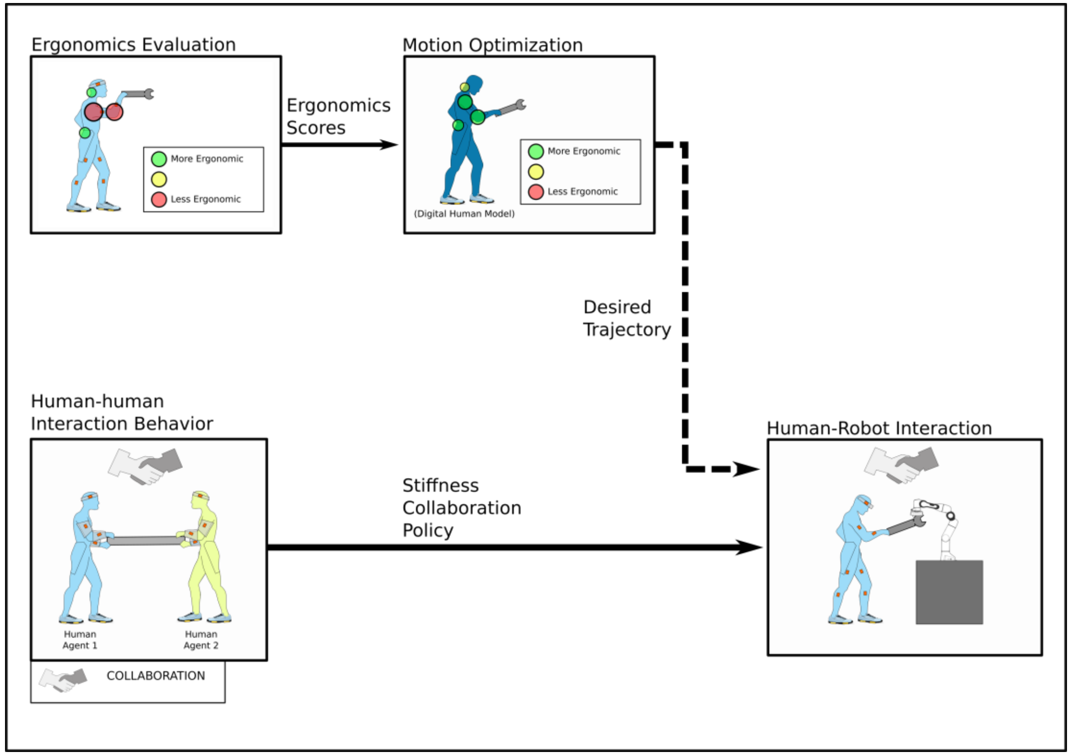
The webcast will begin shortly…

Automatic ergonomics whole-body motion analysis and physical human-robot interaction

February 28th, 2022



Outline

- General introduction to the AnyBody Modeling System
- Presentation by Postdoctoral Researcher Waldez Gomes
  - Automatic ergonomics whole-body motion analysis and physical human-robot interaction
- Upcoming events
- Question and answer session

Presenter:
Waldez Gomes
Postdoctoral Researcher
Human-Exoskeleton Interaction

University Paris-Saclay

Host(s):
Bjørn Keller Engelund
R&D Engineer

Kristoffer Iversen
Technical Sales Executive

Control Panel

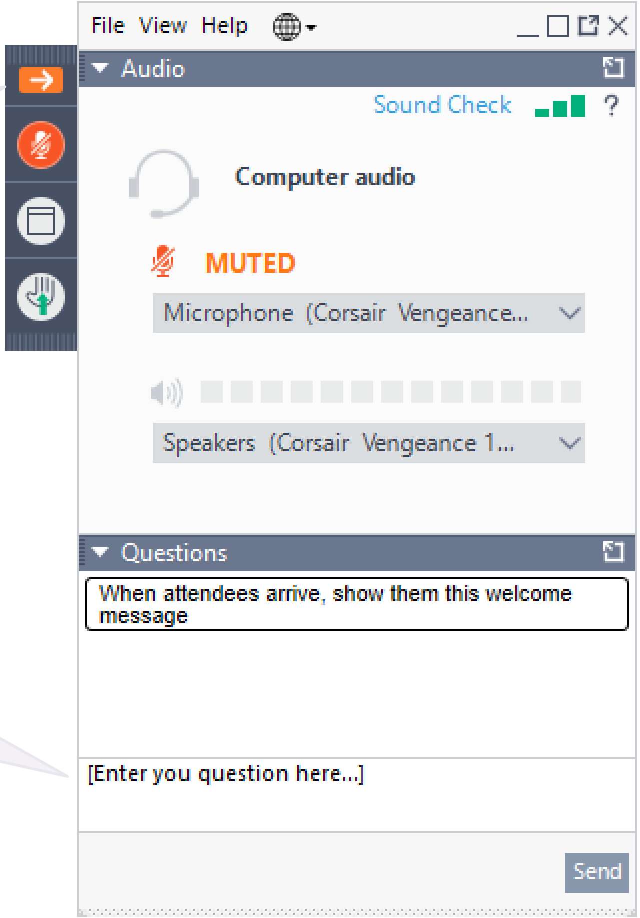
The Control Panel appears on the right side of your screen.

Submit questions and comments via the Questions panel.

Questions will be addressed at the end of the presentation. If your question is not addressed, we will do so by email.

Expand/Collapse the Control Panel

Ask a question during the presentation

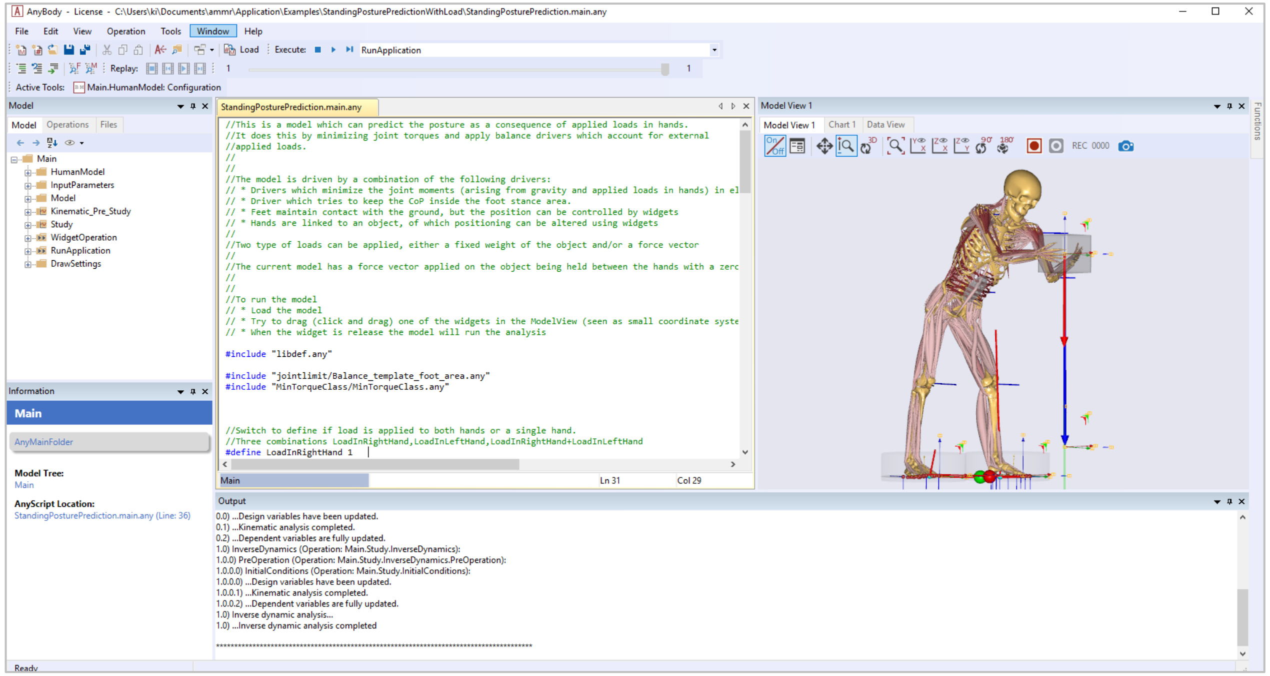


Musculoskeletal Simulation

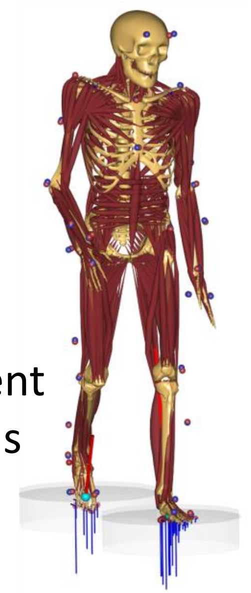
Motion Data
Kinematics and Forces

AnyBody
Modeling System

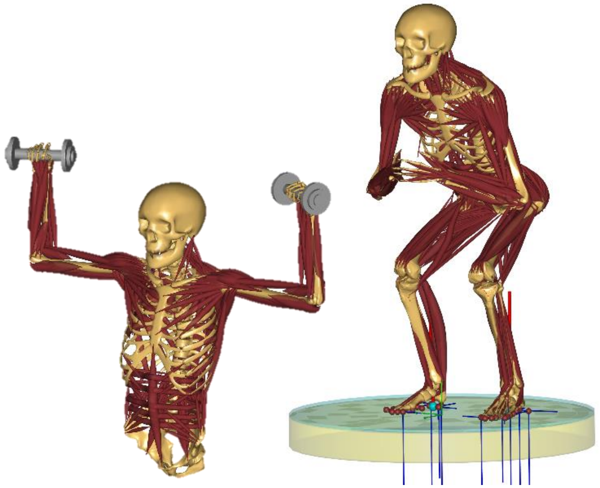
Body Loads
- Joint moments
- Muscle forces
- Joint reaction forces



Product optimization design

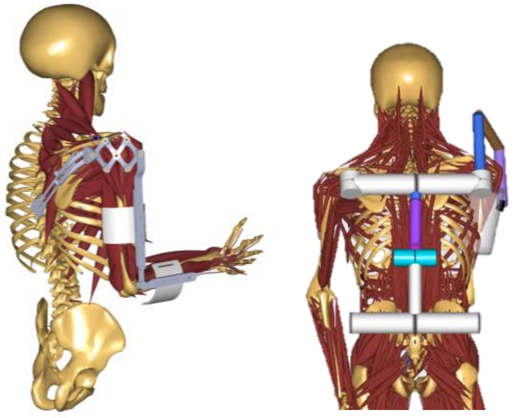


Movement Analysis

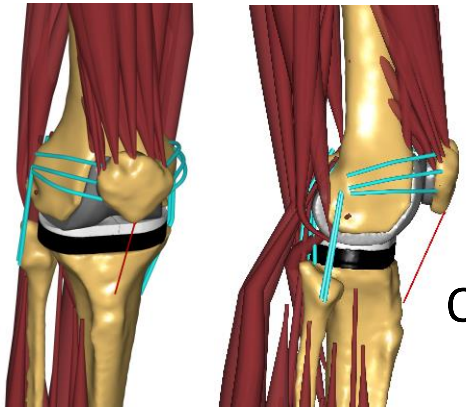


Sports

ANYBODY
Modeling System



Assistive Devices



Orthopedics and rehab

AnyBody Modelling System

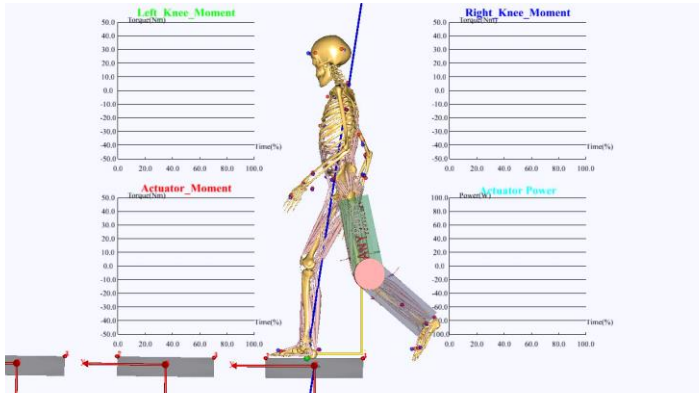
Motion and Forces

Body model

Environment model

Inverse dynamics
Muscle recruitment

Simulation



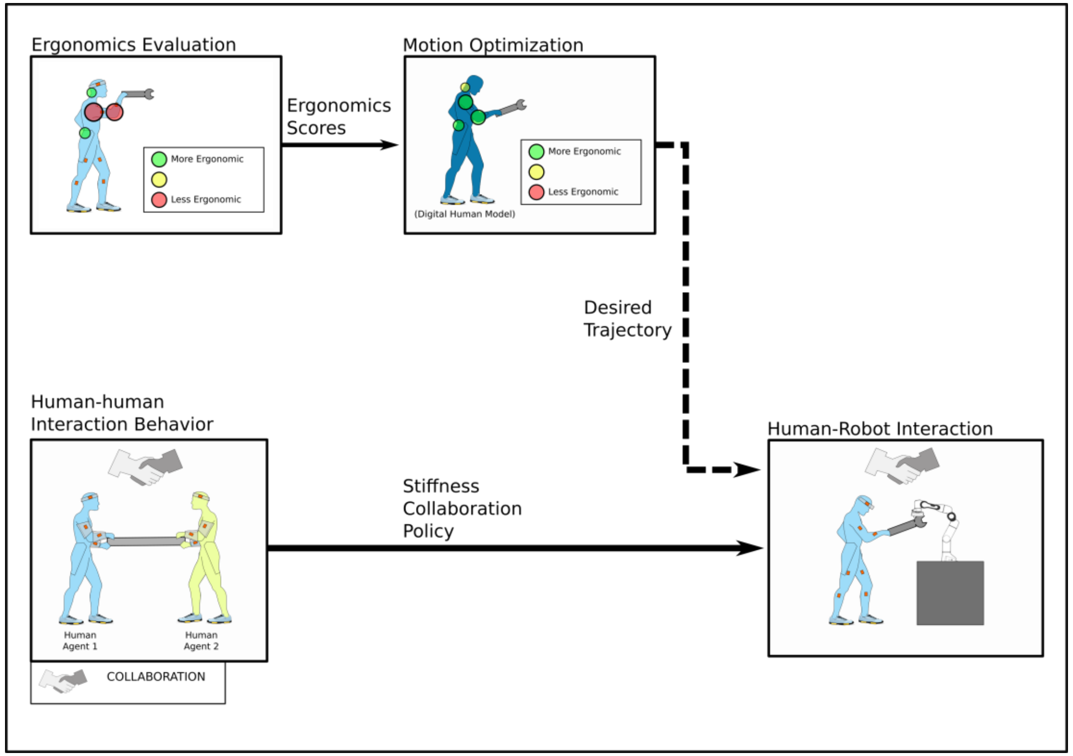
Internal body loads
- Muscle forces
- Joint moments

Design Optimization

Post Processing (e.g. Finite element tools)

Automatic ergonomics whole-body motion analysis and physical human-robot interaction

Presented by Waldez Gomes



Automatic ergonomics whole-body motion analysis and physical human-robot interaction

28/02/2022

Dr. Waldez Gomes

Encadrants: Dr. Jean-Baptiste Mouret, Dr. Serena Ivaldi

Co-Encadrant: Dr. Pauline Maurice

Presentation Outline

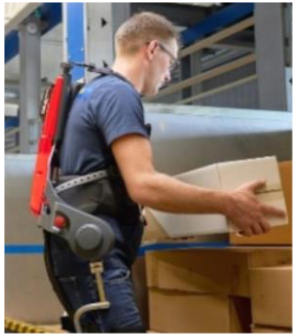
PART I - Introduction

PART II - Automatic Ergonomics Evaluation

PART III - Ergonomic Motion Generation

PART IV - Human Motor Behavior and Physical Human-Robot Interaction

PART V - Conclusions



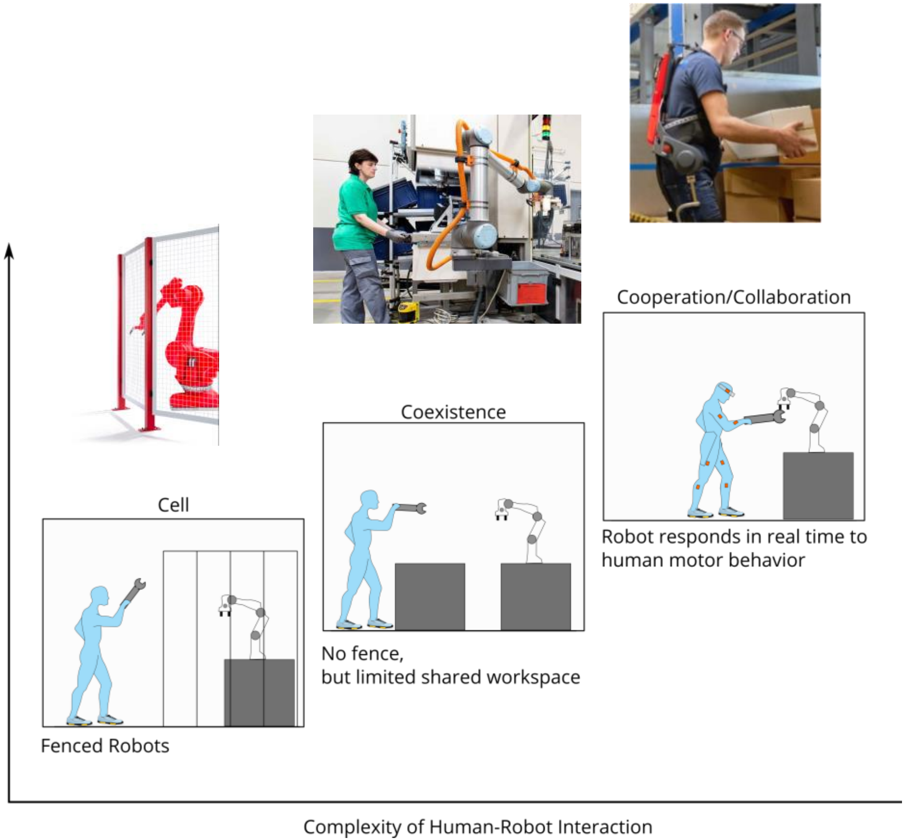
Part I - Introduction

Introduction: Human-Robot Interaction

Fenced Robots
- power
- task automation
- not aware of the environment

Coexistence
- limited shared workspace
- human-centric safety design

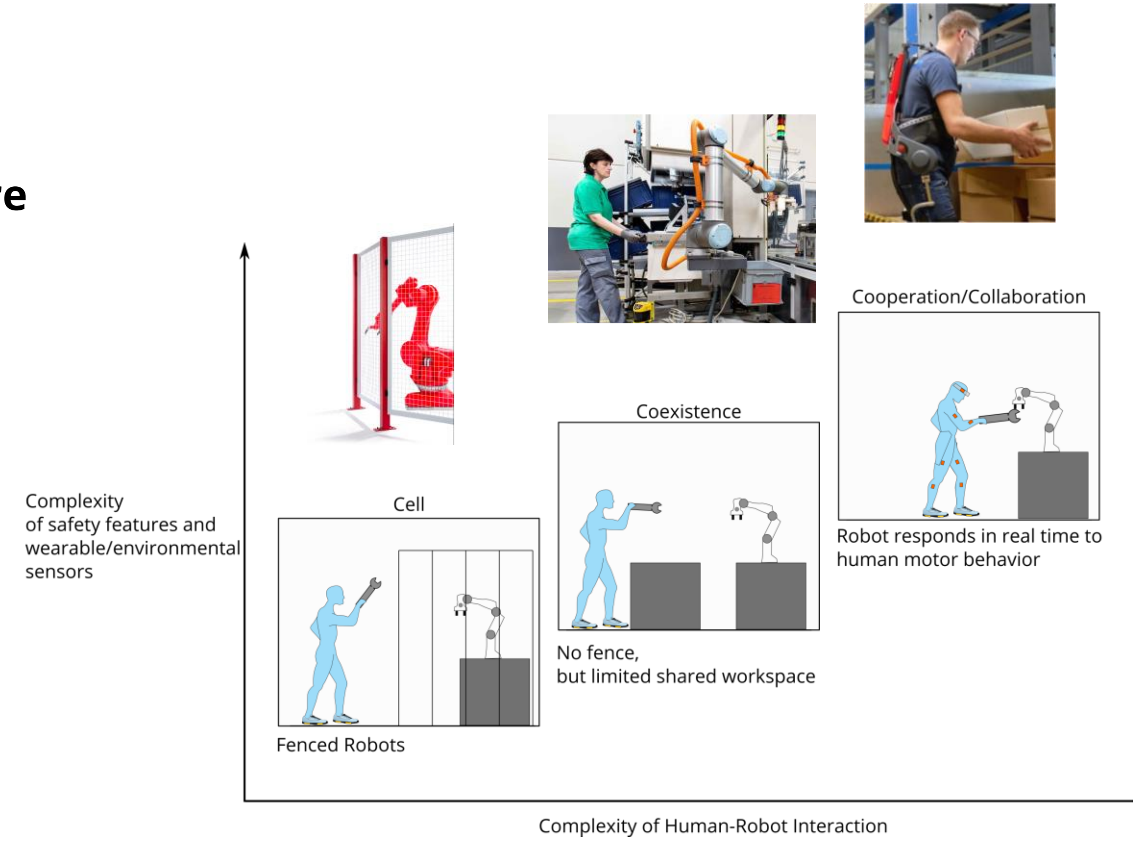
Cooperation/Collaboration
- physical human-robot interaction



K. Goldberg “Robots and the return to collaborative intelligence”, 2019

Introduction: Human-Robot Interaction

Complex interactions require human-awareness



Introduction: Human-Robot Interaction

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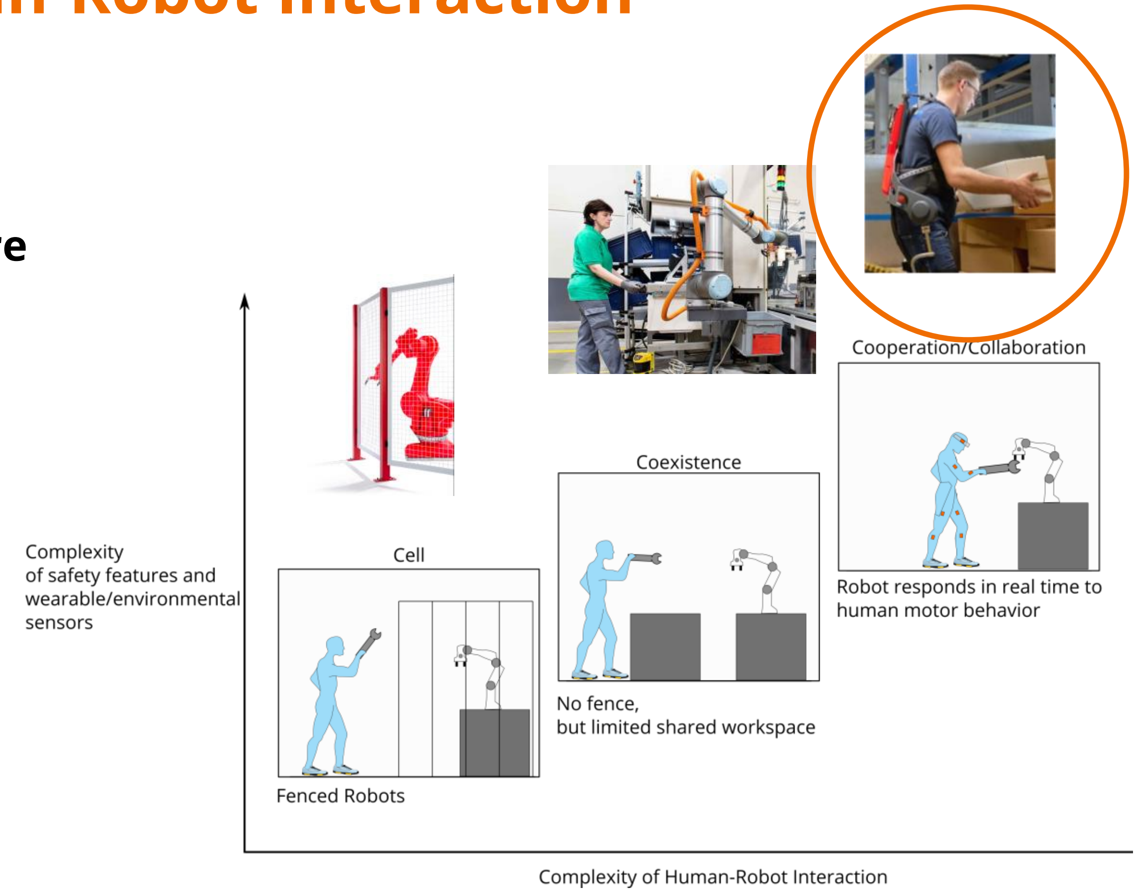
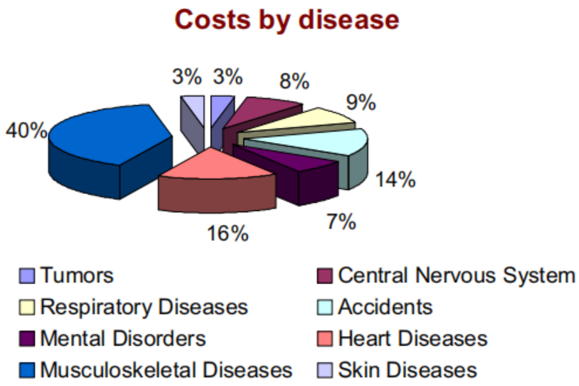


Introduction: Ergonomics

Poor ergonomy:

- Overexertion of forces
- Awkward postures
- Excessive motion repetition

Such conditions can cause **work-related musculoskeletal health disorders (WMSD’s)** in the short/long term



Takala and Niu “Responses to the equity challenge in safety and health at work: improvement of working conditions in equitable bases”, 2003

Introduction: Research Goal

How should we design a **human-robot collaboration** to favor **ergonomics**?

GOAL:

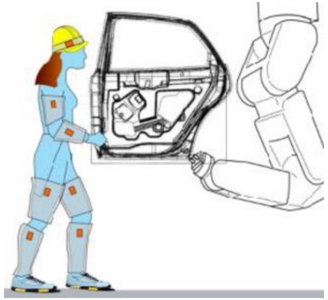
- Provide **tools** to **make ergonomics** interventions using robots (exoskeletons) as a medium

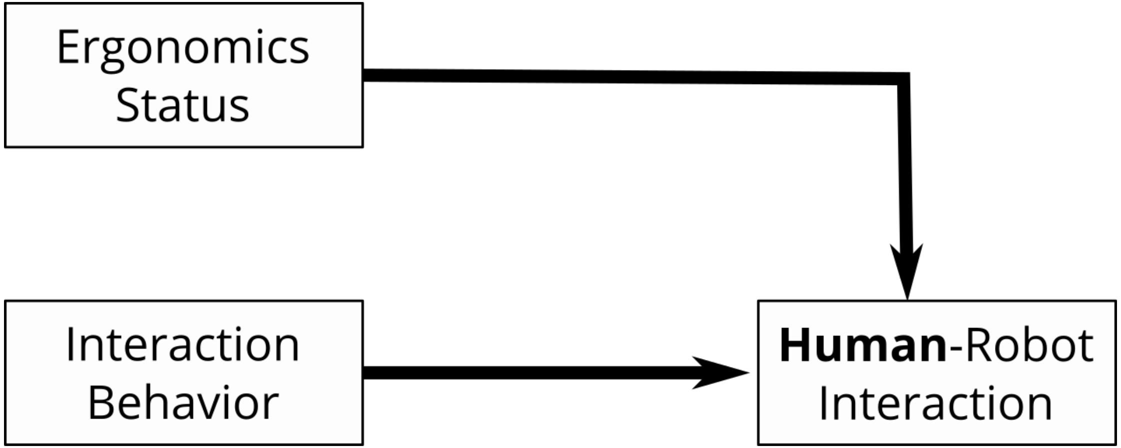
Introduction: Human Awareness

AnDy Project

- **Sensing**, prediction and anticipation
- **Relevant data** measurement
- Improved robot response

Human-Centered Approach





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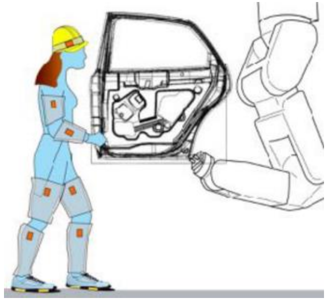

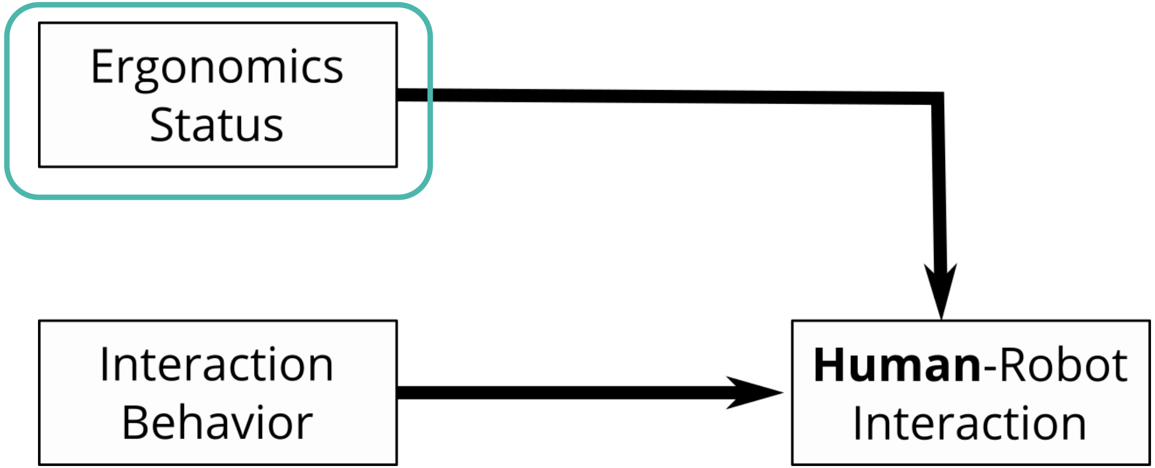

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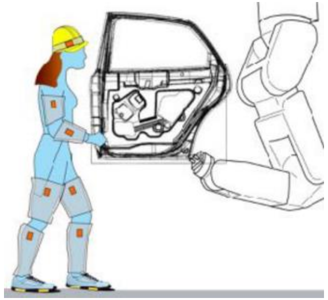

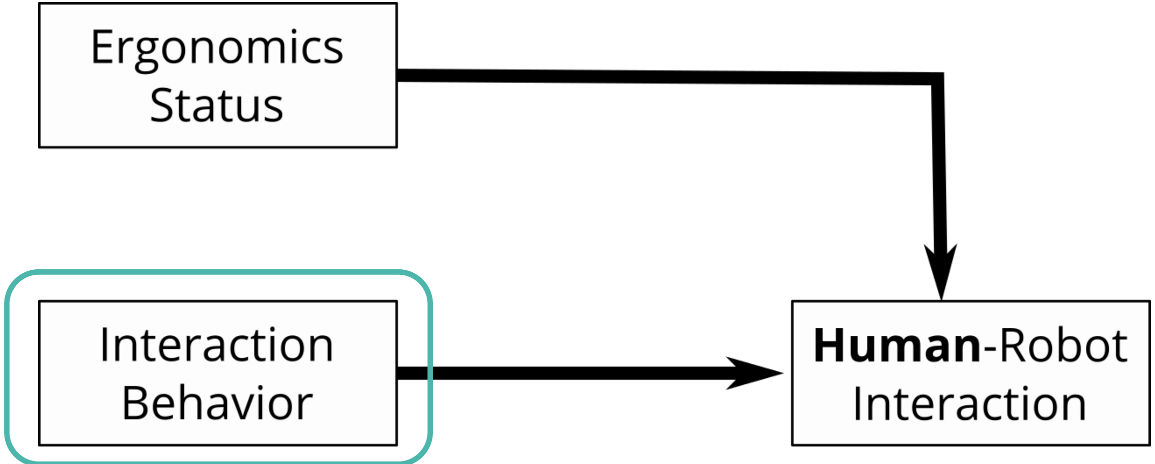

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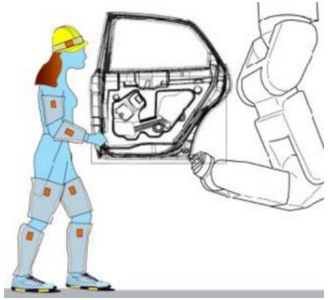
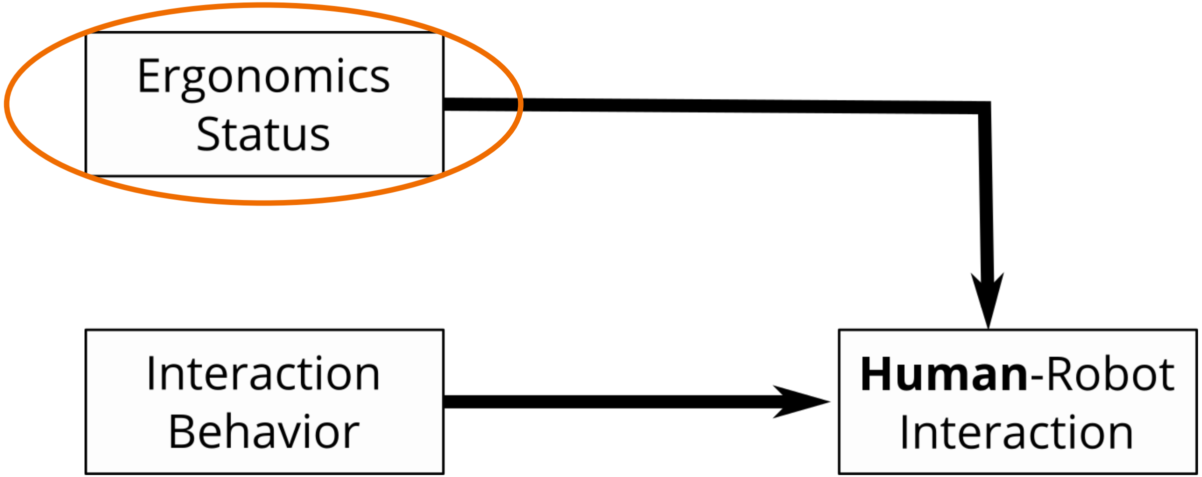


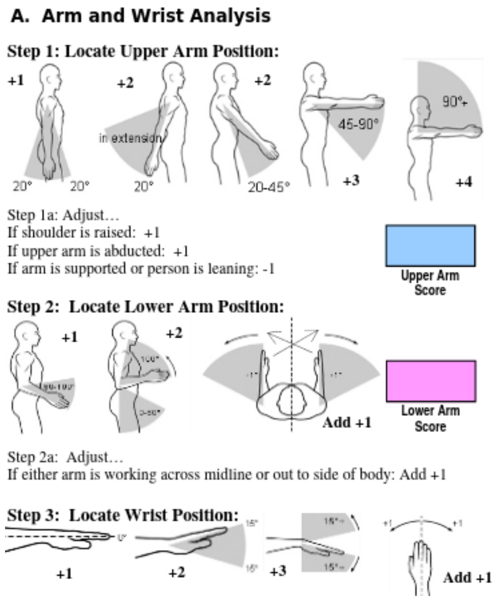


Introduction: Ergonomics Status

Large force/torque at the lumbar back?

Which ergonomics criteria to use?
Ergonomics evaluation tools!

- **RULA**
- REBA
- EAWS
- ... and others.



SCORES

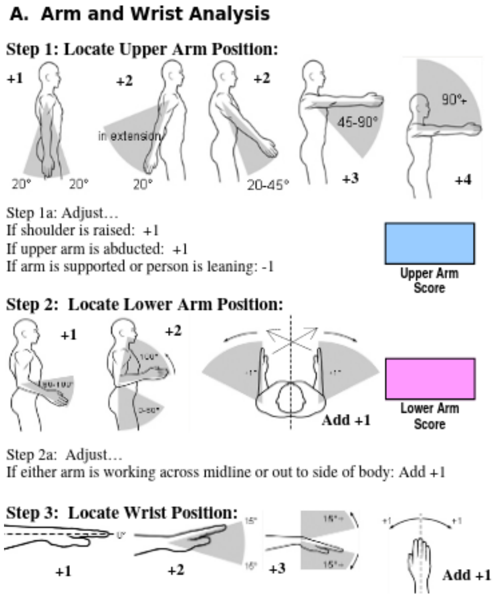
Table A: Wrist Posture Score

Upper Arm	Lower Arm	1 Wrist Twist 1	1 Wrist Twist 2	2 Wrist Twist 1	2 Wrist Twist 2	3 Wrist Twist 1	3 Wrist Twist 2	4 Wrist Twist 1	4 Wrist Twist 2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	1	2	3	3	3	3	4	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	7	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

Introduction: Ergonomics Status

The classic tools are **manually filled worksheets:**

- **Visual selection of posture**
  - Inter-observer variability!
- **Lacks flexibility**
  - Expert is required for any re-evaluation



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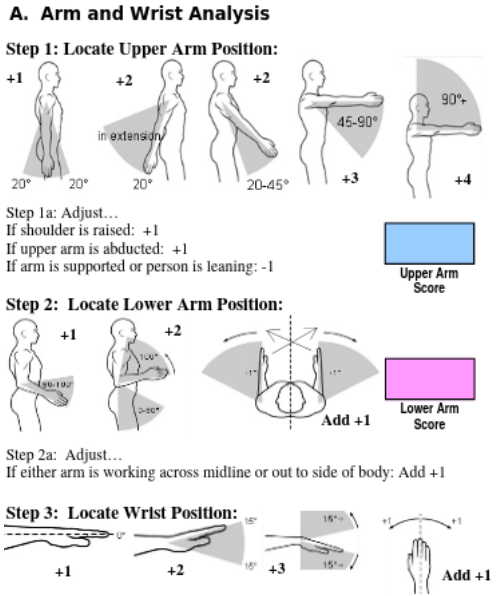

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	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

The ergonomics status must be evaluated **automatically**!

Introduction: Ergonomics Status - Dynamics

The classic tools are manually filled worksheets:

- **Poor dynamics evaluation**
  - Different weights may penalize scores equally
  - Different weights generate different torque/force efforts
  - People have different power capabilities

10 Kg ✓

20 Kg ?

Introduction: Ergonomics Status - Dynamics

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10 Kg ✓

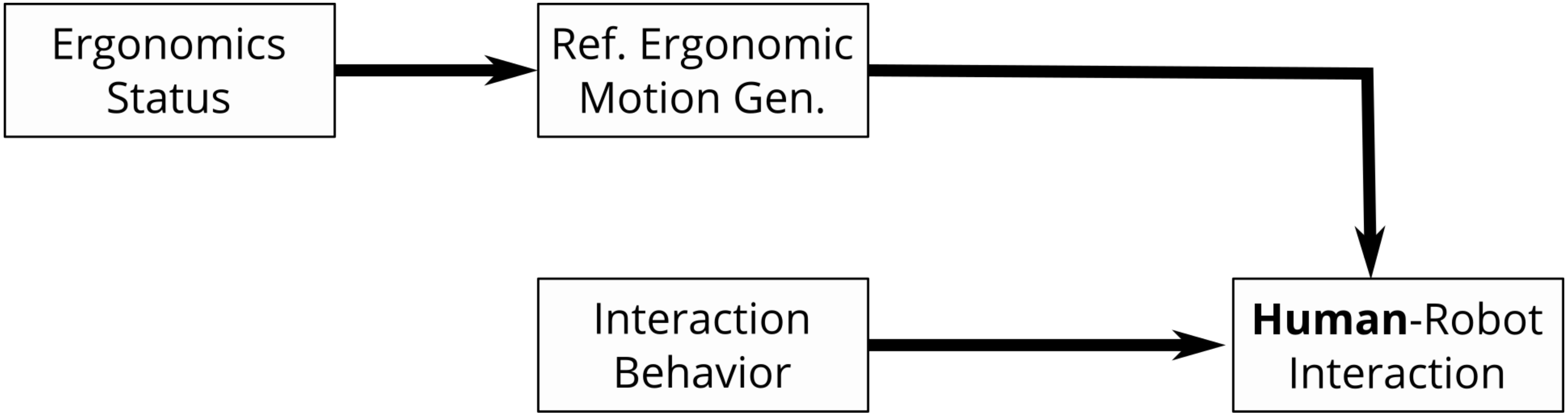
20 Kg ?

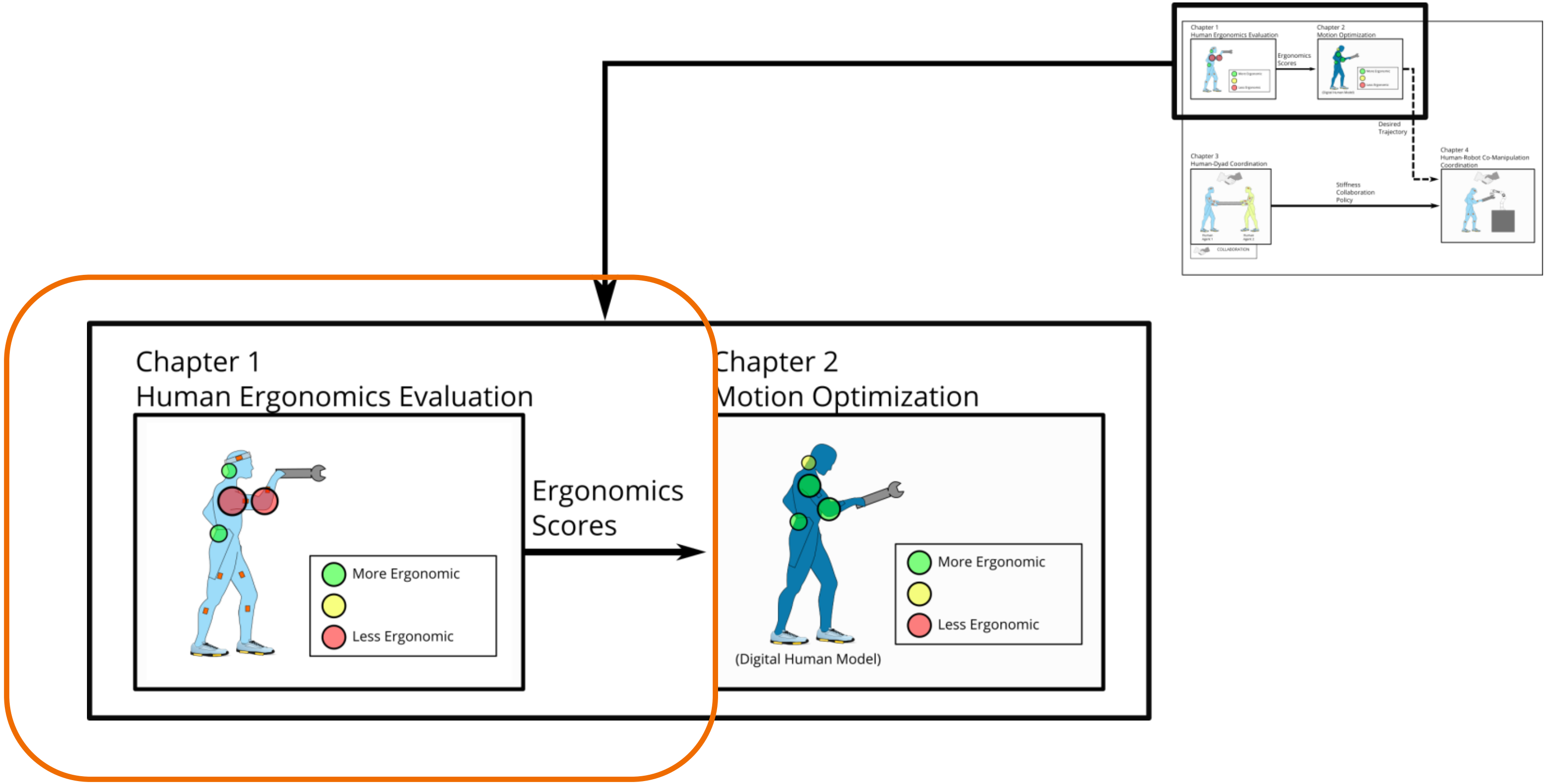
Fine **dynamics** evaluation is **relevant** for the ergonomics status

Introduction: Ergonomic Motion Generation

Kinematics and Dynamics **custom** ergonomics evaluation

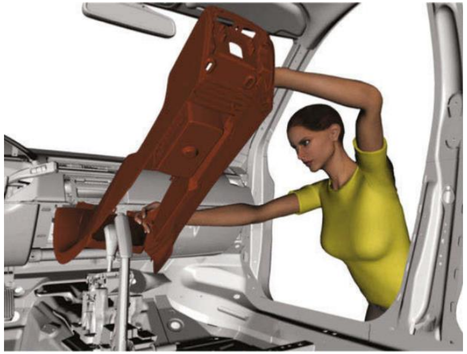
- **Reference motion** generation may be used by robot controller





Part II - Automatic Ergonomics Evaluation

Digital Human Model (DHM)



Simulation of human motion

- Varied work environment/setups
- Varied motion strategies

Simulated motion can be repeated with no harm

Some models (e.g. AnyBody) can estimate complex musculoskeletal efforts

Blab et al. “New approaches for analysis in ergonomics: From paper and pencil methods to biomechanical simulation”, 2016

Firouzabadi et al. “Sex-Dependent Estimation of Spinal Loads During Static Manual Material Handling Activities—Combined in vivo and in silico Analyses”, 2021

Digital Human Model (DHM)
Application: Paexo Exoskeleton Analysis

- **PAEXO**-shoulder exoskeleton (**Ottobock**)
- Ergonomics assessment by teams from AnyBody, IMK, IIT, Inria, Ottobock, JSI

Fritzsche et al. “Assessing the efficiency of exoskeletons in physical strain reduction by biomechanical simulation with AnyBody Modeling System”, 2021

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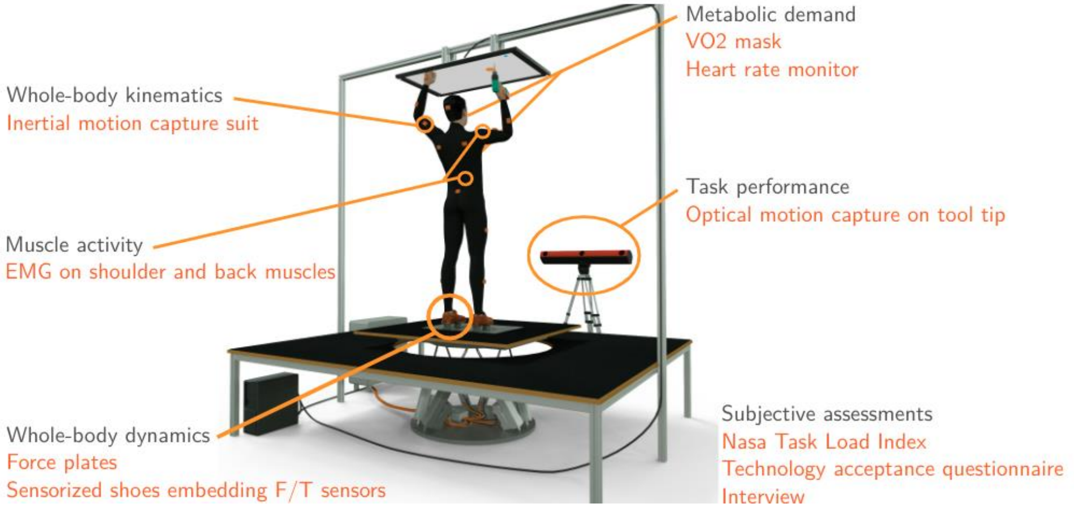
Application: Paexo Exoskeleton Analysis



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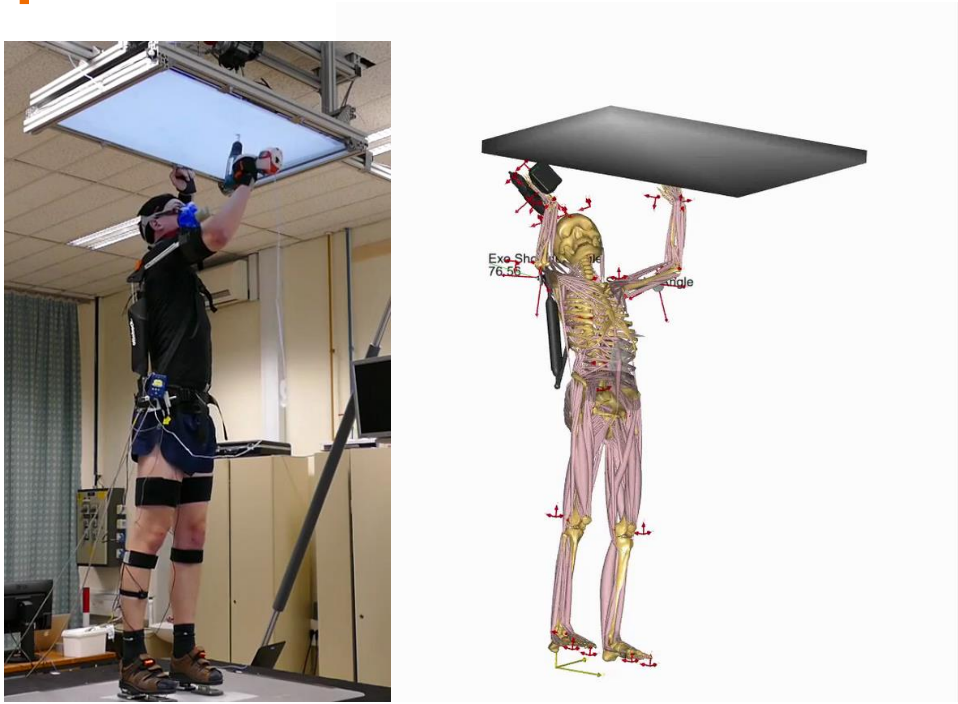


Input
- Human Kinematics
- Ground Reaction Force
- PAEXO angle-torque

Output
- **Muscle Activity**
- **Joint reaction Forces**

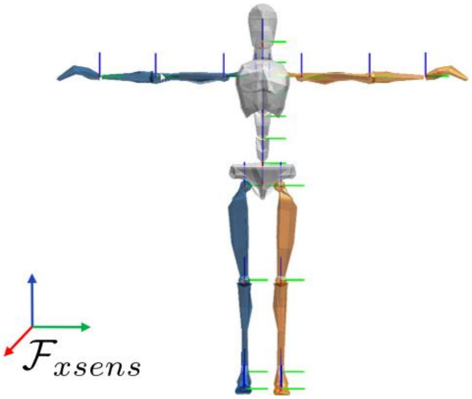
PAEXO model
- Validated by Ottobock

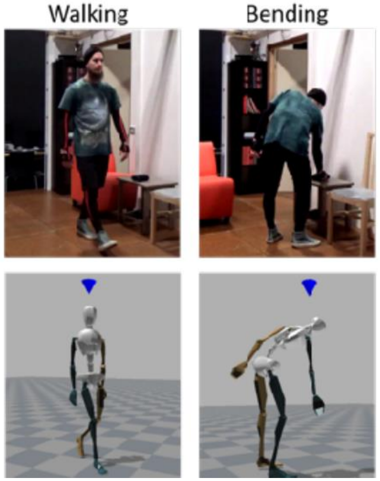
Fritzsche et al. “Assessing the efficiency of exoskeletons in physical strain reduction by biomechanical simulation with AnyBody Modeling System”, 2021

Digital Human Model (DHM)

Xsens MVN Model

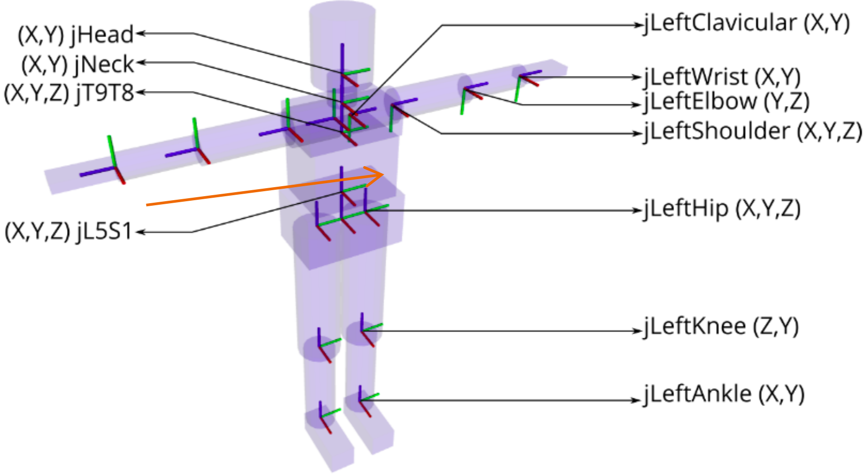
- 66 degrees of freedom
- Scalable geometry
- Body segments without inertia
- Kinematics-based evaluations





Our DHM

- 43 degrees of freedom
- Kinematic
- Scalable geometry
- **Scalable inertia** (body weight)
- **Kinematics**- and **Dynamics**-based **evaluations**



Digital Human Model (DHM): QP Controller

Quadratic **P**rogram controller

- Reference Cartesian Trajectories
  - Different body segments
- Reference Body Posture Trajectories

- QP minimizes each task tracking error
  - **Joint velocity output**
  - Joint position and velocity bounds
  - Stack of tasks hierarchy

$$\dot{q}^* = \arg\min_{\dot{q}} \|\boldsymbol{A_n}\dot{q} - \boldsymbol{b_n}\|_{\boldsymbol{W}}$$

$$\text{s.t.} \qquad \mathbf{C_{1,n}\dot{q}} \leq \mathbf{b_{1,n}}$$

$$\mathbf{C_{2,n}q} \leq \boldsymbol{b_{2,n}}$$

Mingo-Hoffman et al. “Robot control for dummies: Insights and examples using opensot” , 2017

Digital Human Model (DHM): QP Controller

Quadratic **P**rogram controller

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  - Different body segments
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$$
\begin{aligned}
\dot{\boldsymbol{q}}^* = \arg\min_{\dot{q}} & \|\boldsymbol{A}_n \dot{\boldsymbol{q}} - \boldsymbol{b}_n\|_{\boldsymbol{W}} \\
\text{s.t.} \quad & \mathbf{C}_{1,n}\dot{\mathbf{q}} \le \mathbf{b}_{1,n} \\
& \mathbf{C}_{2,n}\mathbf{q} \le \boldsymbol{b}_{2,n}
\end{aligned}
$$

- QP minimizes each task tracking error
  - Joint velocity output
  - Joint position and velocity bounds
  - **Stack of tasks** hierarchy

Stack of Tasks

High Priority	W_1	Task 1	W_2	Task 2
Low Priority	W_3	Task 3		

Ergonomics Evaluation

Description	Score	ε_{obj}
RULA - C	Regression of RULA	ε_{rc}
Normalized Wholebody Effort	$\frac{1}{n_{joints}} \sum_{i \in joints} \left(\frac{\tau_t^i}{\tau_{max}^i} \right)^2$	ε_{nwe}
Torques Shoulder	$\lVert \boldsymbol{\tau}_{shoulder} \rVert$	ε_{tsh}
Torques Lumbar	$\lVert \boldsymbol{\tau}_{lumbar} \rVert$	ε_{tlb}
Back Flexion	$\lVert \boldsymbol{\theta}_{flexion} \rVert$	ε_{back}

- Different scores quantify **different WMSD risk factors**

McAtamney, Lynn, and E. Nigel Corlett. "RULA: a survey method for the investigation of work-related upper limb disorders.",1993

Digital Human Model (DHM) Application: Exoturn Project

Prone-positioning work activity (video)

- Strenuous for health workers
- Very common to perform on **COVID-19** patients at the **ICU**

An Exoskeleton to alleviate the torque/force at the lumbar back

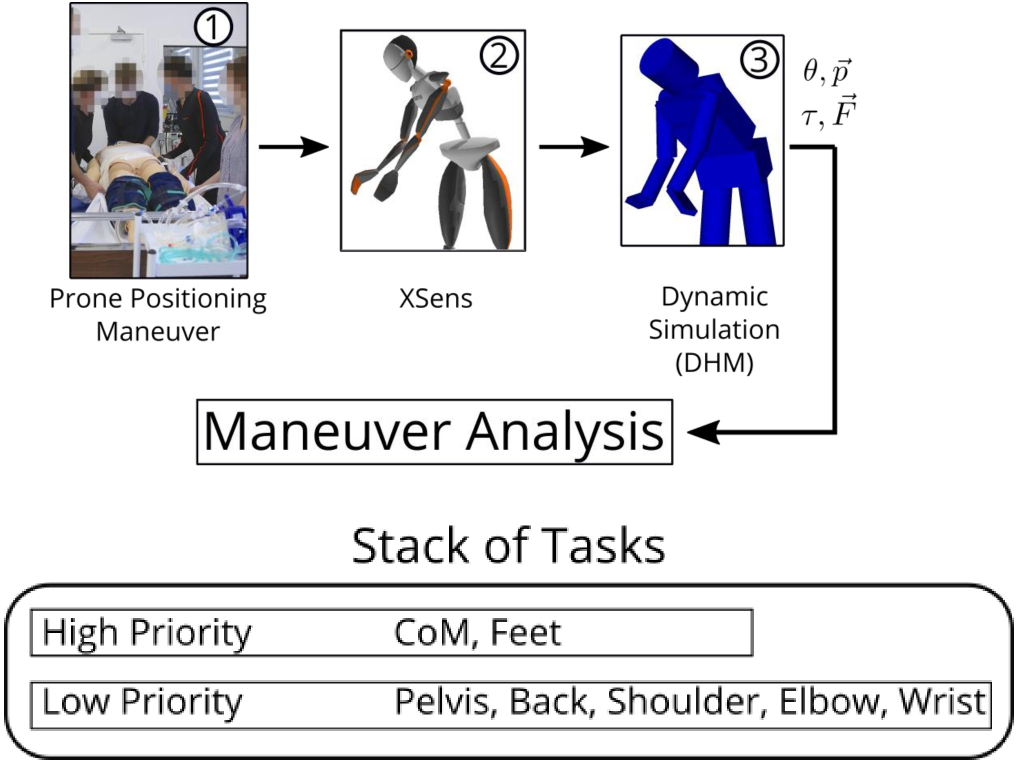
"The use of exoskeletons to help with prone positioning in the intensive care unit during COVID-19" Settembre et. al 2020

Digital Human Model (DHM) Application: Exoturn Project

Qualitative Assessment:

- Perceived lower effort for all but CORFOR
- CrayX and BackX “too cumbersome”
- **Laevo** exoskeleton **easy to deploy and** to **use** during PP

Digital Human Model (DHM) Application: Exoturn Project

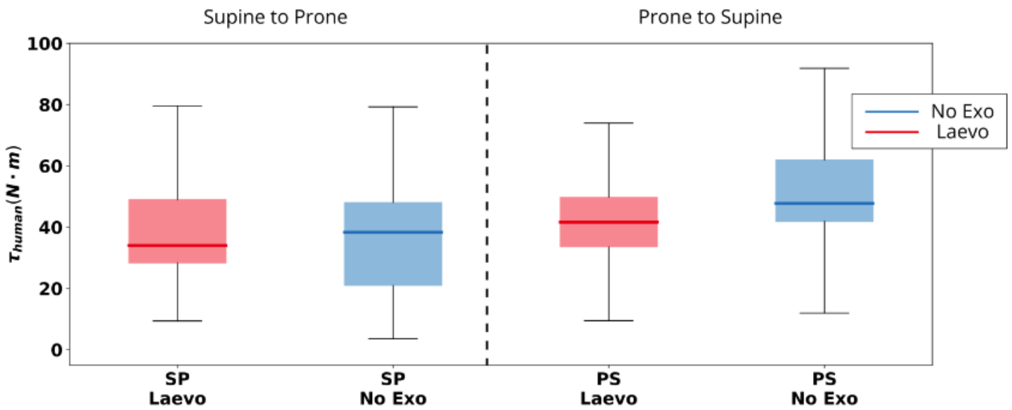


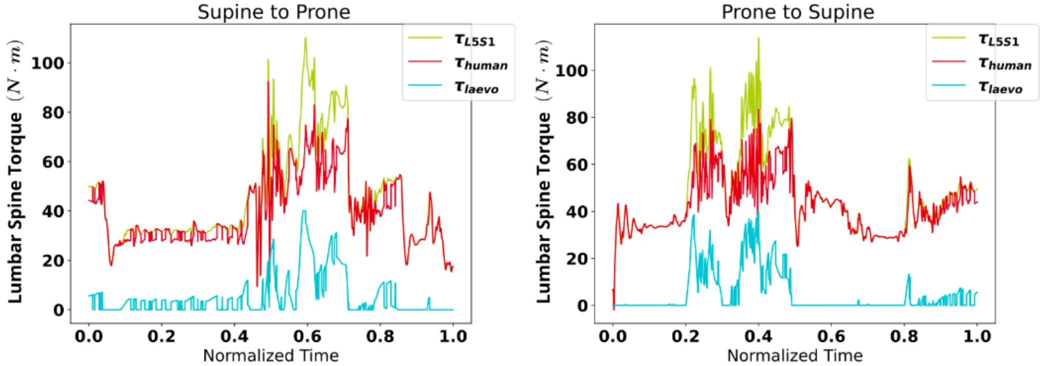
DHM simulation **evaluates prone-positioning motion**

- Estimate human back joint torques with and without Exoskeleton

“Using exoskeletons to assist medical staff during prone positioning of mechanically ventilated COVID-19 patients: a pilot study” Ivaldi et. al 2021

Digital Human Model (DHM) Application: Exoturn Project





DHM simulation evaluates prone-positioning motion

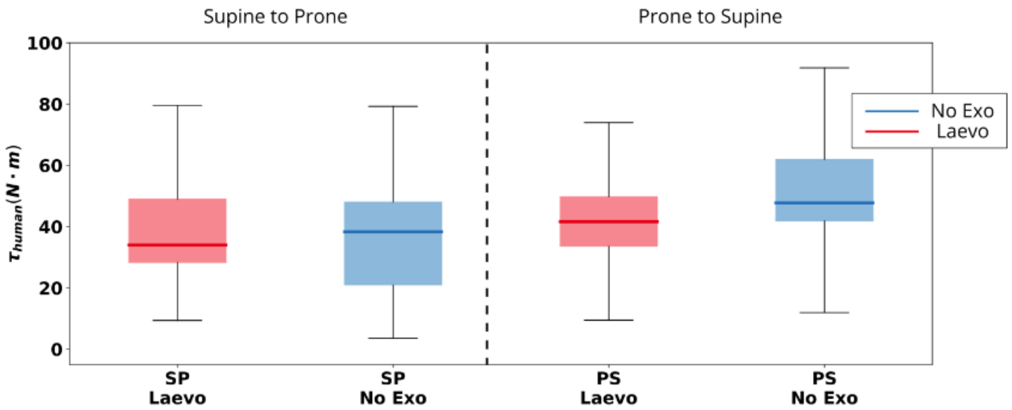
- **Estimate** human back **joint torques** with and without Exoskeleton

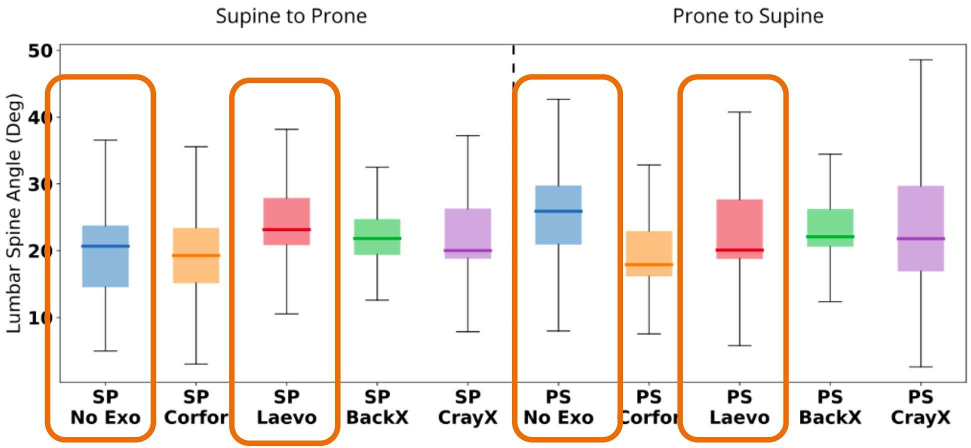
$$\tau_{exo}(\theta) = \begin{cases} k_0 + k_1\theta, & \dot{\theta} > 0 \\ k_0 + k_1\theta - k_{loss}, & \dot{\theta} < 0 \end{cases}$$

$$\tau_{L5S1}(\theta) = \begin{cases} \tau_{exo} + \tau_{human}, & \text{with exo} \\ \tau_{human}, & \text{without} \end{cases}$$

Koopman et al.“Effects of a passive exoskeleton on the mechanical loading of the low back in static holding tasks”, 2019

Digital Human Model (DHM) Application: Exoturn Project



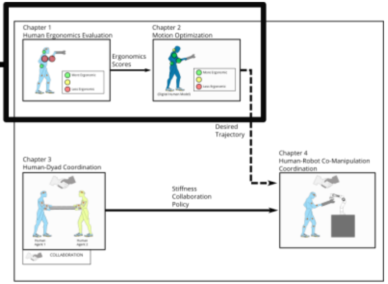


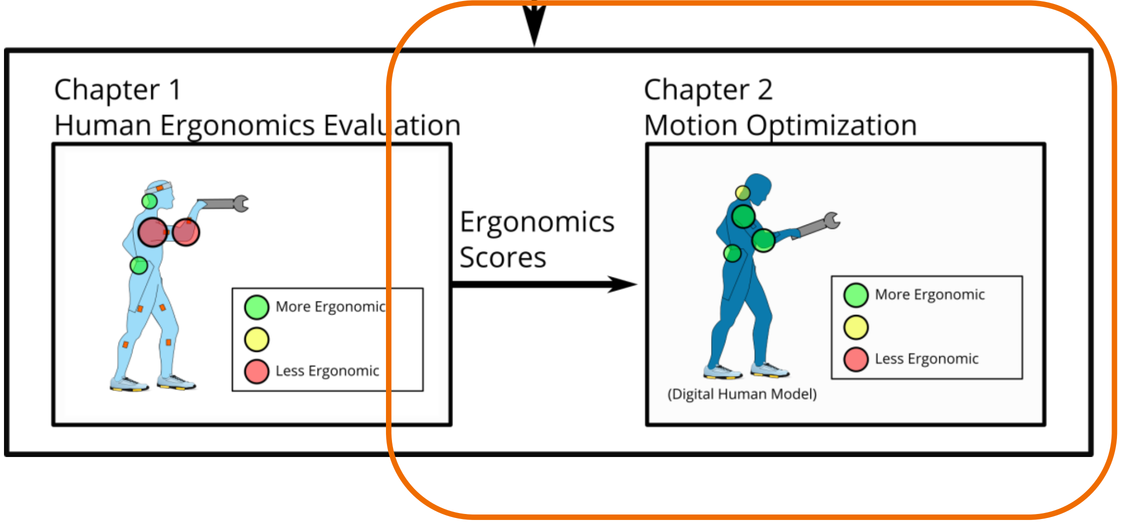
Reduced torque

- Supine to Prone: 11.3% reduction
- Prone to Supine: 13% reduction

Same range of motion

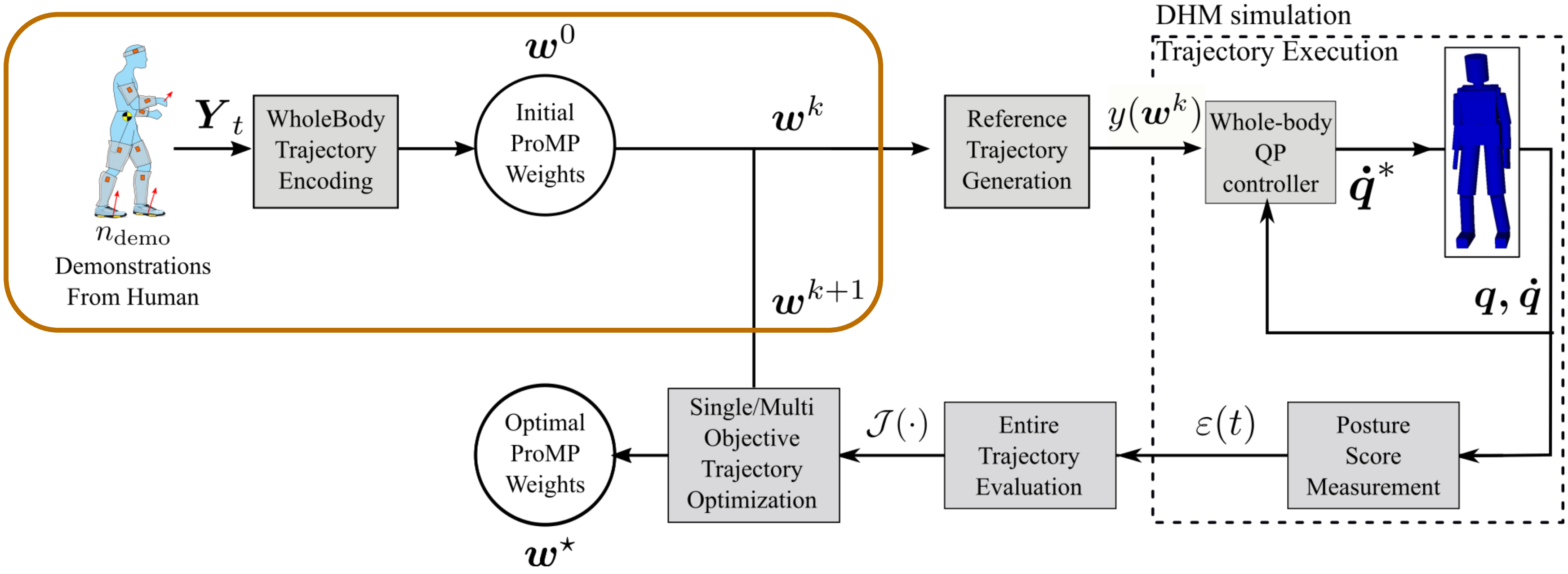
- Peak motion of 50 deg





Part III - Whole-Body Motion Optimization

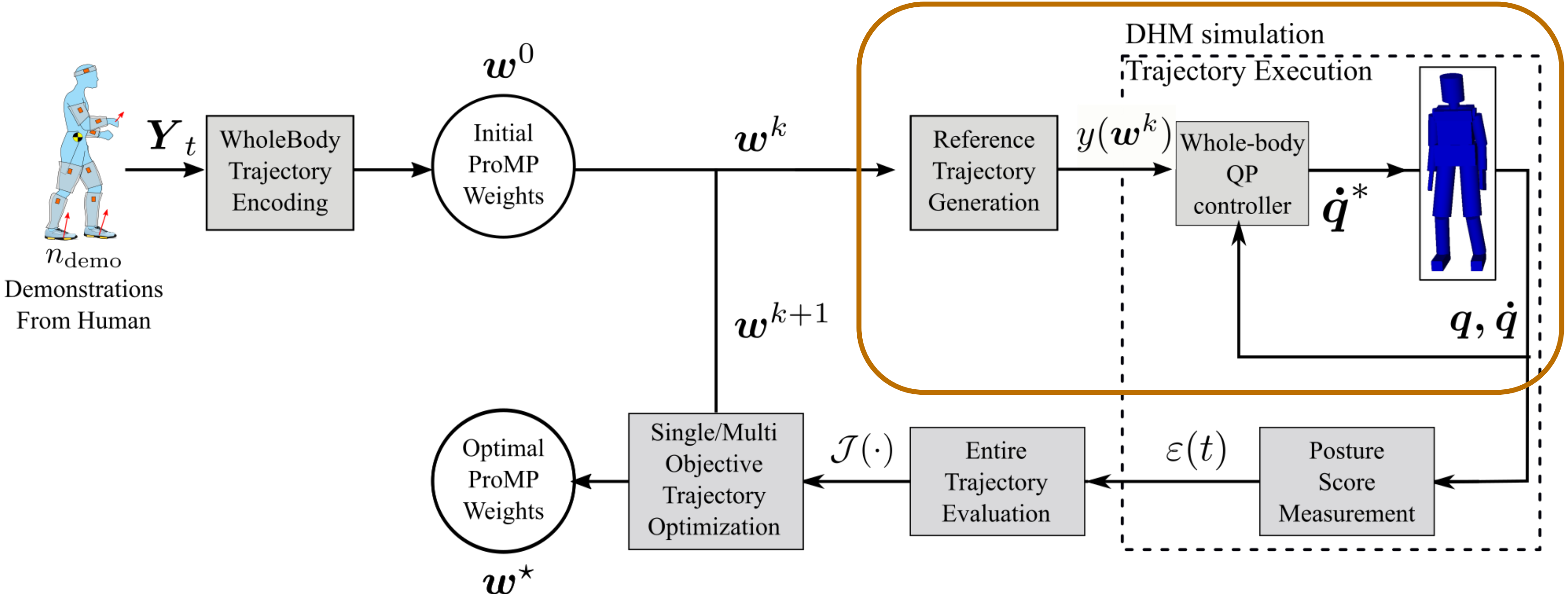
Wholebody Motion Optimization



Captures initial movement, and encode it

Gomes. et al. “Multi-objective Trajectory Optimization to Improve Ergonomics in Human Motion”, 2021

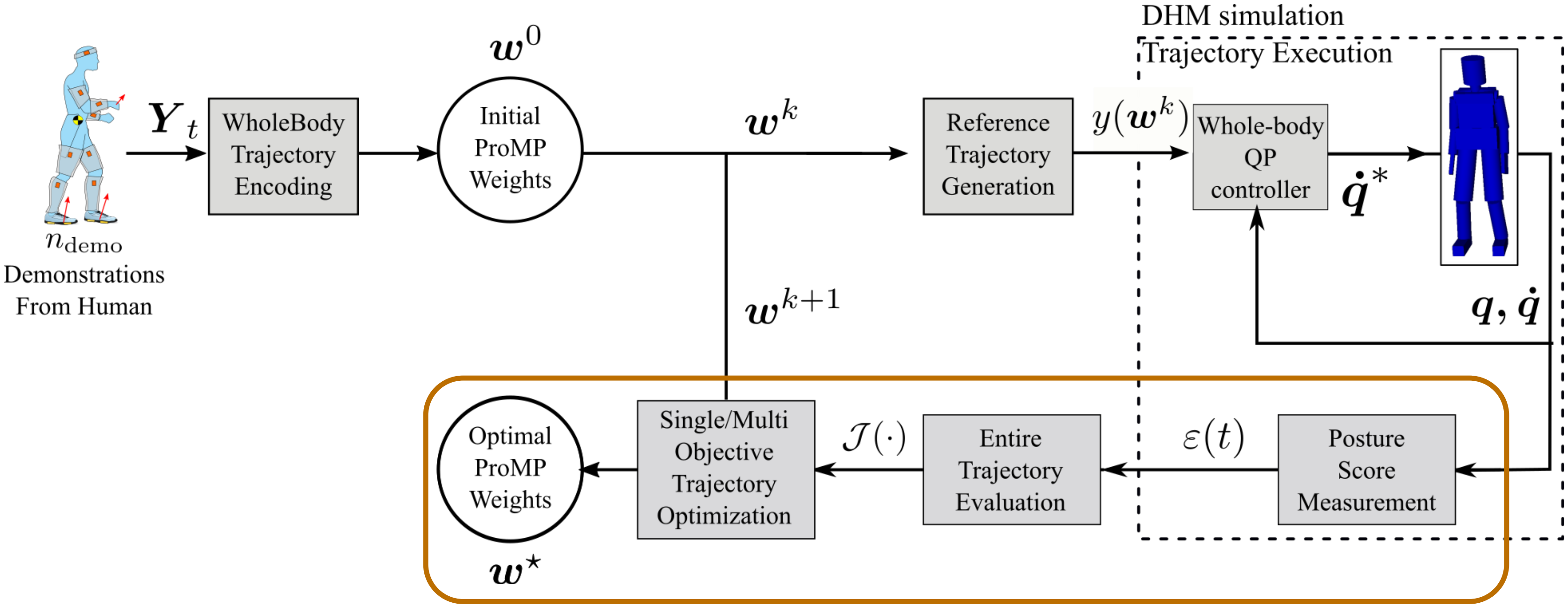
Wholebody Motion Optimization



Executes the movement in a DHM simulation

Gomes. et al. “Multi-objective Trajectory Optimization to Improve Ergonomics in Human Motion”, 2021

Wholebody Motion Optimization



Optimize it

Gomes. et al. “Multi-objective Trajectory Optimization to Improve Ergonomics in Human Motion”, 2021

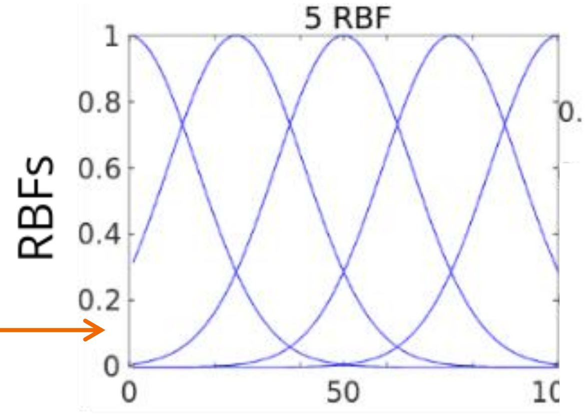
Wholebody Trajectory Encoding

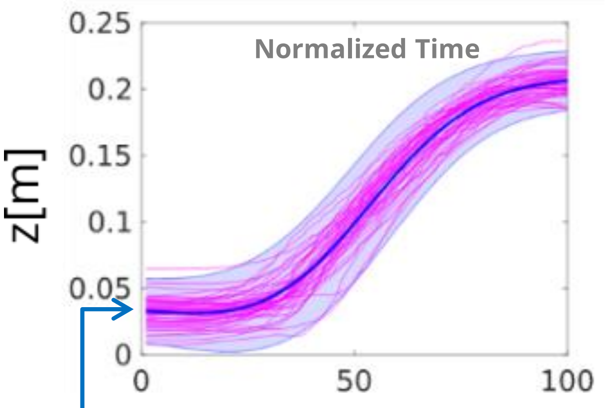
Parameterization done with Probabilistic Movement Primitives

ProMP ==> **Stochastic representation** (Gaussian) of a **movement trajectories**.

- ProMPs are trained from demonstrations
- Mean trajectories can be represented by a low number of parameters

$$\boxed{y_t^{traj}} = \boxed{\phi_t^\top} \boldsymbol{w}_{traj}$$





Normalized Time

Paraschos, Alexandros, et al.. "Using probabilistic movement primitives in robotics." , 2018
Dermy, O. et al.. Prediction of Intention during Interaction with iCub with Probabilistic Movement Primitives, 2017

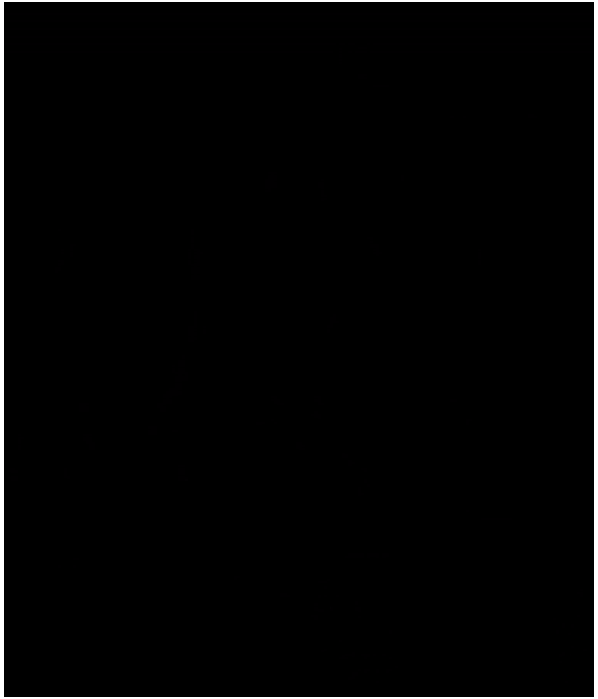
Wholebody Trajectory Encoding

For trajectories that describe the desired motion, a set of **mean weights** is **learned** from **demonstrations**

$$\boldsymbol{w}_{traj}$$

Wholebody optimization variable (defines motion)

$$\boldsymbol{w} = [\boldsymbol{w}_1 \dots \boldsymbol{w}_{n_{trajs}}]$$



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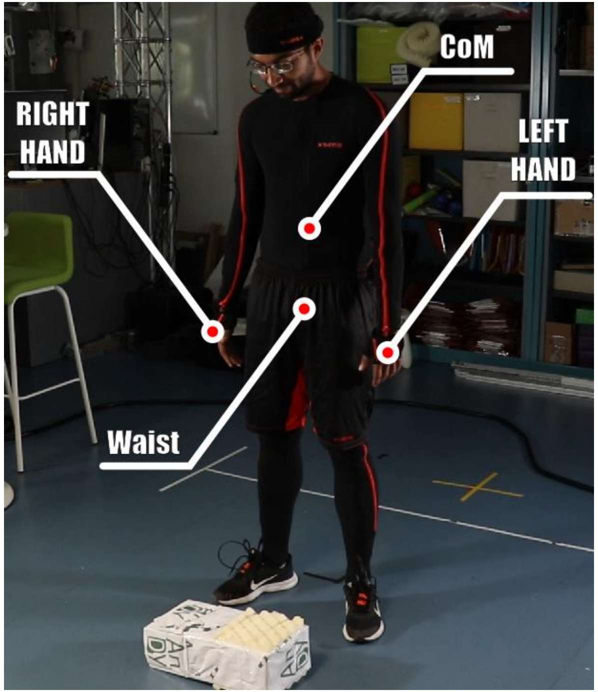
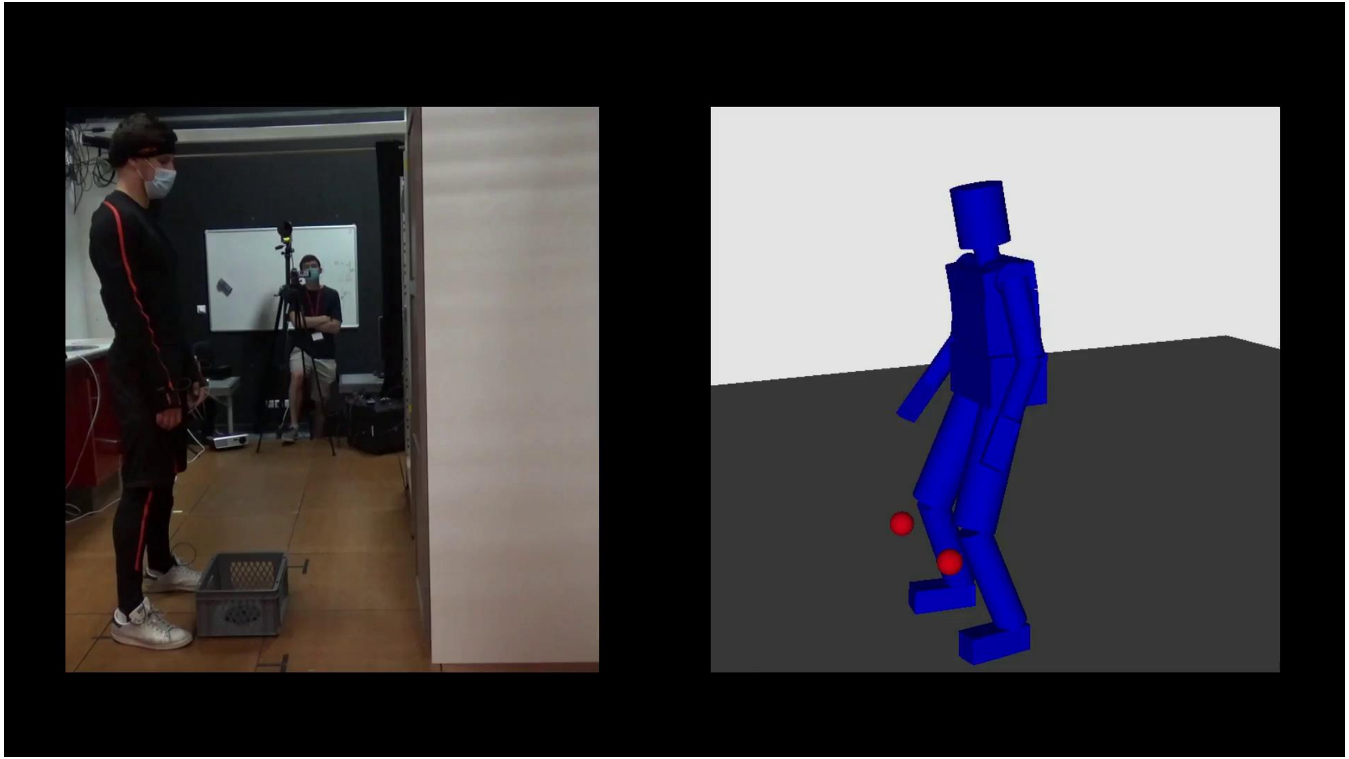
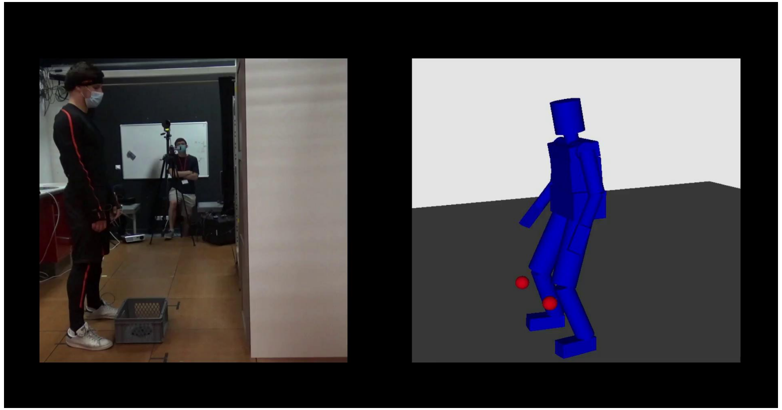


Example: Box Lifting



Non-ergonomic, excessive back flexion

Example: Box Lifting - QP controller

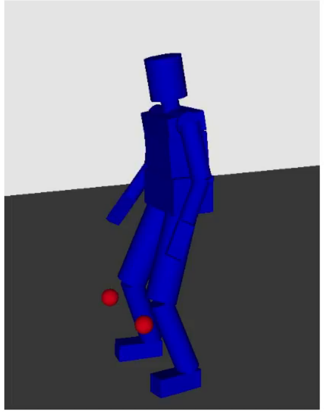


Stack of Tasks

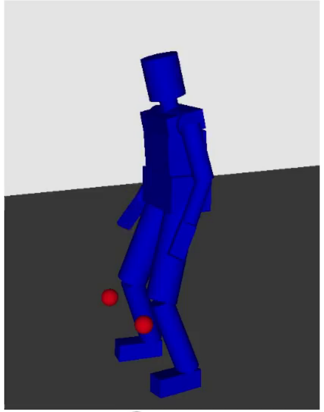
High Priority	Feet (X,Y,Z)	CoM (X,Y)	
Low Priority	Hand (X,Y,Z, r, p, y)	Pelvis (Z, p)	Ref. Joint Posture

Optimize Center of Mass planar projection, and **Pelvis Vertical Trajectory**

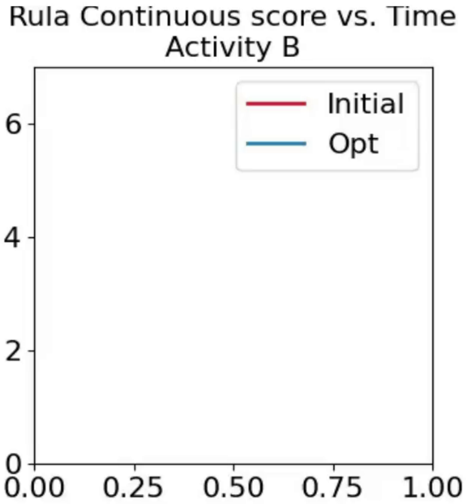
Example: Box Lifting - Single-Objective Optimization



Initial

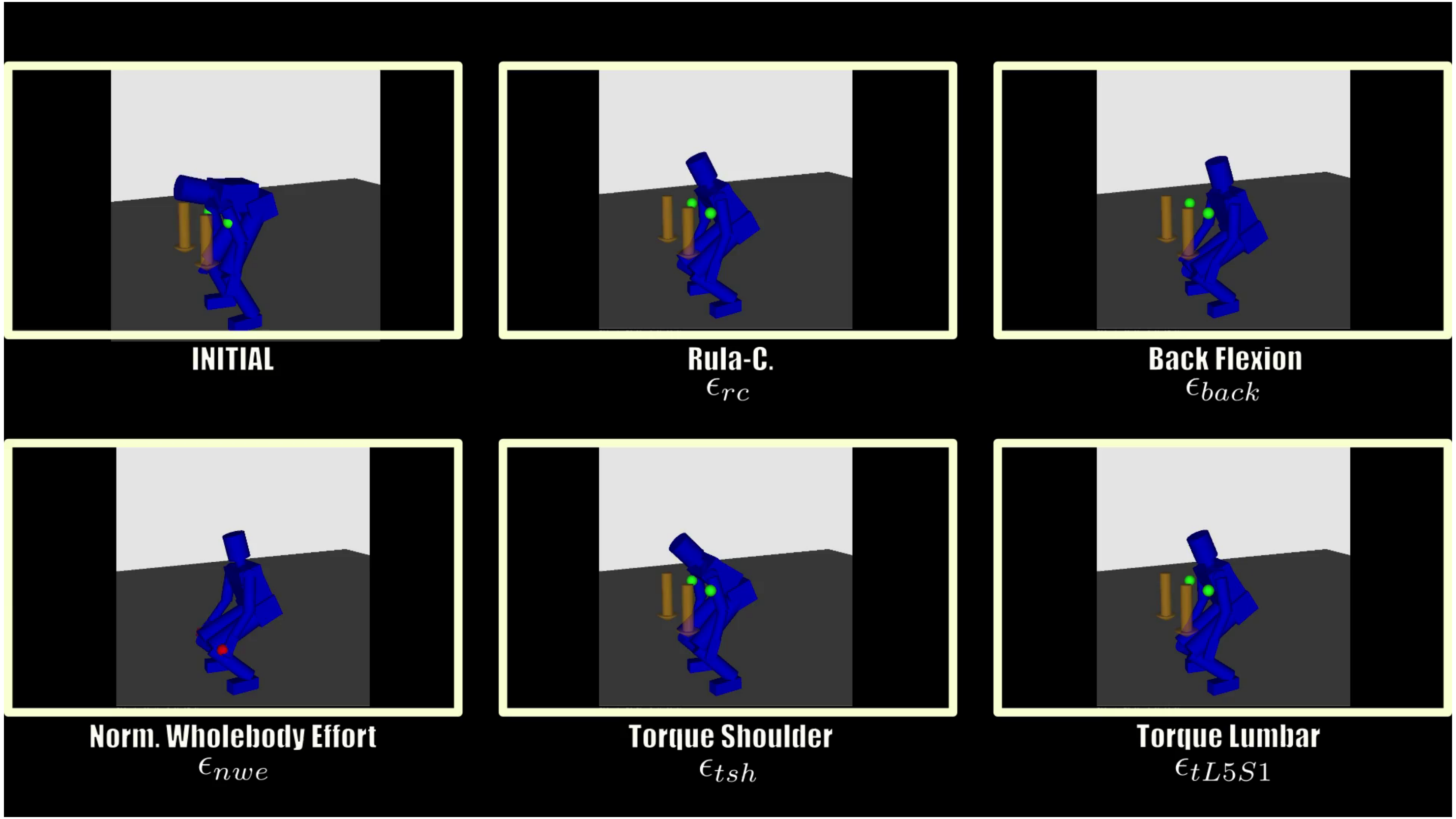


Opt.
Rula-c



black-box optimization with non-linear constraints

Example: Box Lifting - Single-Objective Optimization

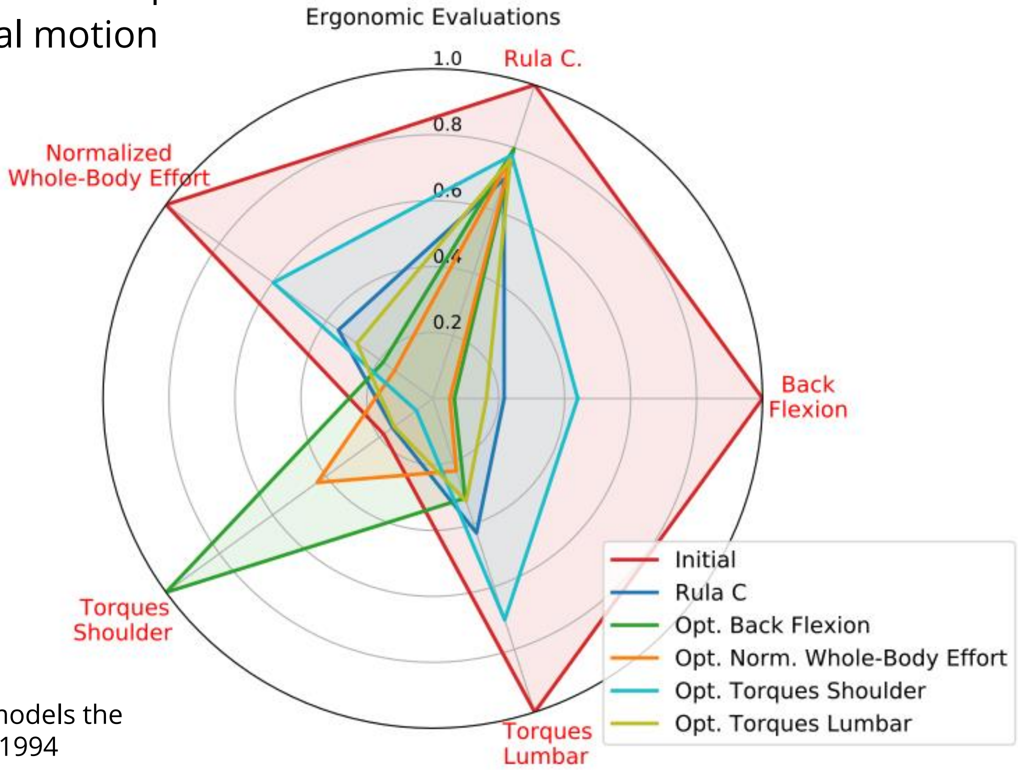


Example: Box Lifting - Single-Objective Optimization

- Some optimal solutions highly increased the torques at the shoulders in comparison to the initial motion

- Solutions with conflicting objectives
  - Torques shoulder, and lumbar

- COBYLA optimizer
  - 1500 max. rollouts / optimization
  - 15 hours / motion
  - Each optimization run in parallel



M. J. D. Powell, "A direct search optimization method that models the objective and constraint functions by linear interpolation", 1994

Example: Box Lifting - Single-Objective Optimization

- Some optimal solutions highly **increased** the **torques** at the **shoulders** in comparison to the initial motion

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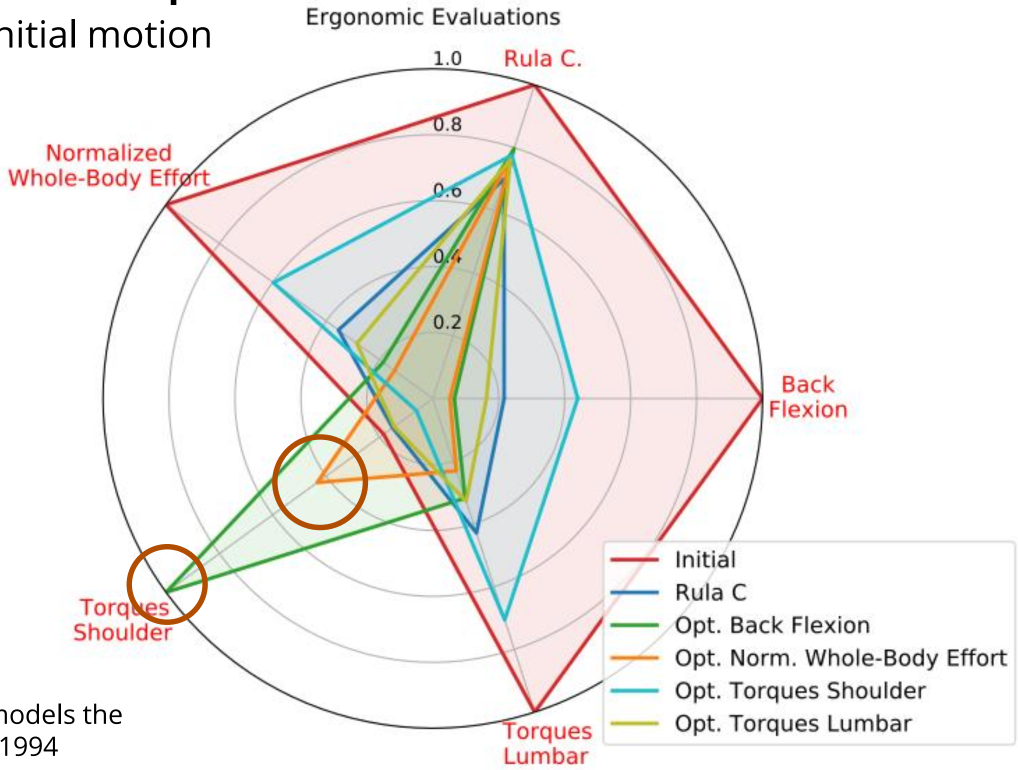


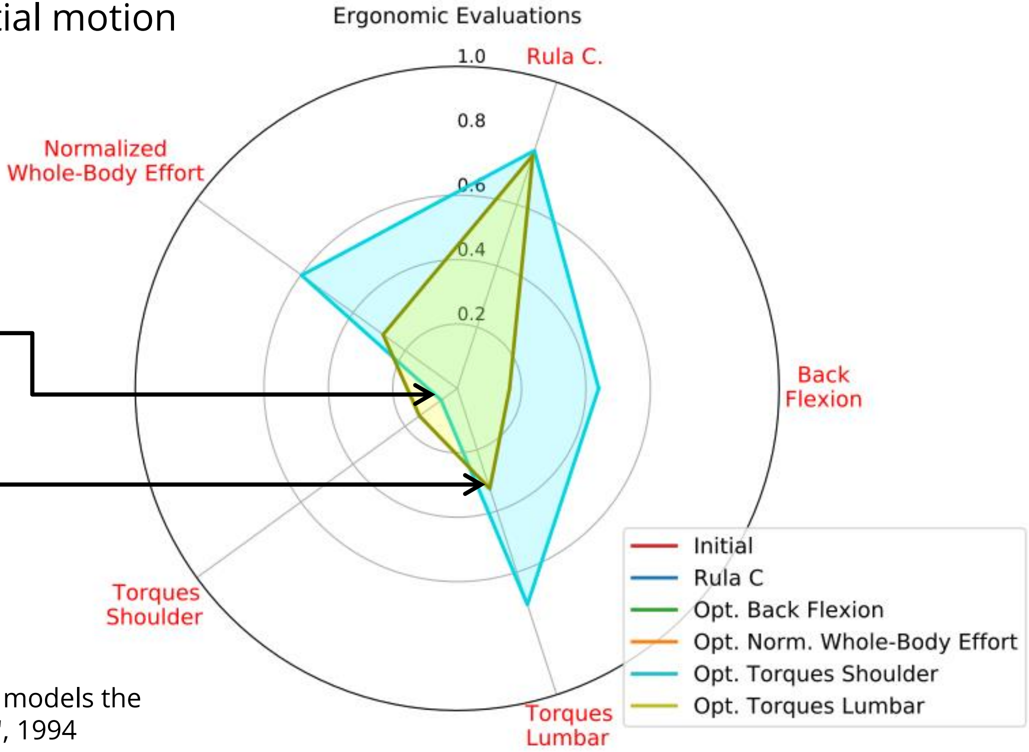
M. J. D. Powell, "A direct search optimization method that models the objective and constraint functions by linear interpolation", 1994

Example: Box Lifting - Single-Objective Optimization

- Some optimal solutions highly increased the torques at the shoulders in comparison to the initial motion

- Solutions with conflicting objectives
  - Torques shoulder, and lumbar
  - Low at shoulder, high at lumbar
  - High at shoulder, low at lumbar

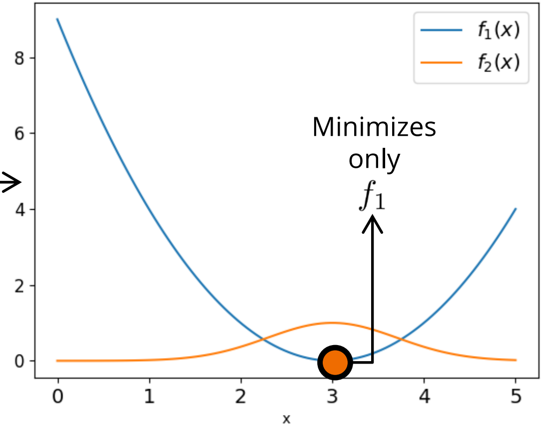
- COBYLA optimizer
  - 1500 max. rollouts / optimization
  - 15 hours / motion
  - Each optimization run in parallel



M. J. D. Powell, "A direct search optimization method that models the objective and constraint functions by linear interpolation", 1994

Example: Box Lifting - Single-Objective Optimization

Minimizing f_1 does NOT minimize f_2
(<u>conflicting objectives</u>)



How do we optimize them simultaneously ?

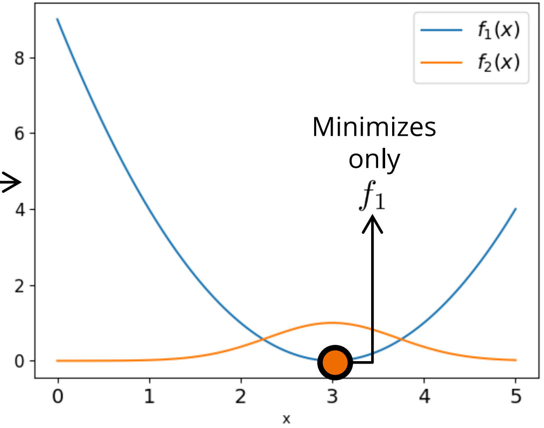
Aggregated Objective Function:

$$g(a_1, a_2) = a_1 f_1 + a_2 f_2$$

$$\min\left(g(a_1, a_2)\right)$$

Example: Box Lifting - Single-Objective Optimization

Minimizing f_1 does NOT minimize f_2
(conflicting objectives)



How do we optimize them simultaneously ?

Aggregated Objective Function:

$$g(a_1, a_2) = a_1 f_1 + a_2 f_2$$

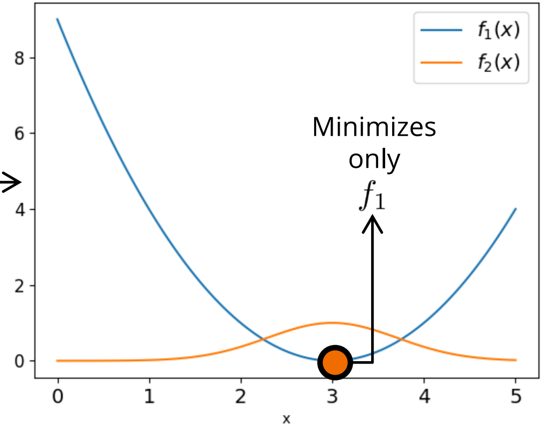
$$\min\left(g(a_1, a_2)\right)$$

a_1, a_2 **implicitly encode solution preferences** to f_1 or f_2

- They have to be chosen carefully!
- New optimization may be time-costly

Example: Box Lifting - Single-Objective Optimization

Minimizing f_1 does NOT minimize f_2
(conflicting objectives)

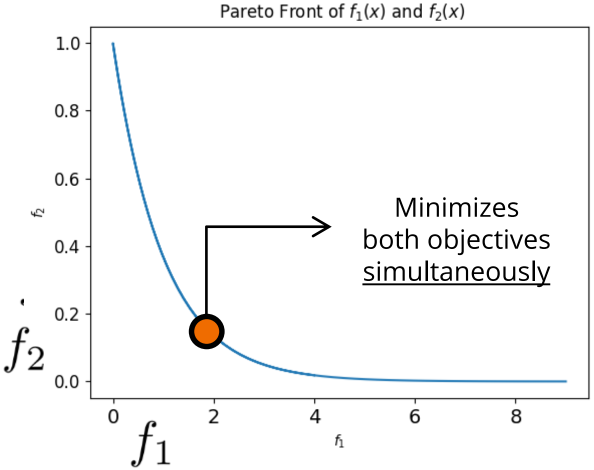


How do we optimize them simultaneously ?

Pareto-Based Multiple-Objective Optimization:

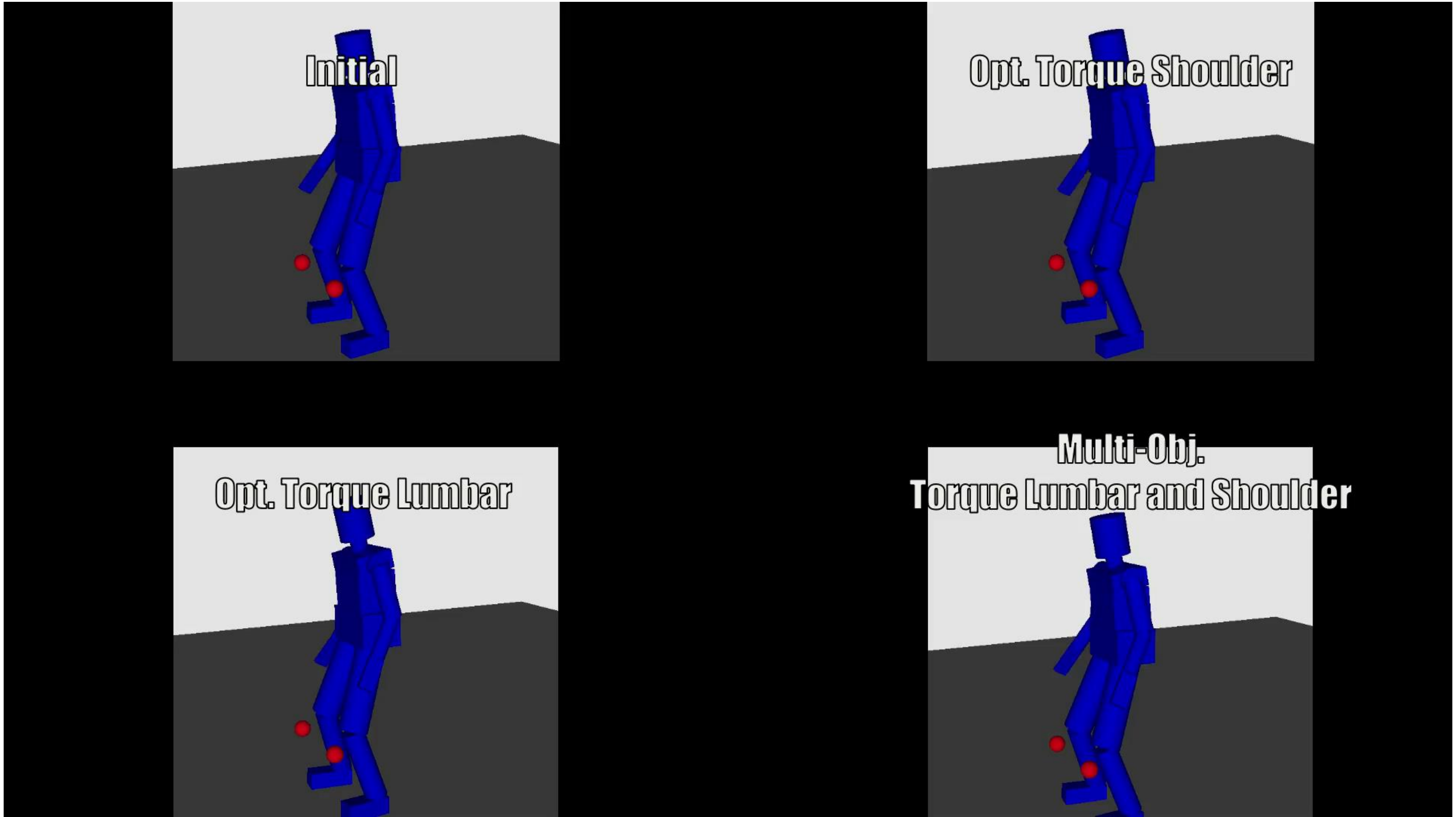
$$\min_{x \in X} (f_1, f_2)$$

$$x_1 \text{ dominates } x_2 \iff (f_1(x_1) < f_1(x_2)) \wedge (f_2(x_1) < f_2(x_2))$$

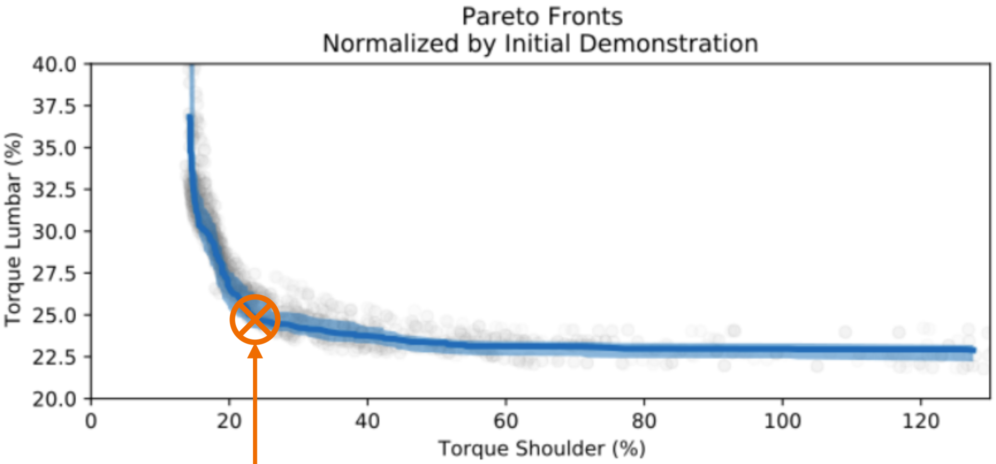


Pareto Front: Set of **non-dominated solutions**

Example: Box Lifting - Multi-Objective Optimization



Example: Box Lifting - Multi-Objective Optimization



Motion	Torques Shoulder	Torques Lumbar
Initial	100%	100%
Opt. Torques Shoulder	33.6%	70.6%
Opt. Torques Lumbar	78.8%	32.75%
Multi-Objective	22.4%	25.9%

Solution from **Multi-Objective Opt. is safer than** both solutions from **single-objective** optimization.

NSGA-II Optimizer

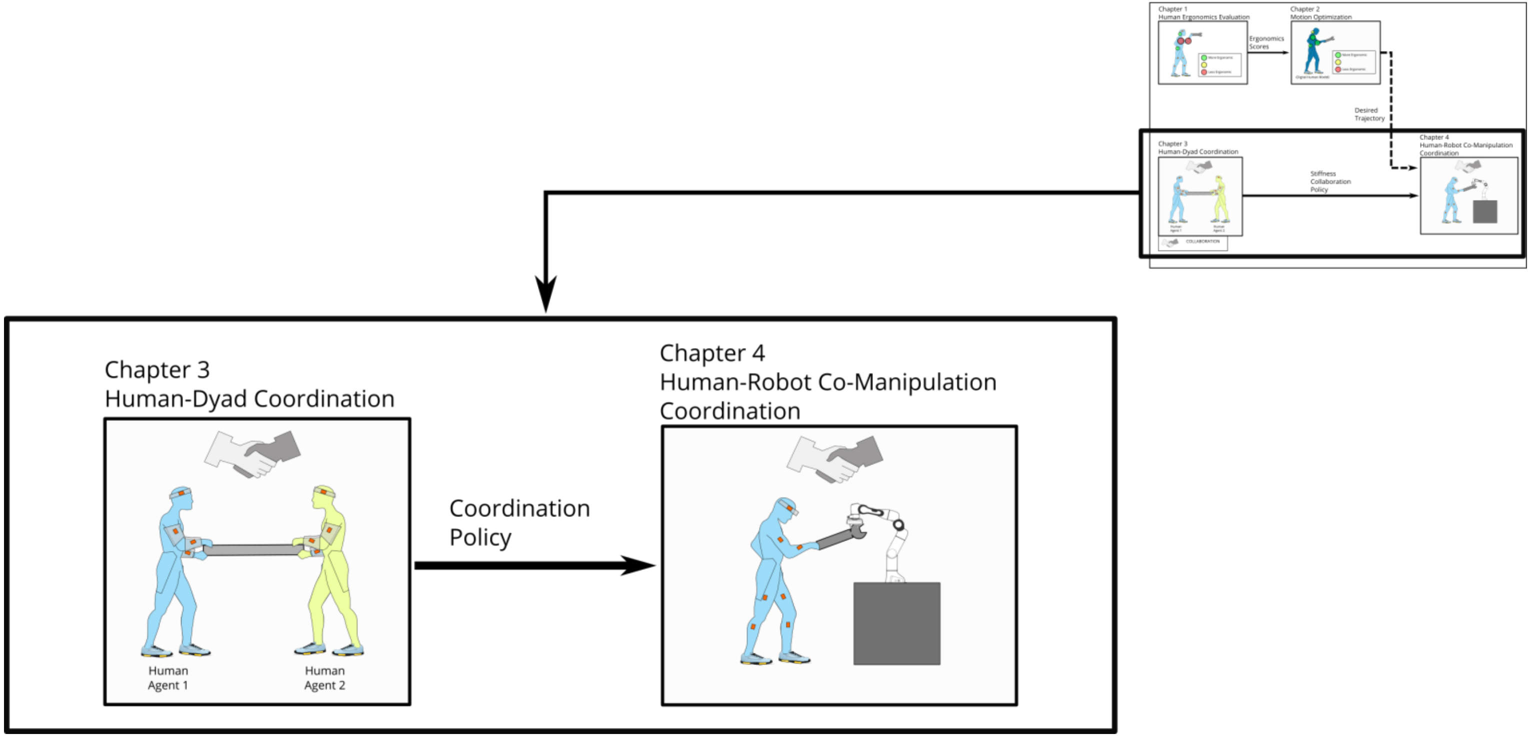
Run in Parallel 20 times, 24 hours in total

Cross rate= -0.5; mutation rate= 0.4; Pop. Size= 100; Nb. Generations =600;

Deb, K. et al. "A Fast Elitist Non-dominated Sorting Genetic Algorithm for Multi-objective Optimization: NSGA-II", 2000

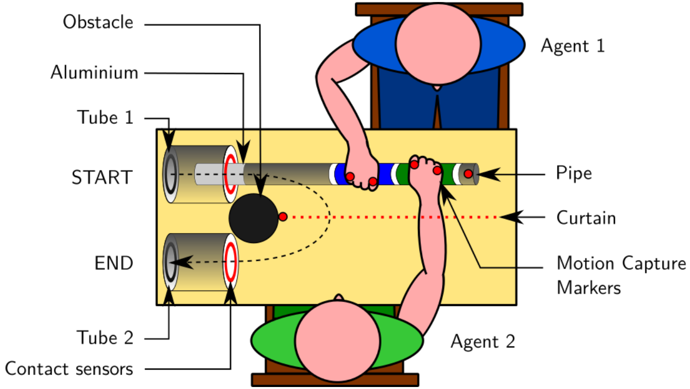
Summary

- Methods for **wholebody motion optimization**
- **Multi-Objective optimization** to handle several ergonomics scores (safer!)
- Ergonomics trajectories for **human-robot collaboration**



PART IV - Human Motor Behavior and pHRI

Object Co-Manipulation: Human-Human

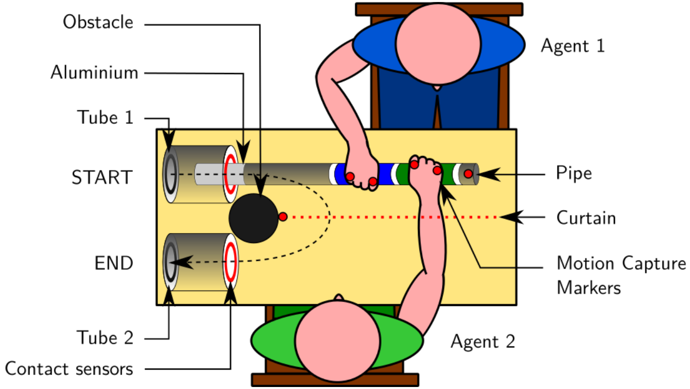


Precise co-manipulation task

- Remove pipe from tube 1
- Move pipe around obstacle
- Insert pipe in tube 2

Gomes et al. “In a collaborative co-manipulation, humans have a motor behaviour similar to a leader”, [PREPRINT, 2022]

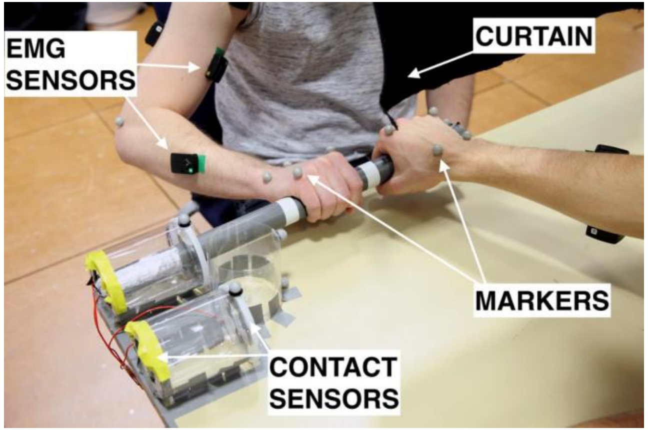
Object Co-Manipulation: Human-Human



- 20 participants, 10 dyads
- Randomly assigned conditions:
  - **Leader/Follower** (Cooperation)
  - Follower/Leader (Cooperation)
  - **No Leadership** (Collaboration)
- 5 trials for each condition
- 2 practice trials between conditions

Which strategy is the most effective for co-manipulation?

Object Co-Manipulation: Human-Human



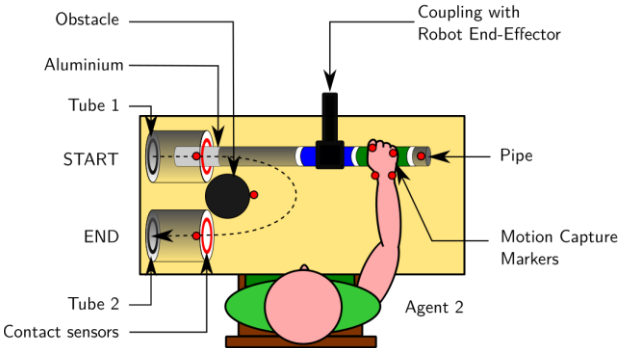
- Optical **motion capture**
  - Hand, elbow, and shoulder
- Contact Sensors
  - Touch the tube walls = error
- **sEMG sensors**
  - Forearm muscles/participant
  - Muscle co-contraction

Object Co-Manipulation: Human-Human

The **dyads** were **more effective during collaboration** (no leaders), than during cooperation (leader/follower)

Collaboration leads to muscle **co-contraction** (arm stiffness) as **high** as in leaders

Object Co-Manipulation: Human-Robot



One of the human agents is replaced by a Franka robot

GOAL: Emulate the collaboration condition using variable impedance control to control the robot

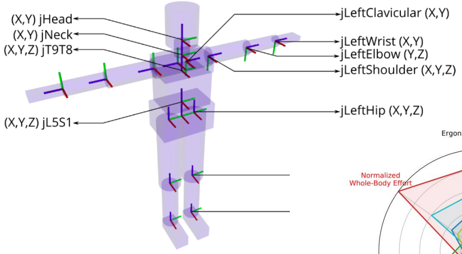
Vianello et al. “Cooperation or collaboration? On a human-inspired impedance strategy in a human-robot co-manipulation task”, [SUBMITTED TO RA-L]

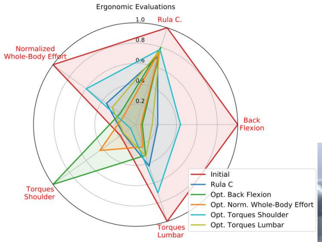
Object Co-Manipulation: Human-Robot

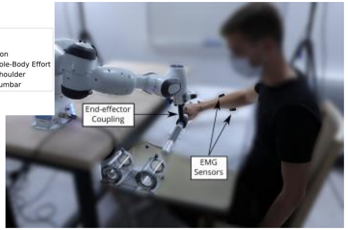
Collaboration is more effective for the task execution

- In contrast to the human-human experiment, the co-contraction was lower during collaboration conditions (**Less energy expenditure**)
- Lower number of task execution errors than during the cooperation conditions

Vianello et al. “Cooperation or collaboration? On a human-inspired impedance strategy in a human-robot co-manipulation task”, [SUBMITTED TO RA-L]







Part IV - Conclusions

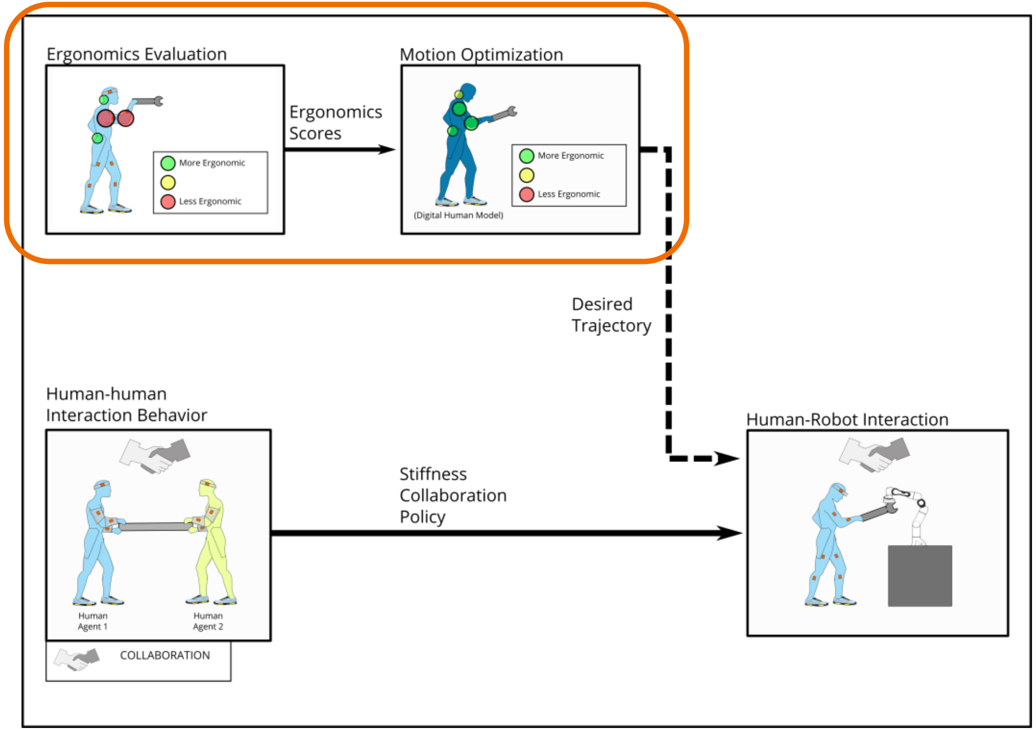
Goals and Contributions

Automatic whole-body ergonomics evaluation and optimization

- Kinematics and dynamics
- Multi-objective approach

Human physical interaction

- Human-Human
- Human-Robot



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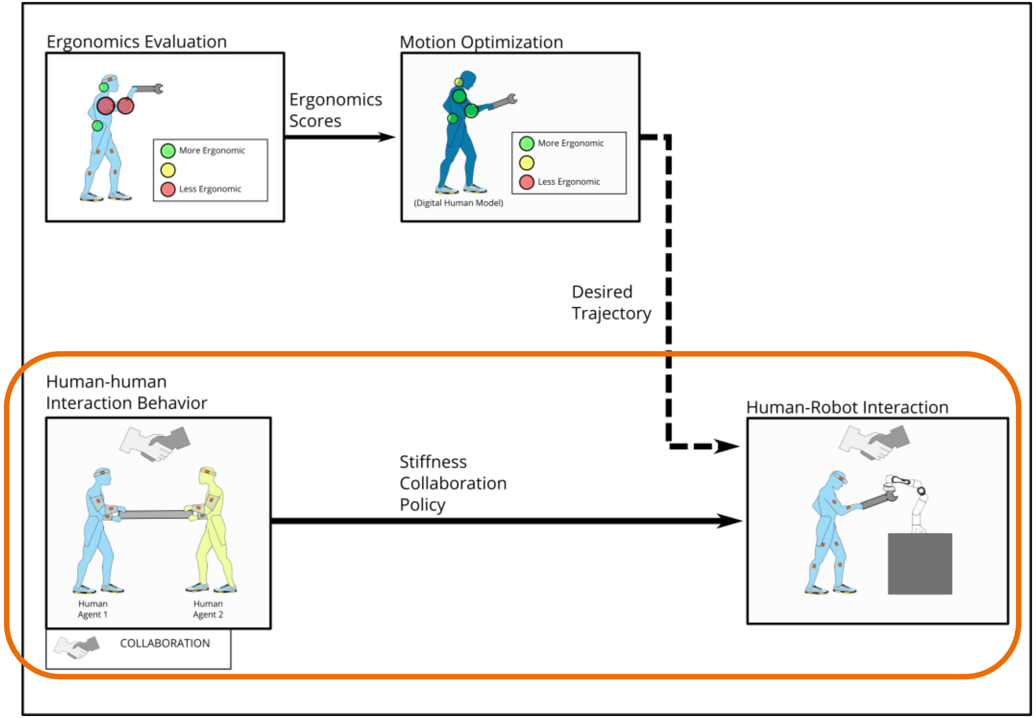
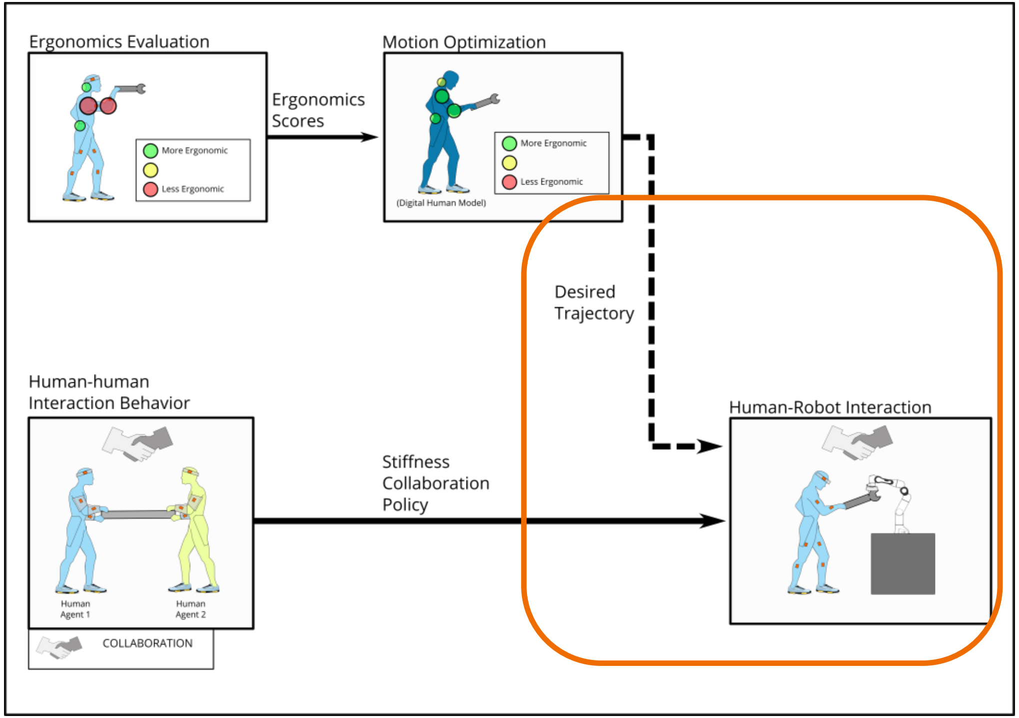


Goals and Contributions

Ergonomic desired trajectory to be integrated



Automatic ergonomics whole-body motion analysis and physical human-robot interaction

28/02/2022

Dr. Waldez Gomes

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Website: waldezjr.github.io

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www.anyscript.org

- Wiki, Blog, Repositories, Forum

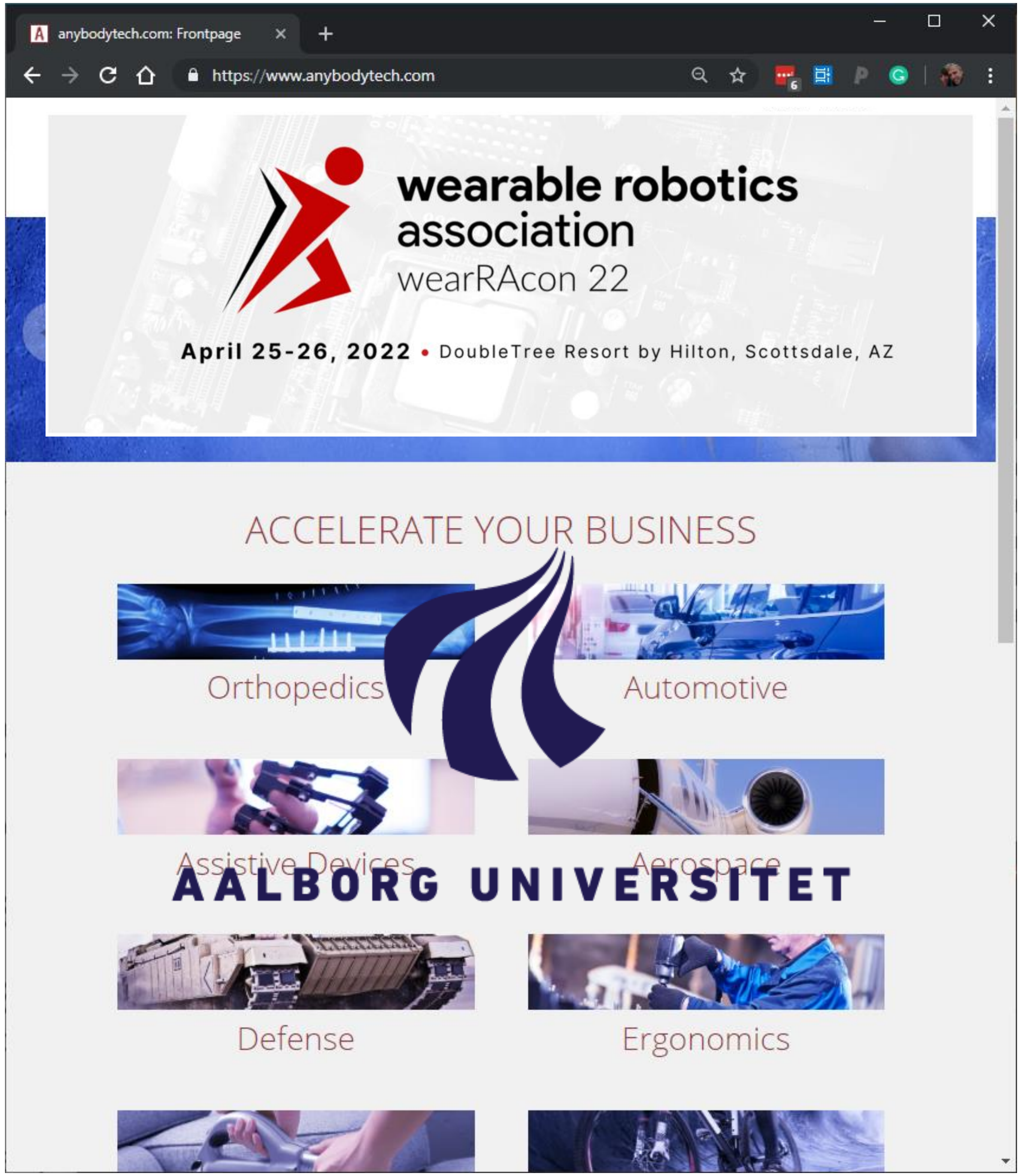
Upcoming events

- WearRAcon
  - April 25 – 26, 2022 in Scottsdale, AZ

- Musculoskeletal Modeling by Multibody Dynamics – PhD Course by Aalborg University
  - May 2 – 6, 2022 (Online)
  - Registration deadline: April 15, 2022

Meet us? Send email to sales@anybodytech.com

Want to present? Send email to ki@anybodytech.com



Thank you for your attention
- Time for questions