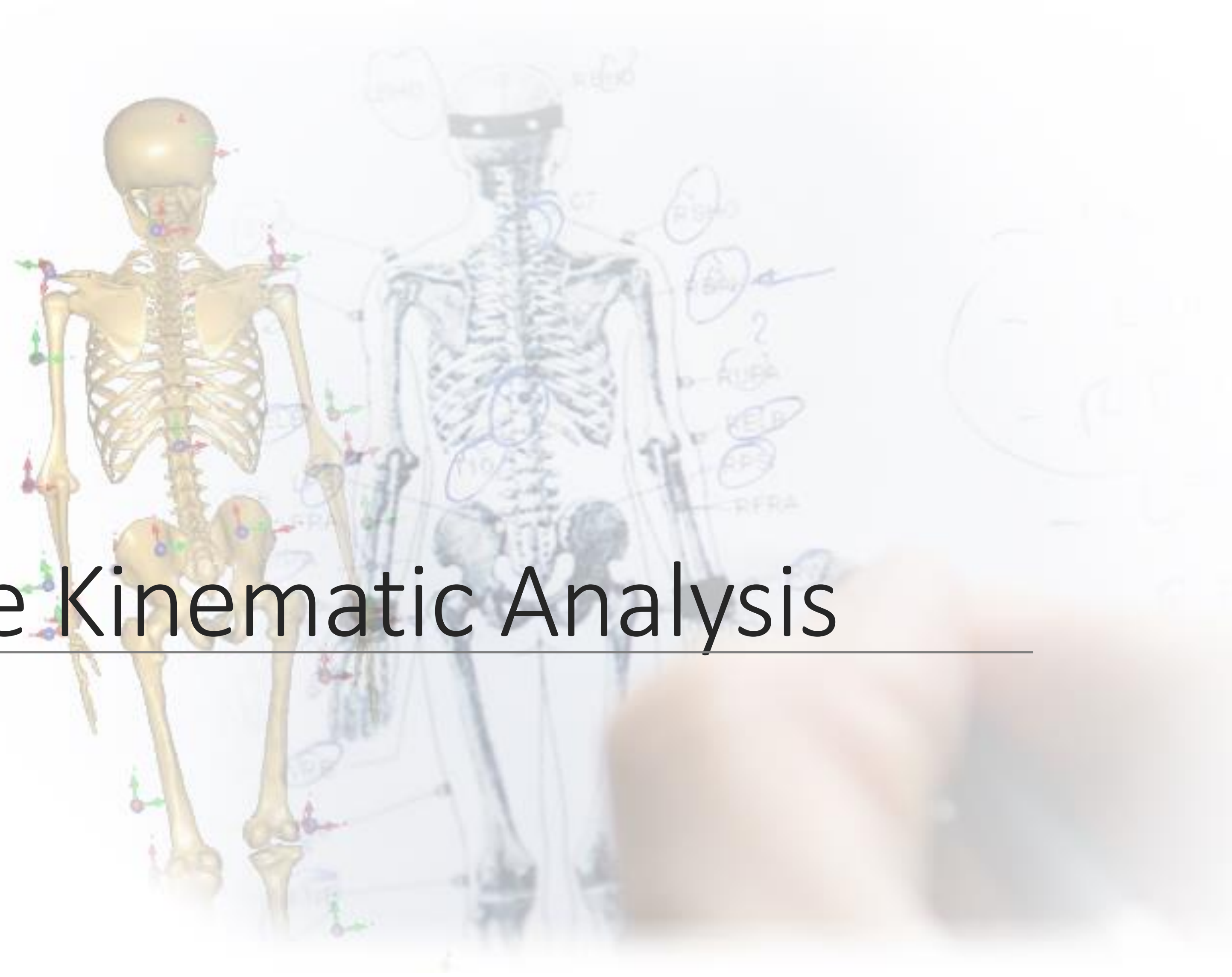
The webcast will start in a few minutes….



Over-determinate Kinematic Analysis

FOR MUSCULOSKELETAL MODELING

Outline

- General introduction to the modeling system
- The math over-determinate kinematics
- Applications to musculoskeletal models.
- Final words and Q&A session.

John Rasmussen
Professor, PhD
Aalborg University

Michael Skipper Andersen
Assoc. Professor, PhD
Aalborg University

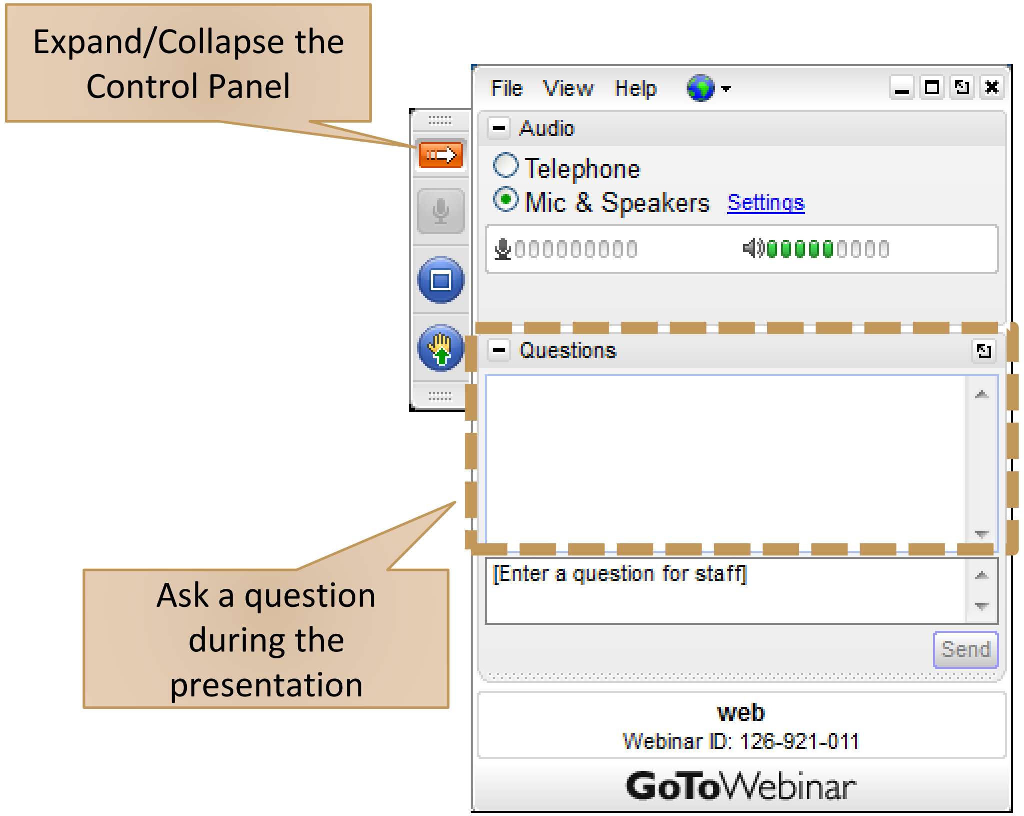
Host:
Ananth Gopalakrishnan, PhD
AnyBody Technology

Control Panel

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

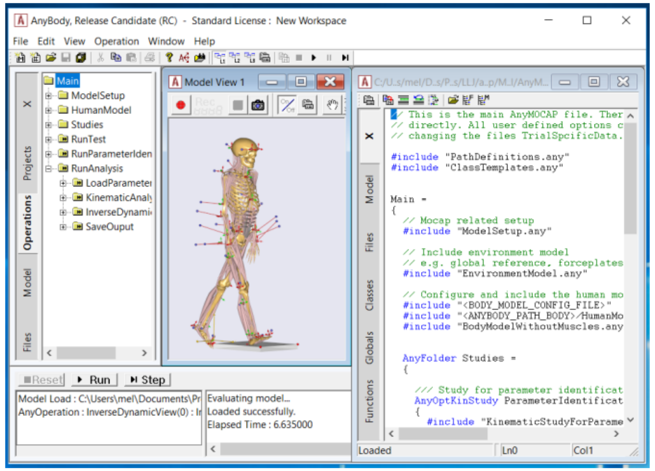
Submit questions and comments via the Questions panel.

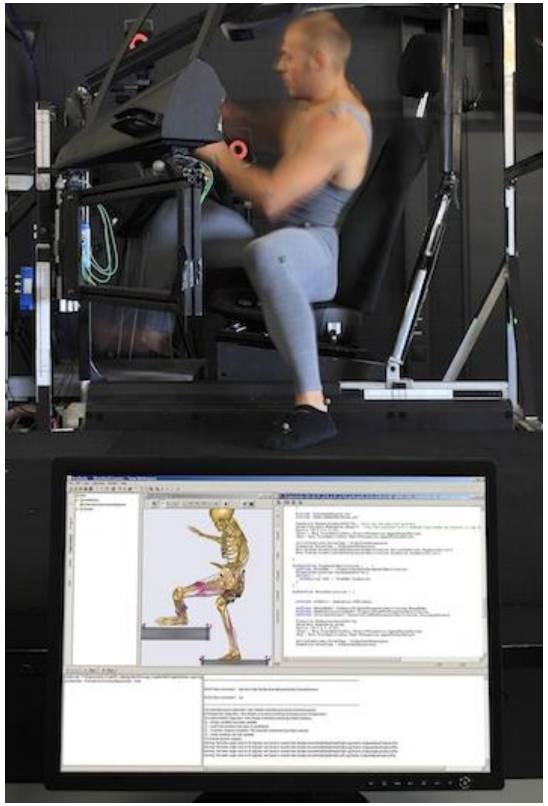
> *Questions will be addressed at the end of the presentation. If your question is not addressed we will do so by email.*



AnyBody Modeling System

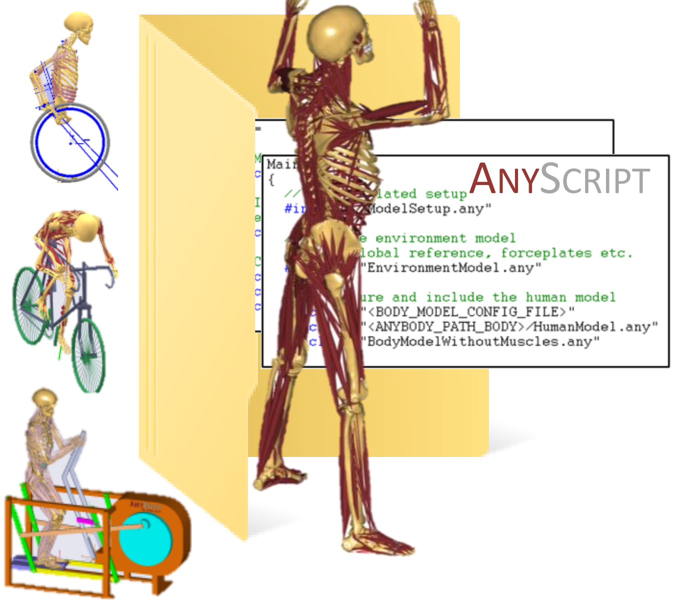
AnyBody Modeling System

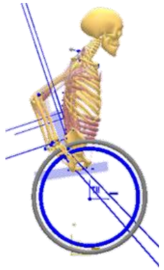




Rasmussen et. al. (2011), ORS Annual Meeting

AnyBody Managed Model Repository





Product Design Optimization

Movement Analysis

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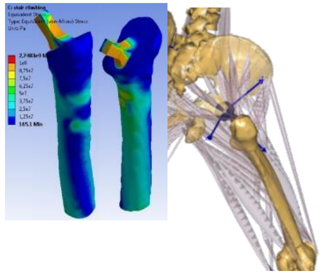
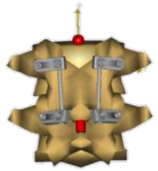
Modeling System

Ergonomic Analysis



Load Cases for Finite Element Analysis

Surgical Planning and Outcome Evaluation



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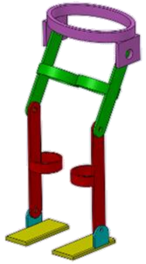
AnyBody Modeling System

Motion and Forces

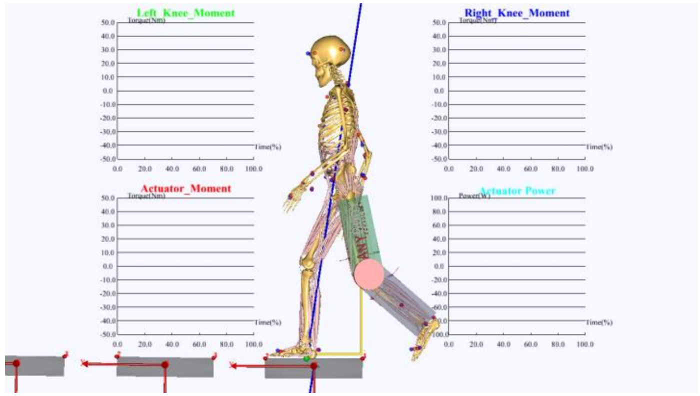
Body model

Environment model



Inverse dynamics
Muscle recruitment

Simulation



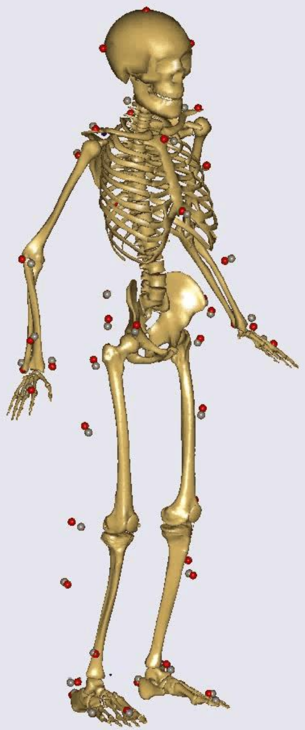
Internal body loads
- Muscle forces
- Joint forces

Design Optimization

Post Processing (e.g. FE tools)

Over-determinate kinematics

Associate Professor Michael Skipper Andersen, Ph.D.



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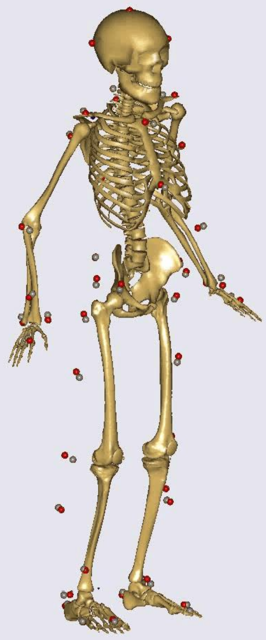
Kinematic analysis

- Analysis of motion without consideration of forces.

- Description of
  - Bodies (whether rigid or flexible)
  - Their connection (joints)
  - Motion

- Aim:
  - Compute the position, velocity and acceleration of the involved bodies.



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Degrees of freedom

Degrees of freedom (DOF): the independent ways of motion for a mechanical system

Counting the number of DOF

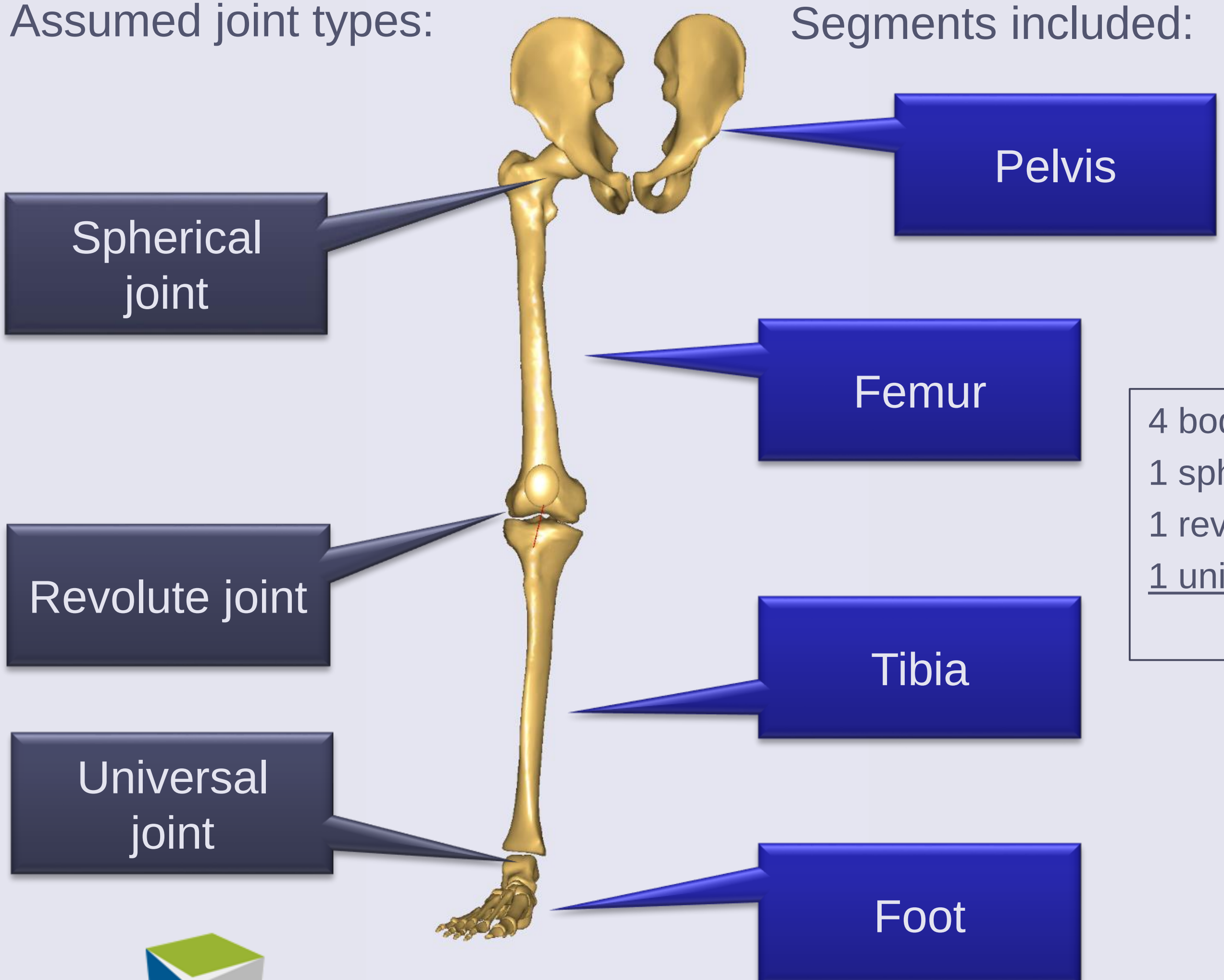
3D: $$n^{\mathrm{DOF}} = 6n^{\mathrm{bodies}} - \sum_{\mathrm{joints}} n^{\mathrm{constraints,\,3D}}$$

Constraints that include motion information are called ***kinematic drivers***

Degrees of freedom

Assumed joint types:

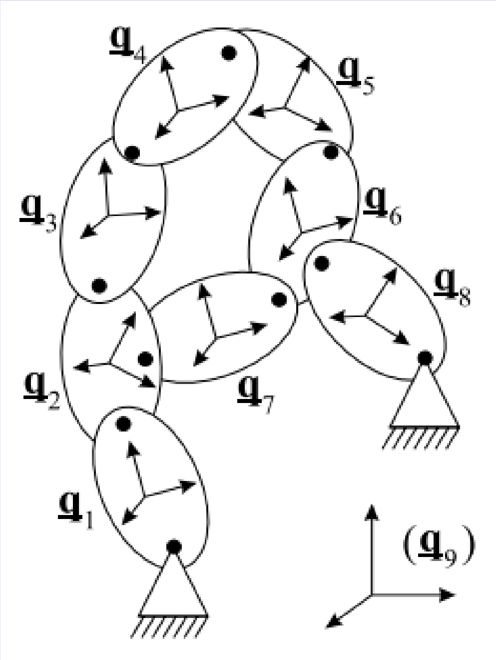
Segments included:



4 bodies	x 6 DOF	24
1 spherical joint	x 3 DOF	-3
1 revolute joint	x 5 DOF	-5
1 universal joint	x 4 DOF	-4
		12 DOF

Full cartesian formulation

- Position and orientation of each segment:
  - Three positions
  - Three rotations
- A segment introduces six unknowns when added
- Constraint equations (joint constraints or drivers) add equations



Kinematic analysis

$$\underline{\Phi}(\underline{q}(t), t) = 0$$

Equations

Coordinates

Time

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Kinematic determinacy

$n^{\text{DOF}} > n^{\text{Drivers}}$: **Kinematically under-determinate system**

- Not enough driver information to fully describe the motion.
- The most general in dynamics of mechanical systems.
- The forces in the system must be considered to determine the motion.
- The second-order differential equations of motion must be solved.

Kinematic determinacy

$n^{\mathrm{DOF}} = n^{\mathrm{Drivers}}$: **Kinematically determinate system**

- As many drivers as DOFs.
- The motion is completely prescribed by the drivers.
- Kinematics and kinetics are decoupled problems.

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Kinematic determinacy

$n^{\mathrm{DOF}} < n^{\mathrm{Drivers}}$: **Kinematically over-determinate system**

- More driver information than strictly needed.
- The kinematic equations can generally not be solved.
- Violations of constraint equations must be allowed.

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Marker-based motion capture

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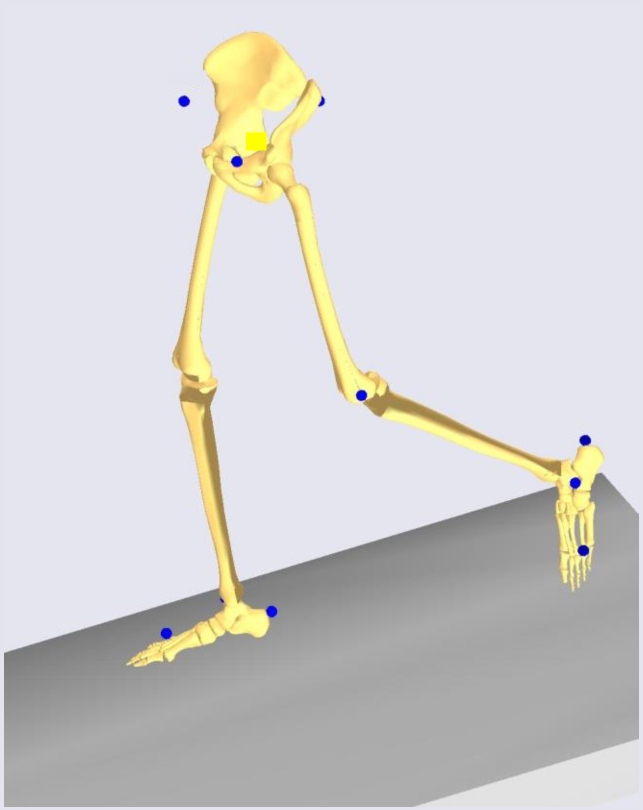
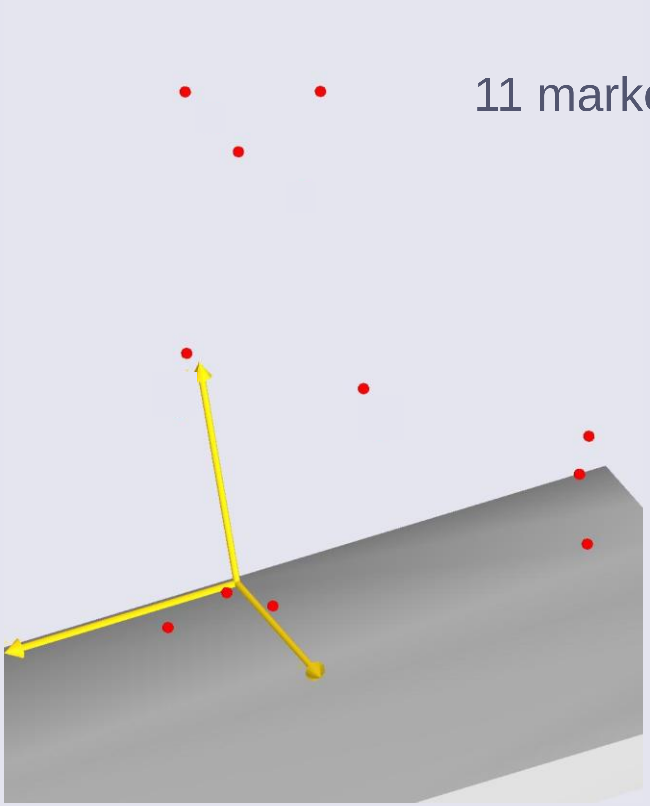
Over-determinacy problem



Model degrees of freedom: 18



Measured coordinates: 33

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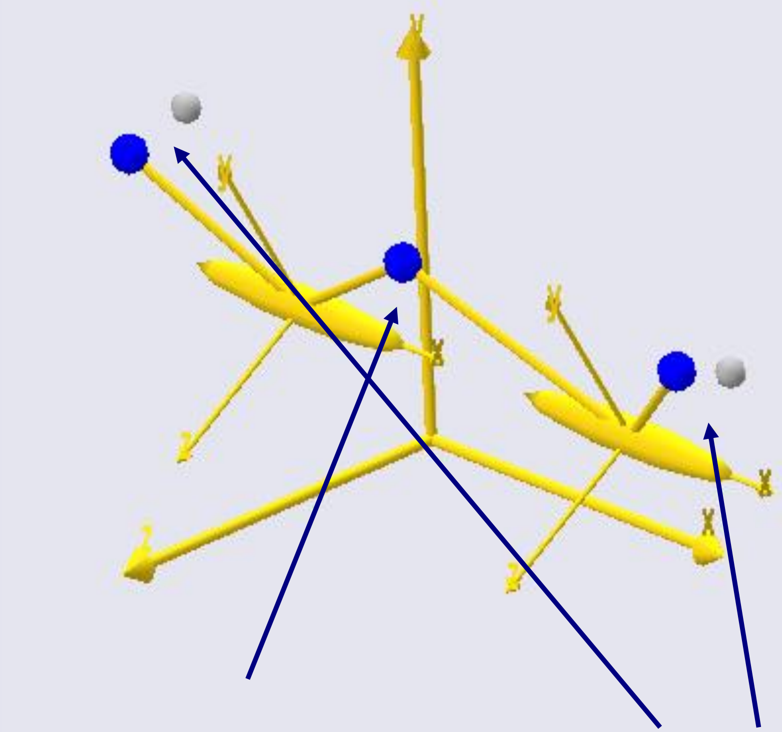
Over-determinate kinematics



$\underline{\Phi}(\underline{q}(t),t)$

"hard" constraints

$\underline{\Psi}(\underline{q}(t),t)$

"soft" constraints

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Over-determinate kinematics

$$\min_{\underline{q}(t)} G(\underline{\Psi}(\underline{q}(t),t))$$

$$s.t.\ \ \underline{\Phi}(\underline{q}(t),t) = \underline{0}$$

- One choice of objective function could be a least-square:

$$G(\underline{\Psi}(\underline{q}(t),t)) = \frac{1}{2}\underline{\Psi}(\underline{q}(t),t)^T \underline{\underline{W}}(t)\underline{\Psi}(\underline{q}(t),t)$$

Andersen et al. 2009. Kinematic analysis of over-determinate biomechanical systems. Comput Meth Biomech Biomed Eng, 12(4): 371-384.

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Frame #1

Initial guess:
Model input

Solution

$$\min_{\underline{q}_1} G(\underline{\Psi}(\underline{q}_1, t_1))$$
$$s.t.\ \ \underline{\Phi}(\underline{q}_1, t_1) = \underline{0}$$

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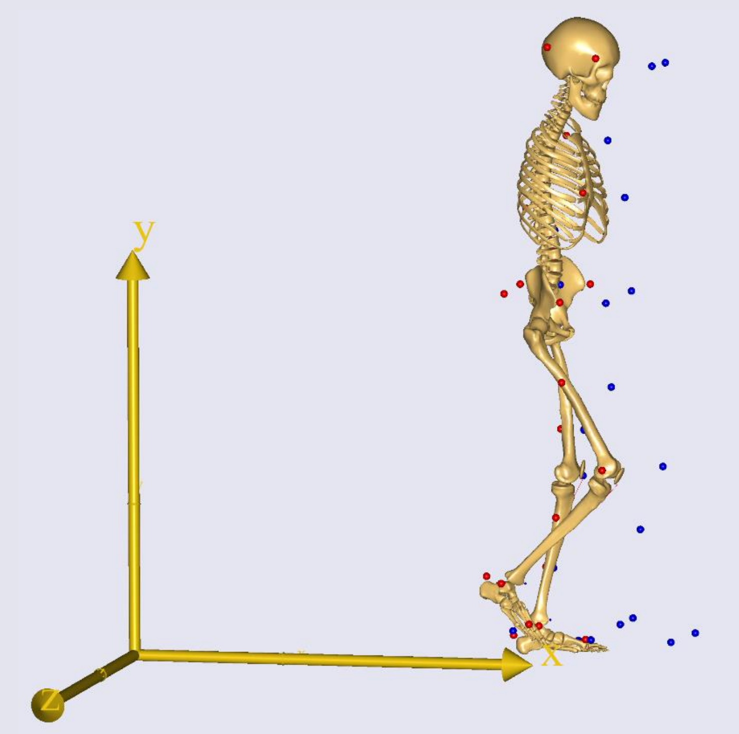
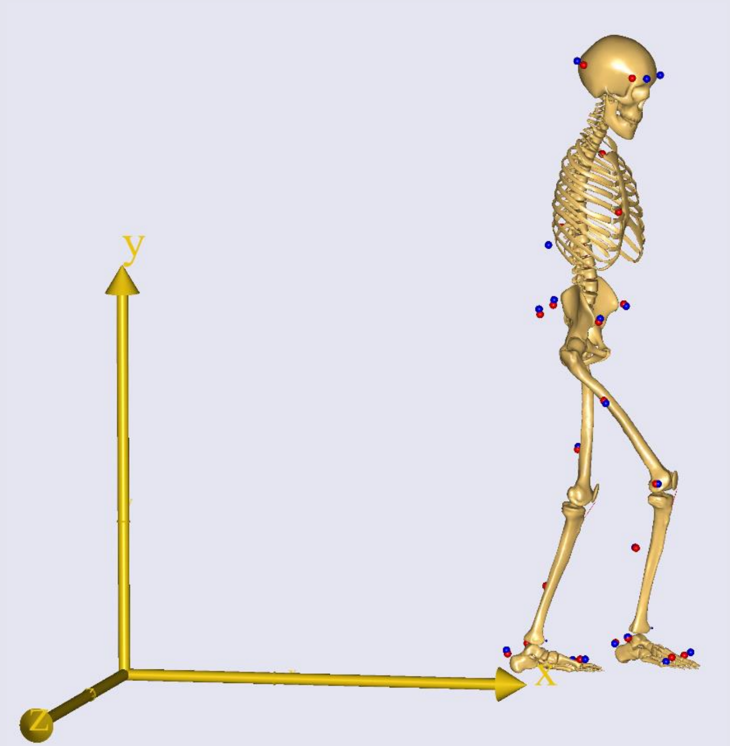
Frame #i



Initial guess:
Solution from previous time step



Solution

$$\min_{\underline{q}_i} G(\underline{\Psi}(\underline{q}_i, t_i))$$
$$s.t.\ \underline{\Phi}(\underline{q}_i, t_i) = \underline{0}$$

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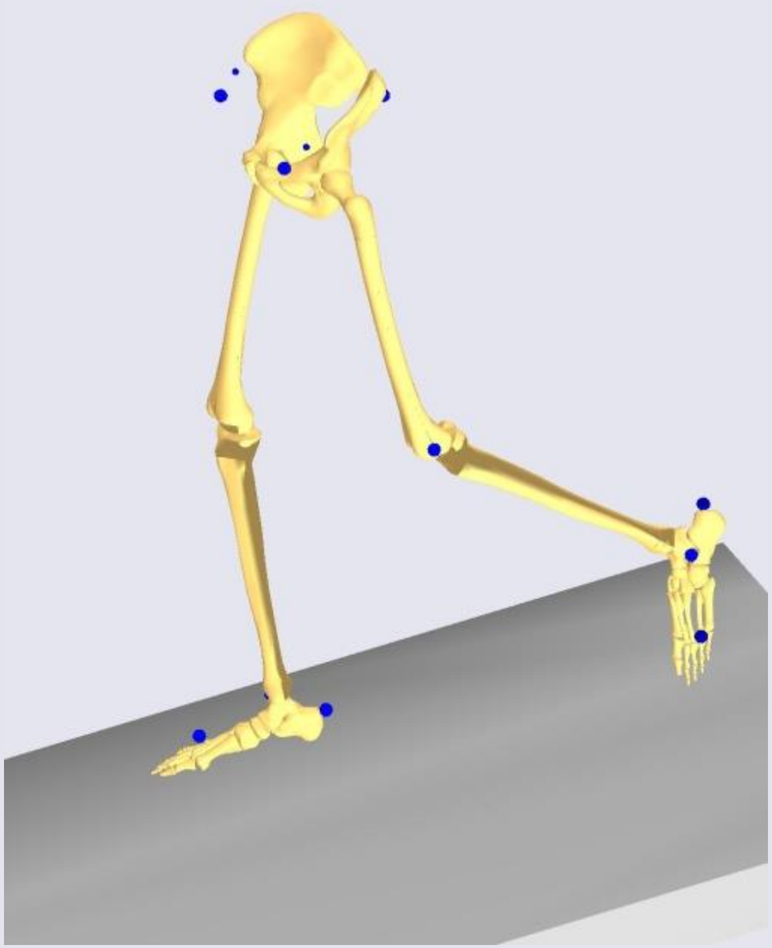
Parameter identification

- Some model parameters are difficult to measure directly:
  - Segment lengths.
  - Joint axis orientations.
  - Marker placements.

- Possible solution: use optimization to find the best fitting model to the marker trajectories.



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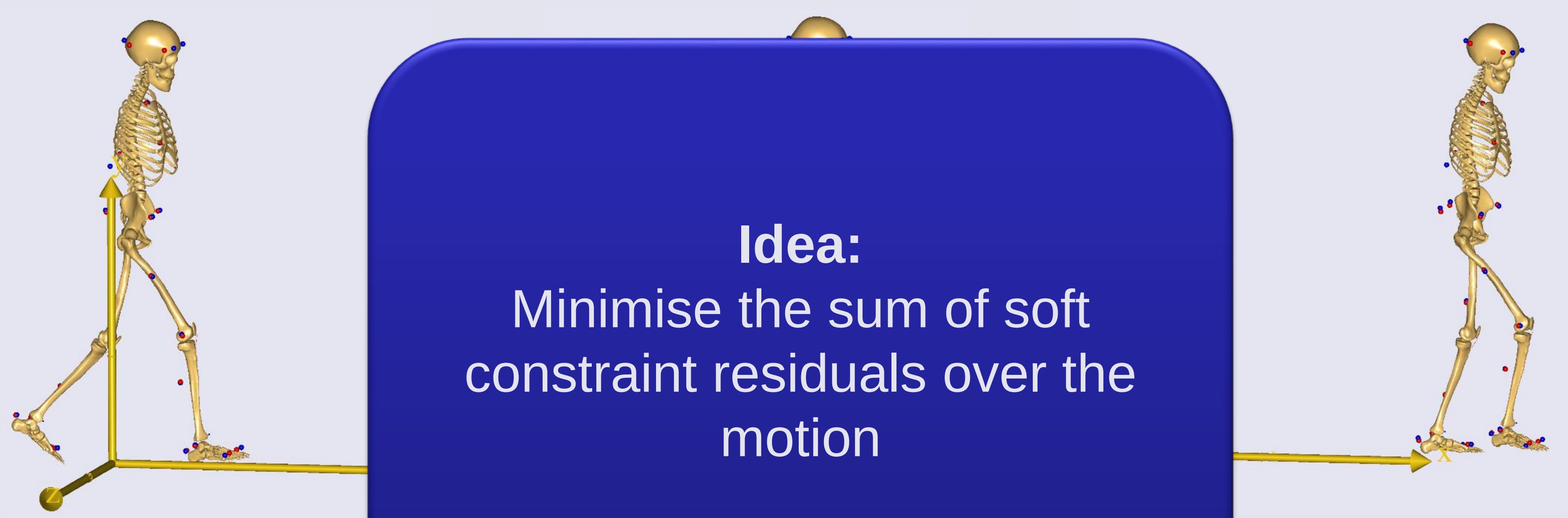
Parameter identification



Idea:
Minimise the sum of soft constraint residuals over the motion

$$\min_{\underline{q}_1} G(\underline{\Psi}(\underline{q}_1, \underline{\hat{d}}, t_1))$$

$$s.t.\ \underline{\Phi}(\underline{q}_1, \underline{\hat{d}}, t_1) = 0$$

$$s.t.\ \underline{\Phi}(\underline{q}_i, \underline{\hat{d}}, t_i) = 0$$

$$G(\underline{\Psi}(\underline{q}_N, \underline{\hat{d}}, t_N))$$

$$s.t.\ \underline{\Phi}(\underline{q}_N, \underline{\hat{d}}, t_N) = 0$$

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Parameter identification

$$\min_{\underline{q}_1,\underline{q}_2,\ldots,\underline{q}_N,\underline{d}} \sum_{i=1}^{N} G(\underline{\Psi}(\underline{q}_i,\underline{d},t_i))$$

$$\text{s.t.} \quad \underline{\Phi}(\underline{q}_i,\underline{d},t_i) = 0$$

$$\underline{T}(\underline{d}) = 0$$

- A general and computationally-efficient solution algorithm is derived for this problem in Andersen et. al. 2010 and available in AnyBody.

Andersen et al. 2010. A computationally efficient optimisation-based method for parameter identification of kinematically determinate and over-determinate biomechanical systems. Comput Meth Biomech Biomed Engin, Vol. 132: 171-183.

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Advanced uses of Over-determinate kinematics

Prof. John Rasmussen

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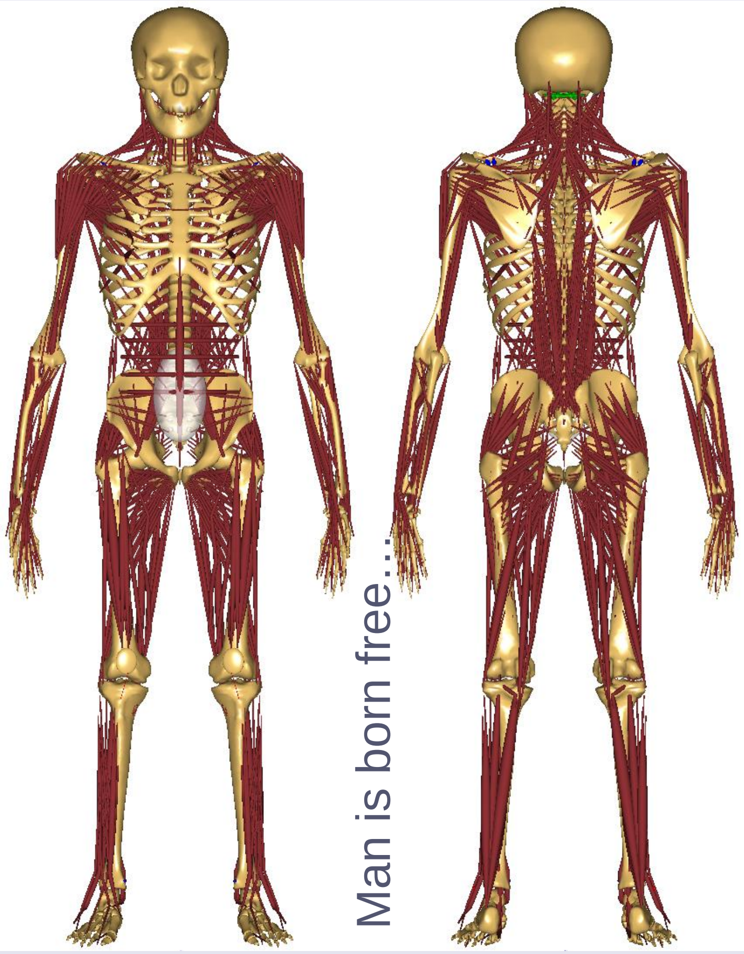
“L'homme est né libre, et partout il est dans les fers.” Jean-Jacques Rousseau



Endless motion opportunities

…and everywhere he is in chains

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Perhaps

…motion planning is a compromise between (too many) constraints?

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How to use this for "Rousseau constraints"?

- All DOFs get default, weak drivers. Weak drivers define preferences, for instance comfortable postures.
  - L'homme est né libre…
- Any stronger or strong drivers we define will take preference. These are Rousseau's chains.
  - et partout il est dans les fers.
- Anything not defined by strong drivers will be governed by weak drivers.

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Dans les fers…

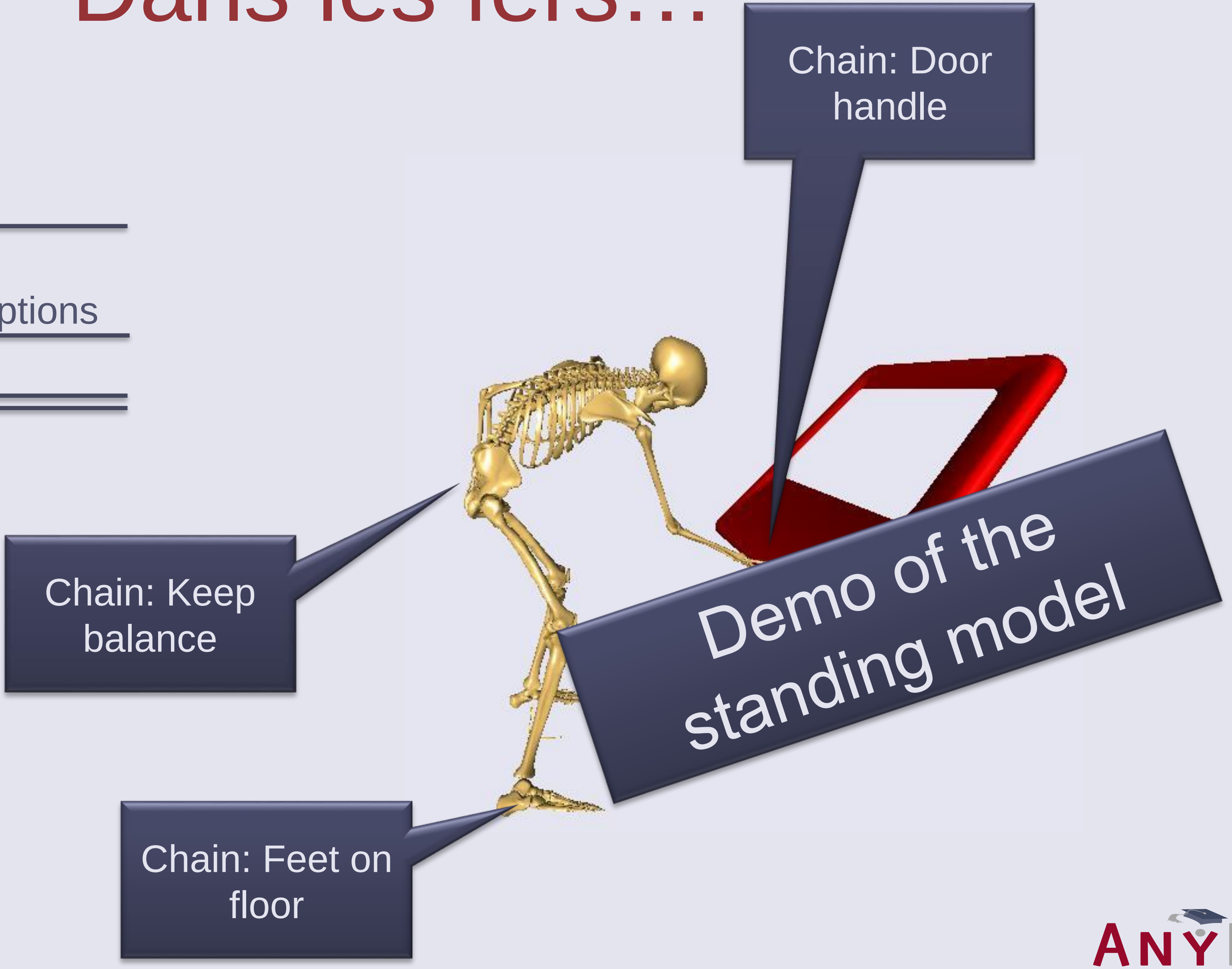
Man is born free

- all of the chains (constraints)

= A little freedom remaining

- reasonable kinematic assumptions

= predicted motion



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Weight functions

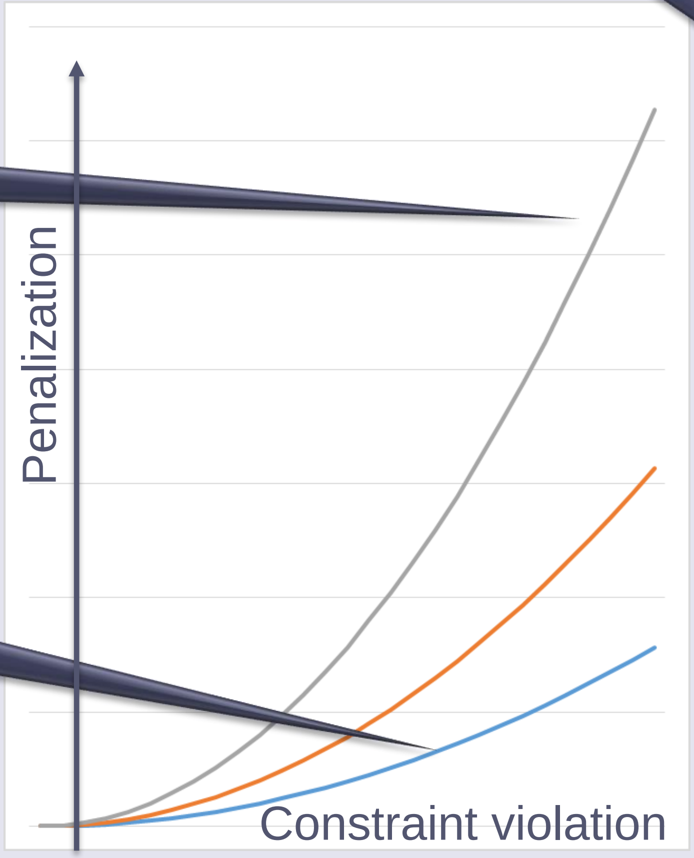
Minimize

$$G(\Psi(q,t)) = \frac{1}{2}\Psi(q,t)^{\mathrm{T}} W(t) \Psi(q,t), \qquad (10)$$

M.S. Andersen et al.

Large, constant W

Small, constant W



Notice: W can be a function

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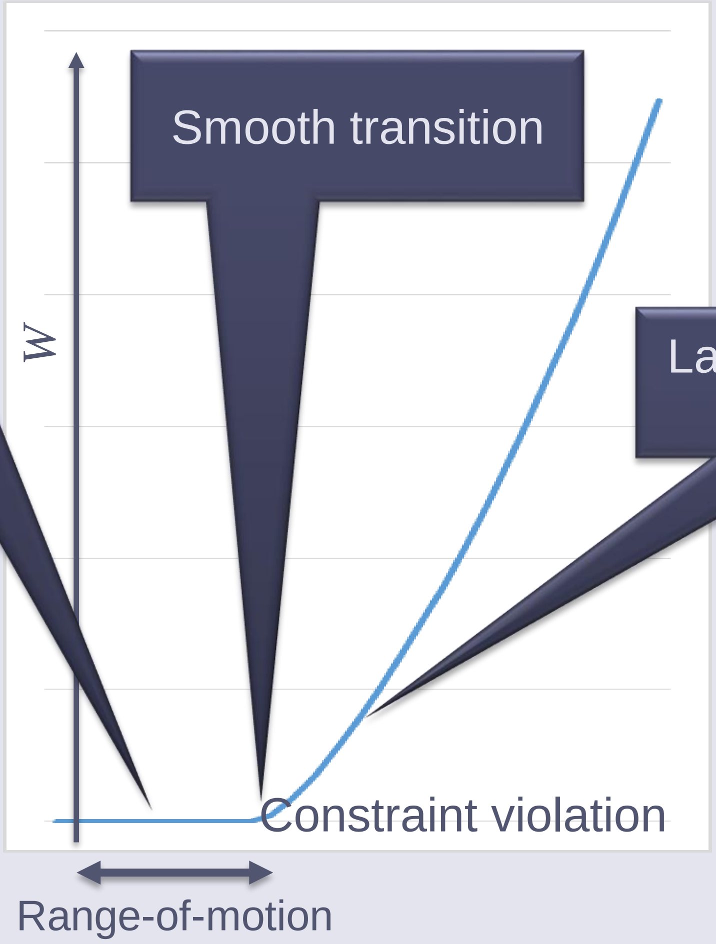
Weight function for territorial constraints



Types of constraints:

- Joint R-o-M limits
- No-collision constraints
- Environment R-o-M limits

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Conclusions

- A simple way to synthesize coordinated motions.
- Motions honor constraints
  - Balance
  - Range-of-motion
  - Territorial
  - Connections to the environment
- Not totally automatic, but can provide plausible results with little effort.
- After addition of muscles and ID analysis, we can get forces.

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