Kinematic analysis of over-determinate systems

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Presenters

Michael Skipper Andersen
(Presenter)

Arne Kiis
(Host)

Søren Tørholm
(Panelist)

Michael Damsgaard
(Panelist)

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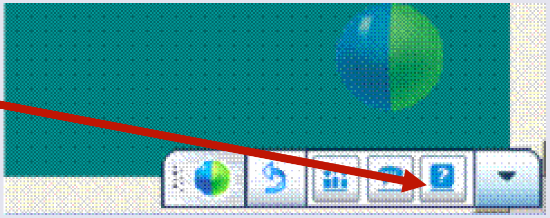

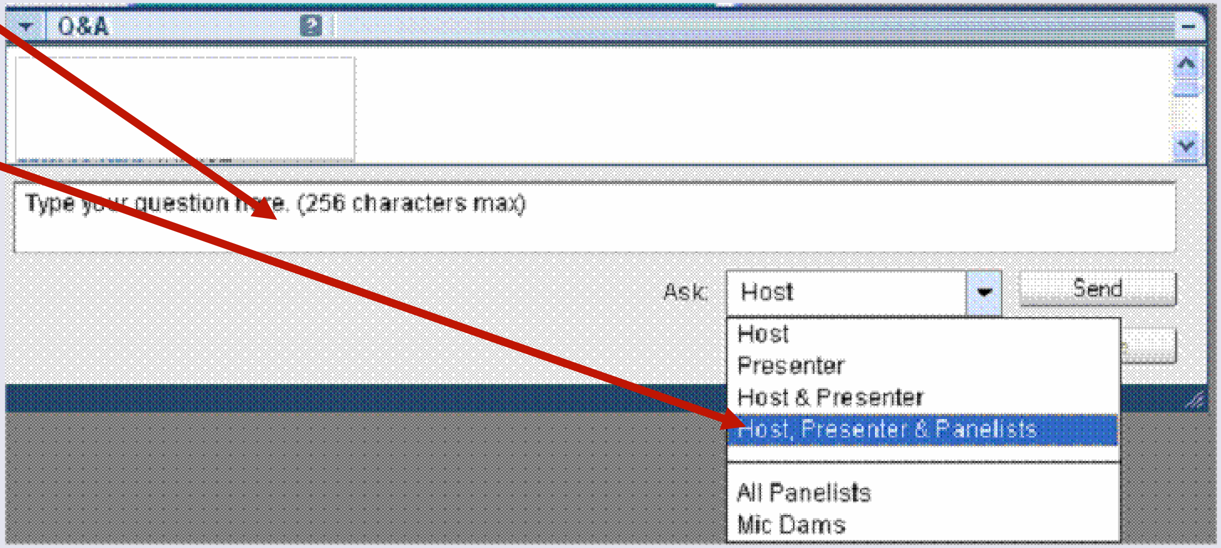

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The presenter: Michael Skipper Andersen

Ph.D student

The AnyBody Research Project
Department of Mechanical Engineering
Aalborg University
Denmark

Ph.D project:
Numerical modeling of kinematically over- and under-determinate musculoskeletal systems.

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Agenda

- Introduction
- The standard approach to kinematic analysis.
- Kinematic analysis of over-determinate systems.
- Gait model example.
- Model scaling and local marker coordinate determination.
- Conclusion.
- Q & A.

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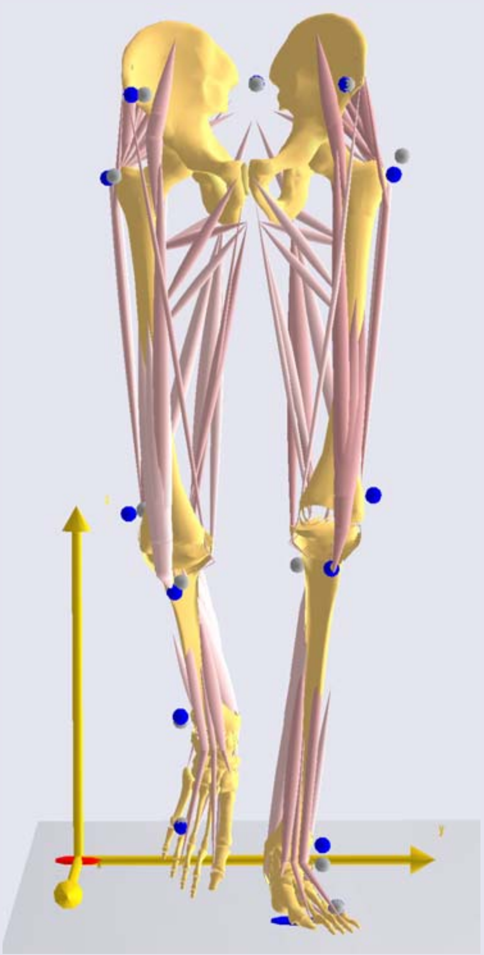
Introduction

- Goal:
  - To create a general interface between motion capture and musculoskeletal modeling.
    - Determination of positions, velocities and accelerations of all involved model segments.
    - Automatic scaling of models and local marker coordinates, i.e. constant parameter determination.
    - Advanced filtering techniques.
    - Should be general enough to allow analysis of any multi-body model subject to holonomic constraints.

Introduction

- The usual AnyBody approach:
  - The marker trajectories are filtered using a Butterworth filter.
  - Over-determinacy is handled by excluding some marker coordinates from consideration.
- The methods I am going to talk about are currently not available in AnyBody.



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Classical kinematical analysis

- Constraints (joints and drivers):

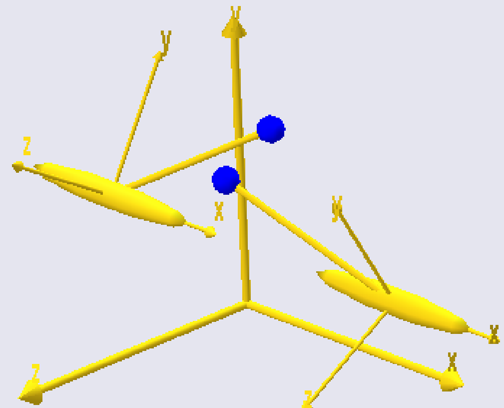
$$\Gamma(q,t) = 0, \ \ q \in Q, t \in \Re_{+}$$

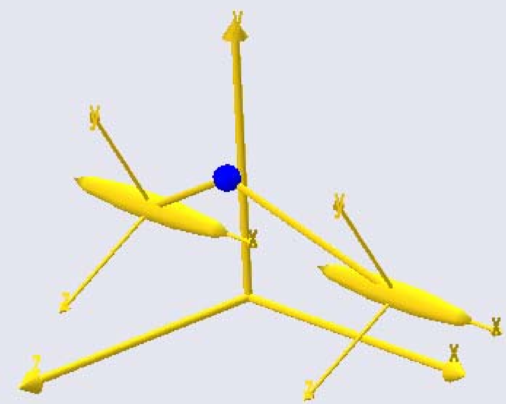
- Position analysis:
  - Solve this set of equations.
- Velocity analysis:

$$\Gamma_q \dot{q} + \Gamma_t = 0$$

- Acceleration analysis:

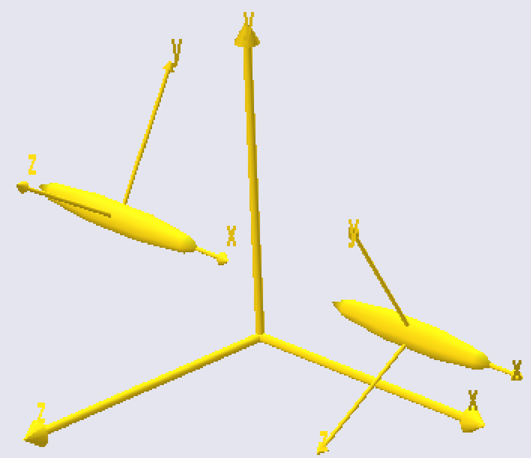
$$\Gamma_q \ddot{q} + (\Gamma_q \dot{q})_q \dot{q} + 2\Gamma_{qt} \dot{q} + \Gamma_{tt} = 0$$





Full cartesian formulation

- Segments:
  $\{S^1, S^2, \ldots, S^m\}$
- Reference frames:
  $\{A\}, \{B_1\}, \{B_2\}, \ldots, \{B_m\}$
- Configuration space:
  $Q = Q^1 \times Q^2 \times \cdots \times Q^m$
- See the previous webcast on kinematics for details.



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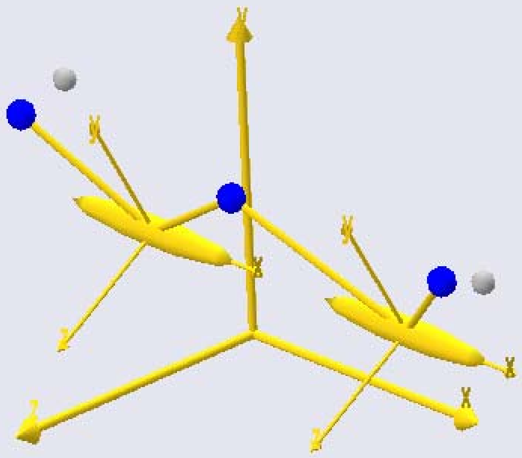
The over-determinacy problem

- Marker measurements:
  $z_j^{S_i}(t)$ for all i and j.
- Marker errors in global coordinates:
  $e_j^{S_i}(q,t) = z_j^{S_i}(t) - (r^{S_i} + A_A^{S_i}(q)s_j^{S_i})$
- Consider the marker errors as driver constraints:
  $e_j^{S_i}(q,t) = 0$
- Generally leads to an over-determinate set of equations with no solution!

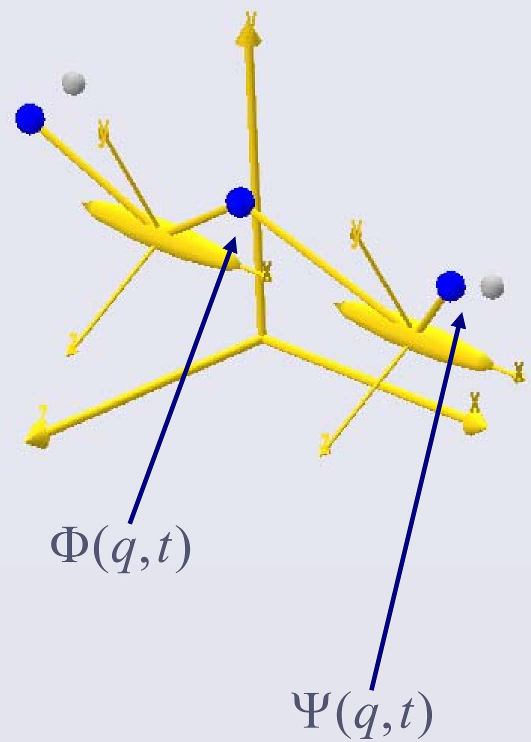


Constrained optimization approach

- Over-determinacy is handled using optimization.
- The equations are split into two sets:

$$\Gamma(q,t) = \begin{bmatrix} \Psi(q,t) \\ \Phi(q,t) \end{bmatrix}$$

- Where $\Psi(q,t)$ is a set of equations that only have to be solved ”as well as possible” in some sense.
- And $\Phi(q,t)$ have to be solved exactly.



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Constrained optimization approach: Position analysis

- Can be cast as an optimization problem:

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

- Where one choice of objective function could be:

$$G(\Psi(q,t)) = \Psi(q,t)^T W(t) \Psi(q,t)$$

- The time-dependent weight matrix $W(t)$ can be used to weigh the data differently along the motion, e.g. markers that disappear can be ”faded out”.

Constrained optimization approach: Position analysis

- Notice that the optimization problem reduces to the global optimization with joint constraints method introduced by Lu and O'Connor when generalized coordinates are used, the weight matrix is constant, and there are no subject to constraints.

T.-W. Lu and J. J. O'Connor. Bone Position Estimation from Skin Marker Co-ordinates using Global Optimization with Joint Constraints. *J. Biomechanics*, Vol. 32, 129–134, (1999).

Constrained optimization approach: Velocity and acceleration analysis

- Do there exist a method similar to the kinematically determinate case?
- The answer is in the the Karush-Kuhn-Tucker (KKT) first order optimality conditions:

$$G_q^T + \Phi_q^T \lambda = 0$$
$$\Phi = 0$$

- This set of equations is always fulfilled when a local minimizer has been found.
- Only differentiable functions are involved.

Constrained optimization approach: velocity and acceleration analysis

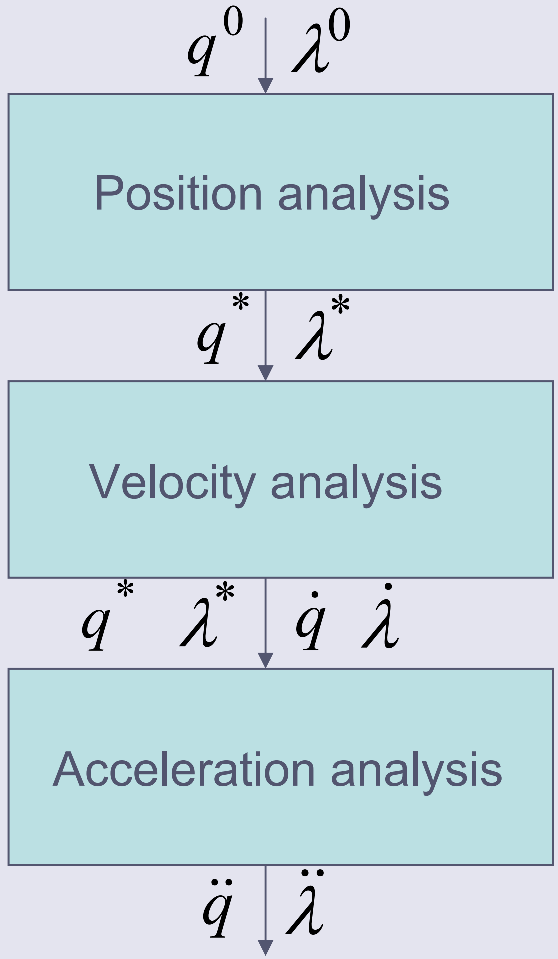
- By differentiation of the KKT conditions, the velocity equations are obtained:

$$\begin{bmatrix} G_{qq}^T + (\Phi_q^T \lambda)_q & \Phi_q^T \\ \Phi_q & 0 \end{bmatrix} \begin{bmatrix} \dot{q} \\ \dot{\lambda} \end{bmatrix} = \begin{bmatrix} -G_{qt}^T - \Phi_{qt}^T \lambda \\ -\Phi_t \end{bmatrix}$$

- Differentiation one more time gives the acceleration equations:

$$\begin{bmatrix} G_{qq}^T + (\Phi_q^T \lambda)_q & \Phi_q^T \\ \Phi_q & 0 \end{bmatrix} \begin{bmatrix} \ddot{q} \\ \ddot{\lambda} \end{bmatrix} = \begin{bmatrix} \gamma_1 \\ \gamma_2 \end{bmatrix}$$

Constrained optimization approach: Solution algorithm



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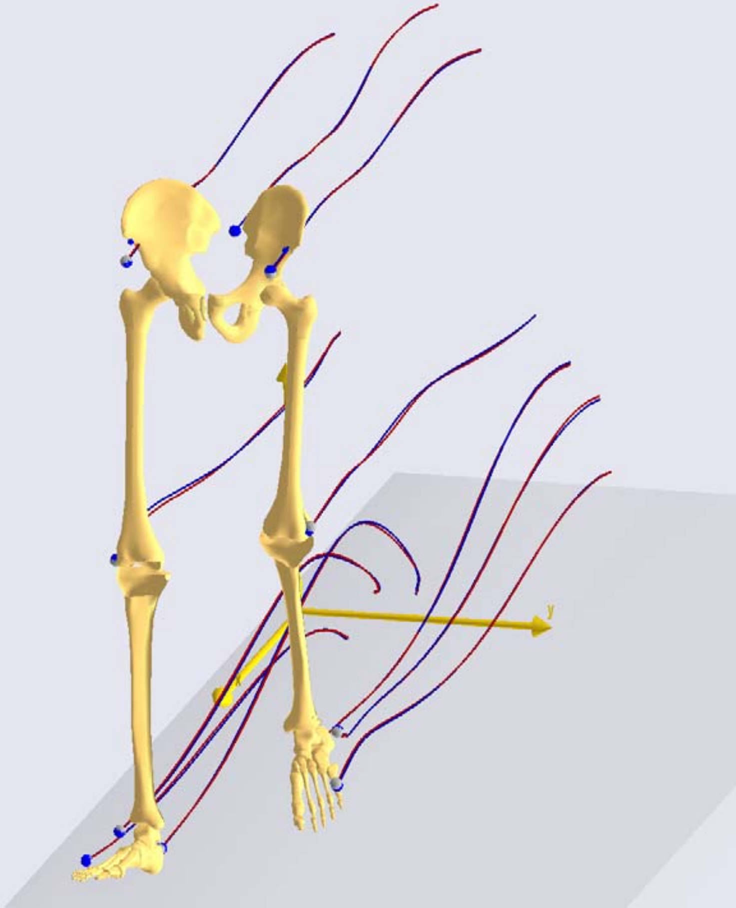
Example – 3D gait model

- 7 segments.
- 11 markers.
- Hips: spherical joints.
- Knees: revolute joints.
- Ankles: universal joints.
- 18 DOF.
- A full cartesian formulation.
- Local marker coordinates and scaling have been determined automatically. Details later.



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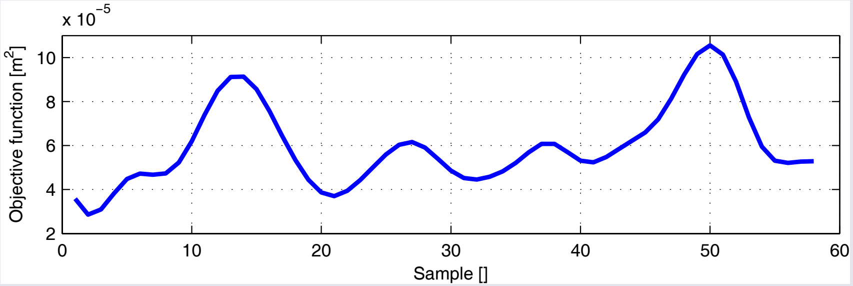
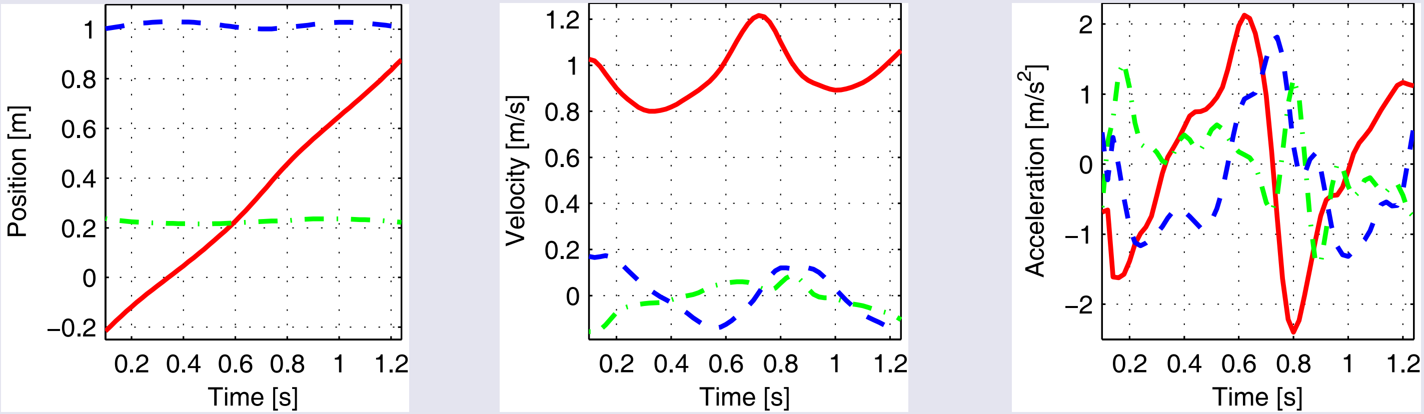
Example – 3D gait model

- Objective function:



- Position of pelvis:



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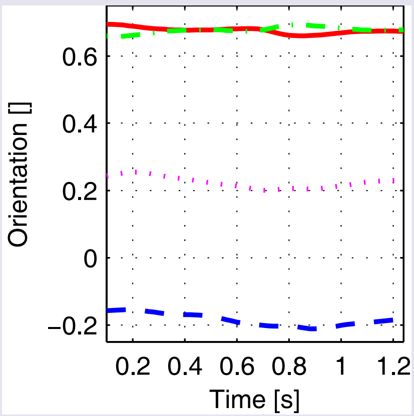
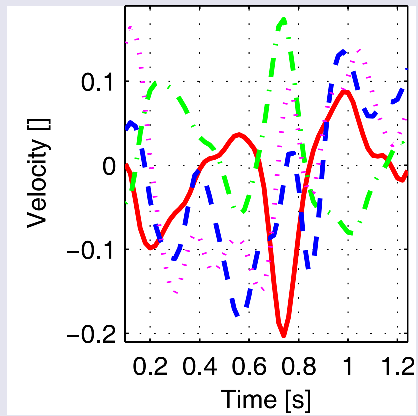
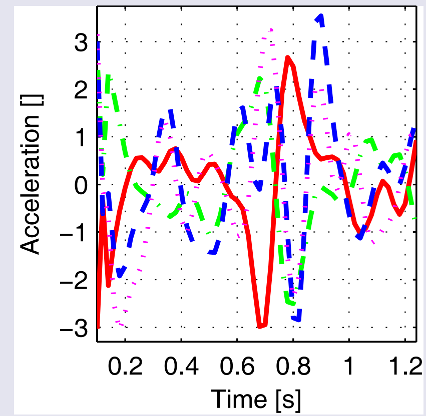
Example – 3D gait model







- The orientations show the same result. Here, the Euler parameters for pelvis are given.
- The remaining segments in the gait model show similar results.

Local marker coordinate determination and scaling

- Besides the coordinates and time, the constraint equations can also include constant parameters, *p:*
  - Local marker coordinates.
  - Model scaling (i.e. local joint coordinates).
  - Joint axes of rotation.
- These parameters we also want to determine from the measured motion.
- The new constraint equations: $\Phi(q, p, t)$ and $\Psi(q, p, t)$

Local marker coordinate determination and scaling

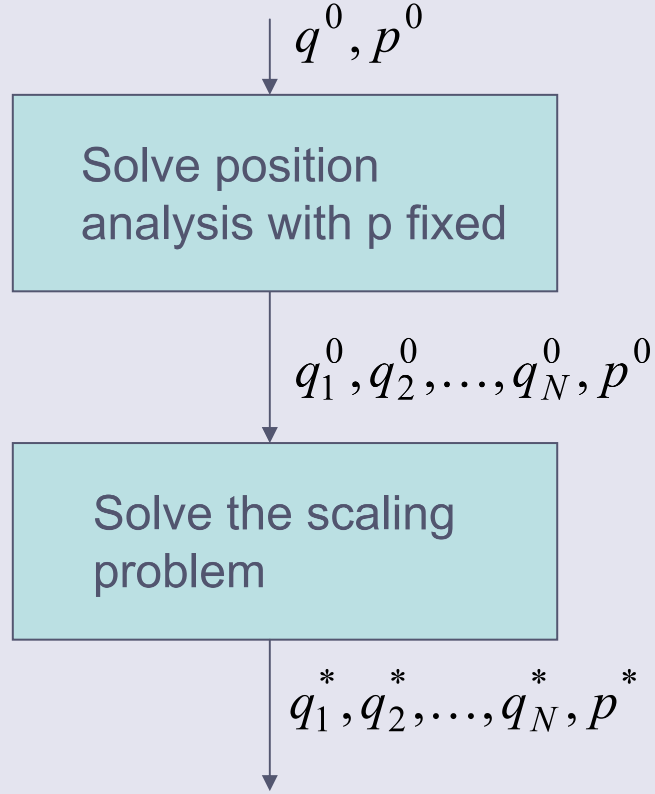
- The previous optimization problem can be re-written into a large-scale optimization problem:

$$\min_{p,q_i} \sum_{i=1}^{N} G(\Psi(q_i, p, t_i))$$
$$s.t.\ \ \Phi(q_i, p, t_i) = 0$$

- Where *N* is the number of samples.
- Due to the special structure of this problem, a local minimizer can be found efficiently.

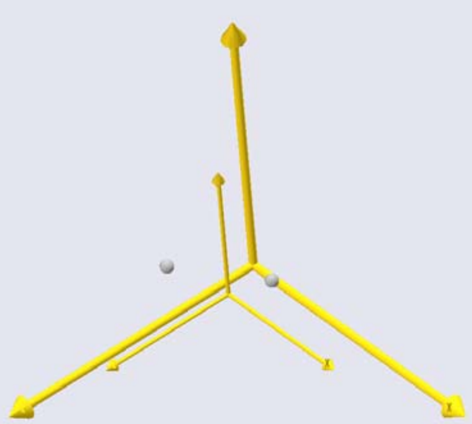
Local marker coordinate determination and scaling

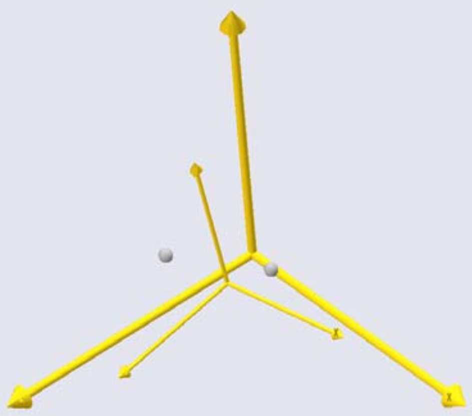
- Solution algorithm:



Local marker coordinate determination and scaling

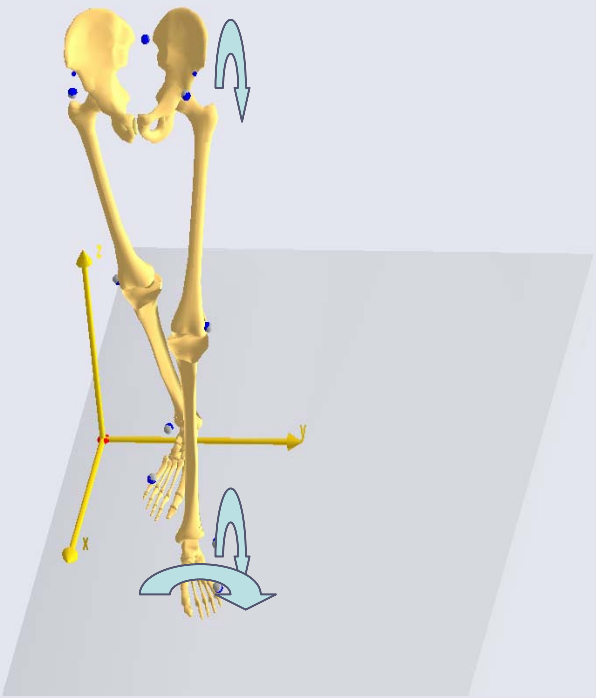
- Eventhough there are more equations than unknowns, the optimization problem may be indeterminate when only the standard equations are included.





Local marker coordinate determination and scaling

- Extra equations are required to define the coordinate systems.
  - Align with inertia axis (introduce geometrical scaling laws).
  - Extra equations for the end segments are required.
    - Manual definition of a few markers.
    - Orientation of end segments defined directly.



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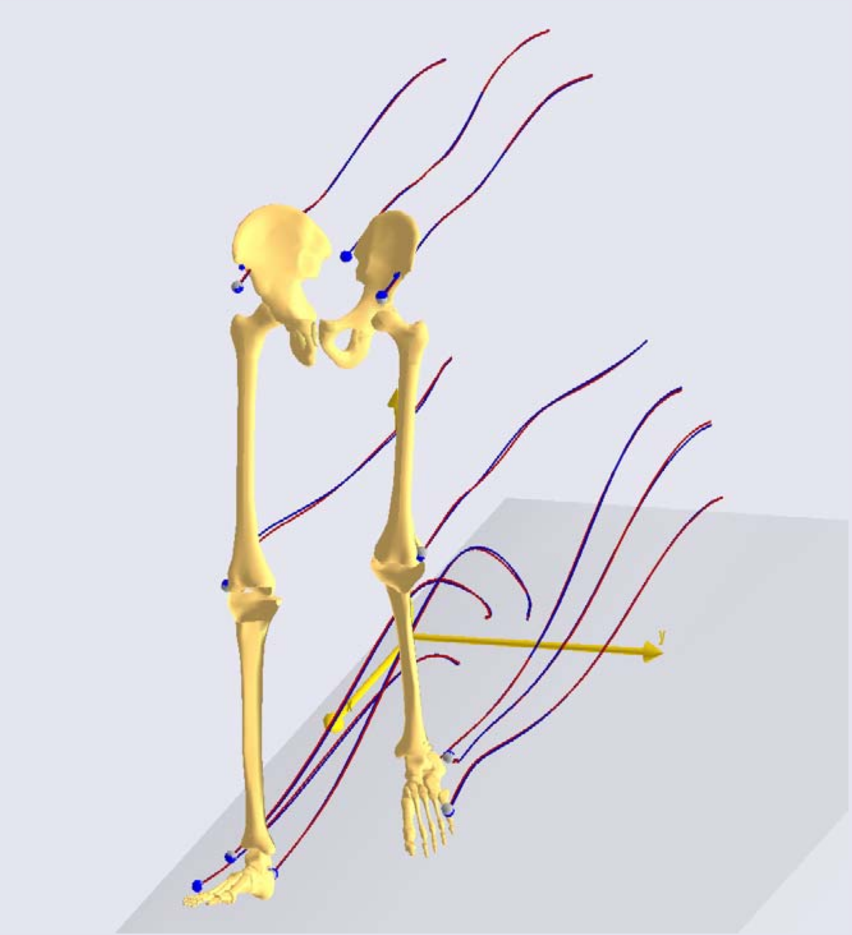
3D gait model (again)

- Uniform geometrical scaling of each model segment.
- z-coordinate of the sacrum marker defined manually.
- heel and metatarsal markers defined manually.



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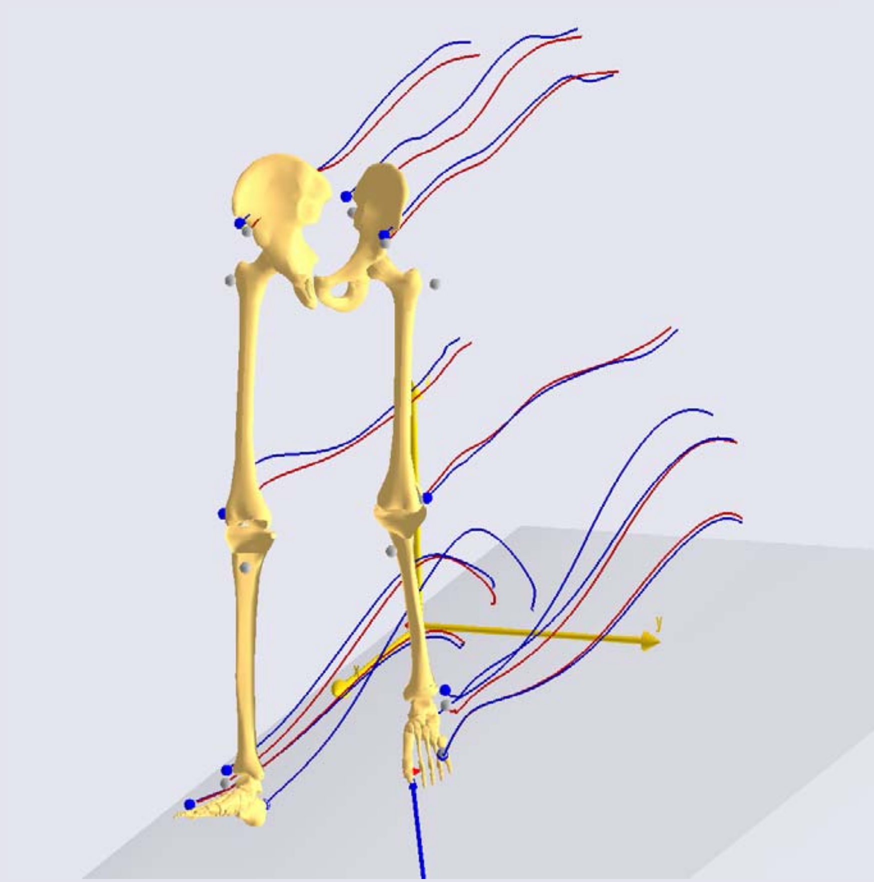
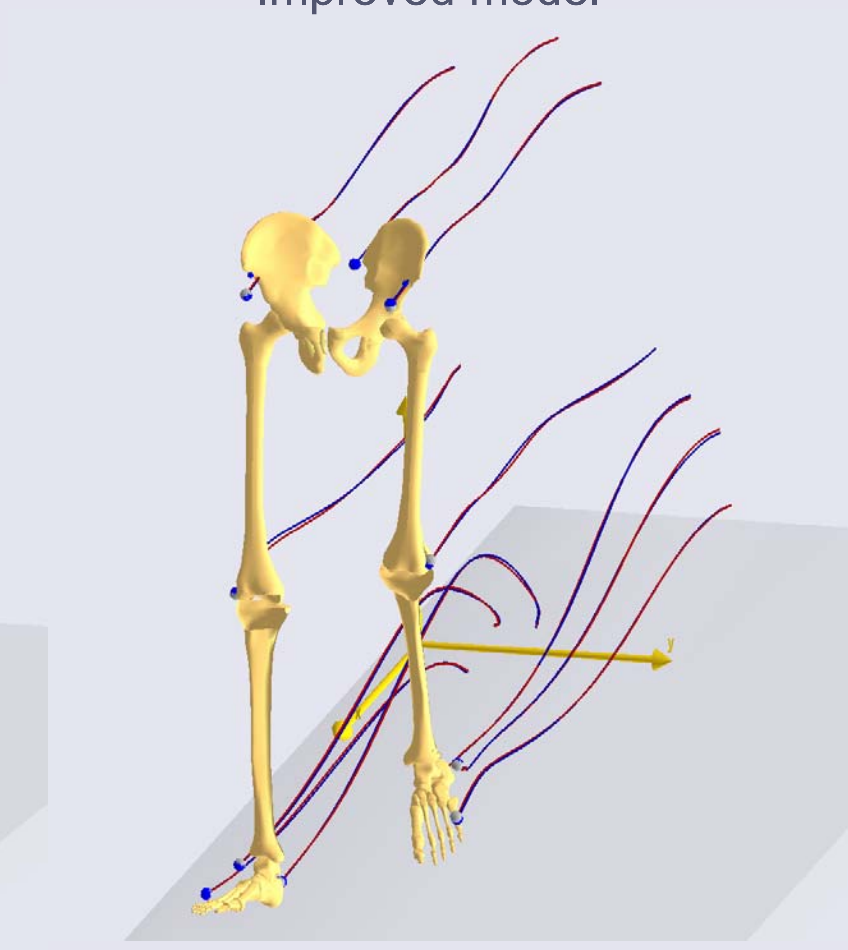
Comparison with AnyBody model

AnyBody gait model



Improved model



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Conclusion

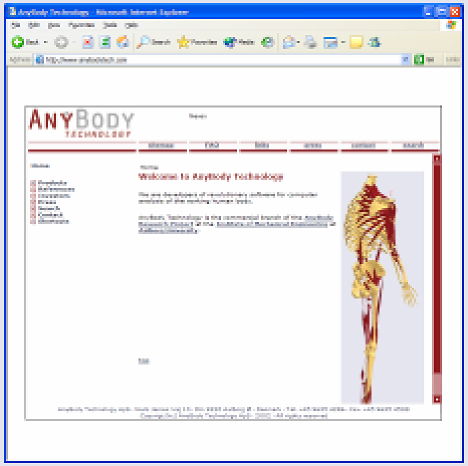
- A general method for performing position, velocity, and acceleration analysis of any over-determinate system subject to holonomic constraints.
- Allows any choice of system coordinates to be used.
- Local minima may be present.
- Enables the implementation of a general-purpose inverse dynamics-based modeling system where the motion is given from a motion capture experiment.

- A general method for performing geometric model scaling and local marker coordinate determination were developed.
- Indeterminacy problem can be handled by introducing additional system equations.
- No guarentee of finding the global minimum. Good start guess is required.

- These methods are not yet available in AnyBody, but the facilities are under development.

Online resources

- The AnyBody Research Project: www.anybody.aau.dk
  - Publications, model repository
- AnyBody Technology: www.anybodytech.com
  - Software.
  - Demo licences.
  - Previous webcasts.
- Michael Skipper Andersen
  - Email: msa@ime.aau.dk



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Upcoming webcast

- April 26. Validation of the AnyBody version of the Dutch shoulder model by the in vivo measurement of GH contact forces by Bergmann et. al.

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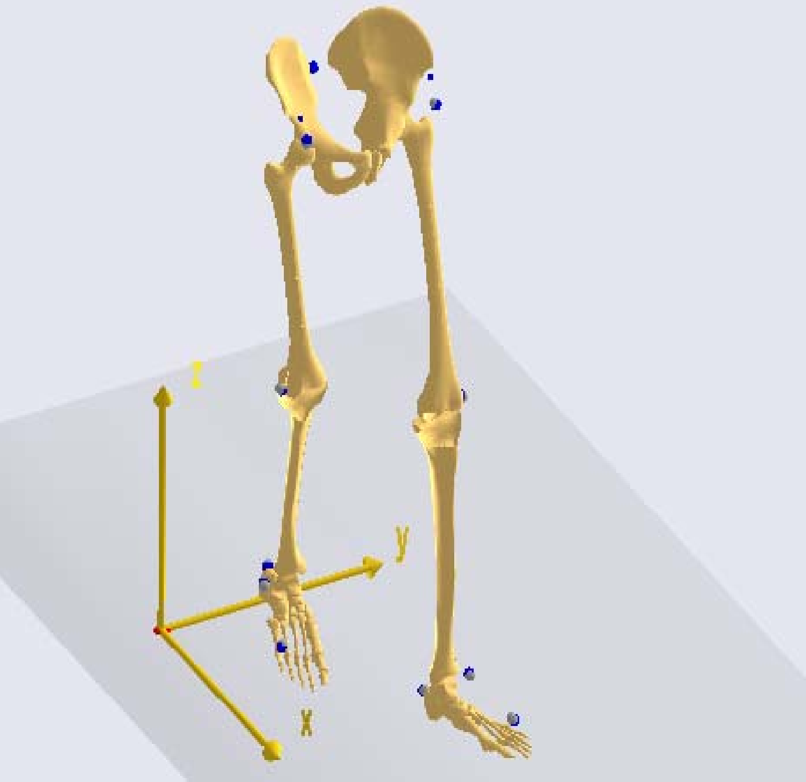
Thanks!



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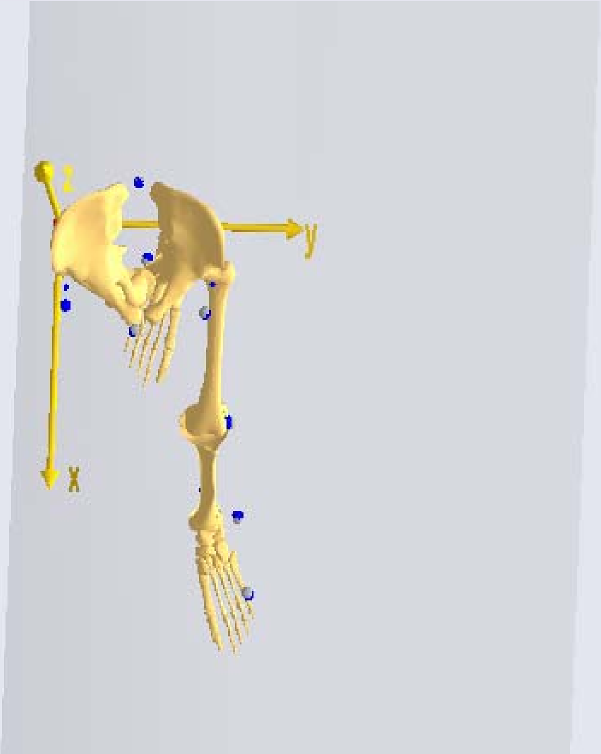

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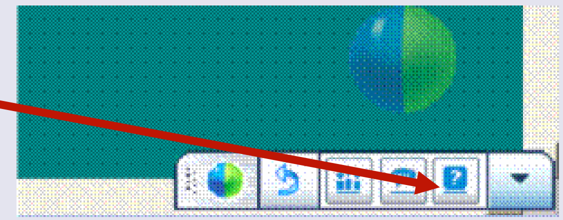

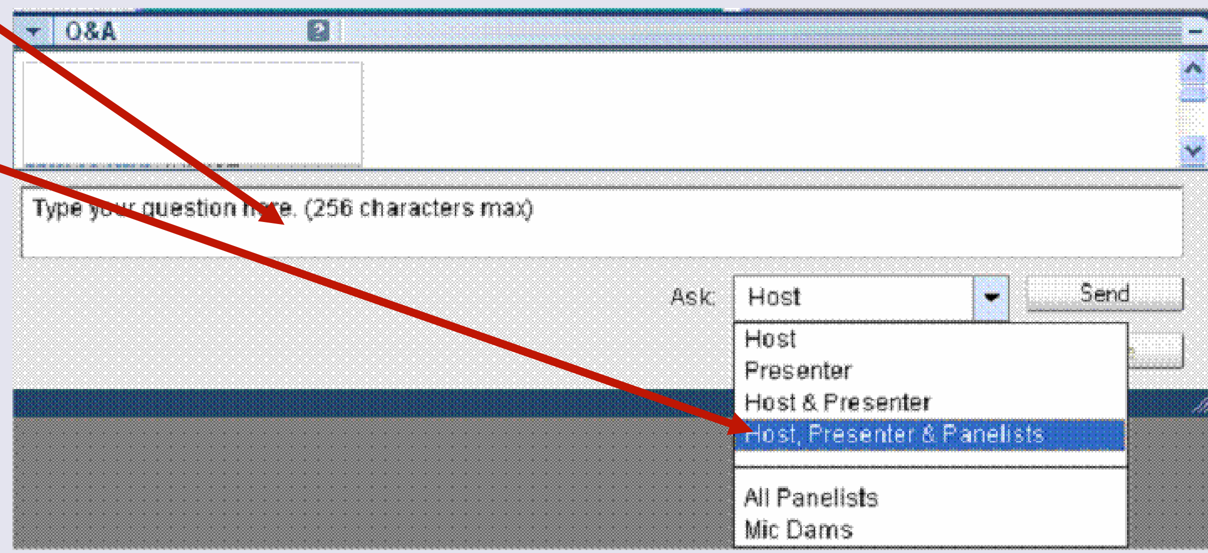

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