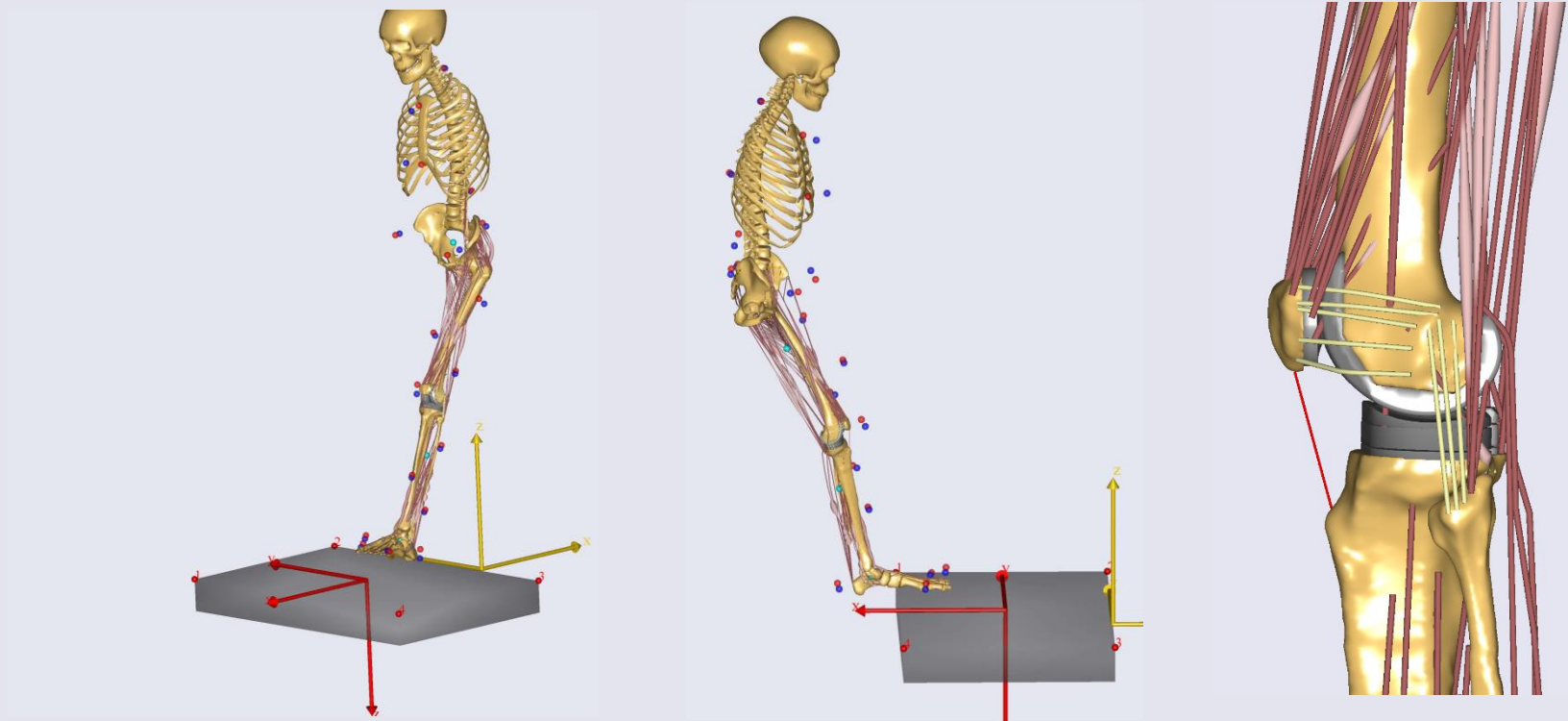


# Patient-specific Musculoskeletal Modelling of Total Knee Arthroplasty using Force-dependent Kinematics

MS Andersen<sup>1</sup>, MA Marra<sup>2</sup>, V Vanheule<sup>3</sup>, R Fluit<sup>4</sup>, N Verdonschot<sup>2</sup>, J Rasmussen<sup>1</sup>

<sup>1</sup>Aalborg University, Denmark, <sup>2</sup>Radboud University Medical Centre, The Netherlands,  
<sup>3</sup>Materialise, Belgium, <sup>4</sup>University of Twente, The Netherlands



Winner of the 5<sup>th</sup> Grand Challenge Competition to Predict In Vivo Knee Loads



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RESEARCH PROJECT

# Motivation

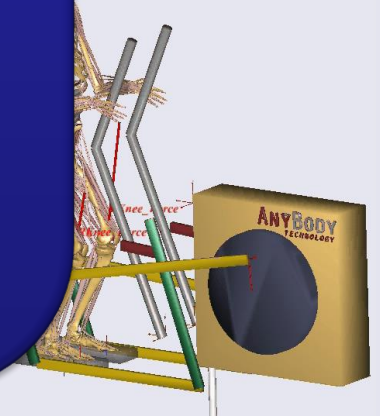
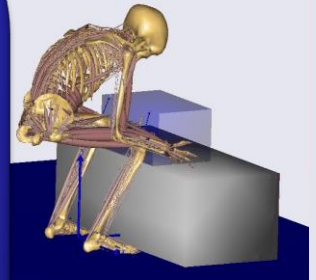
## *Non-invasive e*

- Muscle loads
- Joint loads.
- Bone loads.
- Ligament loads
- Joint movement
- Etc.

Insight into quantitative  
impossible or im

## For clinical applications

- Patient-specific models.
- Model validity is crucial.



# Grand Challenge

- A unique opportunity for blind model validation
- Data:
  - Marker trajectories.
  - Ground reaction forces.
  - CT scans (pre- and post-op).
  - EMG.
  - *Measured knee forces.*
  - Single plane fluoroscopy.
- **2014 Competition:** predict the medial and lateral knee contact forces during gait and right turn trials. (Blinded and unblinded)

The screenshot shows the Simtk.org website interface. At the top, there is a navigation bar with links for Home, About Simtk.org, How to Contribute, Search Simtk.org, News, Log In, Create Project, and Register. The main content area features a sidebar with navigation links: Overview (Statistics, Geography of use), Team, Downloads, Documents, Publications, and Advanced. The main content area is titled "Grand Challenge Competition to Predict In Vivo Knee Loads" and includes a "Project Overview" section. This section contains a description of the project, a list of available downloads and their potential uses, and a "Project Lead" section with photos and contact information for B.J. Fregly, Darryl D'Lima, and Thor Besier. A large image of a knee joint is also visible.

**Grand Challenge Competition to Predict In Vivo Knee Loads**

**Project Overview**

**Description:** Knowledge of muscle and joint contact forces during gait is necessary to characterize muscle coordination and function as well as joint and soft-tissue loading. Musculoskeletal modeling and simulation is required to estimate muscle and joint contact forces, since direct measurement is not feasible under normal conditions. This project provides the biomechanics community with a unique and comprehensive data set to validate muscle and contact force estimates in the knee. This data set includes motion capture, ground reaction, EMG, tibial contact force, and strength data collected from a subject implanted with an instrumented knee prosthesis.

**Available Downloads and Their Potential Uses:** The following raw and synchronized experimental data are available for download:

- Marker trajectories - plus description of marker set and static trials (200 Hz)
- Ground reaction forces - from 4 Bertec plates (1000 Hz)
- EMG signals - from 14 muscles in the implanted lower limb (1000 Hz)
- Tibial contact forces - measured from the instrumented prosthesis (200 Hz)

**Project Lead**

**B.J. Fregly**  
Contact

**Darryl D'Lima**  
Contact

**Thor Besier**  
Contact

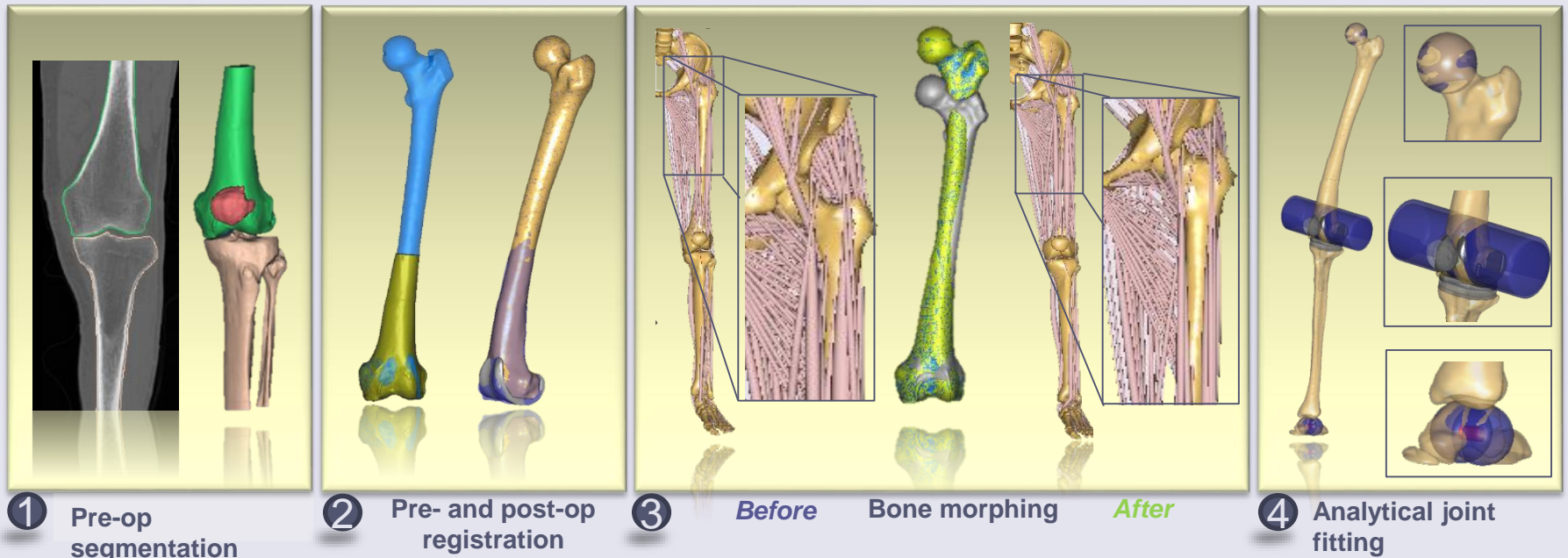
**Driving Biological Problems**  
This project is part of

Fregly et al., (2012)



# Modelling overview

Twente Lower Extremity Model (TLEM) v. 2.0 (Fluit et al, 2013)

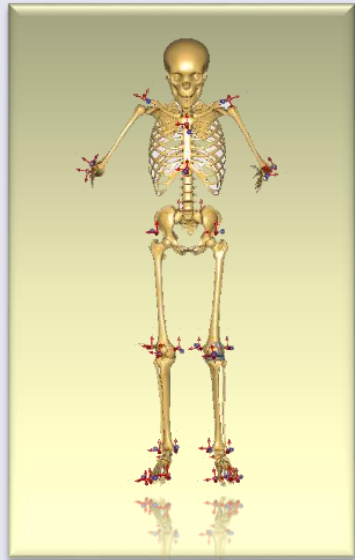


Nonlinear using  
Radial Basis  
Functions

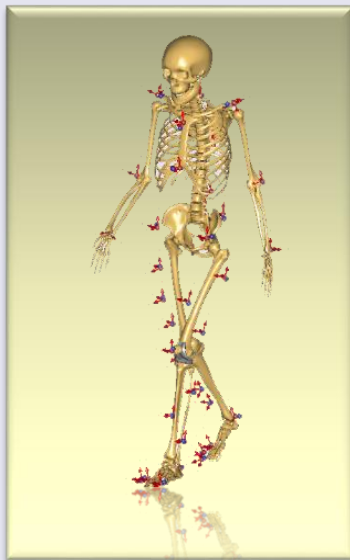


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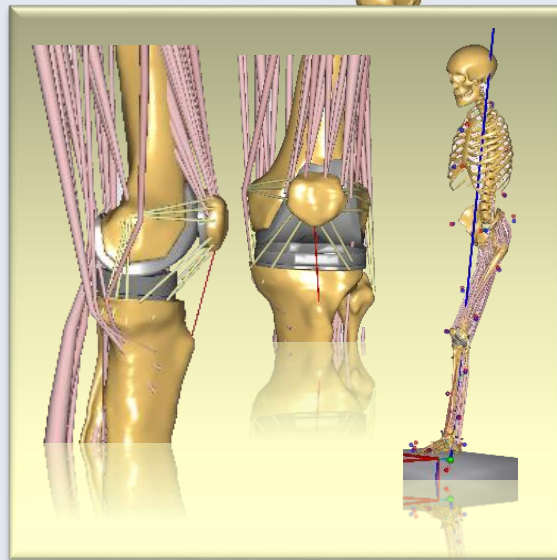
# Modelling overview



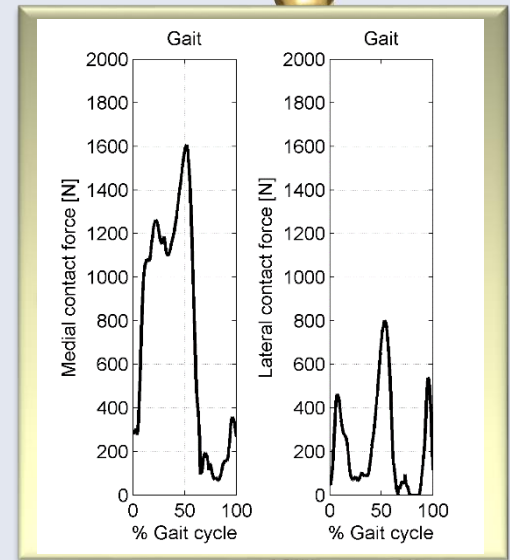
5 Scaling of remaining segments



6 Marker tracking



7 Joint modelling and Force-dependent Kinematics

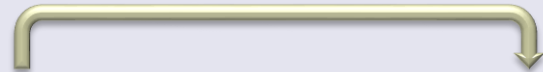


8 Results



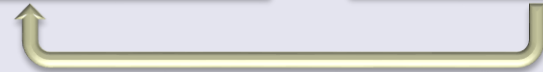
# Force-dependent kinematics (FDK)

FDK positions

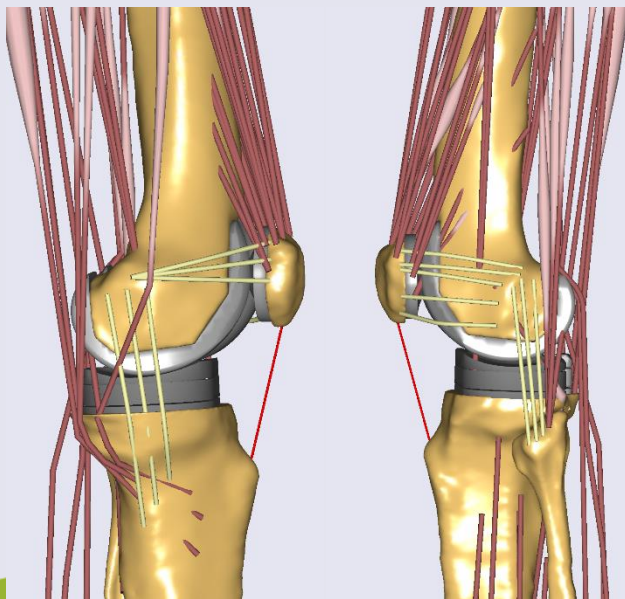


Find static equilibrium  
in FDK DOFs

Inverse dynamic  
analysis



FDK reaction forces



**FDK** (Andersen et al, 2011)

- Simultaneously computes muscle, joint and ligament forces and internal joint kinematics.
- Uses *inverse dynamics* and *quasi-static force equilibrium* in selected DOFs.
- Recruitment criterion: sum of m. activities cubed.

**Knee DOFs** (tibiofemoral and patellofemoral)

- Knee flexion angle driven.
- Rigid patella tendon.
- 10 FDK DOFs.

**Knee contact model**

- Rigid-rigid contact model (STL-based volume penetration).

**Ligaments**

- MCL, LCL, PCL, MPFL, LEPL and LTL.
- Non-linear elastic springs w/ wrapping surfaces.



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# Strength scaling

- Strength scaling based on segment lengths, mass and height (BMI). Rasmussen et al. (2005).
- Reduced strength of knee flexors and extensors after total knee arthroplasty.

The Journal of Arthroplasty Vol. 18 No. 5 2003

## **Knee Strength After Total Knee Arthroplasty**

Mauricio Silva, MD,\* Eric F. Shepherd, MD,\*† Walter O. Jackson, MD,\*†  
Jeffrey A. Pratt, MD, MPH,\*† Christian D. McClung, MPhil (Cantab),\* and  
Thomas P. Schmalzried, MD\*†

Avg. isometric flex. strength reduction: 32 %.

Avg. Isometric ext. strength reduction: 31 %.

Highest reduction for low knee flexion angles.

Up to 40 % reduction around full extension.

- Highly variable among subjects.



The strength of all knee flexors and extensors were reduced by 35 %.



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RESEARCH PROJECT

# Blinded results

Submitted January, 2014

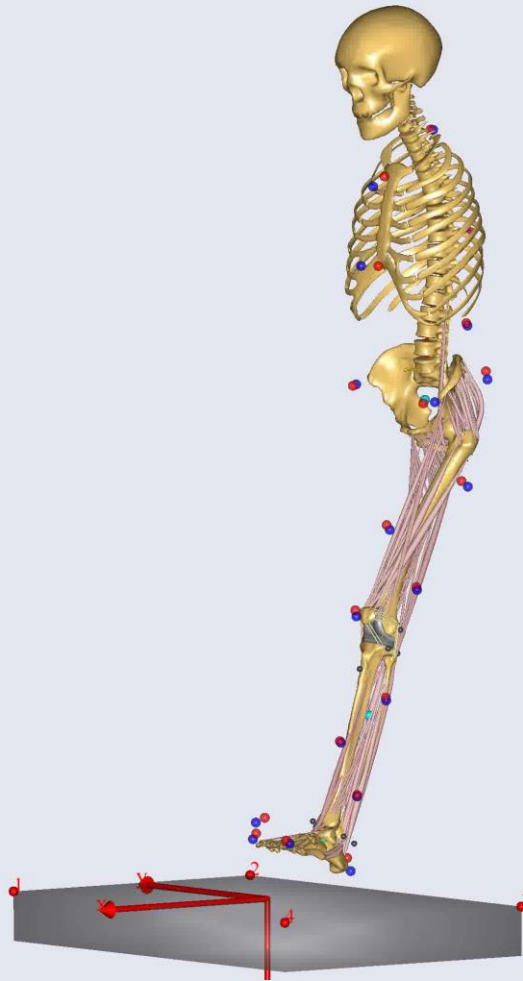


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# Blinded results



Gait

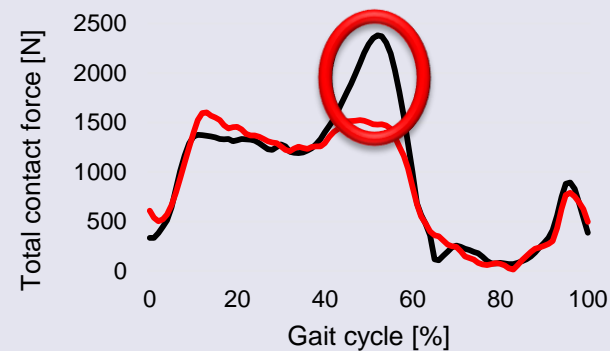
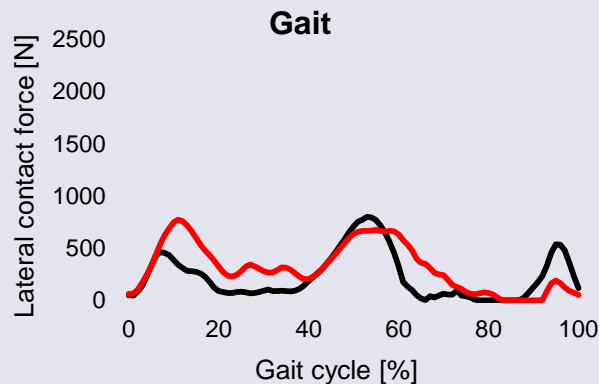
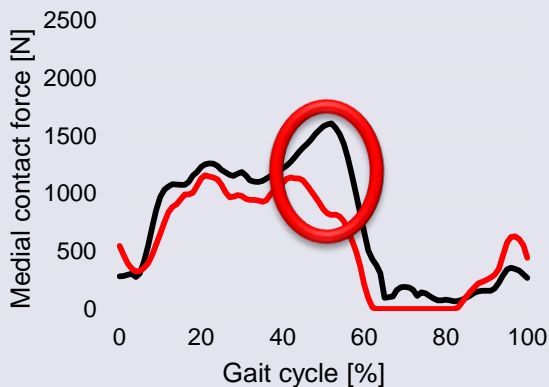
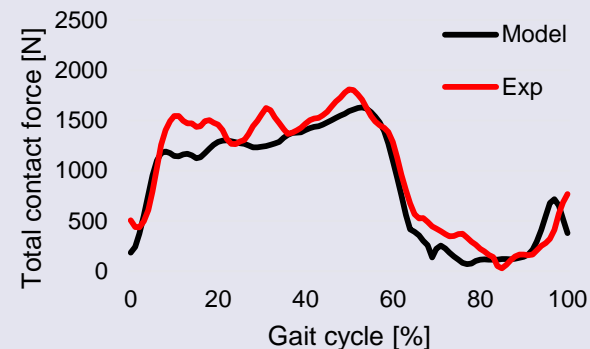
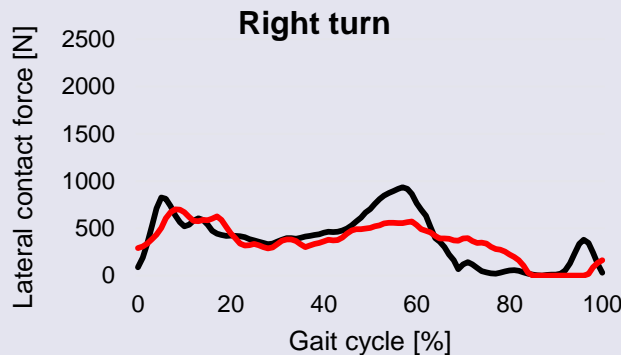
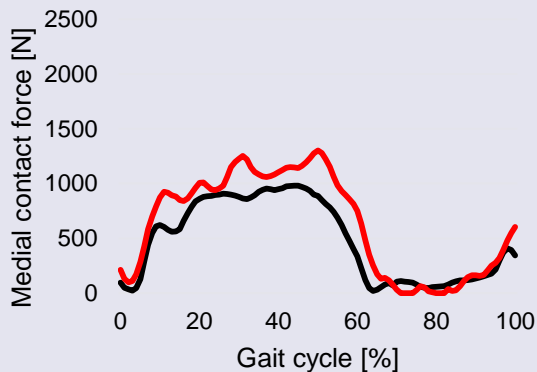


Right turn



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# Blinded results



## Right turn

Medial contact force  
Lateral contact force  
Total contact force

RMSE [N]	R <sup>2</sup>
208	0.92
175	0.57
195	0.93

## Gait

Medial contact force  
Lateral contact force  
Total contact force

RMSE [N]	R <sup>2</sup>
288	0.80
203	0.45
272	0.86



# Model improvements

Knee contact forces released February, 2014



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# Most important change: Recruitment criterion

Multibody Syst Dyn (2012) 28:283–289  
DOI 10.1007/s11044-011-9277-4

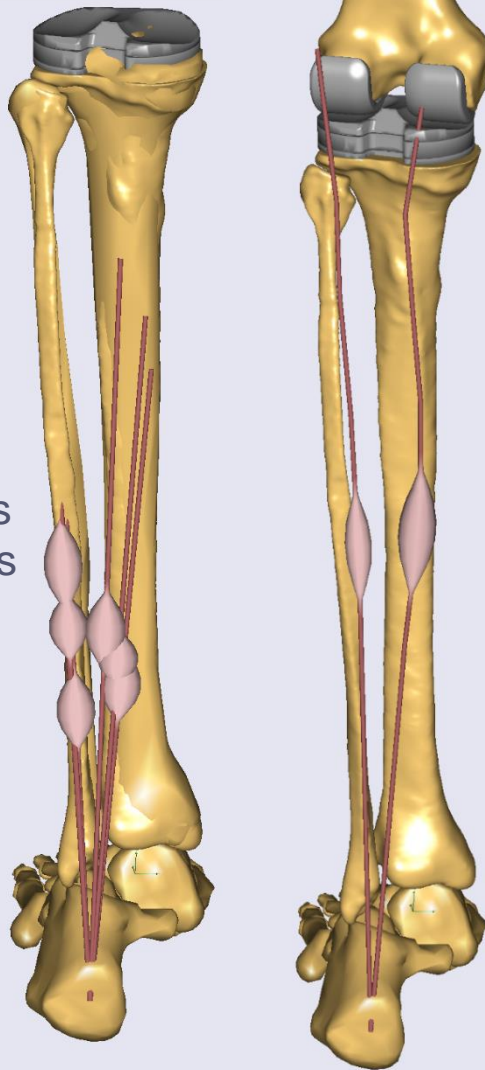
**Muscle decomposition and recruitment criteria influence muscle force estimates**

L. Joakim Holmberg · Anders Klarbring

$$\min_F \sum_{i=1}^N \left( \frac{F_i^{(m)}}{S_i} \right)^p$$

$$\text{s.t. } CF = d$$

$$F_i^{(m)} \geq 0$$

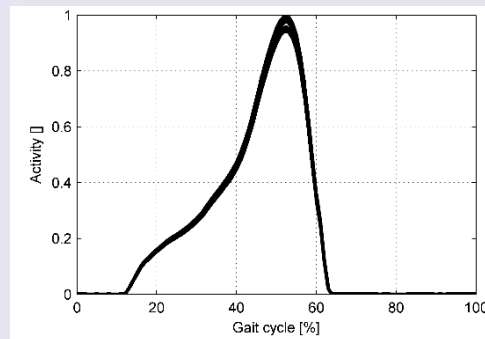


## Soleus

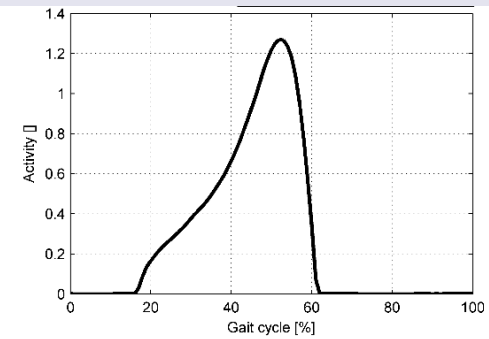
Medialis: 3 branches  
Lateralis: 3 branches

## Gastrocnemius

Medialis: 1 branch  
Lateralis: 1 branch



Soleus



Gastrocnemius medialis



# Most important change: Recruitment criterion

- **Idea** (Happee and Van der Helm (1995))

- Associate a cost to activating a muscle volume element,  $\left(\frac{F_i^{(m)}}{S_i}\right)^p$
- The total cost is obtained by a weighted sum over all muscle volume elements.

$$\begin{aligned} \min_F \quad & \sum_{i=1}^N V_i \left(\frac{F_i^{(m)}}{S_i}\right)^p \\ \text{s.t.} \quad & CF = d \\ & F_i^{(m)} \geq 0 \end{aligned}$$

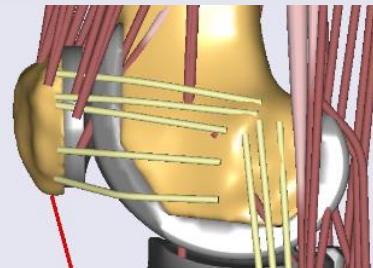
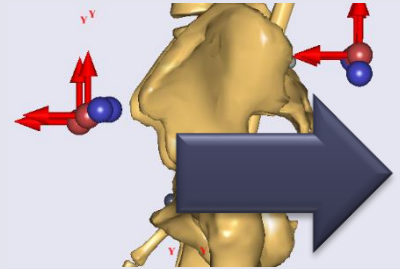
$V_i$  is volume of the  $i$ th muscle (estimated as the product of PCSA and optimum fiber length).

- A split muscle is assigned a fraction of the total muscle volume.



# Minor updates

- **Revised marker placements on the model**
  - The placement of the pelvis markers are particularly tricky.
    - No complete CT of pelvis.
    - Abdominal fat around the stomach.
- **Updated patella tendon length**
  - Length estimated from an unloaded knee flexion/extension flouroscopy trial.
- **Improved modelling of the ligaments.**
  - Improved MPFL, LEPL and LTL wrapping around the femoral condyle and component.
  - Improved PCL wrapping.



# Unblinded results

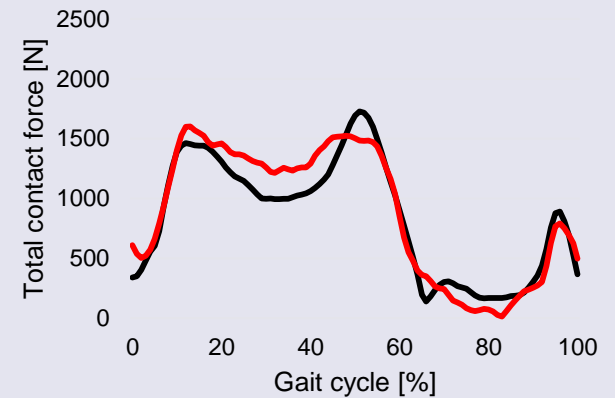
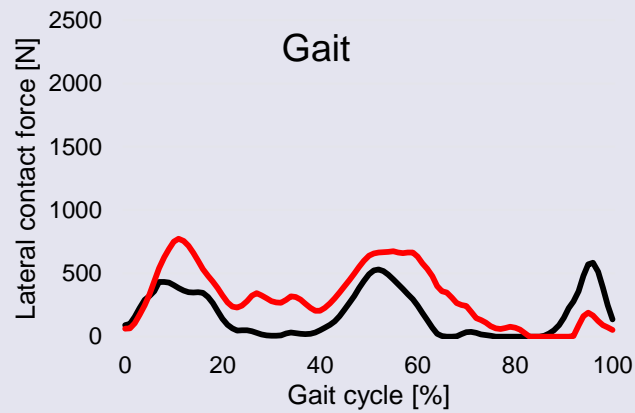
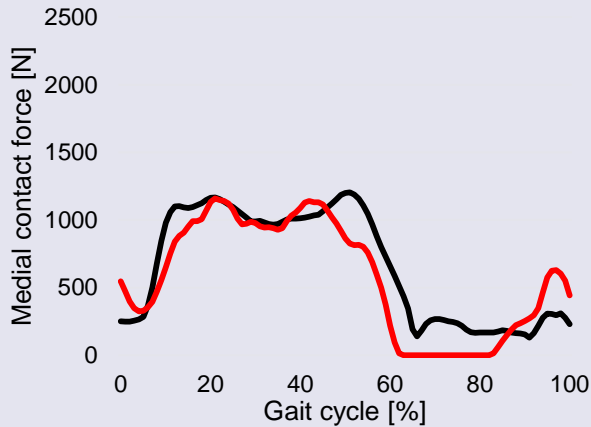
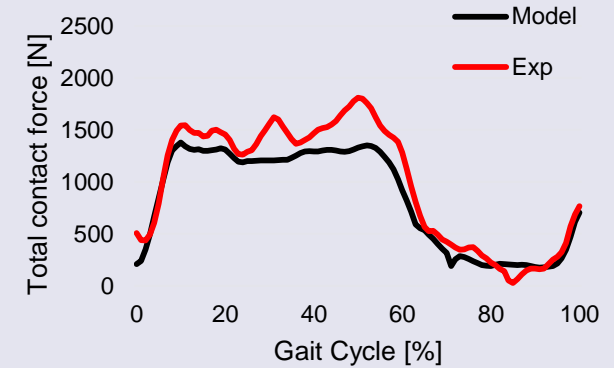
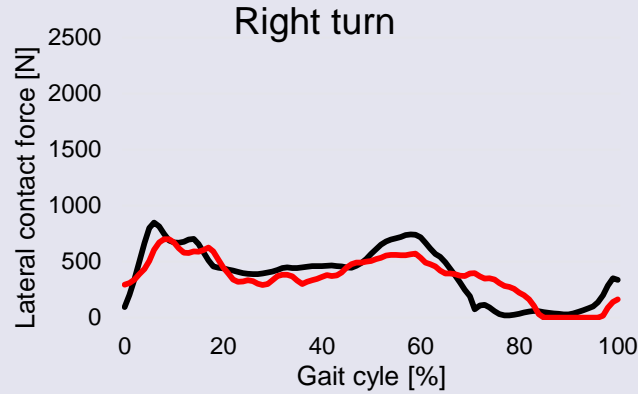
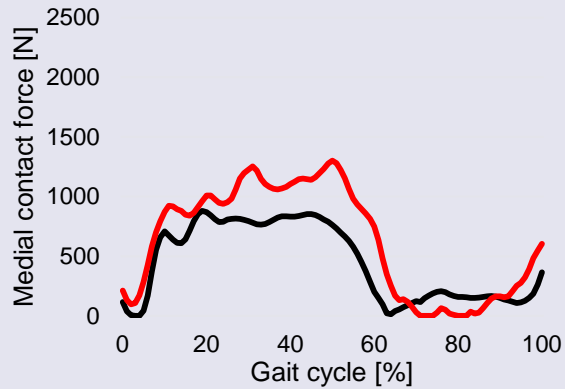
Submitted June, 2014



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# Unblinded results



## Right turn (unblinded)

Medial contact force  
Lateral contact force  
Total contact force

RMSE [N]	R <sup>2</sup>
272	0.85
136	0.71
206	0.96

## Gait (unblinded)

Medial contact force  
Lateral contact force  
Total contact force

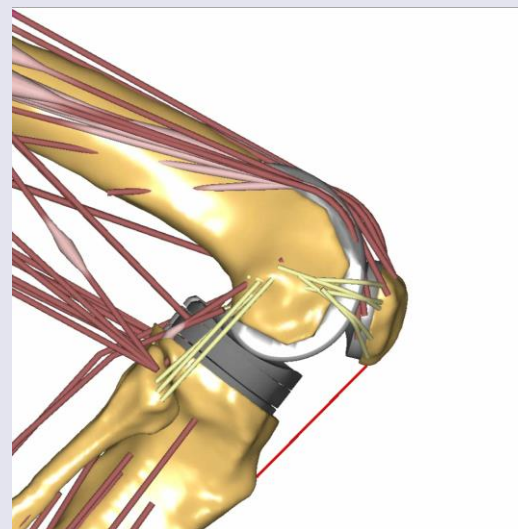
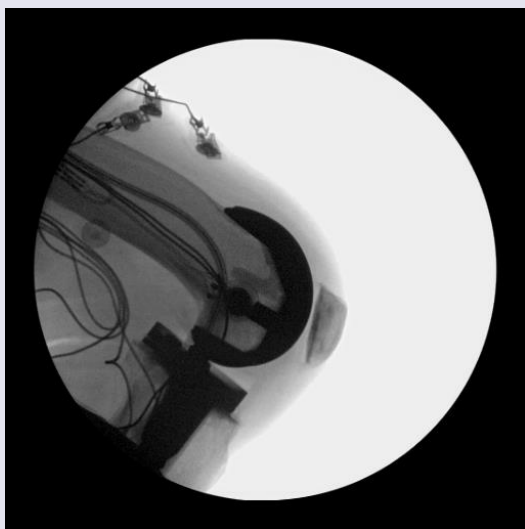
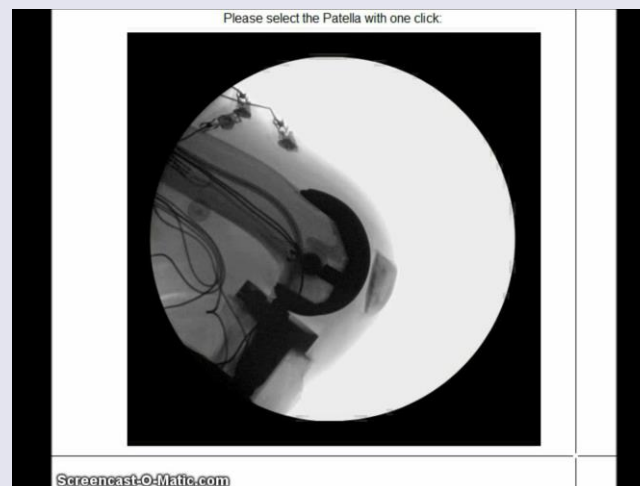
RMSE [N]	R <sup>2</sup>
210	0.80
230	0.36
154	0.93



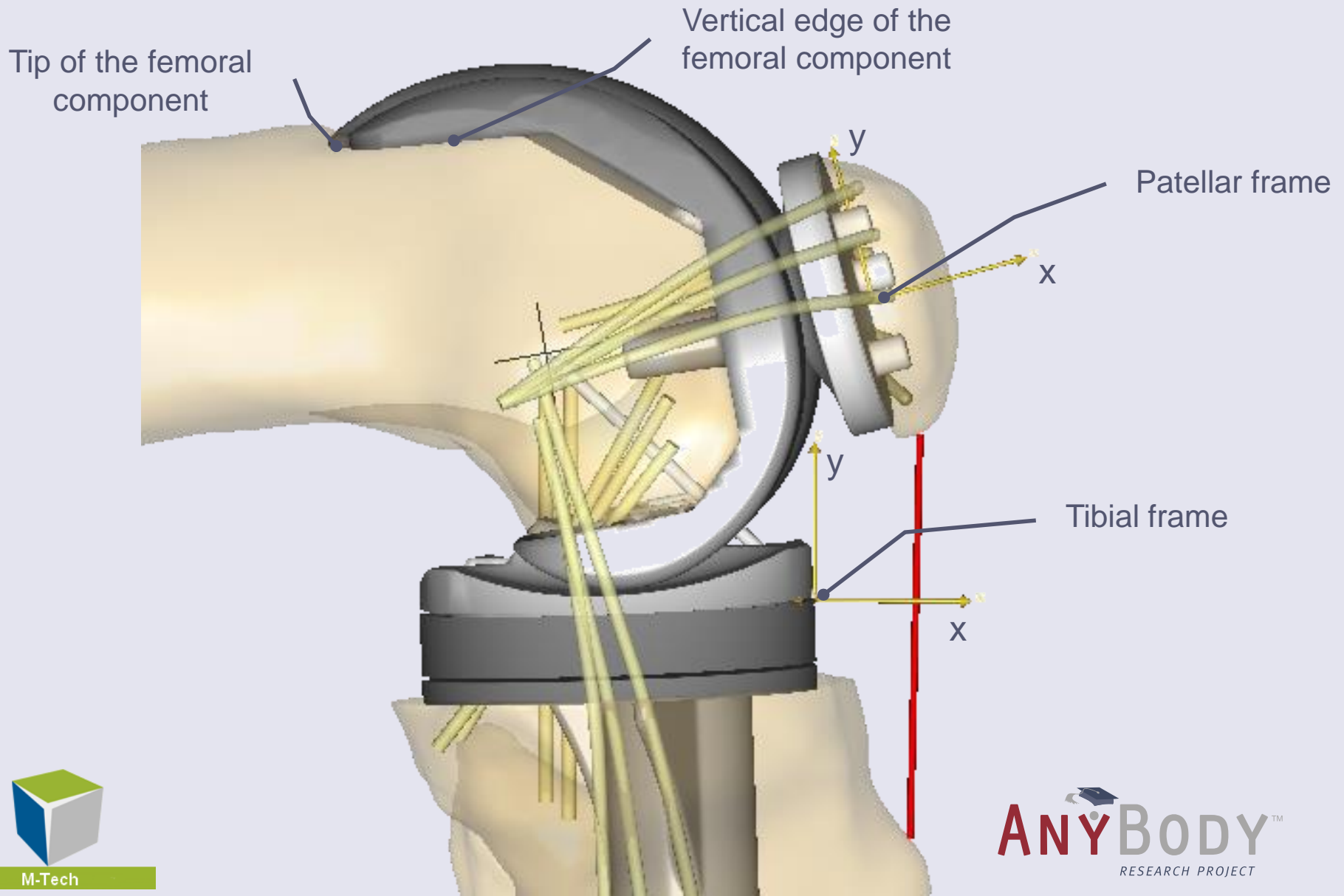
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# Fluoroscopy

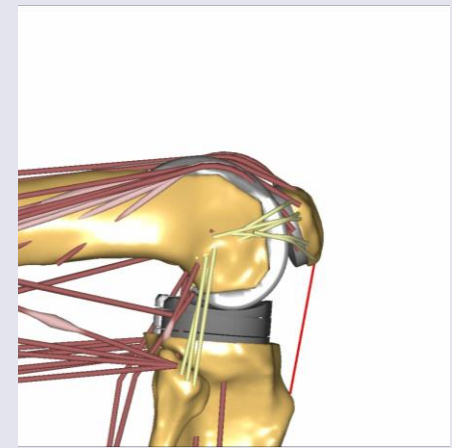
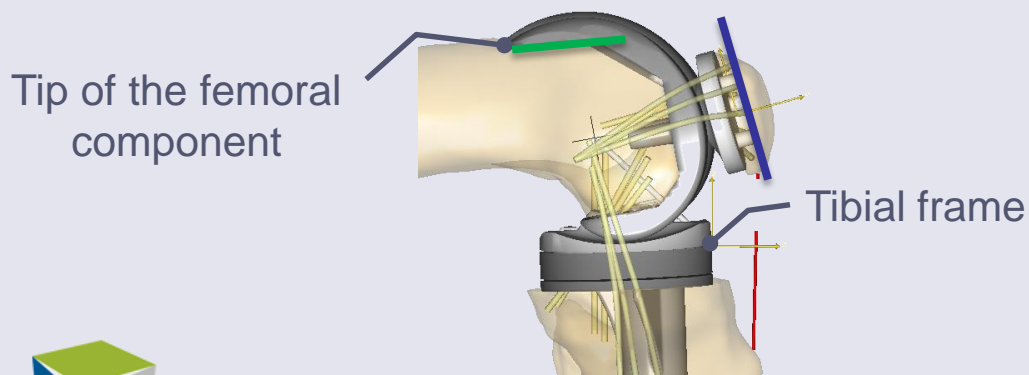
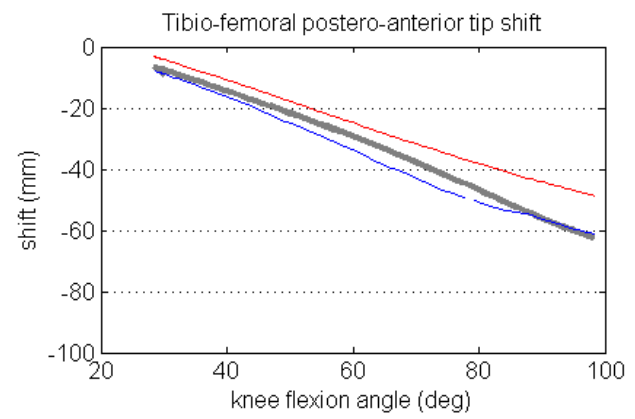
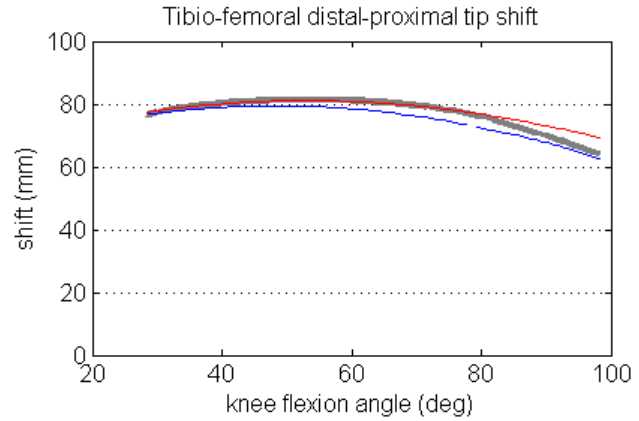
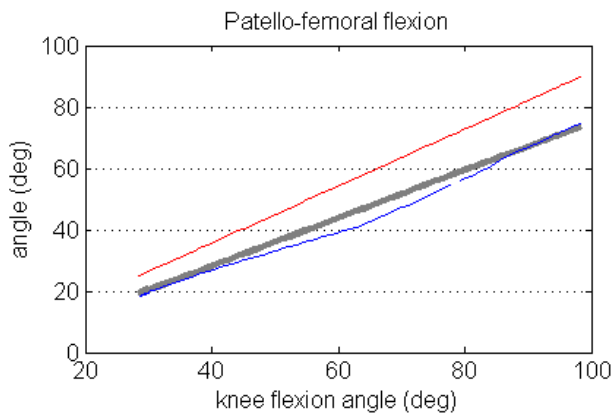


# Fluoroscopy



# Fluoroscopy

Red: Revolute joint-based knee.  
 Blue: FDK knee.  
 Grey: Fluoroscopy.



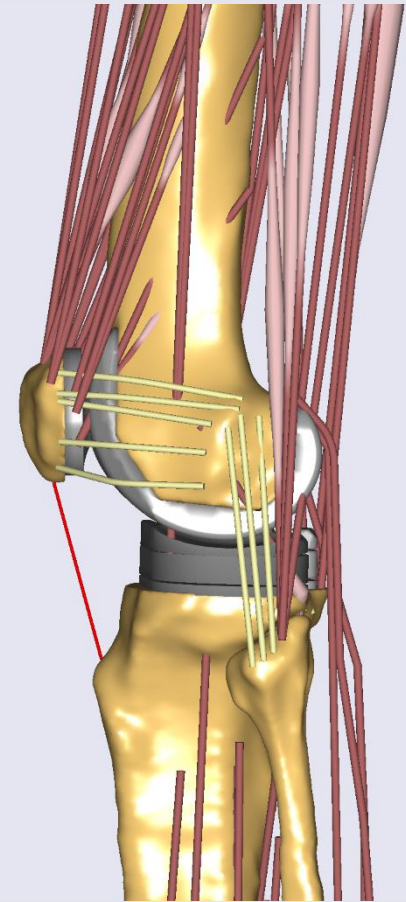
Camera attached to tibia



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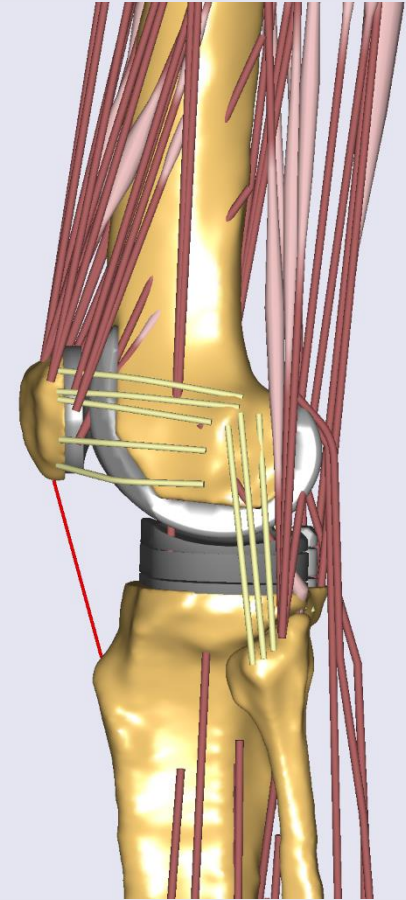
# Lessons learned

- Good estimates of knee forces and secondary (planar) kinematics.
- The computed forces are sensitive to the muscle decomposition (with the typical recruitment criterion).
- Muscle volume weights in the recruitment improved predictions.
- Generation of patient-specific models possible but technically difficult.



# Future work

- Automate the patient-specific modelling process
- Patient-specific ligament properties.
- Patient-specific strength scaling.
- Improve the prediction of co-contraction.
- Apply the model (e.g. to clinical treatment optimisation).



# Thank you!

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