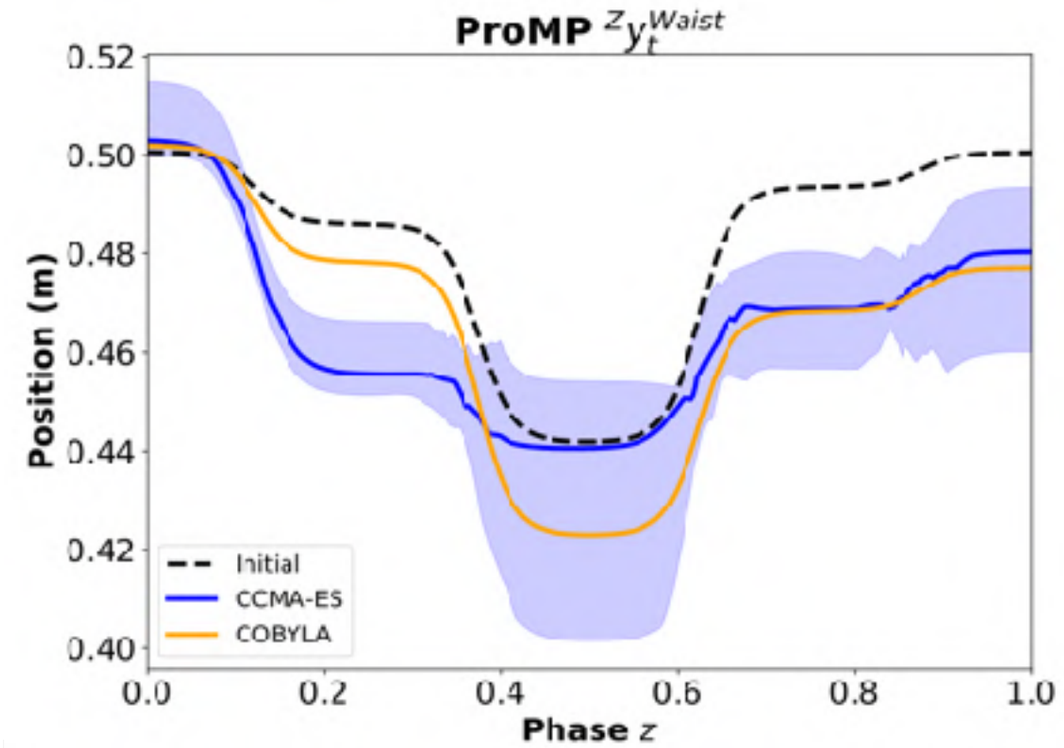
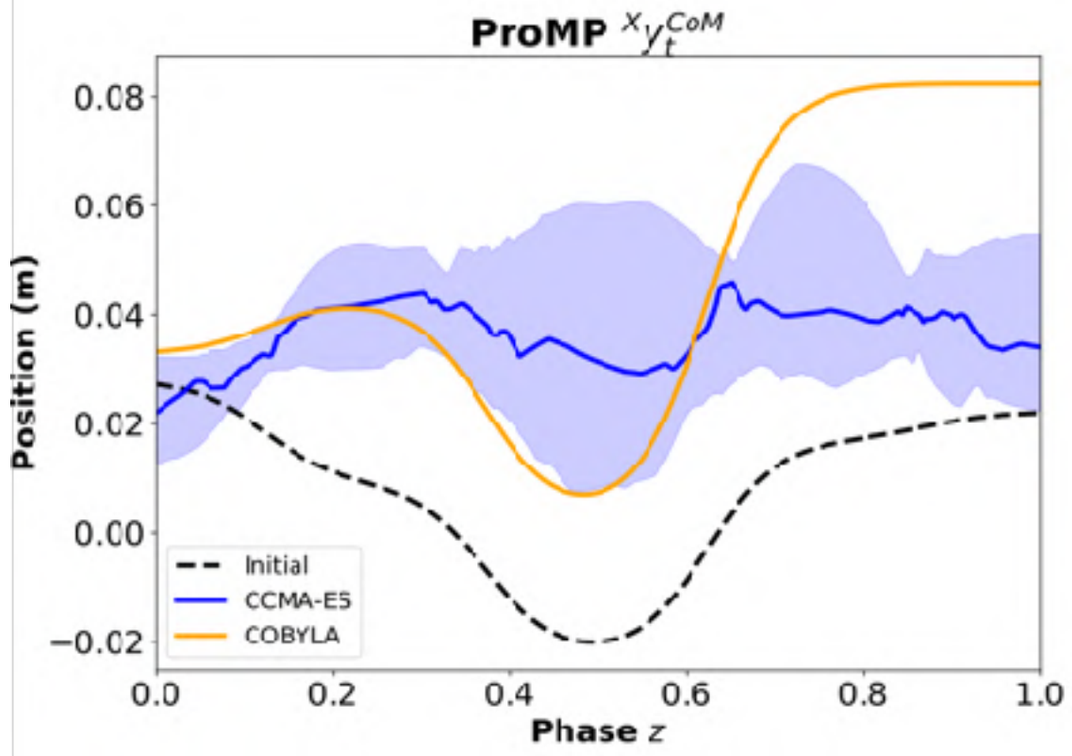


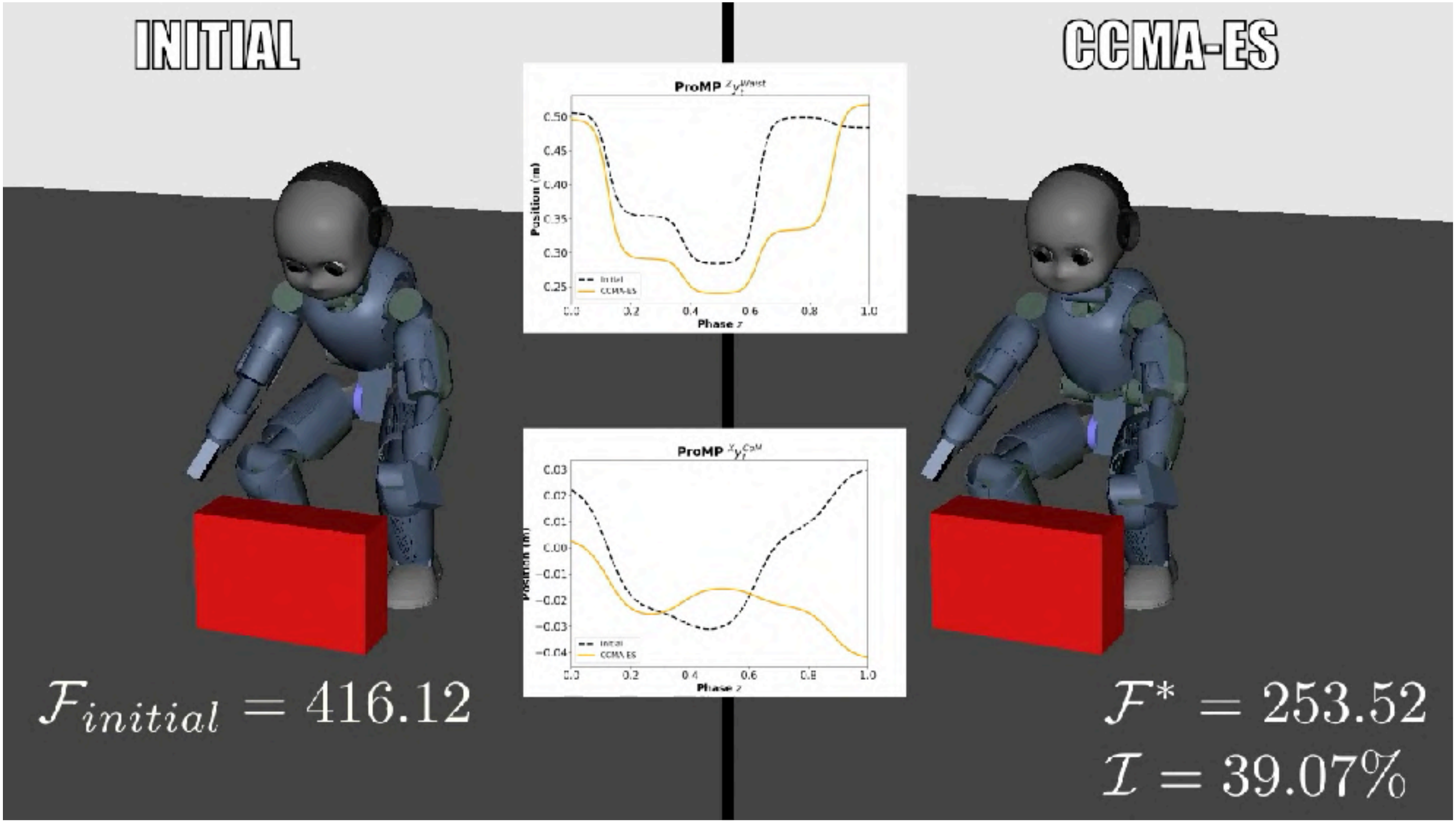






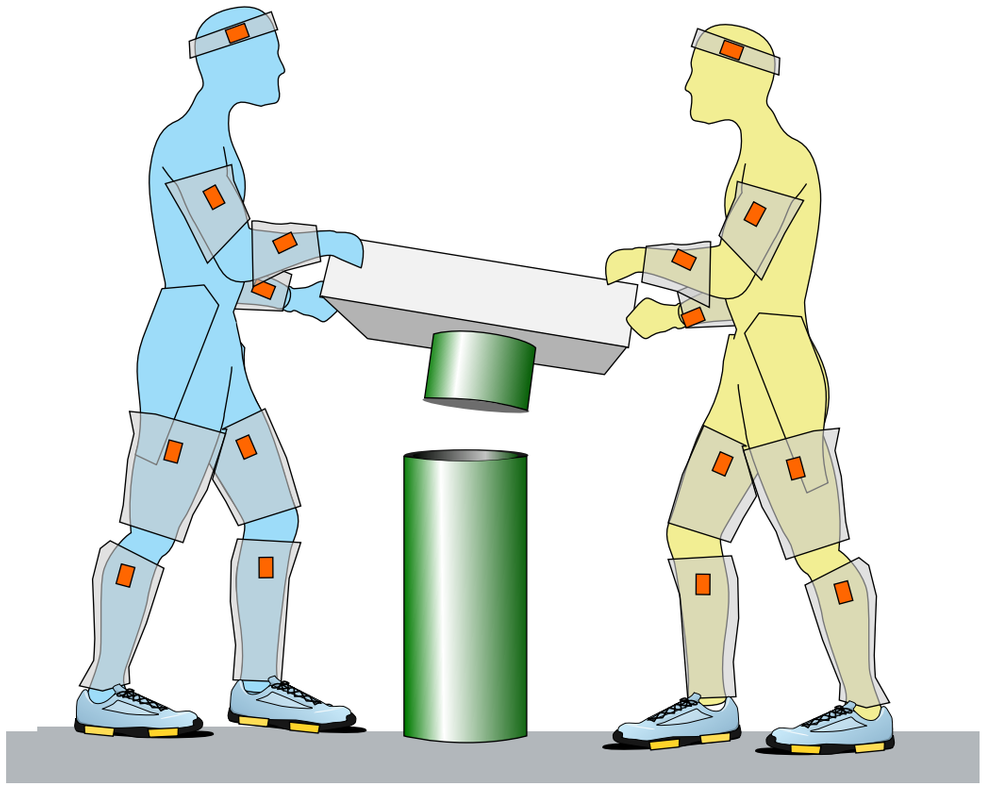
See Gomes' oral presentation tomorrow in the Optimization session!

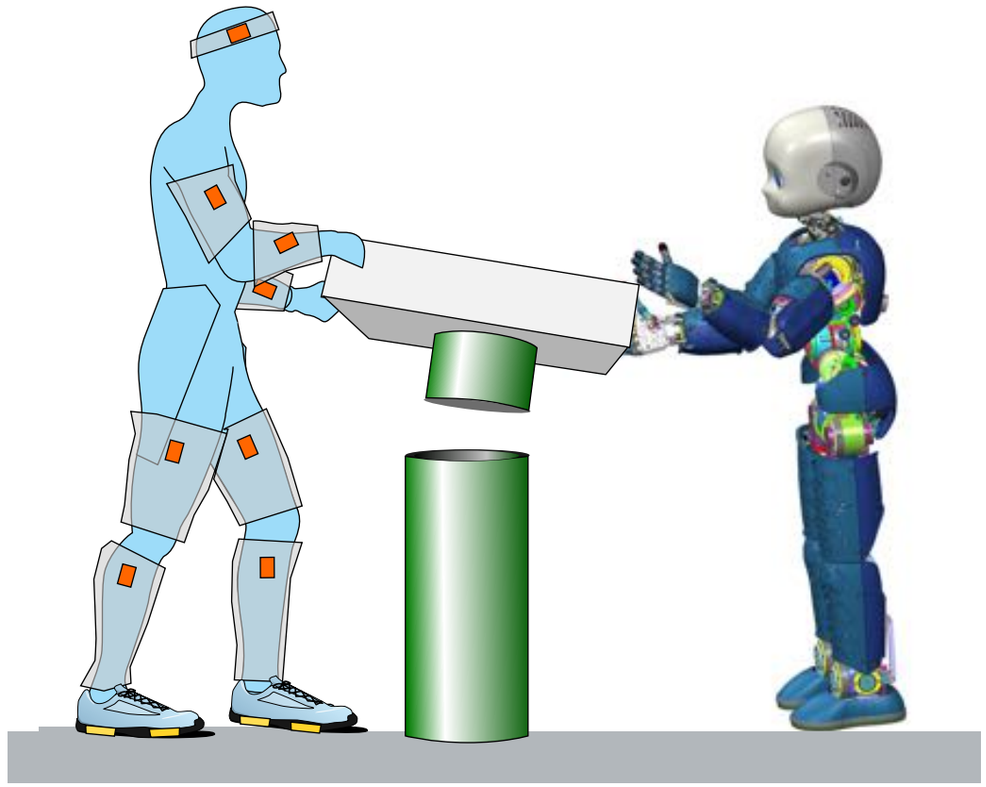
3) optimization of the demonstrated motions



Gomes et al., HUMANOIDS 2019

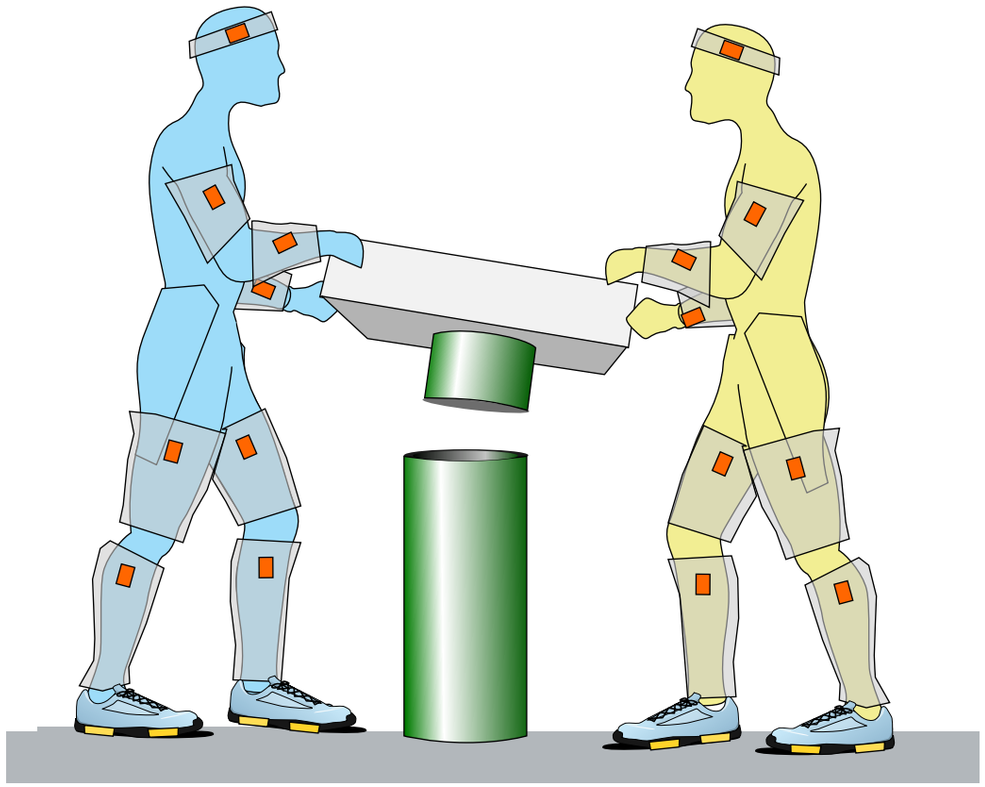
Transfer paradigm: from humans to robots

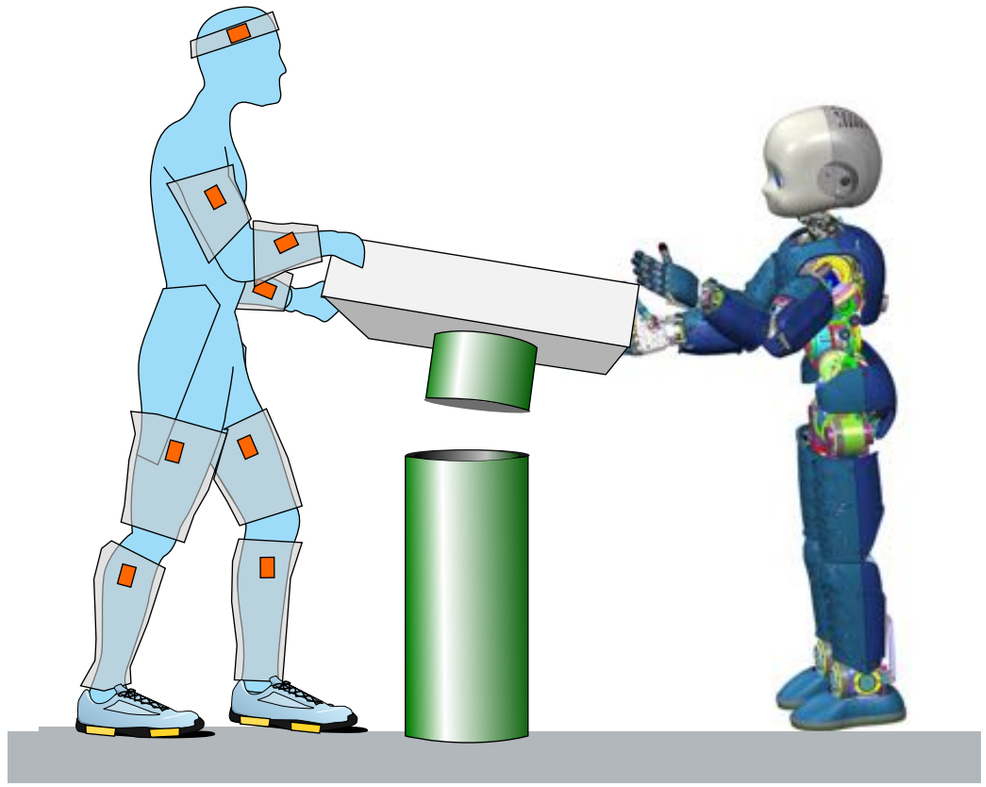




1) Teleoperation of locomotion and manipulation relying on a whole-body controller for the humanoid
2) Optimize the whole-body controller's parameters to be robust to unknown motions from the teleoperator
3) Re-optimize the teleoperated motions for the robot dynamics

Transfer paradigm: from humans to robots





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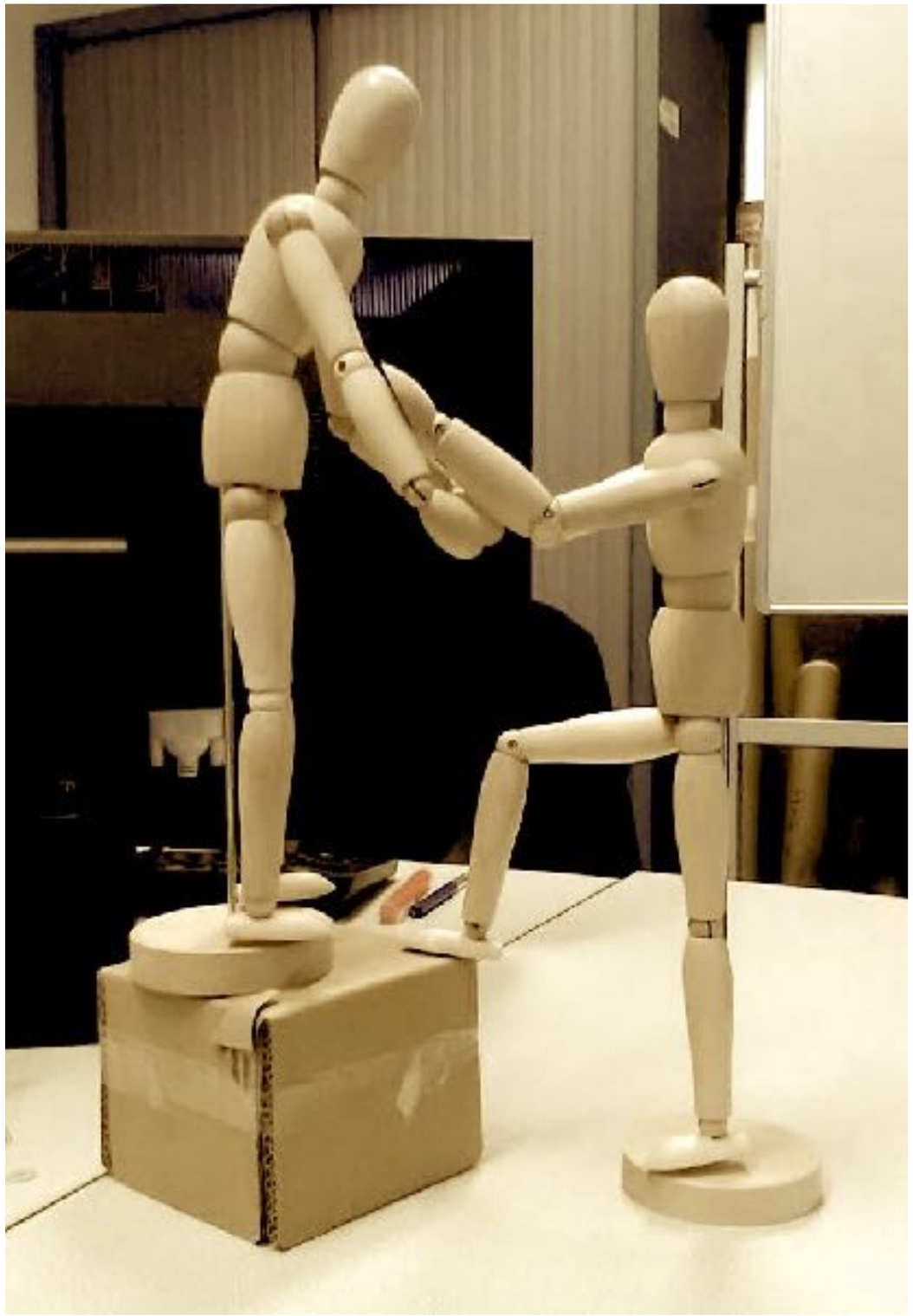
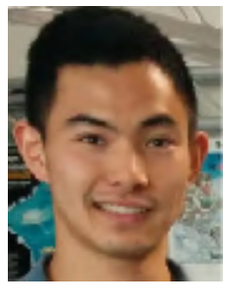
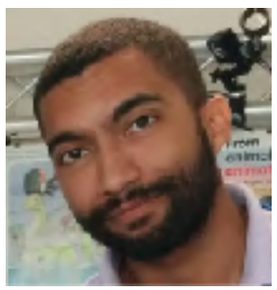


Thank you!
Questions?


L. Penco


K. Otani


W. Gomes

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