# Lecture 6: Adaptive control architecture for efficient interaction of exoskeleton with human body

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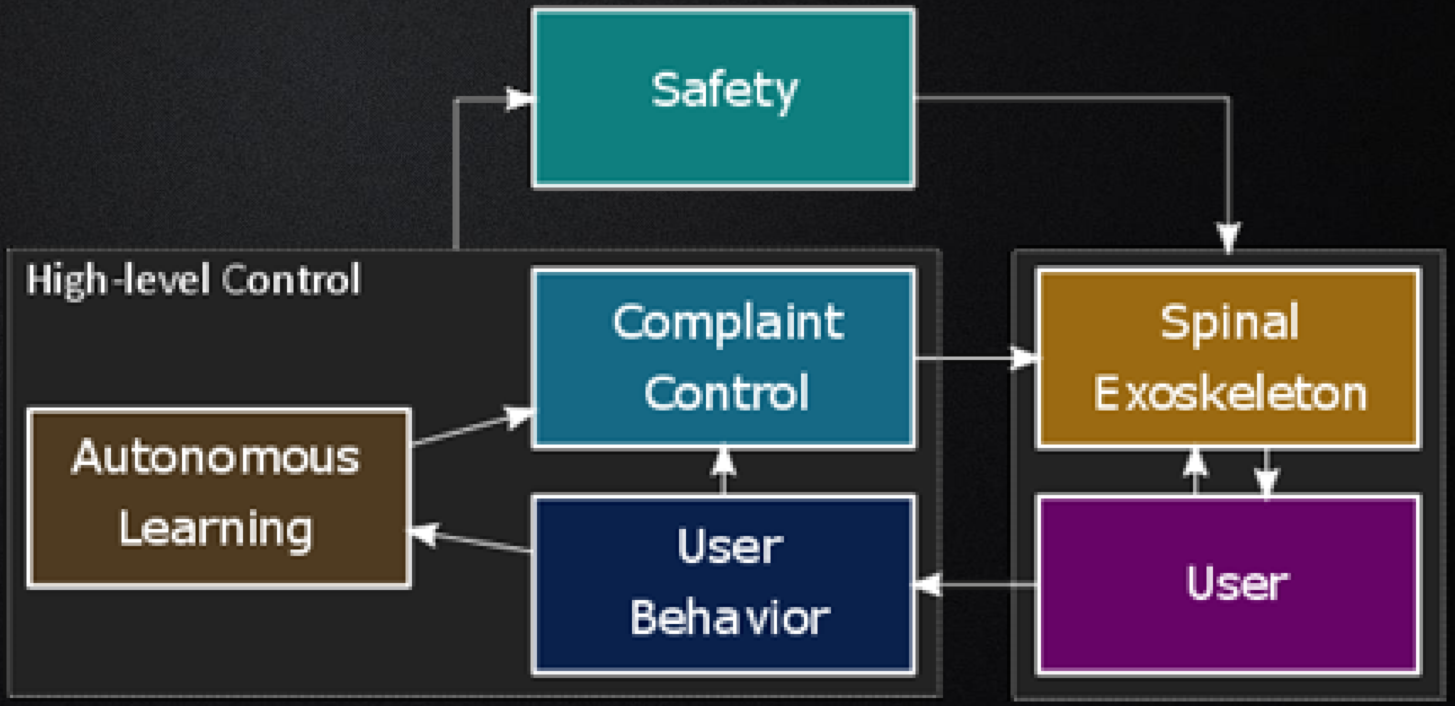
# Exoskeleton control overview

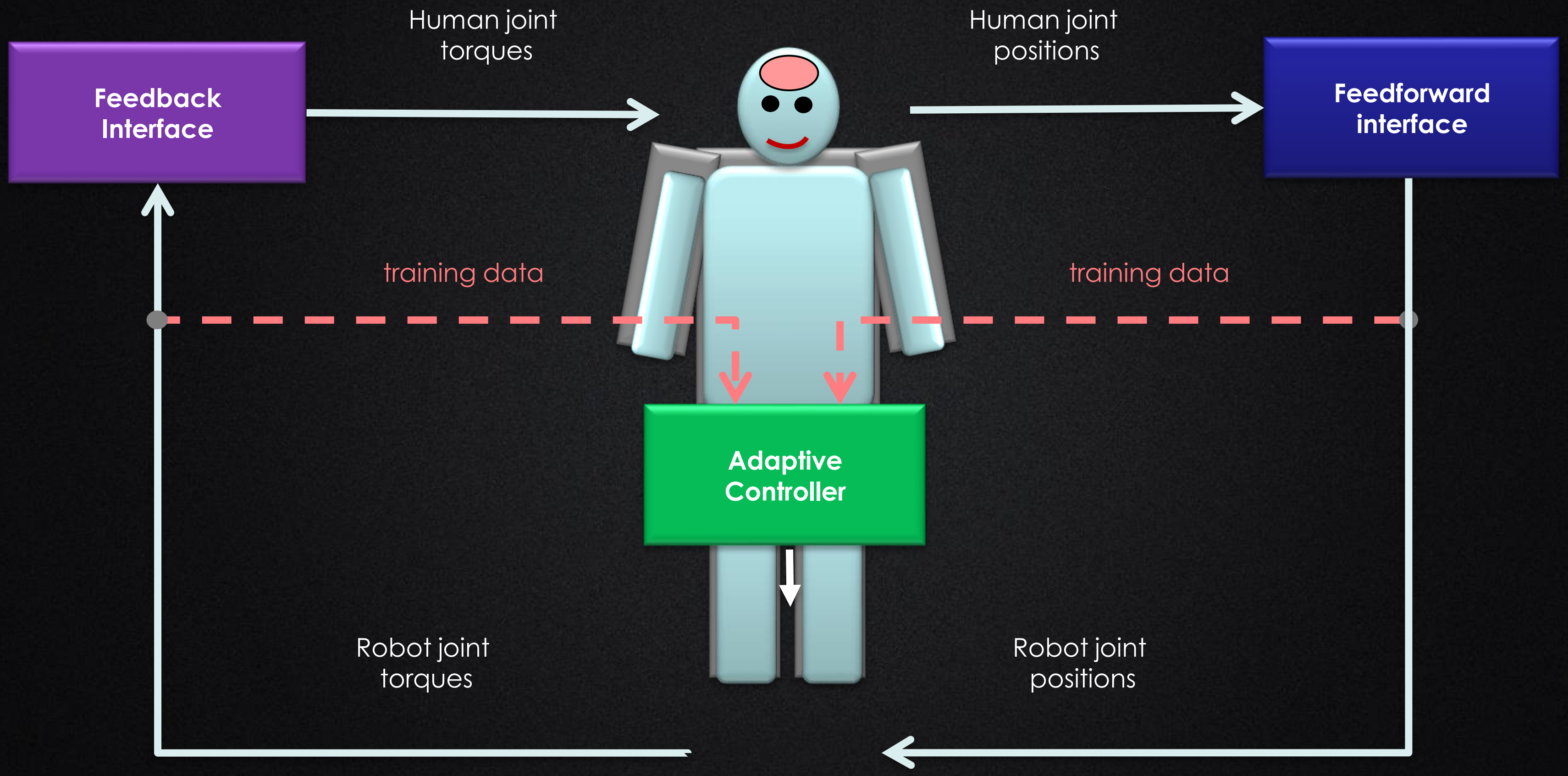
- Exoskeleton control framework
  - Complaint control
  - Human behavior
  - Autonomous learning
  - Safety



Co-adaptive control

# EXOSKELETONS CAN LEARN *FROM* AND *LIKE* HUMANS

# Exoskeleton-robot interaction



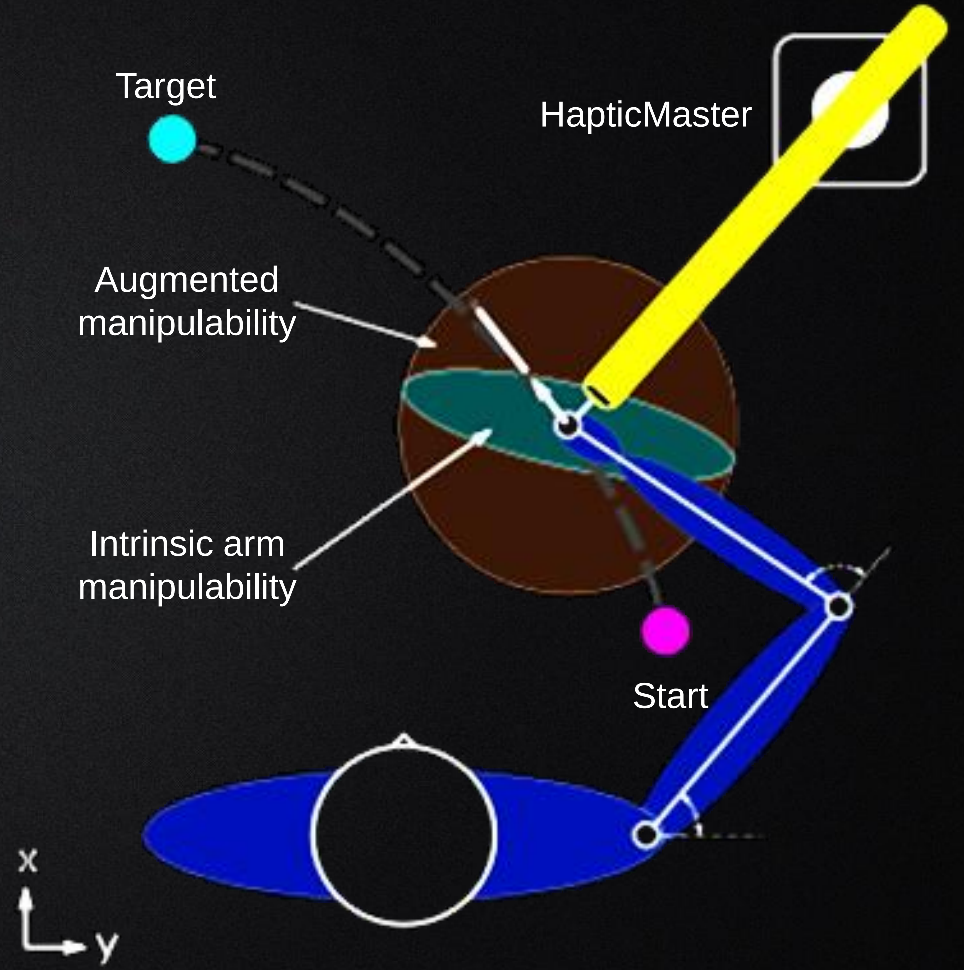
- Petrič, T., Goljat, R., Babič, J. (2016). Augmentation of human arm motor control by isotropic force manipulability. In *2016 IEEE/RSJ International Conference on Inteligent Robots and Systems*.

Feedforward interface

# AUGMENTATION OF HUMAN MOTOR CONTROL BY ISOTROPIC FORCE MANIPULABILITY

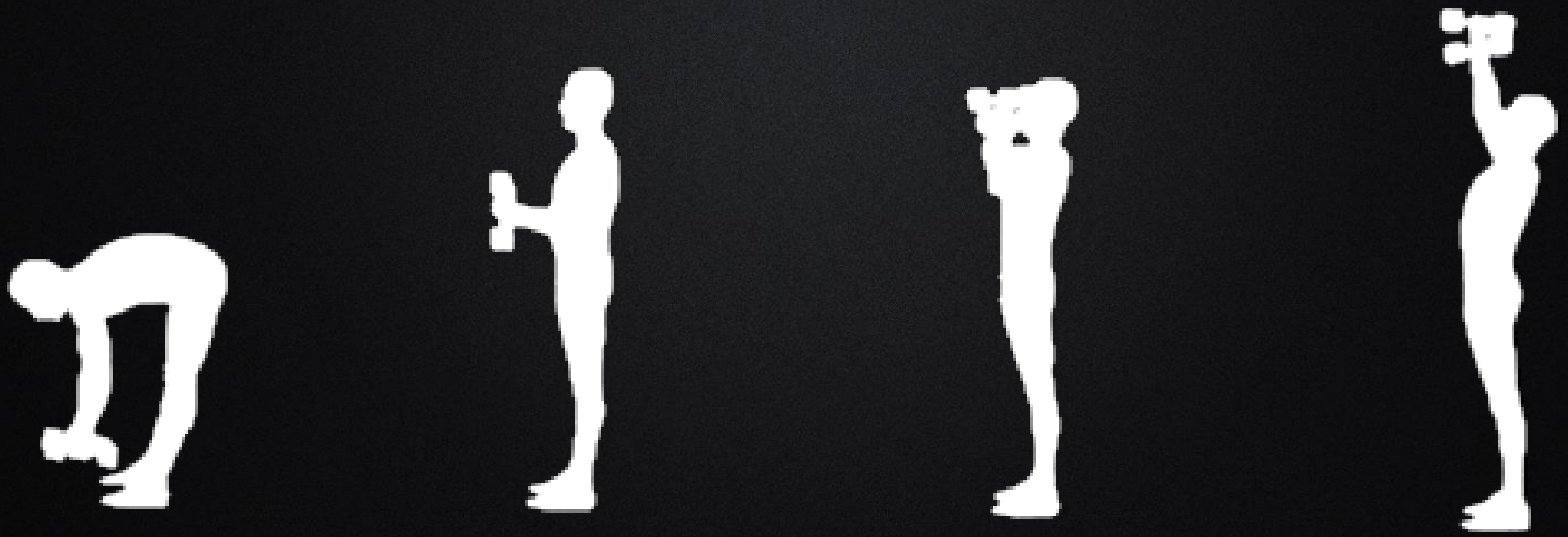
# Augmentation of Human Arm Motor Control

- A novel control approach that augments the motion of the human arm
- Transforms the anisotropy of the intrinsic arm manipulability into an augmented manipulability
- Evaluated on five healthy subjects under three different conditions



# Background

- Manipulability of robotic manipulators applied to human arm
- Major and minor axis of manipulability ellipse represent directions of high and low manipulability
- It is easier to exert larger forces along the major axis than along minor axis



# Control method

- Manipulability ellipse:

$$\mathbf{M} = \mathbf{J}\mathbf{J}^T$$

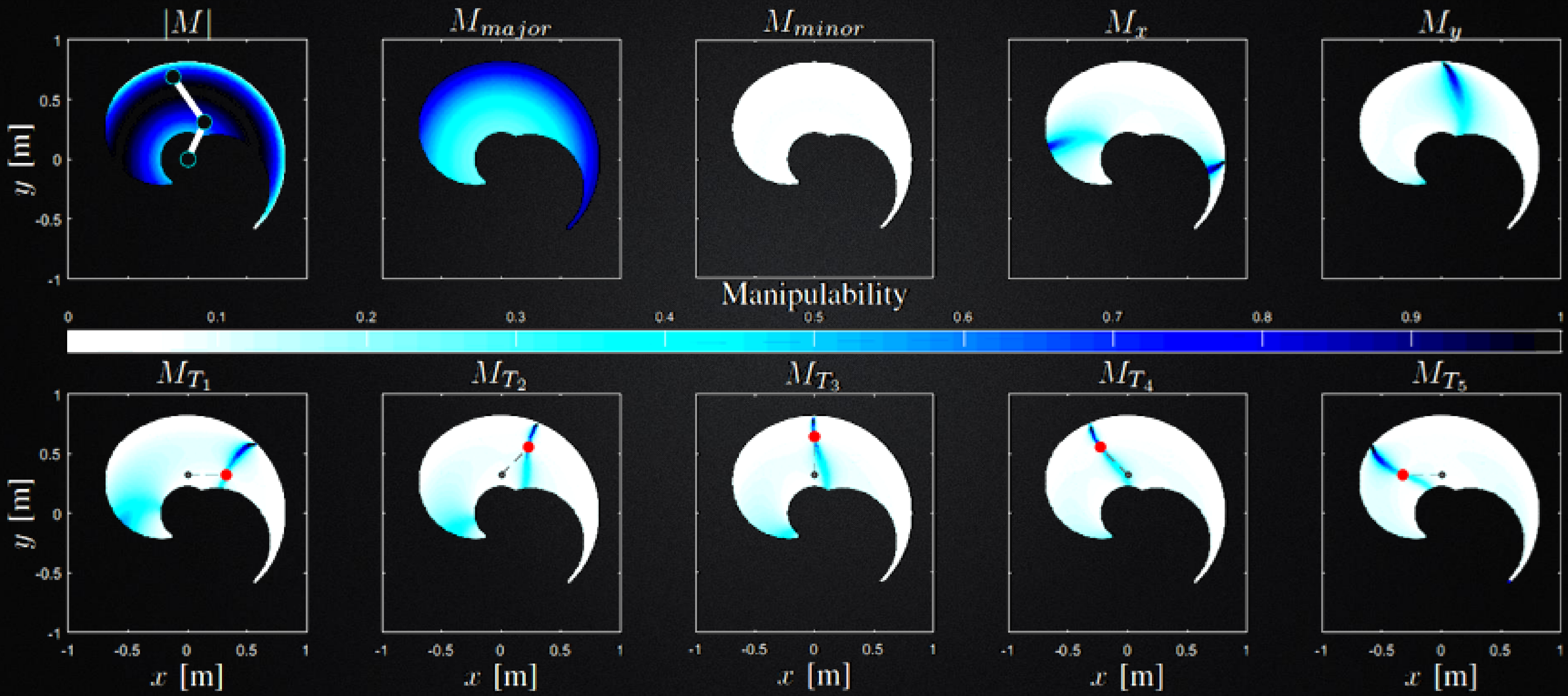
- Ratio between user force and major axis is assistance factor for supportive force:

$$\boldsymbol{F}_s = (K - 1)\boldsymbol{F}_u$$

$$K = \frac{||M_{axis}||}{||F_{axis}||}$$

- When user pushes in direction of major axis, there is no assistance from the robot

# Manipulability for few points in space



# Method evaluation – haptic

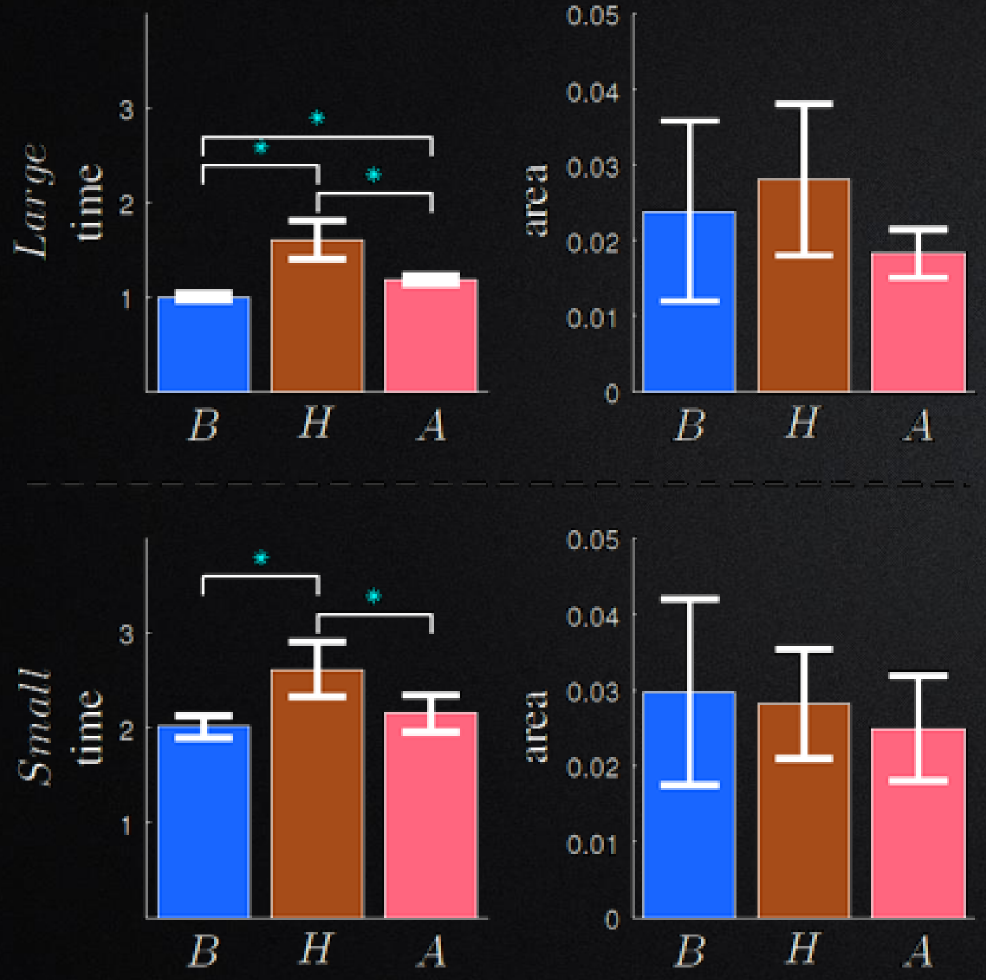
- Baseline session: Move a light load to randomly chosen target without any assistance from robot

- Heavy session: Move a heavy load to randomly chosen target without any assistance from robot

- Assisted session: Move a heavy load to randomly chosen target with assistance from robot

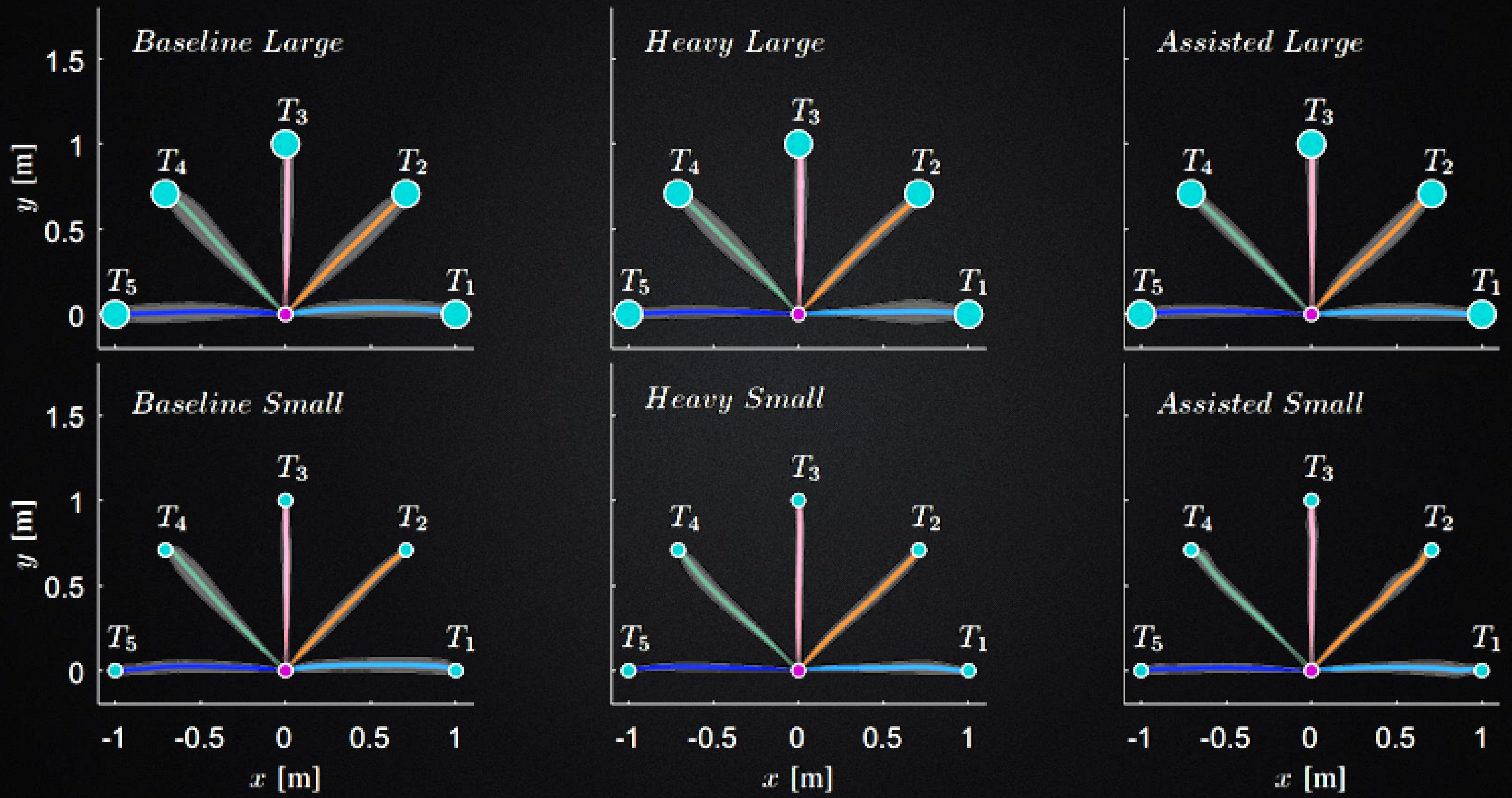
- One starting location and Five target locations
- Session: Large or small target size

# Evaluation results




- Movement time of assisted session is better than heavy session
- Movement time of assisted session is similar to baseline Session
- Deviation from ideal path is not effected

# Evaluation results



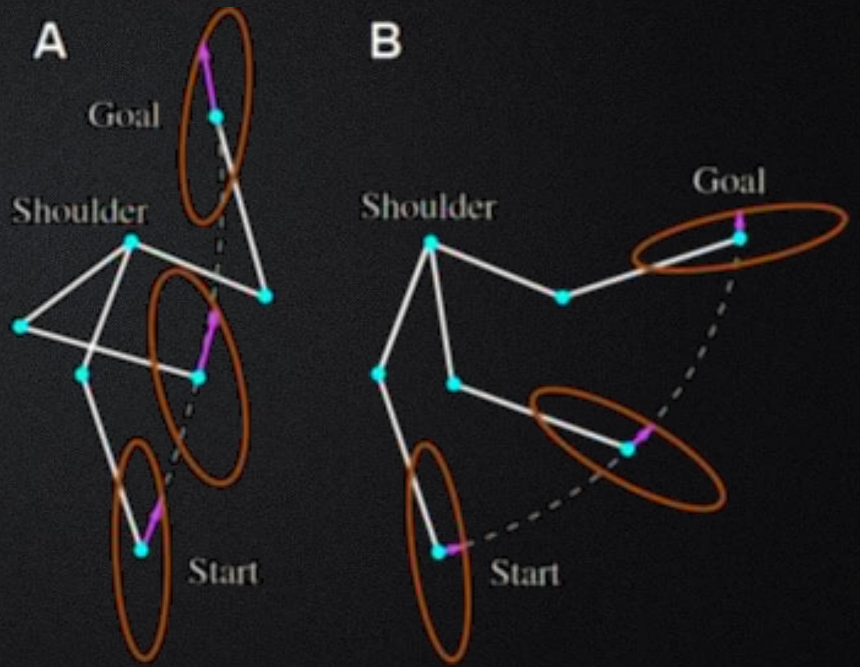

Mean movement trajectories for all subjects with standard deviation

# Method evaluation – arm exoskeleton

- Arm configurations and the corresponding muscular manipulability ellipses during the two motions performed by the subject.

- A: Motion in the region
    of high manipulability.

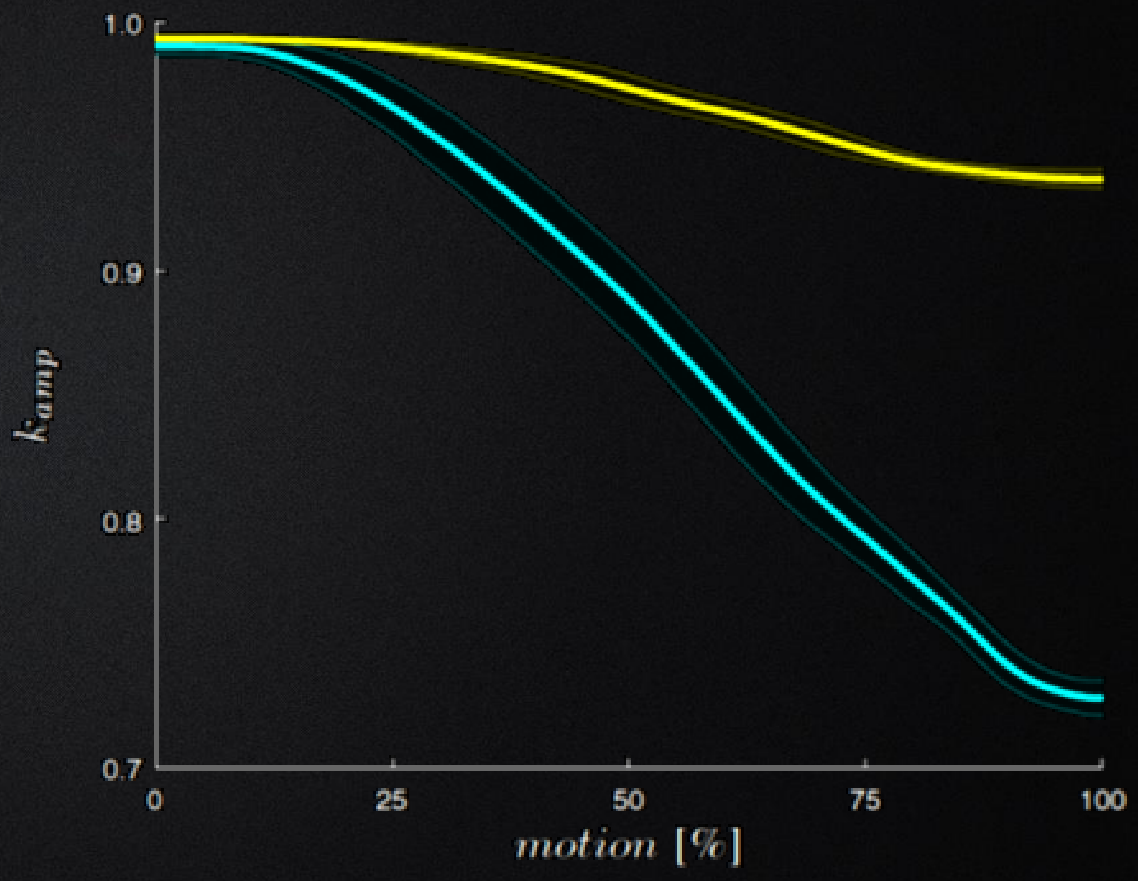
- B: Motion in the region
    of low manipulability.




- The arrows represent manipulabilities in the given direction of motion.

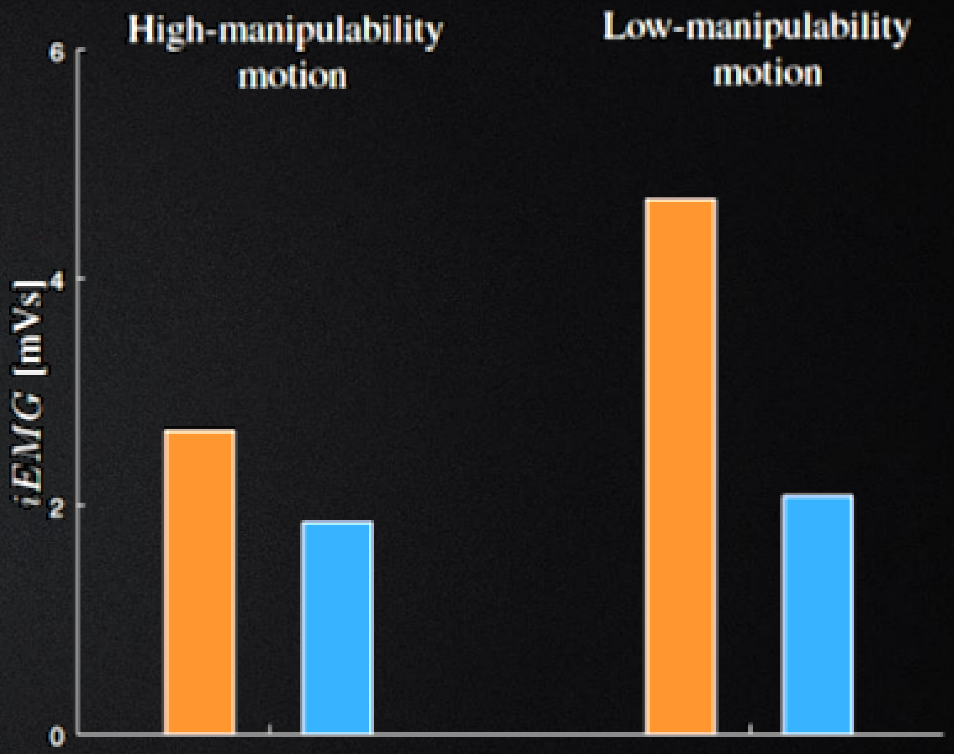
# Evaluation results

- Support of the exoskeleton during motion.
- The average support of the exoskeleton during high-manipulability motion (red) and low-manipulability motion (blue).
- Support remains high during low-manipulability motion,
- Support decreases during high-manipulability motion.



# Evaluation results

- Integrated EMG for unsupported (blue) and supported motions (orange).
- Bars on the left side represent the iEMG during the high-manipulability motion
- Bars on the right side represent the iEMG during the low-manipulability motion.




| Motion (session) | Integrated EMG $[mVs]$ | Motion time $[s]$ |
|---|---|---|
| High-manipulability (unsupported) | 2.66 | 1.33 |
| High-manipulability (supported) | 1.86 | 1.32 |
| Low-manipulability (unsupported) | 4.69 | 1.46 |
| Low-manipulability (supported) | 2.08 | 1.32 |

2016

# Power-Augmentation Control Approach for Arm Exoskeleton Based on Human Muscular Manipulability

Rok Goljat[1,3], Jan Babič[1], Tadej Petrič[1], Luka Peternel[2], Jun Morimoto[3]

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[2]HRI[2] Lab, ADVR, Istituto Italiano di Tecnologia, Italy
[3]BRI, ATR Computational Neuroscience Laboratories, Japan

- Petrič, T., Goljat, R., & Babič, J. (2016). Cooperative human-robot control based on Fitts' law. In 2016 IEEE-RAS 16th International Conference on Humanoid Robots (Humanoids).

Feedback interface

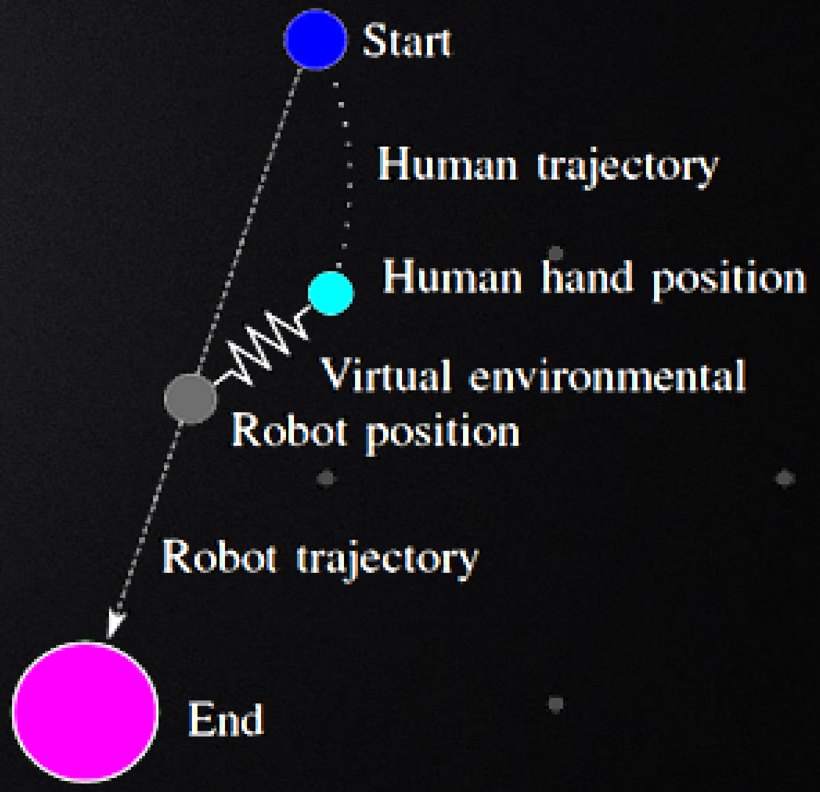
# ENHANCED COLLABORATION

# Complementary human-robot control for enhanced collaboration

- Combining robot control with human control in such a way as to enhance and emphasize the qualities of each other

- 4 HUMAN
  - to improve speed-accuracy trade-off (Fitts' law)
  - to extend the efficient workspace (manipulability)
  - to reduce the variability of motion

- 4 ROBOT
  - to include cognition
  - to improve the workload
  - to use proprioception



# Human-robot control based on Fitts' law

- Fitts' law:

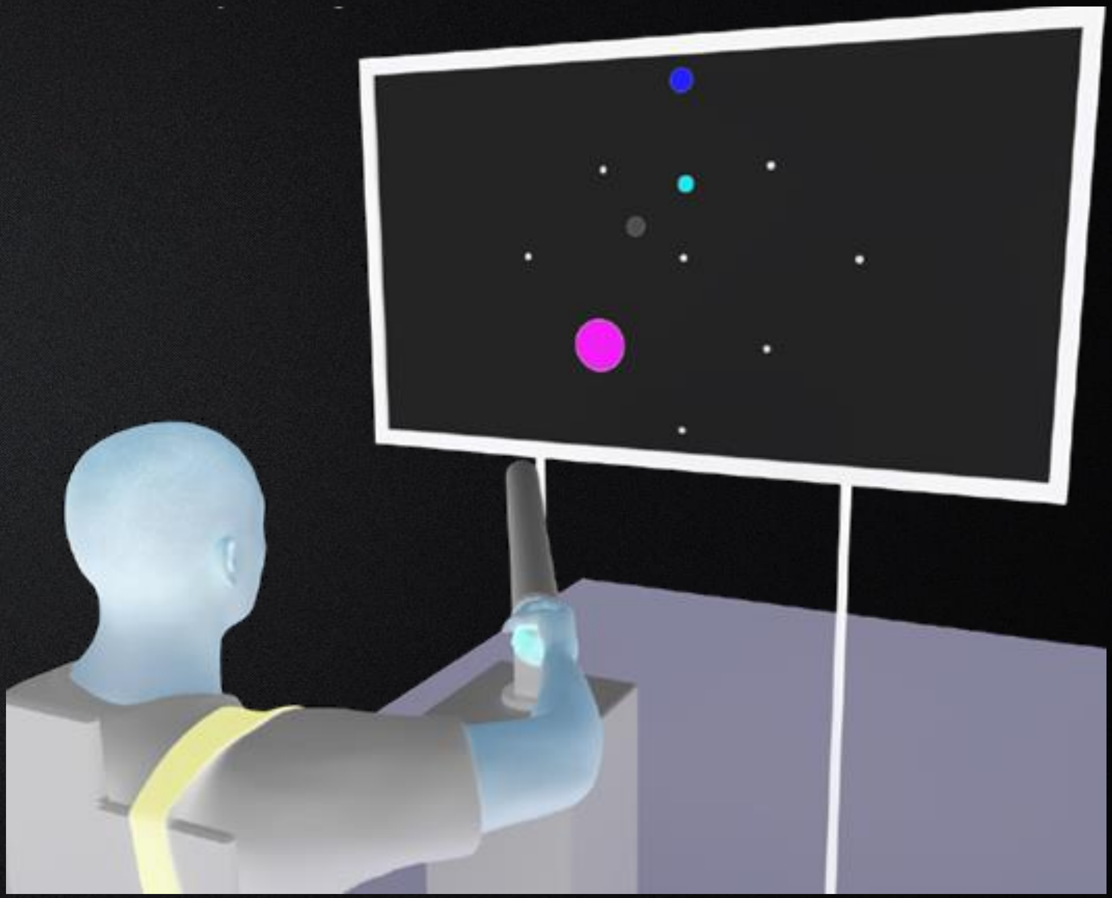
$$T = \zeta_1 + \zeta_2\, ID = [1\ ID]\zeta = \Upsilon'\zeta$$

$$ID = log_2\left(\frac{2D}{W}\right)$$

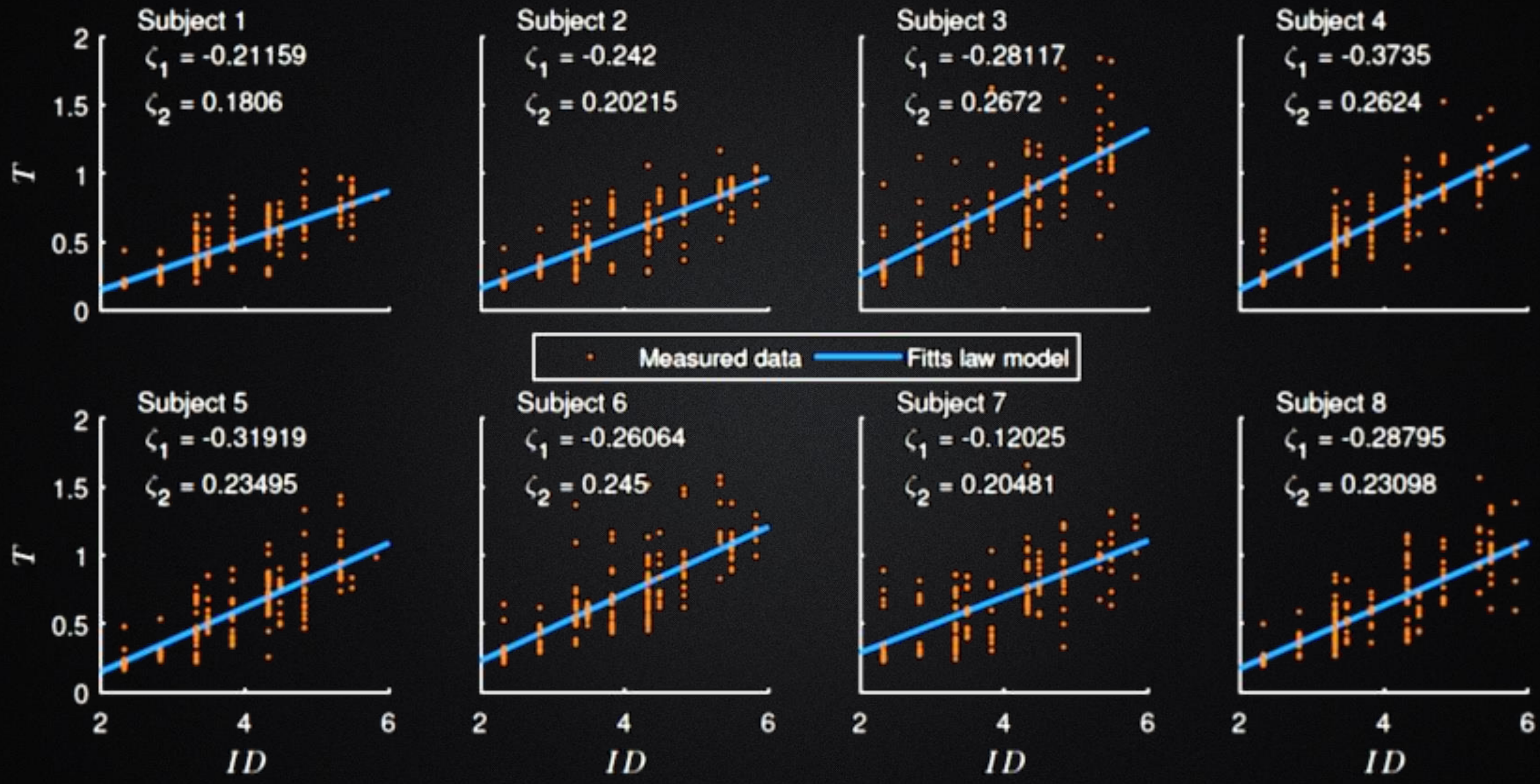
- The recursive least squares updates for the Fitts' law are given by

$$\mathbf{P}_{n+1} = \frac{1}{\lambda}\left(\mathbf{P}_n - \frac{\mathbf{P}_n\Upsilon\Upsilon'\mathbf{P}_n}{\lambda + \Upsilon'\mathbf{P}_n\Upsilon}\right),$$

$$\zeta_{n+1} = \zeta_n + \mathbf{P}_{n+1}\Upsilon\left(T_{n+1} - \zeta_n'\Upsilon\right)',$$

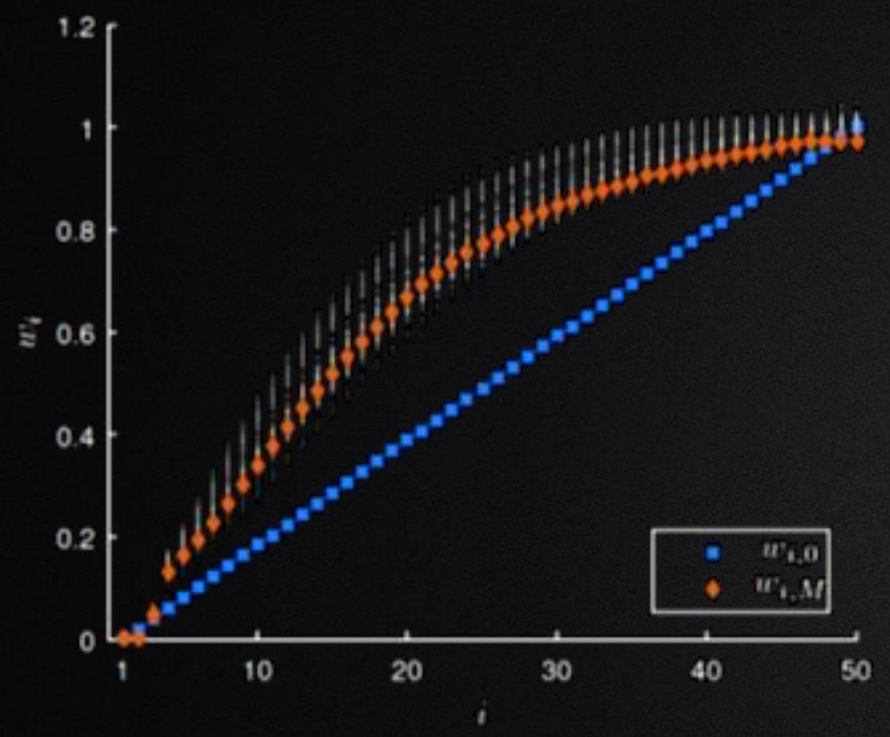


# Fitts‘ law adaptation

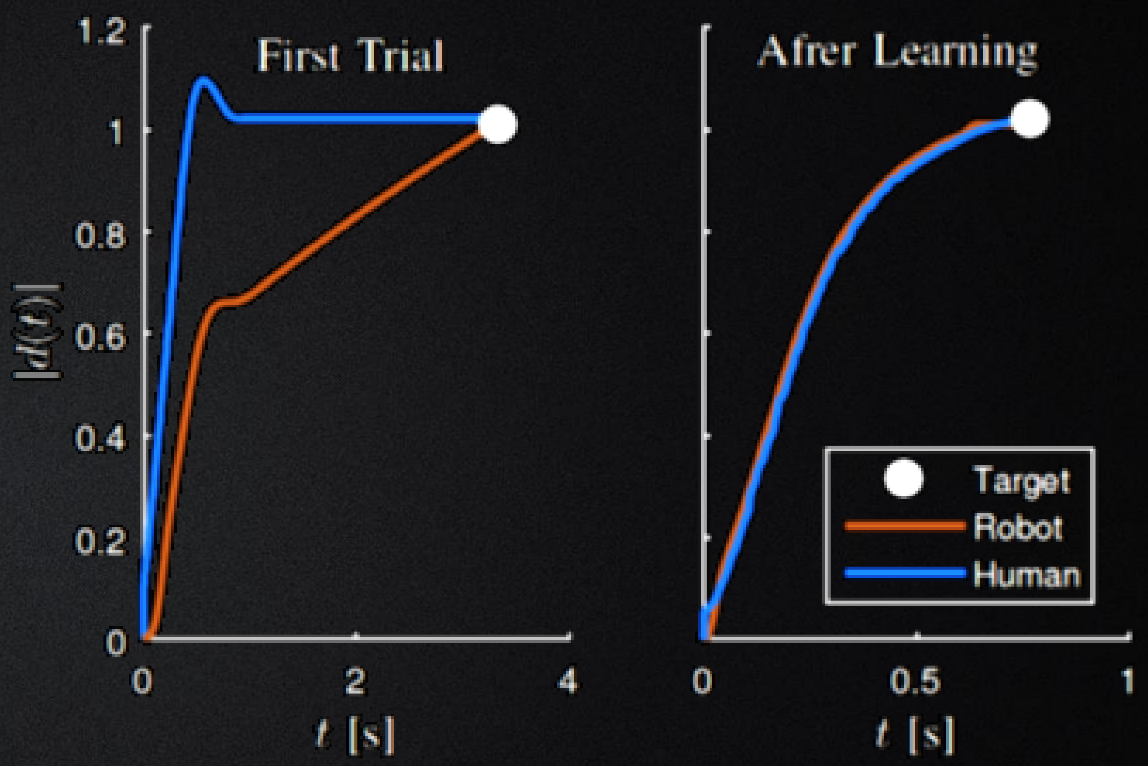



Fitts’ law models for all participated subjects.

# Movement adaptation




Adaptation of DMP weights for one subject during one session. The initial weights are in orange and the final weights are in blue. The intermediate steps are indicated with shades of gray.




Comparison of human and robot trajectories for the initial trial (left plot) and trial after the finished adaptation of the movement profiles and Fitts' law parameters (right plot).


Human - robot collaboration results in
fast and accurate performance
9

- Peternel, L., Noda, T., Petrič, T., Ude, A., Morimoto, J., & Babič, J. (2016). Adaptive Control of Exoskeleton Robots for Periodic Assistive Behaviours Based on EMG Feedback Minimisation. PLOS ONE, 11(2)

Feedback interface

# ADAPTIVE CONTROL BASED ON EMG MINIMISATION

# Adaptive control based on EMG minimization

- Adaptive learning of joint support trajectories based on human muscle activity minimization.
- Dynamics of single muscle and single joint system:

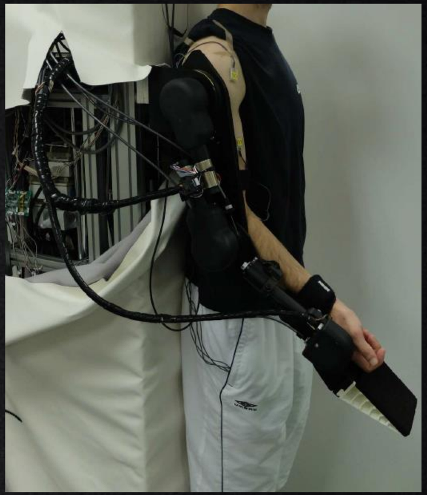
$$\tau_e(\phi) + \tau_m(\phi) = \tau_l(\phi)$$

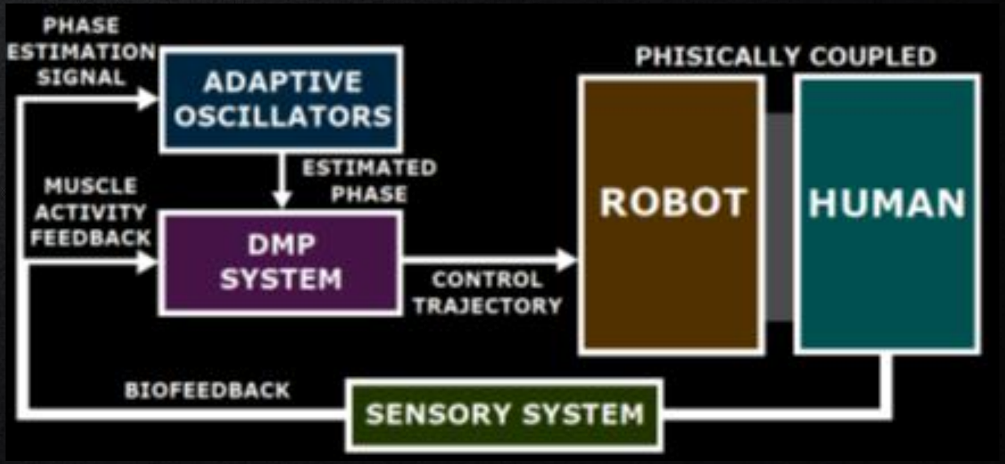
- Joint torque is a function of muscle activation [Fleischer et al. 2008]:

$$\tau_m = f(A_m, \mu)$$

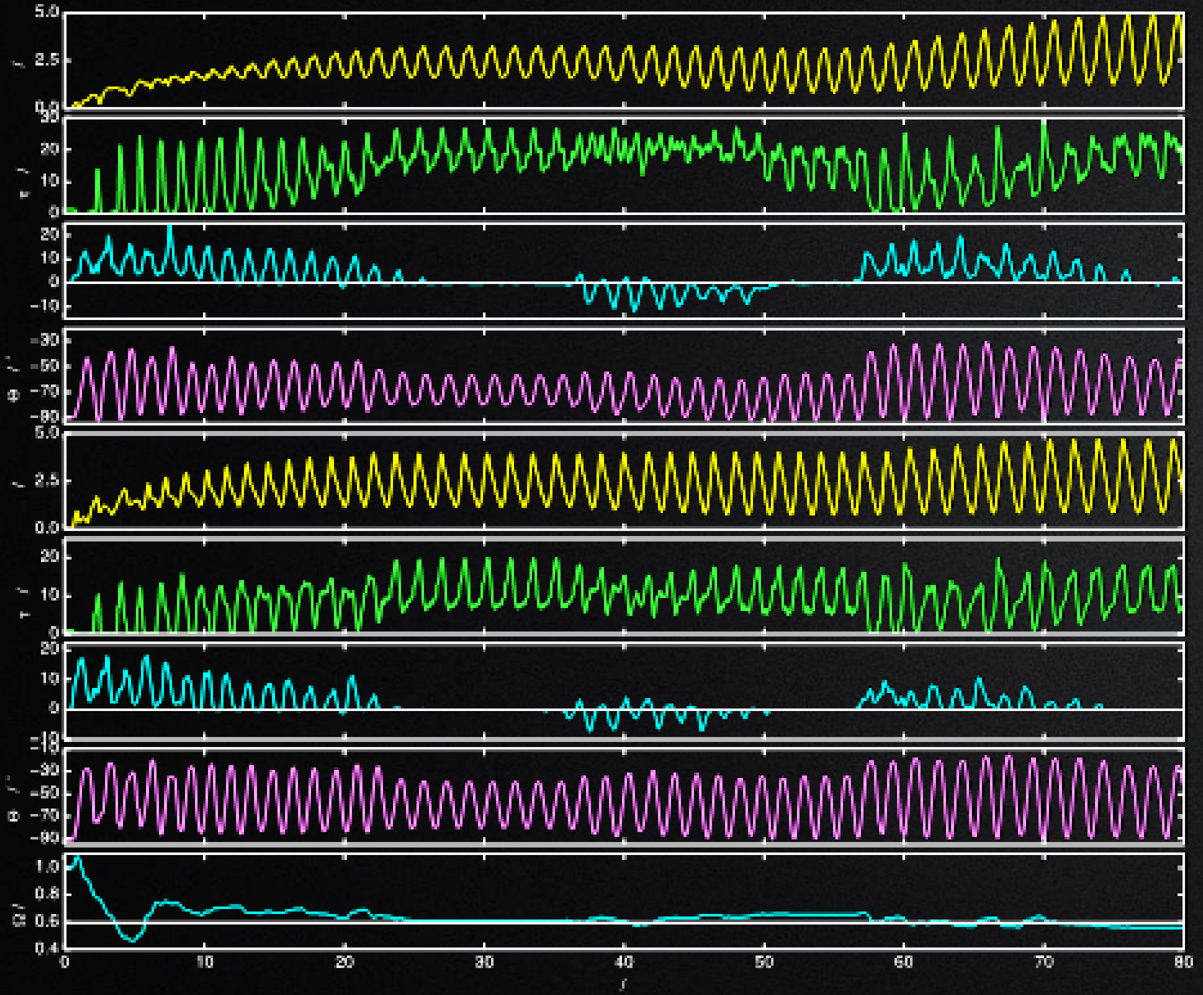
- Adaptation of exoskeleton joint torque is a function of current muscle activity:

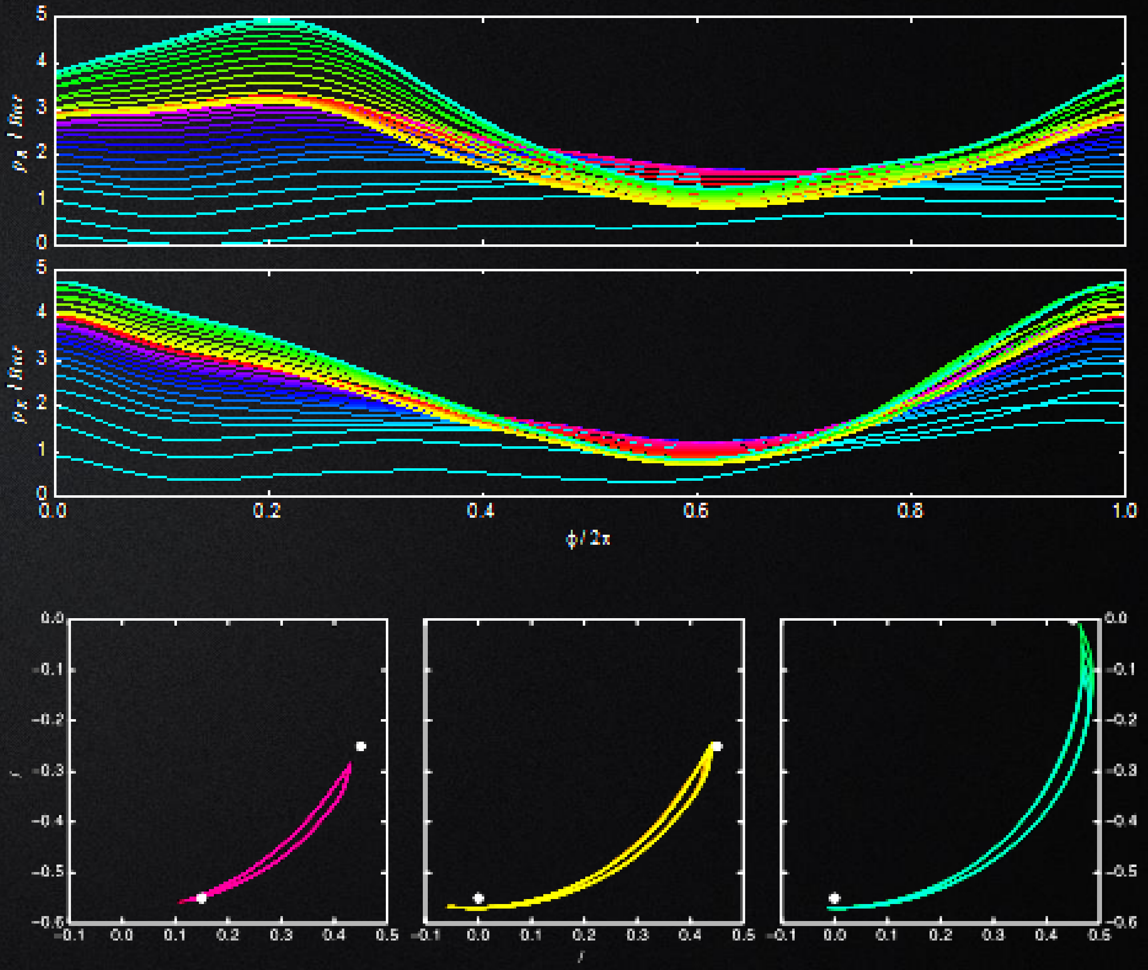
$$\Delta\tau_e(\phi) = G(A_m(\phi))$$

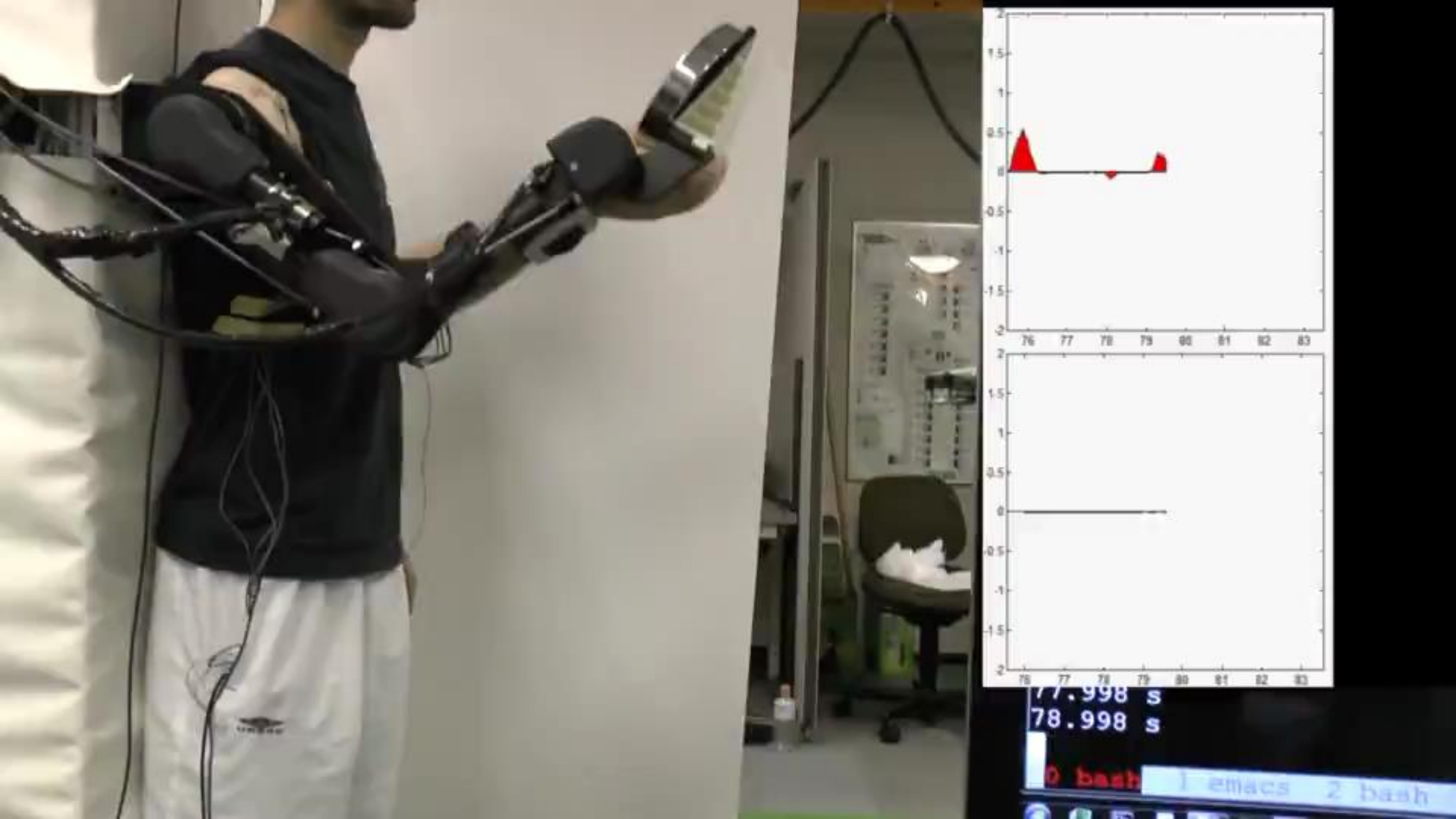




# Adaptation example (2DoF)






77.998 s
78.998 s
0 bash
1 emacs
2 bash


size of
bufsize_in= 112
bufsize_out= 112
test
[ xorexp6-1 ]

Neuromechanical modeling is a powerful tool that can be successfully used as the underlying basis for controlling exoskeletons.

# TAKE HOME MESSAGE