La Robotique au Service de l'Homme

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Human-Centered Robotics

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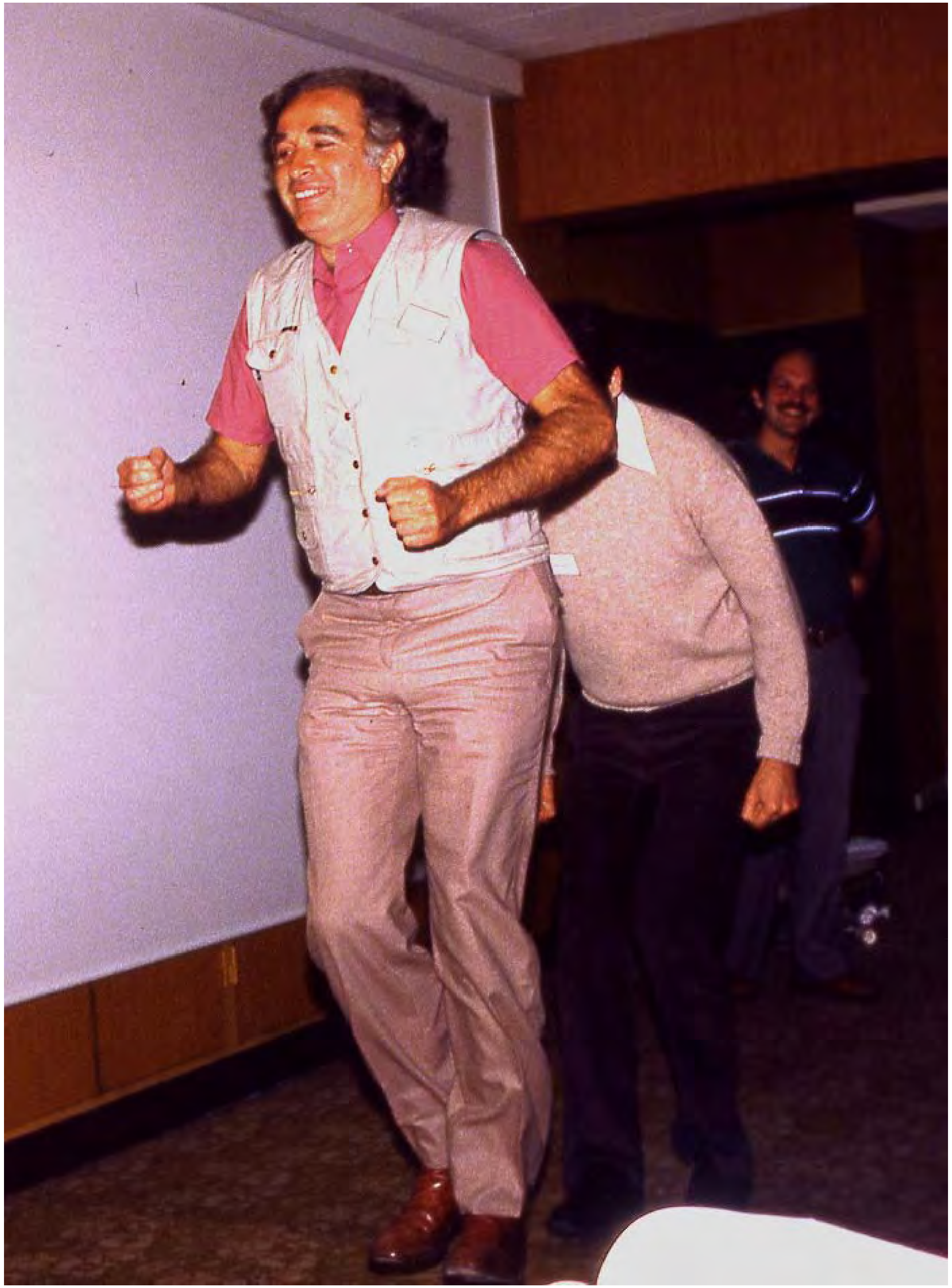
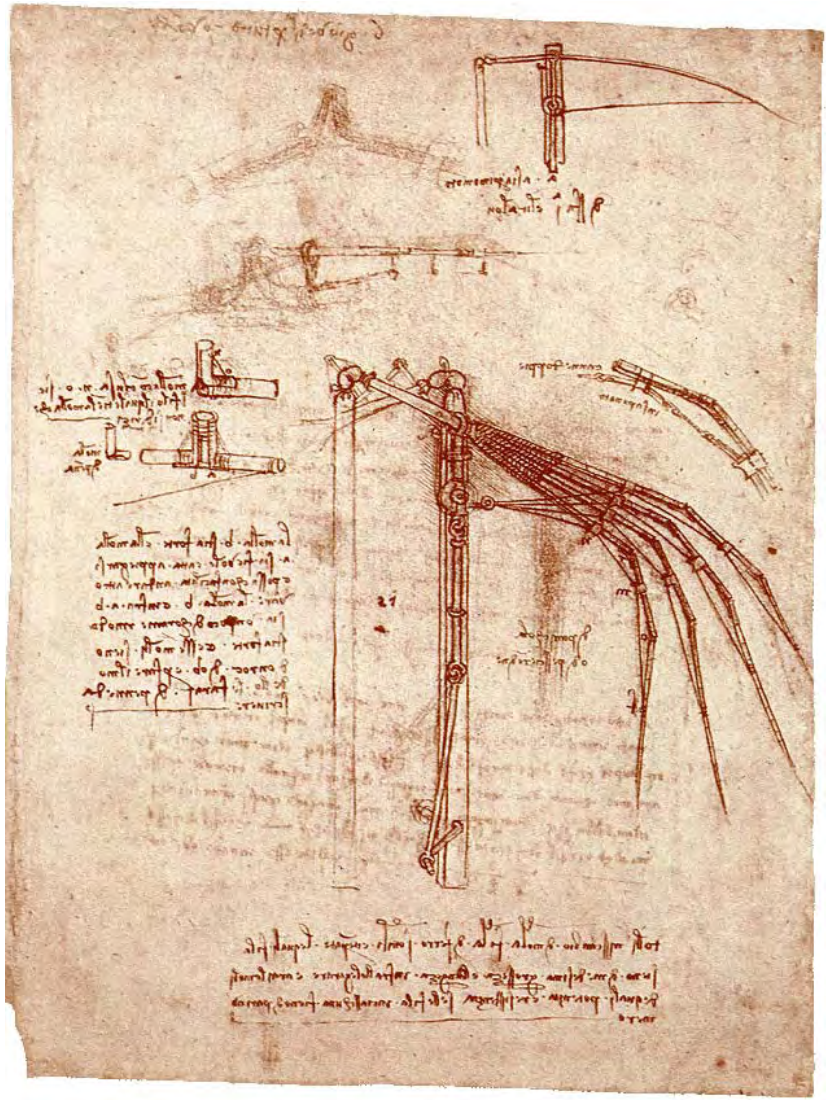




Historical Perspective

Jaquet-Droz's Automata, 1773

The Drawer

Jaquet-Droz's Automata, 1773

The Invention of "A Little Mechanical Family"

The Drawer - The Musician - The Writer

Jaquet-Droz's Automata, 1773

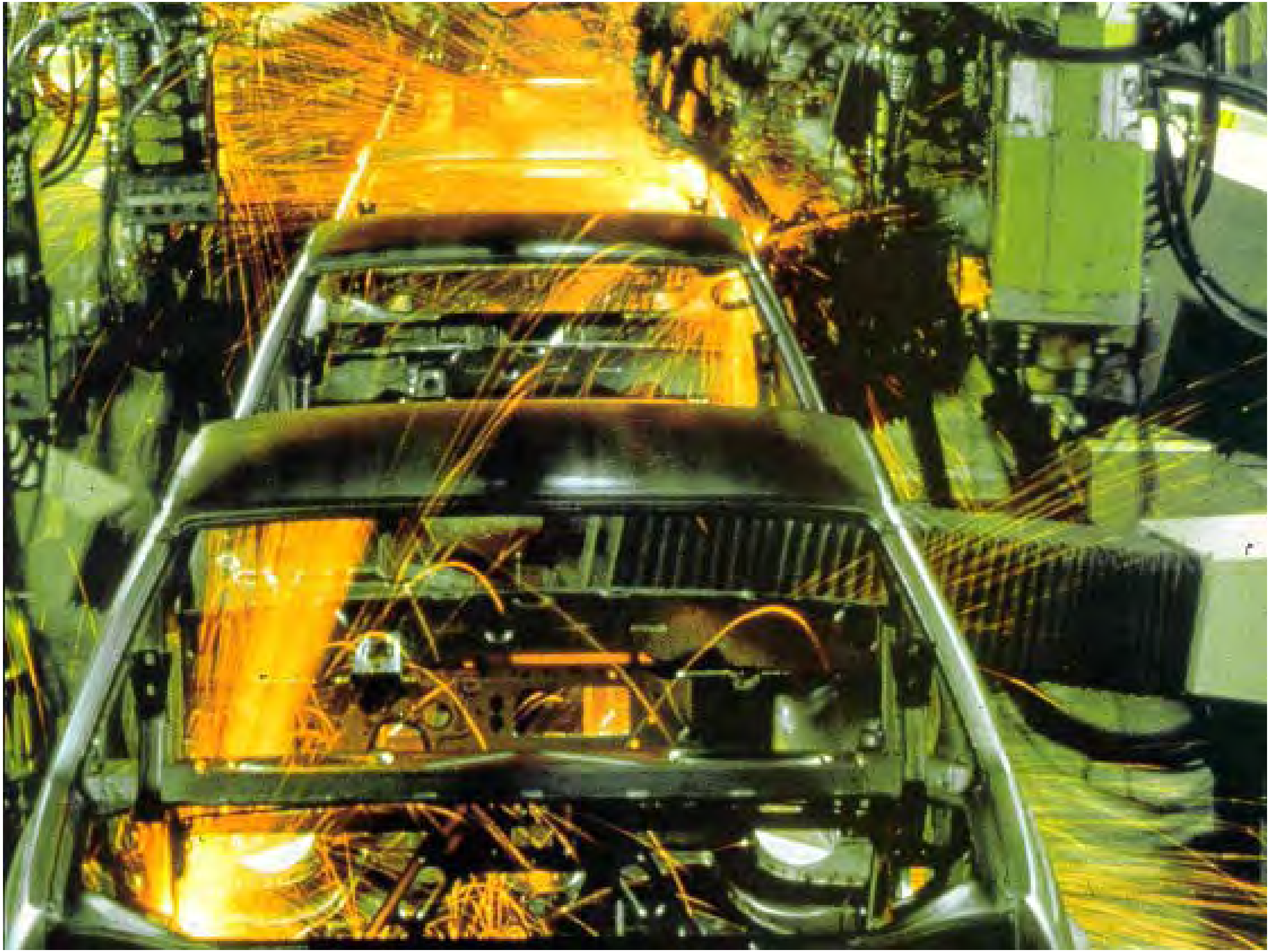
The Musician

Jaquet-Droz's Automata, 1773

The Writer

A Mechanical Computer

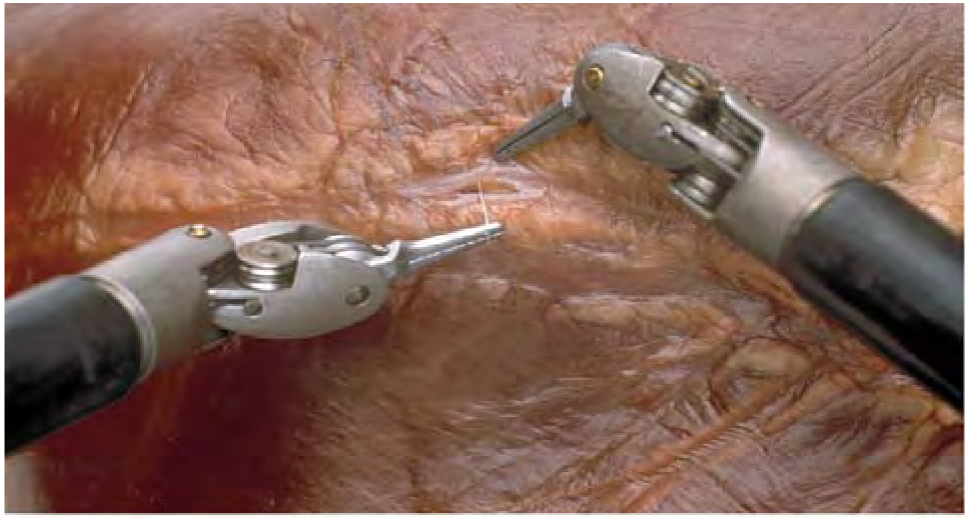
[redacted]



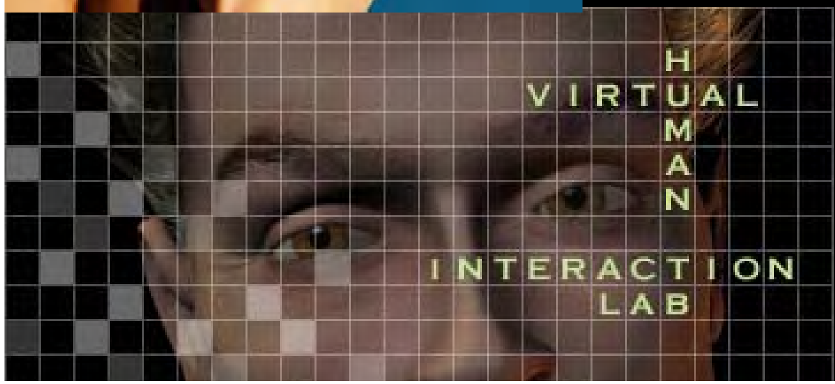
Service & Assistance

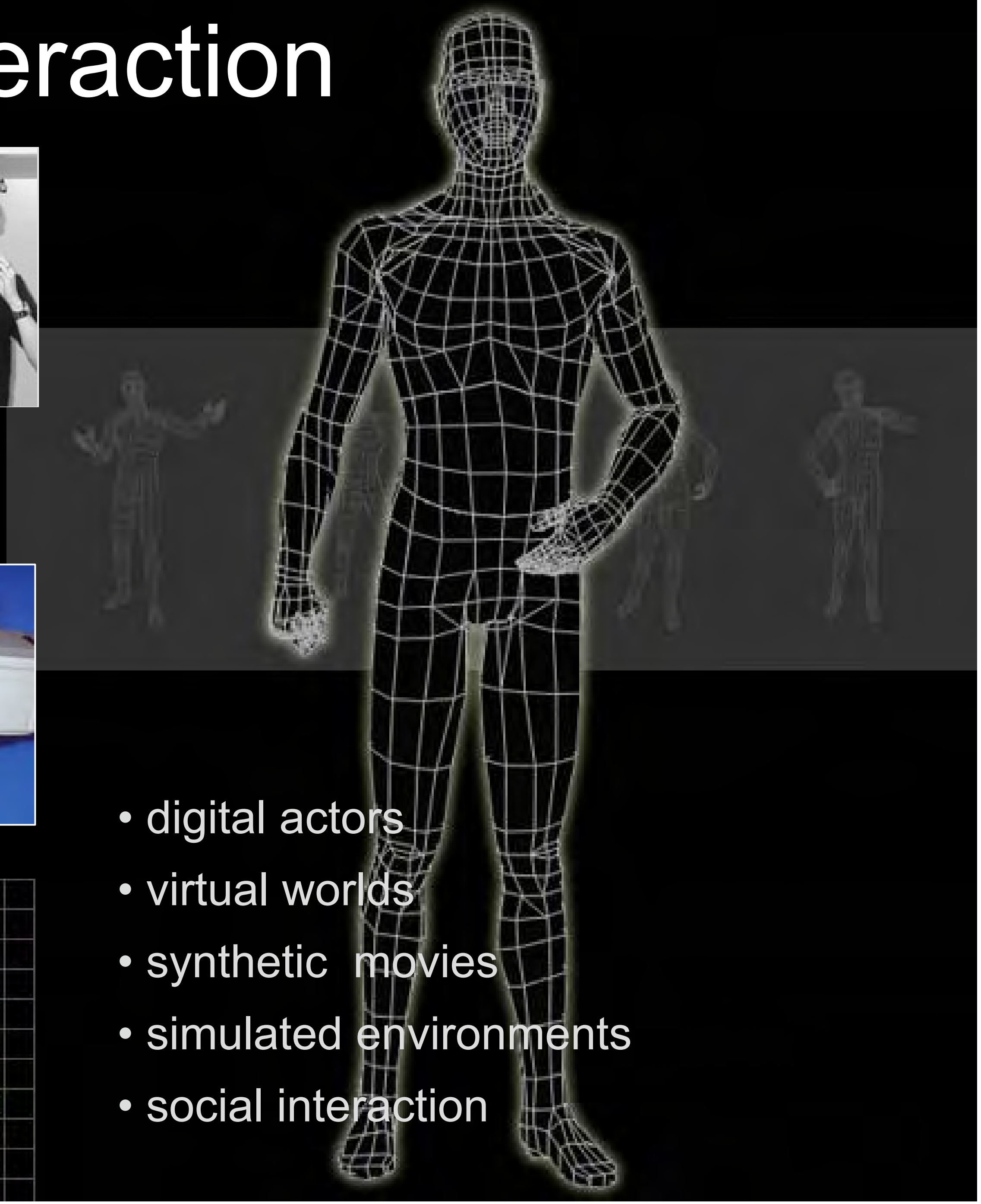
Surgical Environment

Robotically Aided Surgery

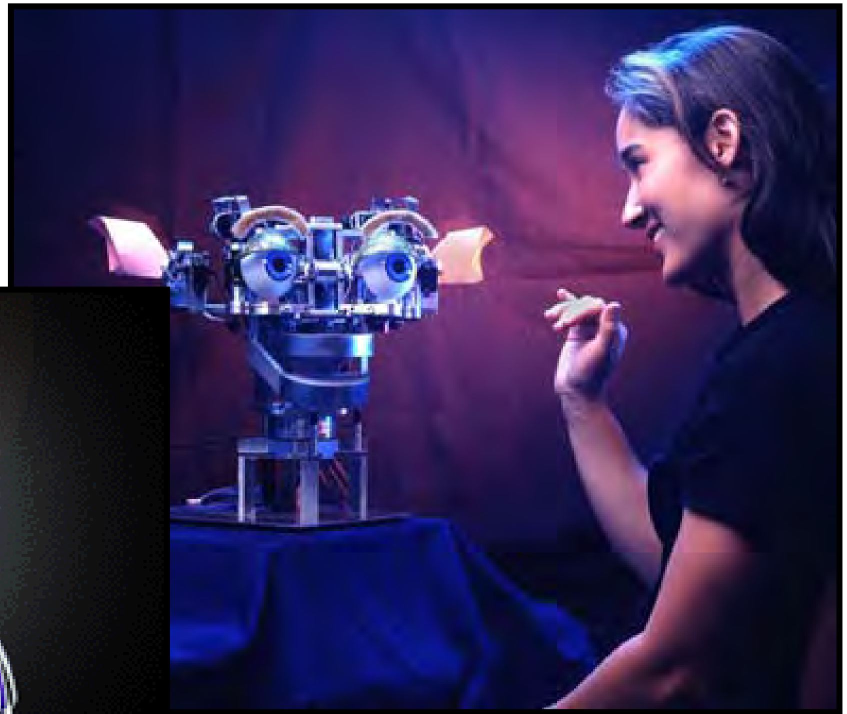
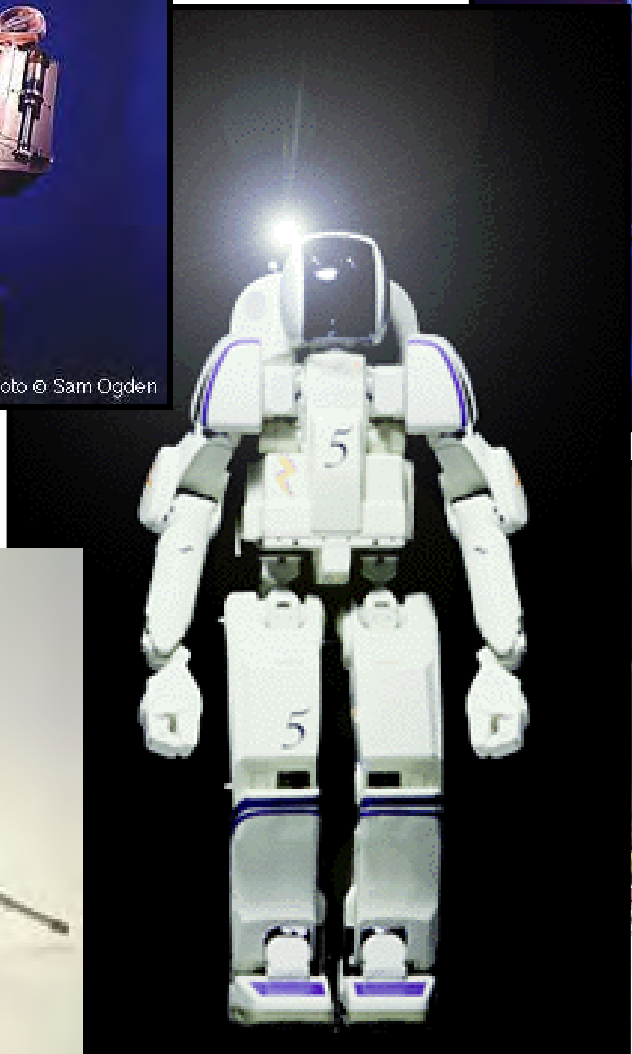


..in human interaction





- digital actors
- virtual worlds
- synthetic movies
- simulated environments
- social interaction


Photo © Sam Ogden



.. in the human environment

The Challenge

Sensing and Perception

real-time, unstructured world

Planning and Control

many degrees of freedom

human-like skills, learning

Human-Robot Interaction

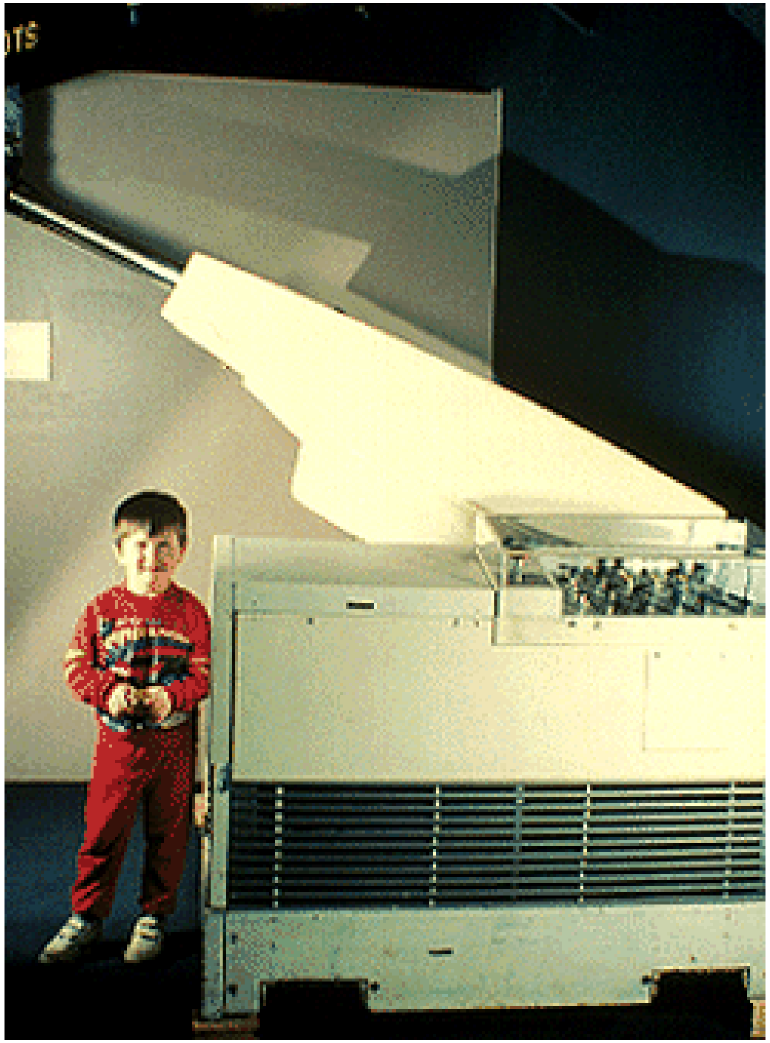
cognitive and physical

Mechanisms and Actuation

Safety & Performance

Interactivity & Human-Friendly

Safety



Human-Friendly Robots

Requirements

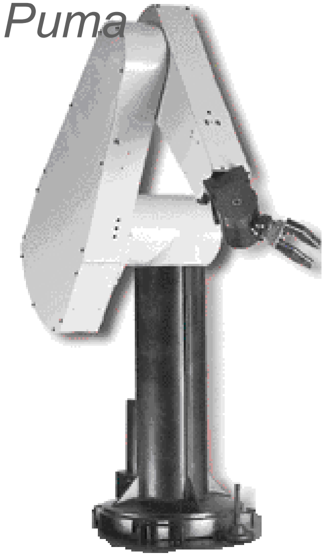
- Safety
- Performance

$\boxed{\textit{Competing?}}$

Technologies

Heavy structure

Puma

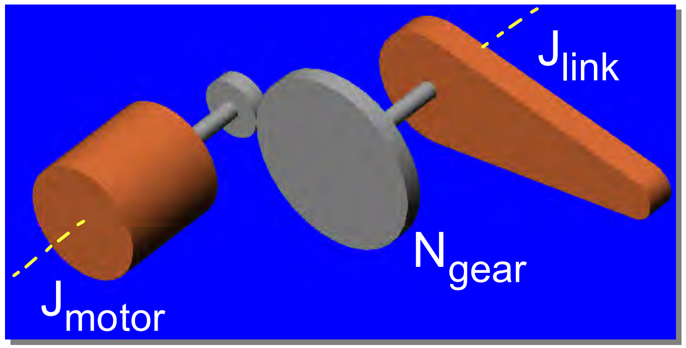


Conventional Geared Drive:

- Lighter structure
- Large reflected actuator inertia

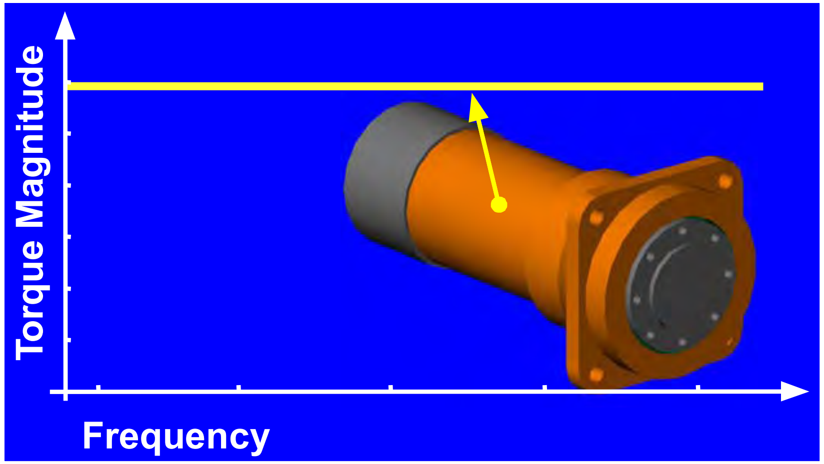
Effective Inertia

$(J_{link} + N^2 J_{motor})$

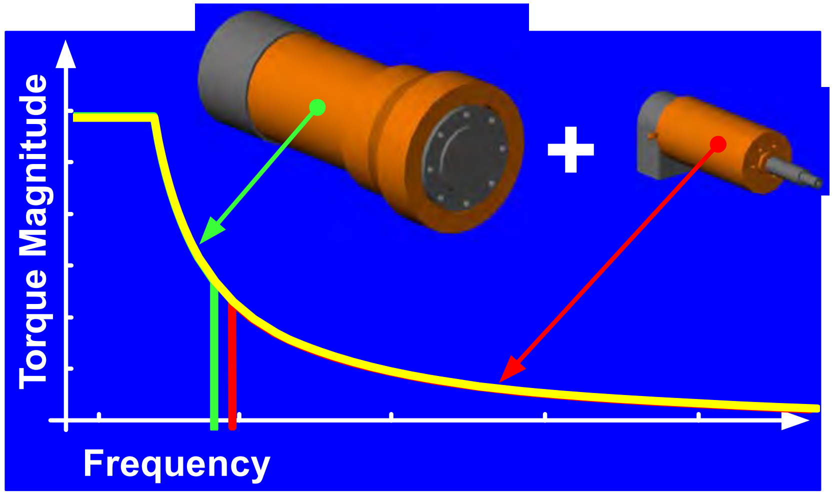


Actuation Requirements

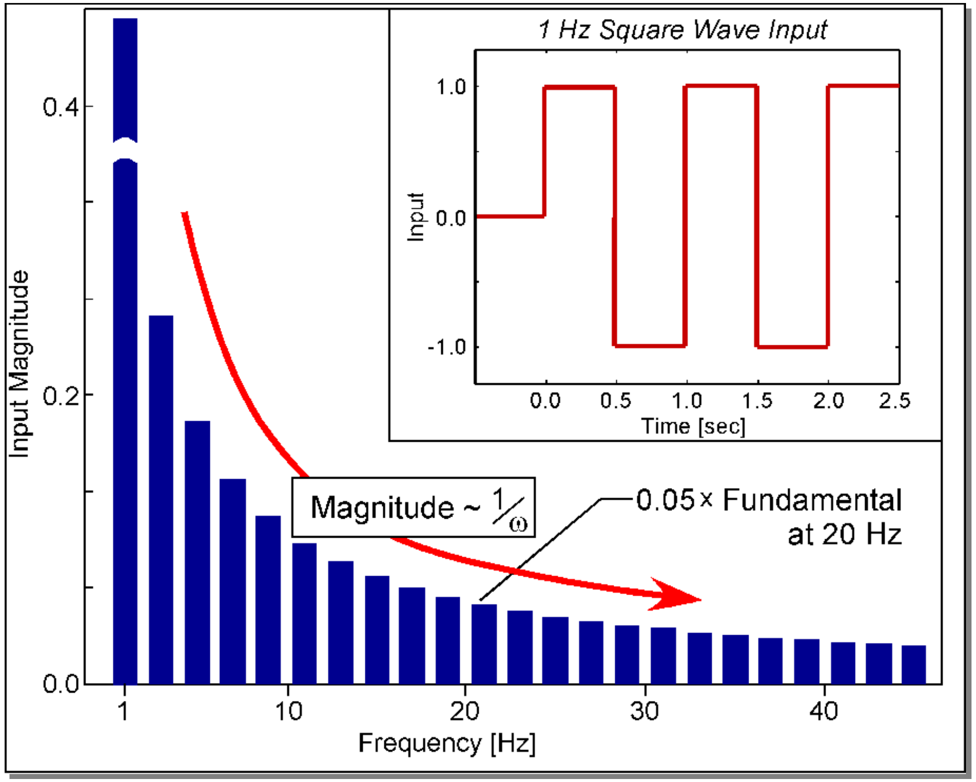
Assumed Torque Requirements



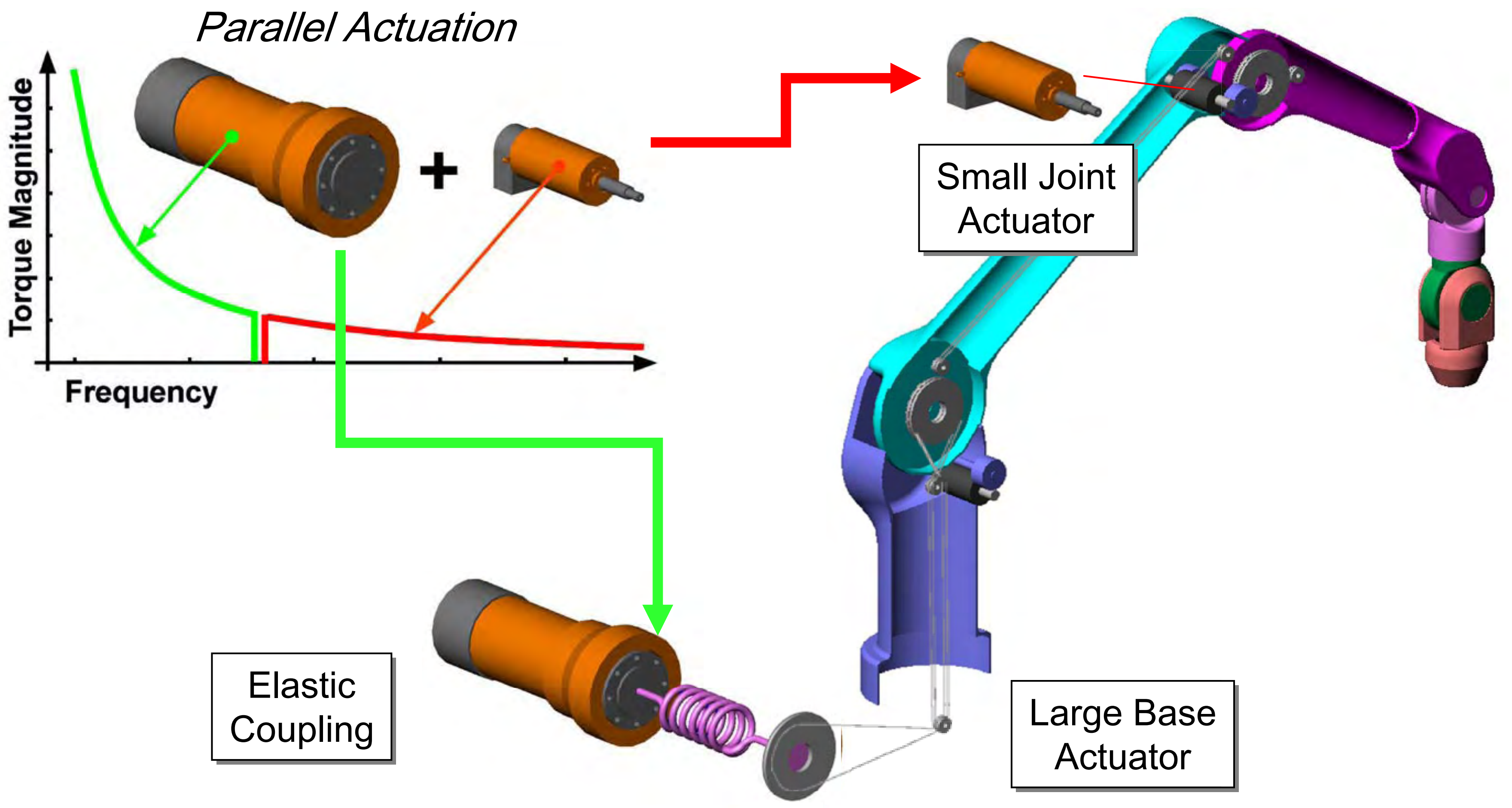
Actual Torque Requirements



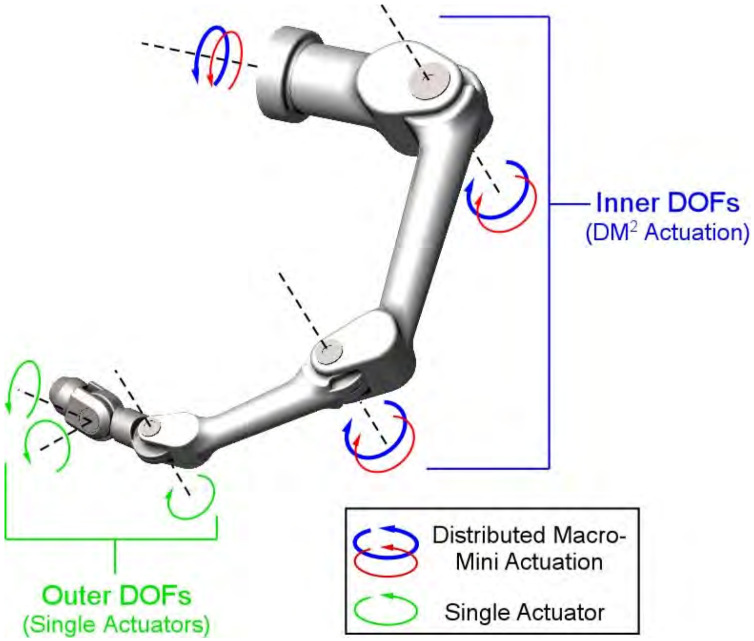
Torque Vs Frequency: Square Wave

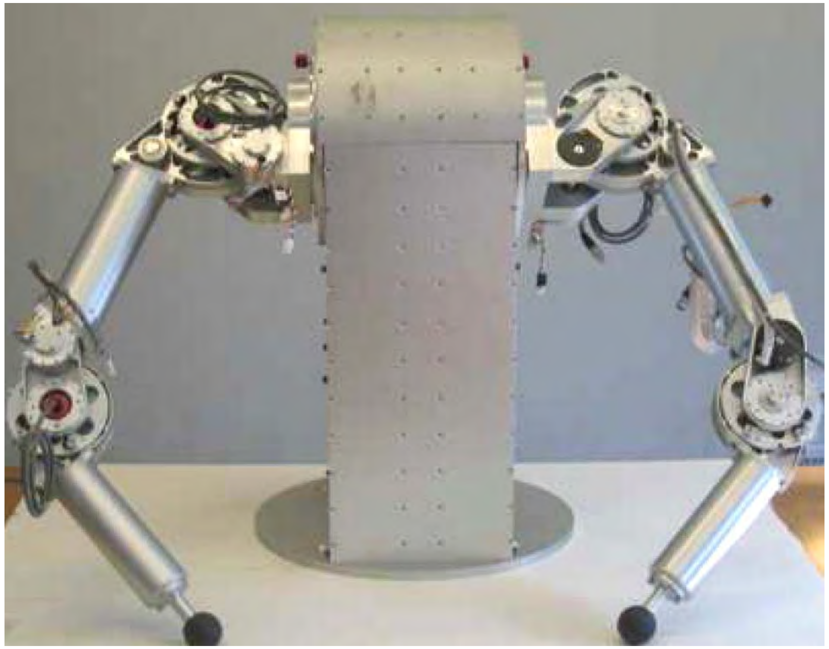


Distributed Macro Mini (DM²) Approach



DM2 - Human-Friendly Robot

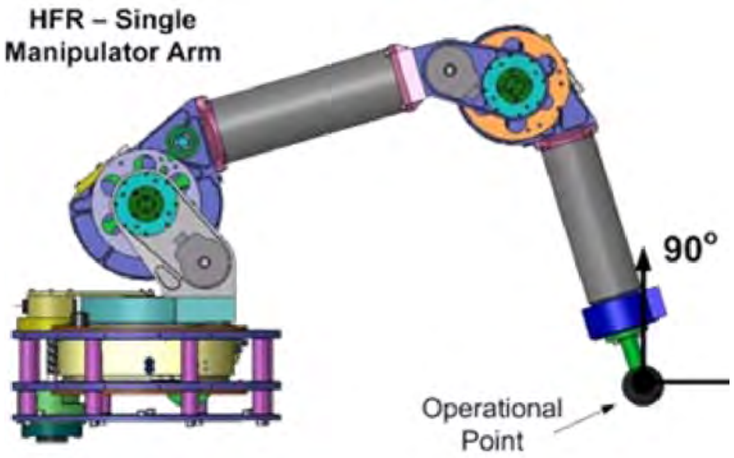




"the high capacity of a large robot with the fast dynamics and safety of a small one"

DM^2 Performance

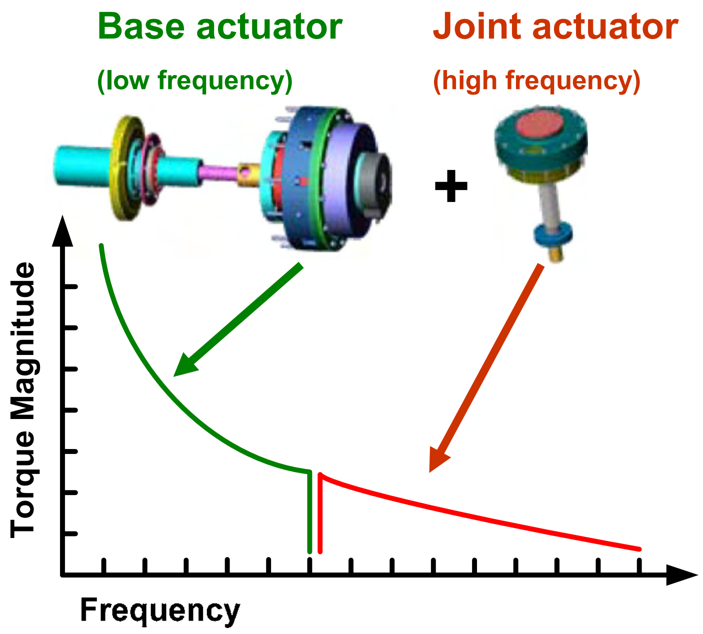
Distributed Macro-Mini Actuation ⇨ DM^2

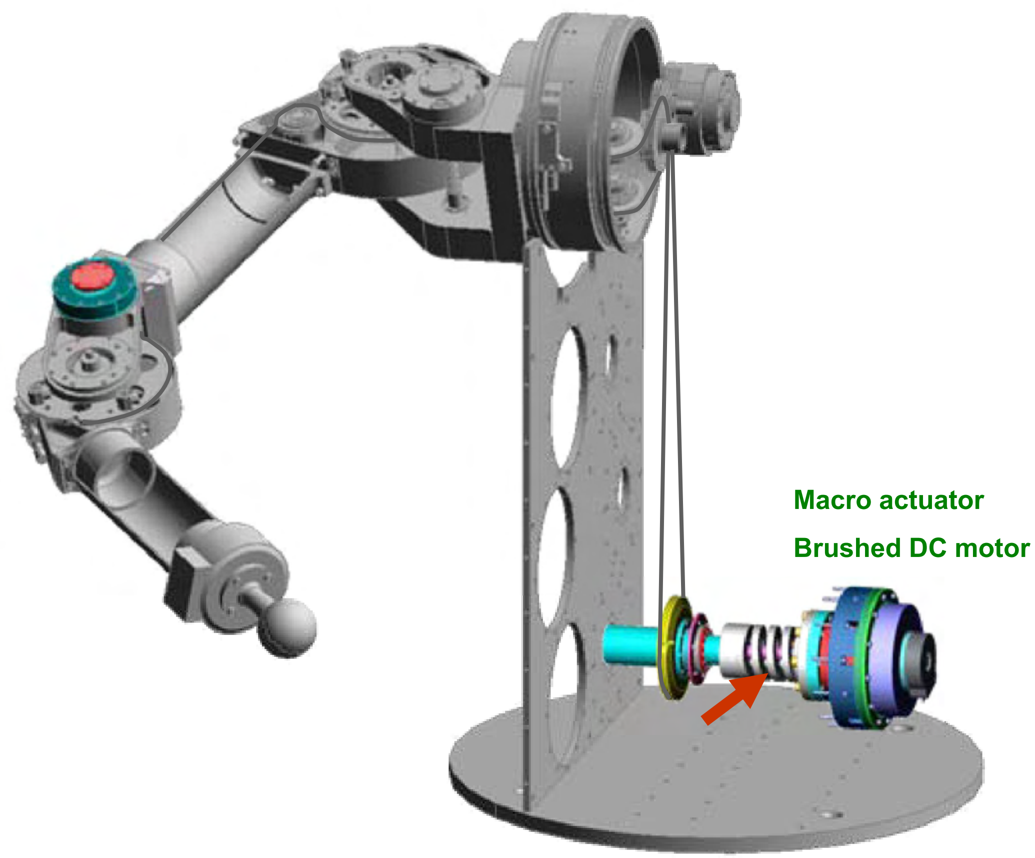


- 10x reduction in effective inertia
- 3x increase in position control bandwidth
- 10x decrease in trajectory tracking error

Safety
AND
Performance

DM^2 Testbed

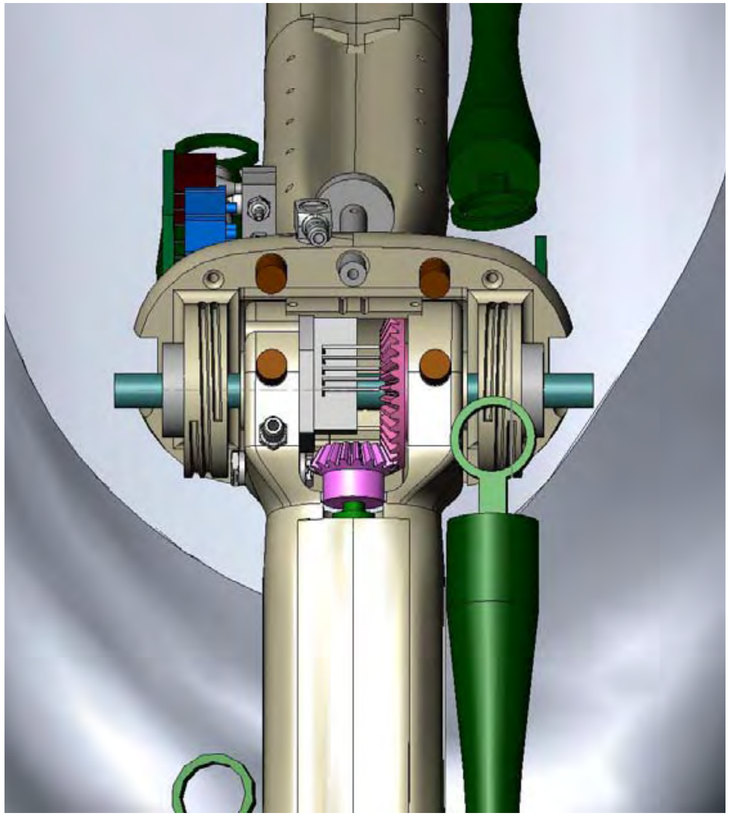

Base actuator
(low frequency)
Joint actuator
(high frequency)
+
Torque Magnitude
Frequency

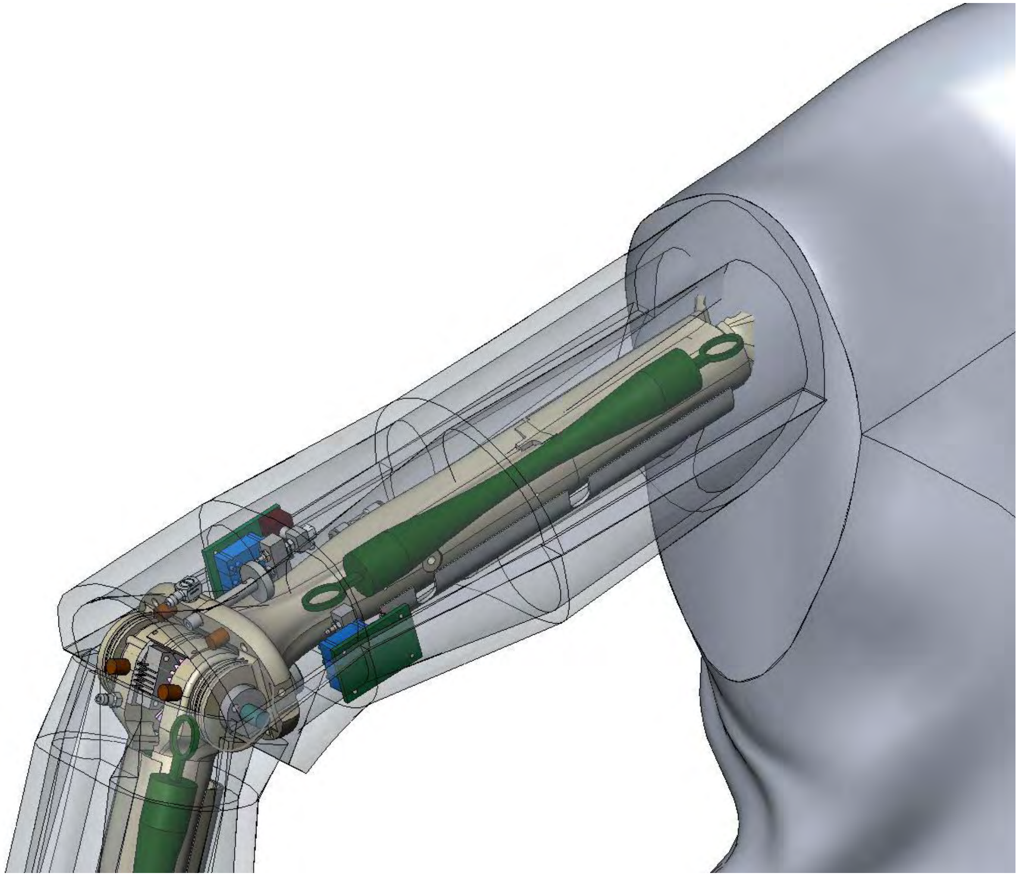

Macro actuator
Brushed DC motor


Elastic Coupler
(Torsional Spring)


NS-5
HABEN SIE AUCH SCHON EINEN?
3-GESETZE-SICHERHEITSZERTIFIKAT
WWW.I-ROBOT-NS5.DE

$s2\rho$: Stanford Human-Safe Robot





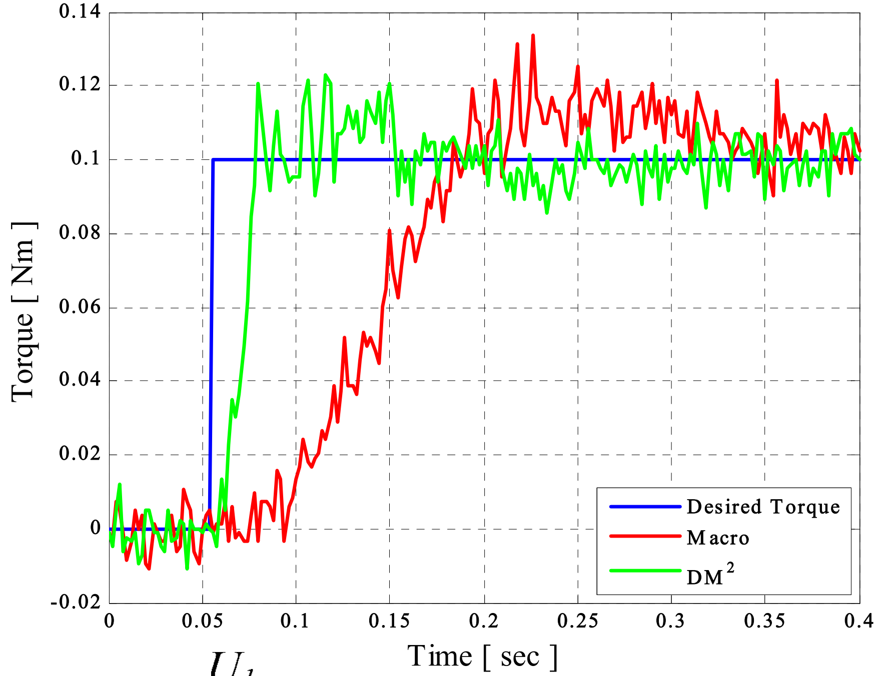
artificial muscles with electrical motors
and compact pressure regulators

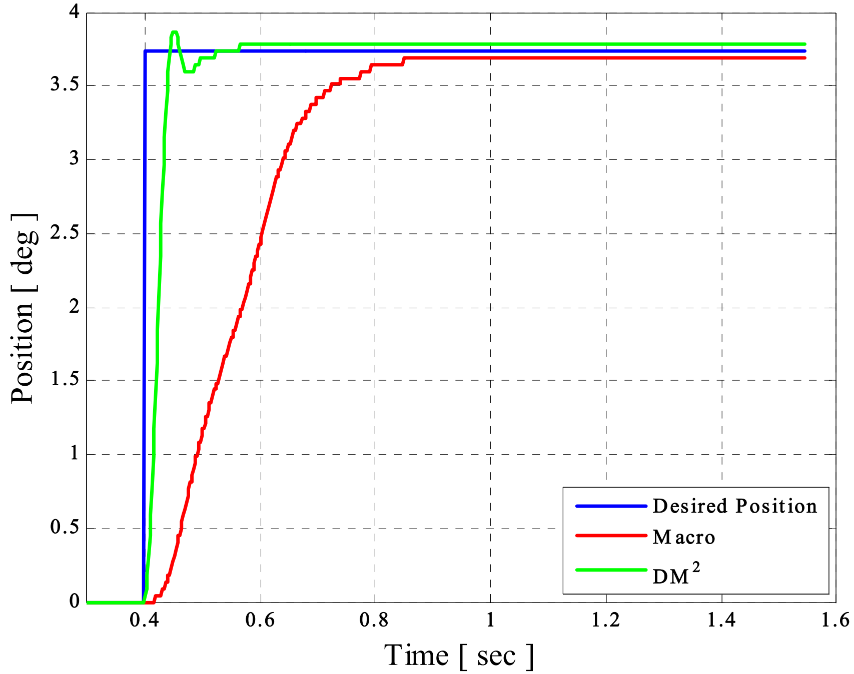
$S2\rho$: Stanford Human-Safe Robot

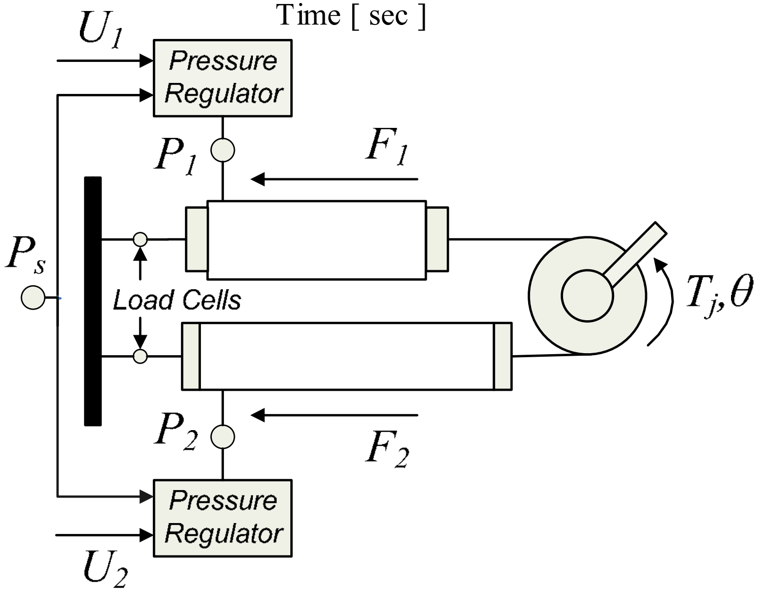
$S2.\rho$

$S2\rho$: Stanford Human-Safe Robot

$s2\rho$: Stanford Human-Safe Robot





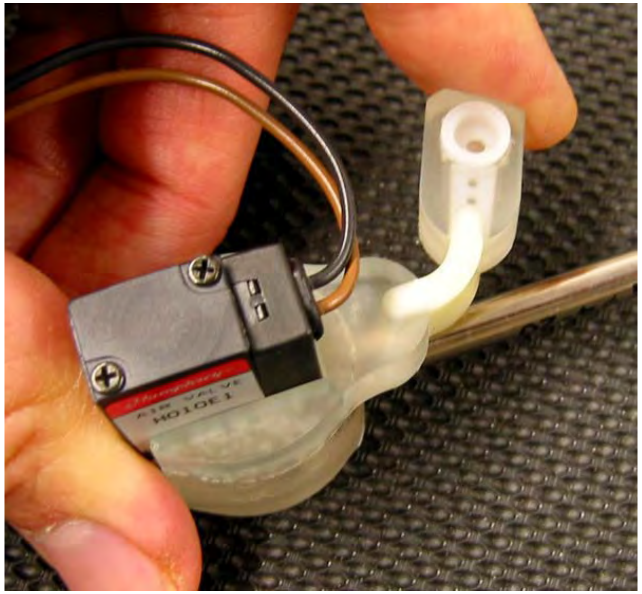


Macro……………0.5Hz

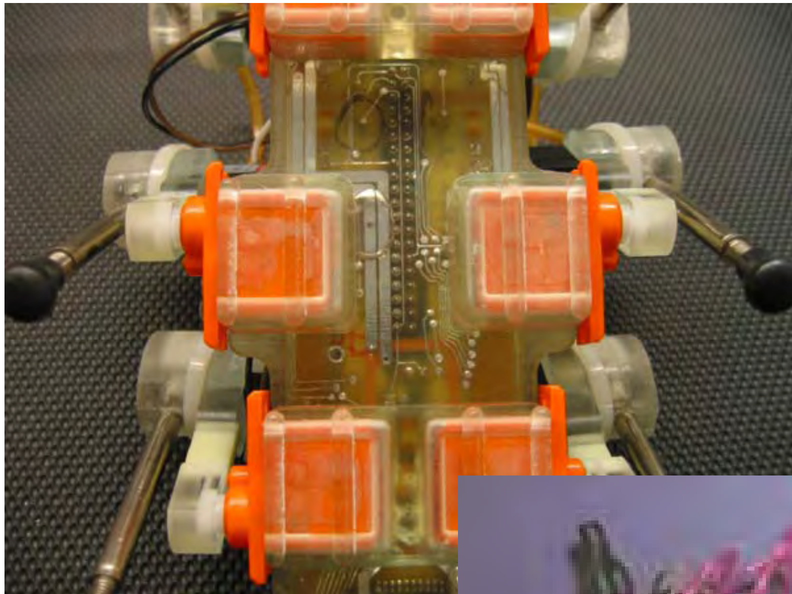
Macro/Tension 7.0Hz

Macro/Mini……. 35Hz

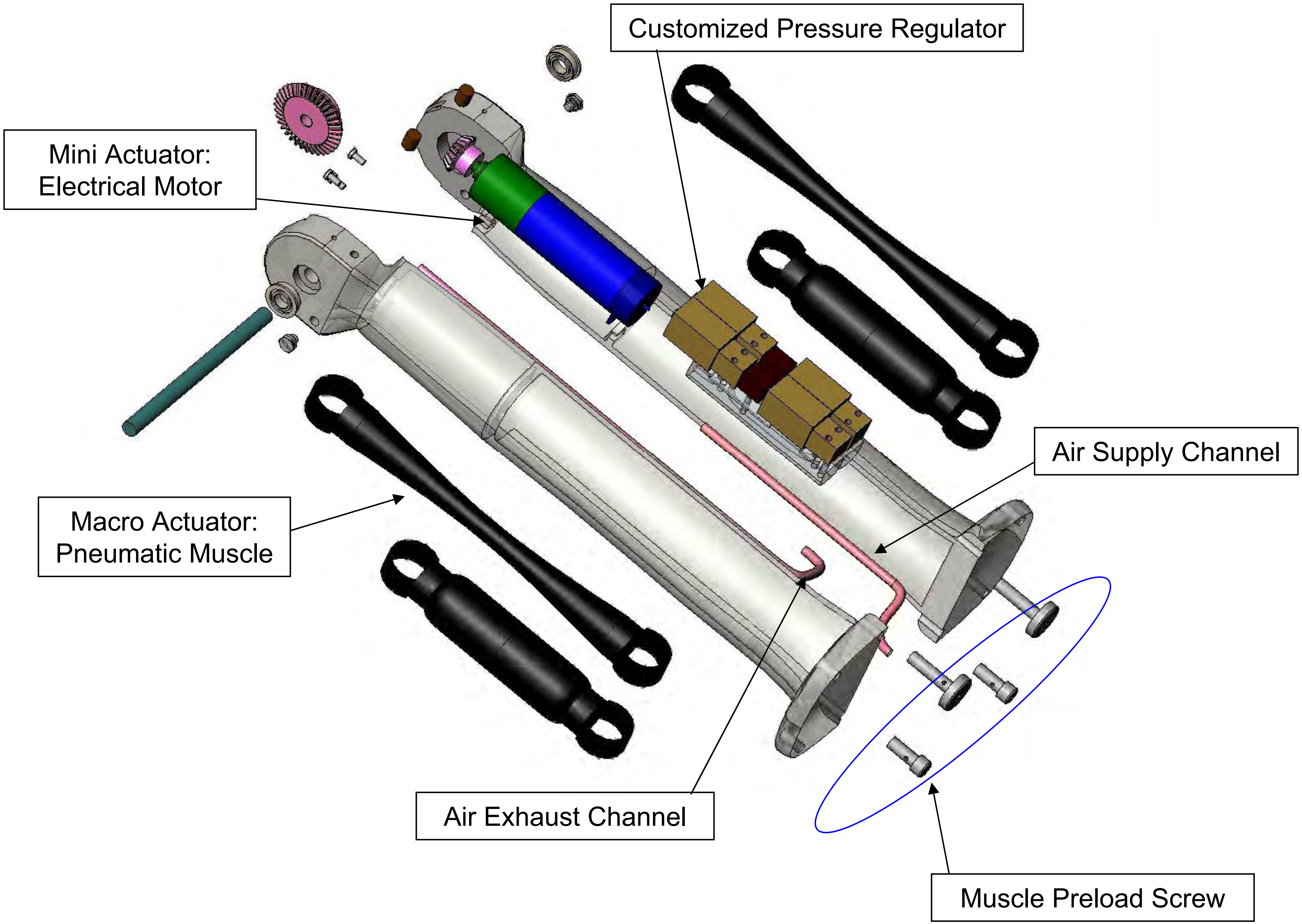
Shape Deposition Manufacturing



Multi-material molding

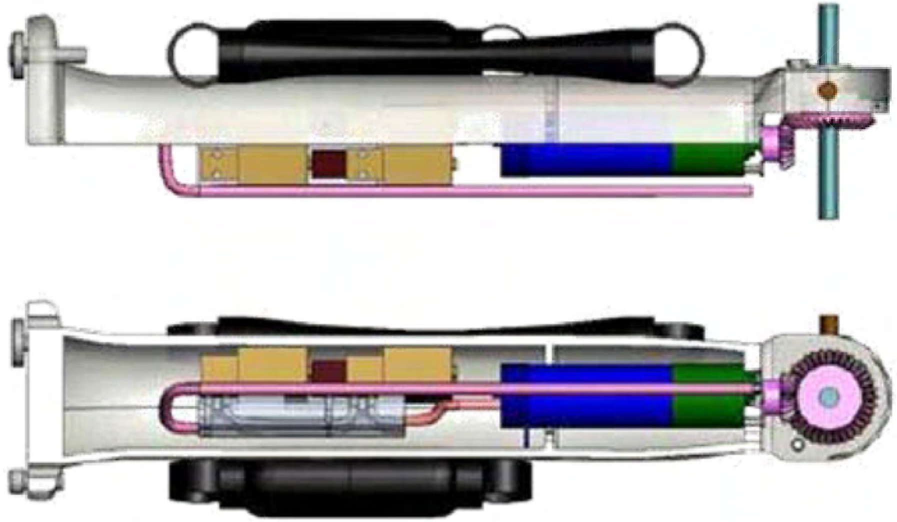


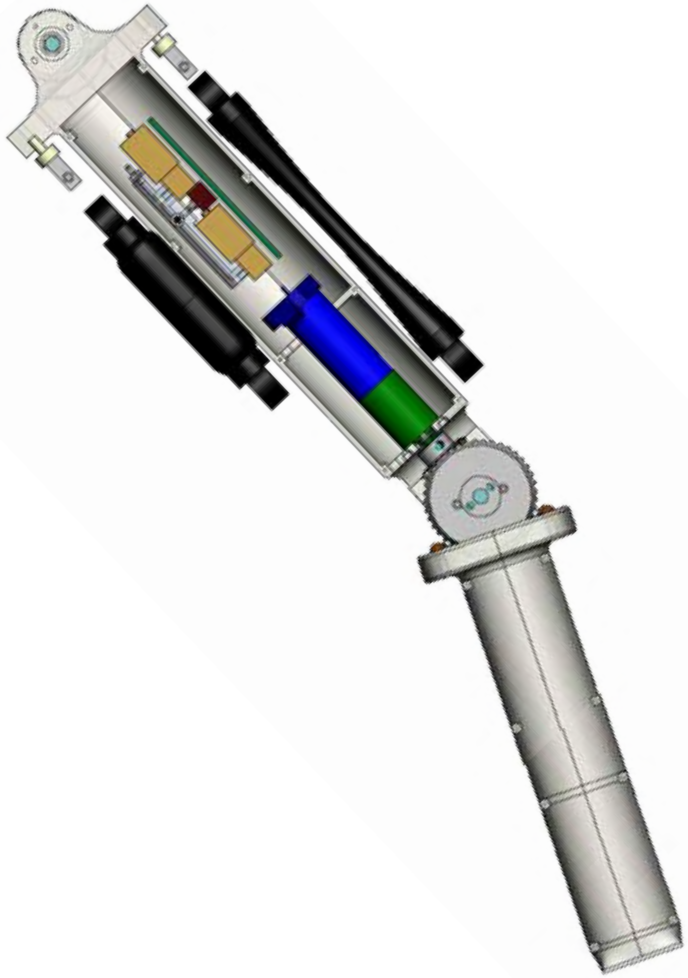
Component embedding



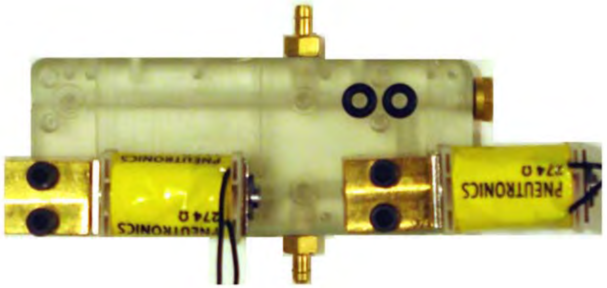
Customized Pressure Regulator
Mini Actuator:
Electrical Motor
Air Supply Channel
Macro Actuator:
Pneumatic Muscle
Air Exhaust Channel
Muscle Preload Screw

$s2\rho_{1.5}$: New Design





$S2\rho_{1.5}$: New Design



Safety Comparison

S2p

Effective Mass: 0.5Kg

DM²

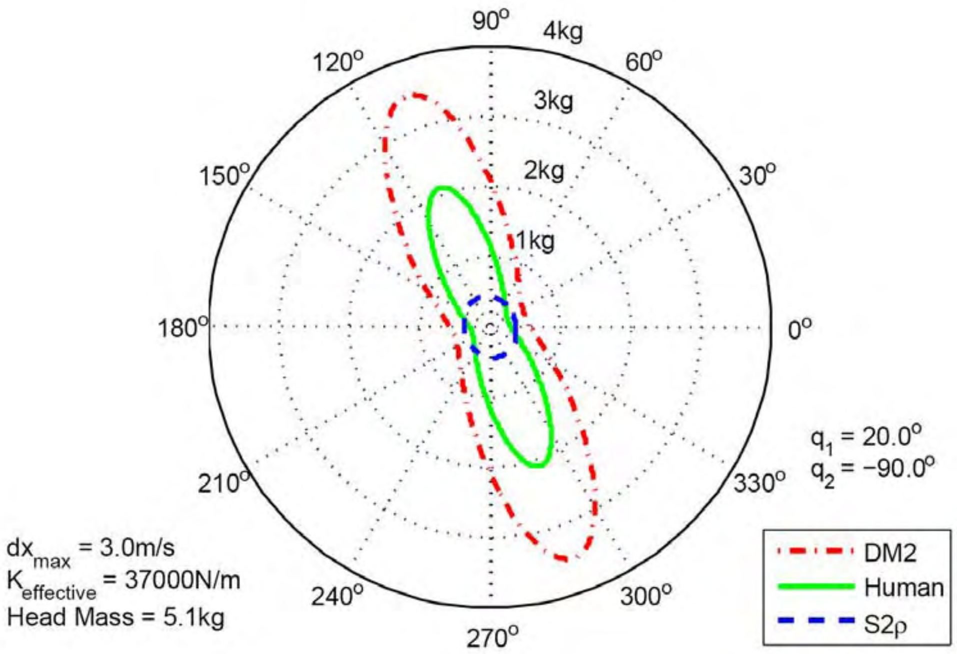
Effective Mass: 3.5Kg

Human

Effective Mass: 2.1Kg

PUMA560

Effective Mass: 25Kg



Safety Comparison

S2p(payload: 33.33N)

Normalized Effective Mass: 0.015

DM² (Payload 60N)

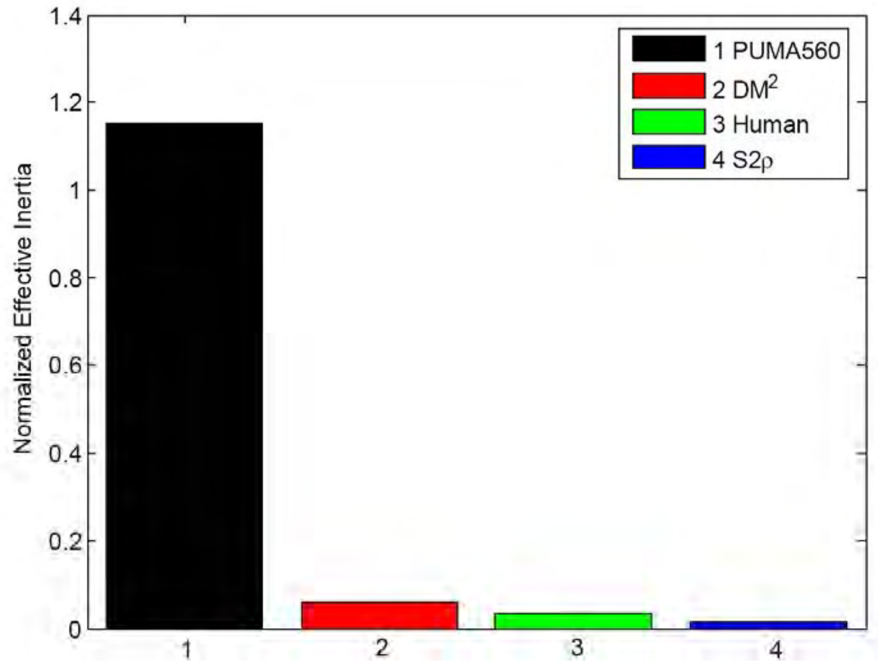
Normalized Effective Mass: 0.058

Human (Payload 62N)

Normalized Effective Mass: 0.034

PUMA560 (Payload 21.56N)

Normalized Effective Mass: 1.154



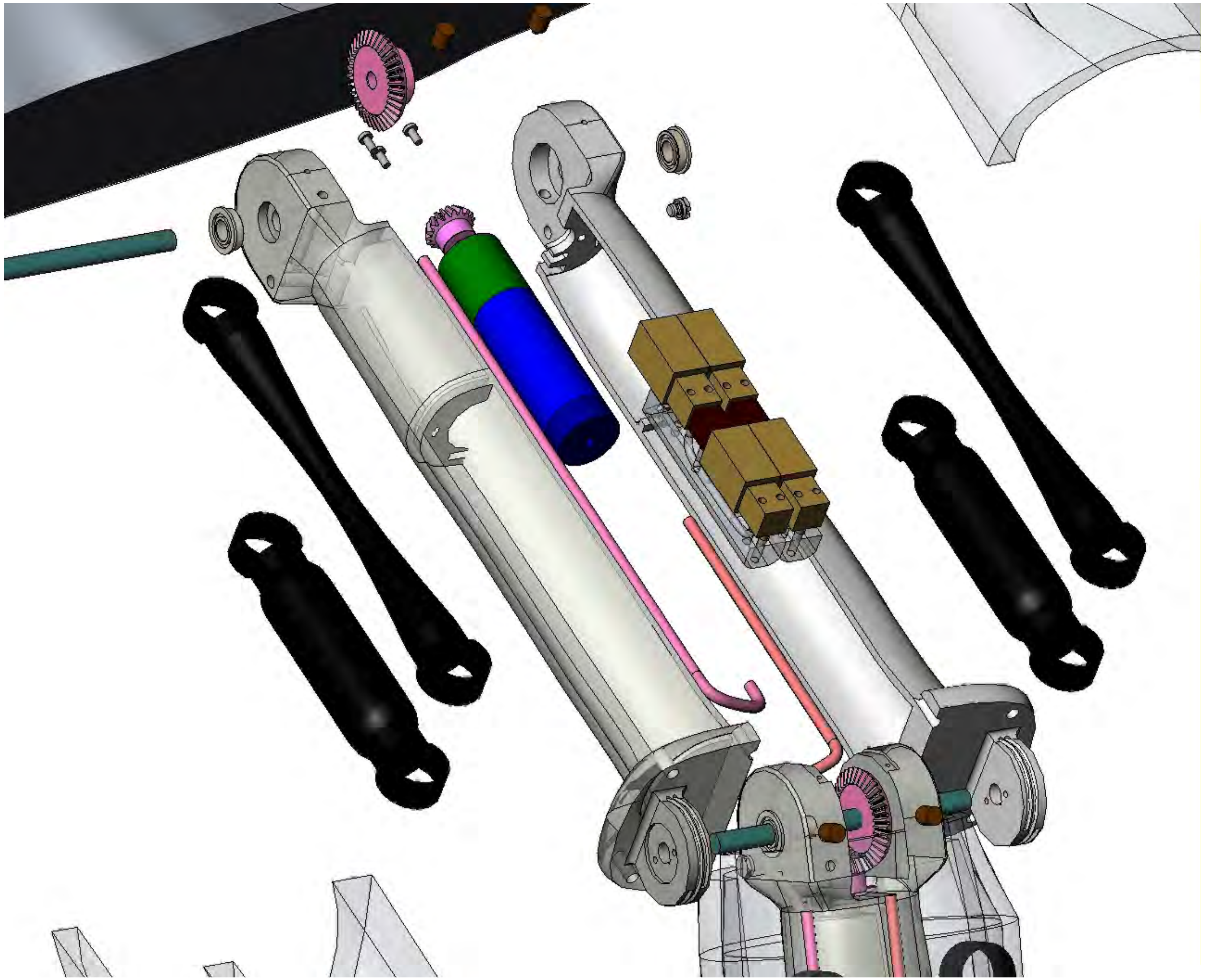
Simulation Condition

Impact velocity: 3 m/s (= 10.8 Km/h)

Stiffness between human and robot: 37000 N/m

Head mass: 5.1kg (mean mass of U.S male)

$s2\rho$: Stanford Human-Safe Robot



The Challenge

Sensing and Perception

real-time, unstructured world

Planning and Control

many degrees of freedom

human-like skills, learning

Human-Robot Interaction

cognitive and physical

Mechanisms and Actuation

Safety & Performance

Interactivity & Human-Friendly

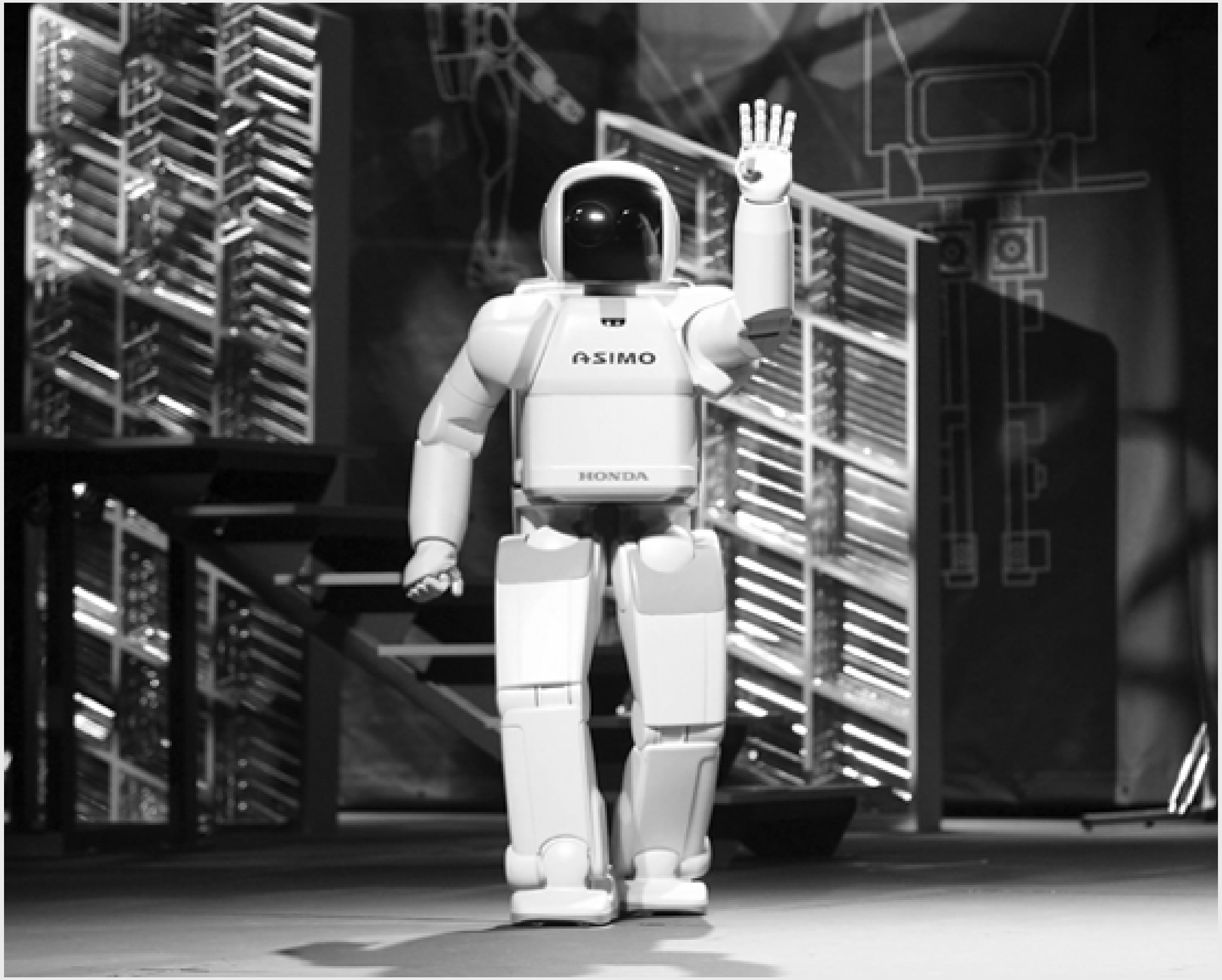
Stanford Robotic Platforms

Romeo & Juliet (1993)

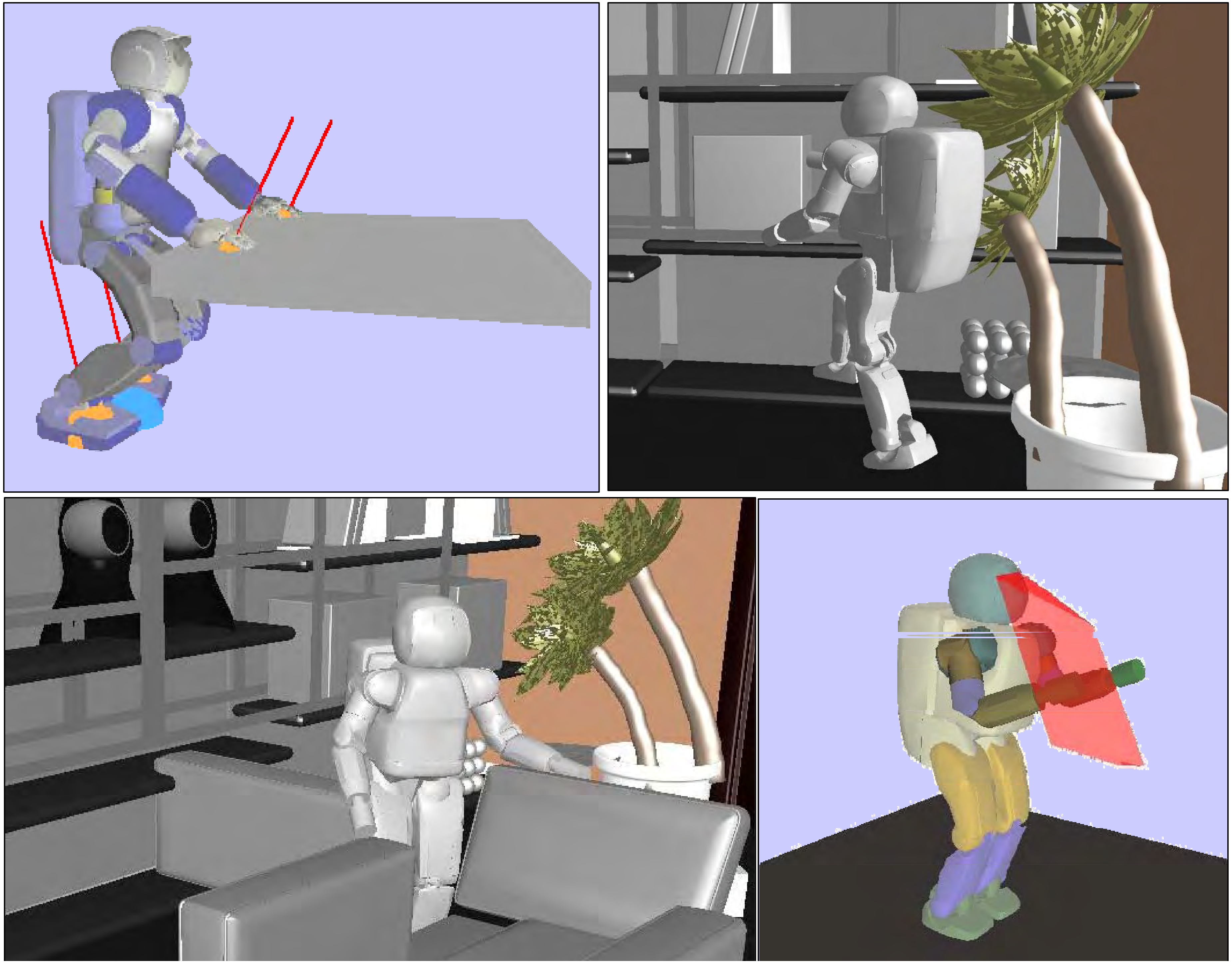
Mobile Manipulation

Human Guided Motion & Human-Robot Interaction

Stanford Robotic Platforms - Romeo & Juliet (1993)



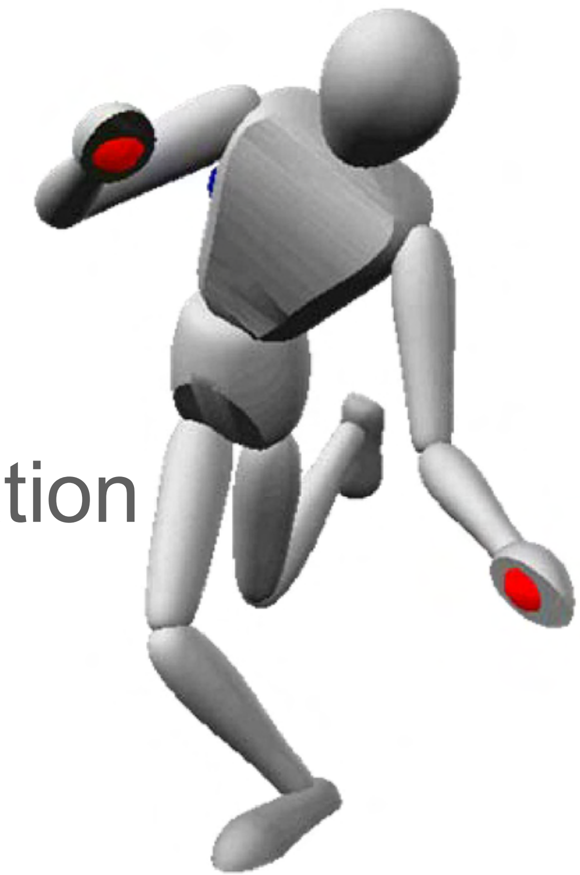
ASIMO

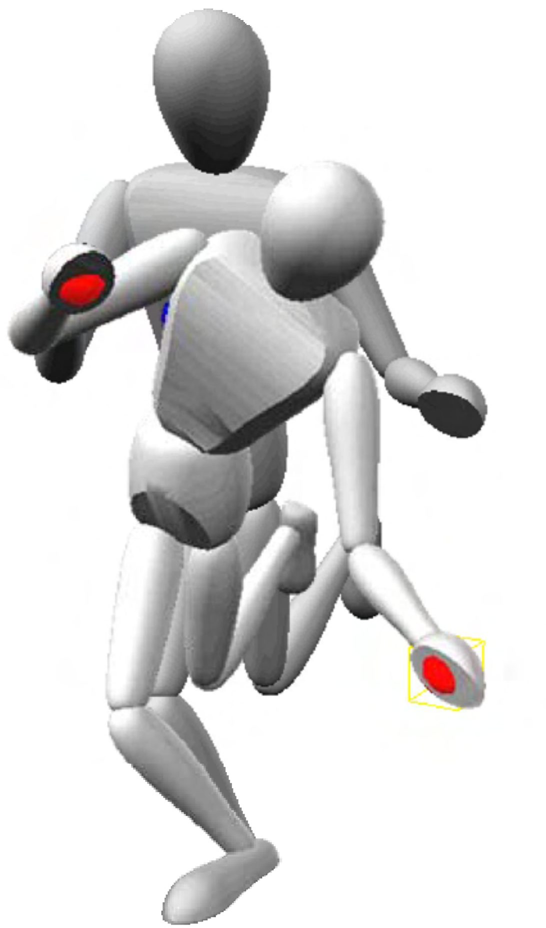


Humanoid Robot Control

branching and under-actuated

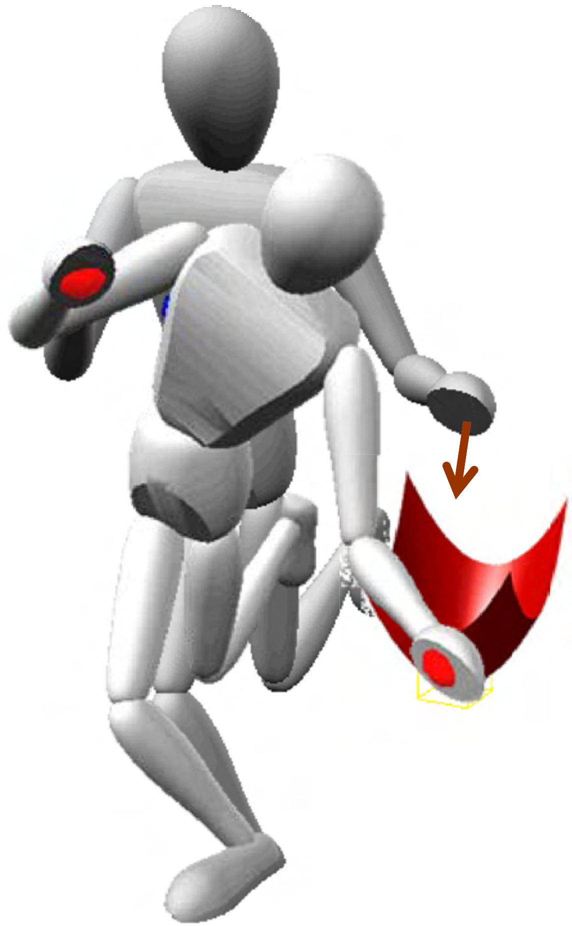
- Whole-body control strategies
- Constraints and Multi-contacts
- Balance, Locomotion, & Manipulation





Joint motions

Inverse Kinematics



Human-like

Artificial Energy

Whole-body Control

Task & Posture Decomposition

Task Dynamics and Control

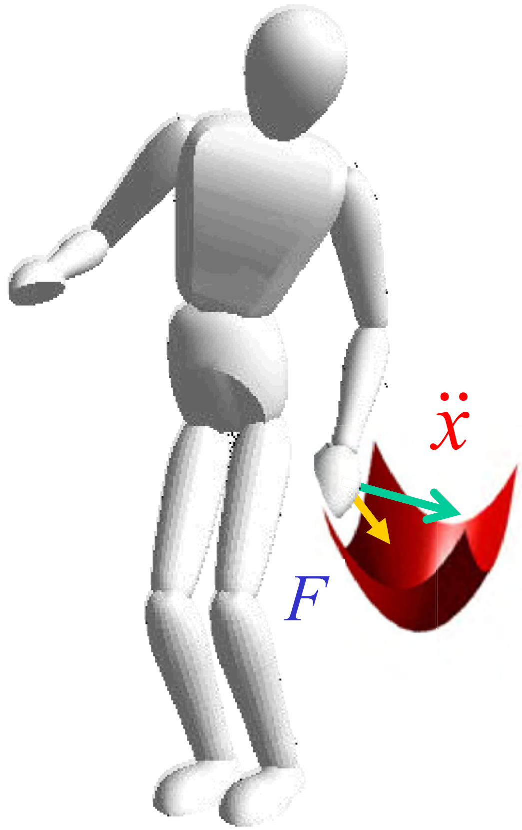
Task Dynamics

$$\Lambda \ddot{x} + \mu + p = F$$

Task Control

$$F = \hat{\Lambda}(-\nabla V_{Task}) + \hat{\mu} + \hat{p}$$

$$\Gamma = J^T F$$



Task Dynamics – Branching Structures

$$x = \begin{pmatrix} x_1 \\ x_2 \\ \cdot \\ x_m \end{pmatrix}$$

$$\Lambda = \begin{pmatrix} \Lambda_{11} \ \Lambda_{12} \ldots \Lambda_{1L} \\ \Lambda_{21} \ \Lambda_{22} \ldots \Lambda_{2L} \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \Lambda_{L1} \ \Lambda_{L2} \ldots \Lambda_{LL} \end{pmatrix}$$

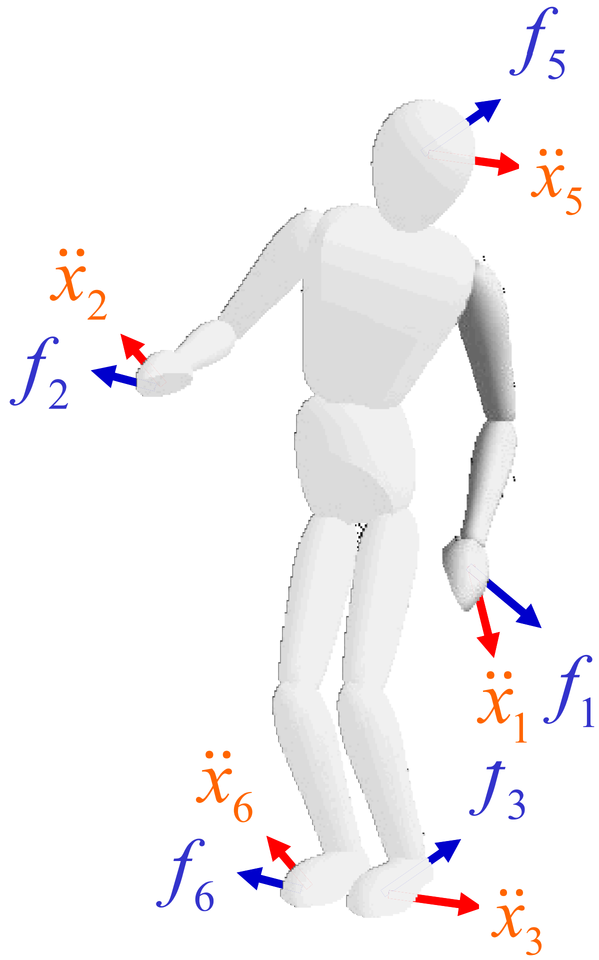
$$x \Rightarrow J \Rightarrow \Lambda$$

Dynamics

$$\Lambda \ddot{x} + \mu + p = F$$

Control

$$F = \hat{\Lambda} F^*_{Task} + \hat{\mu} + \hat{p}$$



Task/Posture Control Structure

Decomposition in torque space

$$\Gamma = J_{task}^{T} F_{task} + N_{task}^{T} \Gamma_{posture}$$

Task Torques: $\Gamma_{task} = J_{task}^{T} F_{task}$

Task Consistent Posture Torques:

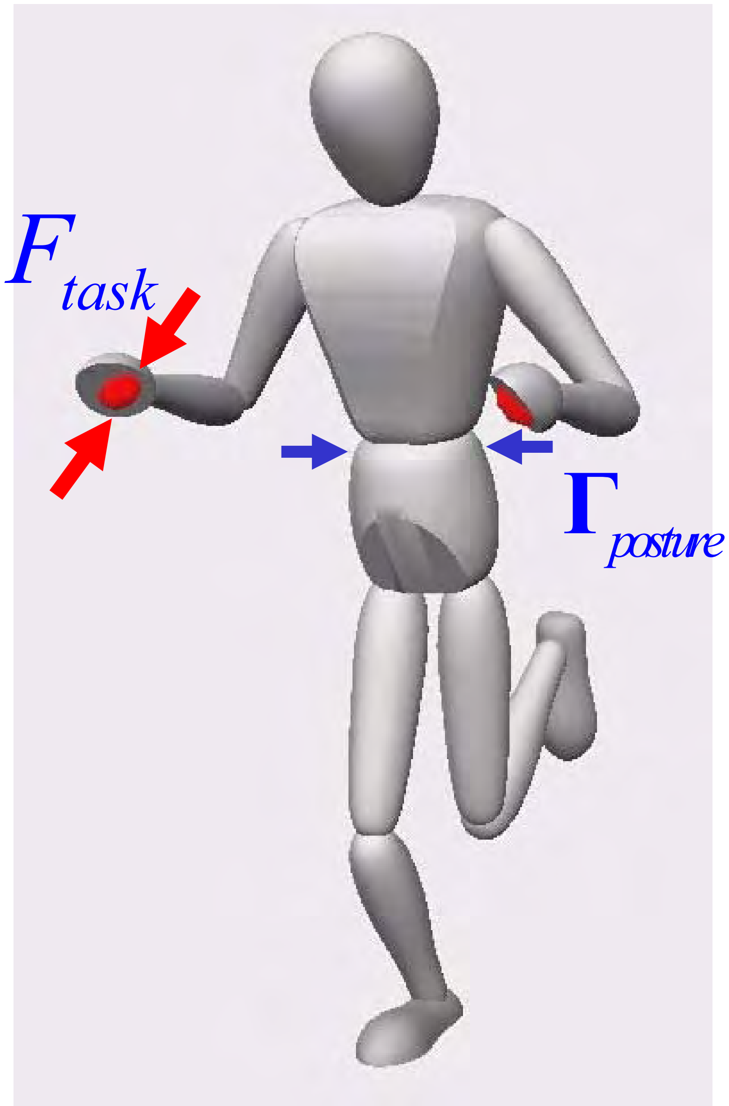
$$\Gamma_{posture|task} = N_{task}^{T} \Gamma_{posture}$$

Dynamic Consistency:

$$N_{task}^{T} \Gamma_{posture} \Rightarrow \boxed{\ddot{x}_{task} = 0}$$

in configuration space

$$\delta q = \bar{J}_{task} \delta x_{task} + N_{task} \delta q_{posture}$$



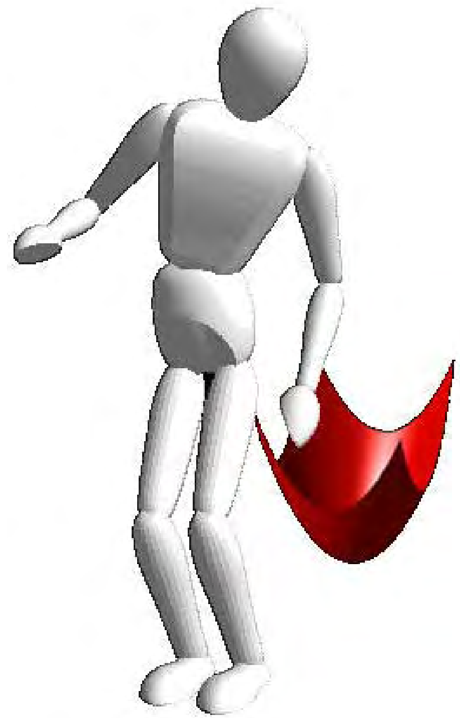
Task and Posture Control

Whole-body Control

- Task Field
- Posture Field

Dynamically Decoupled

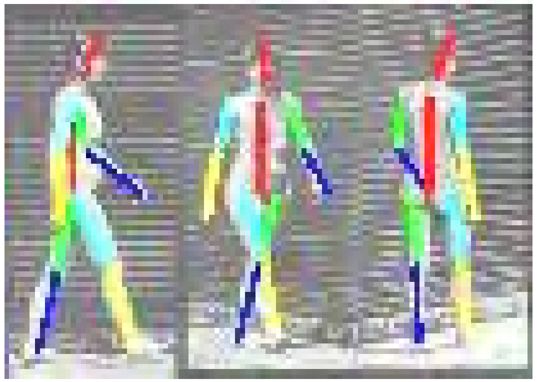
$\Longrightarrow$ no joint trajectories



Learning from the human

Posture Field?

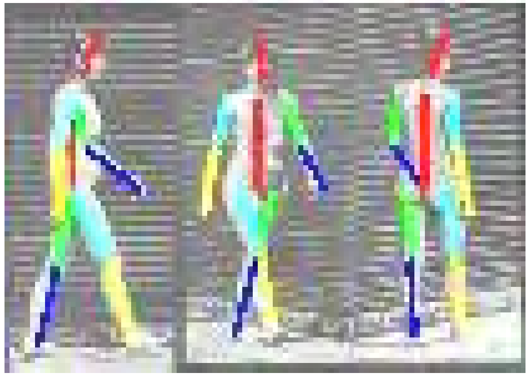
Human Natural Motion



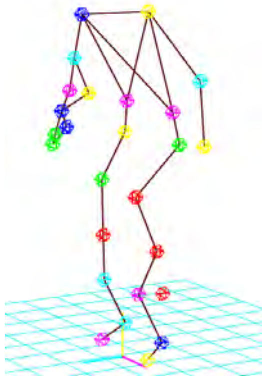
Motion Capture

Motion Characteristics

Human Motion Characterization



Human motion

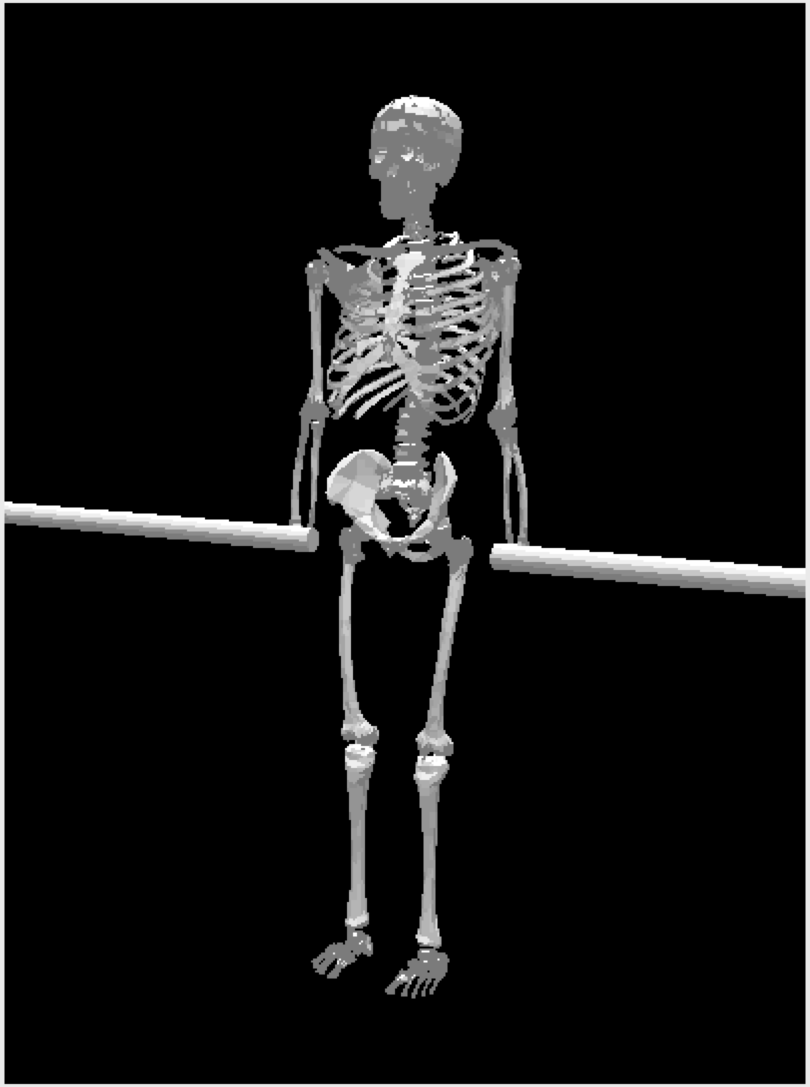


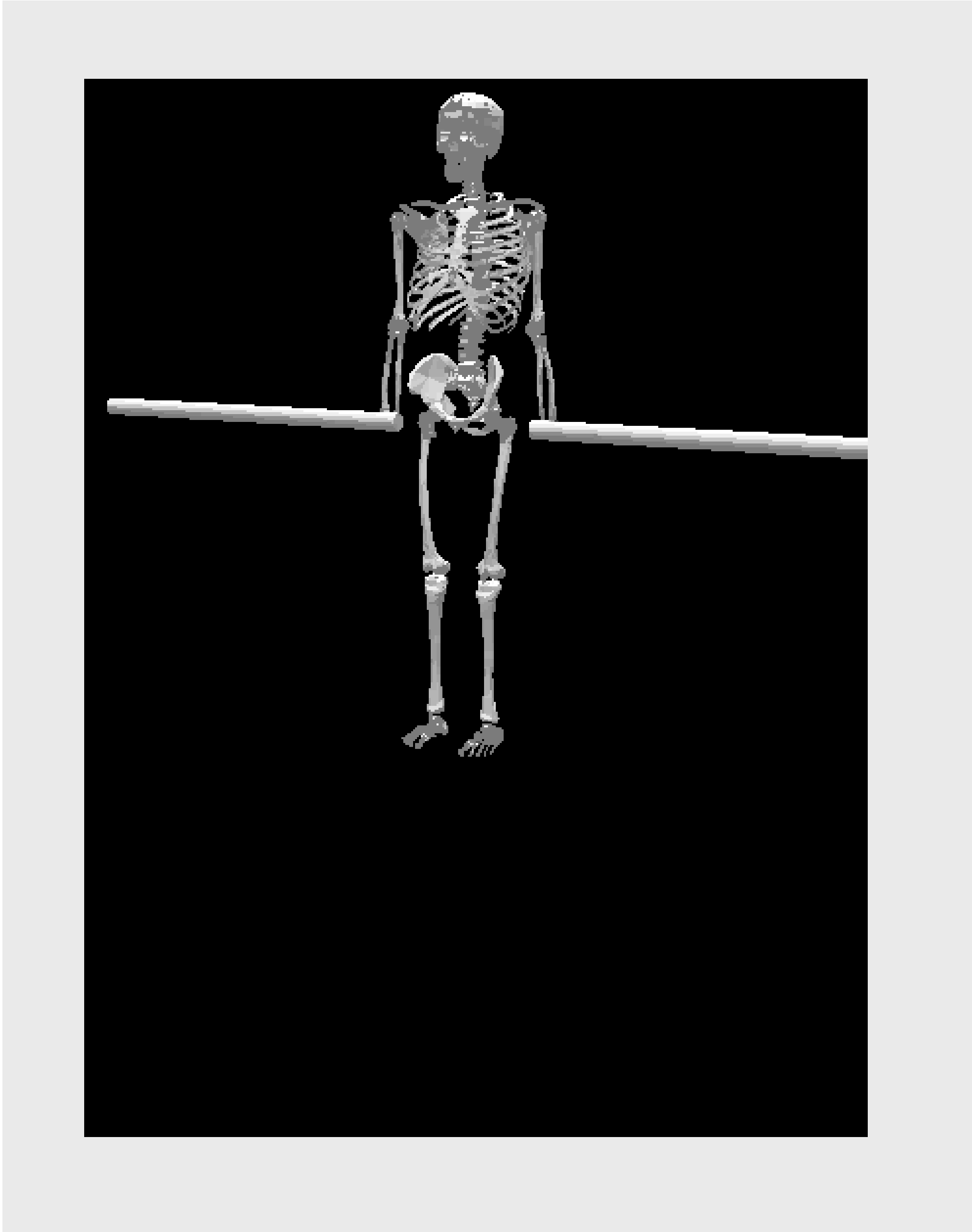
Marker data

Skeletal physiology

Muscular physiology

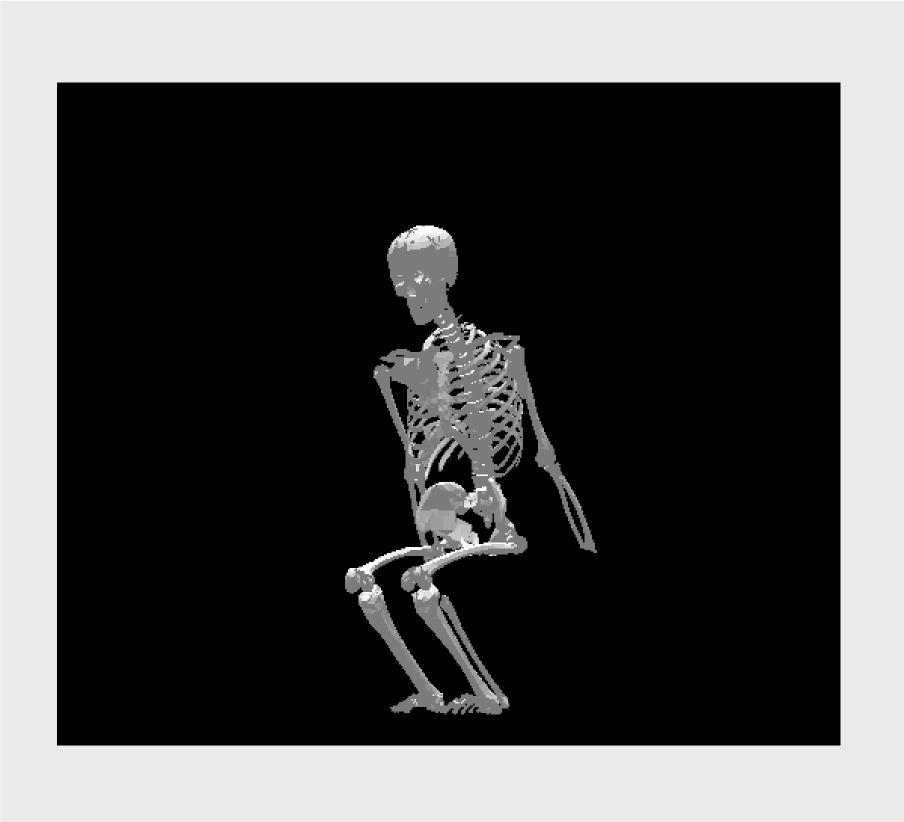
Human Motion Capture ⇒ Human Dynamic Model



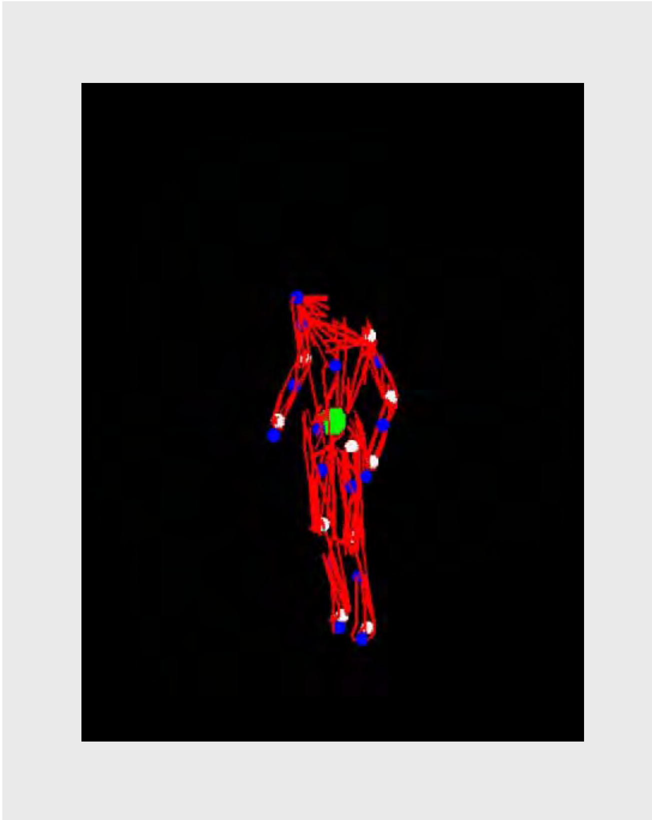


Simulation 79 DOF and 136 Muscles

Biometric Data & Bone Geometry



Dynamic simulation



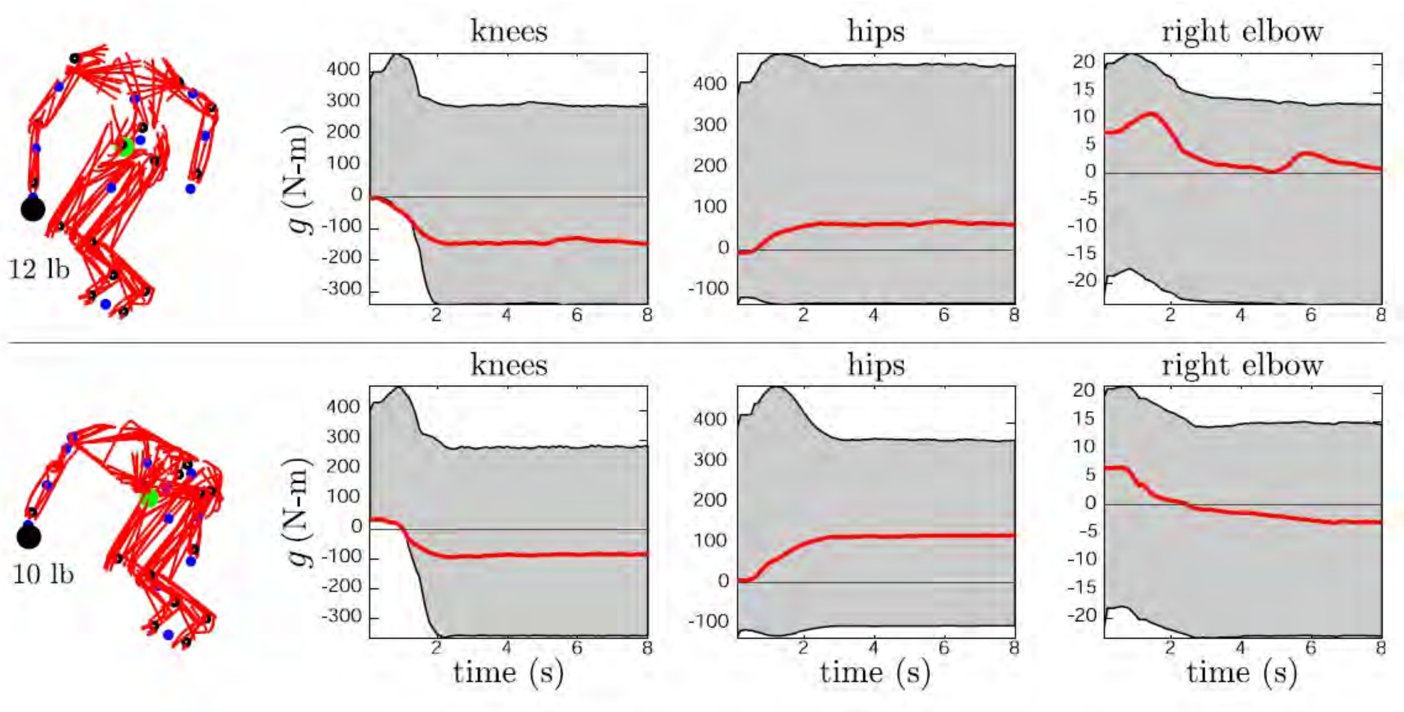
Motion capture

Learning from the Human

In learned tasks, humans minimize muscular effort, under physical and "social" constraints

➡ Physiology-based Posture Field

Physiology-based Posture Field



A Task, *F*: $\Gamma = J^T F$

Muscle actuation: $\Gamma = L^T m$

Muscle capacities: N_c → Configuration-dependent torque bounds

Physiology-based Posture Field

Human posture is adjusted to reduce muscular effort

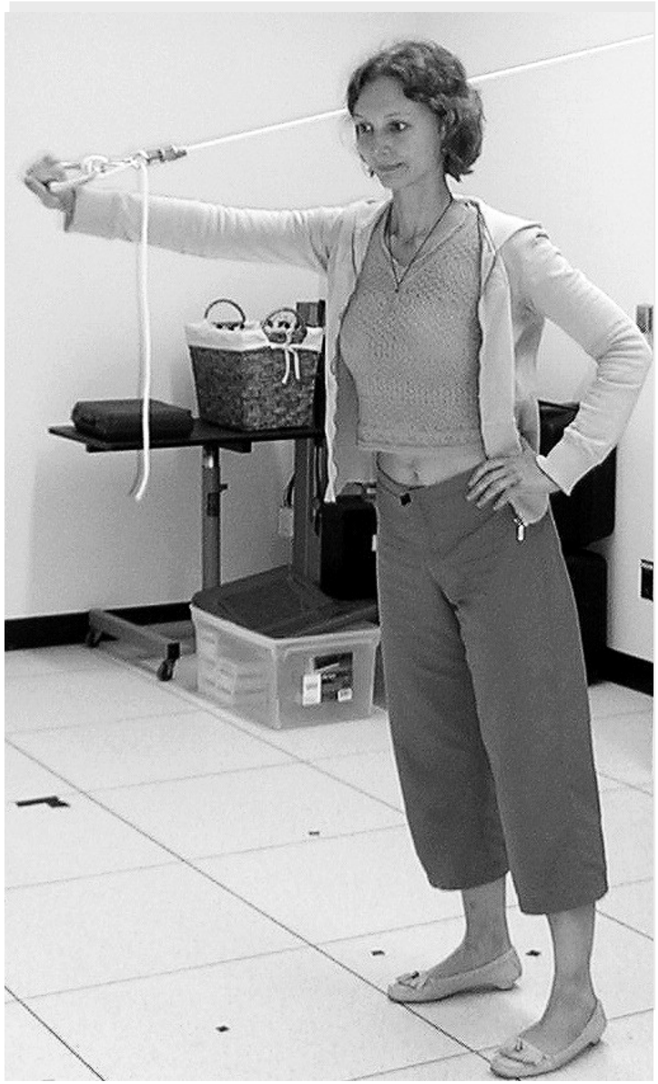
Human-muscular Energy minimized:

$$\boxed{E = c m^2}$$

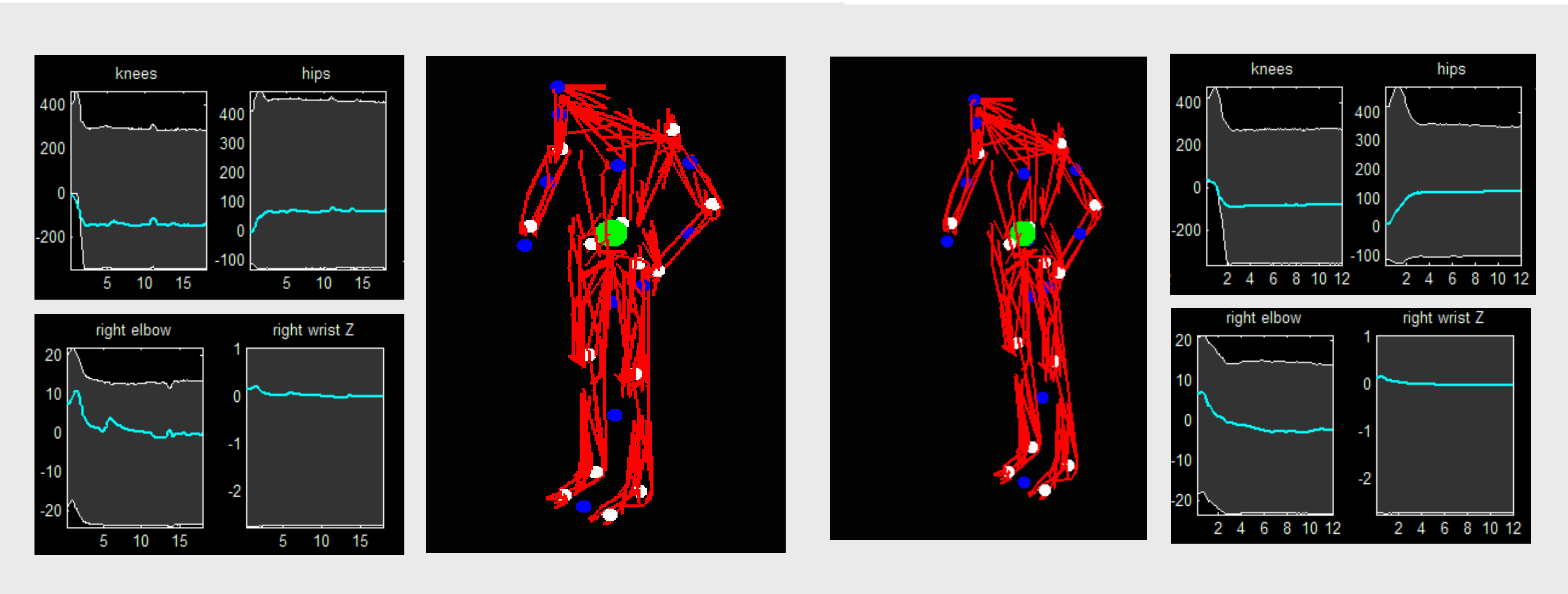
Function of physiology, mechanical advantage, and task

$$E(q) = F^T [J (L^T N_c^{-2} L)^{-1} J^T] F$$

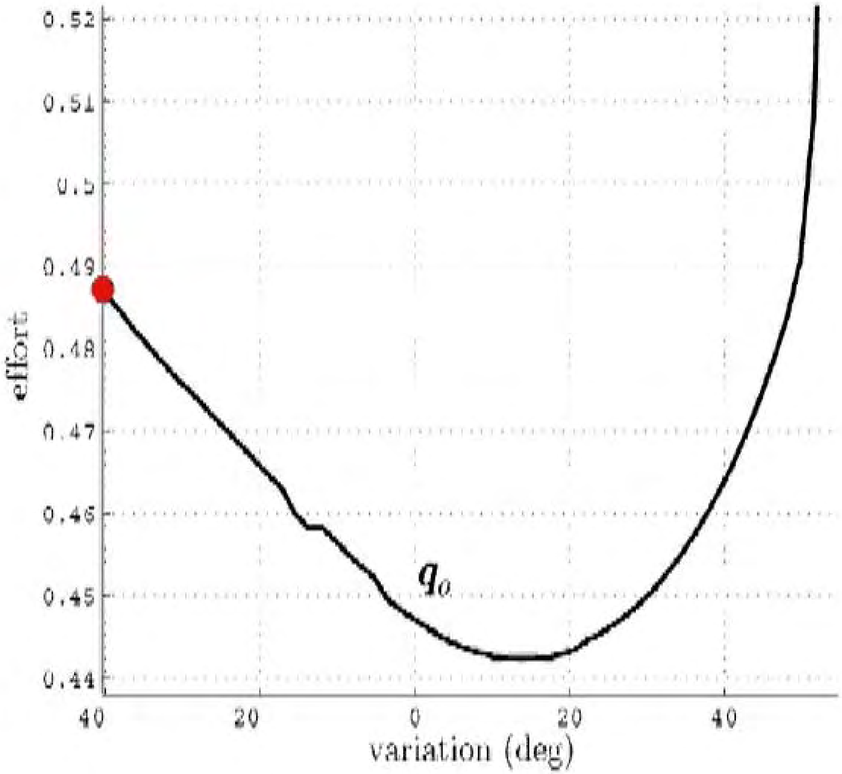
Data from Subjects



Data from Subjects

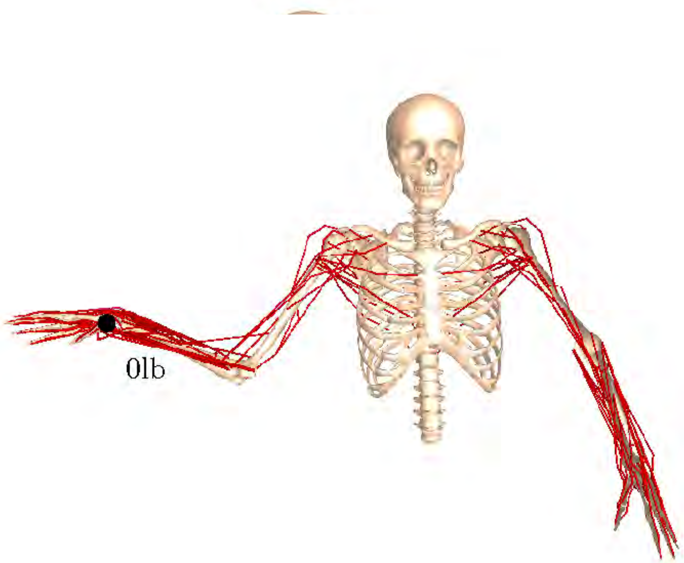


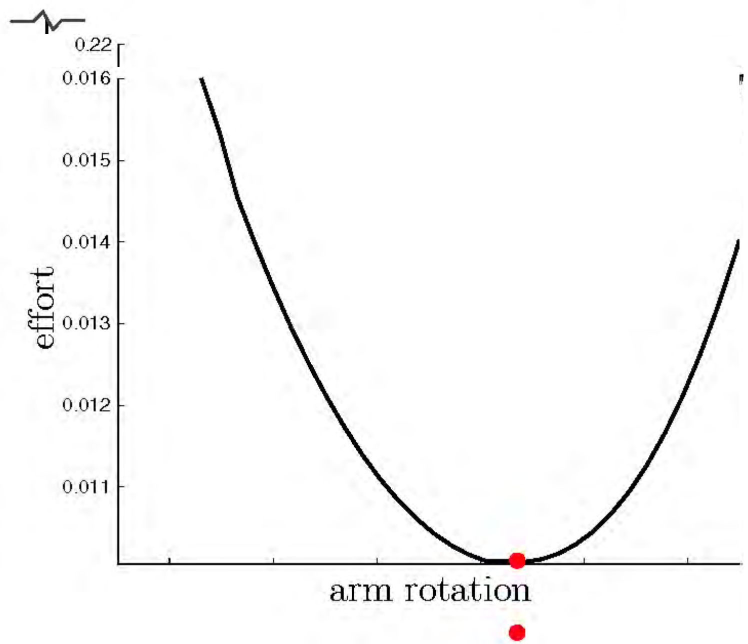
Validation - Arm Effort



$$E = cm^2$$

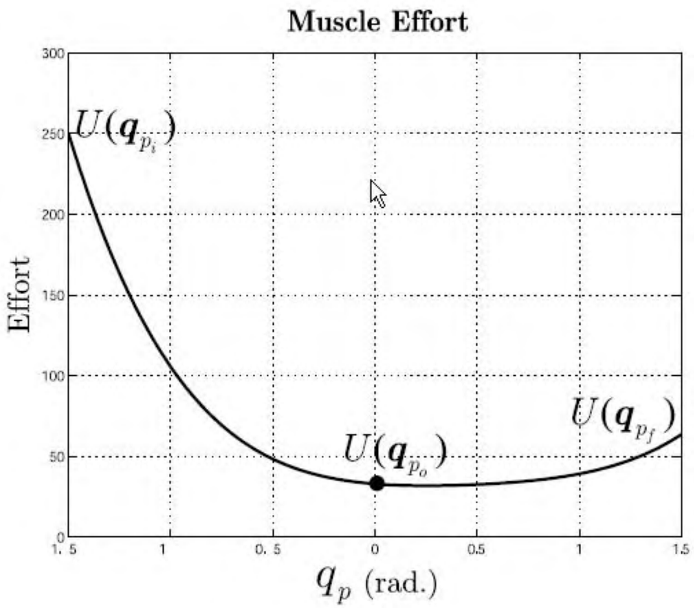
Validation - Arm Effort

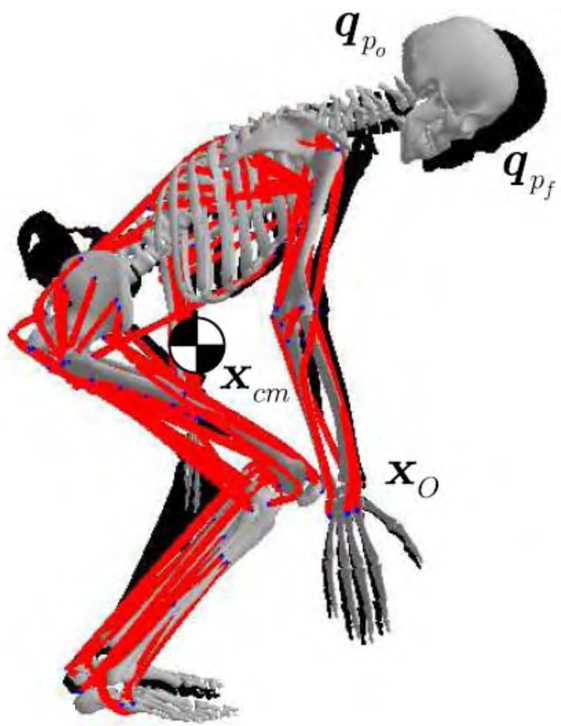




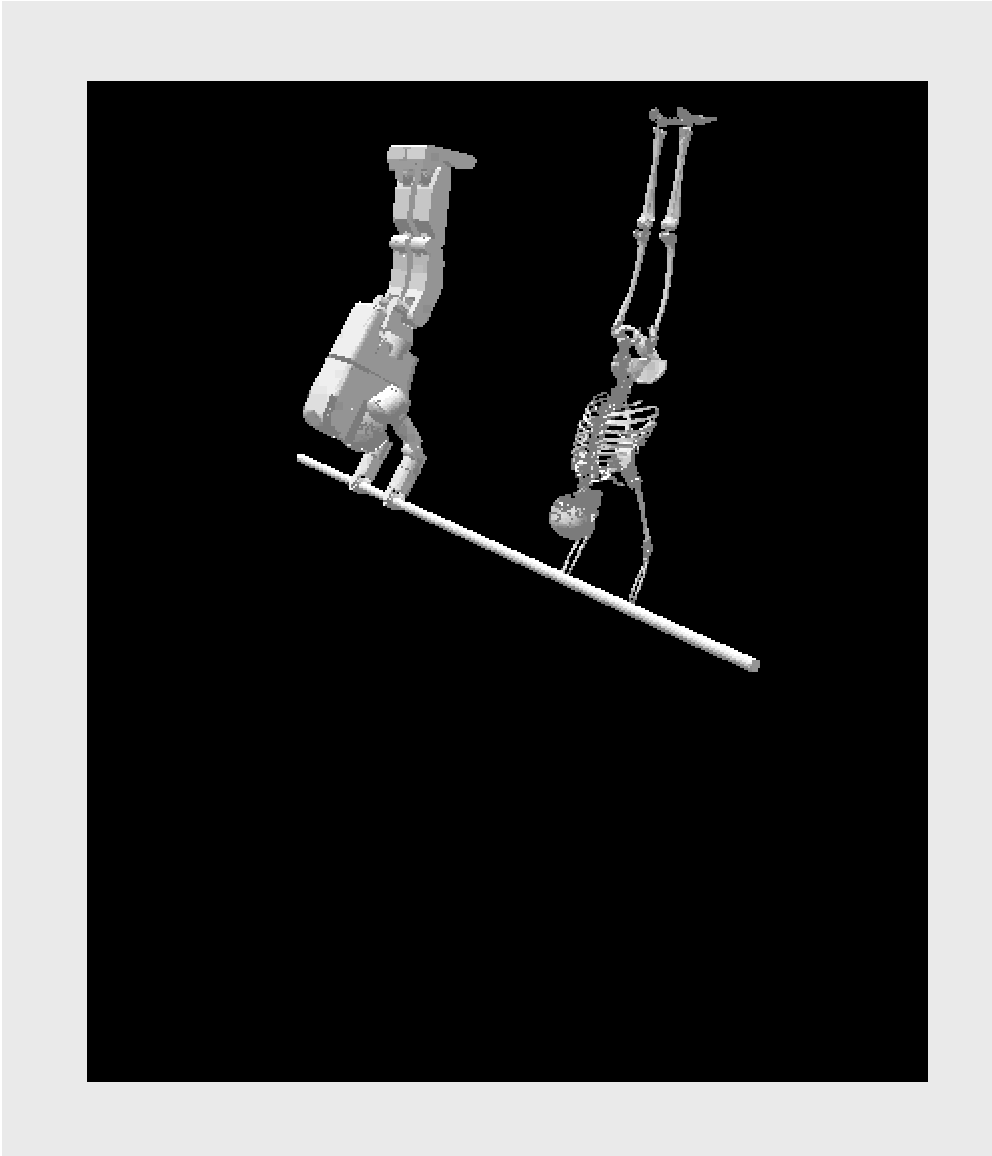
$$E = cm^2$$

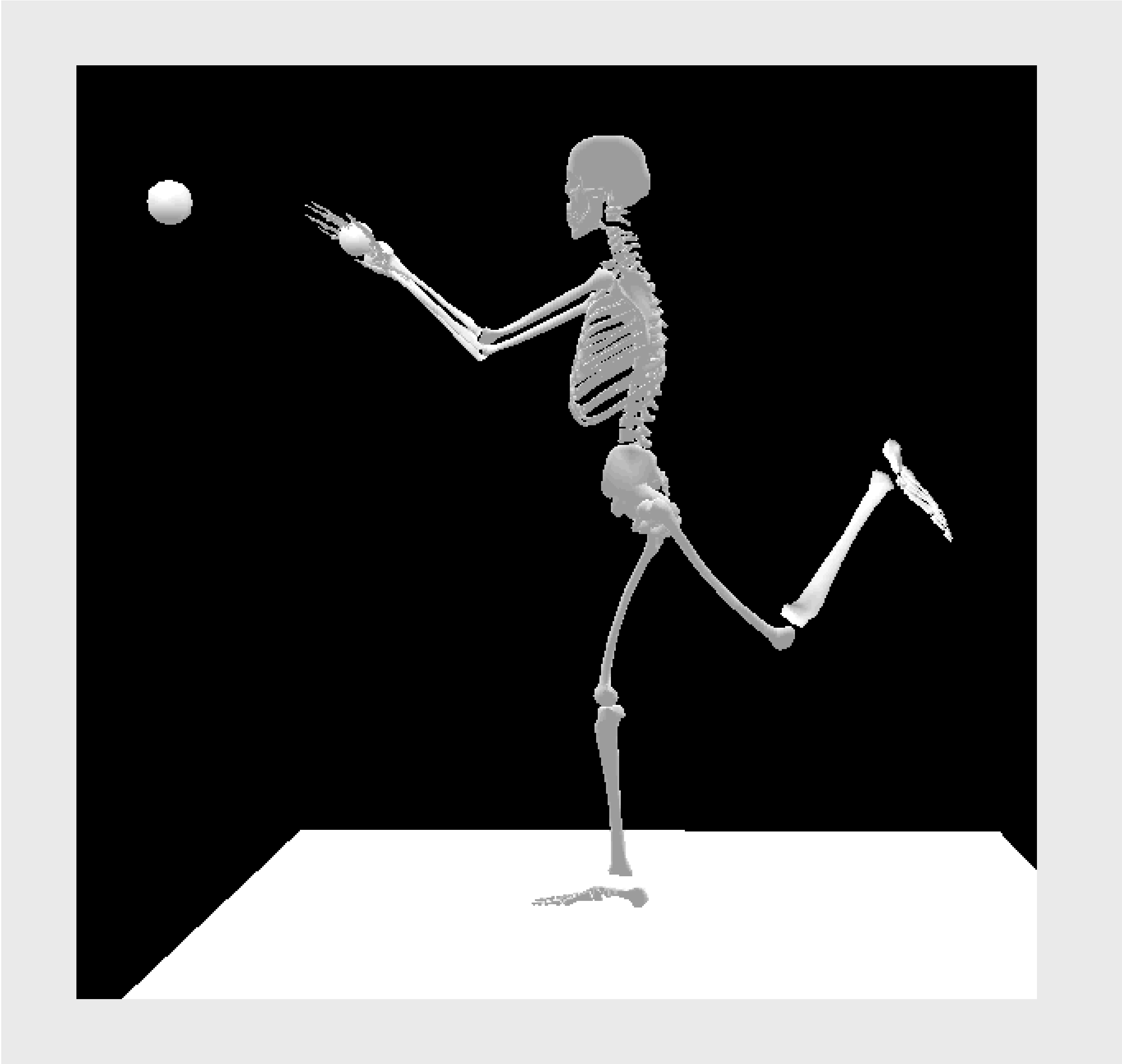
Validation – whole-body effort

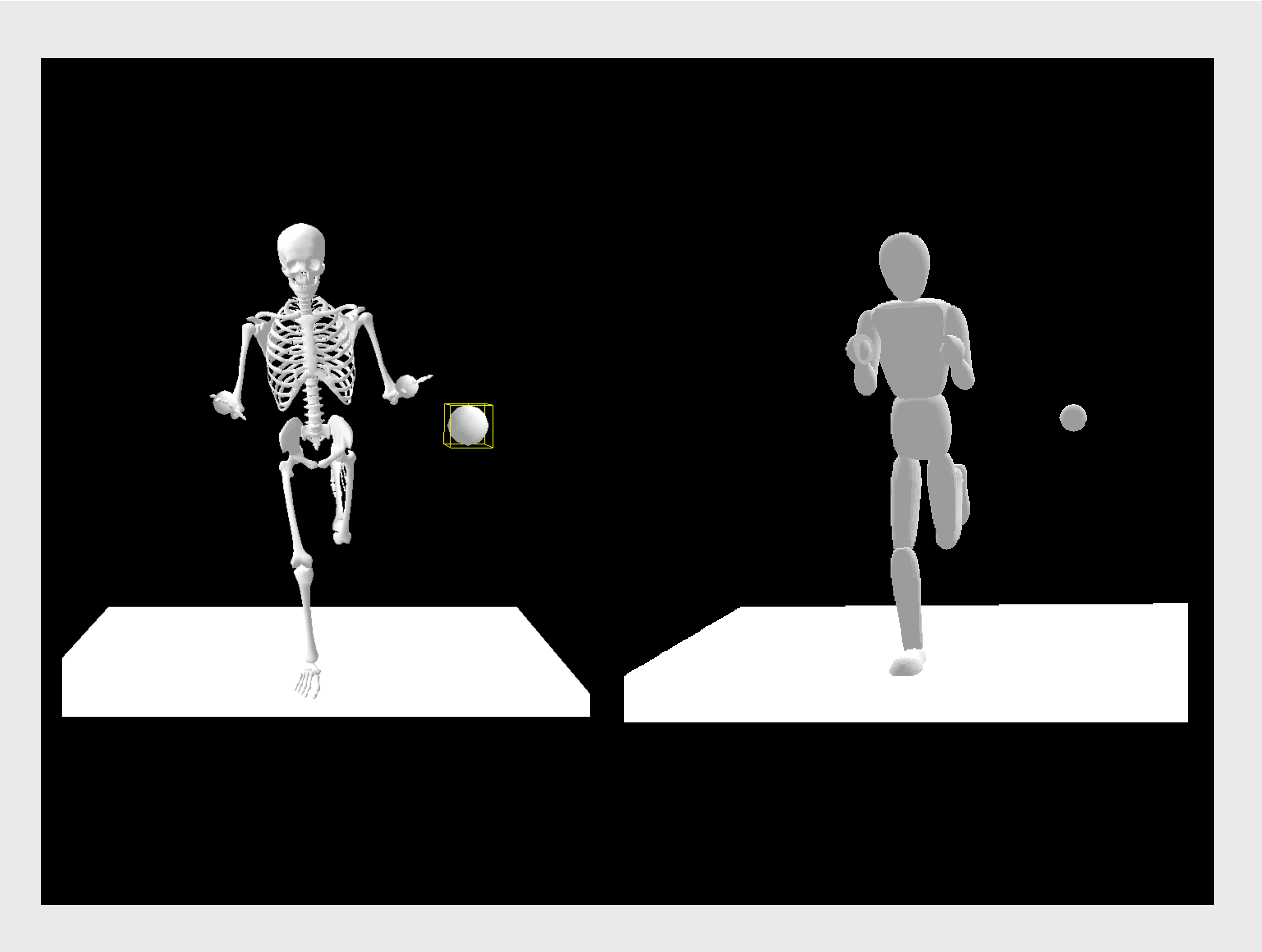


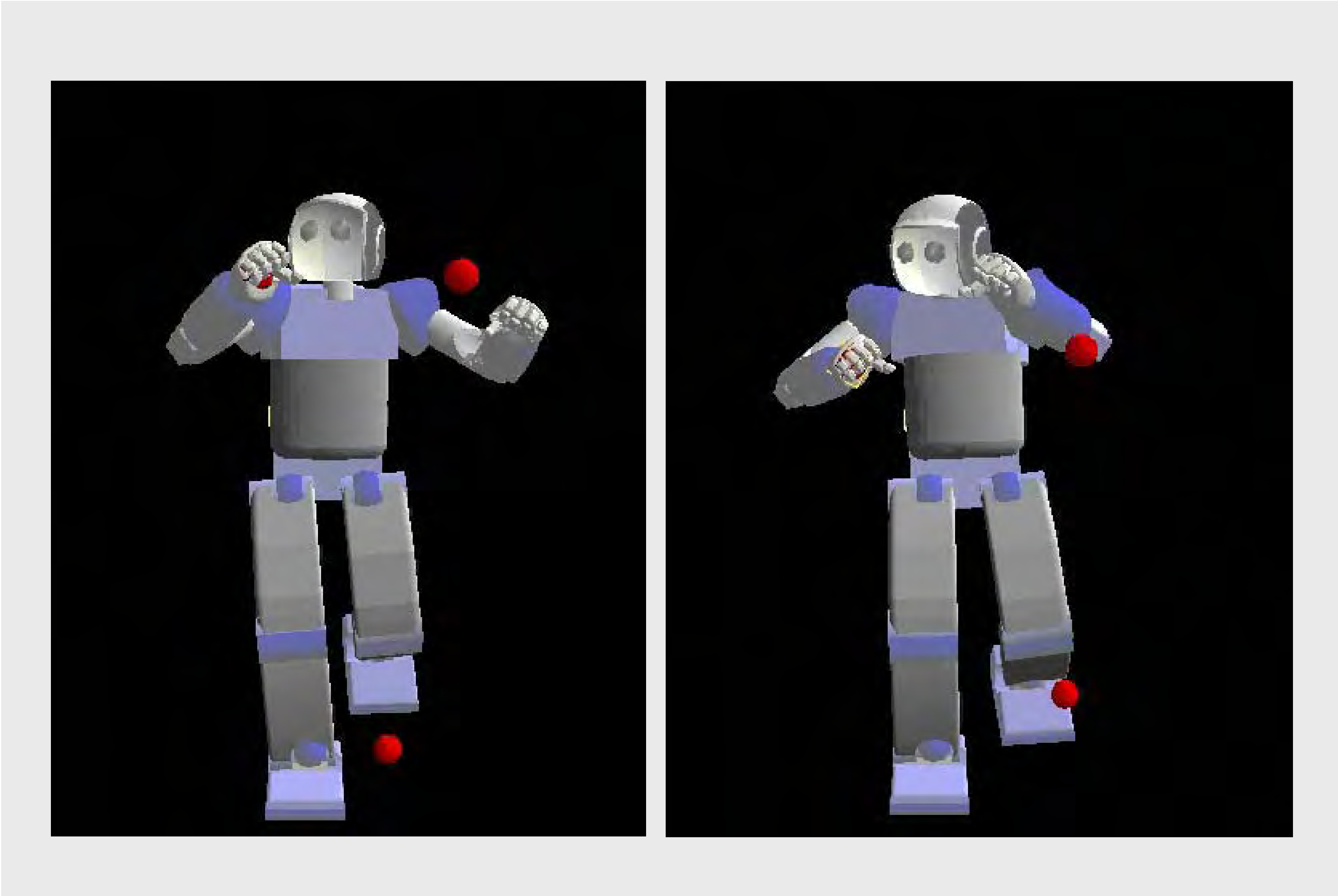


$$E = cm^2$$





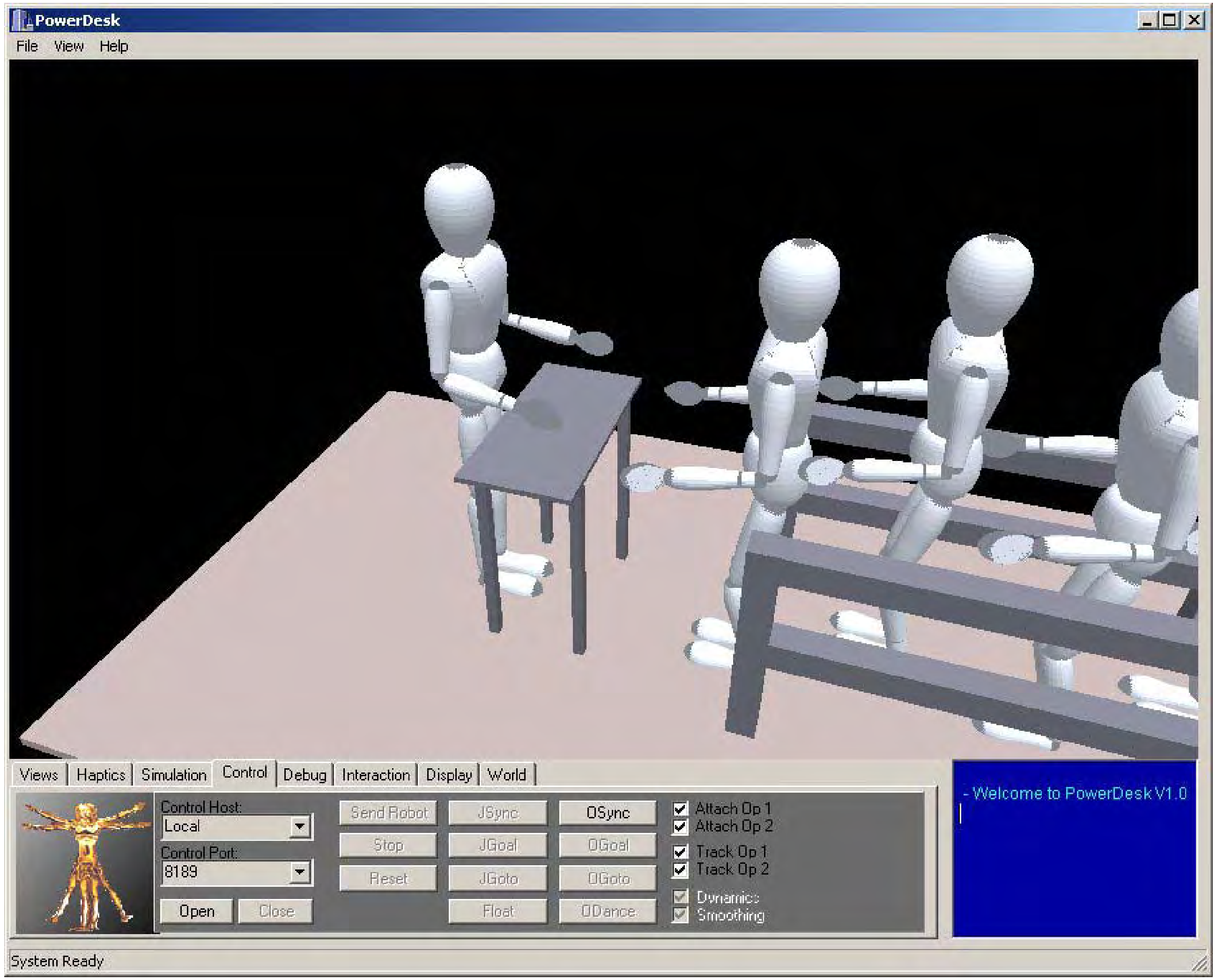




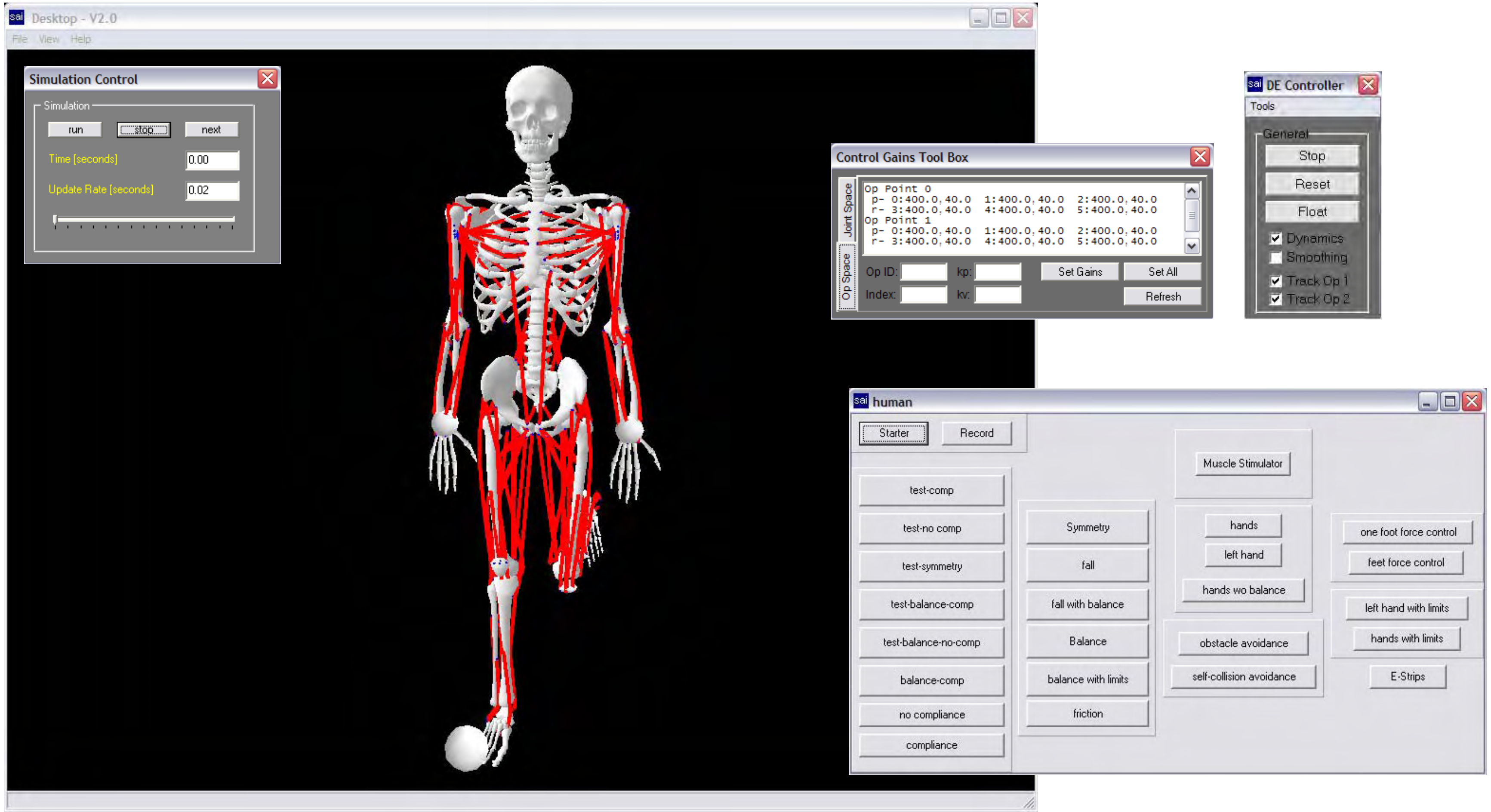
ASMIO

SAI Environment

Dynamic simulation, control, & haptics

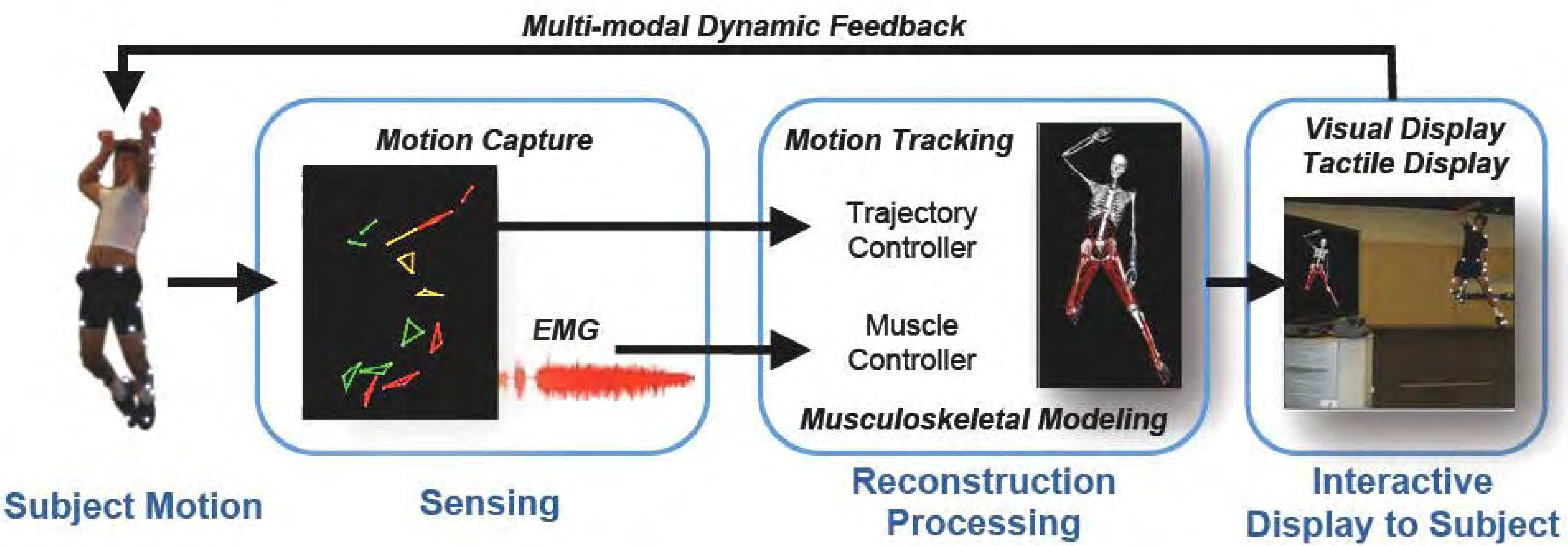


SAI Neuromuscular Library



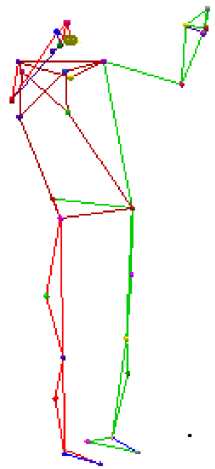
Human Motion Reconstruction

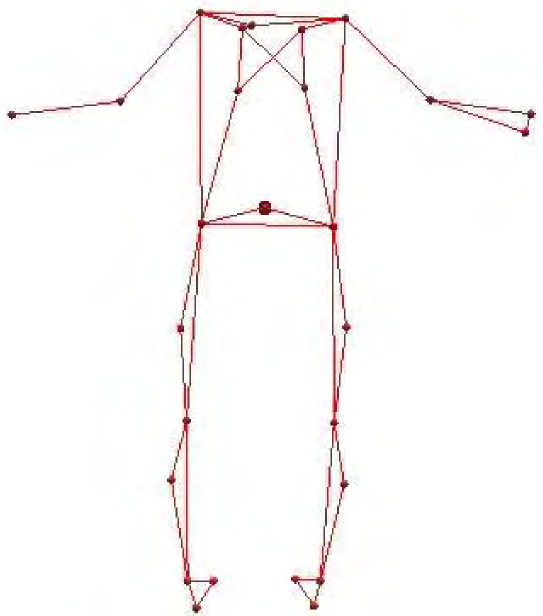
Injury prevention, Pathology Evaluation, and Athletics

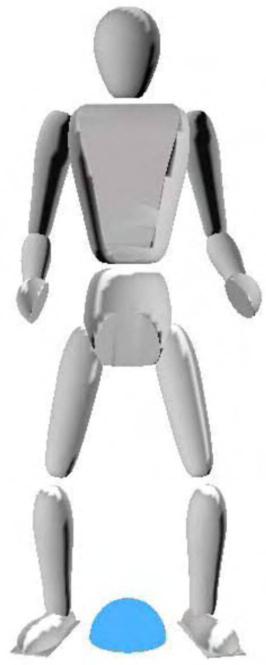


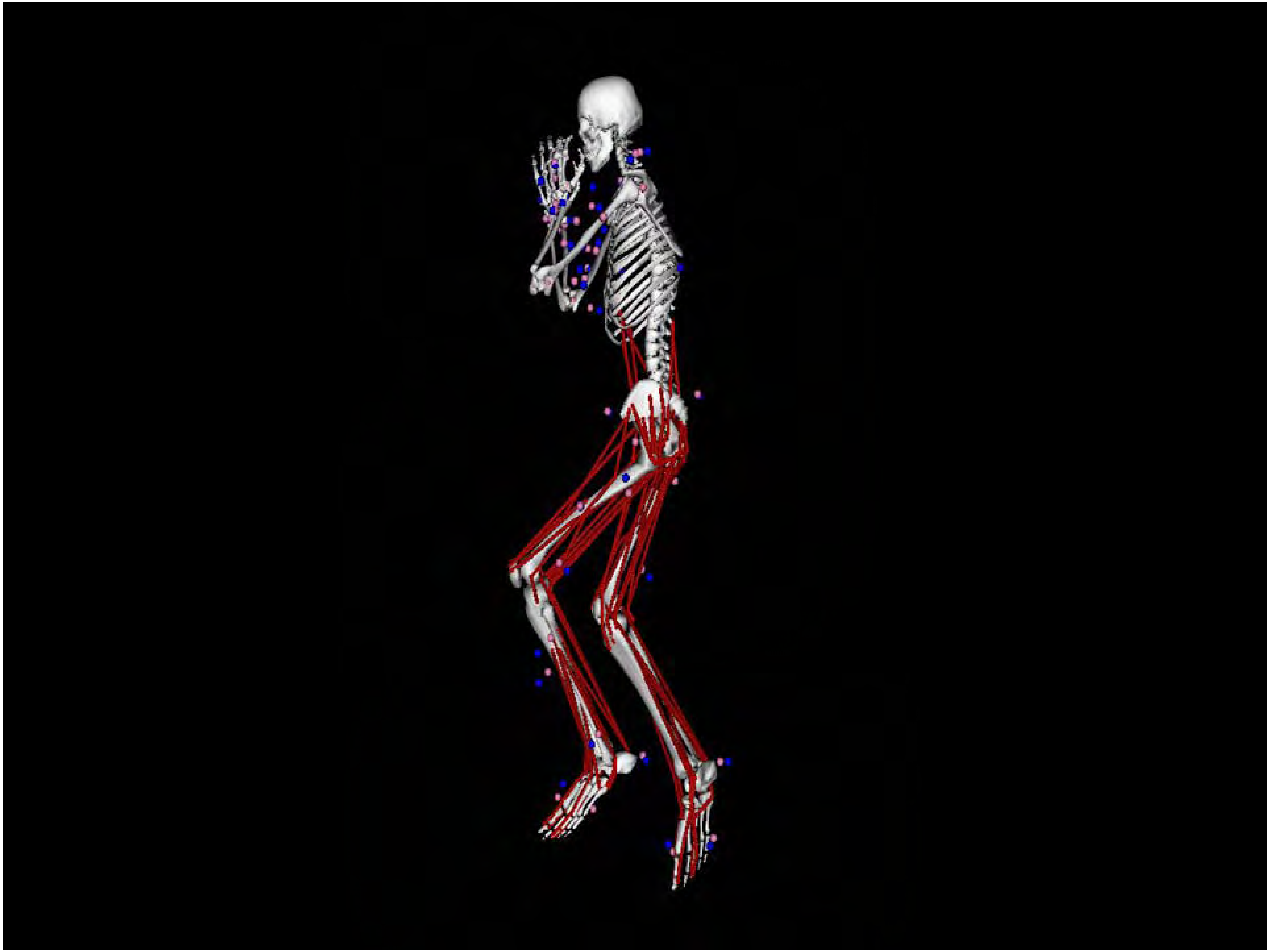
Skill Learning – Tai Chi

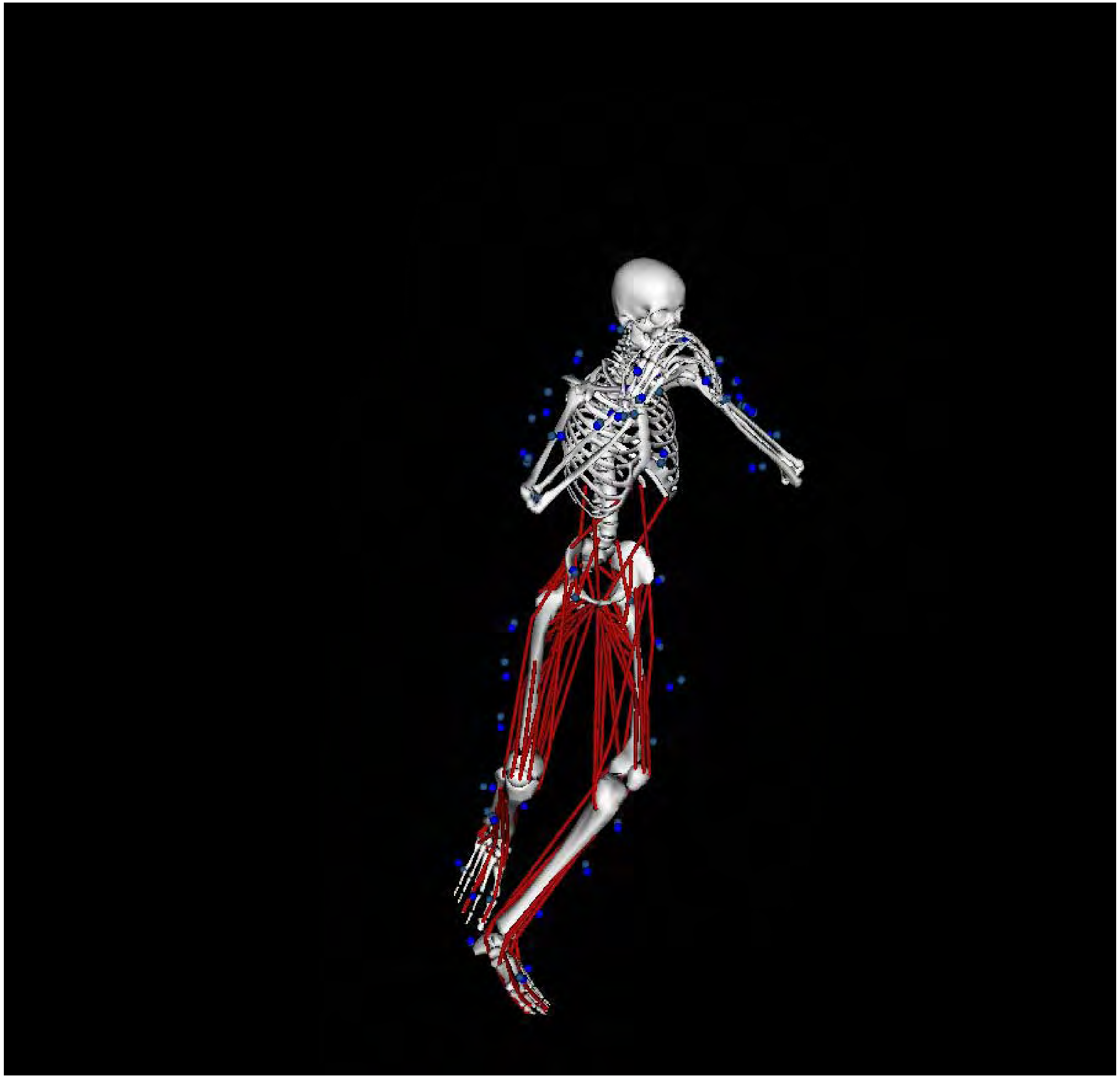
Skill Learning – Tai Chi



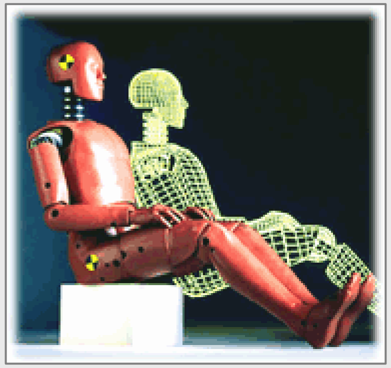




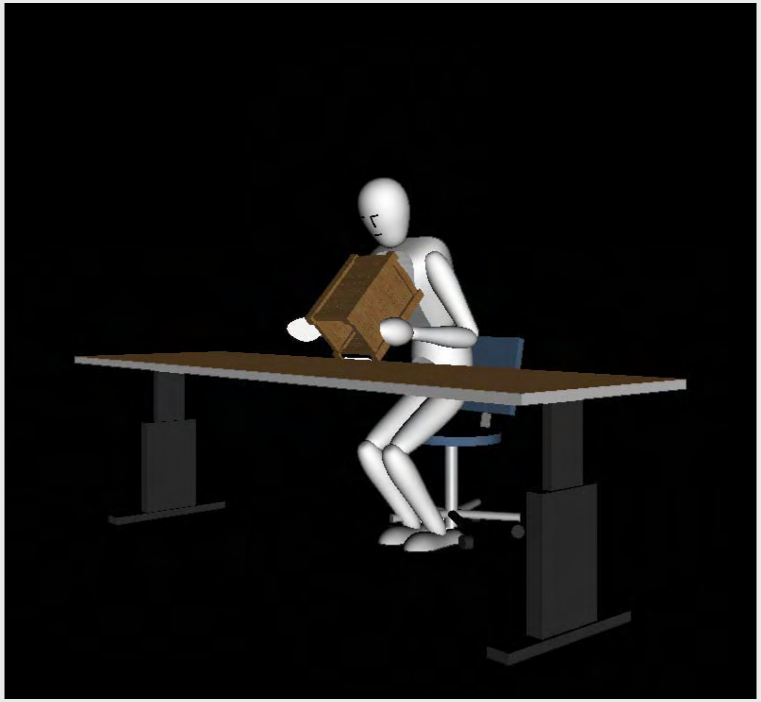




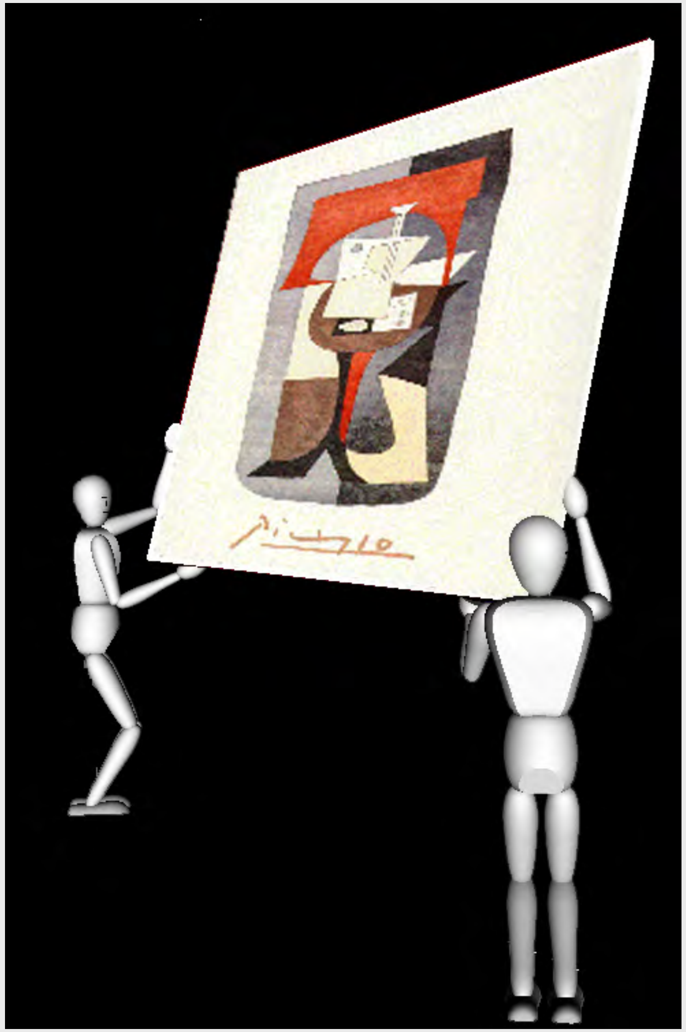
Contact/Collision Resolution



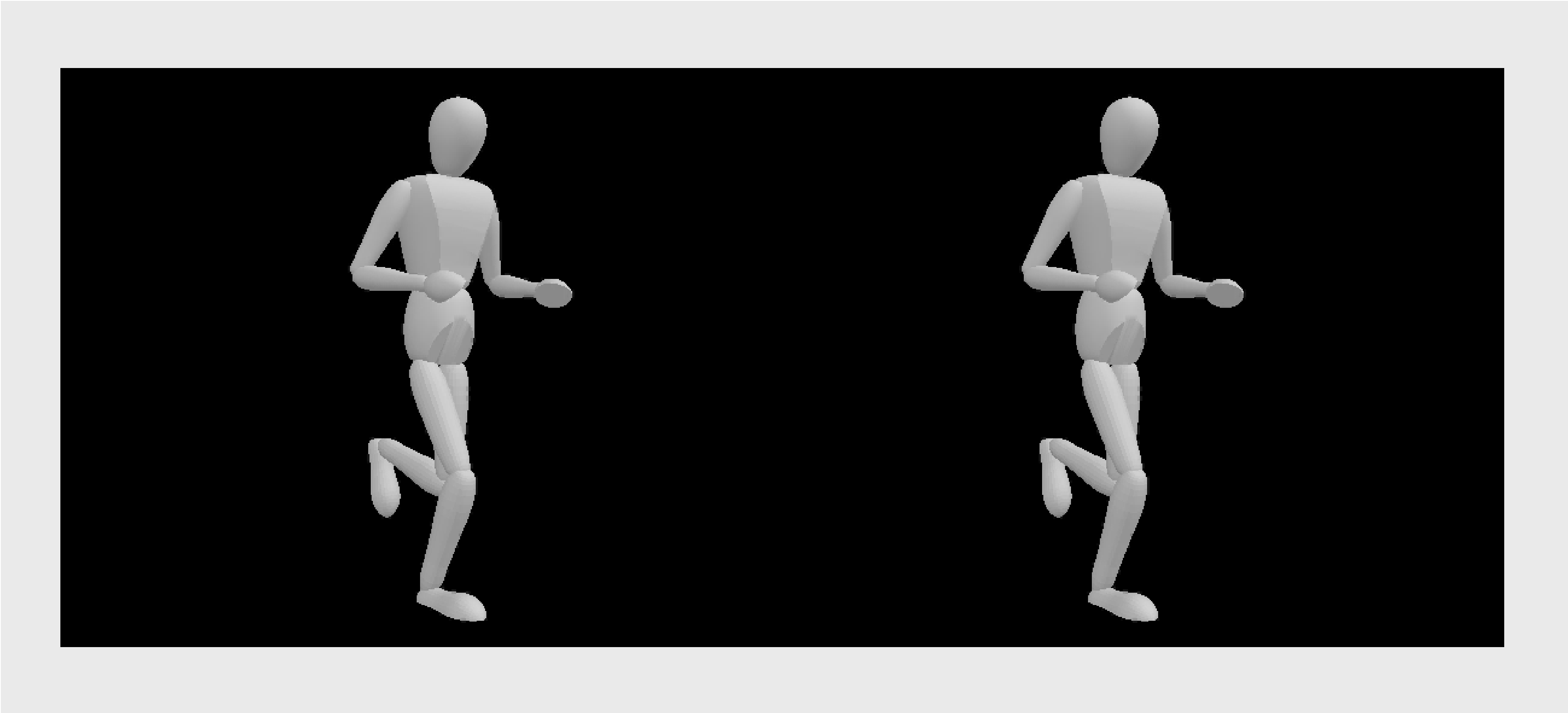
Crash Tests



Constraints

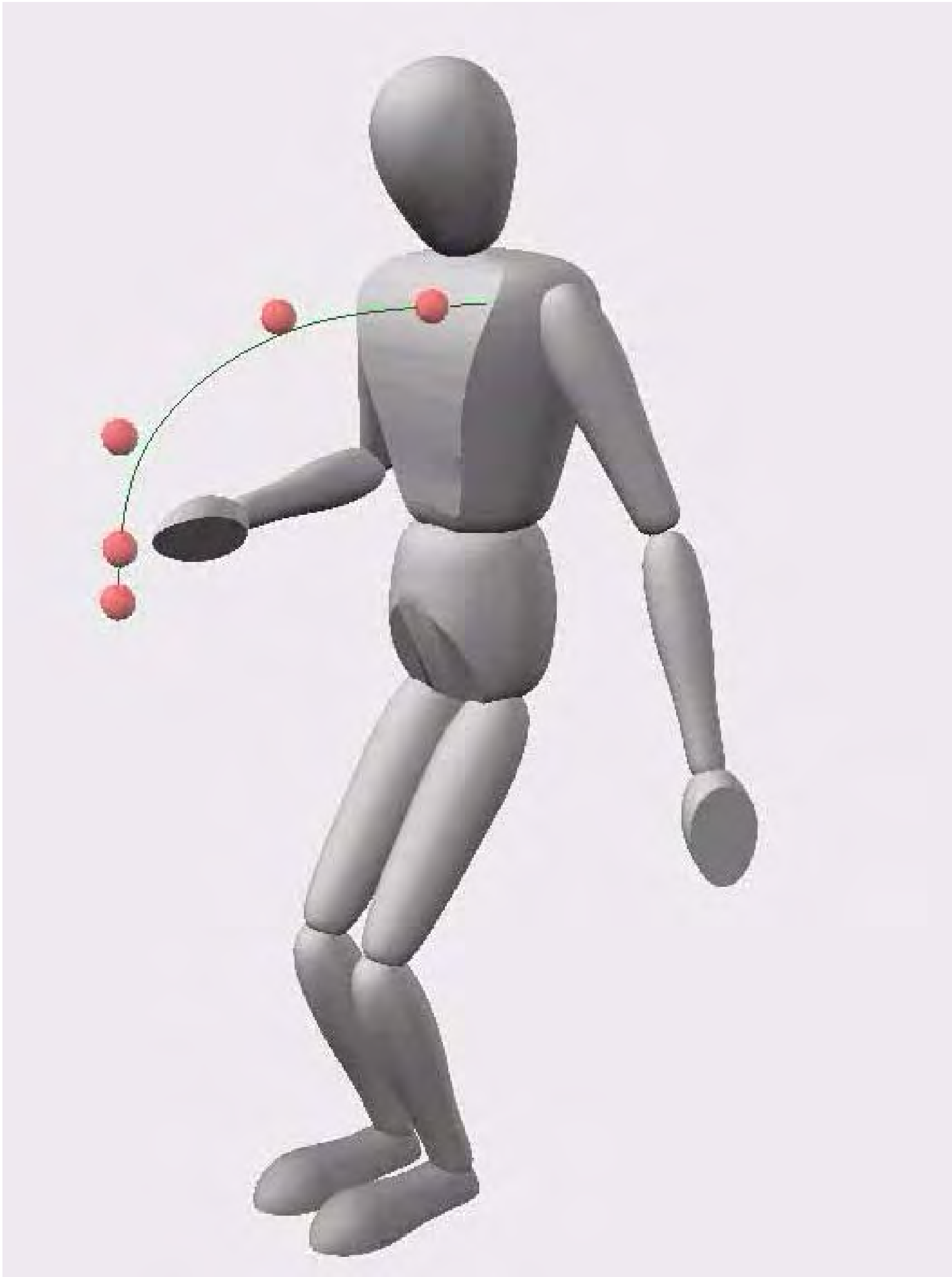


Constraints

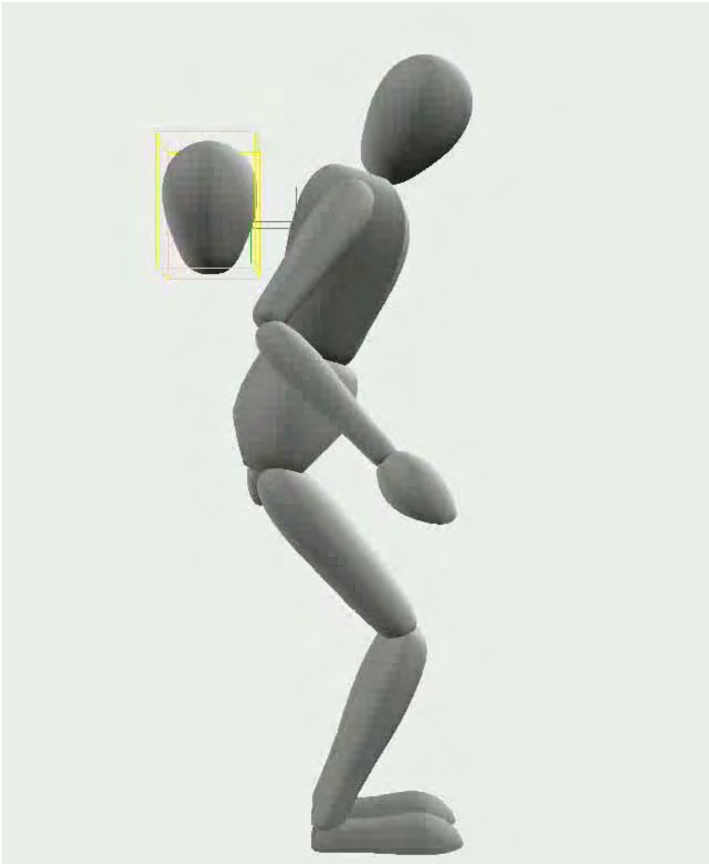


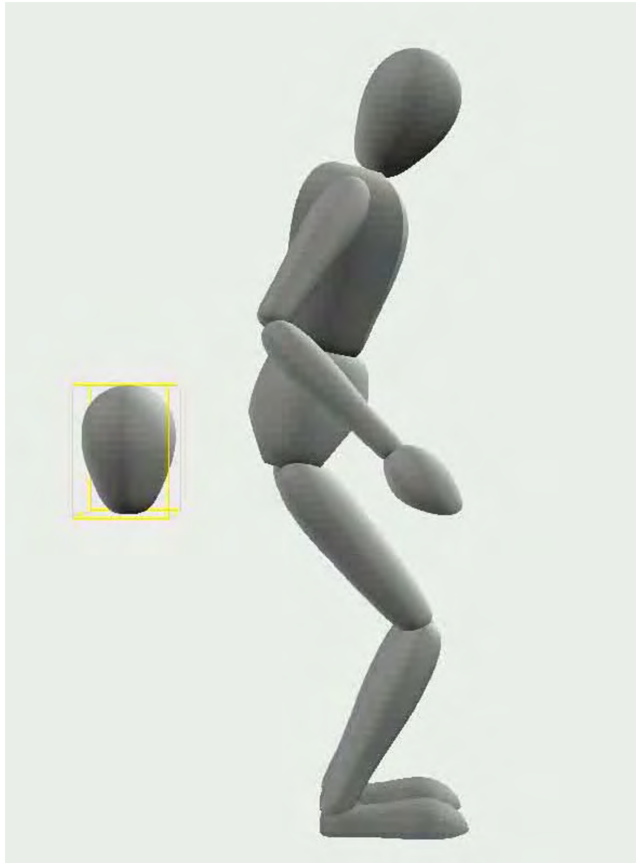
$$\Gamma = J_{cnst}^T F_{cnst} + N_{cnst}^T \left(J_{task}^T F_{task} + N_{task}^T \Gamma_{posture} \right)$$

Self Collision



Obstacles

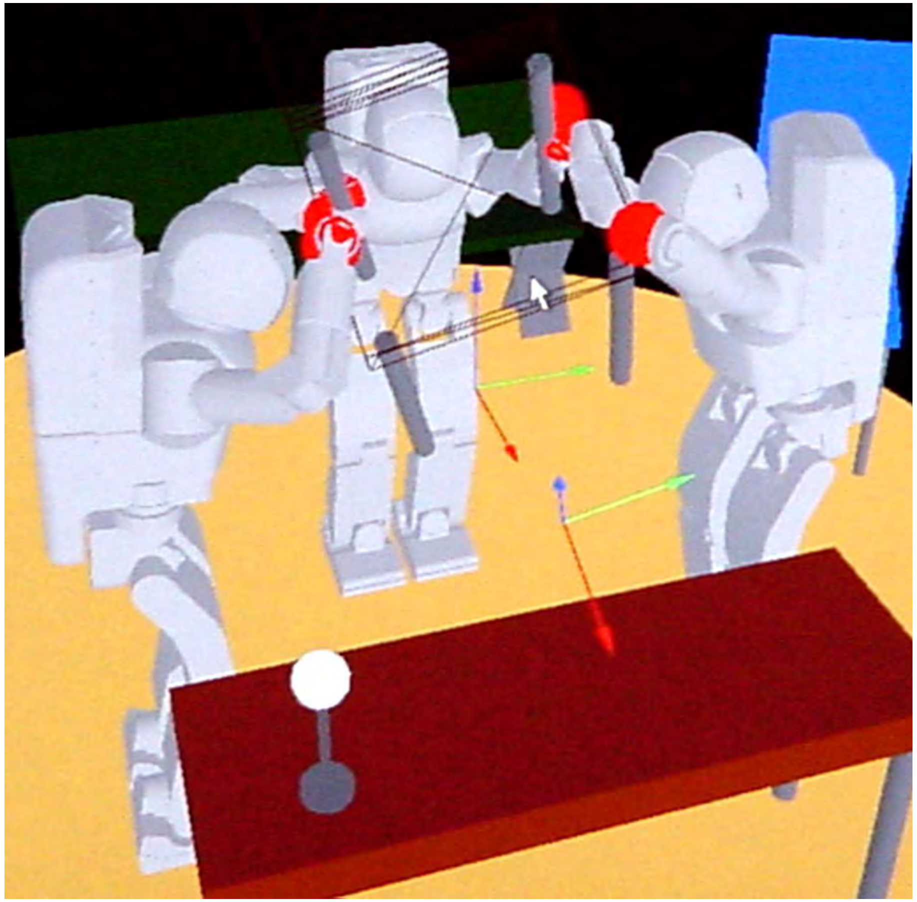




Elastic Planning

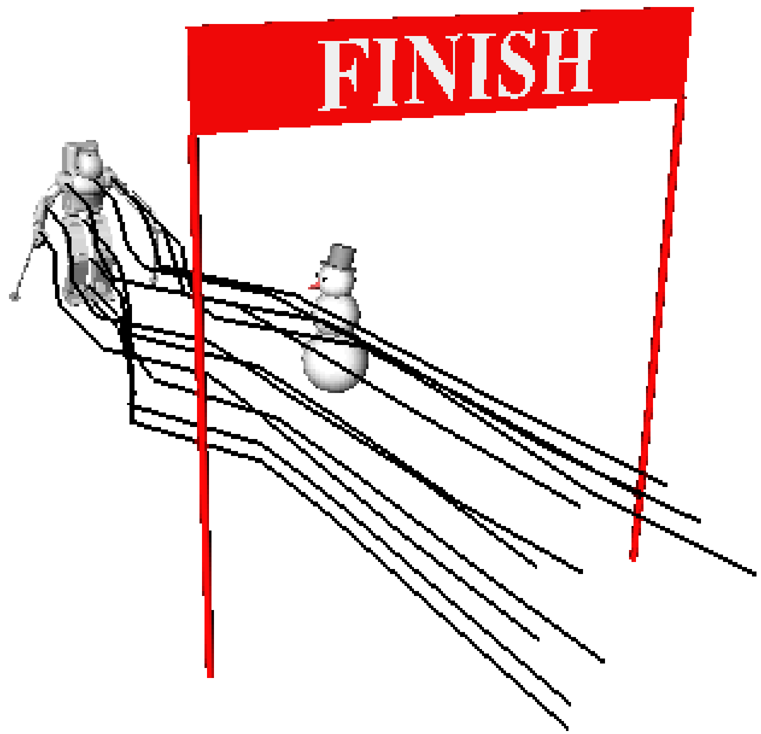
Real-time collision-free path modification

Connecting
Reactive Local Avoidance
with
Global Motion Planning

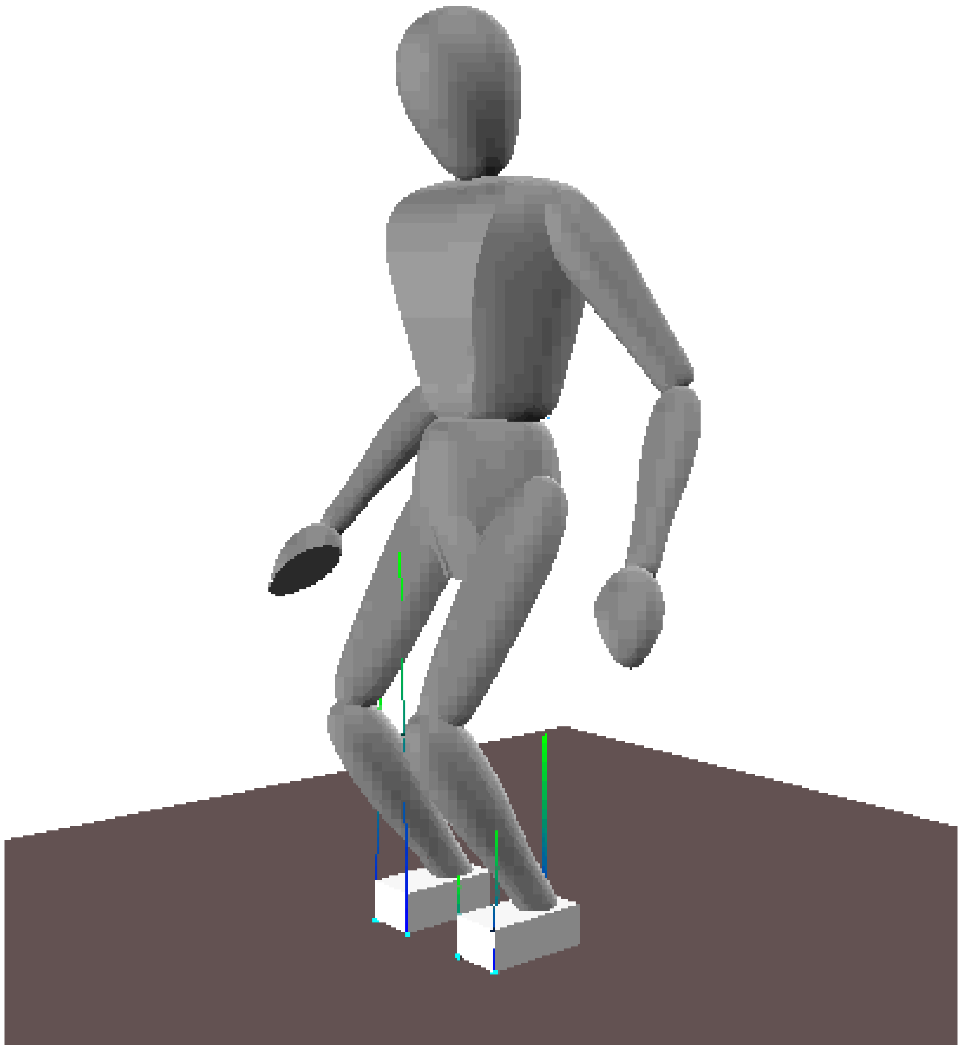


Elastic Planning

Elastic Planning

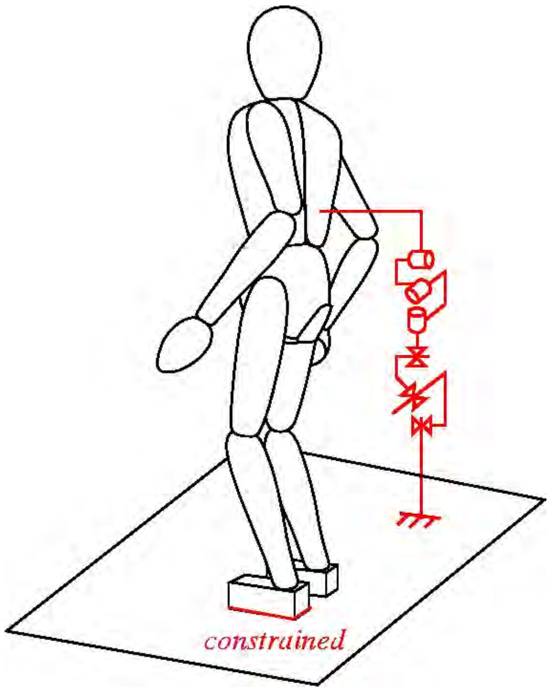


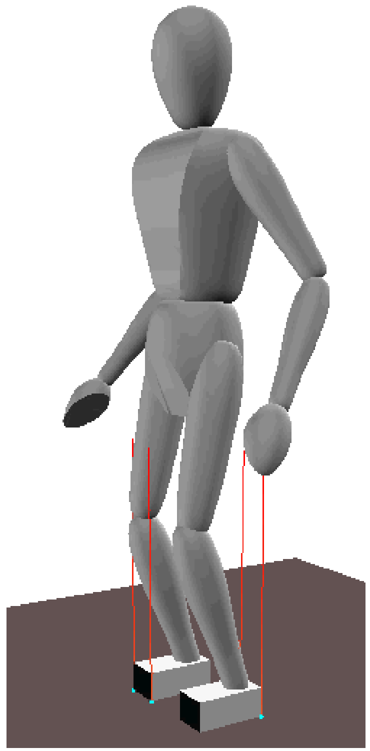
Integration of Locomotion

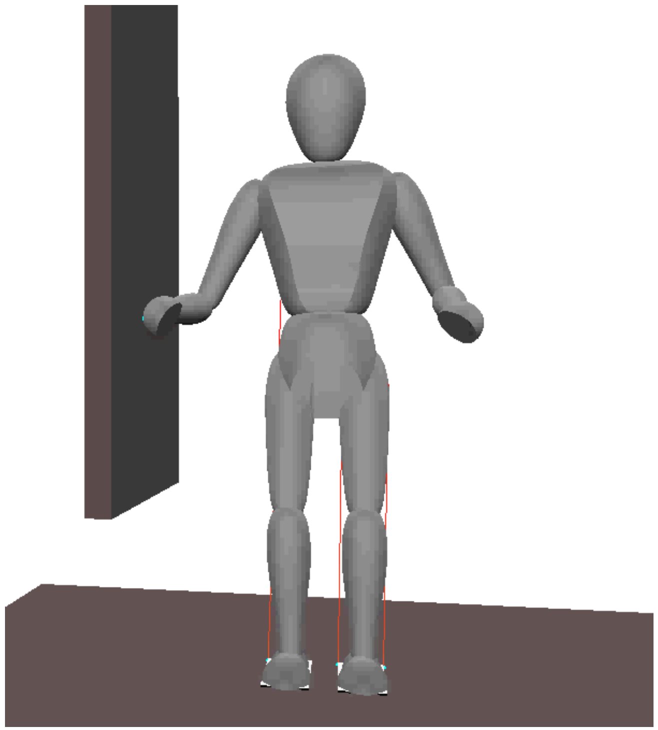


Multi-Contact Whole-body Control

Integration of Whole-Body Control & Locomotion





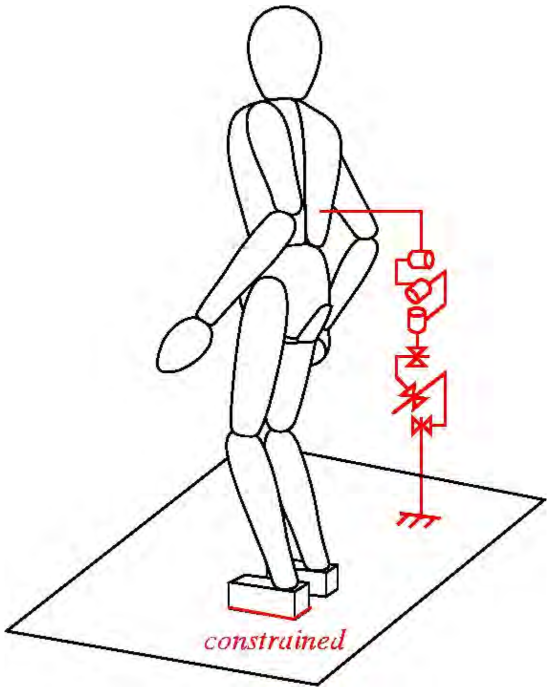


Under-actuated

Balance

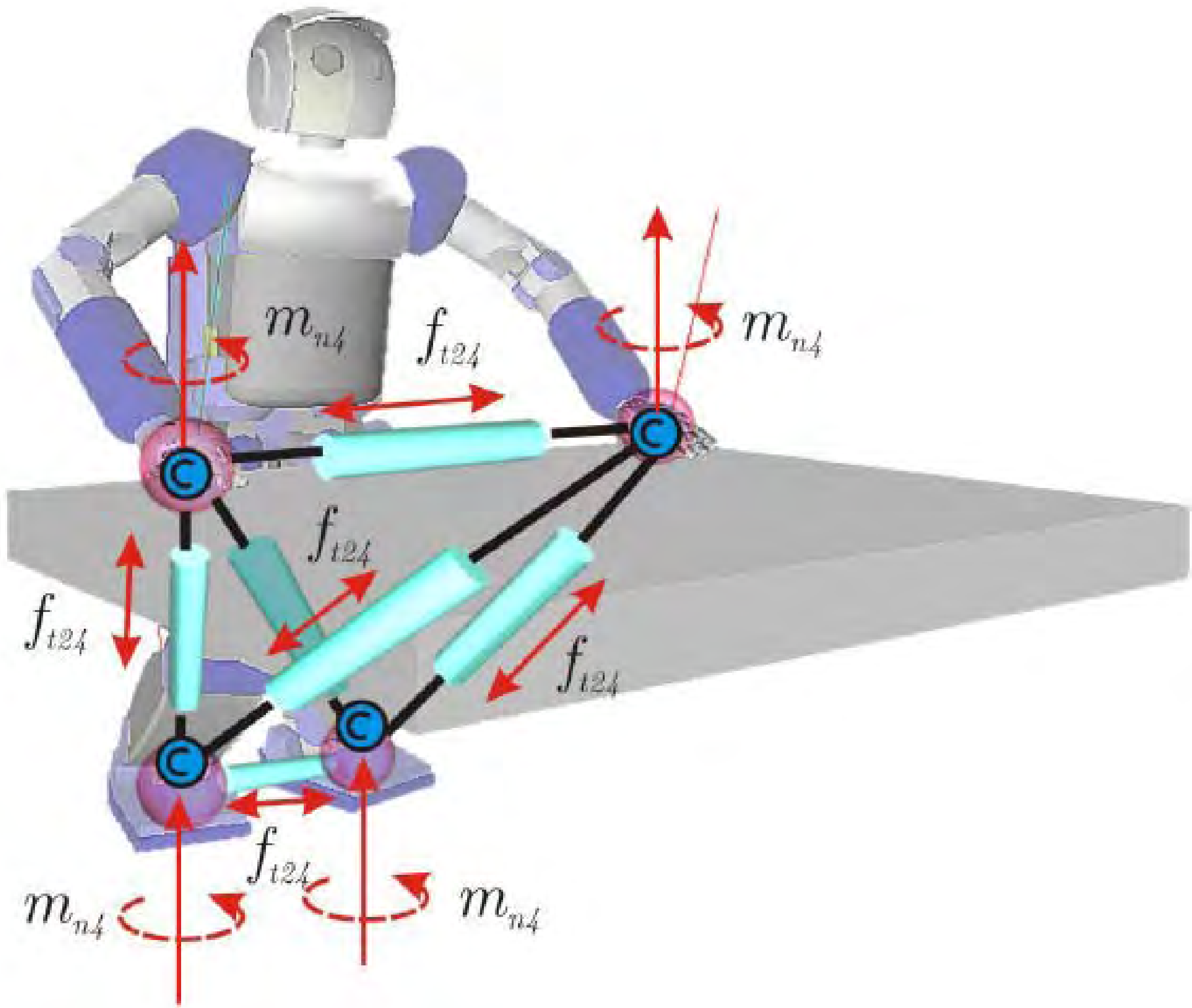
Reaction forces

Multi-Contact Whole-body Control

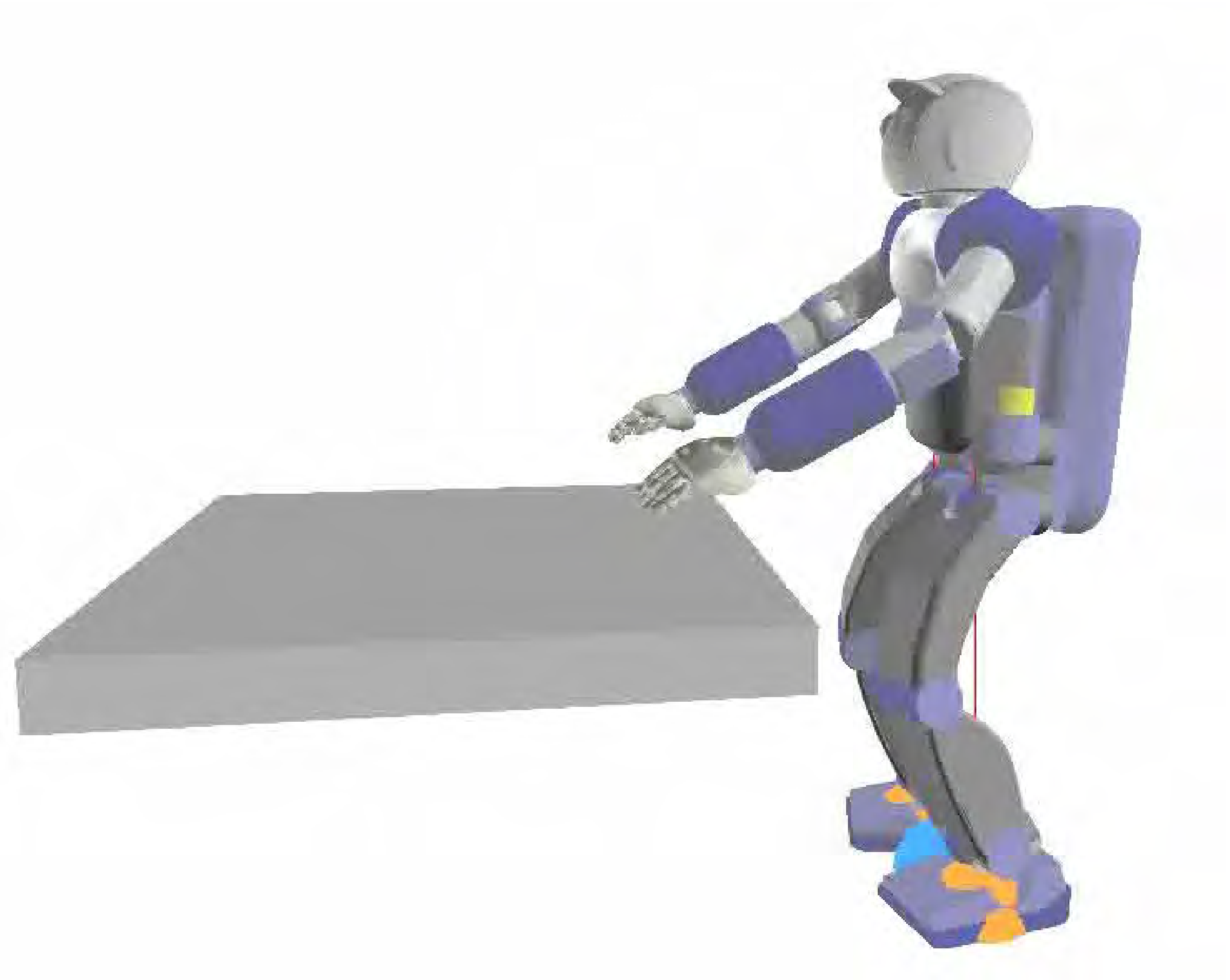


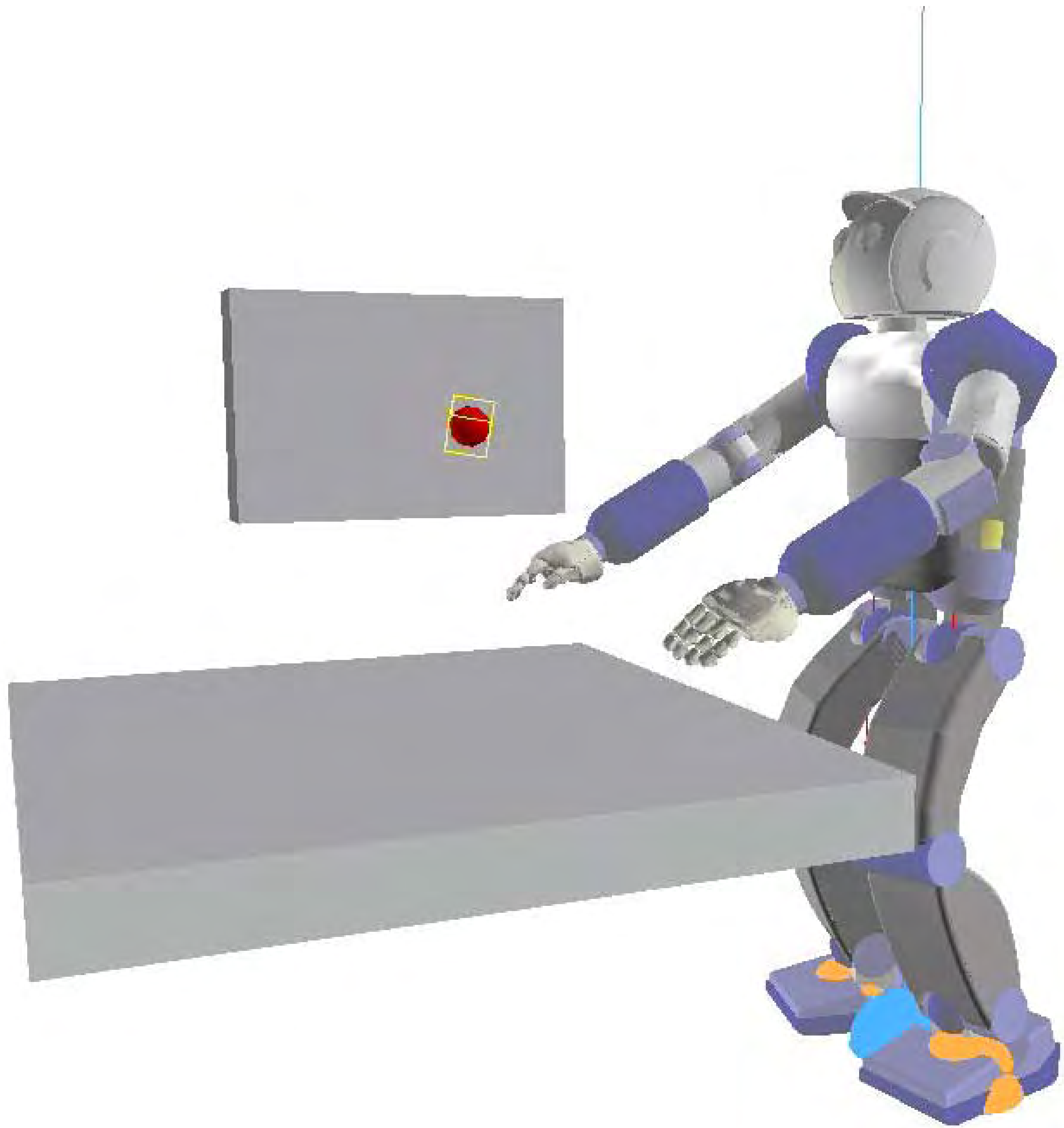
$$\Gamma = J^T_{c} F_{c} + N^T_{c}\left(J^T_{task} F_{task} + N^T_{task}\,\Gamma_{posture}\right)$$

Balanced Supporting Contacts
Internal Force Control – Virtual Linkage



Balanced Supporting Contacts
Internal Force Control – Virtual Linkage





Unified Whole Body Control with Constraints and Contacts

Dynamics

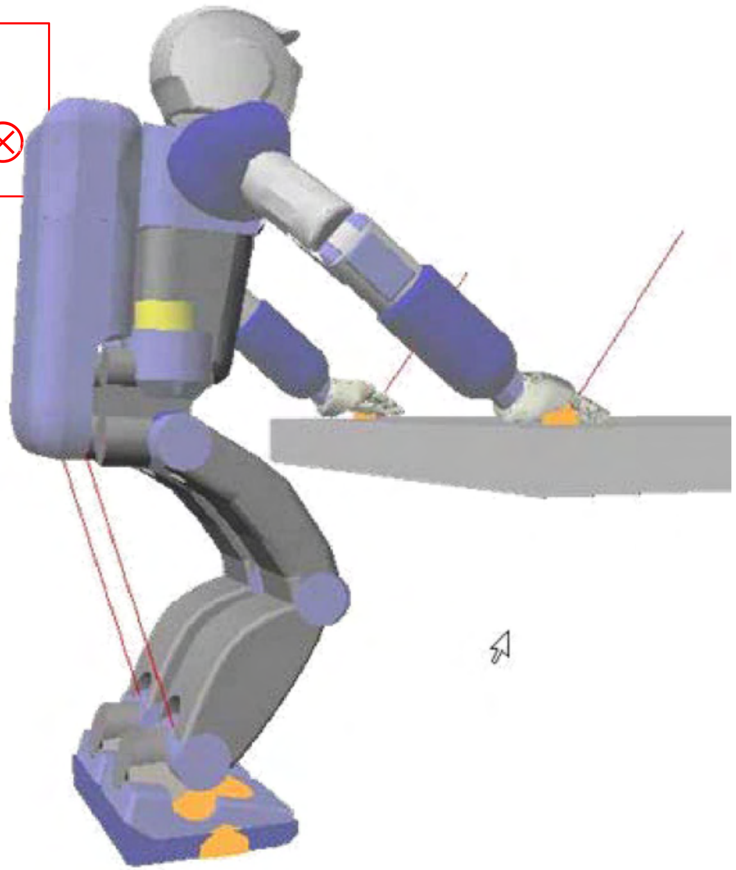
$$\boxed{\Lambda_{\otimes}\dot{\vartheta}_{\otimes} + \mu_{\otimes} + p_{\otimes} + F_f = F_{\otimes}}$$

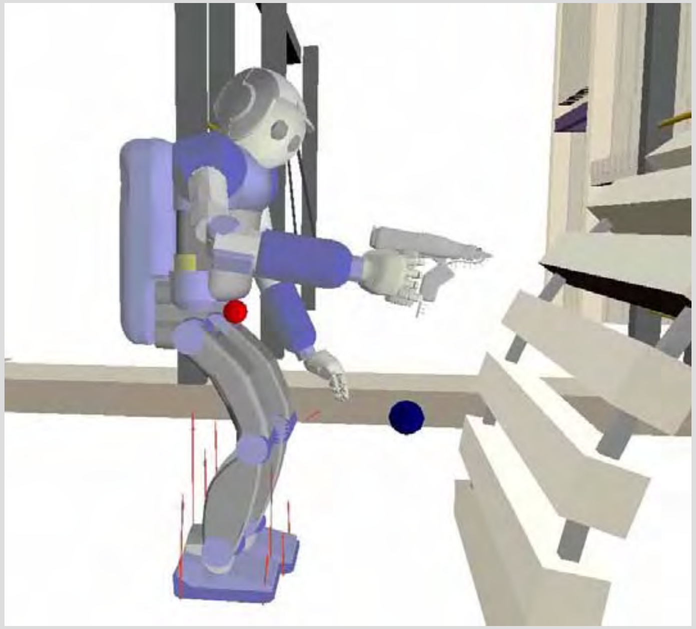
Control

$$\boxed{F_{\otimes} = \hat{\Lambda}_{\otimes} F^{*}_{\otimes} + \hat{\mu}_{\otimes} + \hat{p}_{\otimes}}$$

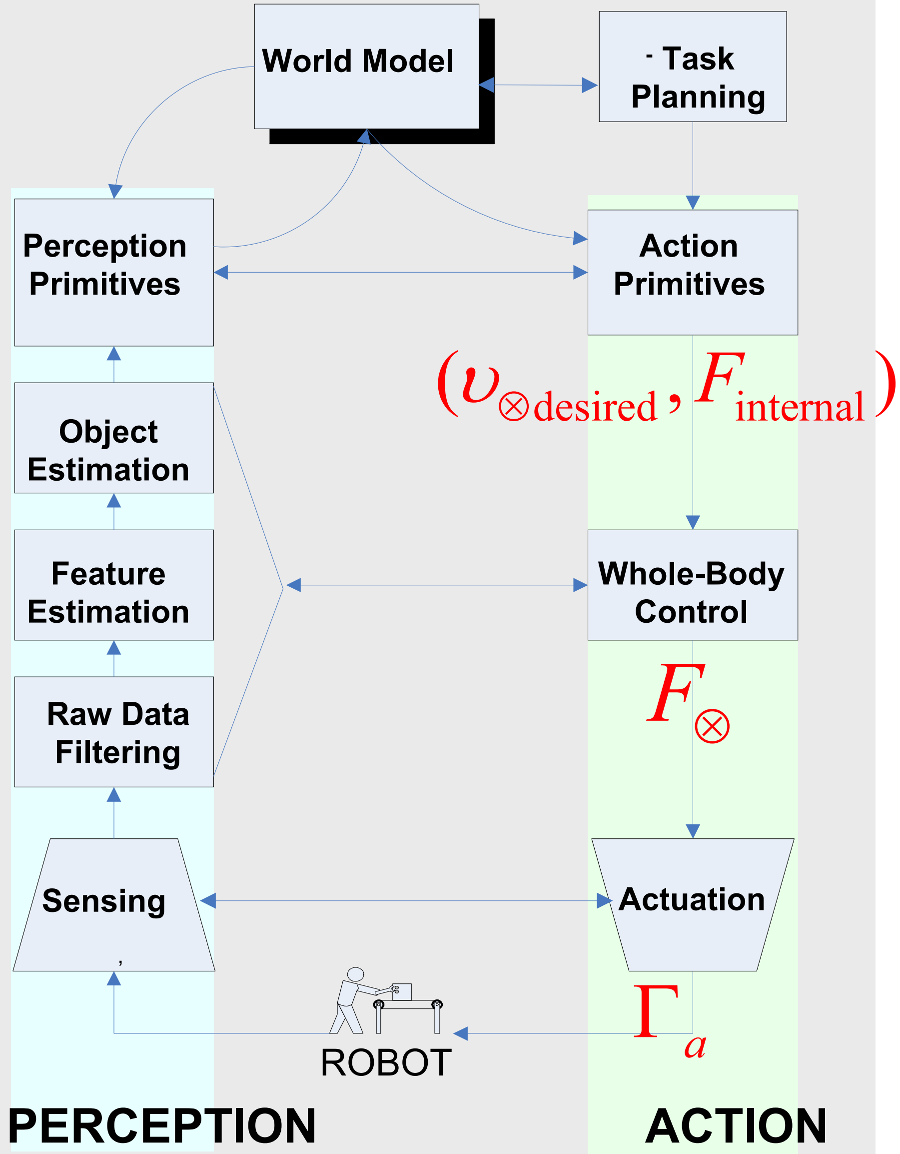
$$F^{*}_{\otimes} = \begin{pmatrix} F^{*}_{c|s} \\ F^{*}_{f|c|s} \\ F^{*}_{m|f|c|s} \\ F^{*}_{p|m|f|c|s} \end{pmatrix}$$

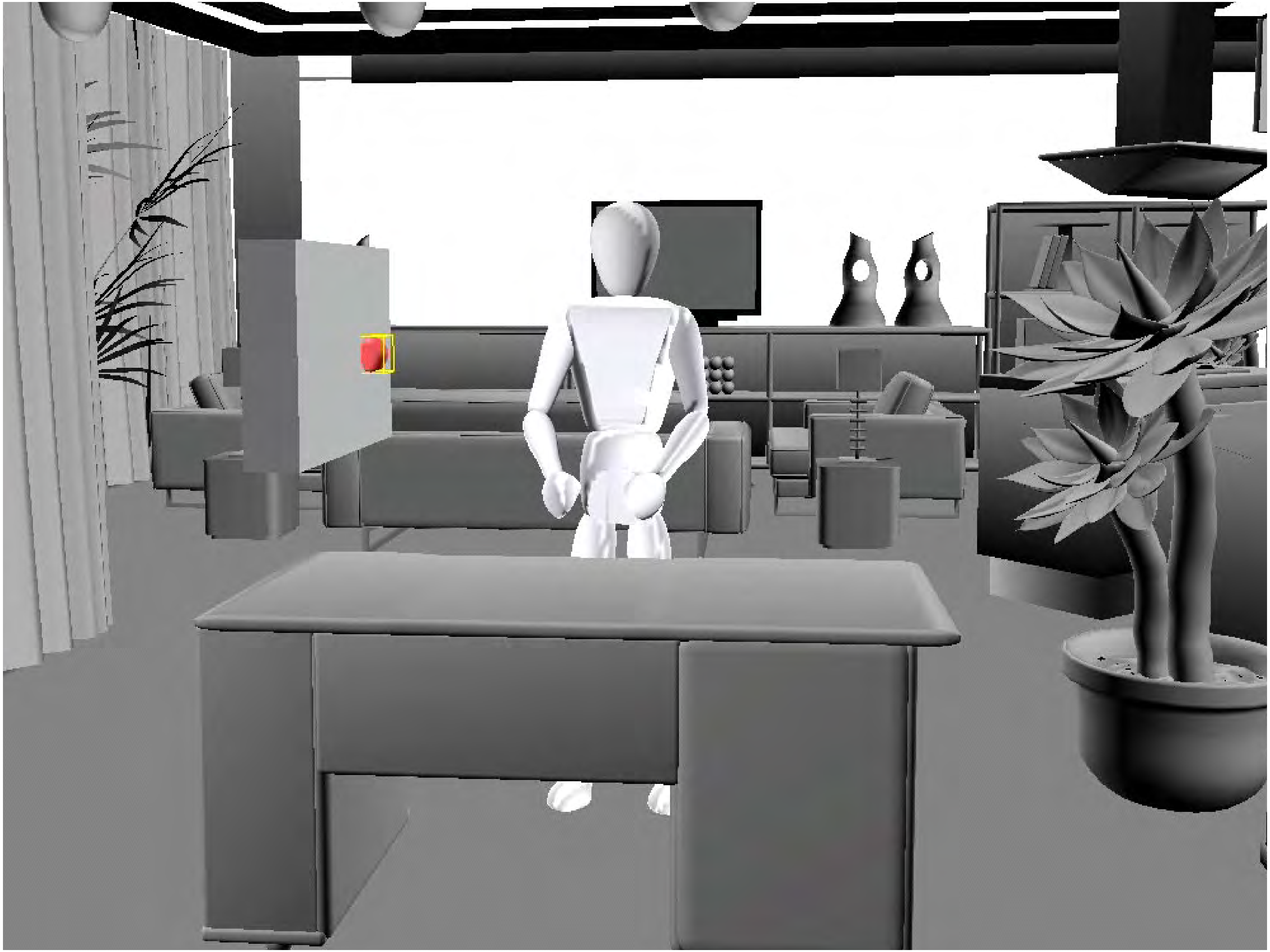
$$\boxed{\Gamma_a = (\overline{UN_s})^T J^T_{\otimes} F_{\otimes}}$$





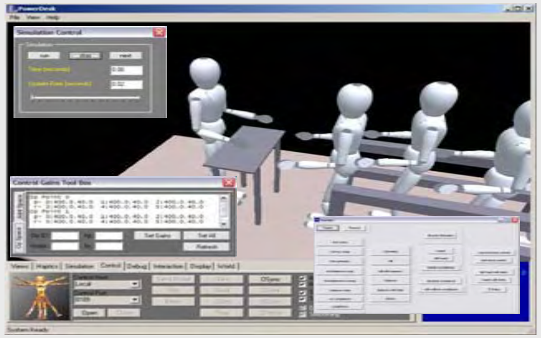
Architecture





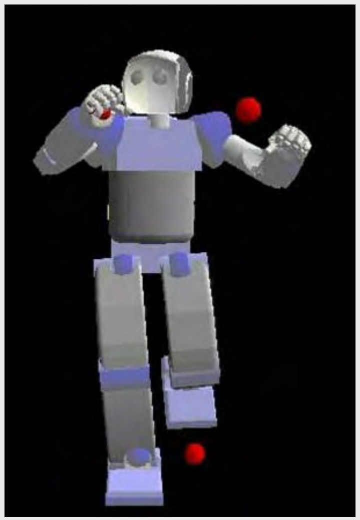
Implementation on the Physical Robot?

SAI



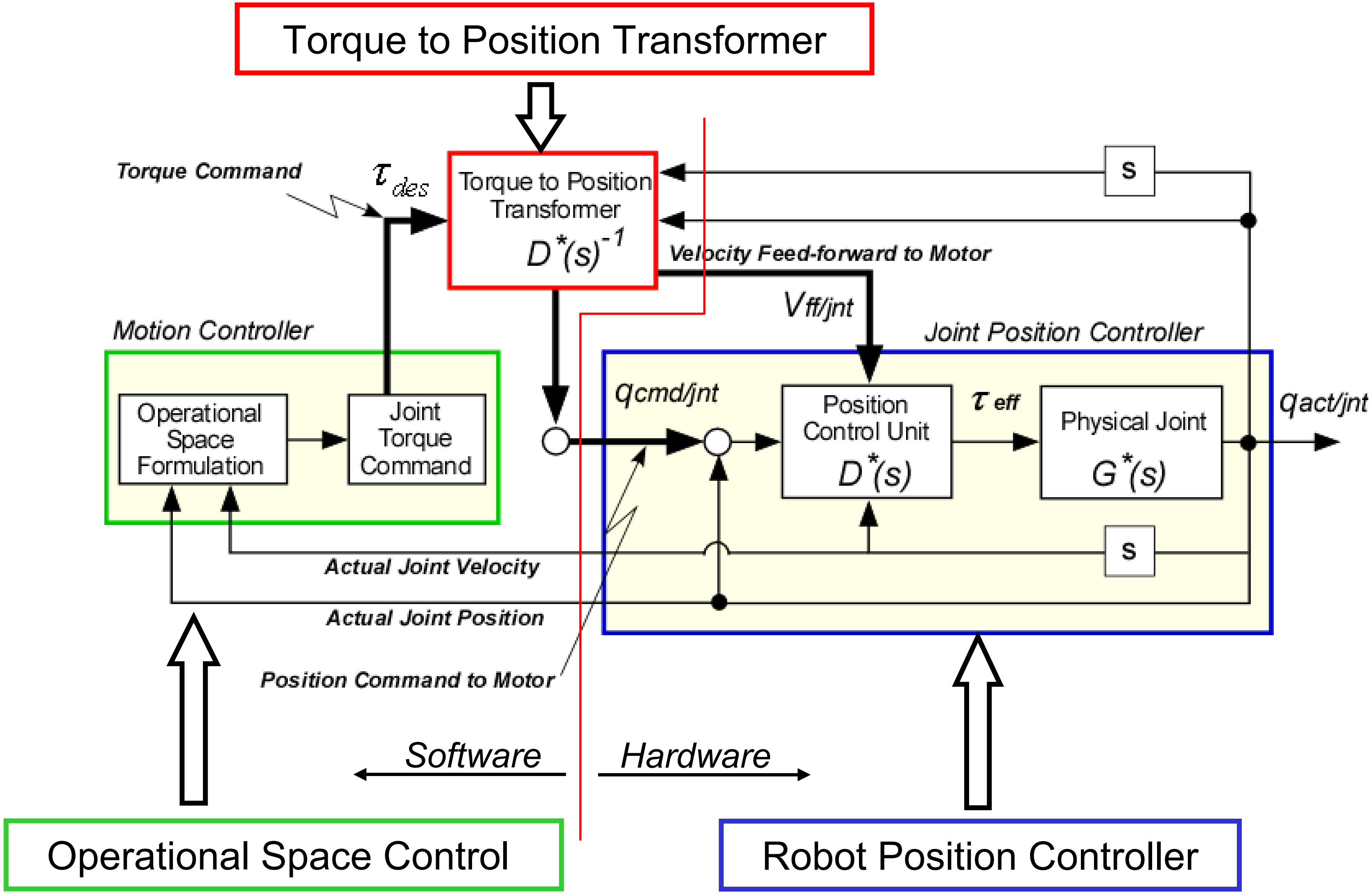
Torques

Positions

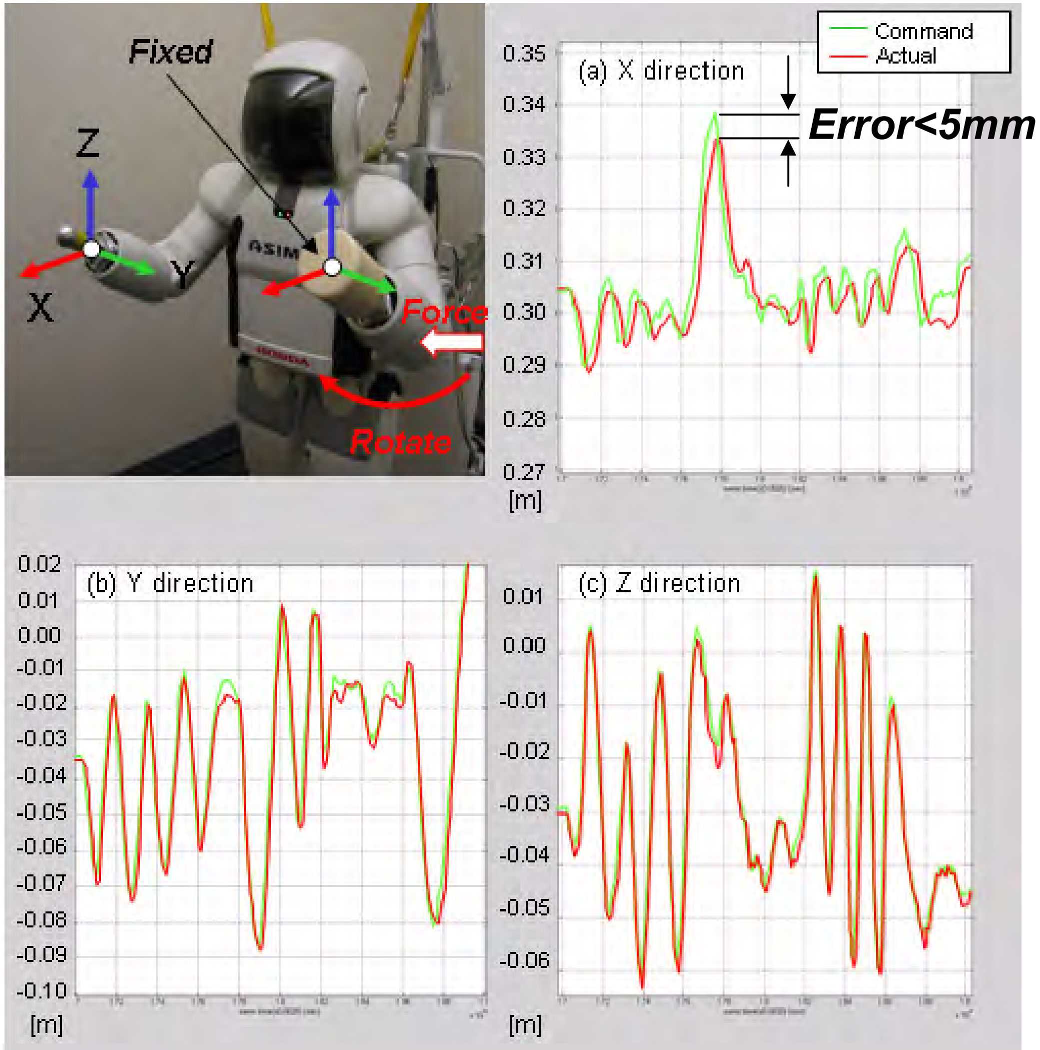


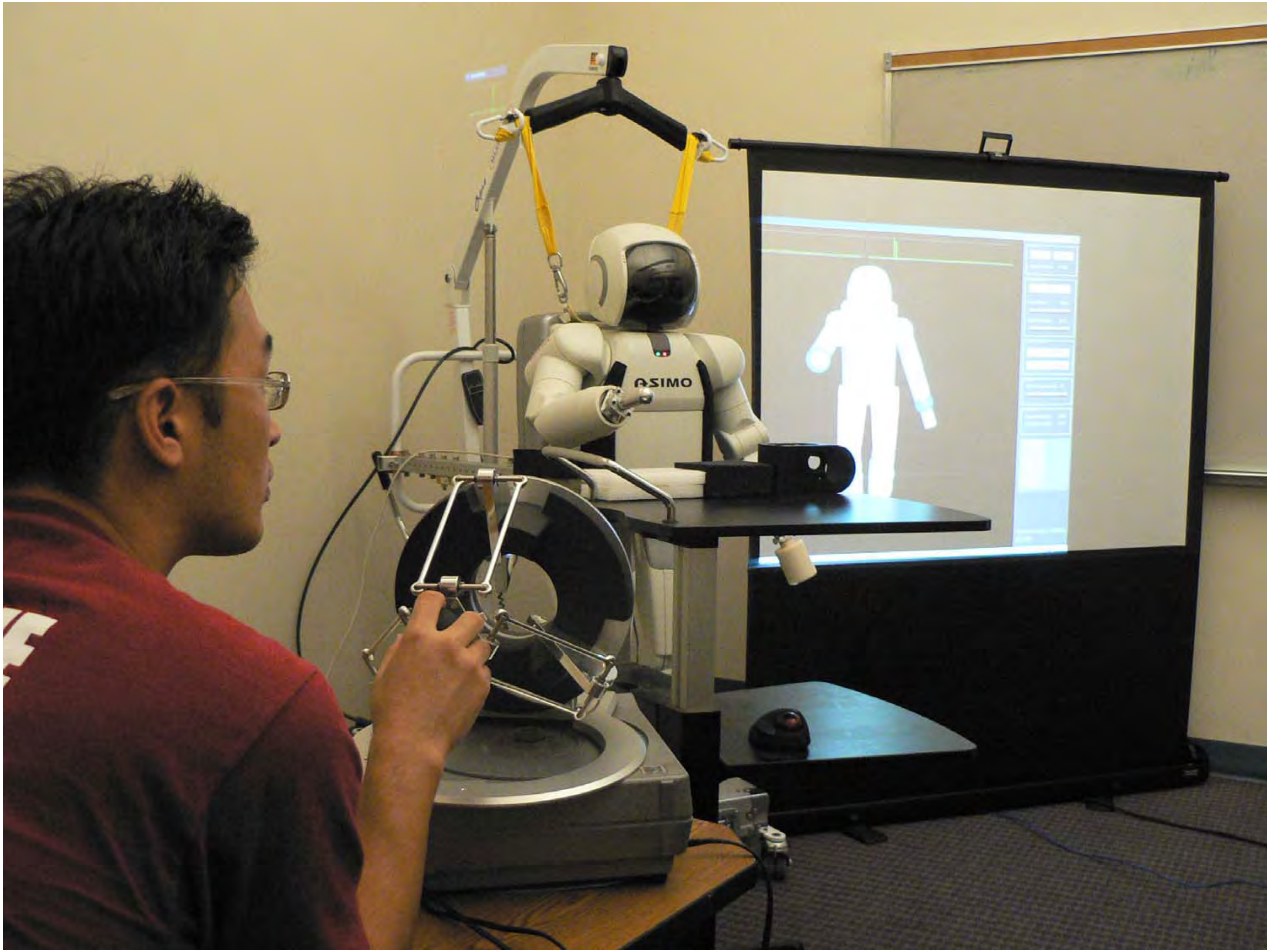
Torque to Position Transformer

Torque to Position Transformer

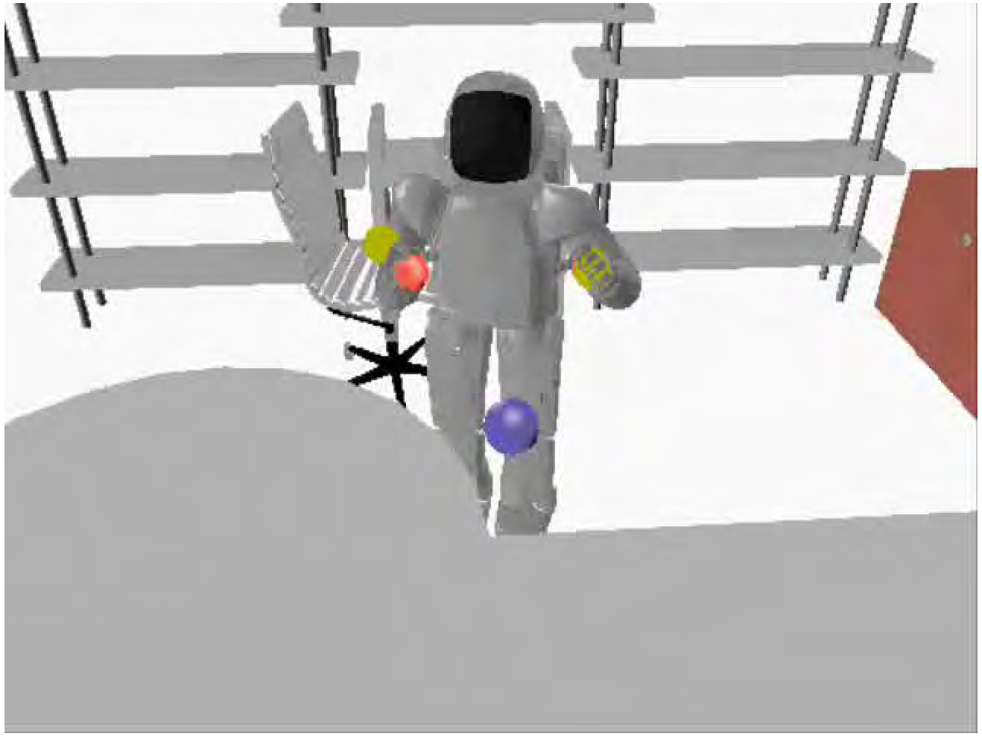


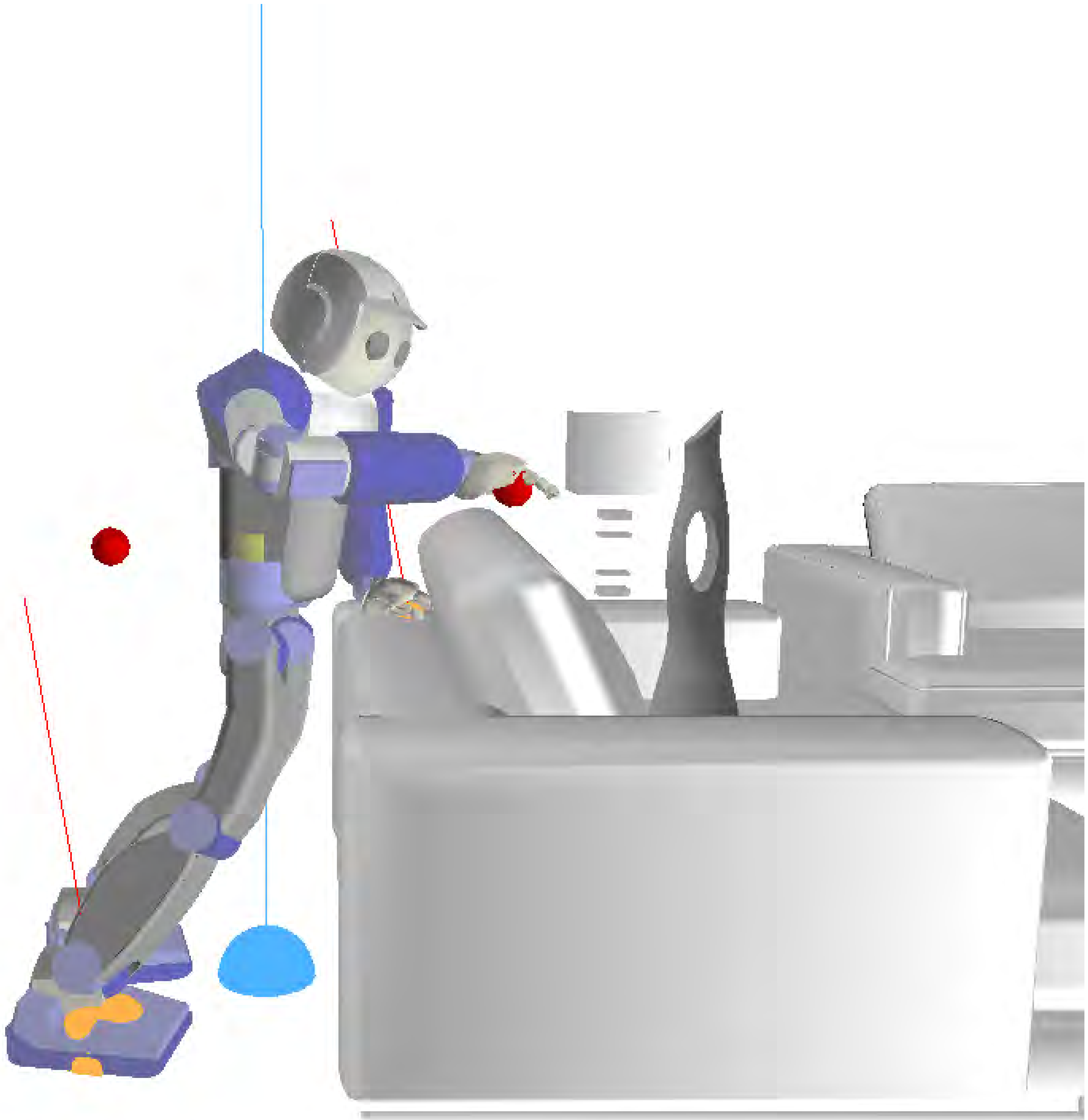
Experimental Result – *hand task*

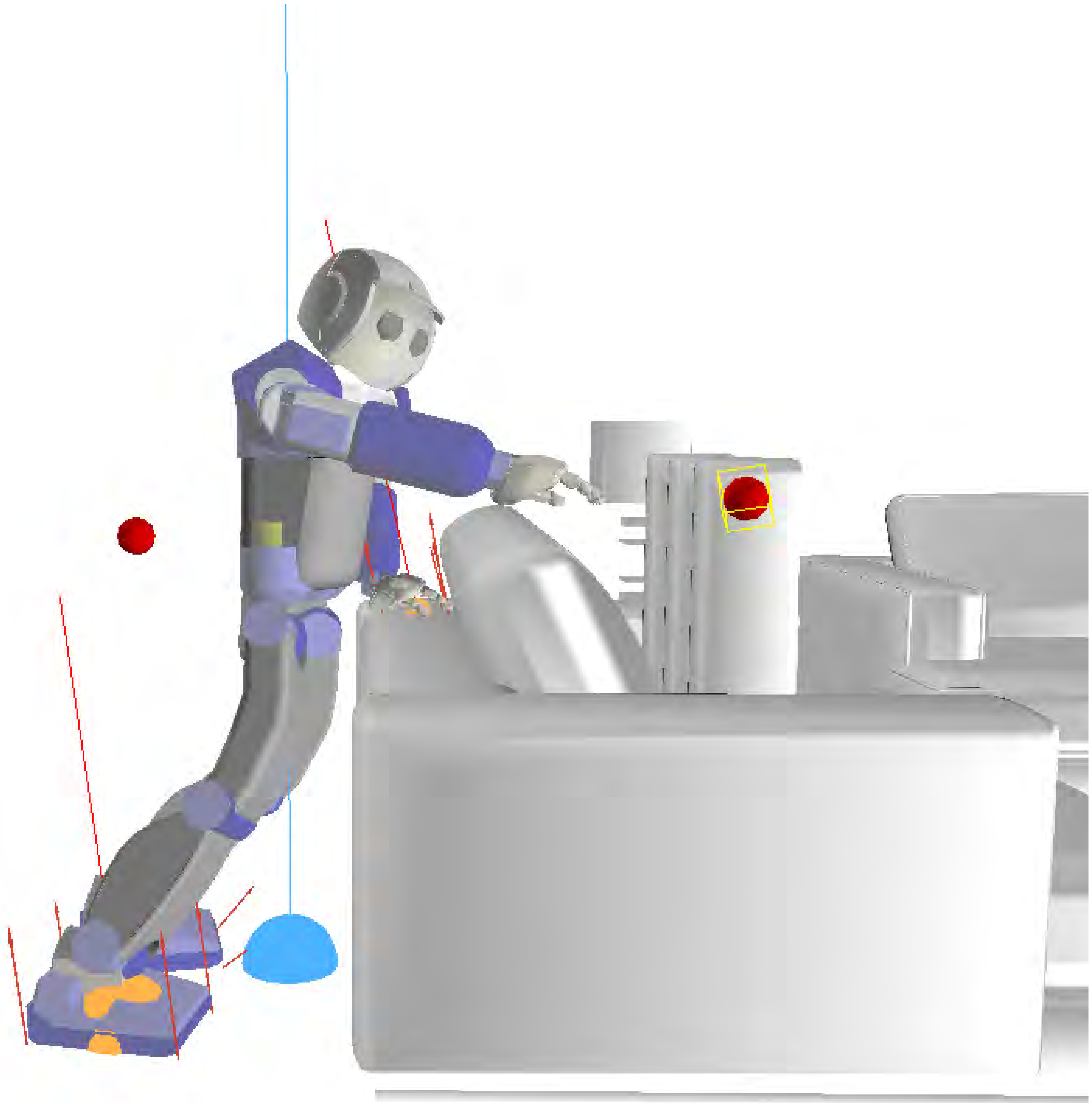


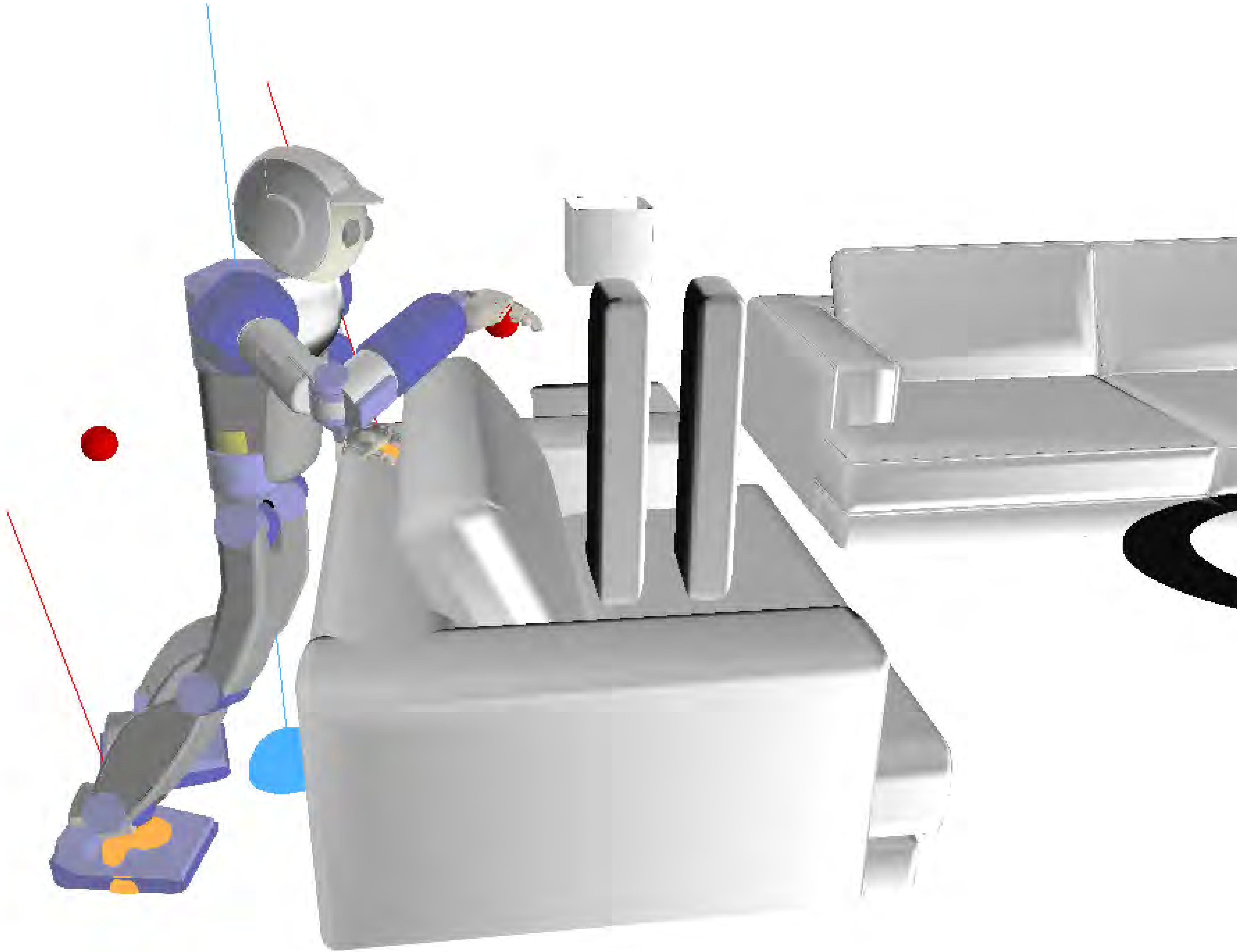

ASIMO

Robot-Human Haptic Interaction










ARTIFICIAL INTELLIGENCE LABORATORY

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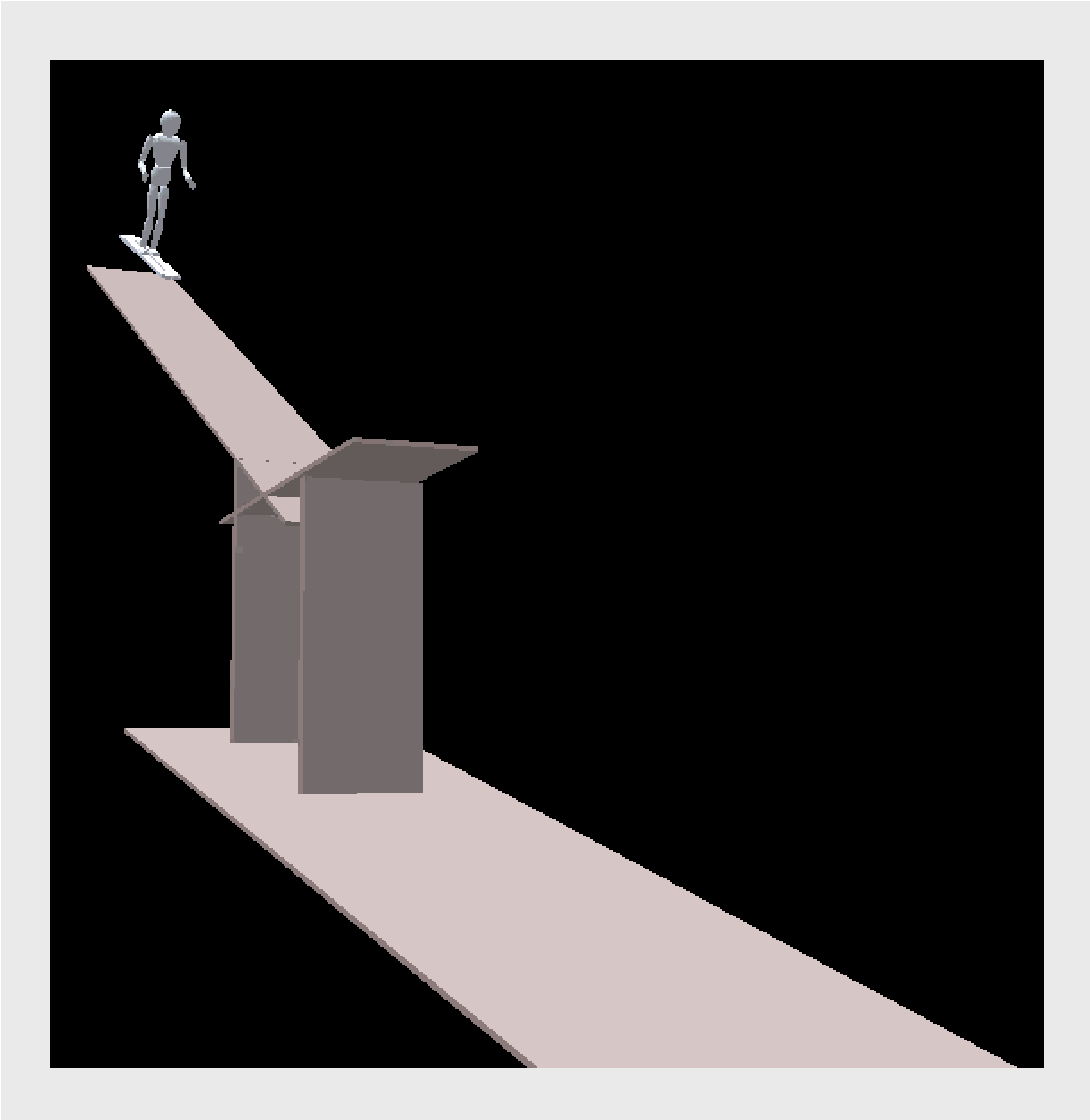


Thank You!