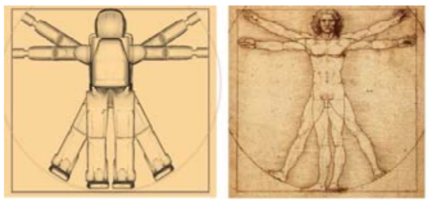
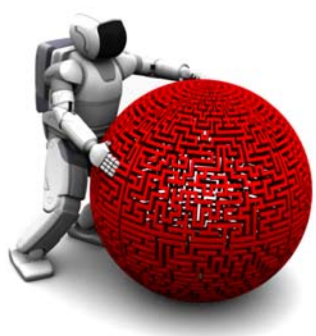


Humanoid Robots

The Challenge:
beyond mobility

.. not only walk, but also interact with the world!
a unified mobility & manipulation framework!

ASIMO



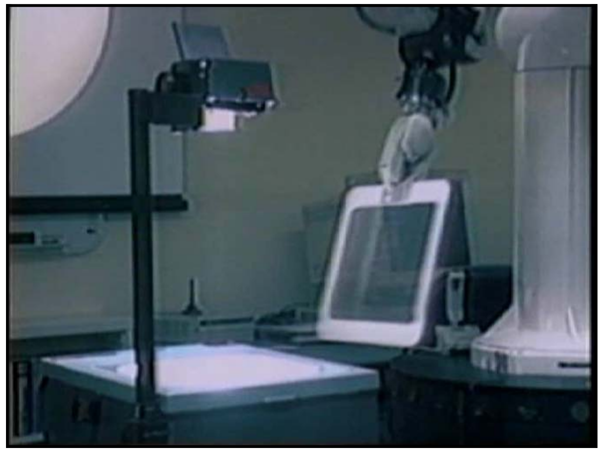
.. not only walk, but also interact with the world!

How much programming?

Mobile Manipulation

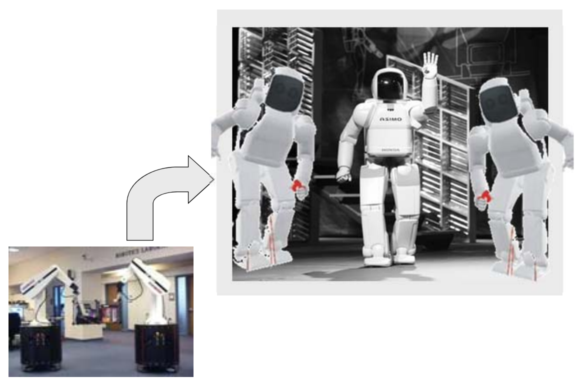
Human Guided Motion & Human-Robot Interaction

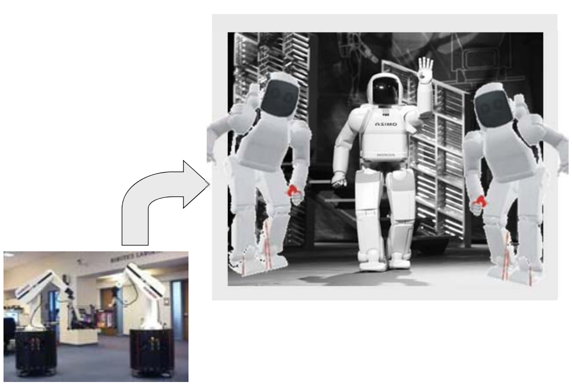
Romeo & Juliet (1993)



Human-Robot Interaction

Romeo & Juliet (1993-96)





Multi-contact Manipulation

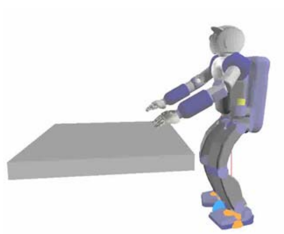
Humanoid Robot Control

branching and under-actuated

- whole-body control
- constraints and obstacles
- multiple contacts
- internal forces & balance
- manipulation skills

Multi-Contact Whole Body Motion

Physical Interaction, Constraints, and Task Behaviors

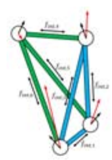


Balanced Supporting Contacts

Internal Force Control – Virtual Linkage

Balanced Supporting Contacts

Internal Force Control – Virtual Linkage

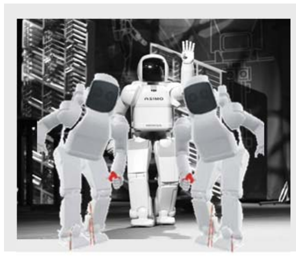


Physical Interaction, Constraints, and Task Behaviors

Posture
Task Behavior
Multiple Contacts
Internal Constraints
Self Collision
Local Obstacles
Balance

Unified Whole-Body Control Framework

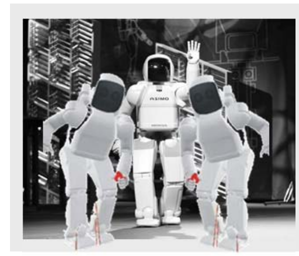
posture
consistent with {
 Task
 consistent with {
  contact
  consistent with {
   internal constraints
   self collision
   local obstacles
   consistent with {
    balance
} } } }



interact with the world, cooperate, and manipulate

Constraint-Consistent Task-Space

$\upsilon_\otimes \in cc - space$



interact with the world, cooperate, and manipulate

Unified Whole Body Control Framework

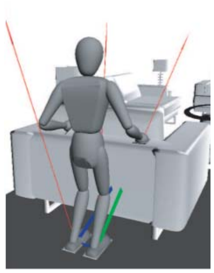
Task, Posture, Constraints, Multiple Contacts, and Balance

Dynamics

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

Control

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



Whole-body Control

Task & Posture Decomposition

Task Dynamics and Control

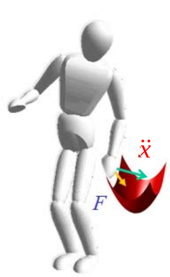
Task Dynamics

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

Task Control

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

$$\Gamma = J^T F$$

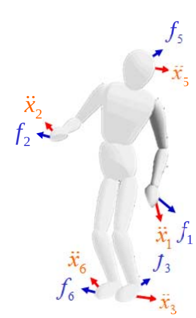


Task Dynamics – Branching Structures

$$x = \begin{pmatrix} x_1 \\ x_2 \\ \cdot \\ x_m \end{pmatrix} \qquad \Lambda = \begin{pmatrix} \Lambda_{11}\ \Lambda_{12} \cdots \Lambda_{1L} \\ \Lambda_{21}\ \Lambda_{22} \cdots \Lambda_{2L} \\ \cdots\cdots\cdots \\ \Lambda_{L1}\ \Lambda_{L2} \cdots \Lambda_{LL} \end{pmatrix}$$

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

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



Posture Space Control

Joint-Space Dynamics

Posture | Task-related $= \Gamma$

$\bar{J}^T \Downarrow \quad \Uparrow J^T$

N^T

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

Task Control: J^T

Posture Control: N^T

Control Structure

$$\boxed{\Gamma = J^T_{task} F_{task} + N^T_{task} \Gamma_{posture}}$$

Decomposition of torque vector

Dynamic Consistency $\Rightarrow$ $\boxed{\ddot{x}_{task} = 0}$

Posture Energy

Whole-Body Control: Dynamics

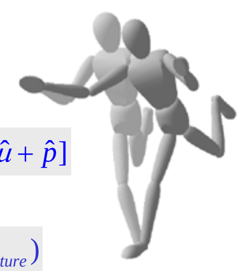
$$\boxed{\Gamma = \Gamma_{Task} + \Gamma_{Posture}}$$

$$\Gamma_{Task} = J^T F$$

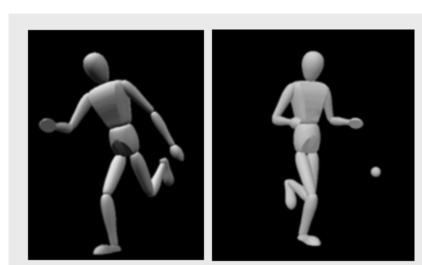
$$\Gamma_{Task} = J^T [\hat{\Lambda}(-\nabla V_{Task}) + \hat{\mu} + \hat{p}]$$

$$\Gamma_{Posture} = N^T \Gamma_{Desired-Posture}$$

$$\Gamma_{Posture} = N^T (-\nabla V_{Desired-Posture})$$



Dynamics in Posture Space



Posture Dynamics & Control

Posture sub-task: $x_p \rightarrow J_p$

Task-consistent posture Jacobian: $\delta x_{p|t} = J_p (N_t \, \delta q)$

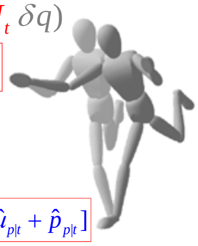
$$\boxed{J_{p|t} = J_p N_t}$$

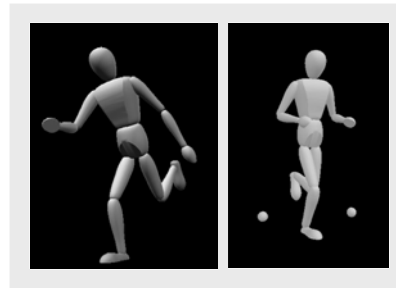
Dynamics:

$$\boxed{\Lambda_{p|t} \ddot{x}_{p|t} + \mu_{p|t} + p_{p|t} = F_{p|t}}$$

Control:

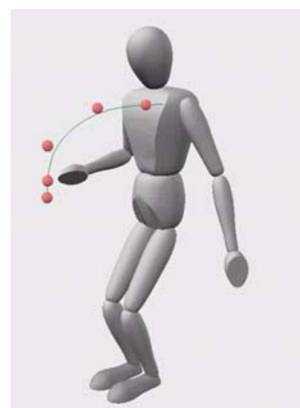
$$\boxed{\Gamma_{posture} = J_{p|t}^T [\hat{\Lambda}_{p|t} (-\nabla V_{posture}) + \hat{\mu}_{p|t} + \hat{p}_{p|t}]}$$



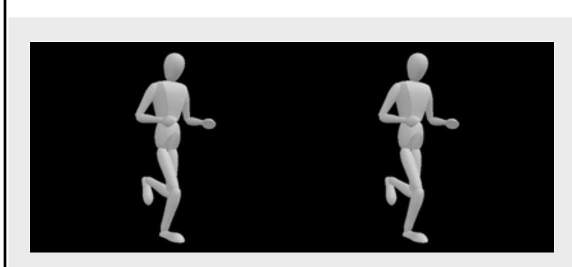


Constraints

Self Collision

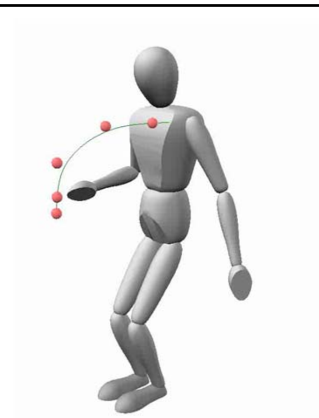


Constraints and Priorities

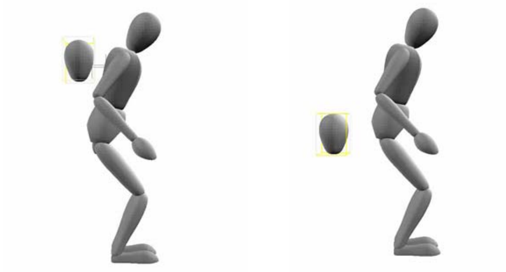


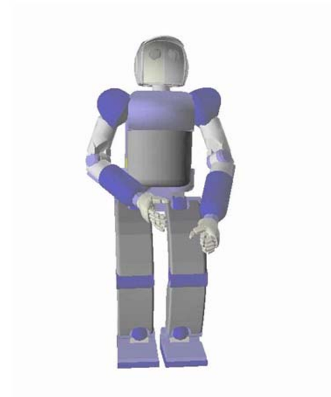
$$\Gamma = J_{cntask}^T F_{cntask} + N_{cntask}^T (\Gamma_{task} + N_{task}^T \Gamma_{posture})$$

Self Collision

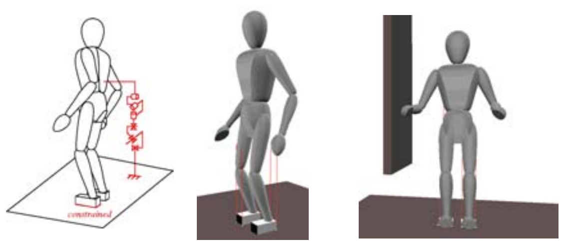


Obstacles



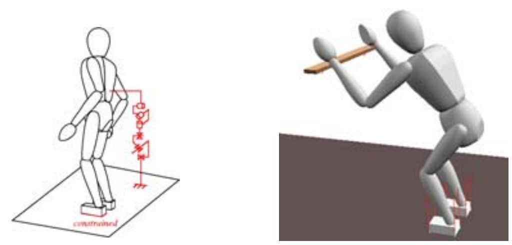


Multi-Contact Whole-body Control
Integration of Whole-Body Control & Locomotion



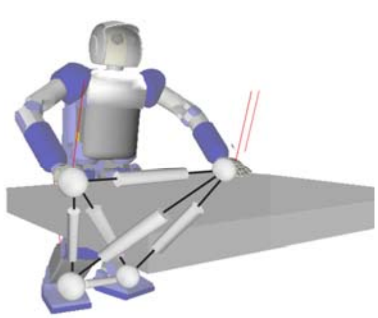
Under-actuated Balance Reaction forces

Multi-Contact Whole-body Control
Integration of Whole-Body Control & Walking

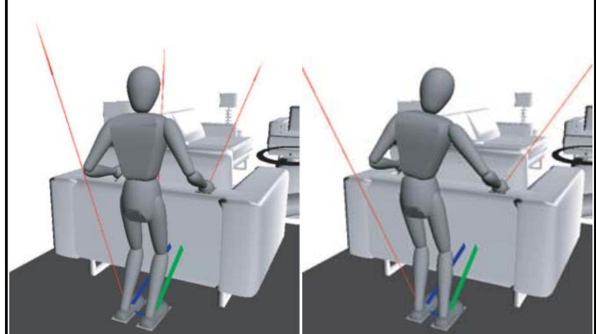


$$\Gamma = J_{contact}^T F_{contact} + N_{contact}^T \left(J_{task}^T F_{task} + N_{task}^T \Gamma_{posture} \right)$$

Balanced Supporting Contacts
Internal Force Control – Virtual Linkage

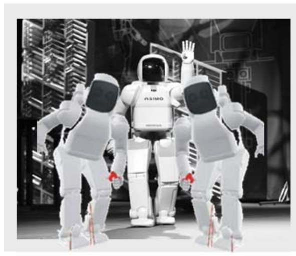


Unified Whole Body Control Framework
Task, Posture, Constraints, Multiple Contacts, and Balance



Unified Framework

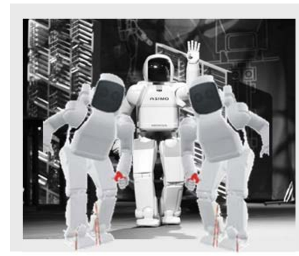
posture
consistent with {
task
consistent with {
contact
consistent with {
internal constraints
self collision
local obstacles
consistent with {
balance
} } } }



interact with the world, cooperate, and manipulate

Constraint-Consistent Task-Space

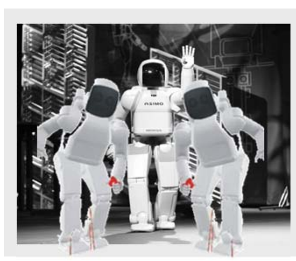
$\upsilon_\otimes \in cc - space$



interact with the world, cooperate, and manipulate

Constraint-Consistent Task-Space

$$\upsilon_\otimes = \begin{pmatrix} \upsilon_{c|s} \\ \upsilon_{f|c|s} \\ \upsilon_{m|f|c|s} \\ \upsilon_{p|m|f|c|s} \end{pmatrix}$$



interact with the world, cooperate, and manipulate

Unified Whole Body Control Framework

Task, Posture, Constraints, Multiple Contacts, and Balance

Dynamics

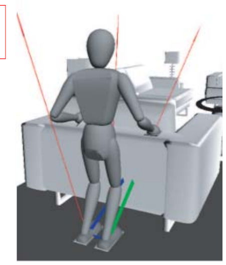
$$\boxed{\Lambda_\otimes \dot{\vartheta}_\otimes + \mu_\otimes + p_\otimes + F_f = F_\otimes}$$

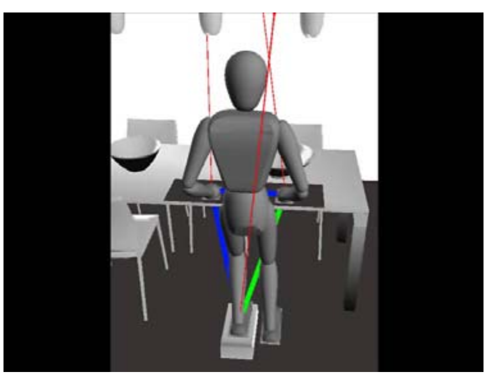
Control

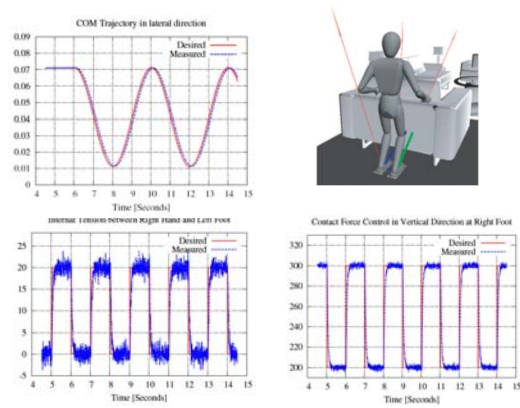
$$\boxed{F_\otimes = \hat{\Lambda}_\otimes F^*_\otimes + \hat{\mu}_\otimes + \hat{p}_\otimes}$$

Actuated Torques

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

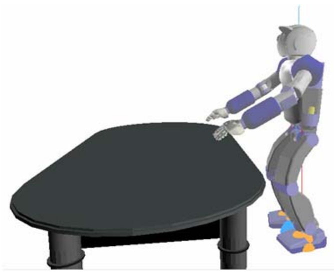


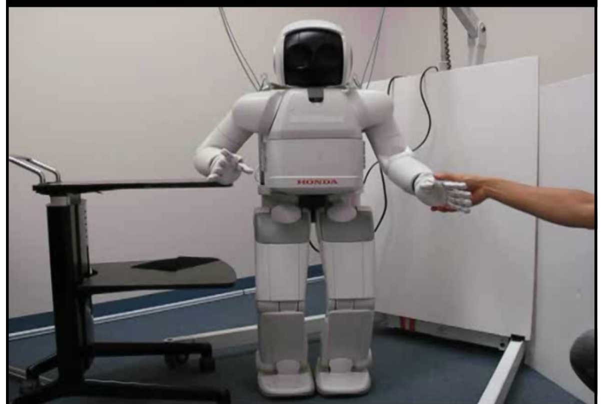


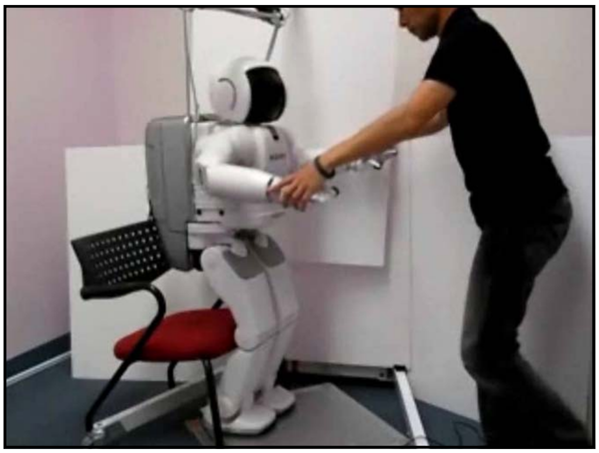


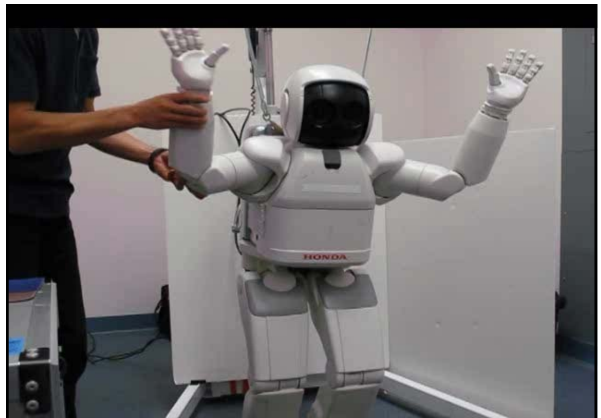
Unified Whole Body Control Framework

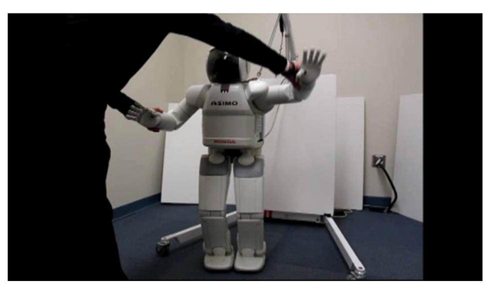
Task, Posture, Constraints, Multiple Contacts, and Balance

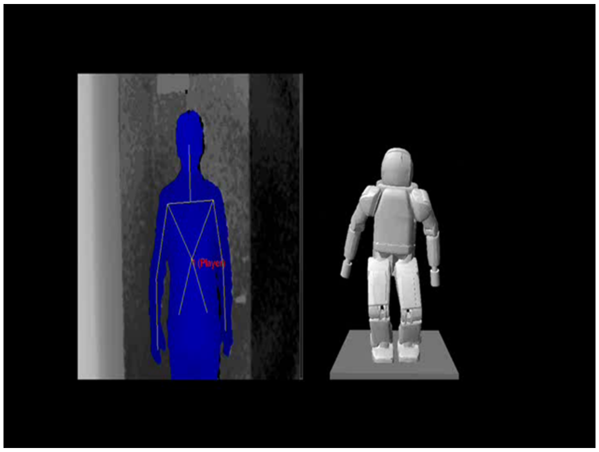




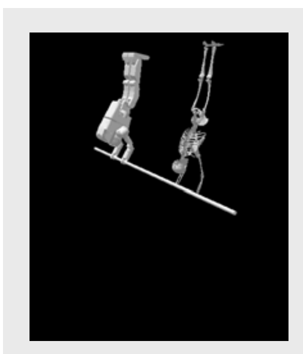








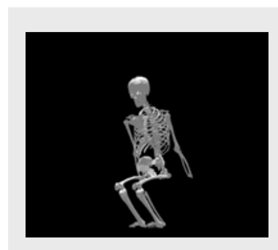
Human Movement



understanding
human movment

Simulation 79 DOF and 136 Muscles

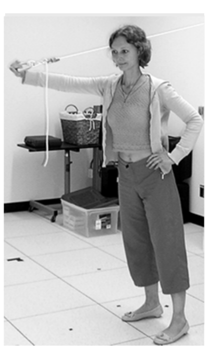
Biometric Data & Bone Geometry



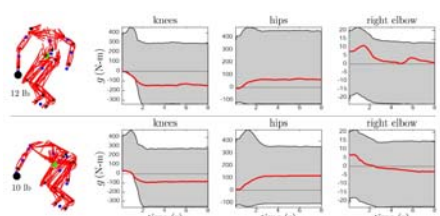
Dynamic simulation

Motion capture

Data from Subjects



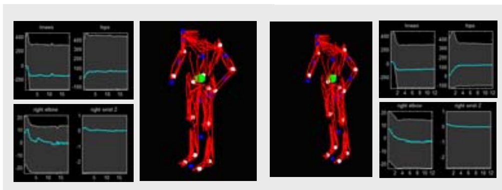
Physiology-based Posture Field



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

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

Data from Subjects

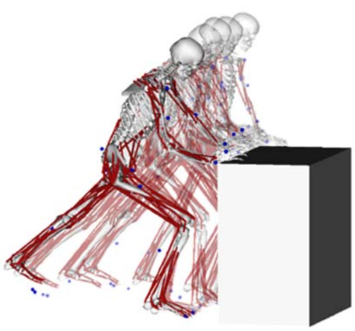


Learning from the Human

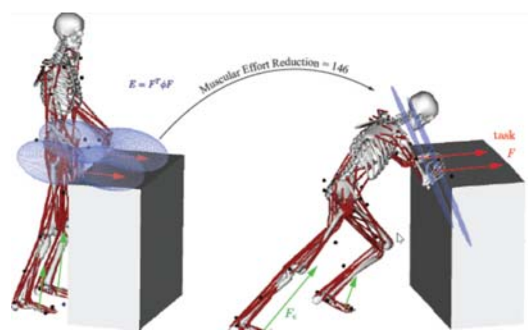
Humans grow to learn the efficiency of the body's *physio-mechanical advantage*

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

Physio-Mechanical Advantage



Physio-Mechanical Advantage



Physiology-based Posture Field

Human posture is continuously adjusted to reduce muscular effort

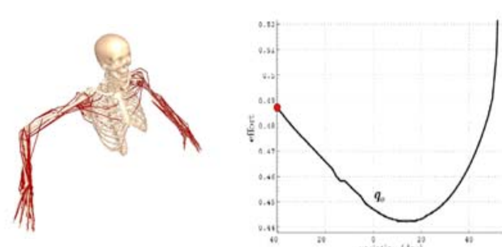
Muscular Energy minimization:

$$\boxed{E = cm^2}$$

Function of physiology, mechanical advantage, and task

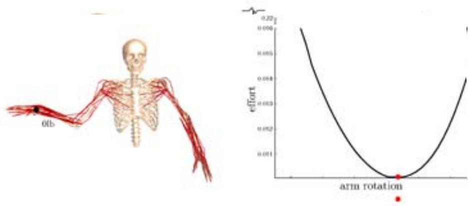
$$E = F^T[J(L^T N_c^{-2} L)^{-1} J^T]F \qquad E = F^T \Phi F$$

Validation - Arm Effort



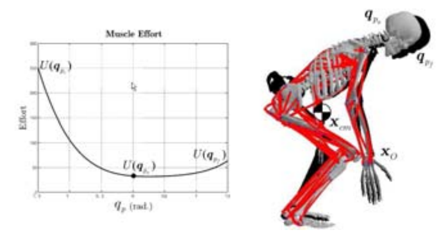
$$E = cm^2$$

Validation - Arm Effort



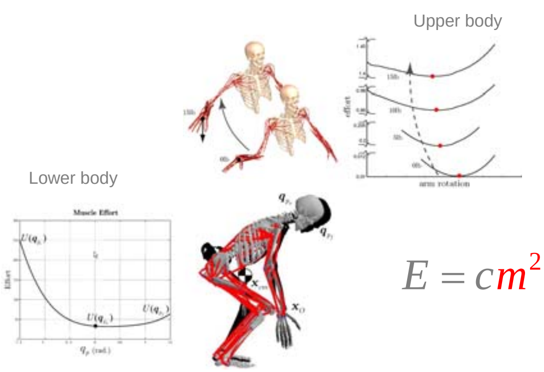
$$E = cm^2$$

Validation – whole-body effort

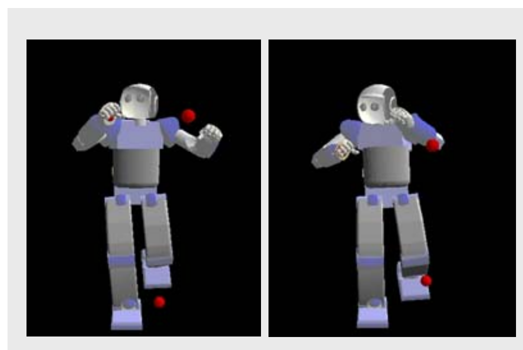


$$E = cm^2$$

Physio-Mechanical Advantage

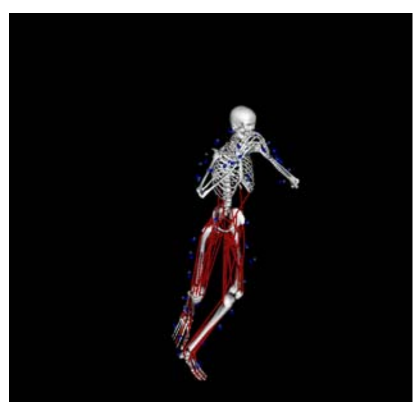


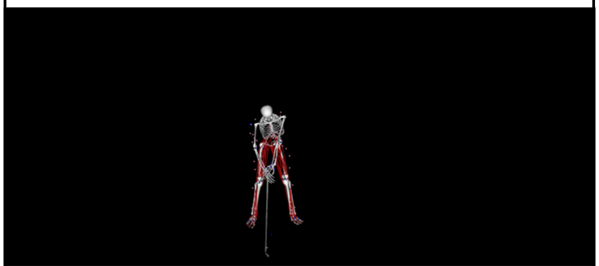
$$E = cm^2$$



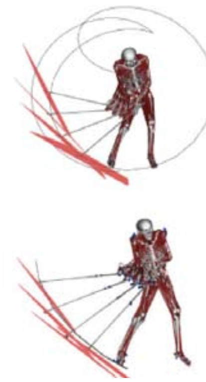
ASIMO

SAI Neuromuscular Library



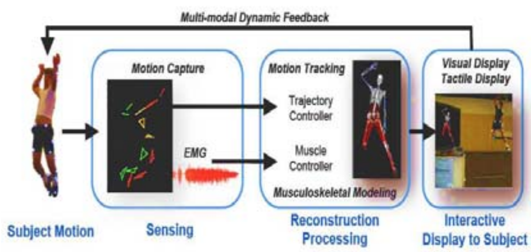


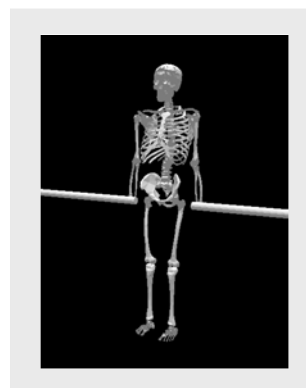
Human Motion Atlas

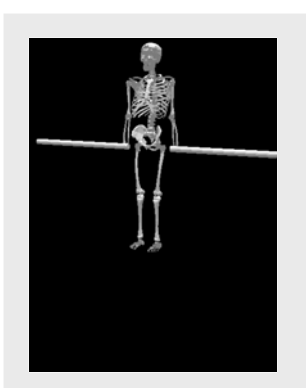


Human Motion Reconstruction

Injury prevention, Pathology Evaluation, and Athletics







Simulation 79 DOF and 136 Muscles

Biometric Data & Bone Geometry

Dynamic simulation

Motion capture