# Musculoskeletal simulation

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# Introduction

- Neuromuscular Biomechanics

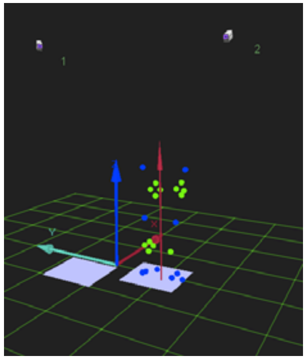
  The use of computational physics, neuroscience, and robotics to analyze muscle form and function while study animal movements and design medical technologies.

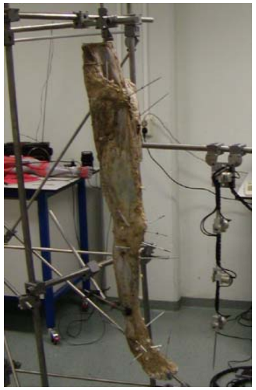
# Introduction

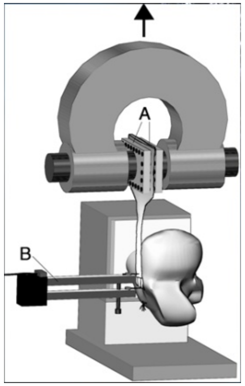
- Musculoskeletal simulation
  - Create dynamic simulations of movement
    - Simulation of healthy patients ⟹ understand motions
    - Simulation of patient with disorders ⟹ (pre surgical tool to understand and plan surgical procedure)
  - No creation of new motions

# Simulation overview

- From physical human to virtual human







# Acquire data

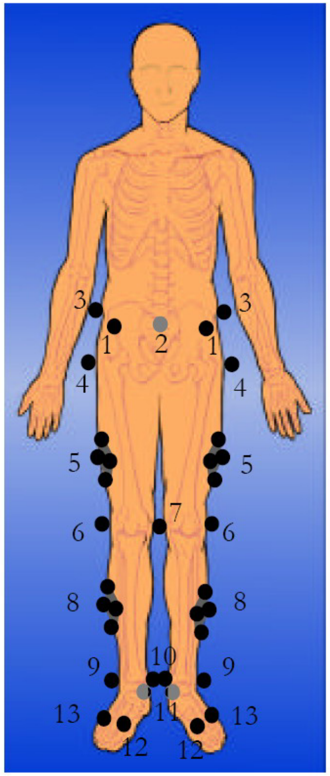
- Motion capture
  - Input data that describe the motion to be simulated/analyzed
  - Common acquired data
    - Motion capture from a marker model
    - Force plates (ground reaction force, GRF)
    - Electromyography (EMG)

# Motion tracking

- Marker Model
  - Track motions (translations, rotations)
  - Usually two marker data set is used
    - Model markers
      - Scaling and position the model in the simulation tool
    - Motion markers
      - Used to drive the simulation
  - Different purpose
    - Medical, capture a **correct** motions for medical purpose
    - Games/cinema. Created to make **fast** motions that humans believe to be real

# Motion tracking

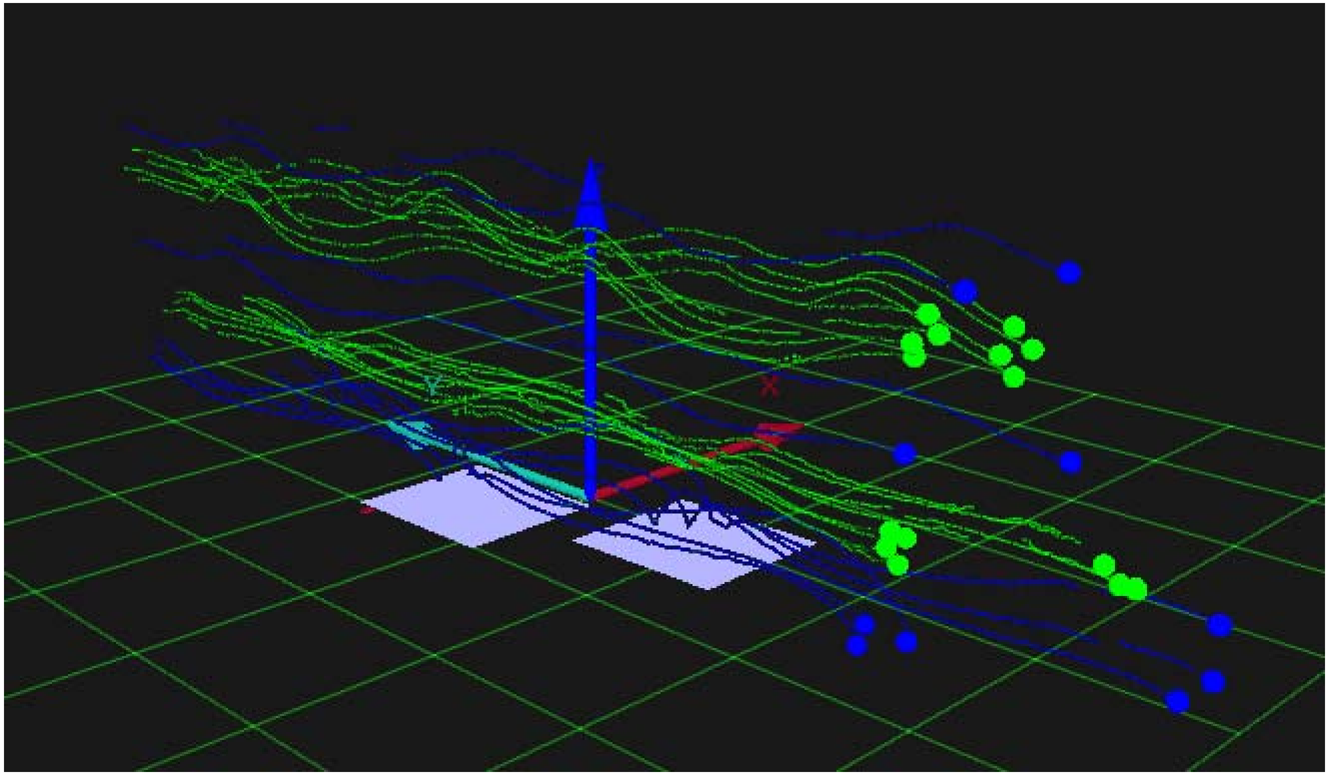
- Examples of marker model




1. ASIS
2. Sacrum
3. Iliac crest
4. Greater trochanter
5. Thigh
6. Lateral knee
7. Medial knee
8. Shank
9. Lateral ankle
10. Medial ankle
11. Heel
12. 1st metatarsal head
13. 5th metatarsal head

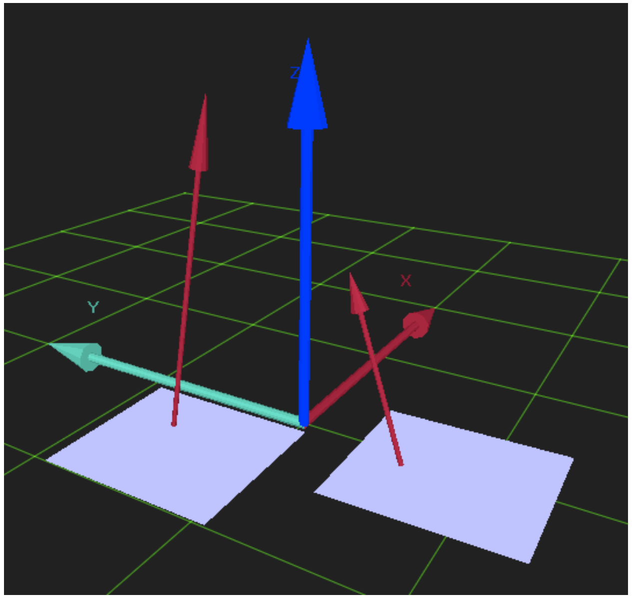
# Motion tracking

- Motion capture output



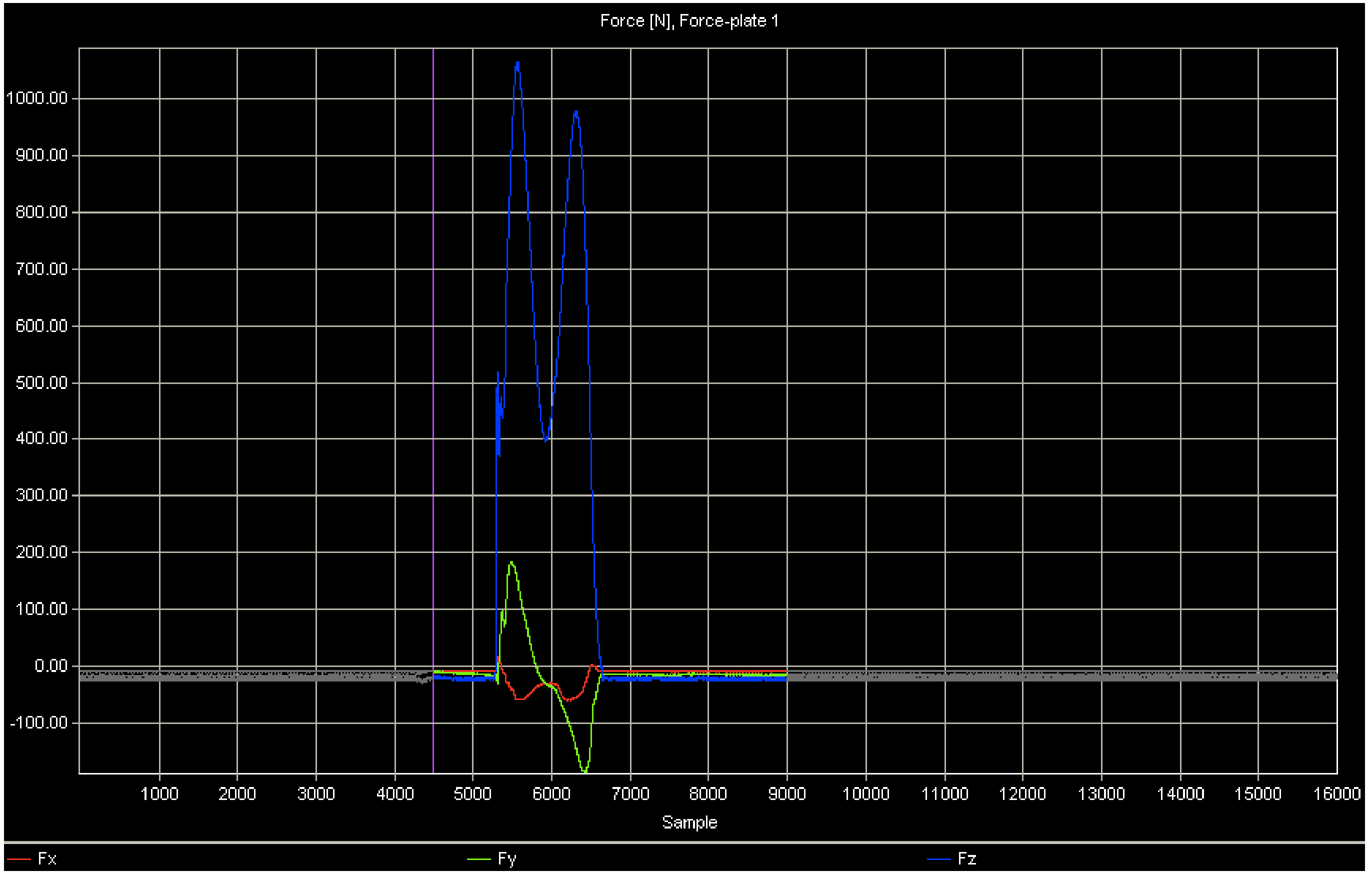
# Simulation overview

- Force plates
  - Used to acquire ground reaction force (GRF)
  - User steps on the plate



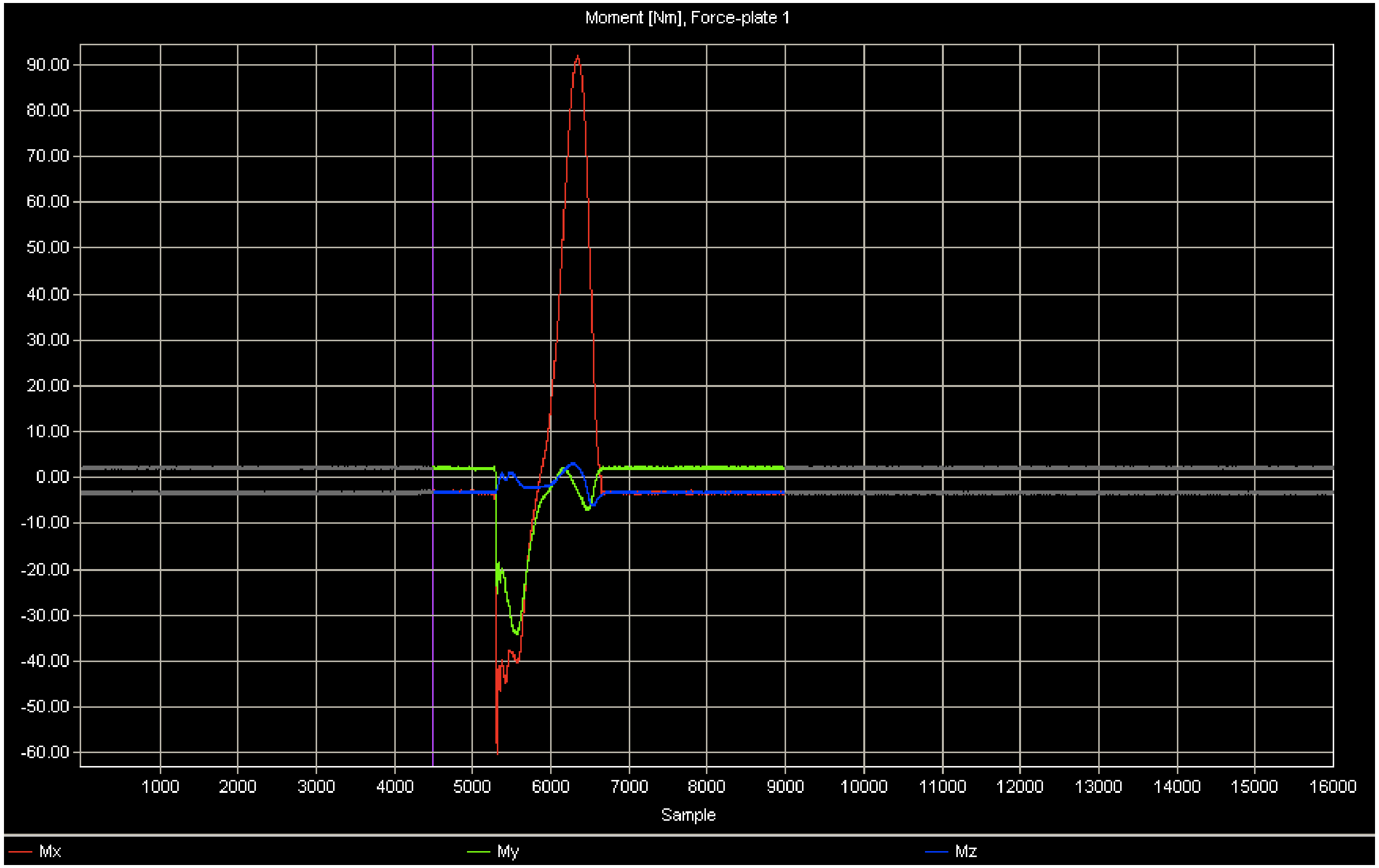
# Simulation overview

- Force in x,y,z direction



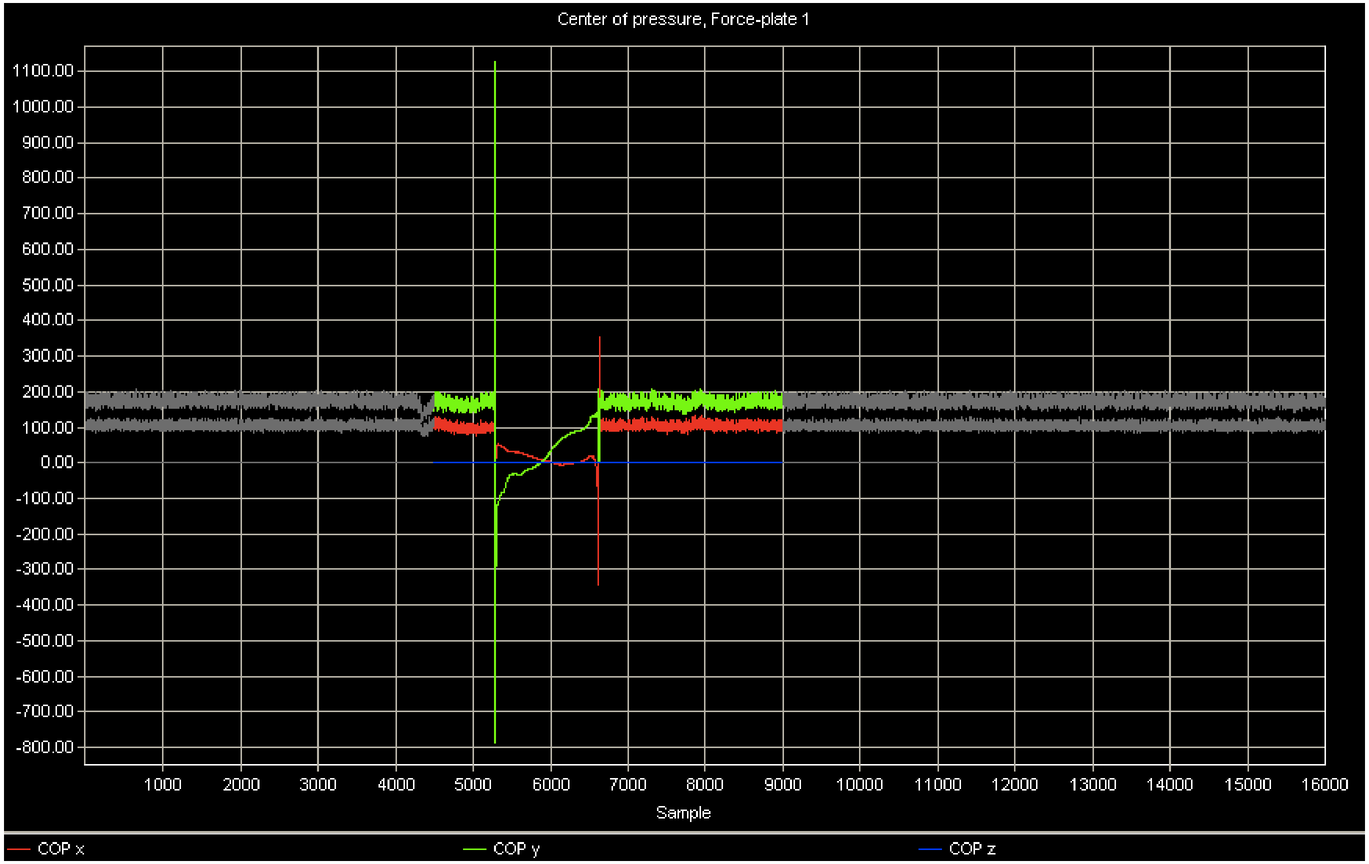
# Simulation overview

- Moment in x,y,z



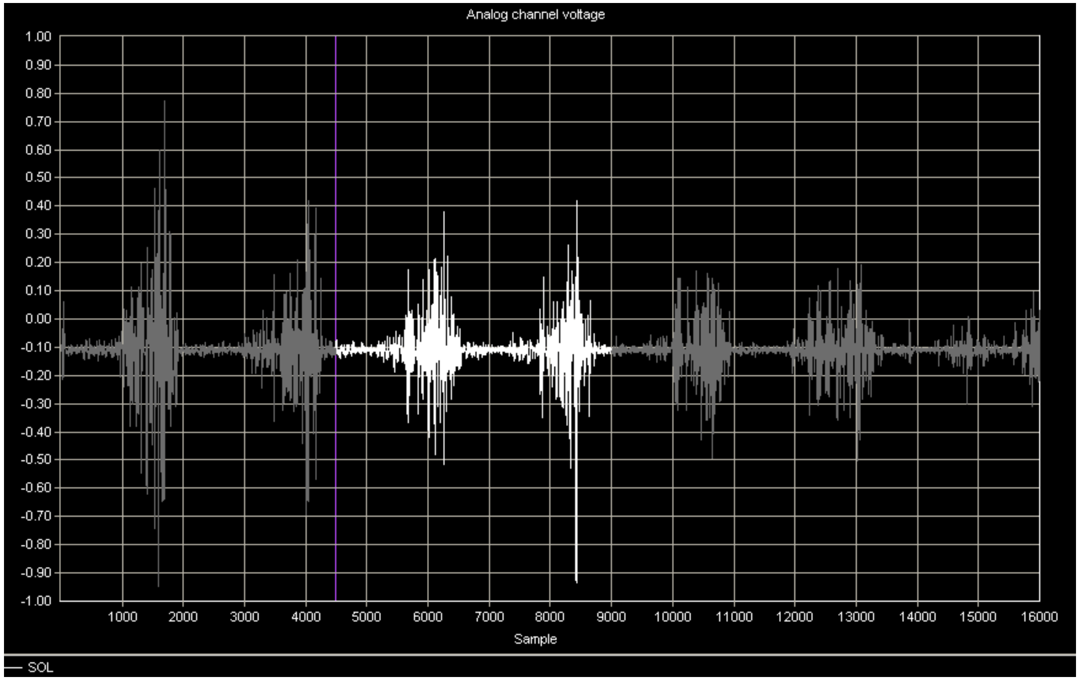
# Simulation overview

- Center of pressure, 2D point

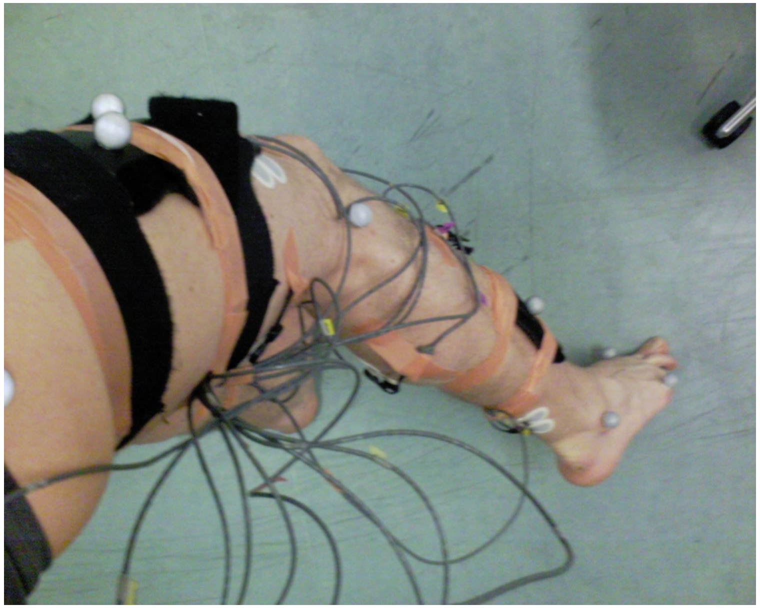


# Simulation overview

- Electromyography
  - Record activity of muscle
  - Sensors placed on the skin

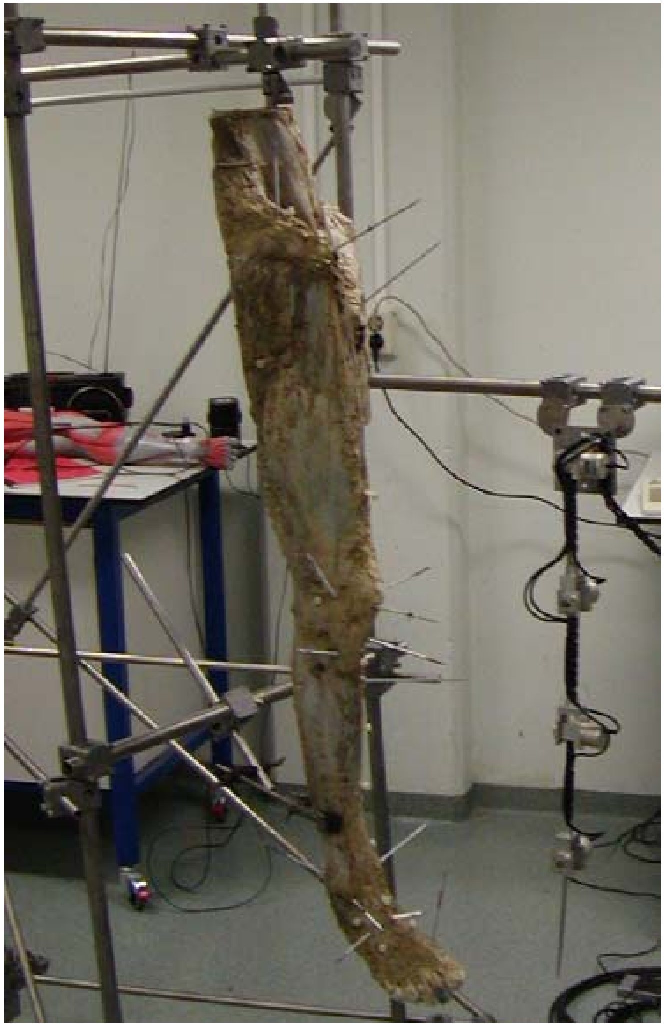


# Simulation overview



# Simulation overview

- Tissue data



# Simulation overview

- Tissue data

| Muscle | Origo | Ins. | # Elem. | S, BC or VP | PCSA ($cm^2$) | $L_{opt}$ (cm) | $L_{ten}$ (cm) | Mass (g) | Pen. ang. (°) |
|---|---|---|---|---|---|---|---|---|---|
| Add. brev. (prox.) | Surf. | Line (3) | 6 | S | 3.8 | 9.5 | 0 | 38.3 | 0 |
| Add. brev. (mid) | | | | S | 3.5 | 10.4 | 0 | 38.3 | 0 |
| Add. brev. (dist) | | | | S | 3.2 | 11.2 | 0 | 38.3 | 0 |
| Add. long. | Line (3) | Line (3) | 6 | S | 15.1 | 10.6 | 0 | 168.5 | 0 |
| Add. magn. (dist.) | Point | Line (2) | 3 | S | 26.5 | 10.8 | 4.2 | 302.0 | 0 |
| Add. magn. (mid.) | Surf. | Line (3) | 6 | S | 22.1 | 10.4 | 0 | 243.0 | 0 |
| Add. magn. (prox.) | Line (1) | Line (1) | 4 | S | 5.0 | 10.7 | 0 | 56.0 | 0 |
| Bic. fem. CL | Point | Point | 1 | S | 27.2 | 8.5 | 13.0 | 245.0 | 30 |
| Bic. fem. CB | Line (3) | Point | 3 | S | 11.8 | 9.1 | 3.1 | 114.0 | 0 |
| Ext. dig. long. | Line (2) | Point | 3 | VP | 5.4 | 6.0 | 30.1 | 34.1 | 8 |
| Ext. hal. long. | Line (2) | Point | 3 | VP | 6.1 | 6.0 | 17.8 | 38.3 | 14 |
| Flex. dig. long. | Surf. | Point | 3 | VP | 6.6 | 3.8 | 16.6 | 26.7 | 28 |
| Flex. hal. long. | Surf. | Point | 3 | VP | 31.1 | 2.6 | 23.4 | 83.7 | 30 |
| Gastrocn. (lat.) | Point | Point | 1 | BC | 24.0 | 5.7 | 23.4 | 144.0 | 25 |
| Gastrocn. (med.) | Point | Point | 1 | BC | 43.8 | 6.0 | 21.2 | 278.0 | 11 |
| Gemellus (inf.) | Point | Point | 1 | S | 4.1 | 3.4 | 0 | 15.0 | 0 |
| Gemellus (sup.) | Point | Point | 1 | S | 4.1 | 3.4 | 0 | 15.0 | 0 |
| Glut. max. (sup.) | Surf. | Surf. | 6 | S | 49.7 | 12.0 | 0 | 629.0 | 0 |
| Glut. max. (inf.) | Surf. | Line (2) | 6 | S | 22.5 | 15.1 | 0 | 360.0 | 0 |
| Glut. med. (ant.) | Surf. | Surf. | 6 | S | 37.9 | 3.8 | 0 | 152.5 | 0 |
| Glut. med. (post.) | Surf. | Surf. | 6 | S | 60.8 | 4.5 | 3.0 | 287.0 | 16 |
| Glut. min. (lat.) | Surf. | Point | 3 | S | 10.0 | 2.8 | 7.3 | 29.1 | 0 |
| Glut. min. (mid.) | | | | S | 8.1 | 3.4 | 7.3 | 29.1 | 0 |
| Glut. min. (med.) | | | | S | 7.4 | 3.7 | 7.3 | 29.1 | 0 |
| Gracilis | Line (1) | Point | 2 | VP | 4.9 | 18.1 | 14.0 | 92.9 | 0 |
| Iliacus (lat.) | Surf. | Point | 3 | BC | 6.6 | 10.3 | 11.3 | 71.5 | 26 |
| Iliacus (mid.) | Surf. | Point | 3 | BC | 13.0 | 5.2 | 11.3 | 71.5 | 0 |

*Klein Horsman et al, Morphological muscle and joint parameters for musculoskeletal modelling of the lower extremity, Clinical Biomechanics 22 (2007) 239–247*

# Simulation overview

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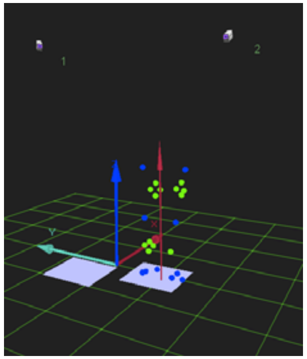
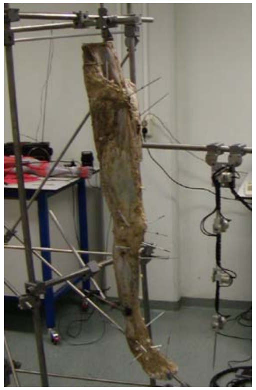
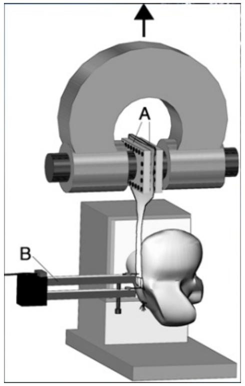
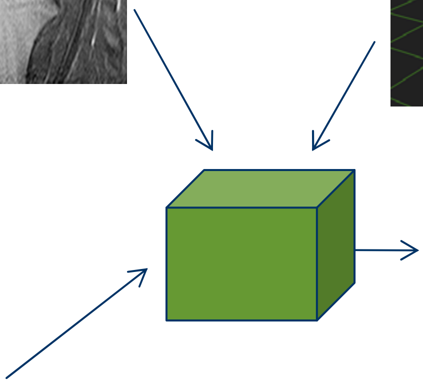
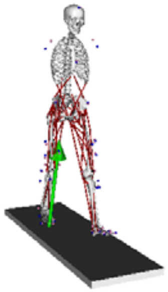


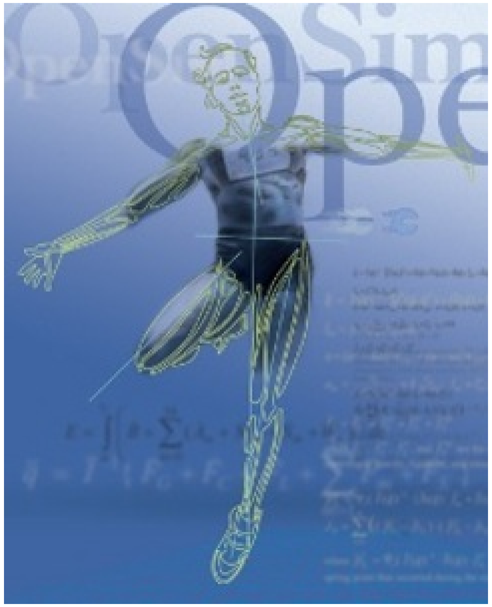




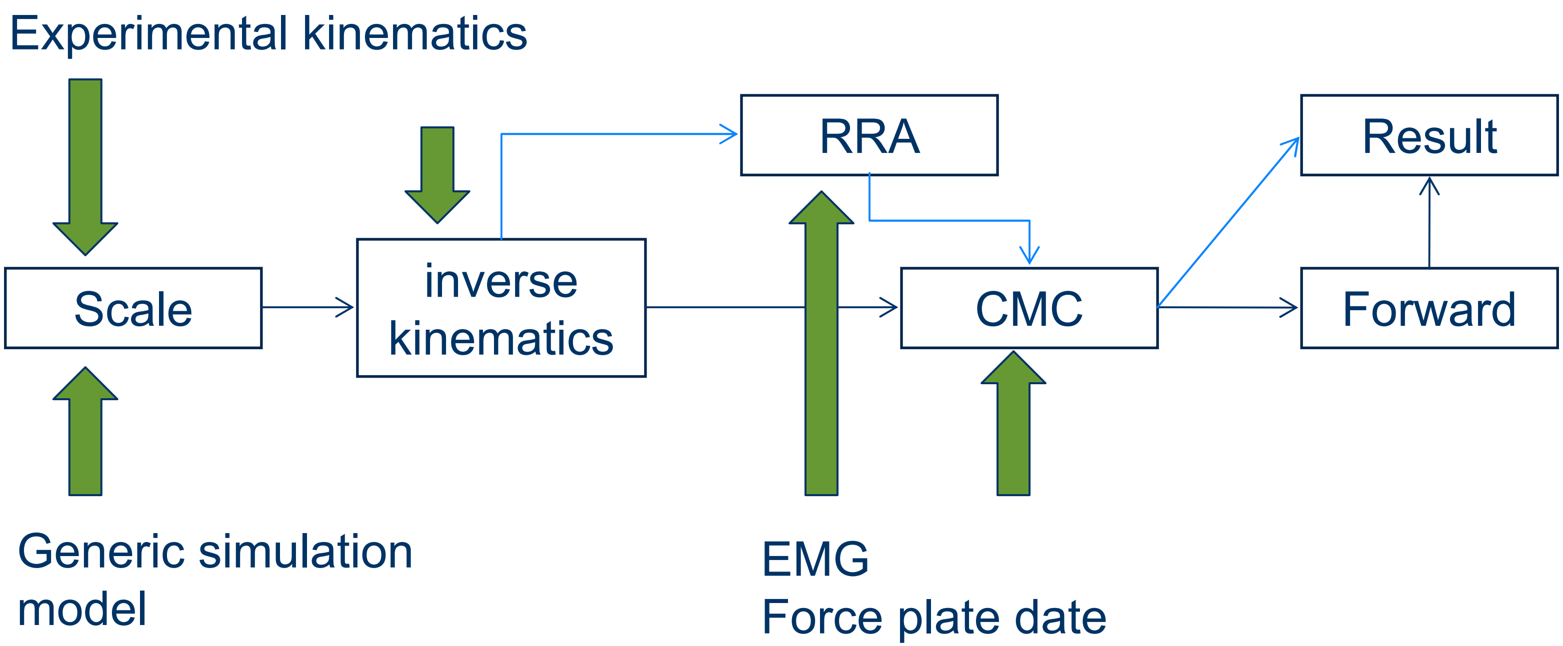


# Simulation phases

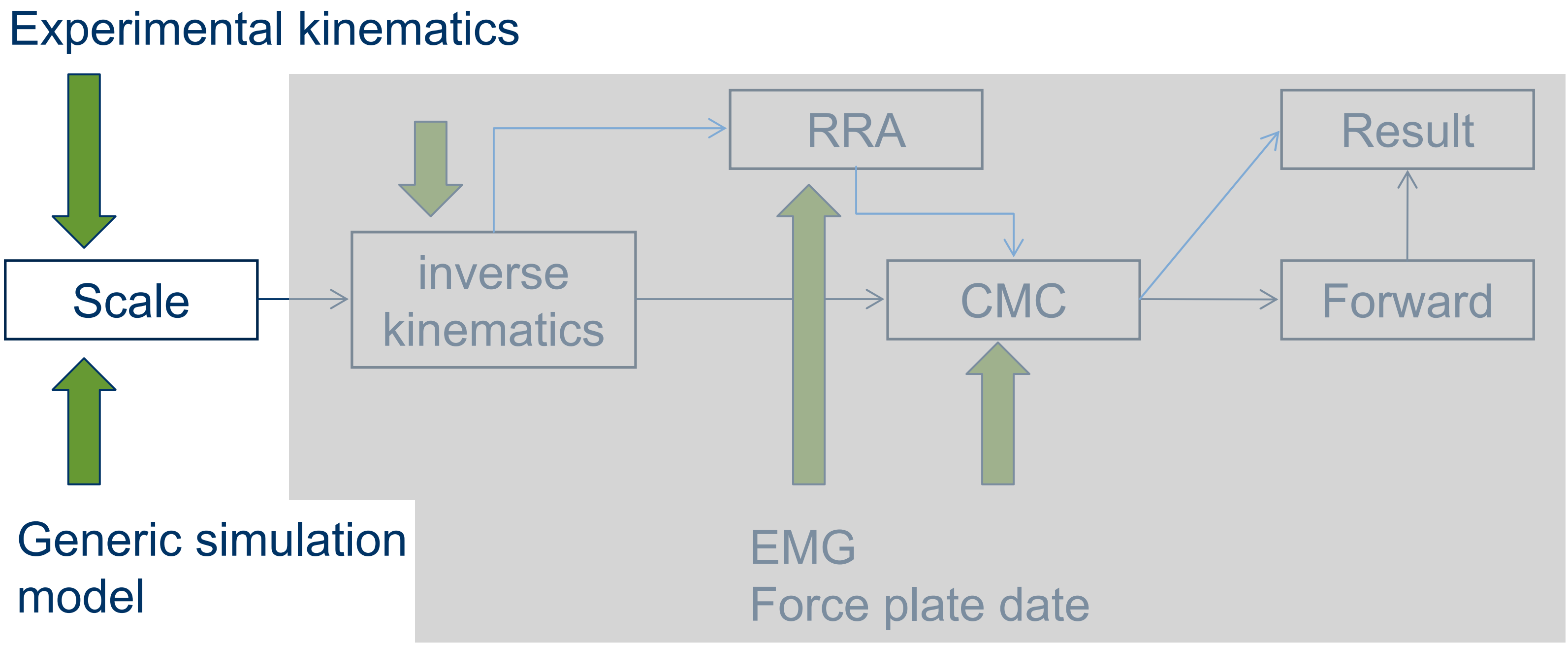


- OpenSim
  - Open source
  - “free”
    - Software (GUI)
    - Library
    - Source code (ANSI C++, Gui Java)
  - Module design
    - Exchange, share modules without alter or compile the source code
  - https://simtk.org/home/opensim

# Simulation phases



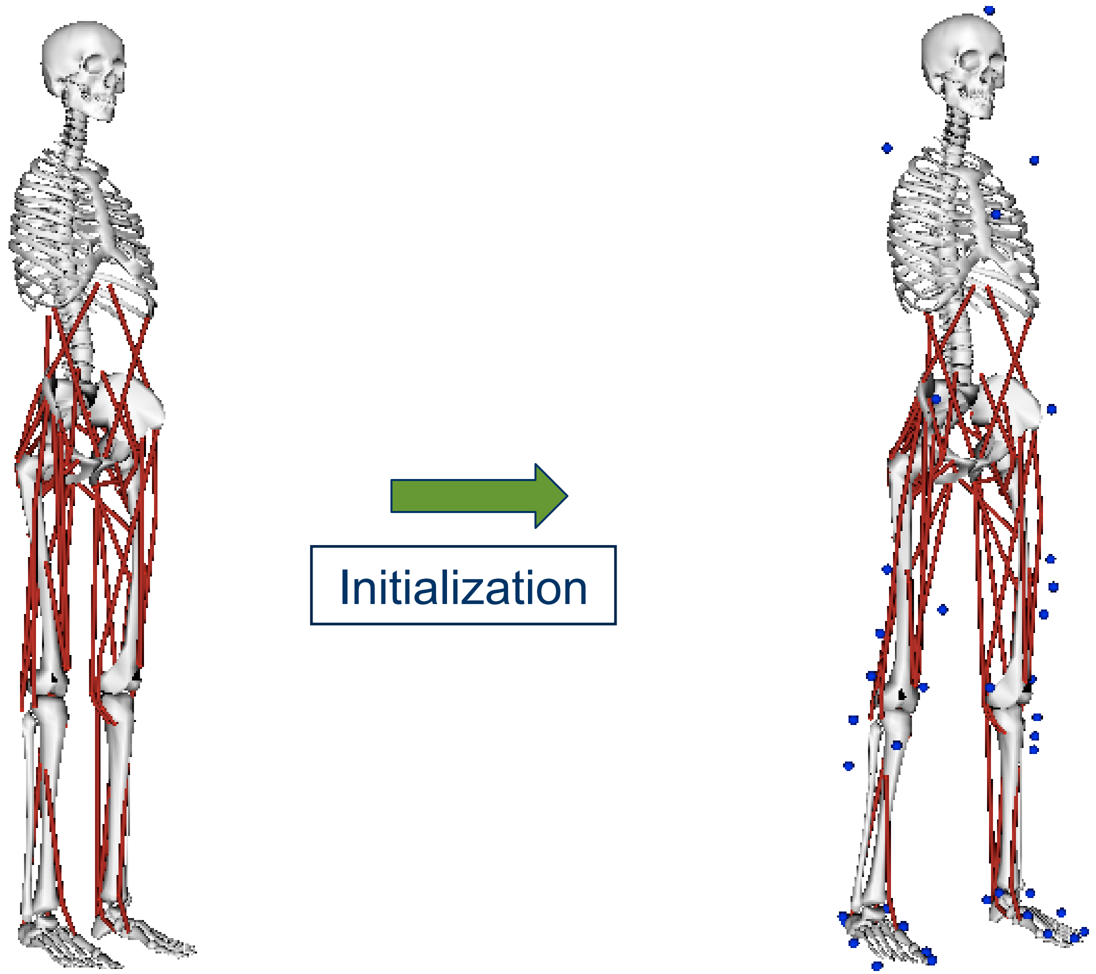
# Simulation phases



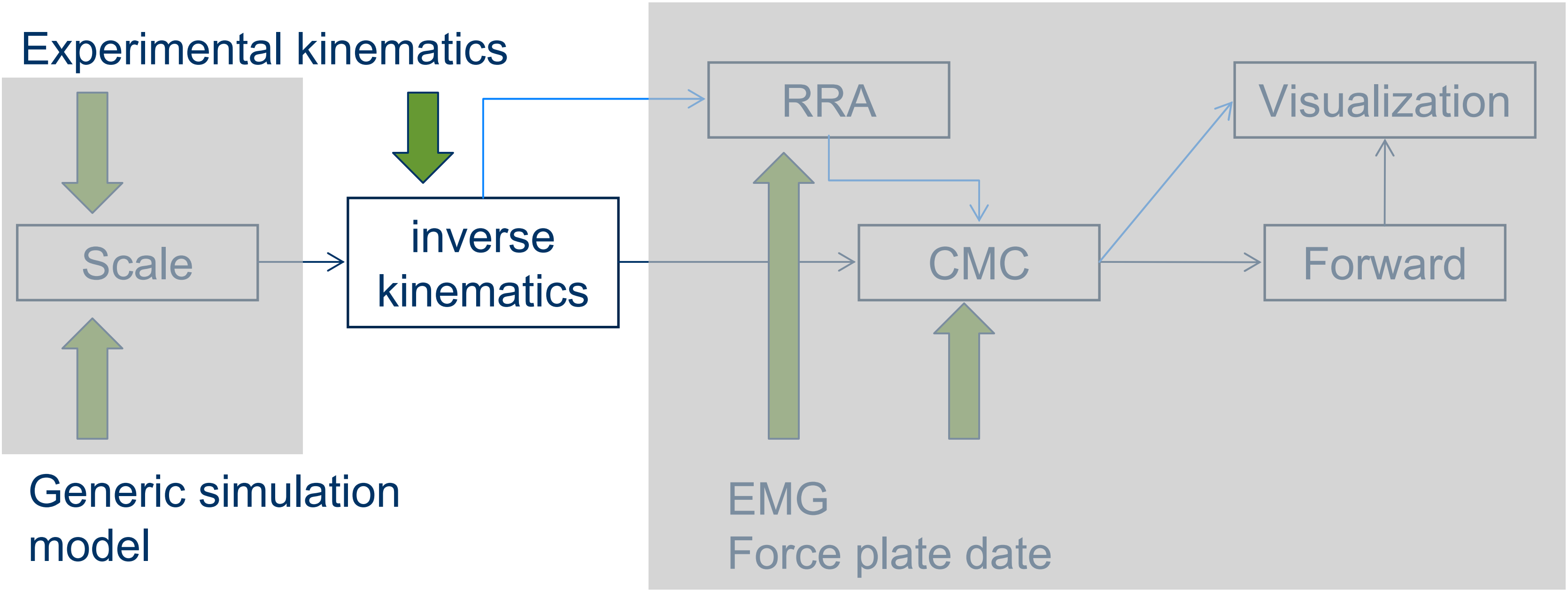
# Scale (initialization)

- Initialization
  - Scale Generic Simulation Model
    - Markers scale the generic simulation model to match the motion model
    - Scaling of individual bones
    - Mass scaling
    - Scaling of muscle fiber length, tendon slack length of the muscle-tendon actuators
  - Inverted Kinematic initialization
    - Align the generic simulation model markers so they match the markers in the first frame of the motion capture data

# Initialization



# Simulation phases

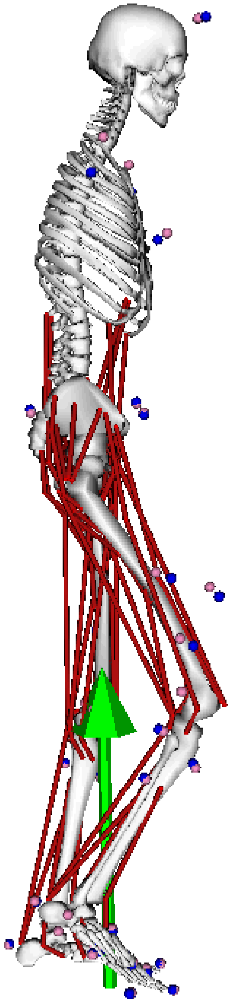


# Inverse Kinematics

- Inverse Kinematic phase
  - In each motion capture frame
    For every joint
    joint angels and translations are solved so the generic model markers match the motion capture markers.

$$\text{Squared Error} = \sum_{i=1}^{\text{markers}} w_i \left( \vec{x}_i^{\text{subject}} - \vec{x}_i^{\text{model}} \right)^2 + \sum_{j=1}^{\text{joint angles}} \omega_j \left( \theta_j^{\text{subject}} - \theta_j^{\text{model}} \right)^2$$

# Inverse Kinematics

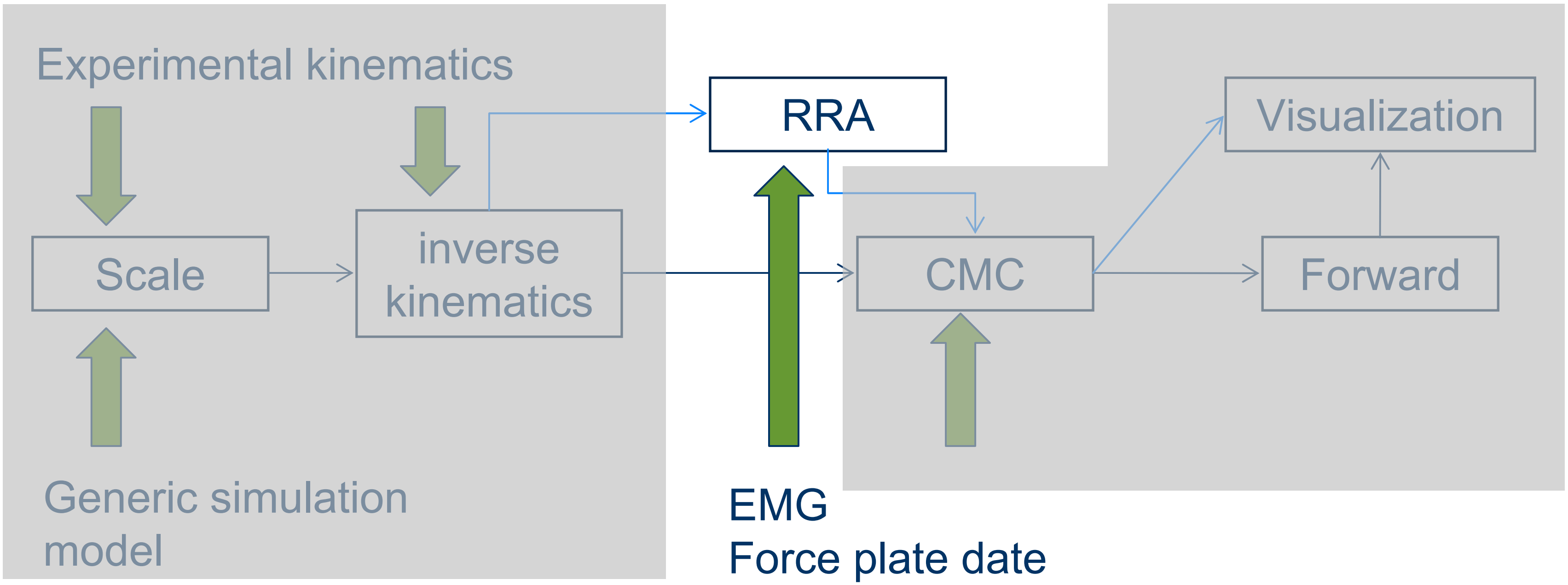


# Inverted Kinematic

- Errors in experimental kinematics and reaction forces => errors in the kinematic solution

- Solution
  - Apply additional residual forces and moments so the model follow the same motion as the subject
- New Problem
  - Adding residual forces will not give a correct solution

# Simulation phases



# Residual reduction algorithm

- Solution
  - Newton's second law links the measured ground
  - reaction force and gravitational acceleration to the accelerations of the body segments

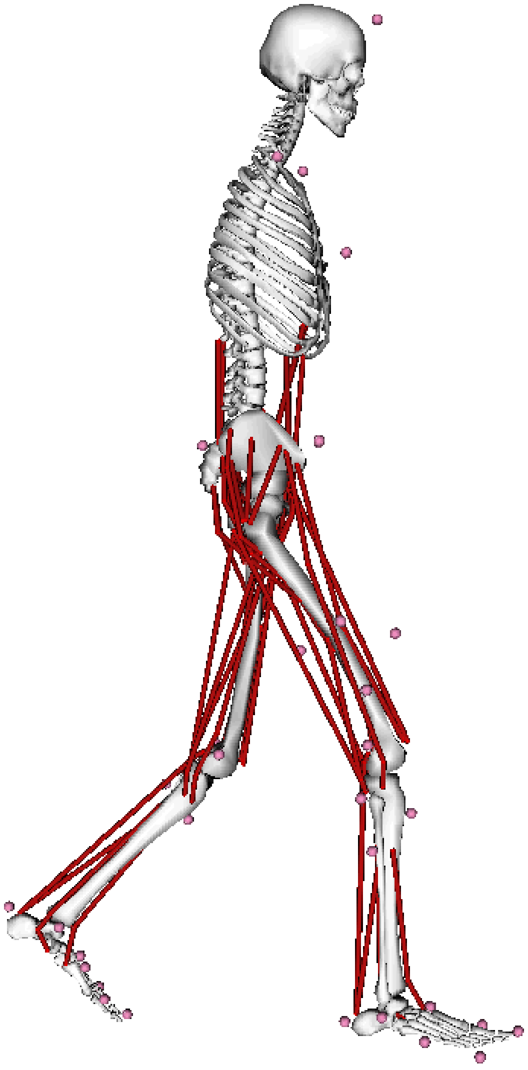
$$\overrightarrow{F}_{\text{external}} = \sum_{i=1}^{\text{segments}} m_i \overrightarrow{a}_i - \overrightarrow{F}_{\text{residual}}$$

↑

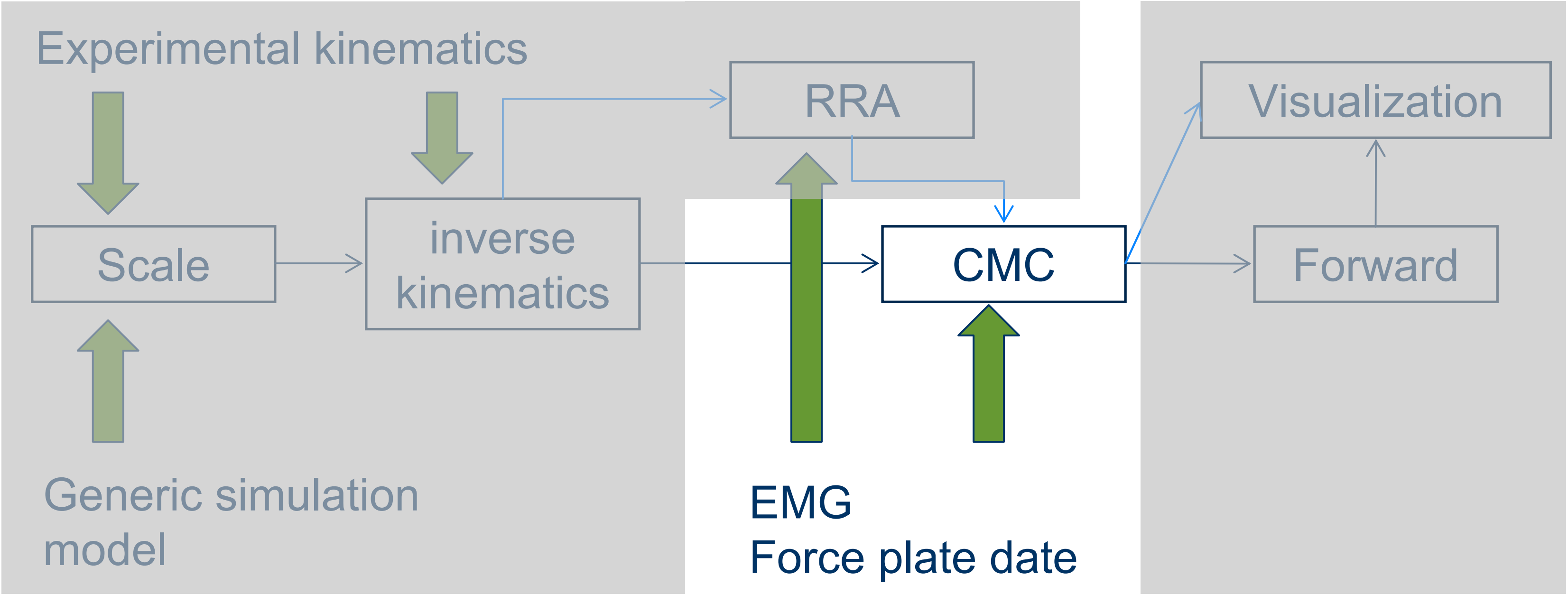
Should be zero

  - Problem becomes to alter the inverted kinematic solution and trunk mass center to minimize Fresidual

# Residual reduction algorithm



# Simulation phases

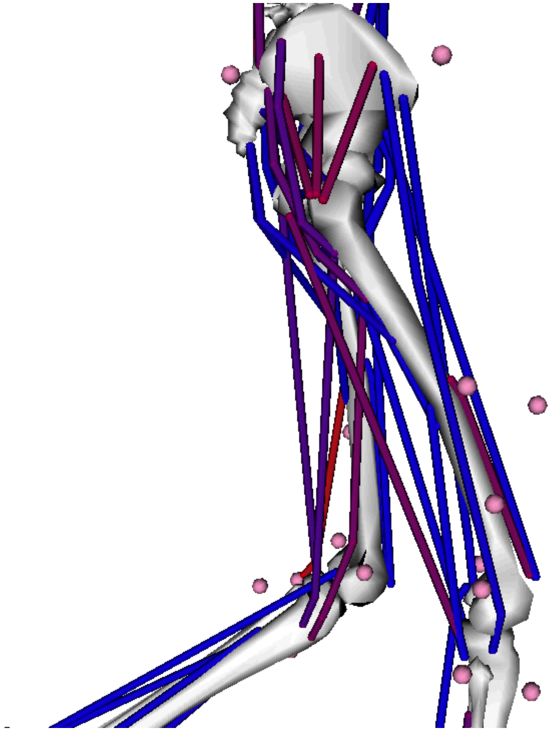


# Computed Muscle Control

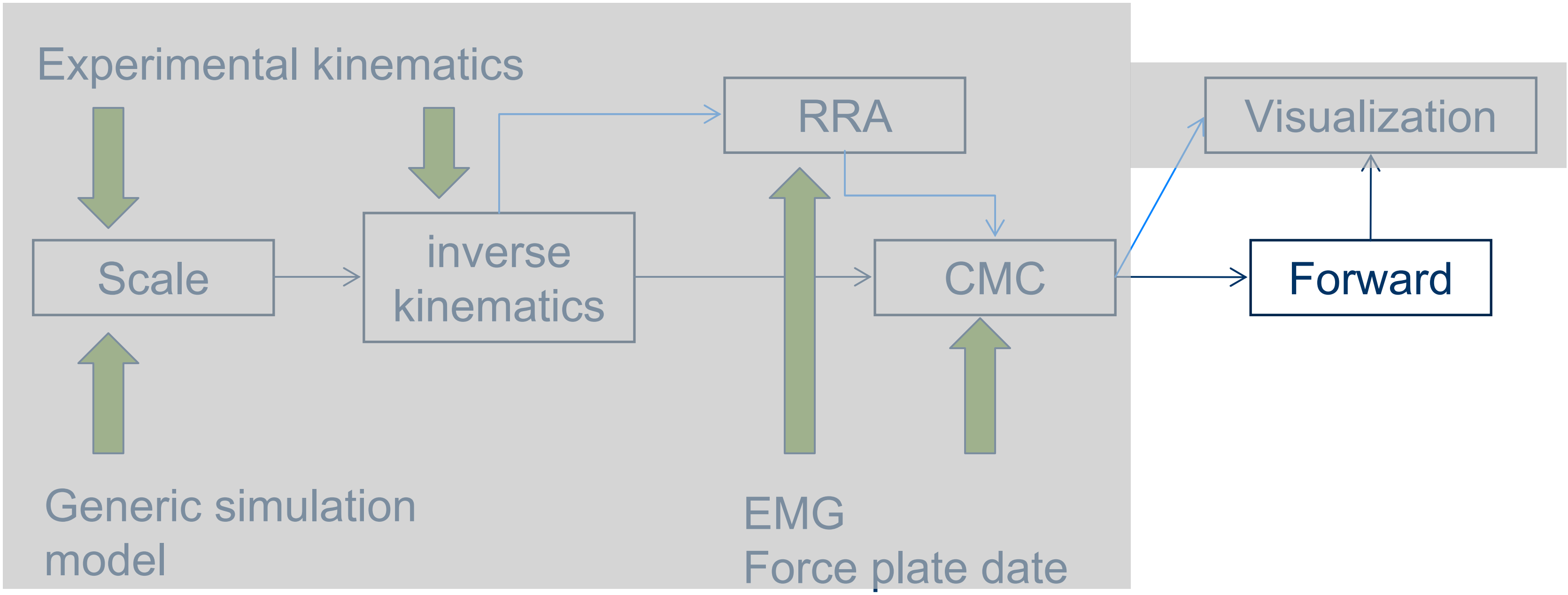
- From motion to muscle forces
  - Calculate muscle excitations to produce a muscle-driven simulation of the motion capture movement
    - Performed using a static optimization criterion to distribute forces across synergistic muscles and proportional-derivative control to generate a forward dynamic simulation

# Computed Muscle Control

- From motion to muscle forces



# Simulation phases

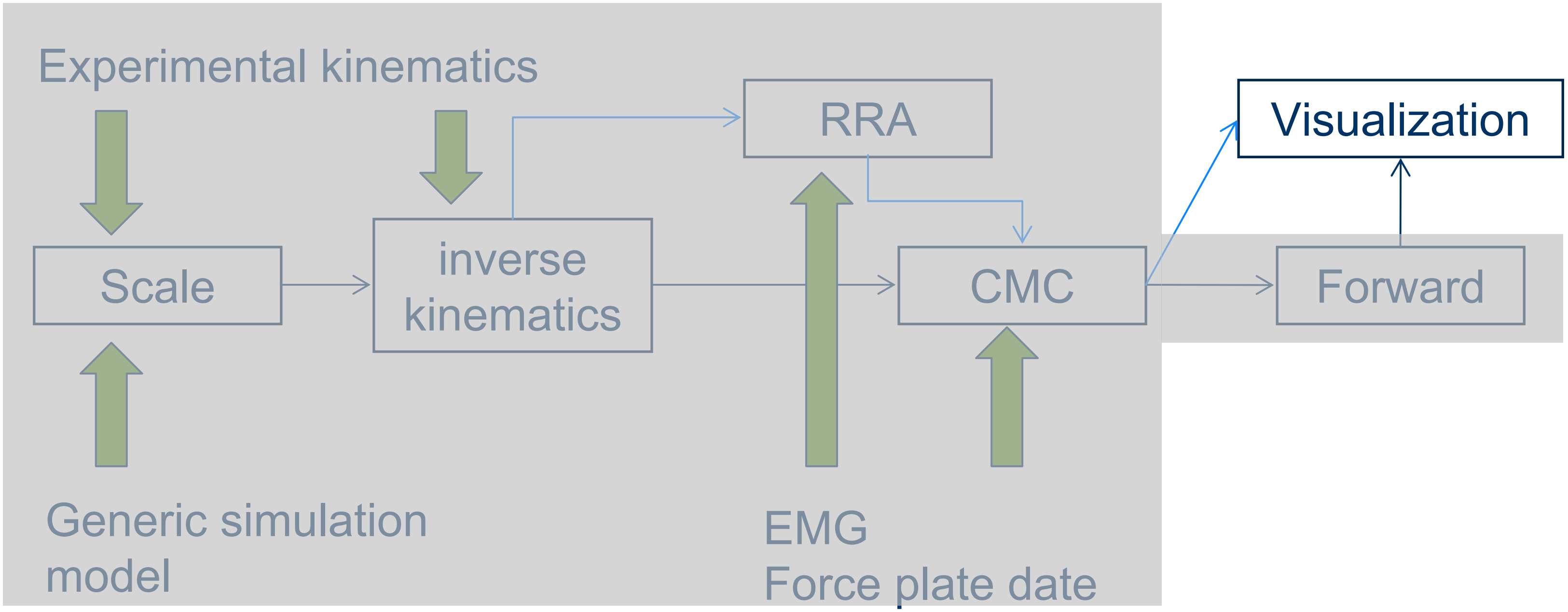


# Forward simulation

- Generation of motion from muscle forces
  - Ground reaction force
  - Compute muscle function (or EMG)
    - Generate motion from, which follow the inverted kinematic simulation.
  - Using a full state equations representing of the activation and contraction dynamics of the muscles

$$\dot{l}_m = f_v^{-1}(l_m, l_{\mathrm{mt}}, a)$$

# Simulation phases

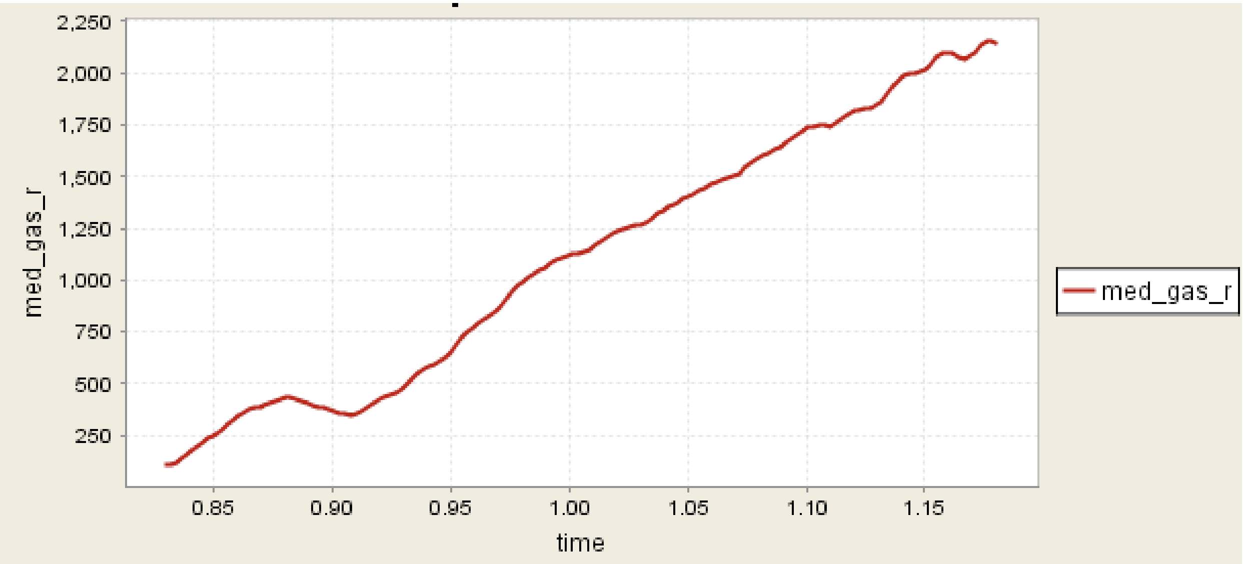


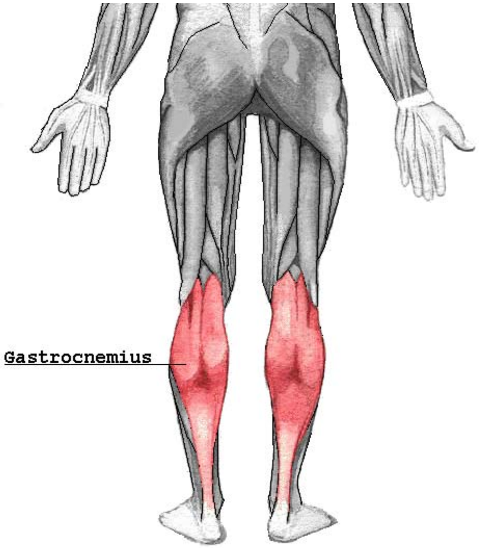
# Visualization

- What to visualize?
  - Simulation performed in 3D and time
  - Can be 100s of variables, depending on model and methods, some with direct medical connection, some used to solve equations/mechanics/solvers
  - Visualization problem.
    What is useful and what is “pretty picture syndrome”

# Visualization

- Visualize Muscle force generated by the right gastrocnemius



# Thank You

# Questions?