Exploiting Redundancy to Optimize the Task Space

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Source: Biomechanics at Manchester Metropolitan University

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What is she thinking about?

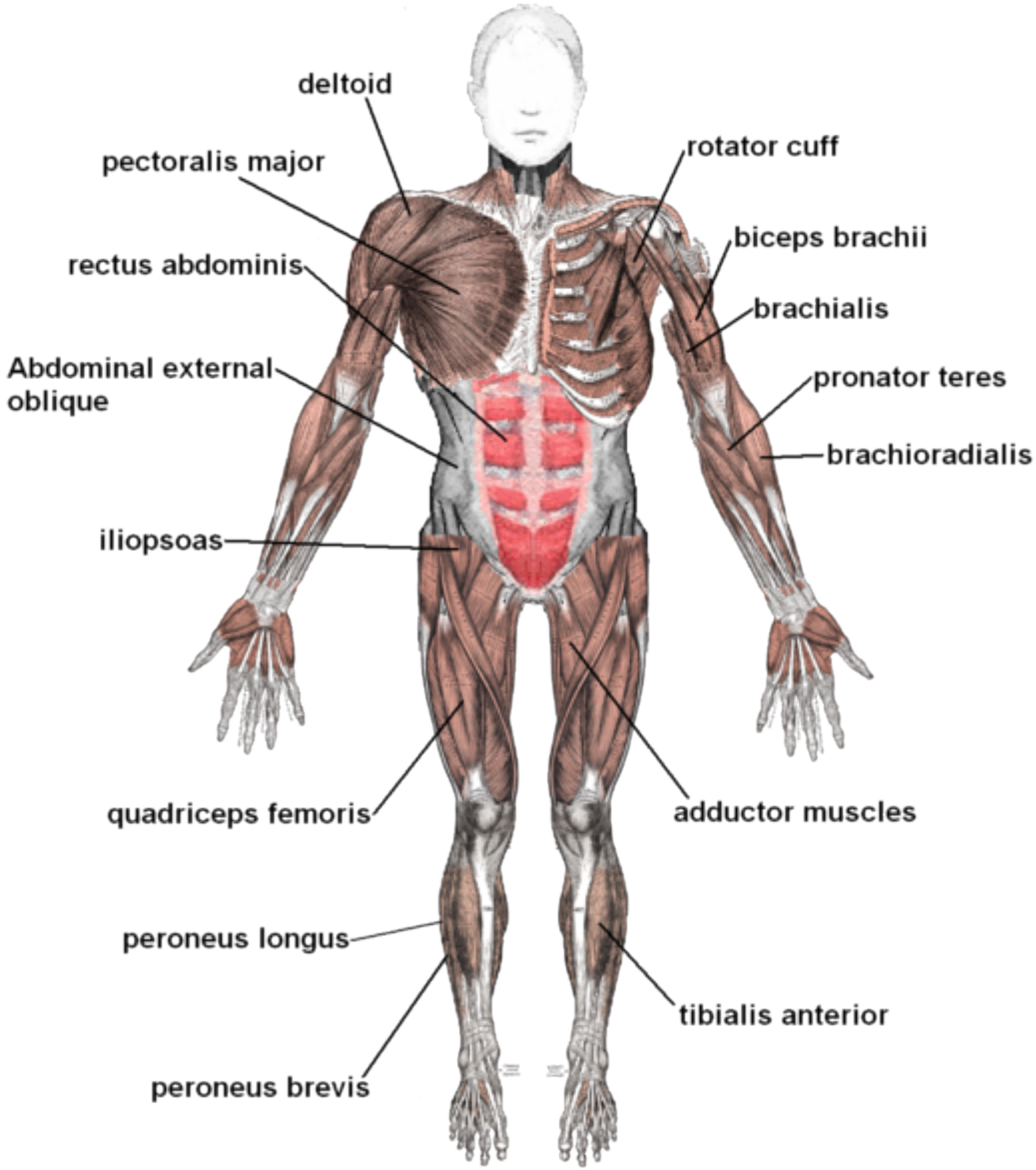
Likely she is focusing her attention on abstract task level objectives, and not the control of individual muscles, joints, etc.

Human Body: many DOFS

206 bones

360 joints (230 movable joints)

600-800 muscles



Source: Wikipedia

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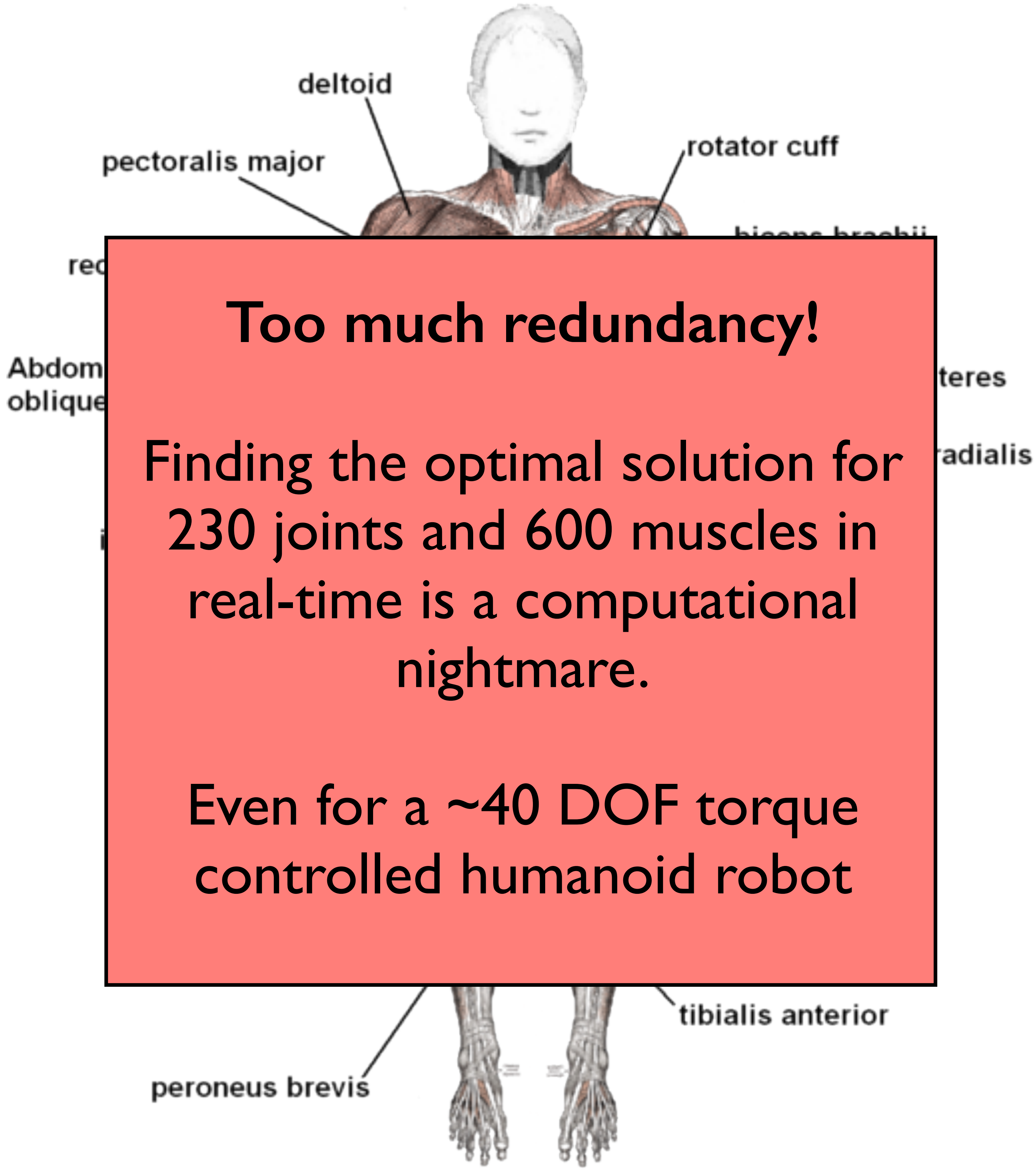

Too much redundancy!

Finding the optimal solution for 230 joints and 600 muscles in real-time is a computational nightmare.

Even for a ~40 DOF torque controlled humanoid robot

Source: Wikipedia

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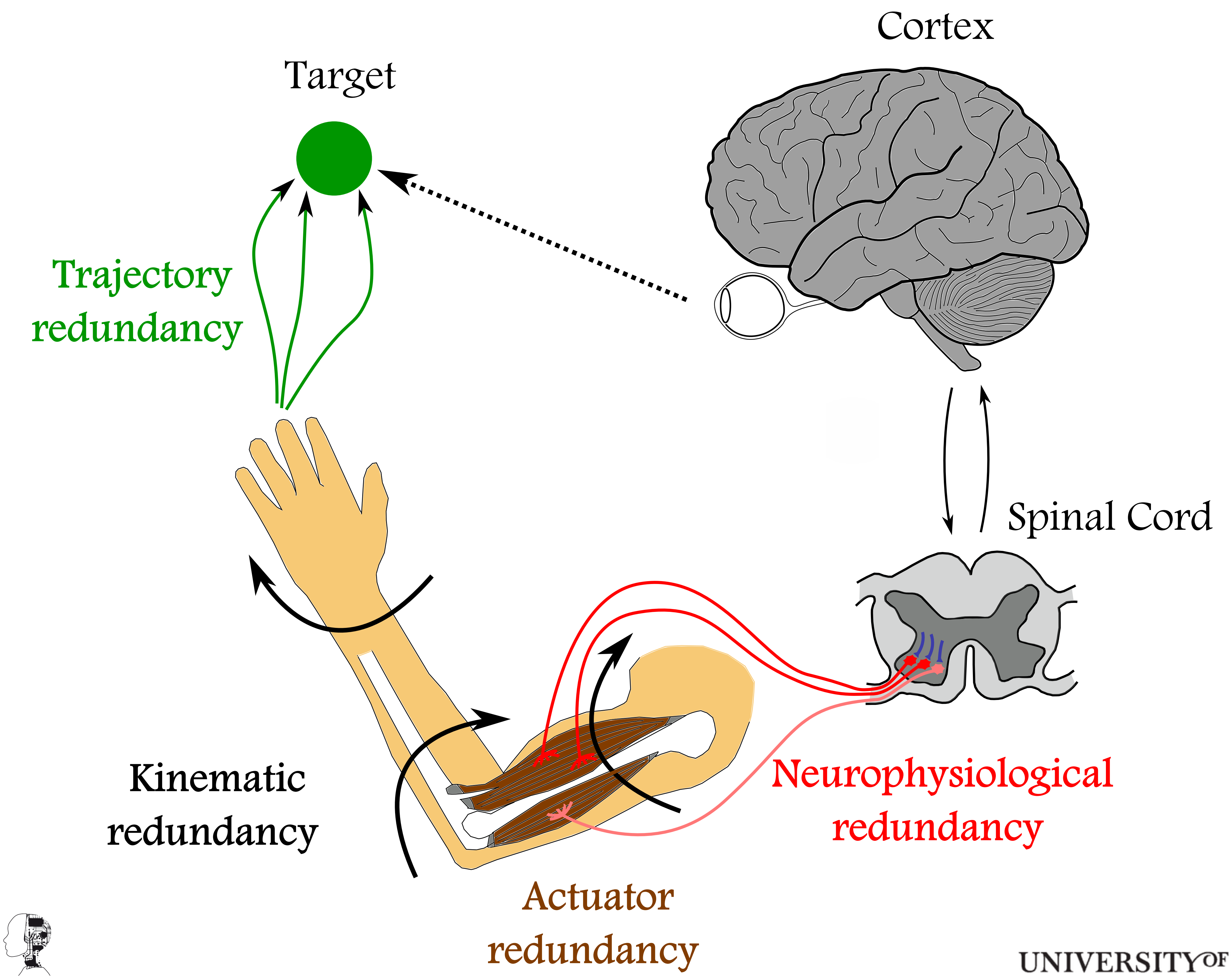
Types of redundancy in the motor system



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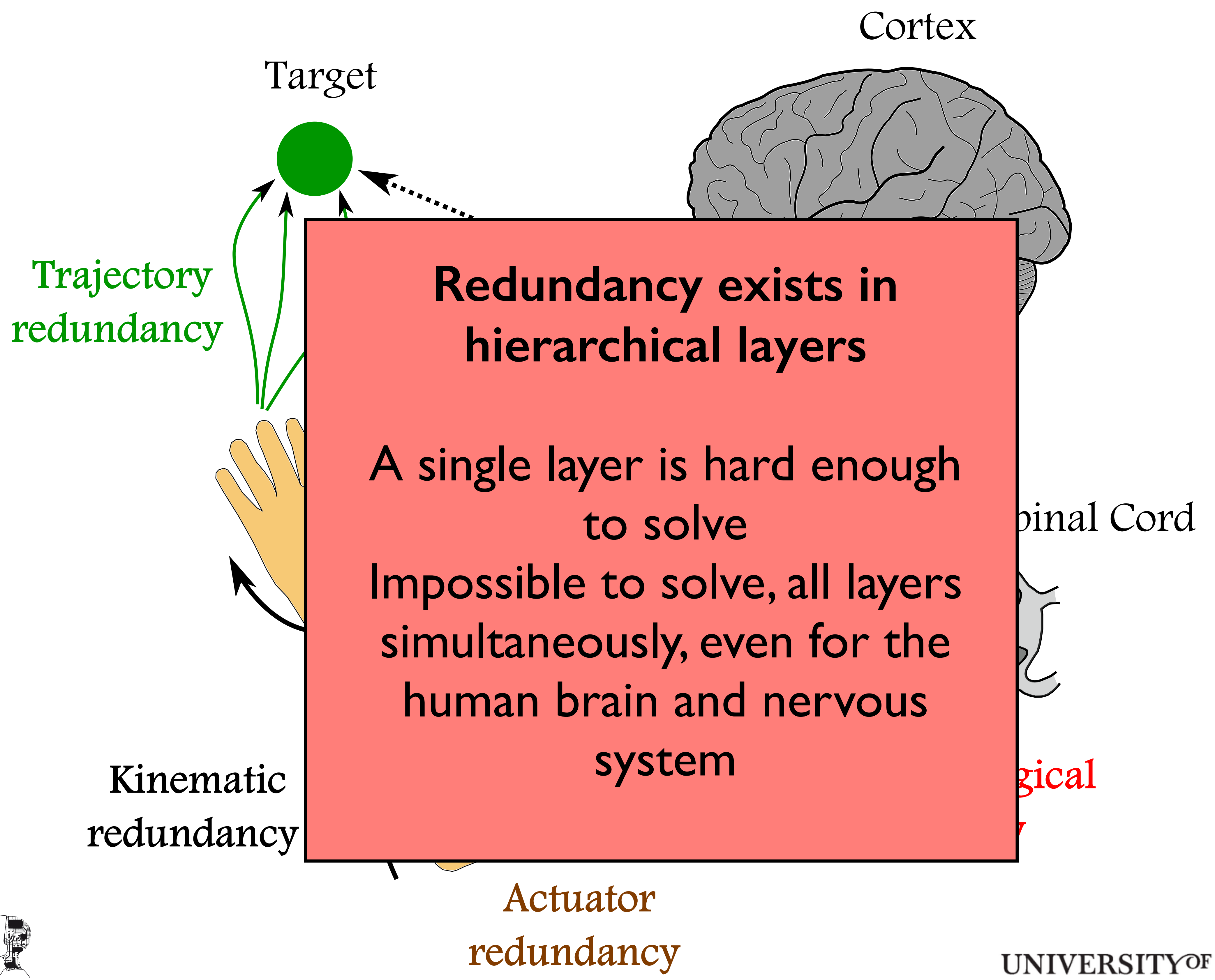

Redundancy exists in hierarchical layers

A single layer is hard enough to solve
Impossible to solve, all layers simultaneously, even for the human brain and nervous system

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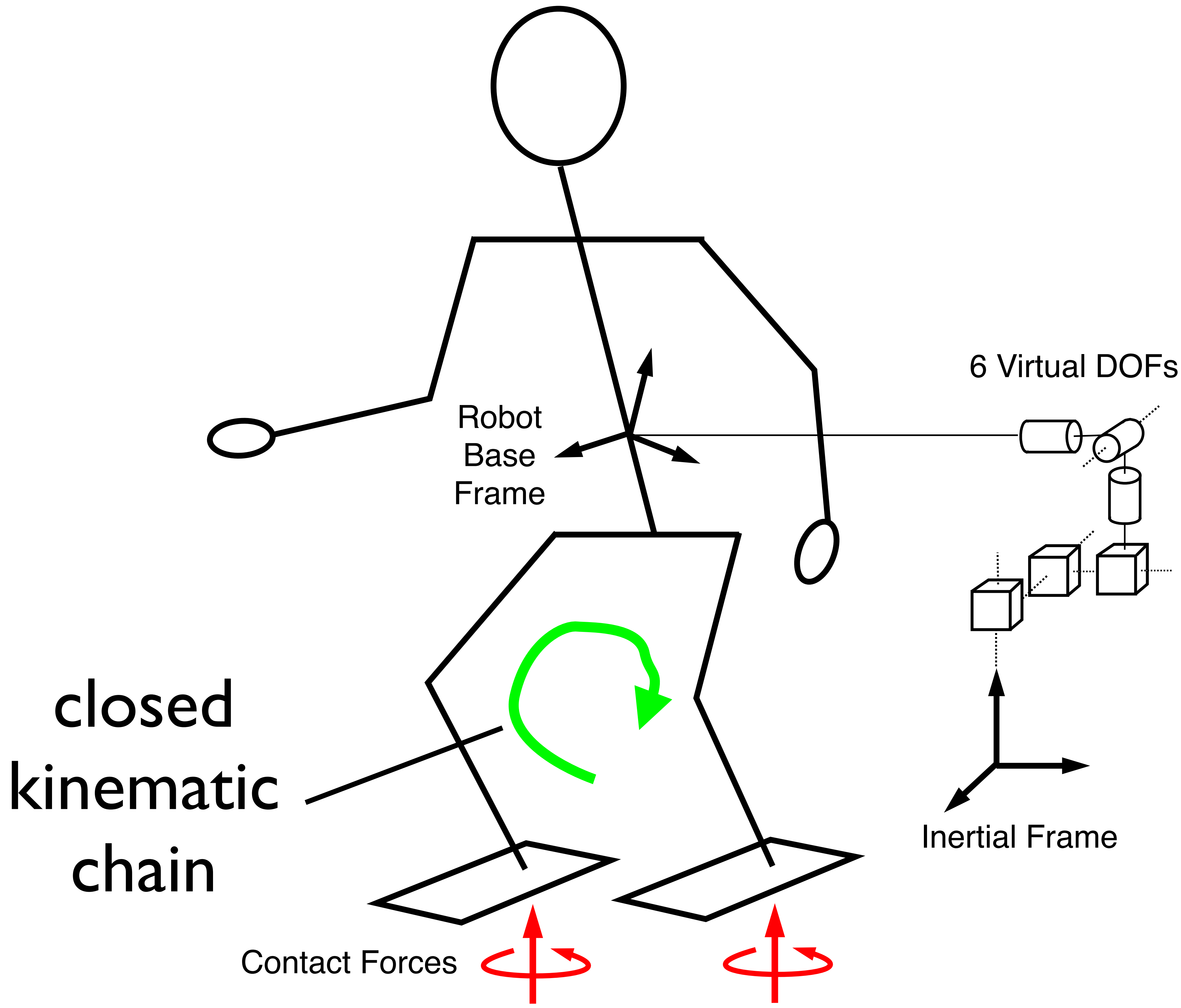
Even another type of redundancy: internal forces created by contact and closed kinematic chains

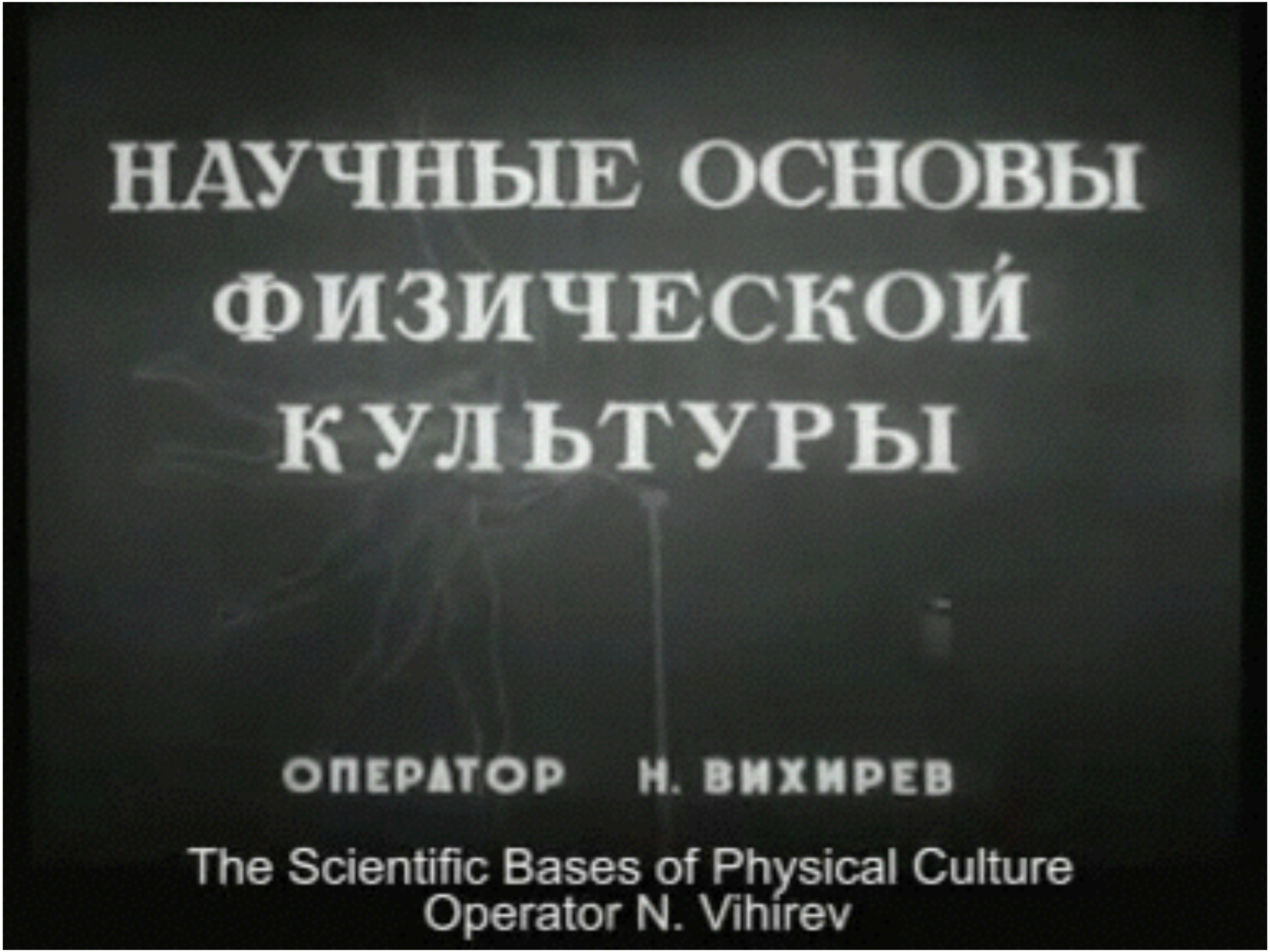
Apparent in whole-body dynamics:



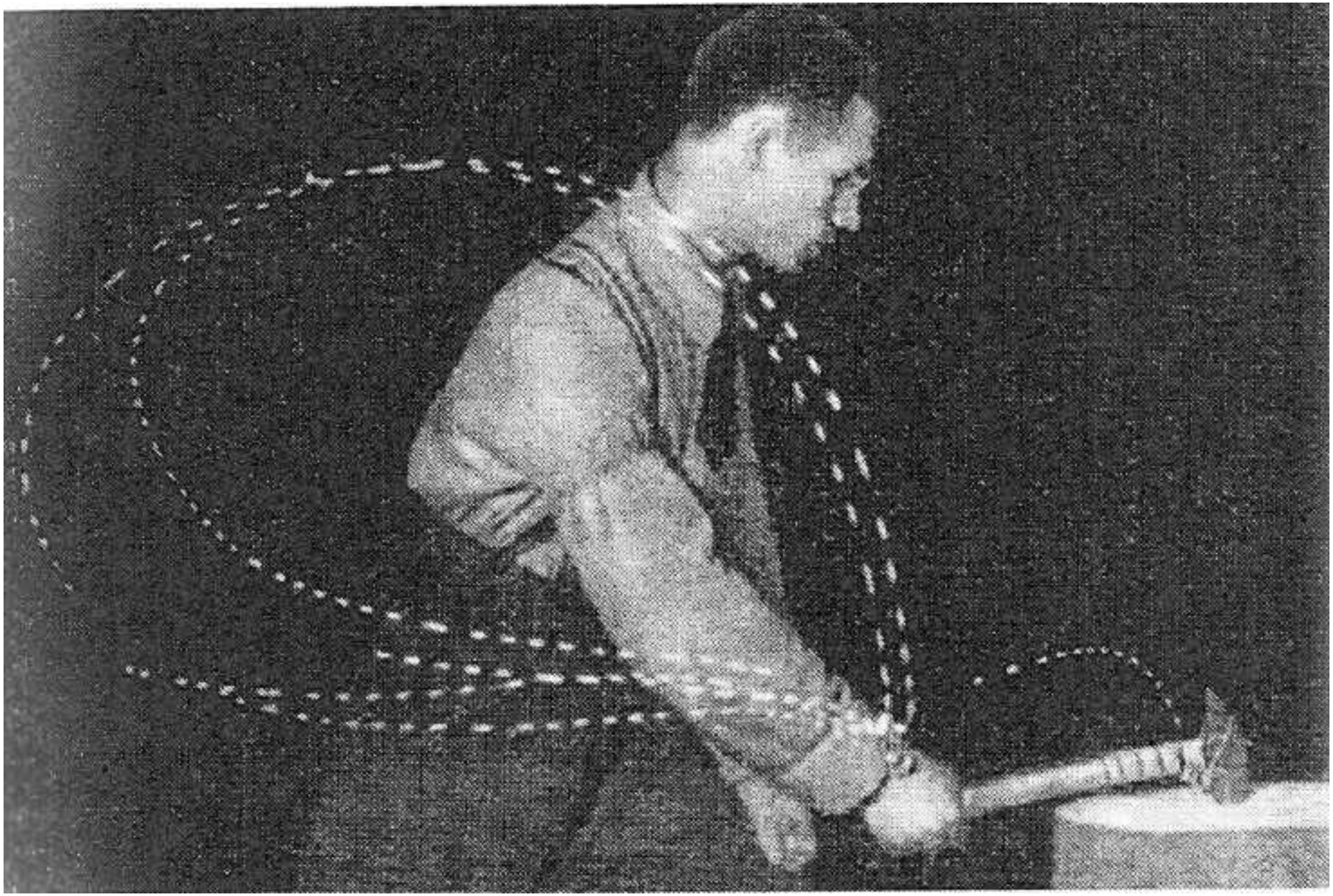
Nikolai Bernstein
(1896-1966)

Central Institute of Labour

One of the earliest researchers to study redundancy in the human motor system


НАУЧНЫЕ ОСНОВЫ
ФИЗИЧЕСКОЙ
КУЛЬТУРЫ
ОПЕРАТОР Н. ВИХИРЕВ
The Scientific Bases of Physical Culture
Operator N. Vihirev

A Bernstein Cyclograph:



Nikolai Bernstein
(1896-1966)

Degrees of Freedom Problem:

"It is clear that the basic difficulties for co-ordination consist precisely in the extreme abundance of degrees of freedom, with which the [nervous] centre is not at first in a position to deal."

One solution to the Degree-of-Freedom Problem:
Bernstein postulated that the nervous system may be functionally "freezing" joints to simplify the complexity.

Think about learning to ski:

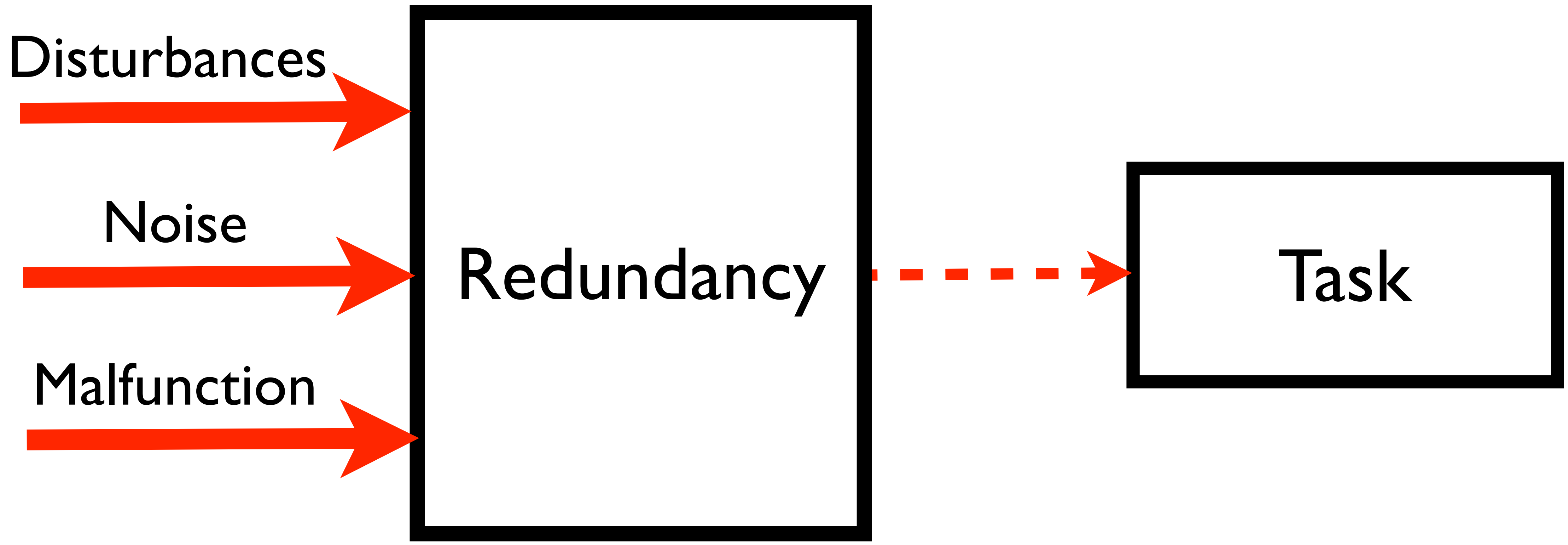
But really redundancy is quite useful:

Source: Christian Ott, DLR

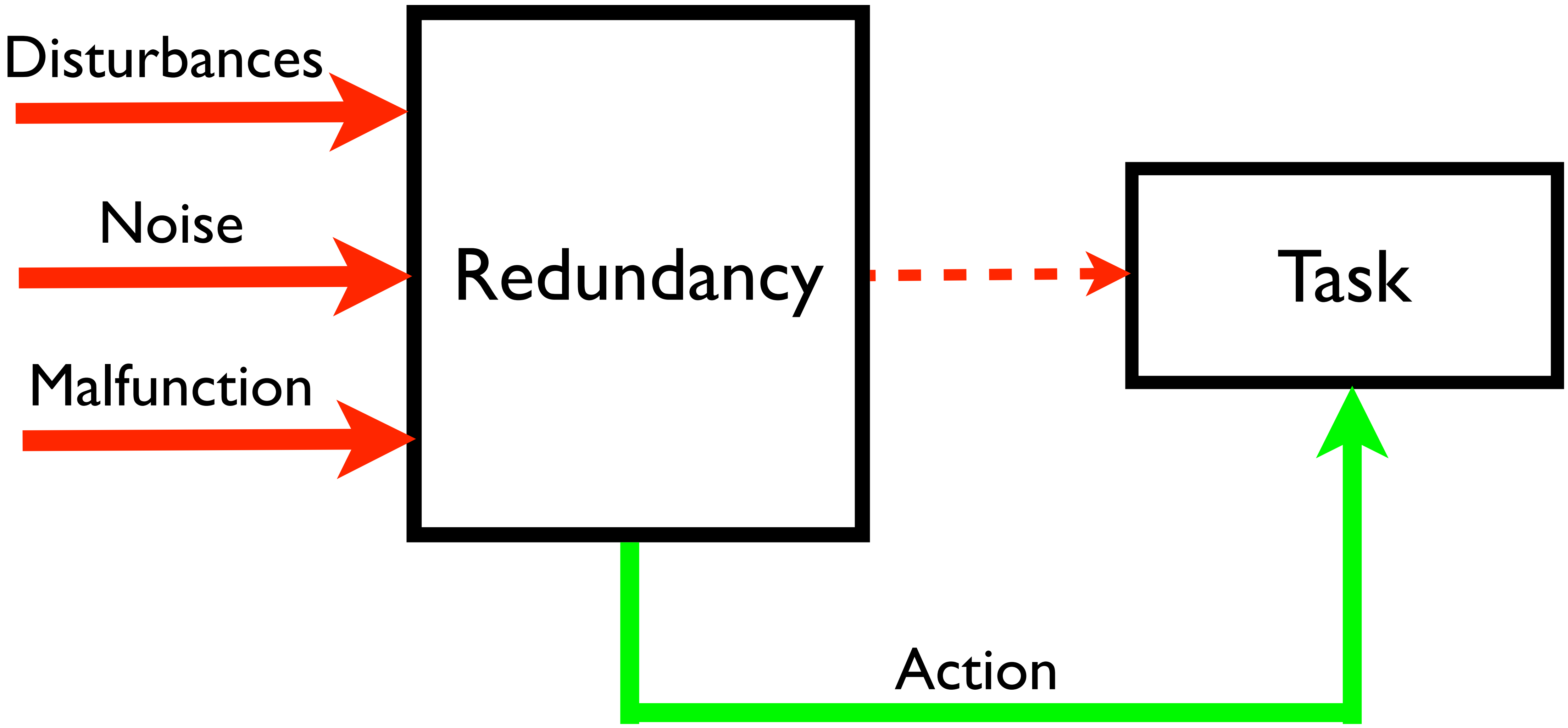
Whole body motion, a challenging problem:

- High degree of freedom
- Highly dynamic
- High cost of failure
- Underactuated
- Internal Model?
- Planning required
- Kinematically Redundant DOFs influence the task dynamics

Redundancy as “Filter” (or “Buffer”) protecting the task:



Redundancy as “adding action”



Operational Space Control (Khatib, 1987)

Assume rigid-body model of arm dynamics:

$$\mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{h}(\mathbf{q}, \dot{\mathbf{q}}) = \tau$$

Input torque

Inertia matrix

centrifugal, gravity, friction forces, etc.

joint position

Operational Space Control (Khatib, 1987)

Rigid Body dynamics: $\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{h}(\mathbf{q}, \dot{\mathbf{q}}) = \tau$

Task: $\mathbf{x} = f(\mathbf{q})$

$$\dot{\mathbf{x}} = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}}$$

We can *decouple* task and null-space forces:

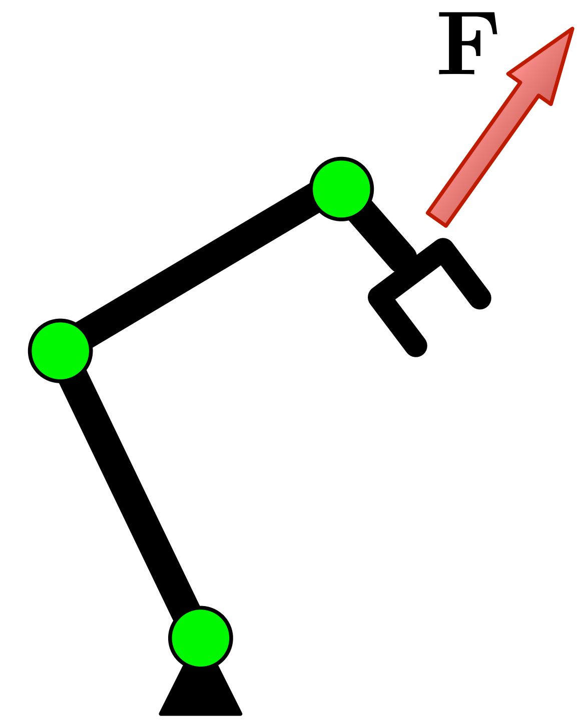
$$\tau = \tau_{\text{task}} + \tau_{\text{null}}$$

$$\tau = \mathbf{J}^T\bar{\mathbf{J}}^T\tau + \left(\mathbf{I} - \mathbf{J}^T\bar{\mathbf{J}}^T\right)\tau$$

$$\bar{\mathbf{J}} = \mathbf{M}^{-1}\mathbf{J}^T\left(\mathbf{J}\mathbf{M}^{-1}\mathbf{J}^T\right)^{-1}$$

We have a tool to compute redundant *forces* and *dynamics*

Operational Space Control (Khatib 1987)

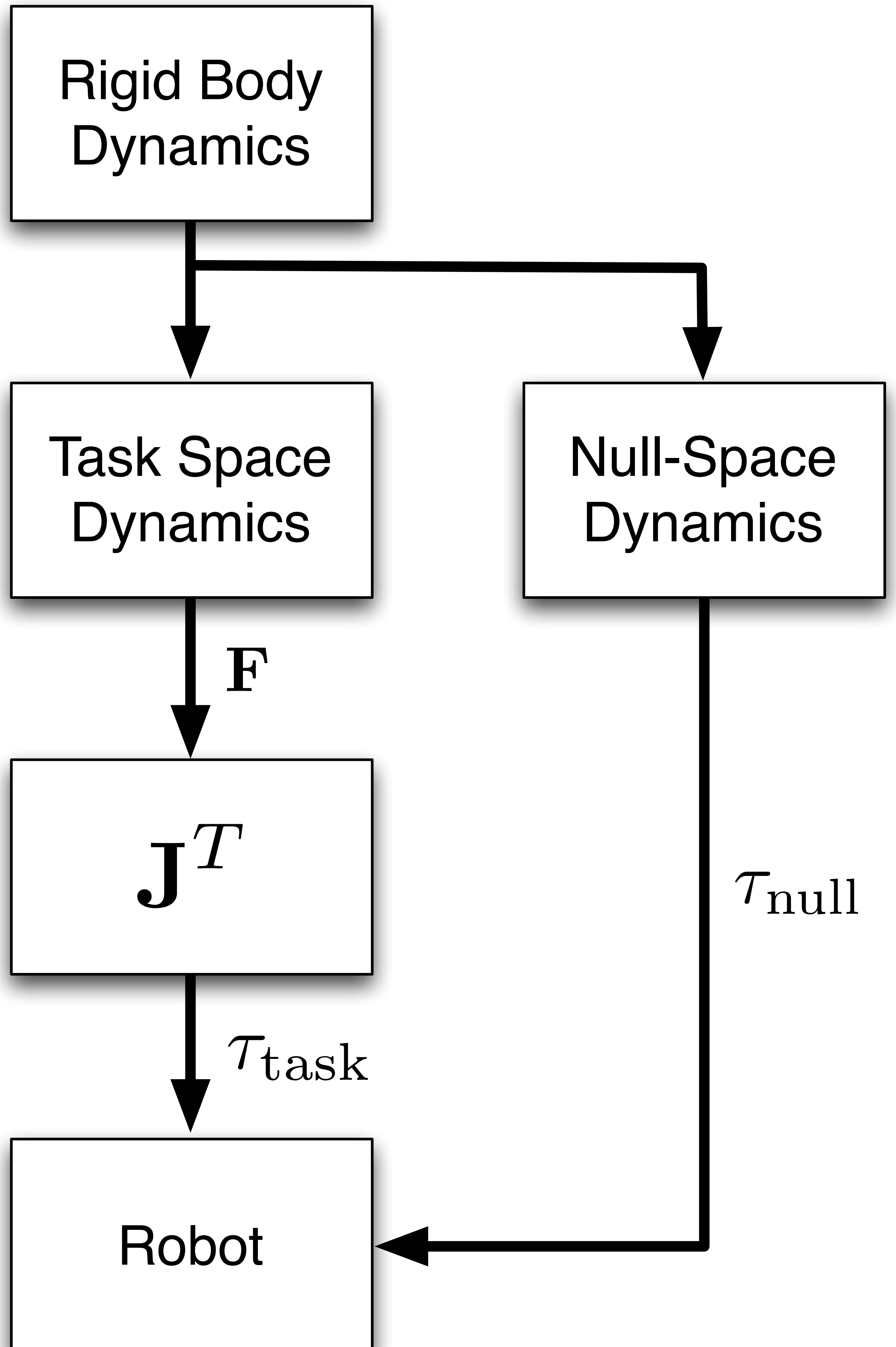


$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{h}(\mathbf{q},\dot{\mathbf{q}}) = \tau$$

$$\boldsymbol{\Lambda}\ddot{\mathbf{x}} + \boldsymbol{\Lambda}\left(\mathbf{J}\mathbf{M}^{-1}\mathbf{h} - \dot{\mathbf{J}}\dot{\mathbf{q}}\right) = \mathbf{F}$$

$$\boldsymbol{\Lambda} = \left(\mathbf{J}\mathbf{M}^{-1}\mathbf{J}^T\right)^{-1}$$

$$\tau = \mathbf{J}^T\mathbf{F}$$



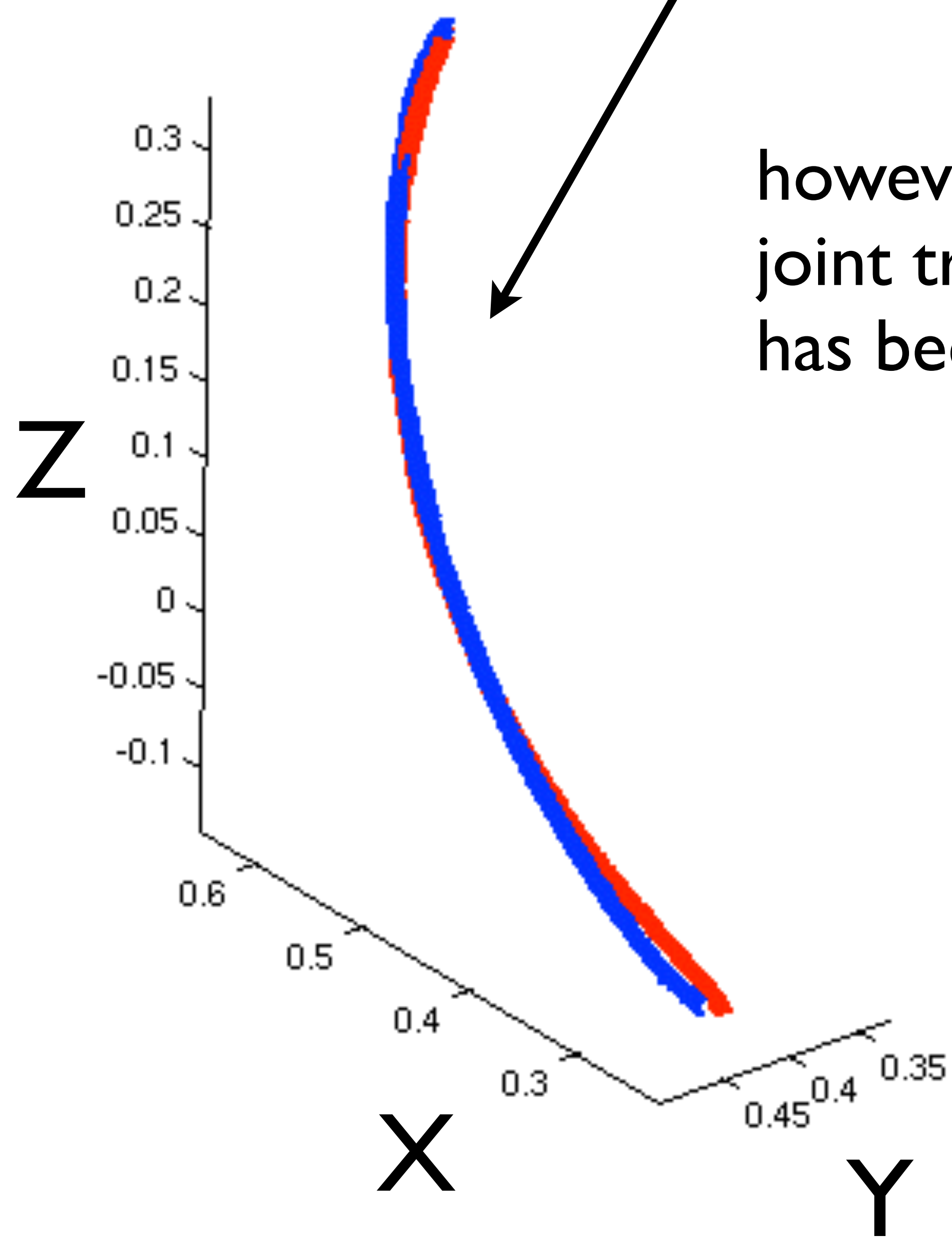
Could the Brain be doing some form of Operational Space Control?

Mistry, M.;Mohajerian, P.;Schaal, S. (2005). Arm movement experiments with joint space force fields using an exoskeleton robot, *IEEE Ninth International Conference on Rehabilitation Robotics*, pp.408-413

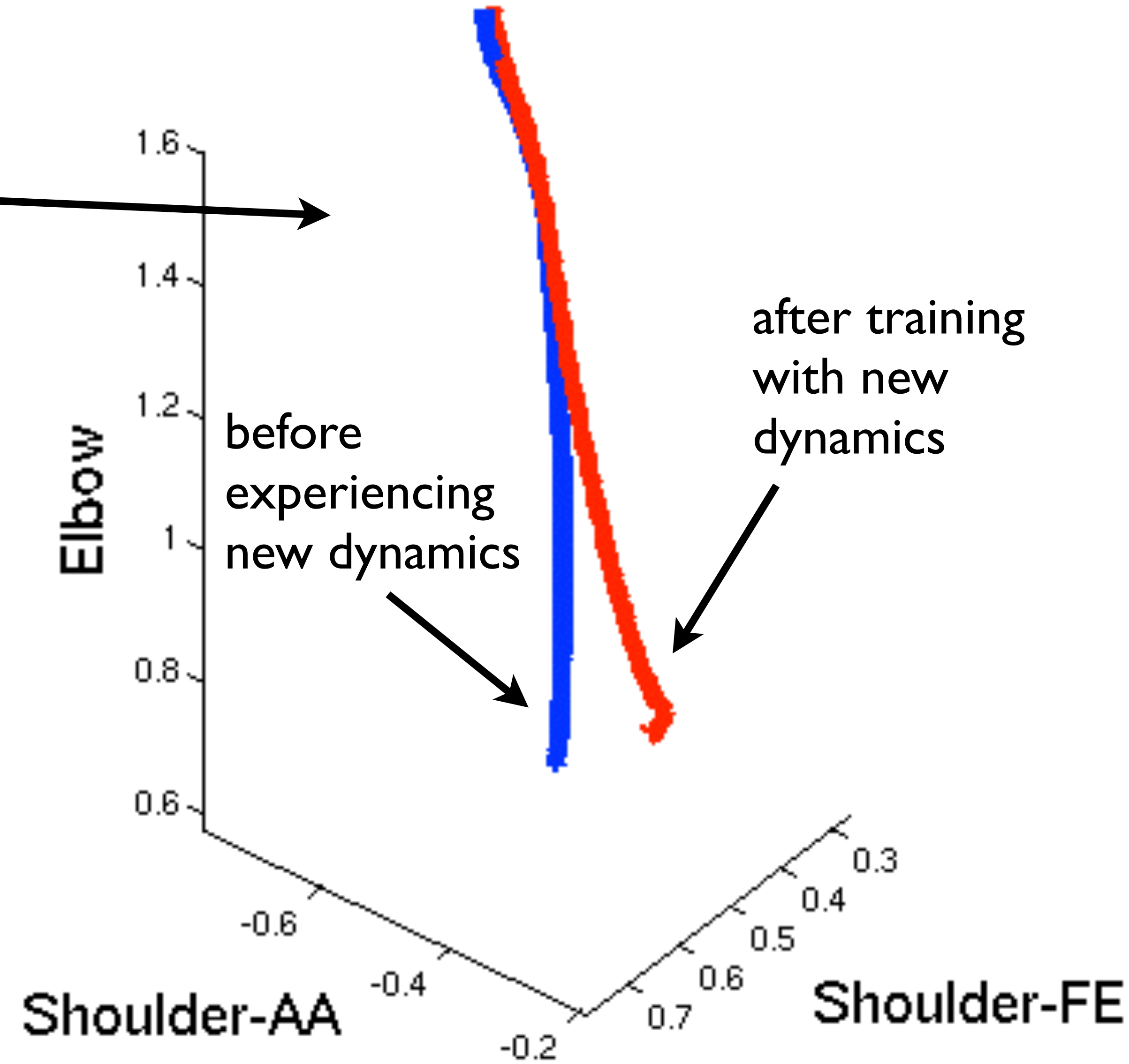
Result:

subjects learn to compensate for the extraneous dynamics, and (after sufficient training) return hand paths to nominal

however, their joint trajectory has been altered



Hand Trajectory



Joint Trajectory

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How to explain what's happening?

The hypothesis: subjects are only learning internal models of *task-relevant* components of the force field

Operational Space Control

Formulate the arm controller as an operational space controller:

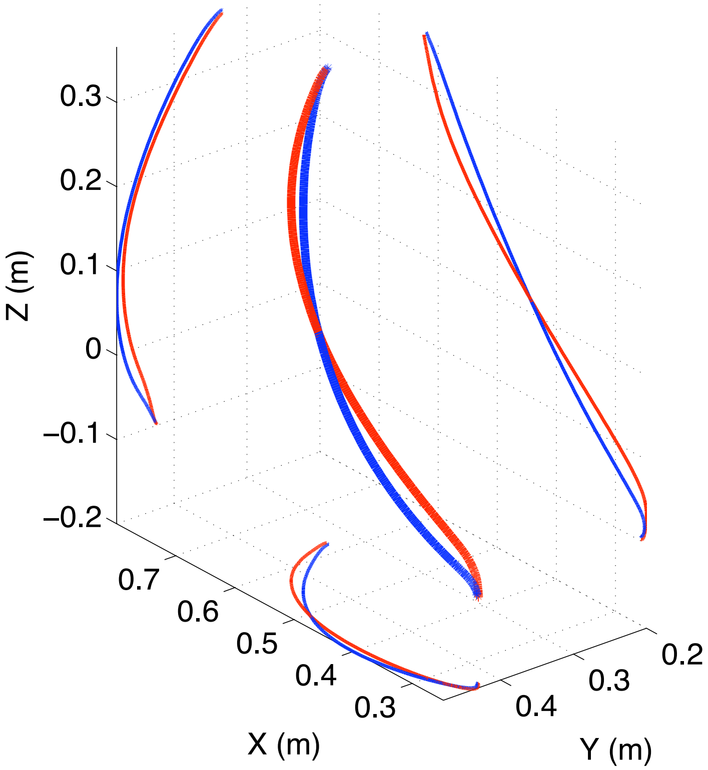
$$\tau = \mathbf{J}^T \bar{\mathbf{J}}^T \left(\hat{\mathbf{M}} \mathbf{J}^+ \left(\ddot{\mathbf{x}}_d - \dot{\mathbf{J}} \dot{\mathbf{q}} \right) + \mathbf{D} \dot{\mathbf{q}} \right) + \hat{\mathbf{h}} + K_P \left(\mathbf{q}_d - \mathbf{q} \right) + K_D \left(\dot{\mathbf{q}}_d - \dot{\mathbf{q}} \right)$$

desired task trajectory

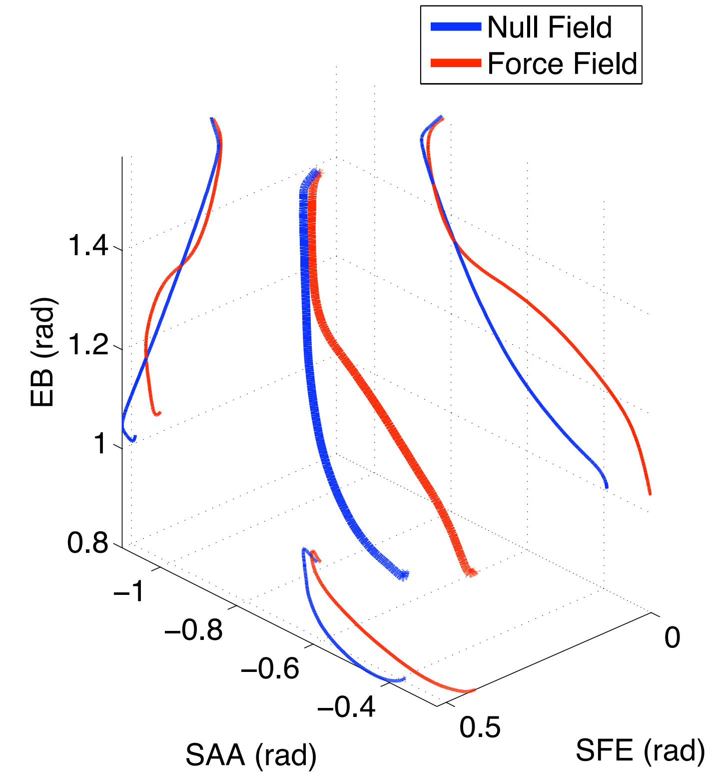
Only the task relevant forces of the force field are compensated.

Humans only learn and compensate for the task *relevant* component of the novel dynamics.

Actual data from subject:



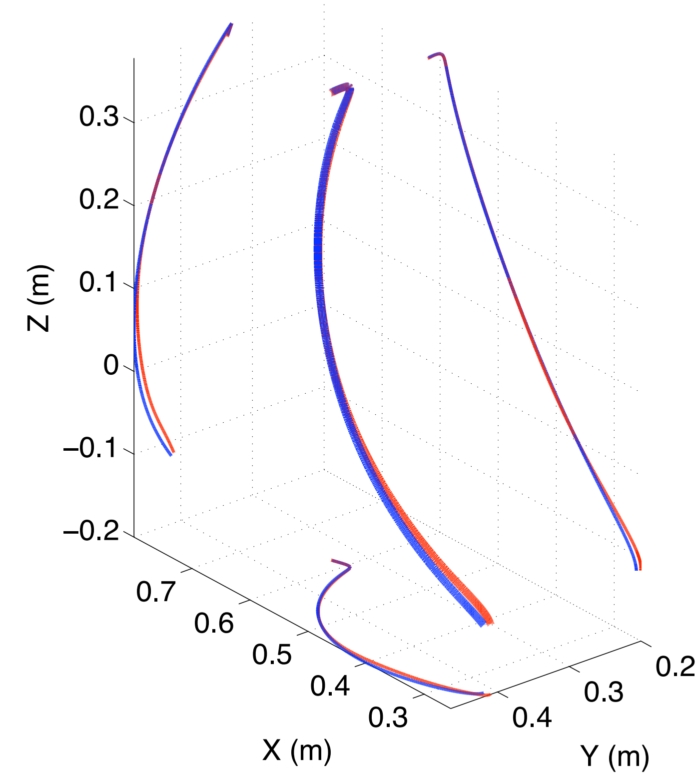
Hand



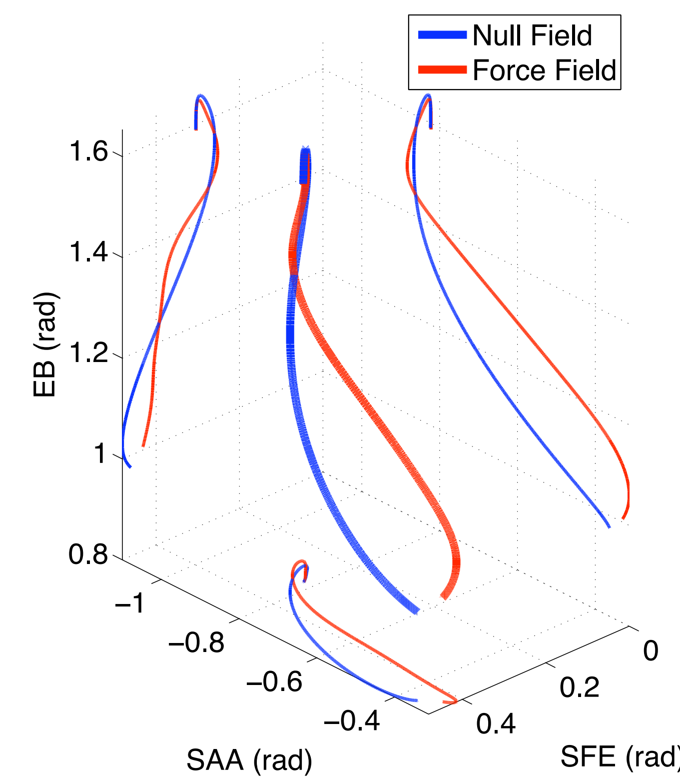
Joints

We test this hypothesis in simulation, using a model of arm dynamics and a *task-space* controller

Simulated results:



Hand



Joints

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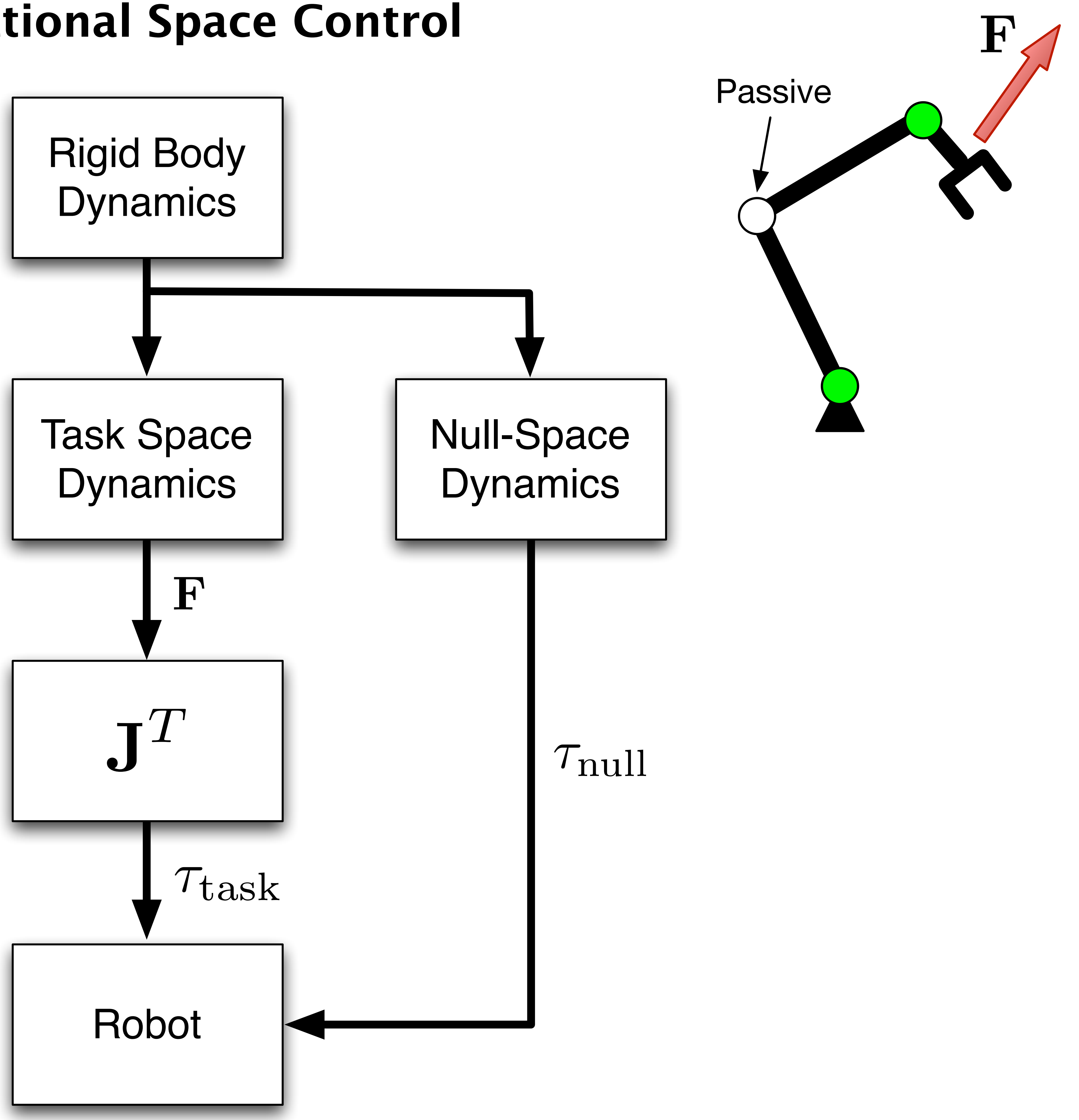
Back to Gymnastics:

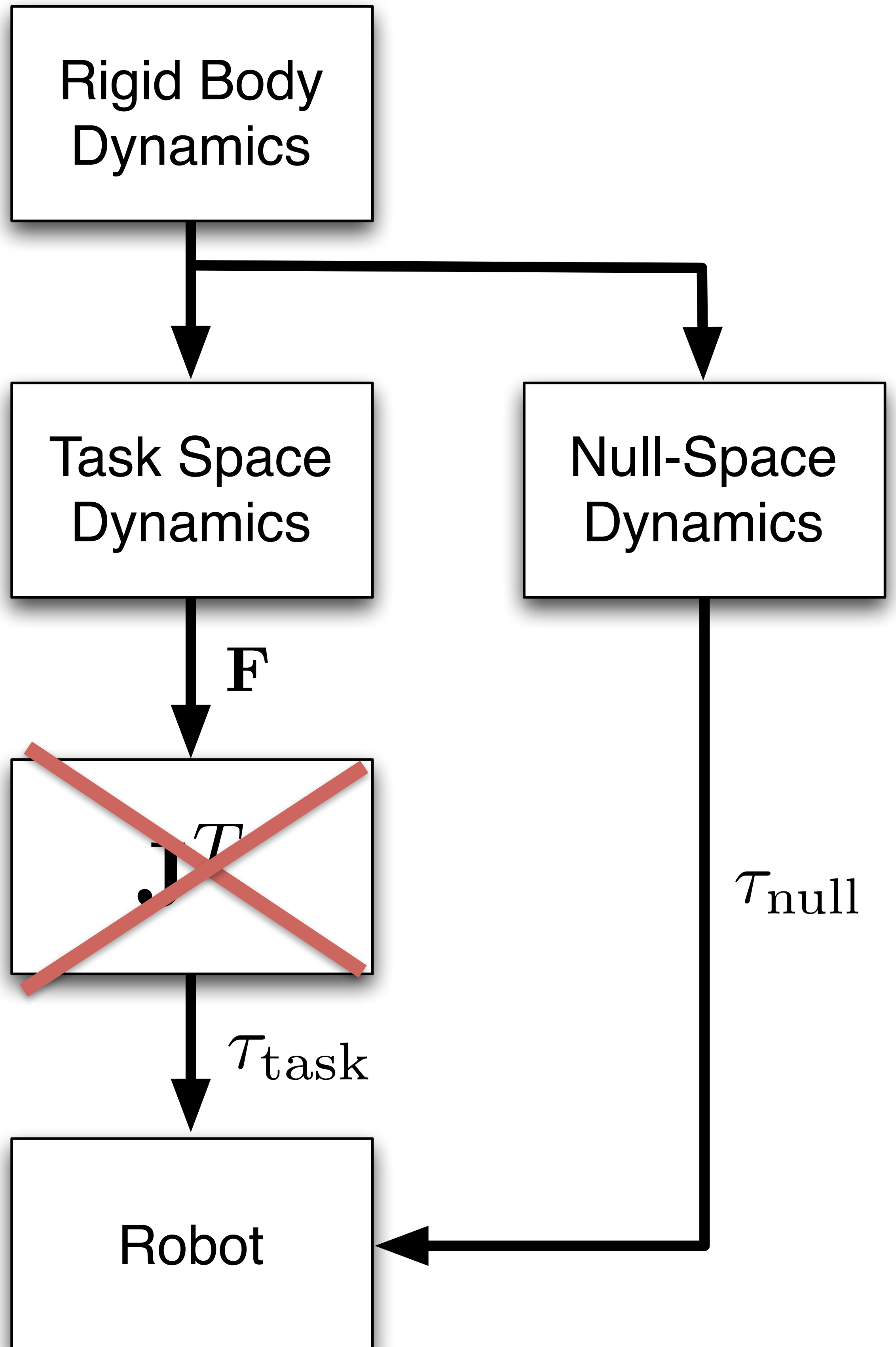
- High degree of freedom
- Highly dynamic
- High cost of failure
- Underactuated
- Internal Model?
- Planning required
- Kinematically Redundant DOFs influence the task dynamics

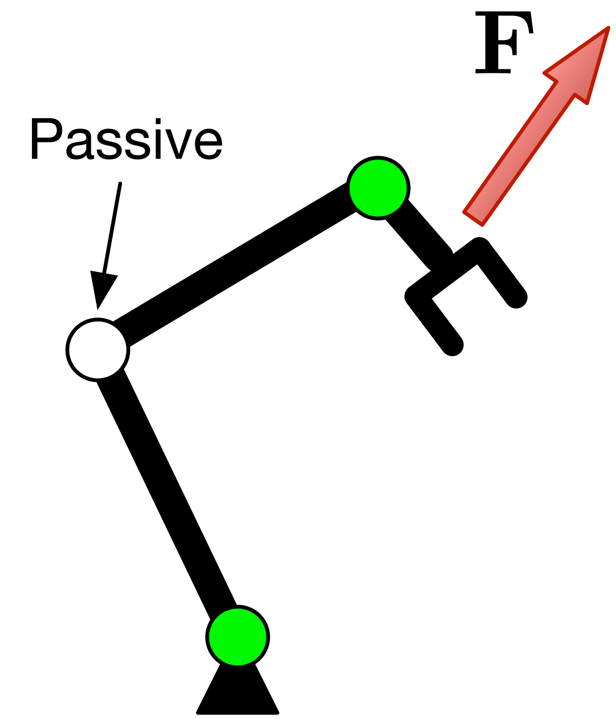
Underactuated Operational Space Control



Mistry and Righetti, Operational Space Control of Constrained and Underactuated Systems, RSS 2011

Underactuated Operational Space Control

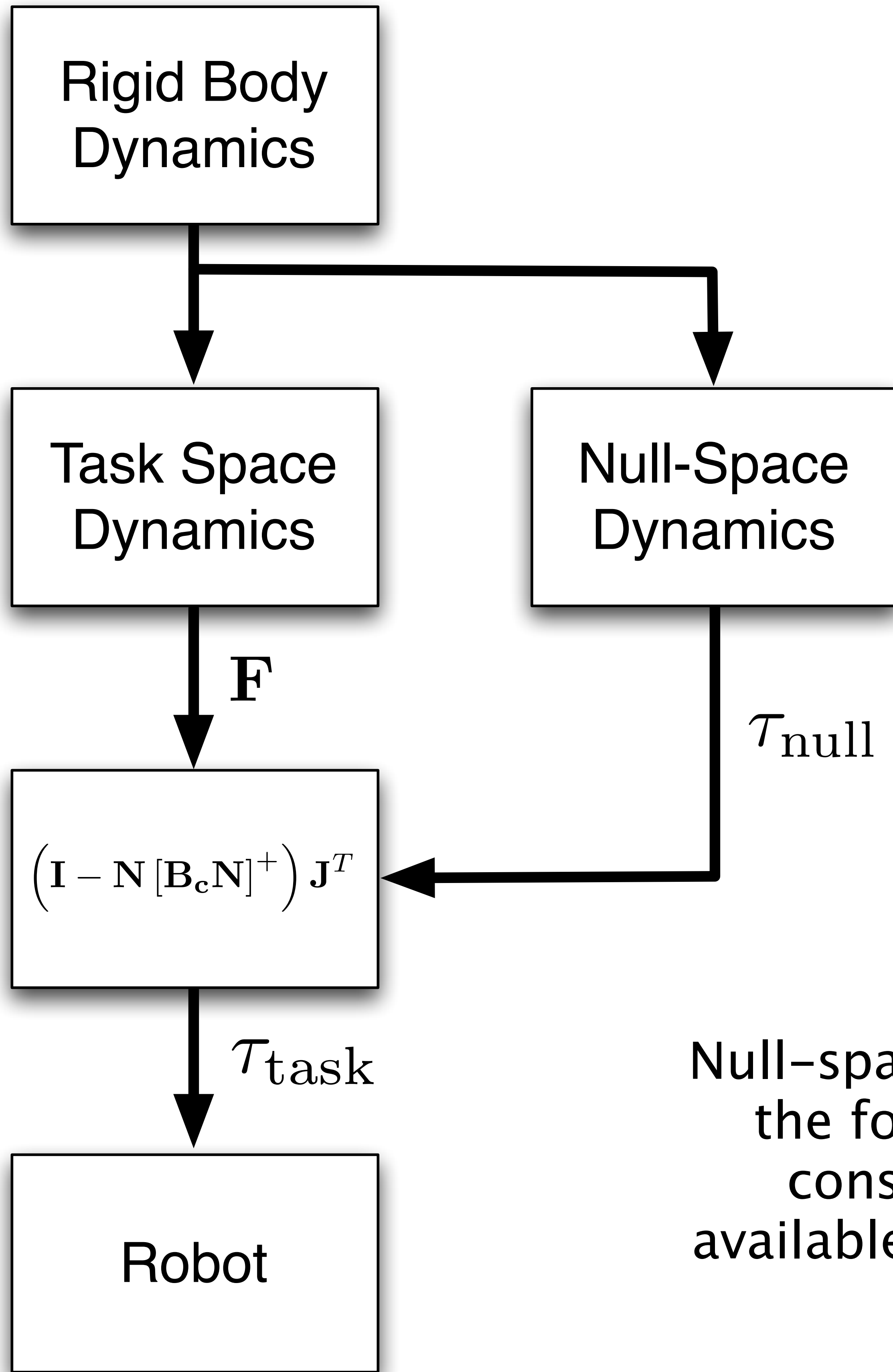


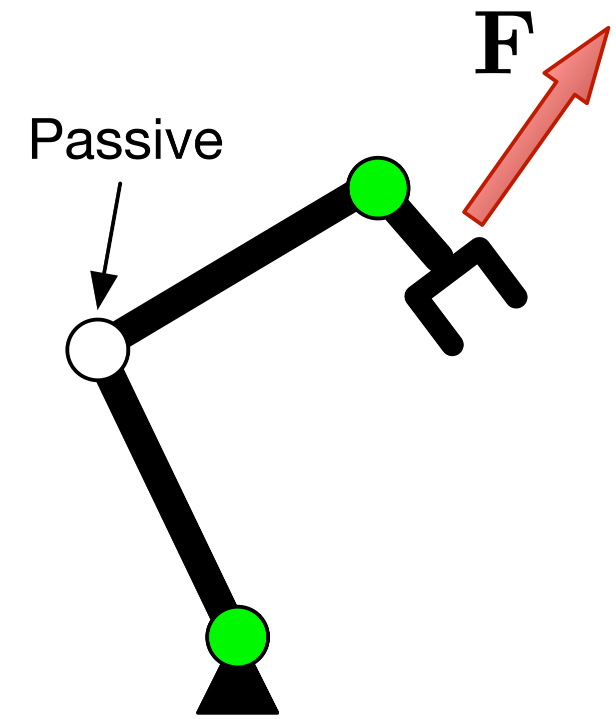


Passive joints do not allow for a direct mapping of end-effector force into joint torques

Mistry and Righetti, Operational Space Control of Constrained and Underactuated Systems, RSS 2011

Underactuated Operational Space Control





Use null-space forces to indirectly apply torque at passive DOFs.

Null-space forces can be in the form of additional constraint forces (if available) or task irrelevant motion

Mistry and Righetti, Operational Space Control of Constrained and Underactuated Systems, RSS 2011

Underactuated Operational Space Control

$$\tau = \mathbf{J}^T\mathbf{F} + \mathbf{N}\tau_0 \qquad\qquad \tau = \mathbf{B}\tau$$

$$\mathbf{B} = \begin{bmatrix} \mathbf{I}_p & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}$$

$$\mathbf{J}^T\mathbf{F} + \mathbf{N}\tau_0 = \mathbf{B}\mathbf{J}^T\mathbf{F} + \mathbf{B}\mathbf{N}\tau_0$$

$$\tau_0 = -\left[(\mathbf{I} - \mathbf{B})\,\mathbf{N}\right]^+ (\mathbf{I} - \mathbf{B})\,\mathbf{J}^T\mathbf{F}$$

$$\tau = \left(\mathbf{I} - \mathbf{N}\left[(\mathbf{I} - \mathbf{B})\,\mathbf{N}\right]^+\right)\mathbf{J}^T\mathbf{F}$$

Generate torque at passive DOFs via inherent dynamic coupling
Similar to Partial Feedback Linearization

Mistry and Righetti, Operational Space Control of Constrained and Underactuated Systems, RSS 2011

Planning behaviors

Operational Space Control structures the problem, such that we can search for a solution in the lower dimensional task space:

$$\tau = \left(\mathbf{I} - \mathbf{N}\left[(\mathbf{I} - \mathbf{B})\,\mathbf{N}\right]^{+}\right)\mathbf{J}^{T}\mathbf{F}$$

search in F "space" instead of τ

One interesting application: control of an “floating base” manipulator for nuclear decommissioning

BROKK®

National Nuclear Laboratory

Conclusions:

Too many DOFs in the human body

Solving redundancy is a computational "problem"

However this redundancy can also be exploited, *to assist the task.*

Thinking about the structure of these problems, e.g. the operational space, helps us do this.