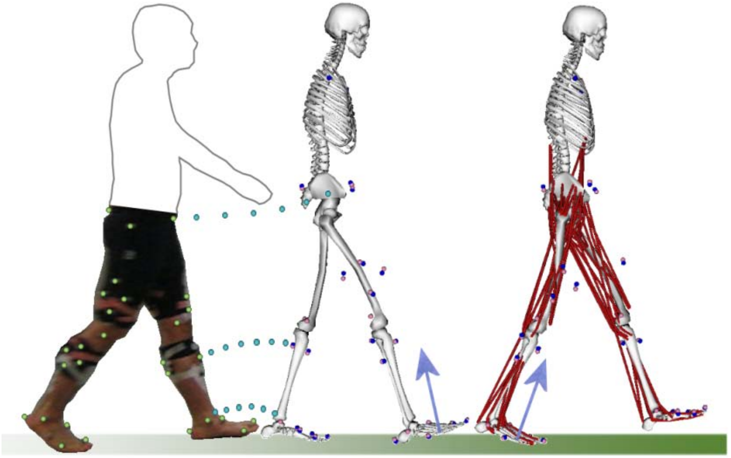
TUTORIAL

3D Physiological Human Workshop

MUSCULOSKELETAL SIMULATION :

FROM MOTION CAPTURE TO MUSCULAR ACTIVITY IN LOWER LIMB MODELS



Nicolas Pronost and *Anders Sandholm*

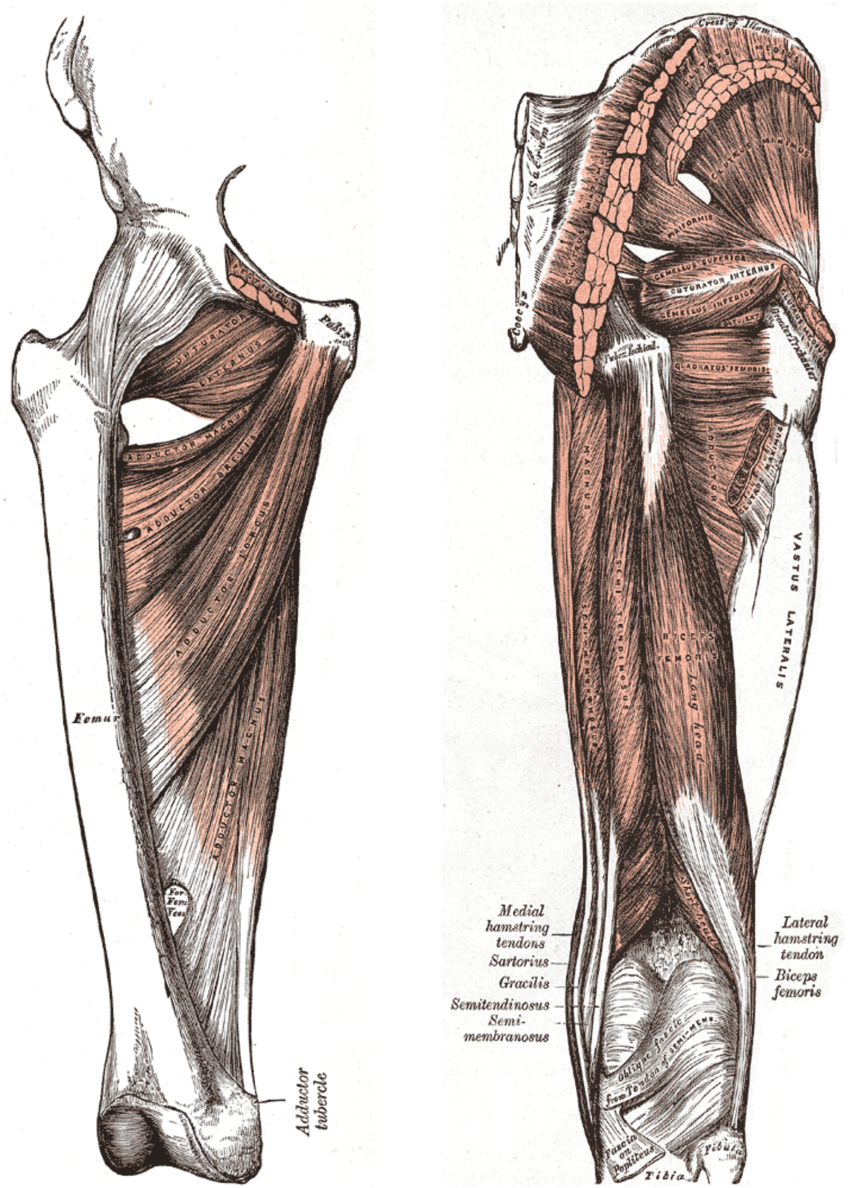
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Musculoskeletal simulation ?

- What is it ?

Musculoskeletal simulation ?

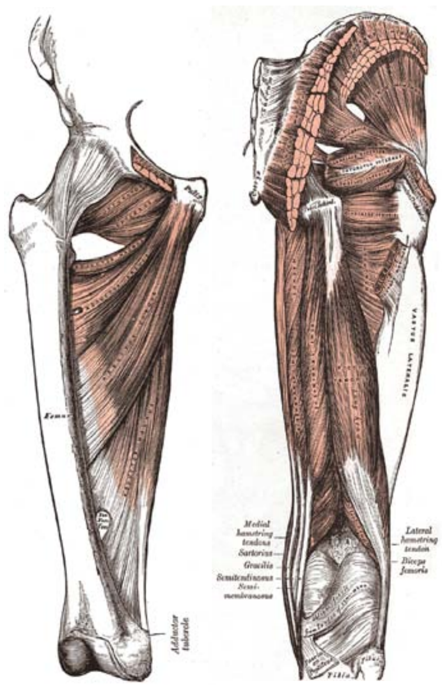
- What is it ?
  - Musculo

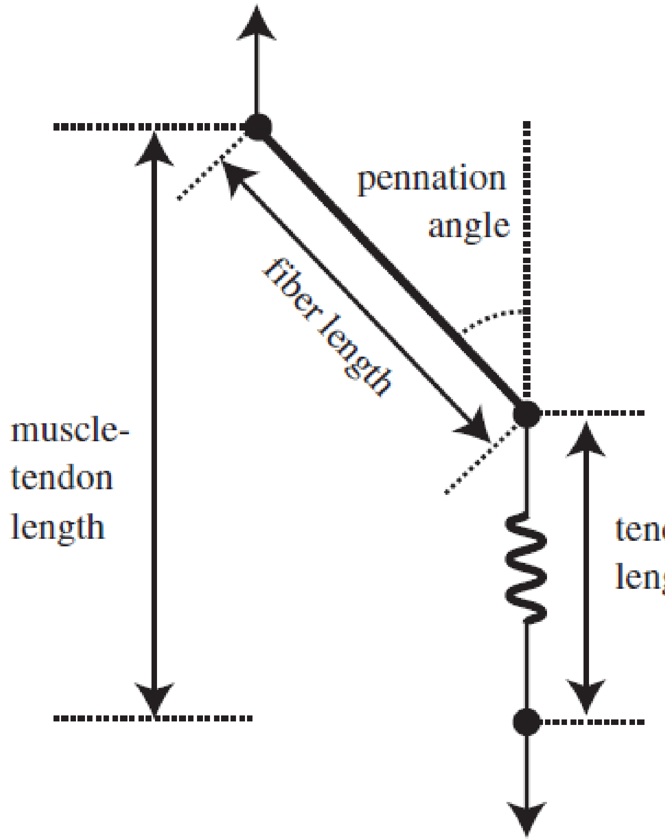


Henry Gray, Anatomy of the human body, 1918

Musculoskeletal simulation ?

- What is it ?
  - Musculo



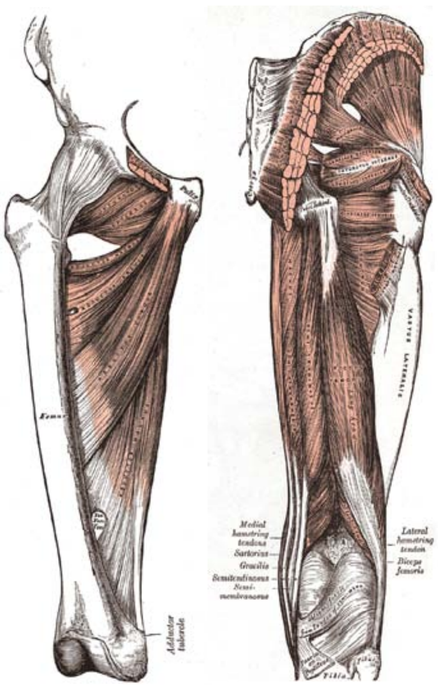


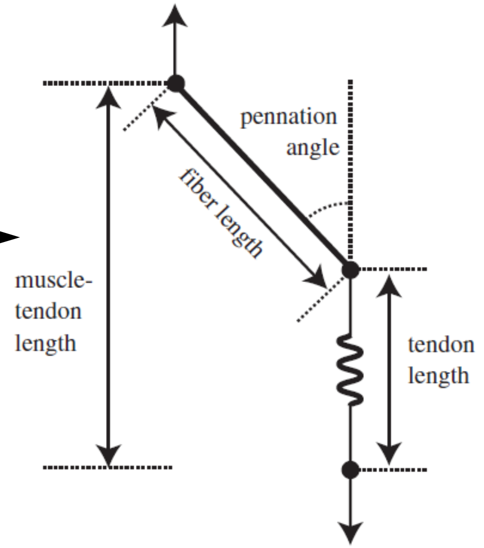
Sylvia S. Blemker, Stanford University, 2006

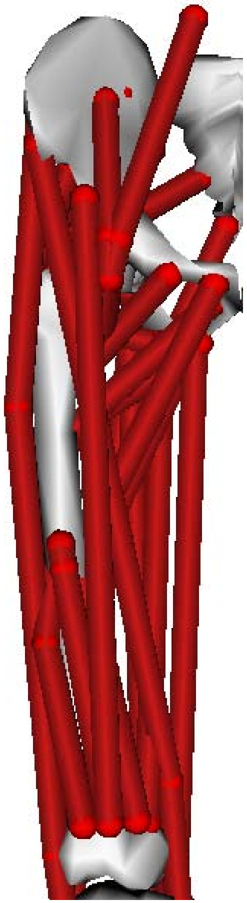
Human anatomy **Musculoskeletal representation**

Musculoskeletal simulation ?

- What is it ?
  - Musculo







OpenSim, University of Stanford

Human anatomy

Musculoskeletal representation

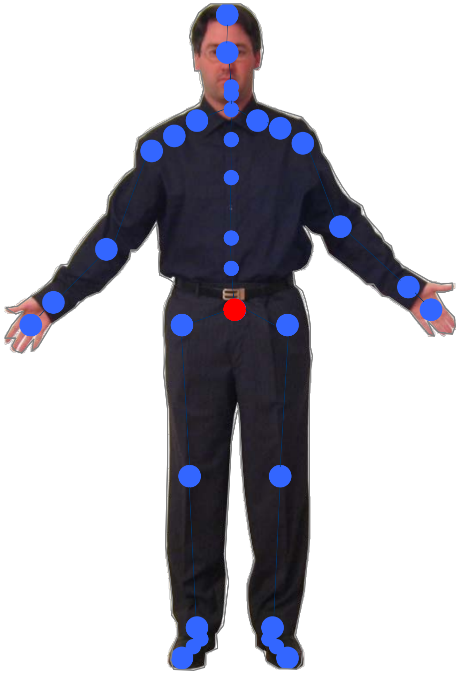
Action lines

Musculoskeletal simulation ?

- What is it ?
  - Musculo
  - Skeletal

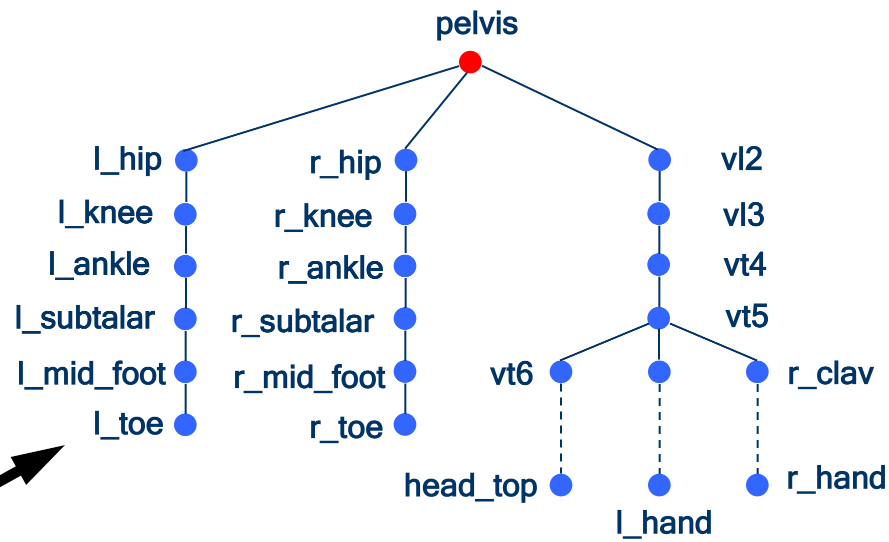
Musculoskeletal simulation ?

- What is it ?
  - Musculo
  - Skeletal

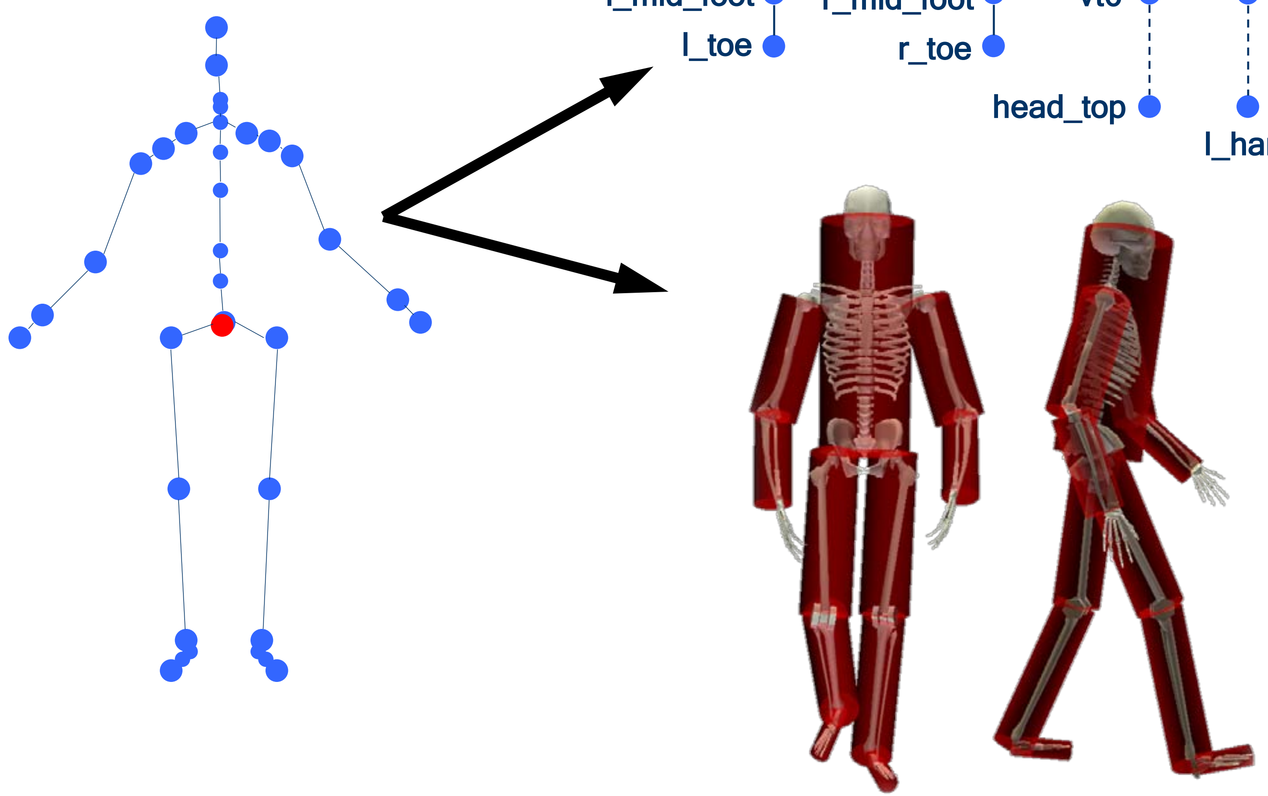


Musculoskeletal simulation ?

- What is it ?
  - Musculo
  - Skeletal



Segments connected by joints and hierarchically organized



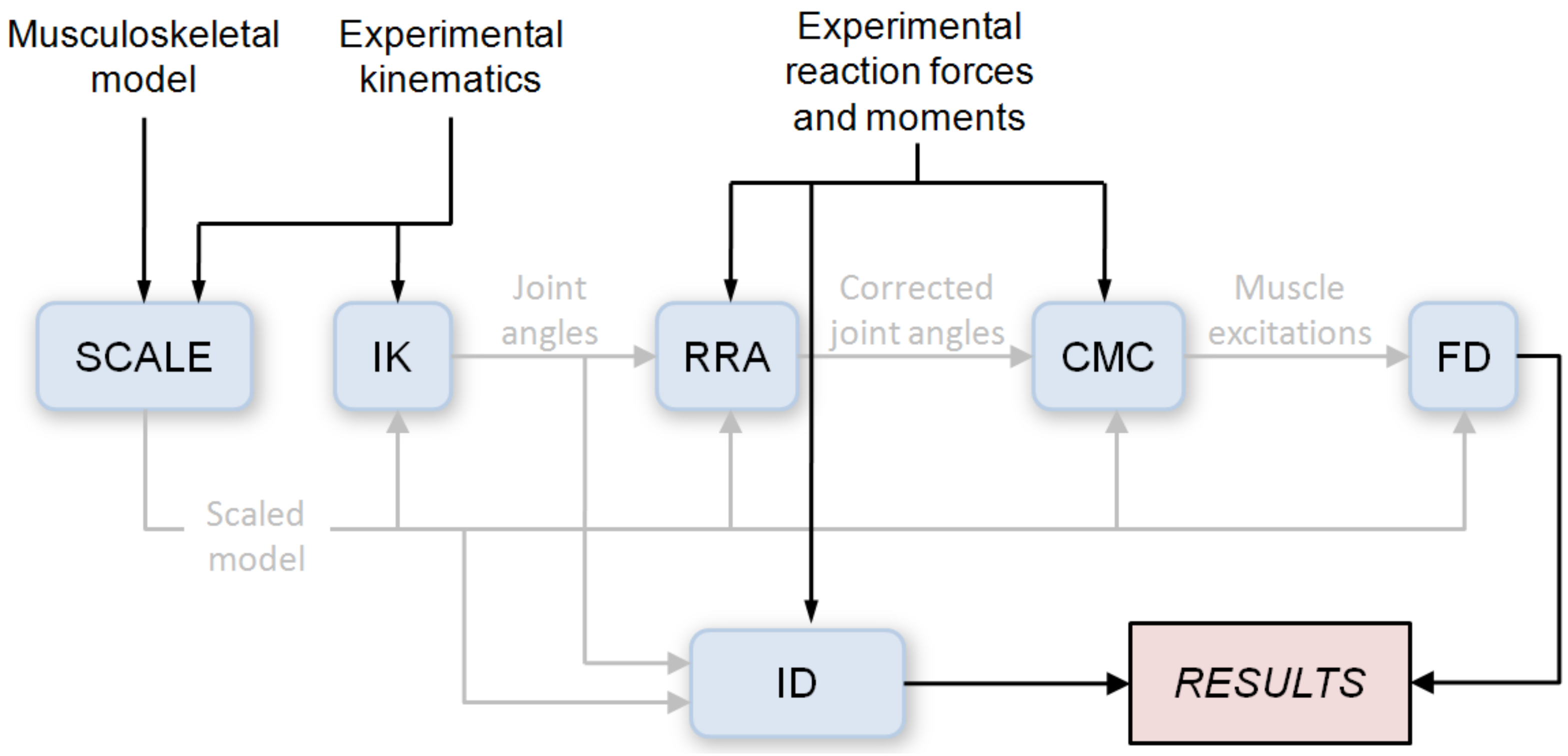
Rigid bodies with mass, inertia matrix and CoM

Musculoskeletal simulation ?

- What is it ?
  - Musculo
  - Skeletal
  - Simulation

Musculoskeletal simulation ?

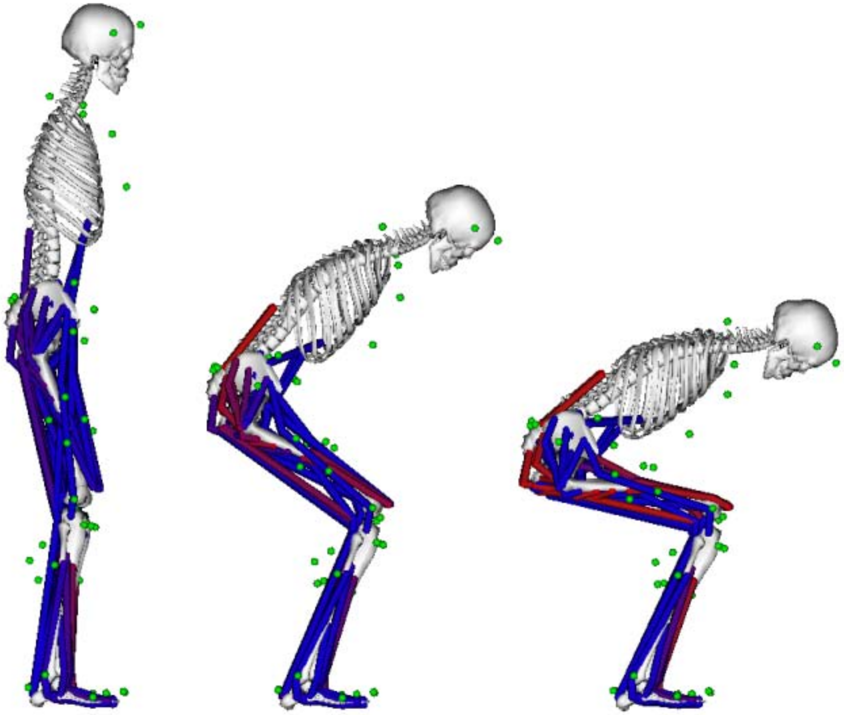
- What is it ?
  - Musculo
  - Skeletal
  - Simulation means analysis



Musculoskeletal simulation ?

- What for ?
  - Analyze athletic performance

OpenSim, University of Stanford



3DAH Marie Curie Project

Musculoskeletal simulation ?

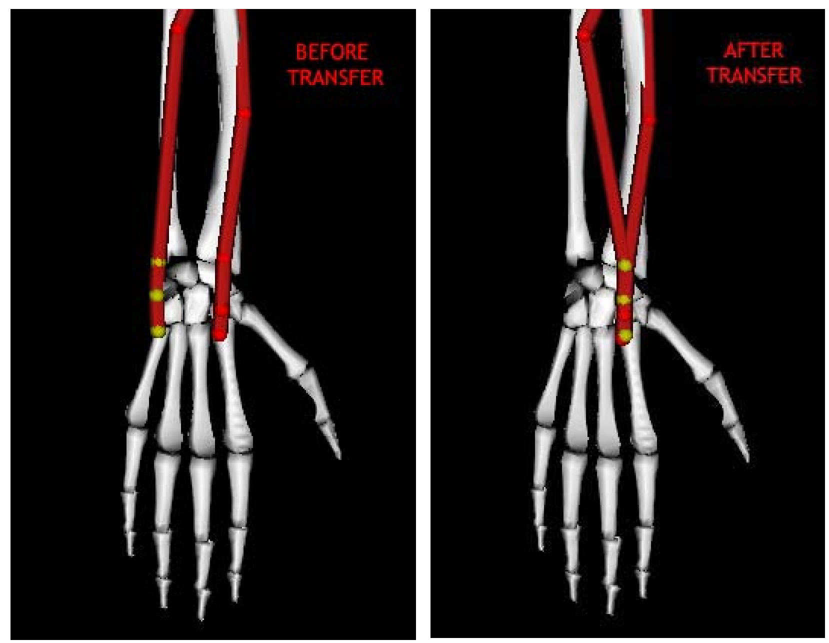
- What for ?
  - Analyze athletic performance
  - Design ergonomically safe environments

AnyBody Technology, Aalborg University

Musculoskeletal simulation ?

- What for ?
  - Analyze athletic performance
  - Design ergonomically safe environments
  - Understand and/or treat movement disorders

3DAH Marie Curie Project



OpenSim, University of Stanford

Musculoskeletal simulation ?

- What you do with ?
  - Visualize complex movement patterns
  - Test “what if” scenario
  - Estimate data difficult to measure
  - Identify cause-effect relationships

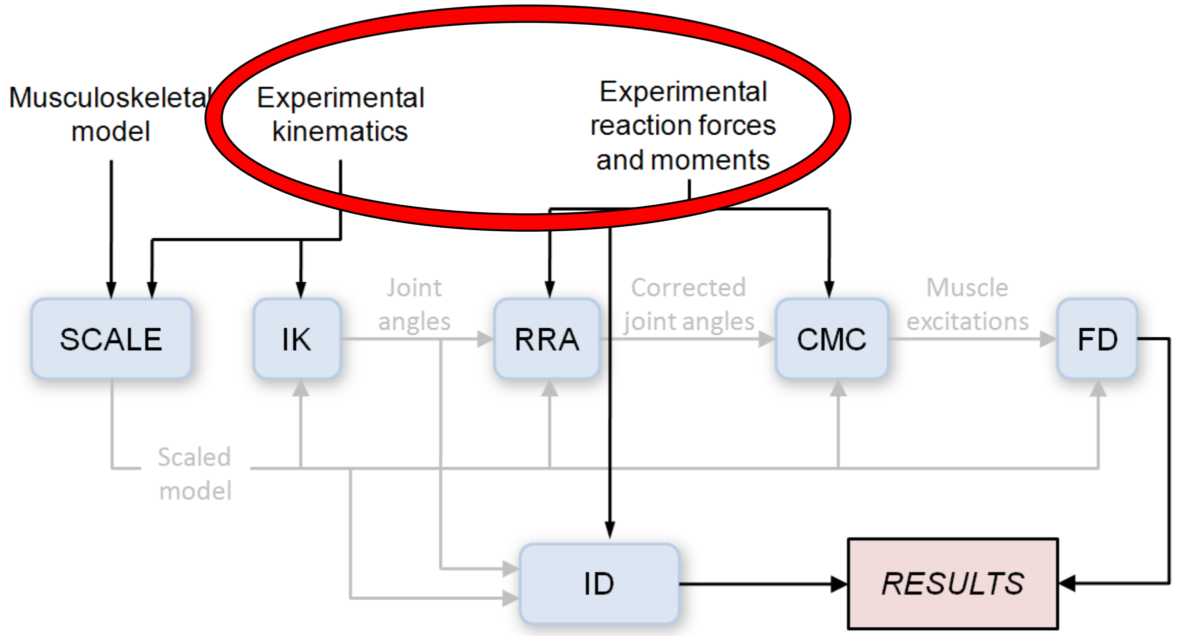
Outlines of the tutorial

- Objective : To perform a musculoskeletal simulation from A to … V
  - Acquisition of the data
  - Definition of the model
  - Inverse Kinematics solving
  - Muscular activation estimation
  - Validation of the simulation
- Extra features
  - How to create a model ?
  - Interactions with medical imaging
  - Towards more visualizations
  - Simulating tendon transfer surgery

Context

- Tools
  - OpenSim
    - Open-source musculoskeletal simulation platform
    - Based on SimTK (biological dynamics)
    - Performs SCALE, IK, ID, RRA, CMC and FD
    - Provided with validated musculoskeletal models
    - GUI and command line based
  - Subject specific data
    - Motion capture (crouch) with ground reaction forces
    - EMG signals

Step 1 : Acquisition of the data



Acquisition of the data

- Motion capture
  - 3D position of anatomical landmarks over time
  - Skin markers vs. clusters vs. bone pins

VICON

QUALYSIS

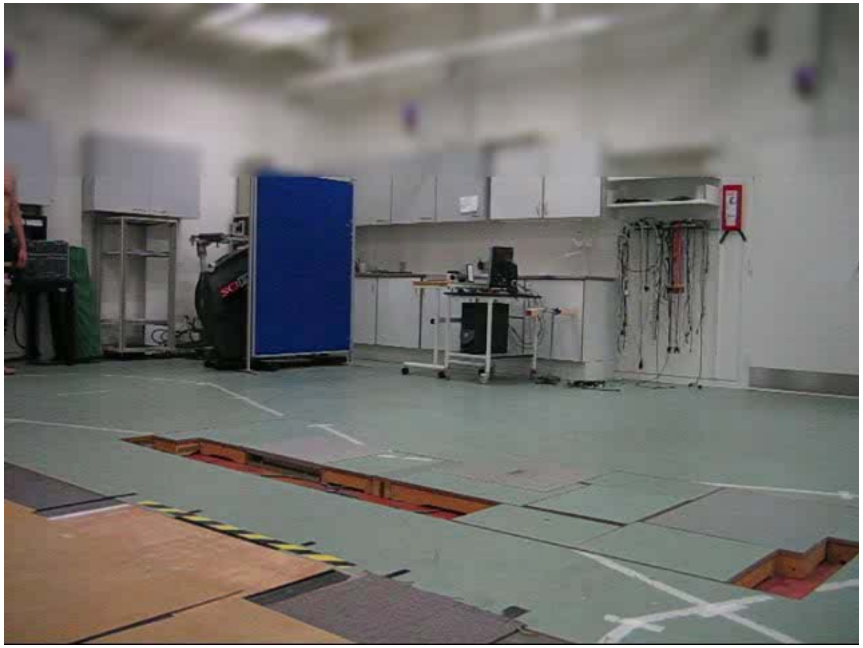
QUALYSIS

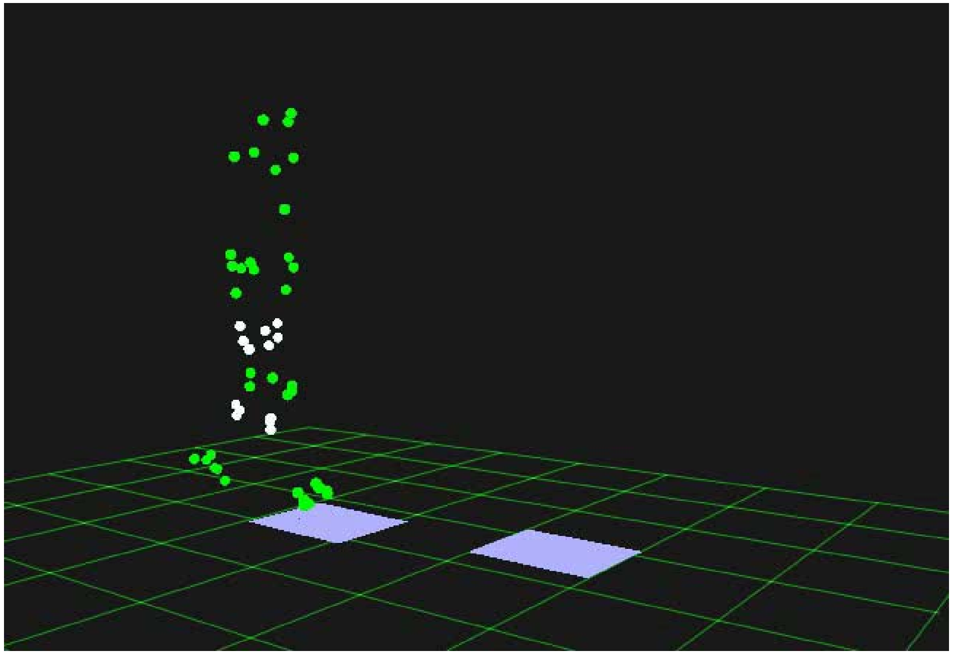
QUALYSIS

C. Nester, University of Salford, 2007

Acquisition of the data

- Motion capture
  - 3D position of anatomical landmarks over time
  - Skin markers vs. clusters vs. bone pins





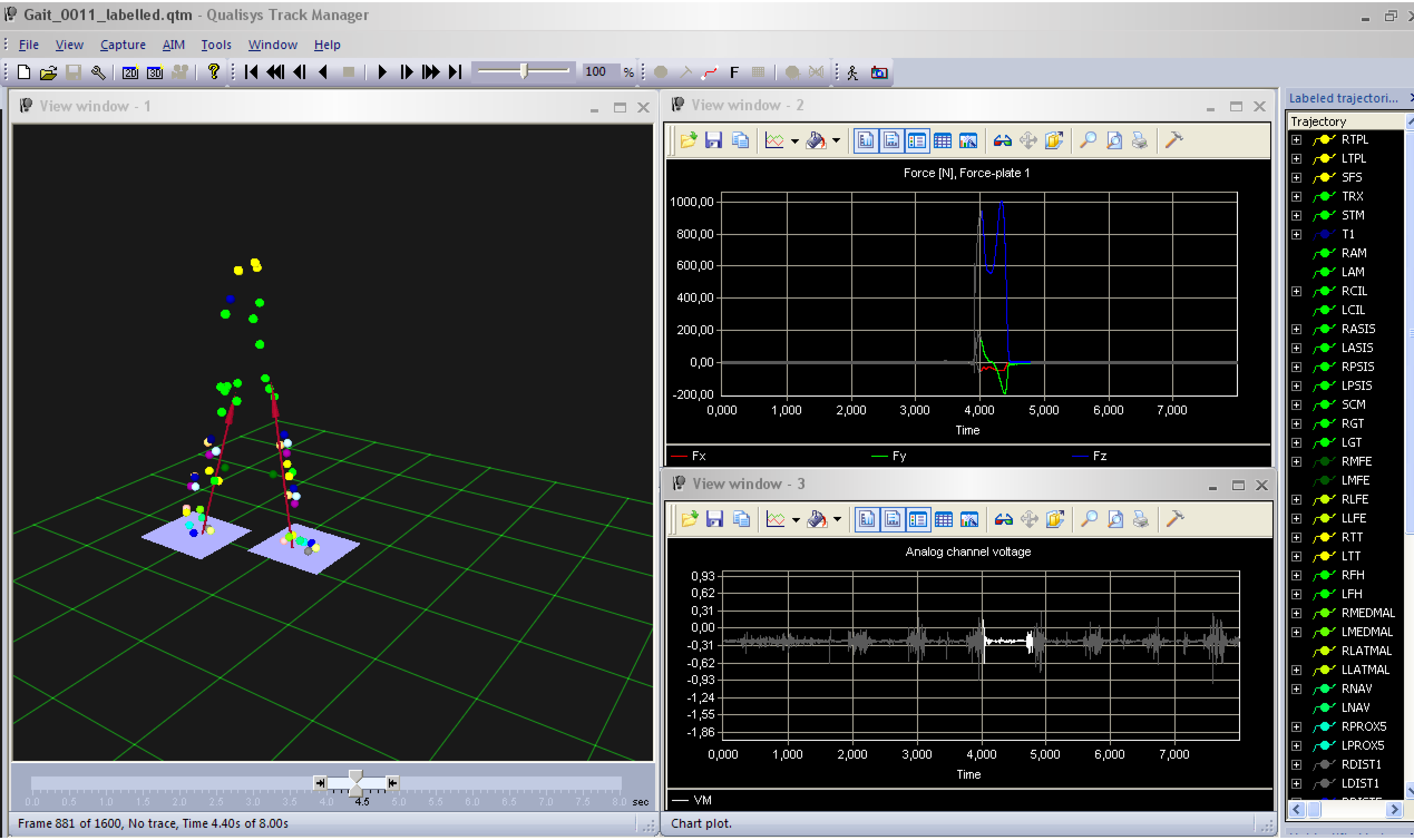
- Ground reaction forces
  - 6D (force + moment) kinetics reaction of the body
  - To solve the inverse dynamics analysis (through the Newton's laws of motion)

AMTI

- Electromyography (EMG) signals
  - As muscles contract, volt level electrical signals are created within the muscle that may be measured from the surface of the body

NORAXON

3DAH Marie Curie Project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View window - 3
Analog channel voltage
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Time
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Chart plot.
Labeled trajectori...
Trajectory
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LTPL
SFS
TRX
STM
T1
RAM
LAM
RCIL
LCIL
RASIS
LASIS
RPSIS
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RGT
LGT
RMFE
LMFE
RLFE
LLFE
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LTT
RFH
LFH
RMEDMAL
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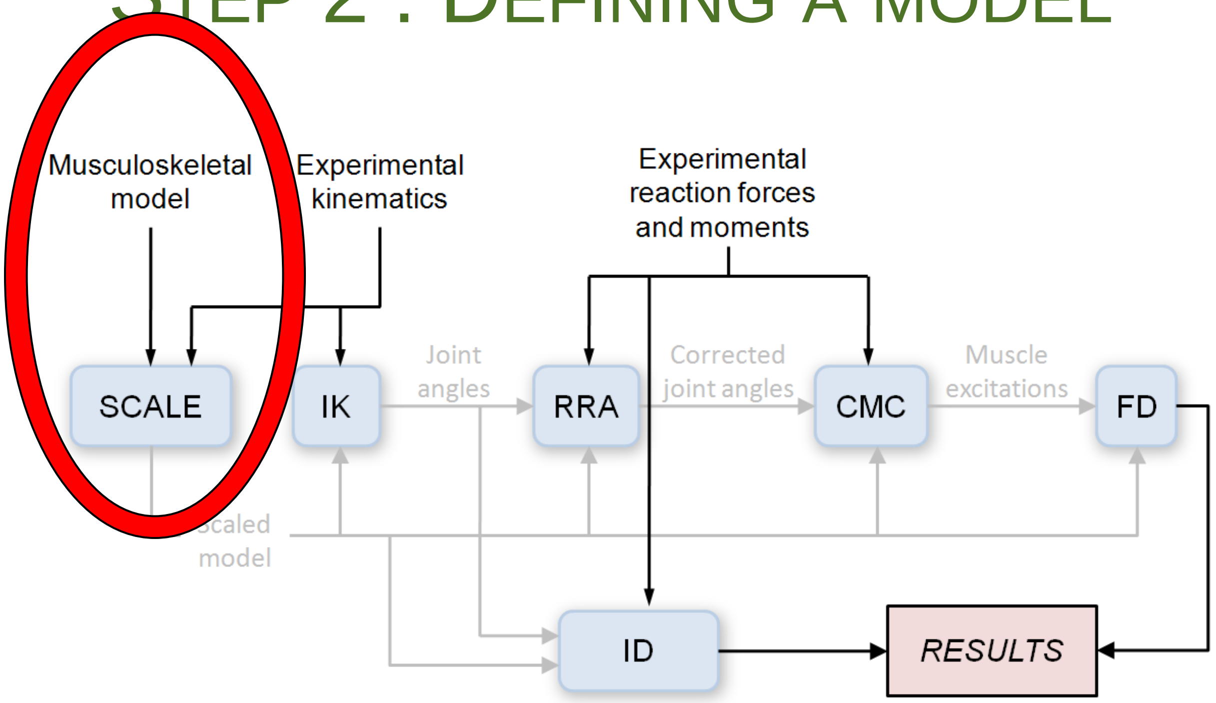
STEP 2 : DEFINING A MODEL

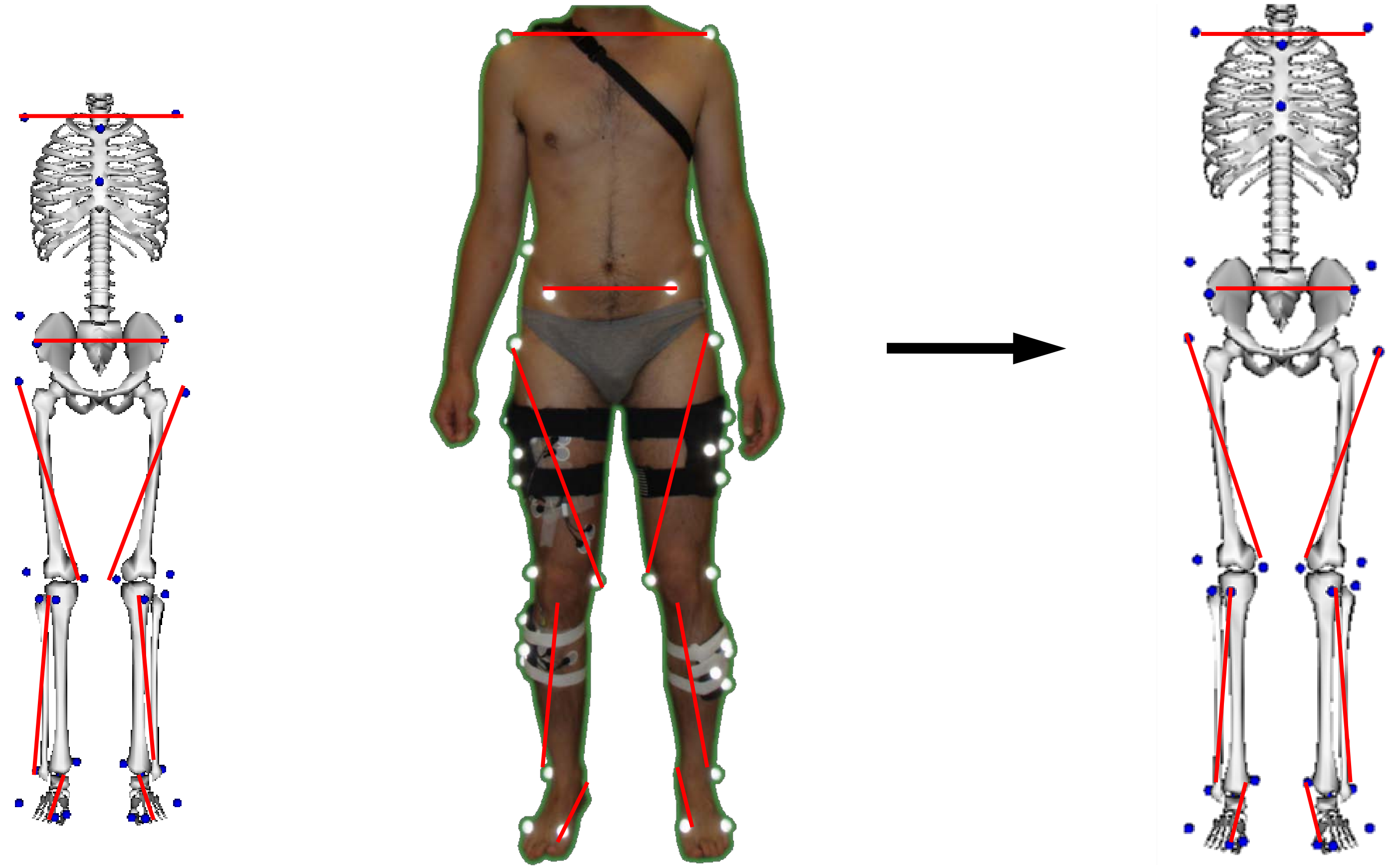


Loading a model

- Start OpenSim
- Menu *FILE >> Open Model*…
- Select /TutorialData/GenericModel.osim
- Manipulate Menu bar, 3D view, *Coordinates* and *Navigator* panels

Scaling the model – Step 1

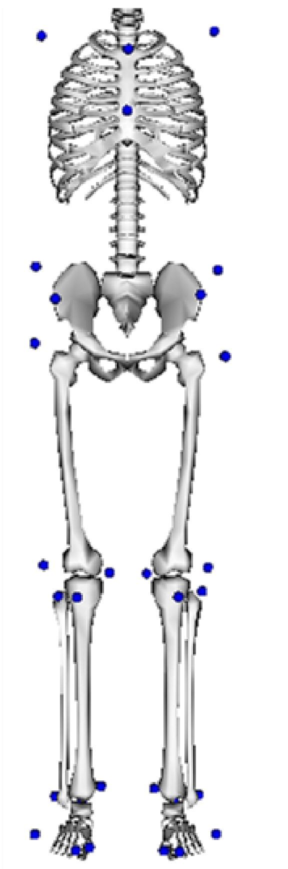
- Scale factors are applied from ratios between markers distances in model and in mocap



Original model Standing pose Scaled model

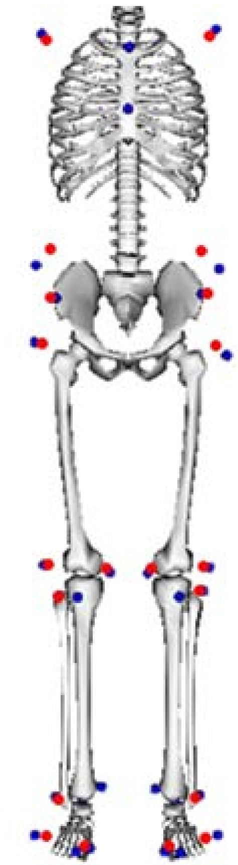
Scaling the model – Step 2

- The virtual markers are moved to match the positions of the experimental markers



Scaled model

Standing pose

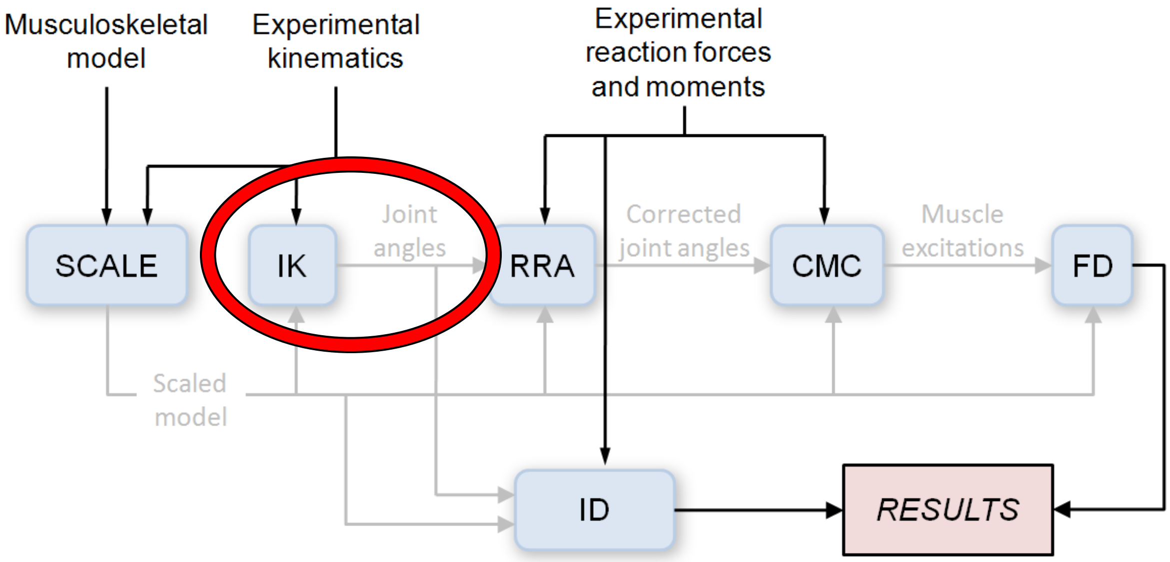


Subject model

Scaling the model

- Menu *Tools >> Scale Model*…
- *Settings >> Load Settings*…
- Select /TutorialData/Setup_SCALE.xml
- *Run* then *Close*

STEP 3 : INVERSE KINEMATICS



Inverse Kinematics

- Goal : to find the joint angles of the model that best reproduce the experimental kinematics of the subject’s motion
  - Weighted least squares optimization solver with the goal of minimizing marker errors

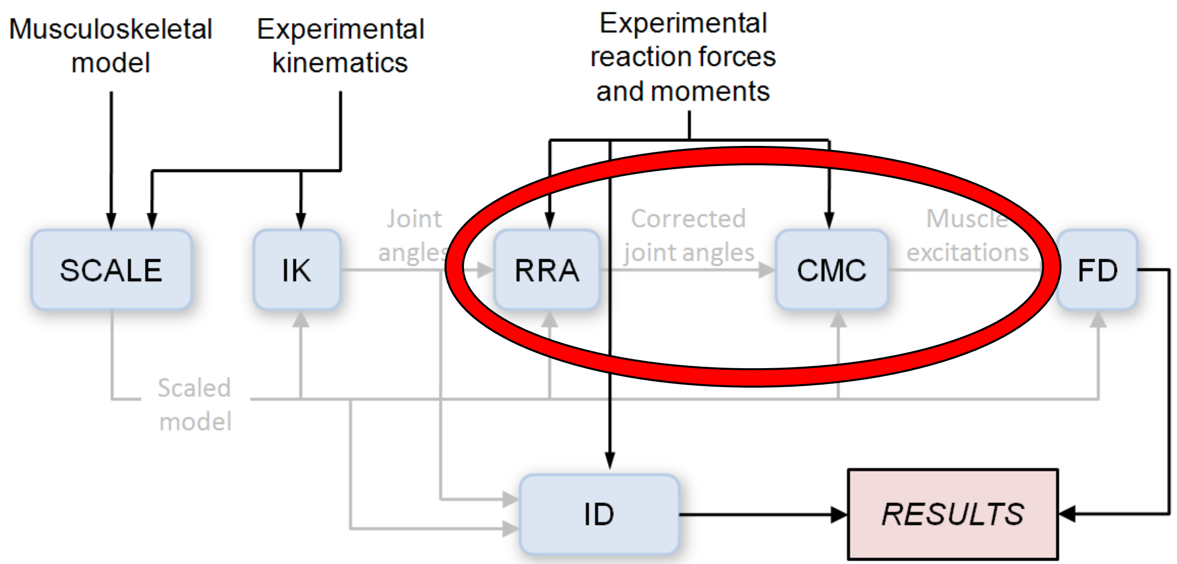
$$\min_{q}\left[\sum_{i \in \text{markers}} w_i \left\| \mathbf{x}_i^{\exp} - \mathbf{x}_i(\mathbf{q}) \right\|^2\right]$$

- q = joint angles , x_i^{exp} = experimental position of marker i
  $x_i(q)$ = virtual position of marker i

Inverse Kinematics

- Menu *Tools >> Inverse Kinematics…*
- *Settings >> Load Settings*…
- Select /TutorialData/Setup_IK.xml
- *Run* then *Close*

Step 4 : Muscular Activation Estimation

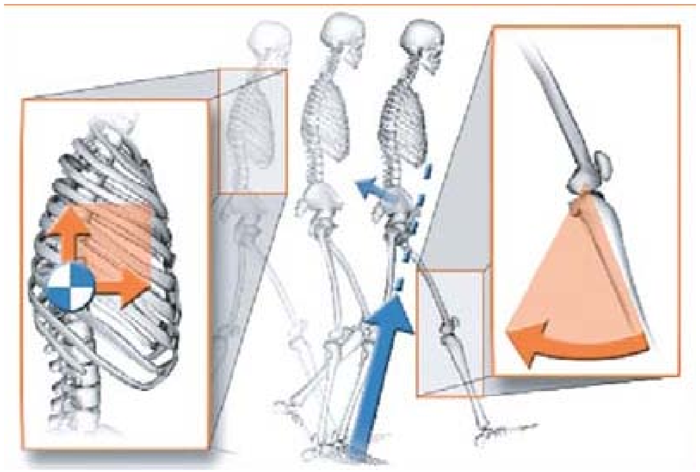


Muscular activation estimation

- Residual Reduction Algorithm (RRA)
  - Dynamics inconsistency due to errors in kinematics and kinetics measurements and in rigid body modeling
  - Additional “residual” forces and moments are added

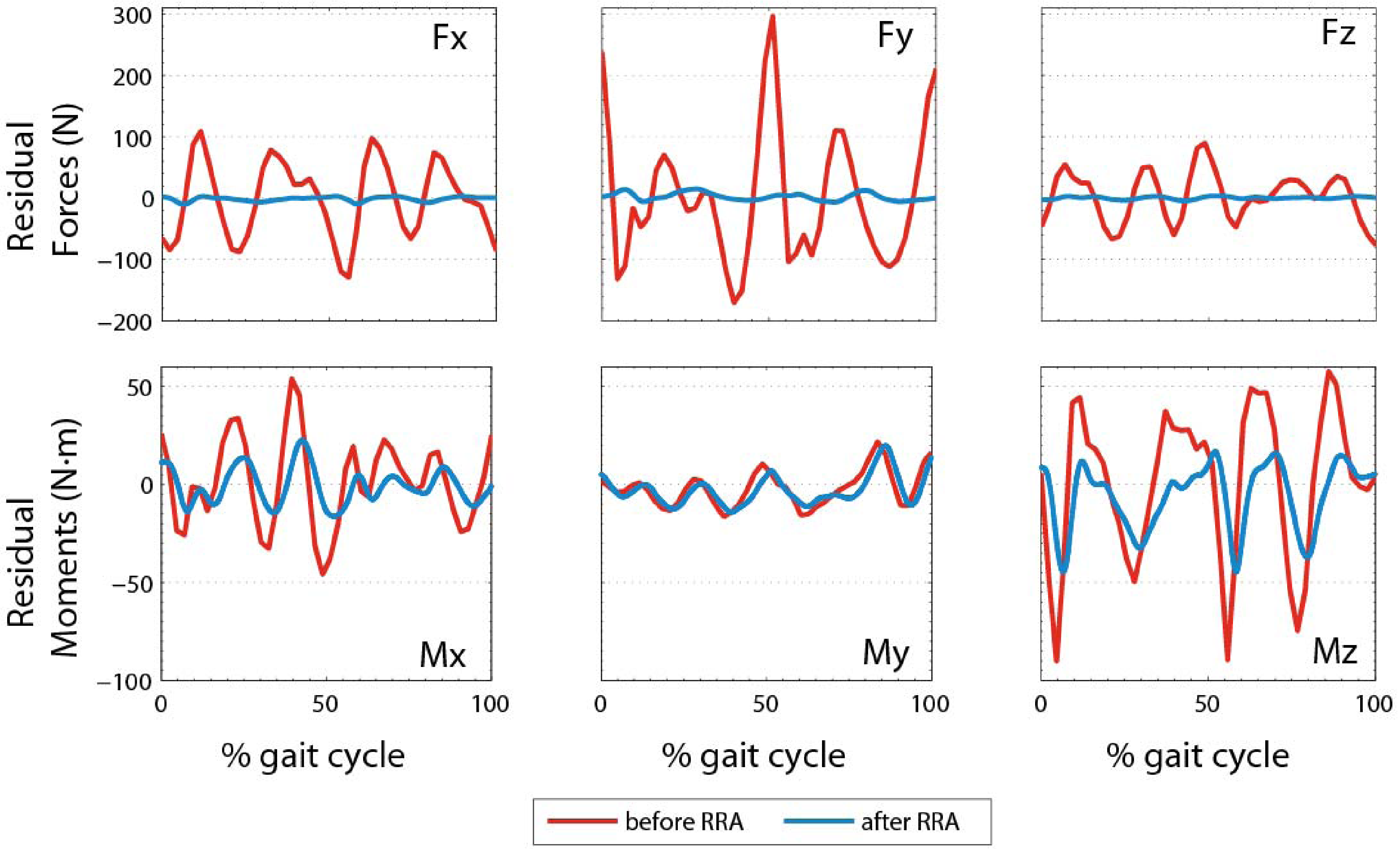
$$F + F_{residual} = m \, . \, a$$

  - Modification of the kinematics and the CoM to reduce $F_{residual}$ without significantly altering the simulation



OpenSim, University of Stanford

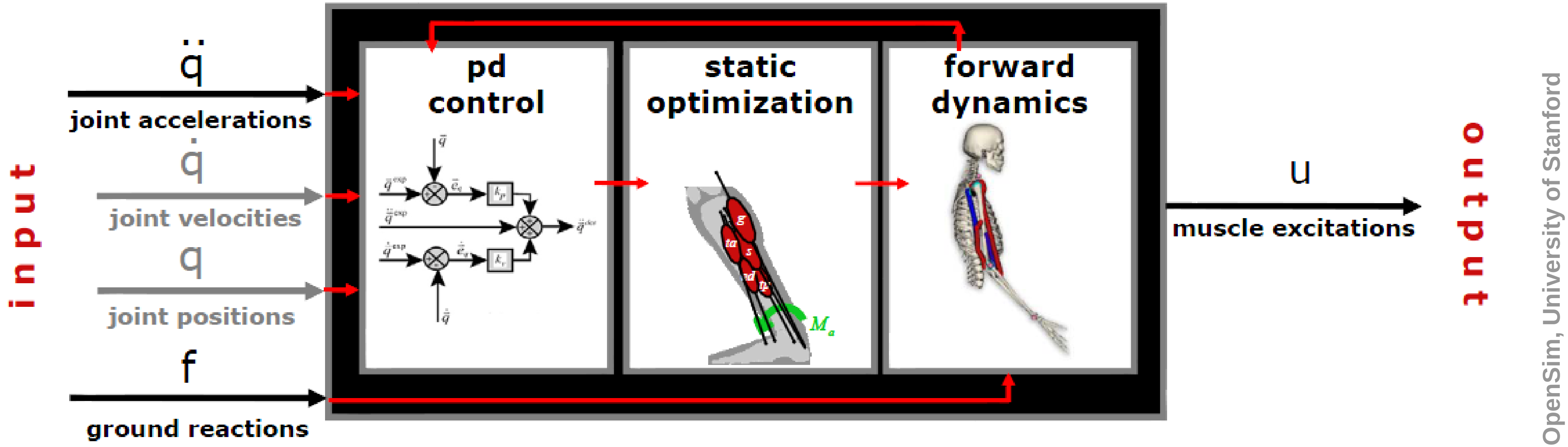
Effect of reducing residuals



OpenSim, University of Stanford

Muscular activation estimation

- Computed Muscle Control (CMC)
  - To compute a set of muscle excitations tracking the desired kinematics
    - PD control law defines the desired accelerations
    - Static optimization distributes the loads across actuators
    - Forward dynamics conducts the simulation advancing in time
    - Repeated until time is advanced to *dt*

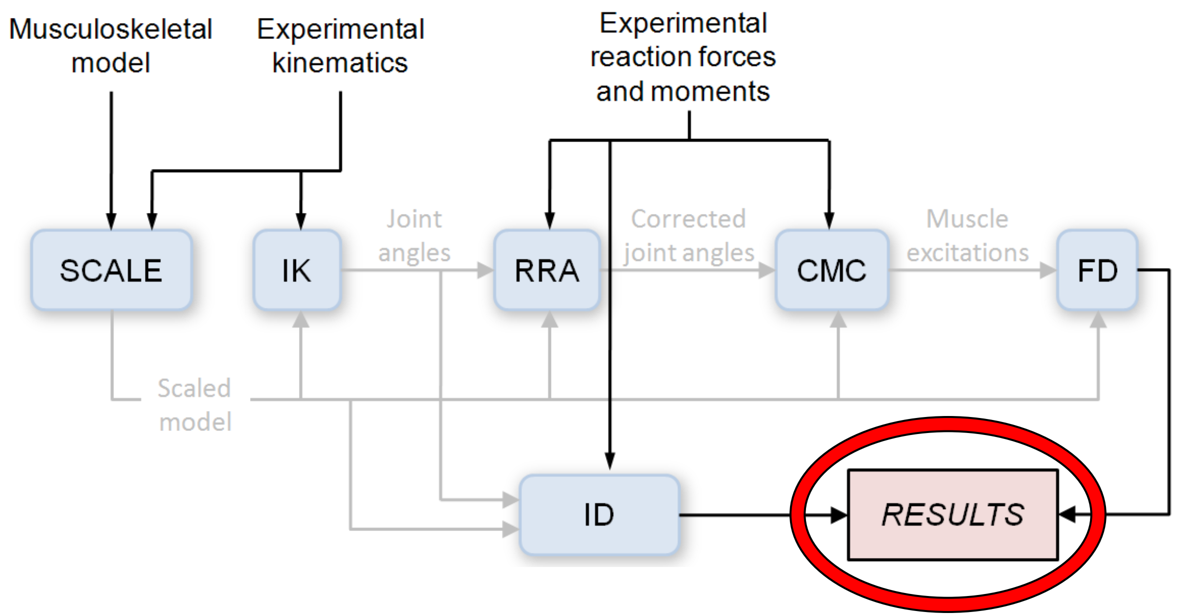


Muscular activation estimation

- Menu *Tools >> Computed Muscle Control…*
- *Settings >> Load Settings…*
- Select /TutorialData/Setup_RRA.xml
- *Run* then *Close*

- Menu *Tools >> Computed Muscle Control…*
- *Settings >> Load Settings…*
- Select /TutorialData/Setup_CMC.xml
- *Run* then *Close*

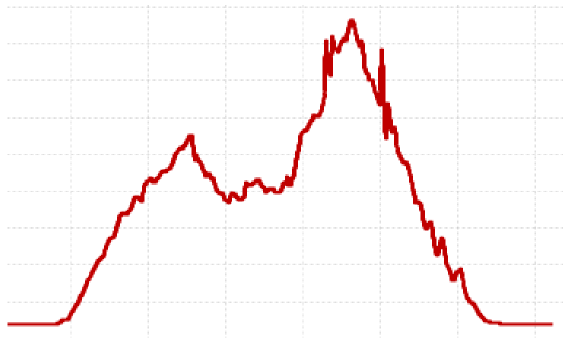
STEP 5 : VALIDATION OF THE SIMULATION

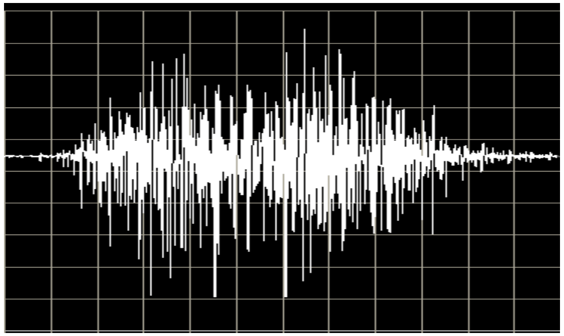


Validation of the simulation

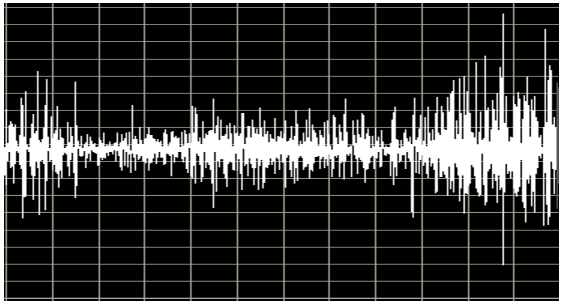
- Comparison against experimental data : EMG

right vastus medialis
crouch motion





right soleus
crouch motion



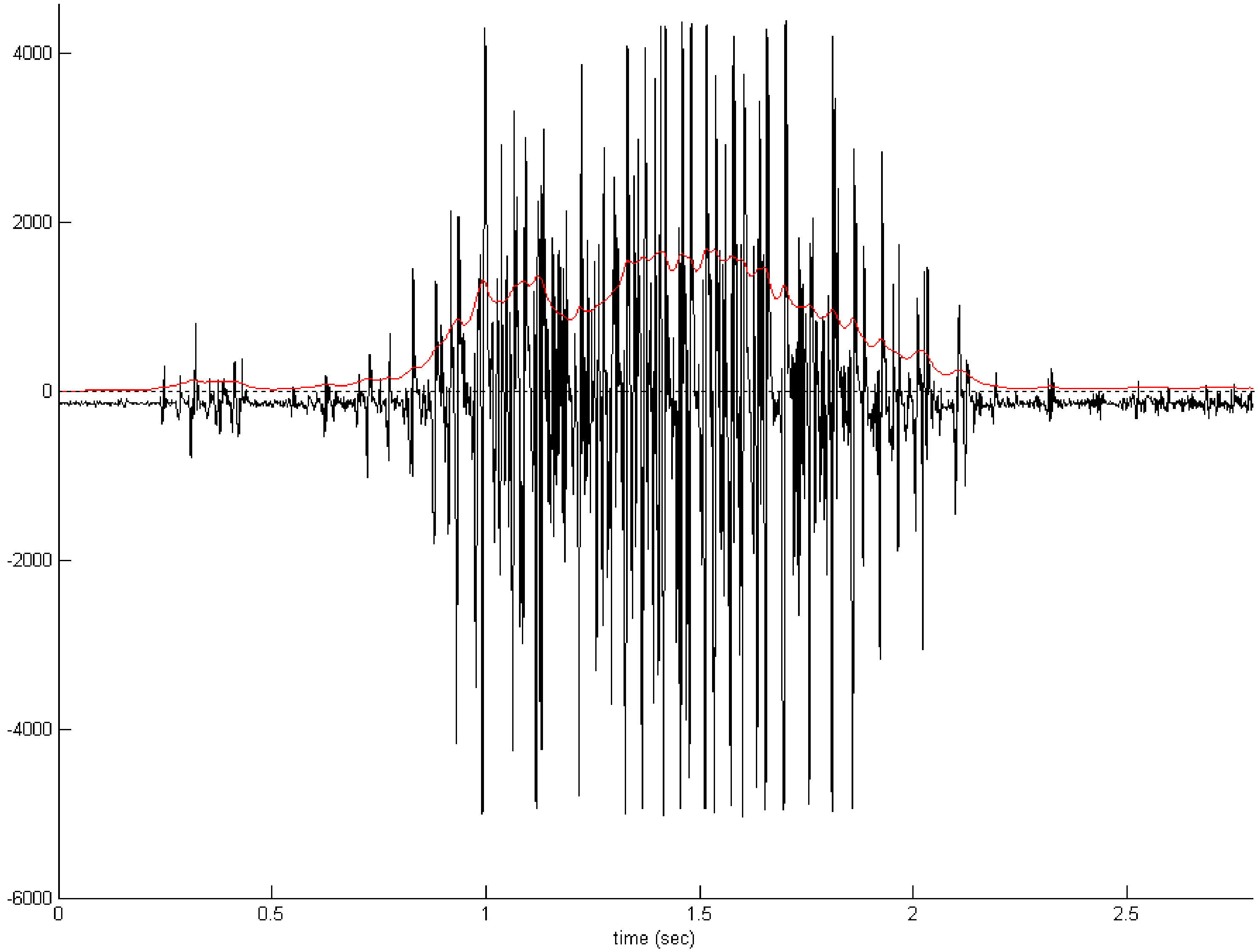
muscle activation from simulation

raw EMG

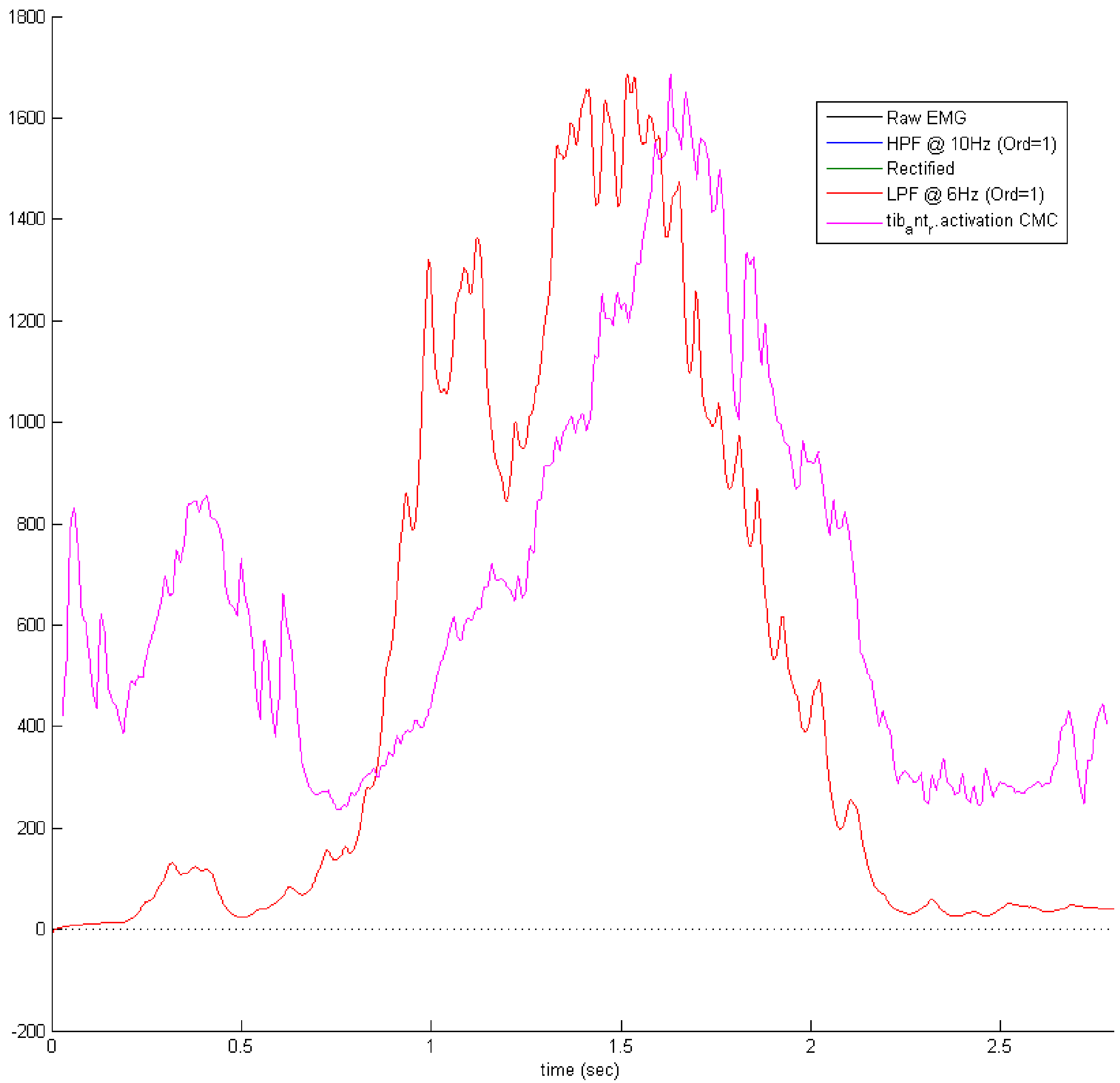
Post processing of EMG

- Electrical potential generated by muscle cells
- Measured in volt, about 90mV
- Signal need to be post–processed
  - Noise
  - Cross reading from other muscles
  - Rectified
- Filtering
  - Box filtering
    - Can cancel out “real” signal
  - Kalman filter/smoother
    - More computational intense

Post processing of EMG



Simulation vs. EMG



How to create a model ?

How to create a model ?

- We need
  - Palpable bony landmarks
    - 3D position (from mocap), definition of a coordinate system
  - Body parts
    - Moment of inertia, mass, position of center of mass
  - The joints
    - DoF, axis and center of rotation
  - Muscle and ligament attachment sites
    - Origin and insertion (and via points) positions, fiber and tendon lengths, mass, pennation angle…
  - Bony constraints
    - Warping points and bony contours

Example

- Klein Horsman dataset
  - University of Twente, The Netherland
  - *[Klein Horsman, Koopman, Van der Helm, Poliacu Prosé, Veeger. Morphological muscle and joint parameters for musculoskeletal modelling of the lower limb, Clinical Biomechanics (22), pp 239-247, 2007]*
  - Measurements performed on a right lower extremity of a male cadaver (age 77, height 1.74m, weight 105kg)

Datasets

Table 1

Segment moments of inertia about the transversal (I_t) and longitudinal axis (I_l) in kg m^2, segment mass (kg) and center of mass with respect to the global frame with the leg in original fixated position (cm)

Segment	I_t	I_l	Mass	X	Y	Z
Pelvis	0.012	0.017	3.18	−1.76	5.45	5.42
Femur	0.197	0.058	11.54	6.45	−40.36	4.40
Tibia	0.058	0.007	4.00	6.46	−86.52	4.89
Foot	0.005	0.001	1.30	53.81	−84.75	5.11

Table 2

Positions of bony landmarks with respect to the global frame with the leg in original fixated position (in cm)

Bony landmark	X	Y	Z
Pelvis			
Right anterior superior iliac spine	3.76	8.78	4.15
Left anterior superior iliac spine	3.76	8.78	−22.09
Right posterior superior iliac spine	−11.33	8.58	−4.53
Left posterior superior iliac spine	−11.14	8.97	−13.34
Right pubic tubercle	6.10	−0.02	−7.33
Left pubic tubercle	5.64	−0.05	−12.09
Femur			
Trochanter major	−5.98	−3.66	5.12
Medial femur epicondyle	7.68	−40.50	−3.21
Lateral femur epicondyle	3.17	−39.96	5.47
Tibia			
Medial tibia epicondyle	7.78	−44.05	−2.06
Lateral tibia epicondyle	3.28	−43.60	5.22
Tibial tuberosity	1.26	−45.65	5.21
Fibular head	8.74	−45.77	4.27
Medial malleolus	11.20	−79.21	1.04
Lateral malleolus	4.50	−81.59	4.55
Foot			
Navicular	10.51	−83.41	6.16
Proximal 1st metatarsal	14.71	−87.38	5.12
Proximal 5th metatarsal	9.96	−90.12	4.72
Distal 1st metatarsal (med)	19.82	−90.81	1.29
Distal 5th metatarsal (lat)	10.42	−95.04	4.52
Big toe (mid)	22.75	−94.83	6.83

Table 3

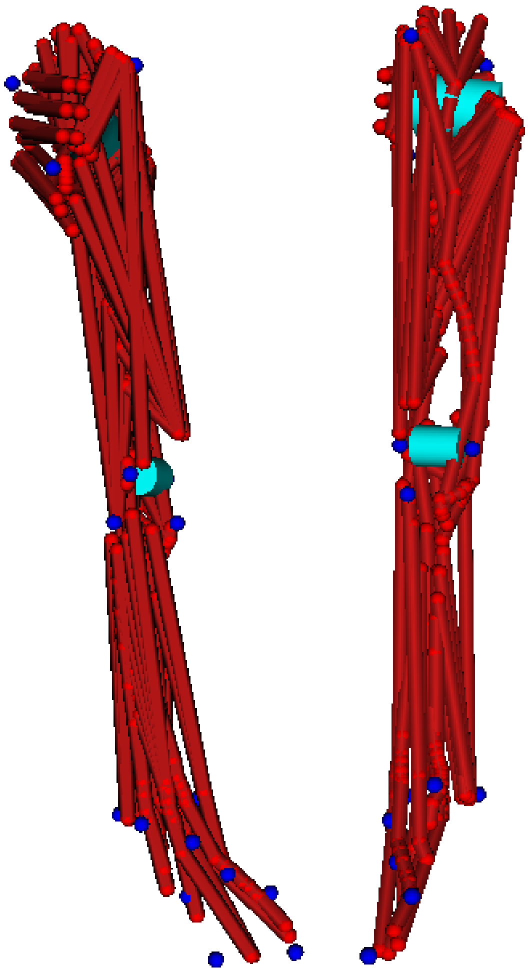
Per muscle part: origin, insertion described as surface, line (order) or point, divided in a number of elements and the muscle parameters: PCSA, optimal fiber length (L_{opt}), tendon length (L_{ten}), mass and pennation angle

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
Iliacus (med.)	Surf.	Point	3	BC	7.6	8.9	15.5	71.5	0
Obt. ext. (inf.)	Line (1)	Point	2	S	5.5	6.9	3.5	40.0	0
Obt. ext. (sup.)	Surf.	Point	3	VP	24.6	2.8	3.0	72.0	0
Obturator int.	Surf.	Point	3	VP	25.4	2.1	8.2	55.0	0
Pectineus	Line (1)	Line (1)	4	S	6.8	11.5	0	82.4	0
Peroneus brev.	Surf.	Point	3	VP	19.0	2.7	6.4	53.9	23
Peroneus long.	Surf.	Point	3	VP	23.9	3.4	15.9	86.0	16
Peroneus tert.	Line (2).	Point	3	VP	6.2	4.3	10.0	28.0	19
Piriformis	Point	Point	1	S	8.1	3.9	1.6	33.0	0
Plantaris	Point	Point	1	S	2.4	4.8	35.0	12.0	0
Popliteus	Point	Line (1)	2	VP	10.7	2.4	1.0	27.0	0
Psoas minor	Point	Point	1	S	1.1	5.9	15.2	7.0	0
Psoas major	Surf.	Point	3	BC	19.5	9.9	11.3	204.0	13
Quadratus fem.	Line (1)	Line (1)	4	S	14.6	3.4	0	52.0	0
Rectus fem.	Point	Line (1)	2	S	28.9	7.8	9.6	239.0	22
Sartorius (prox.)	Point	Point	1	VP	5.9	34.7	7.9	217.0	0
Sartorius (dist.)	Point	Point	1	VP	5.9	34.7	7.9	217.0	0
Semimembr.	Point	Point	1	S	17.1	8.1	15.7	146.0	25
Semitend.	Point	Point	1	VP	14.7	14.2	23.7	220.0	0
Soleus (med.)	Line (2)	Point	3	S	94.3	2.4	8.5	238.5	64
Soleus (lat.)	Line (2)	Point	3	S	85.9	2.6	8.5	238.5	59
Tensor fasc. l.	Line (1)	Point	2	S	8.8	9.5	0	88.0	0
Tibialis ant.	Surf.	Point	3	VP	26.6	4.6	23.5	129.0	10
Tibialis post. (med.)	Surf.	Point	3	VP	21.6	2.4	11.0	55.9	25
Tibialis post. (lat.)	Surf.	Point	3	VP	21.6	2.4	11.0	55.9	43
Vastus interm.	Surf.	Line (1)	6	S	38.1	7.7	12.6	309.0	12
Vastus lat. (inf.)	Surf.	Line (2)	6	S	10.7	4.2	9.6	48.0	0
Vastus lat. (sup.)				S	59.0	9.1	9.6	568.0	0
Vastus med. (inf.)				S	9.8	7.6	9.6	78.0	0
Vastus med. (mid.)				S	23.2	7.6	9.6	186.0	0
Vastus med. (sup.)				S	26.9	8.3	9.6	236.0	0

A muscle line can be straight (S), curving around a bony contour (BC) or consist of via points (VP).

Datasets

- 21 markers
- 4 body parts
  - pelvis, femur, tibia, foot
- 58 muscles from 163 action lines
- 5 joints
  - hip, knee, femur-patella, ankle subtalar
- 2 wrapping constraints
  - Gastrocnemius around femur condyle
  - Iliopsoas around the pelvis
- 104 via points



Validation of the model

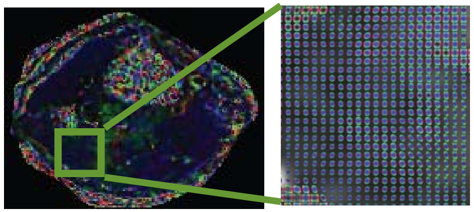
- For musculoskeletal simulation use
  - Technical part of formatting the data
  - Compare simulation results with
    - same motion and previous models
    - experimental data (EMG)

Interaction with medical imaging

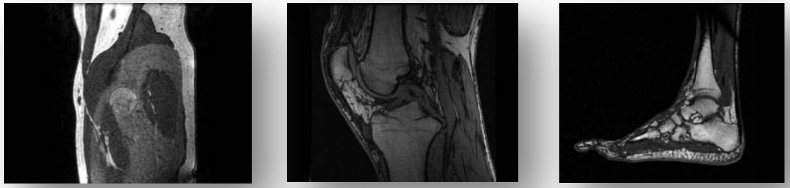
Interaction with medical imaging

- Benefit from the intensive use of medical images to create and validate models

DT-MRI + fiber tracking

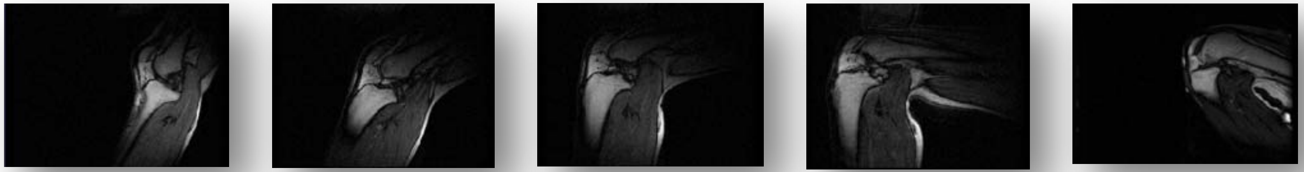


High resolution of joints



Cross sectional long-leg

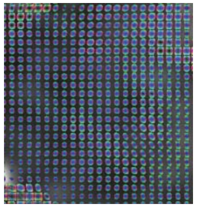
Dynamic MRI



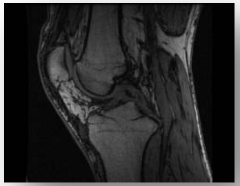
Interaction with medical imaging

- Benefit from the intensive use of medical images to create and validate models and simulations

DT-MRI + fiber tracking → Fiber directions in model

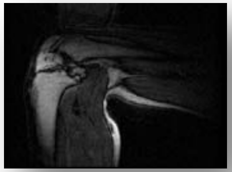


High resolution of joints → Attachment points and FE simulations



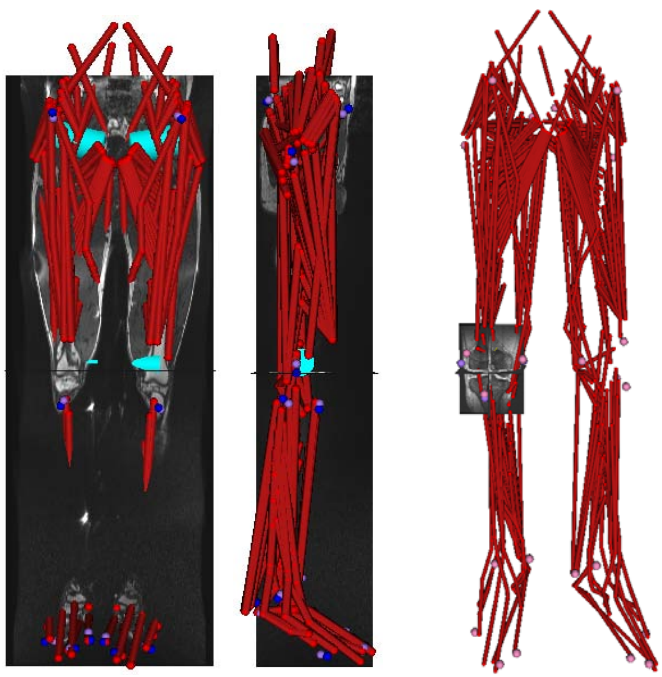
Cross sectional long-leg → Attachment points and scaling validation

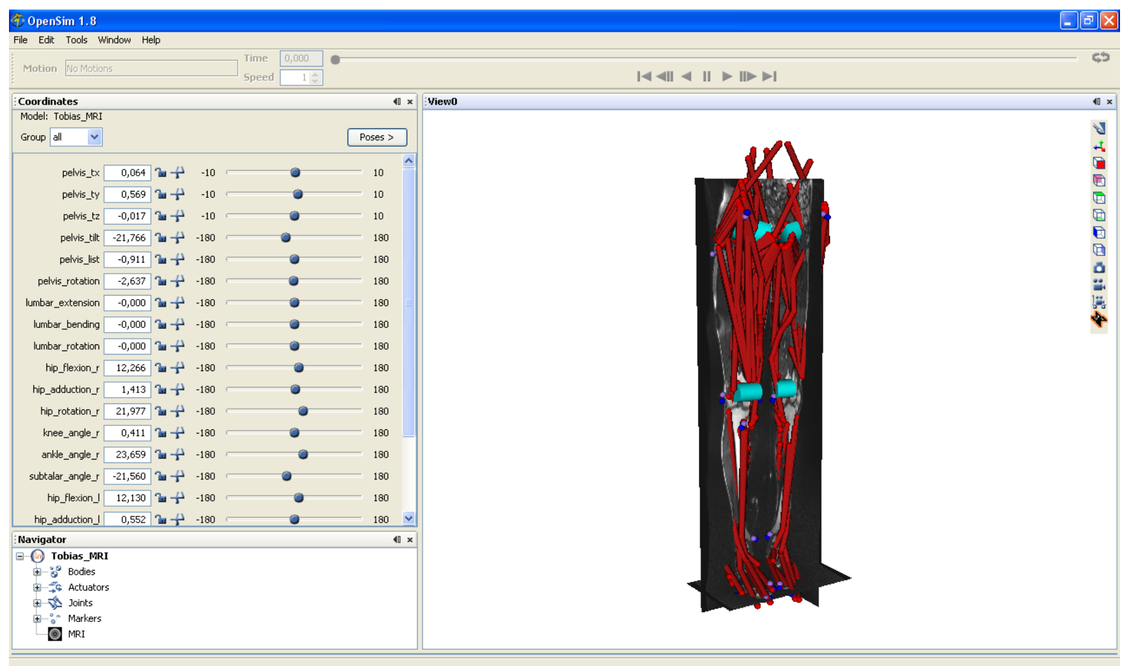
Dynamic MRI → validation of kinematics



Interaction with medical imaging

- MRI viewer in OpenSim
  - Alignment using common markers
  - Comparisons between tendon areas and action lines extremities



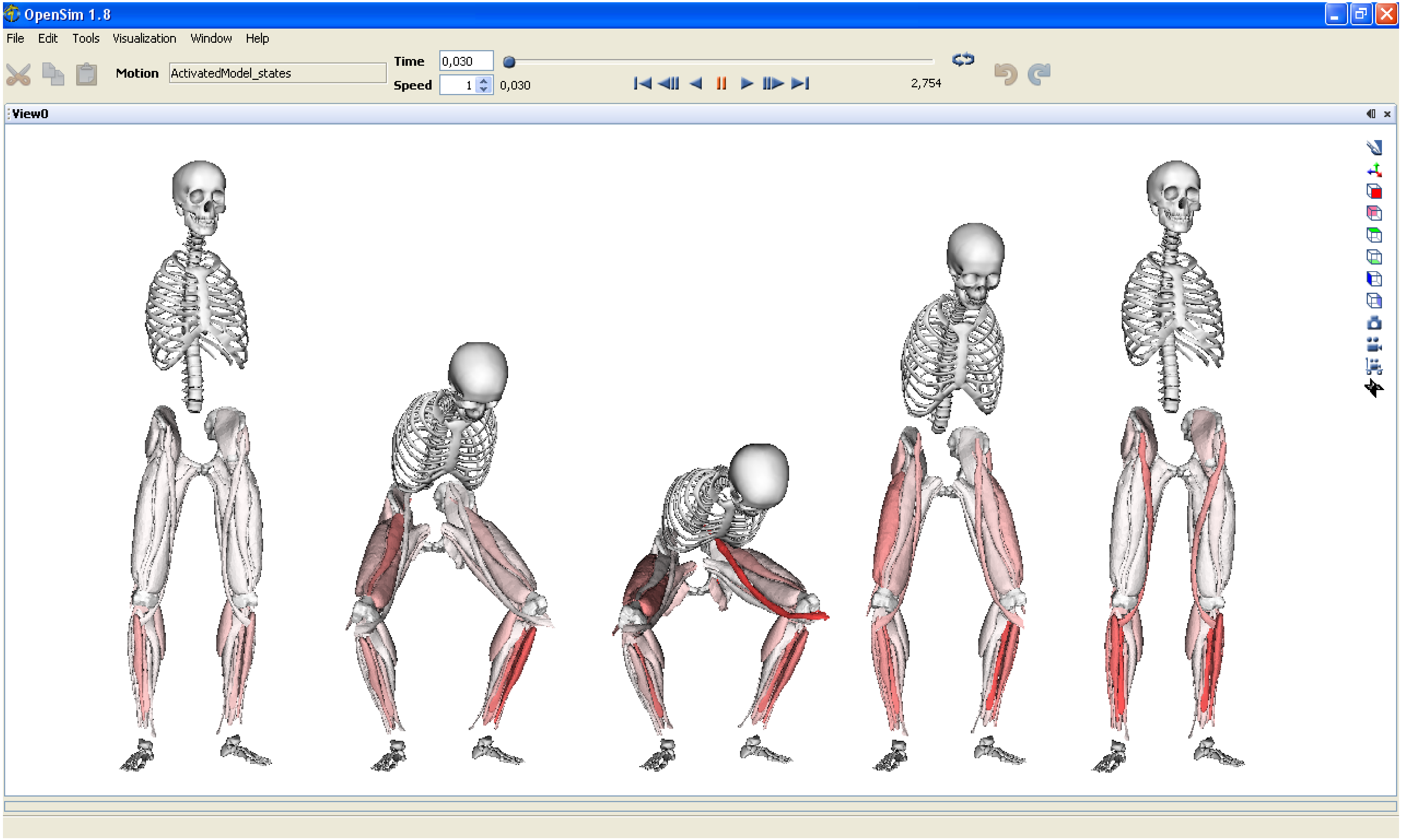


TOWARDS SCIENTIFIC VISUALIZATIONS

Towards more visualizations

- To help estimating results and tuning settings
  - Scale
    - Variation in factors, displacements in second inner step
  - IK
    - Error over time or time-independent
  - CMC
    - Magnitude of activation, reserve or residual forces
  - Validation
    - Difference between activation and EMG patterns
- To integrate external results
  - Nodal displacements or pressure from FE simulations

Towards more visualizations



Thank you for your attention

- References
  - 3DAH Marie Curie Project http://3dah.miralab.unige.ch
  - EPFL – VRLAB http://vrlab.epfl.ch
  - Aalborg University – SMI http://www.smi.hst.aau.dk
  - OpenSim https://simtk.org/home/opensim

- Nicolas.Pronost@epfl.ch Anders.Sandholm@epfl.ch