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

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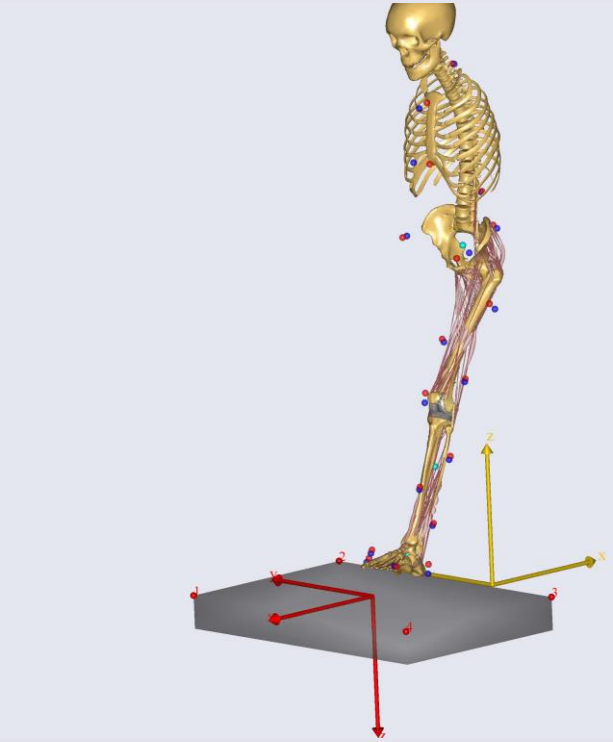

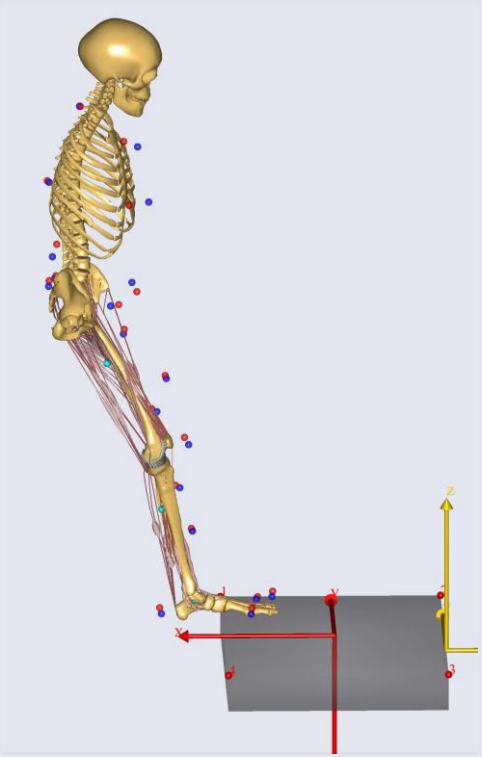

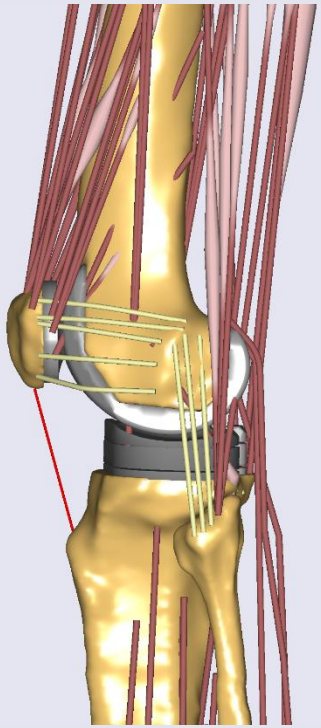

Winner of the 5th Grand Challenge Competition to Predict In Vivo Knee Loads

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Motivation

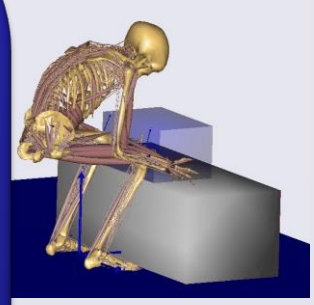
Non-invasive e

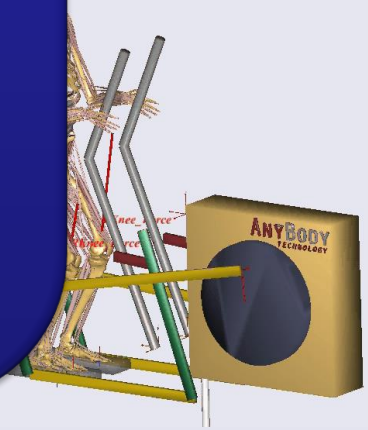
- Muscle loads
- Joint loads.
- Bone loads.
- Ligament loa
- Joint moveme
- Etc.

Insight into quan
impossible or im

For clinical applications

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





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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)

Fregly et al., (2012)

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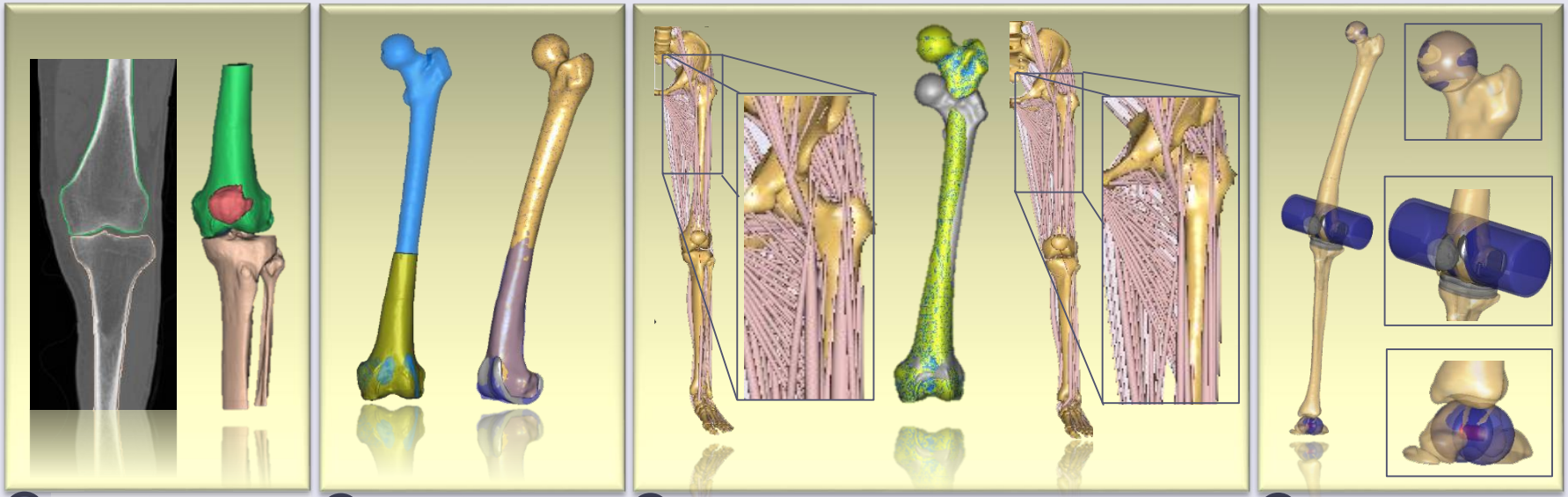
Modelling overview

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



1. Pre-op segmentation
2. Pre- and post-op registration
3. *Before* **Bone morphing** *After*

   Nonlinear using Radial Basis Functions
4. Analytical joint fitting

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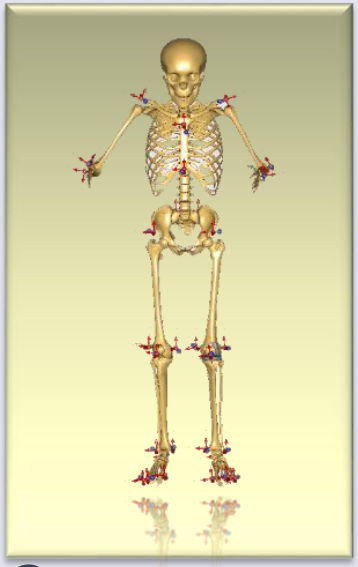
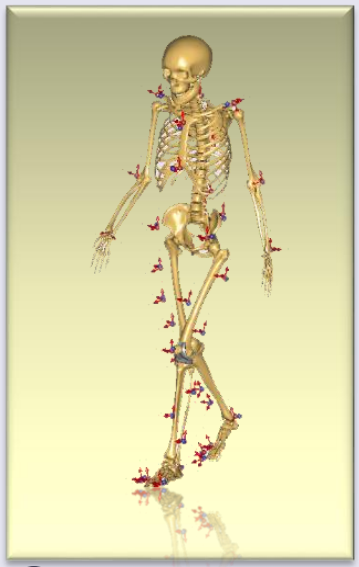
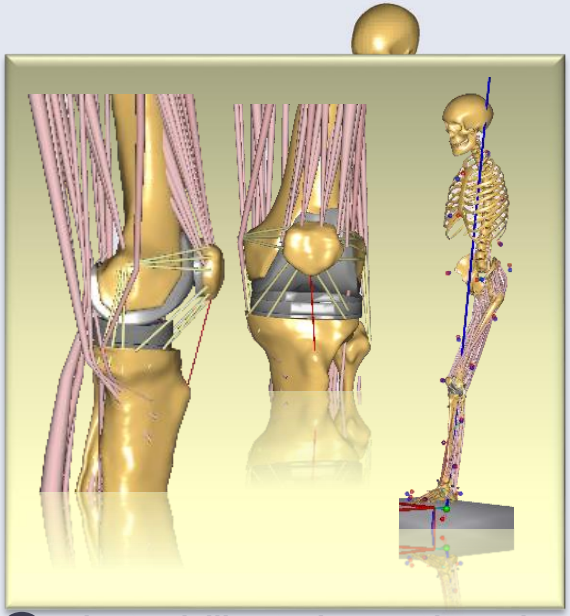
Modelling overview



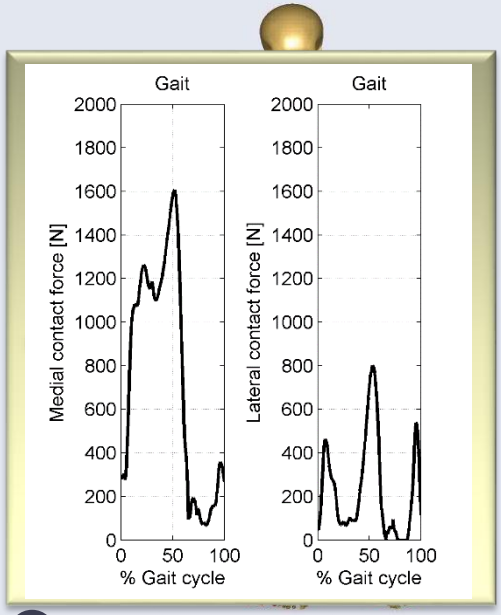
5 Scaling of remaining segments



6 Marker tracking



7 Joint modelling and Force-dependent Kinematics



8 Results

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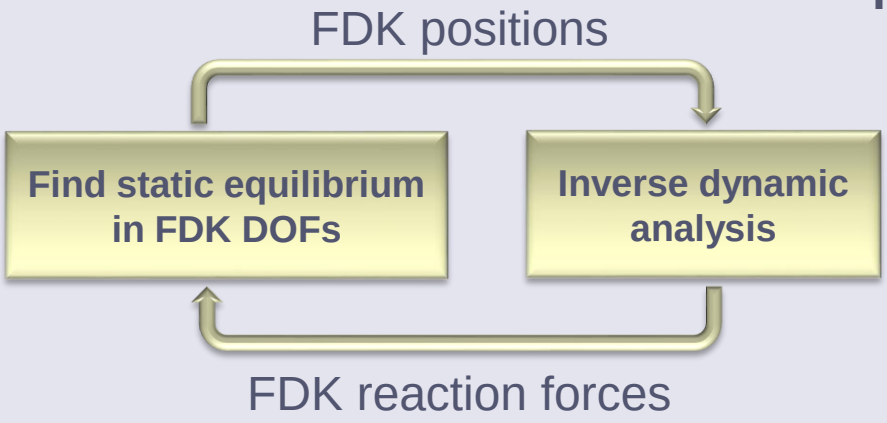
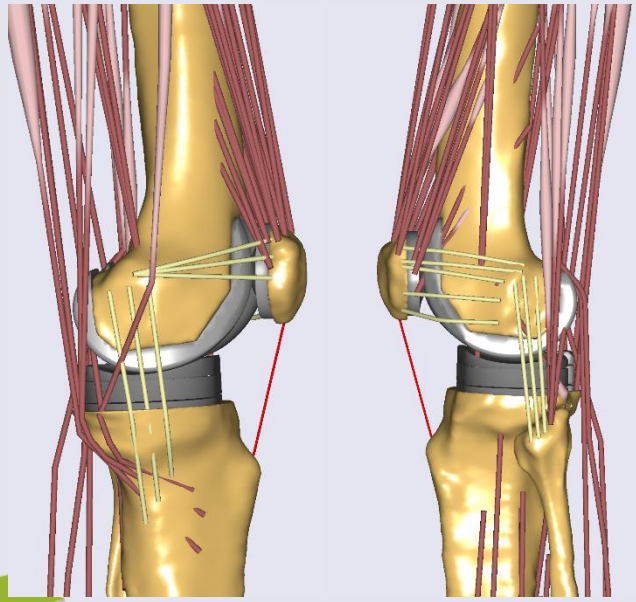
Force-dependent kinematics (FDK)





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 arthoplasty.


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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Blinded results

Submitted January, 2014

Blinded results

Gait

Right turn

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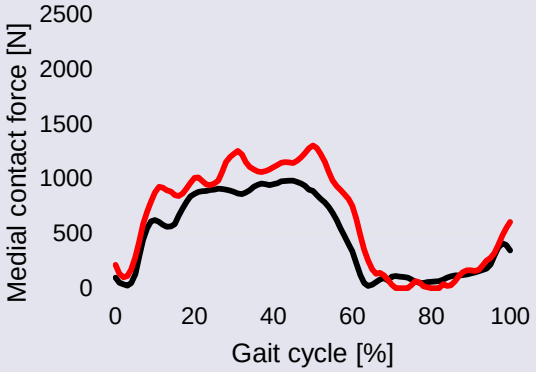
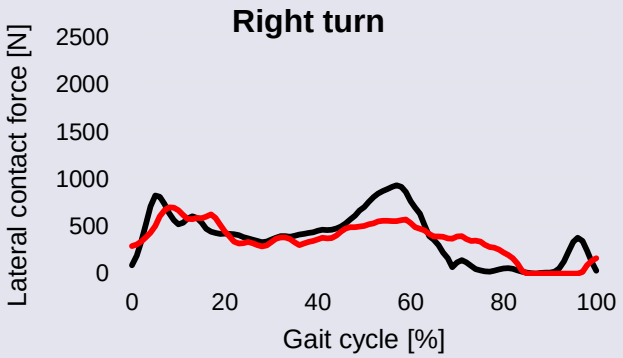
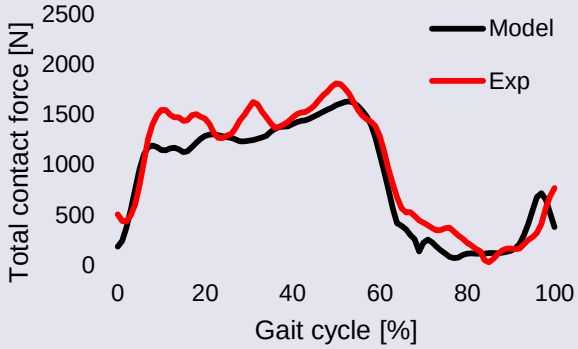
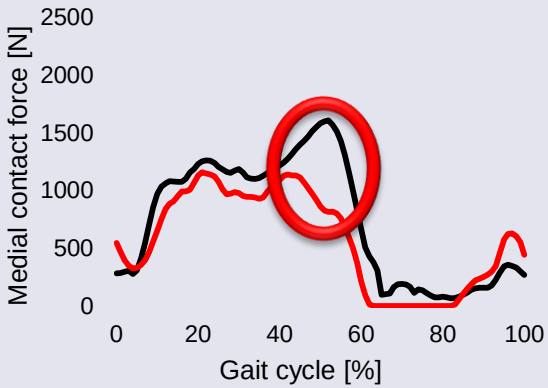
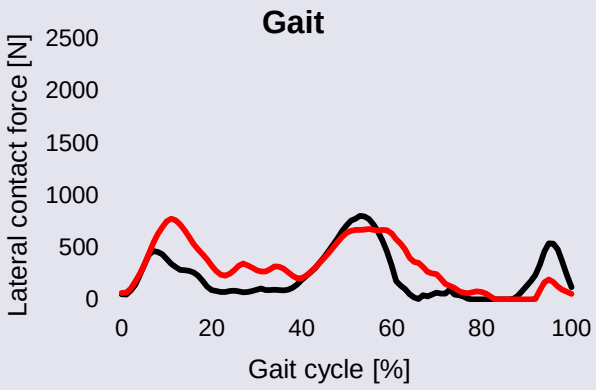
Blinded results

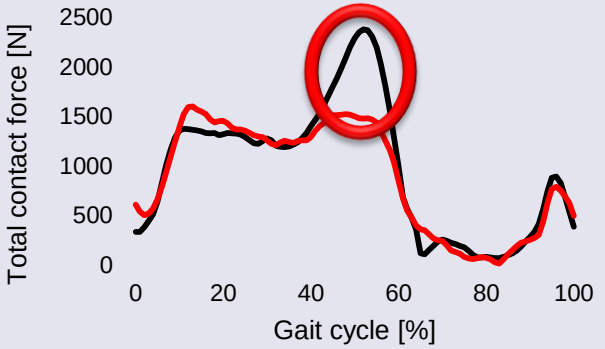












Right turn	RMSE [N]	R^2
Medial contact force	208	0.92
Lateral contact force	175	0.57
Total contact force	195	0.93

Gait	RMSE [N]	R^2
Medial contact force	288	0.80
Lateral contact force	203	0.45
Total contact force	272	0.86

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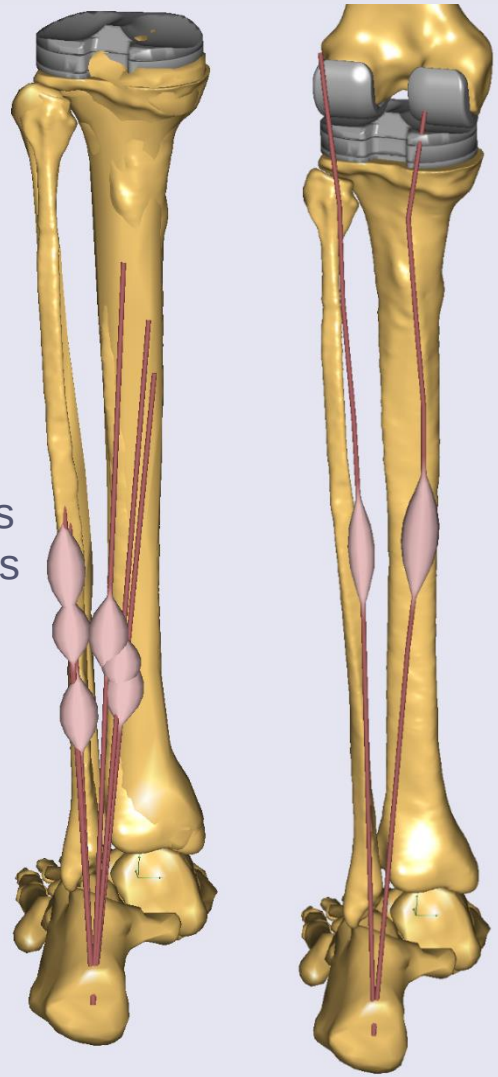
Model improvements

Knee contact forces released February, 2014

Most important change: Recruitment criterion

Soleus
Medialis: 3 branches
Lateralis: 3 branches

Gastrocnemius
Medialis: 1 branch
Lateralis: 1 branch

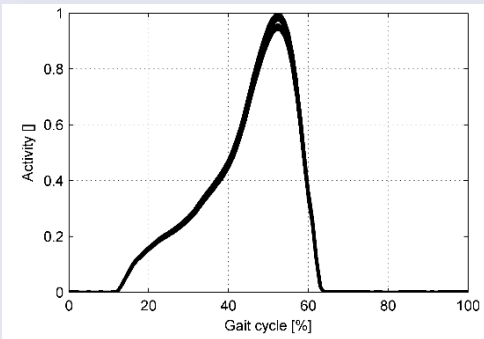


Multibody Syst Dyn (2012) 28:283–289
DOI 10.1007/s11044-011-9277-4

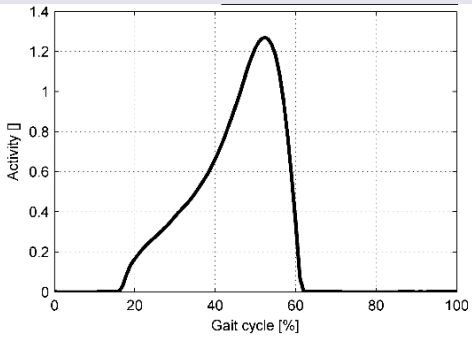
Muscle decomposition and recruitment criteria influence muscle force estimates

L. Joakim Holmberg · Anders Klarbring

$$\min_F \sum_{i=1}^{N} \left(\frac{\mathrm{F}_i^{(m)}}{S_i} \right)^p$$
$$\text{s.t. } \mathrm{C}F = d$$
$$F_i^{(m)} \geq 0$$



Soleus



Gastrocnemius medialis

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Most important change: Recruitment criterion

- **Idea** (Happee and Van der Helm (1995))
  - Associate a cost to activating a muscle volume element, $\left(\frac{\mathrm{F}_i^{(m)}}{S_i}\right)^p$
  - The total cost is obtained by a weighted sum over all muscle volume elements.

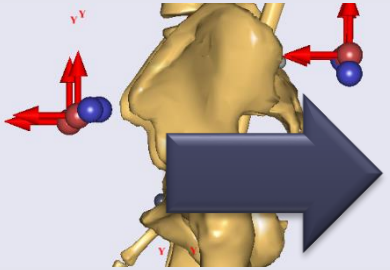
$$\min_F \sum_{i=1}^{N} \boldsymbol{V_i} \left(\frac{\mathrm{F}_i^{(m)}}{S_i}\right)^p$$
$$\text{s.t. } \mathrm{C}F = d$$
$$F_i^{(m)} \geq 0$$

$\boldsymbol{V_i}$ 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.

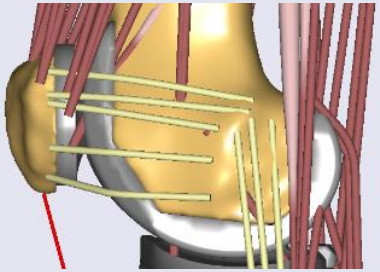
Minor updates

- **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.



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Unblinded results

Submitted June, 2014

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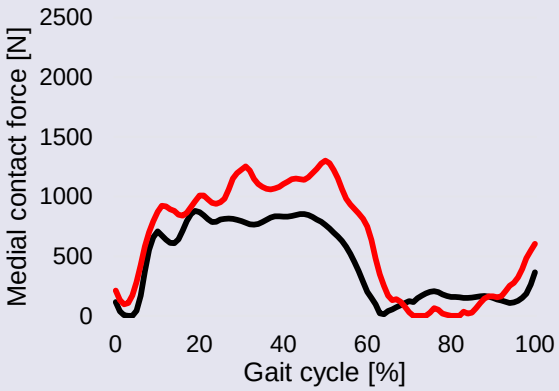
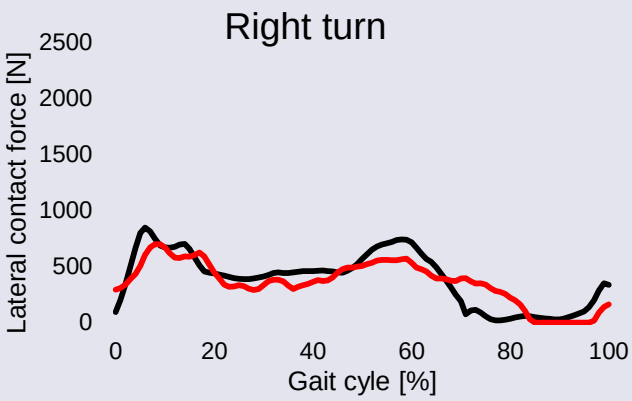
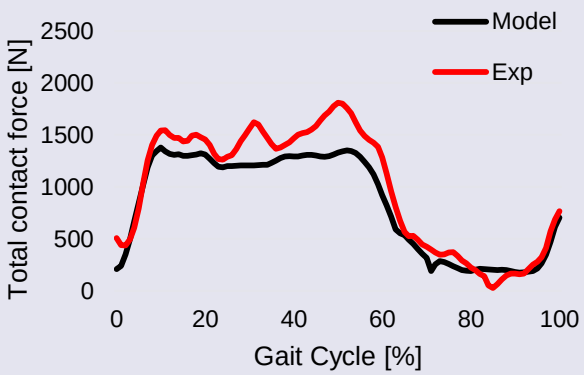
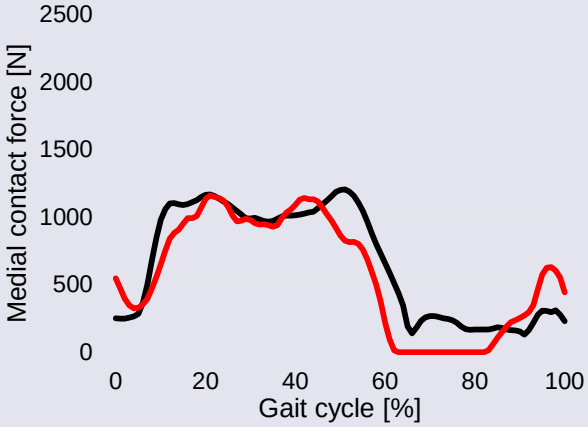
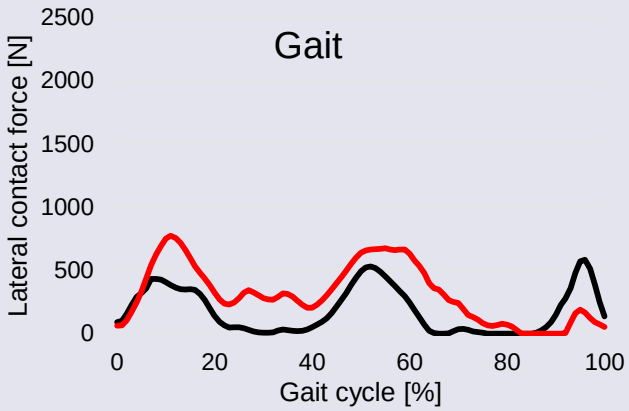
Unblinded results

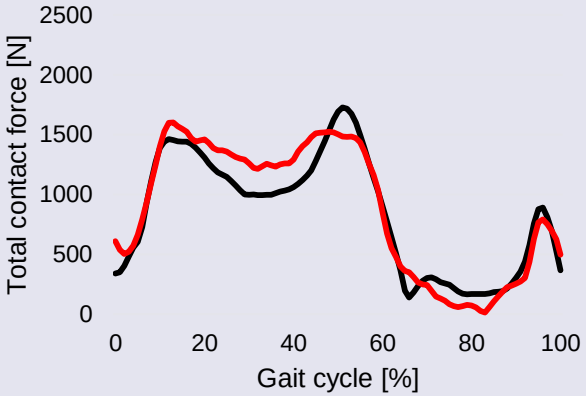












Right turn *(unblinded)*	**RMSE [N]**	**R^2**
Medial contact force	272	0.85
Lateral contact force	136	0.71
Total contact force	206	0.96

Gait *(unblinded)*	**RMSE [N]**	**R^2**
Medial contact force	210	0.80
Lateral contact force	230	0.36
Total contact force	154	0.93

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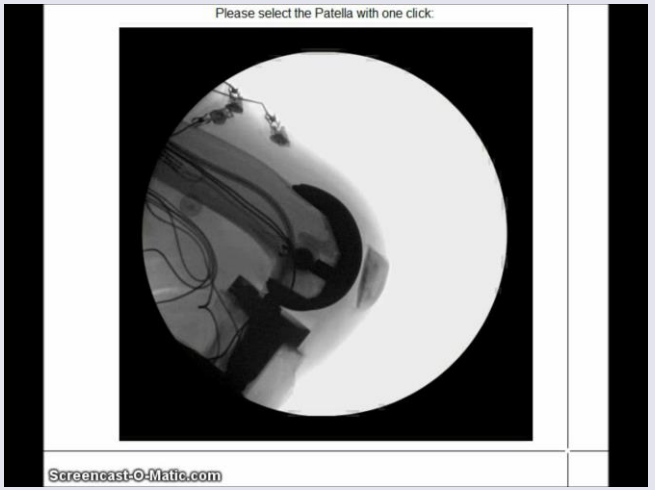
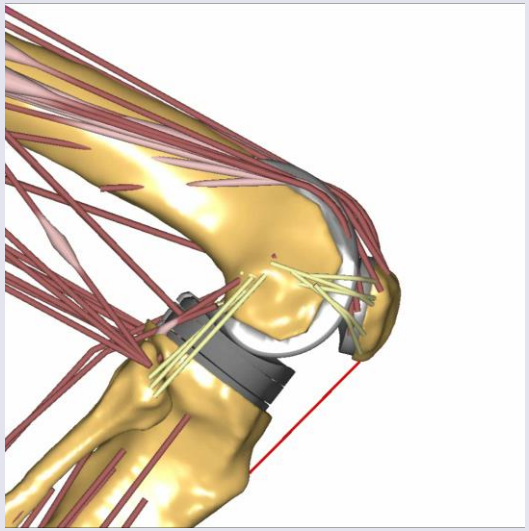
Fluoroscopy





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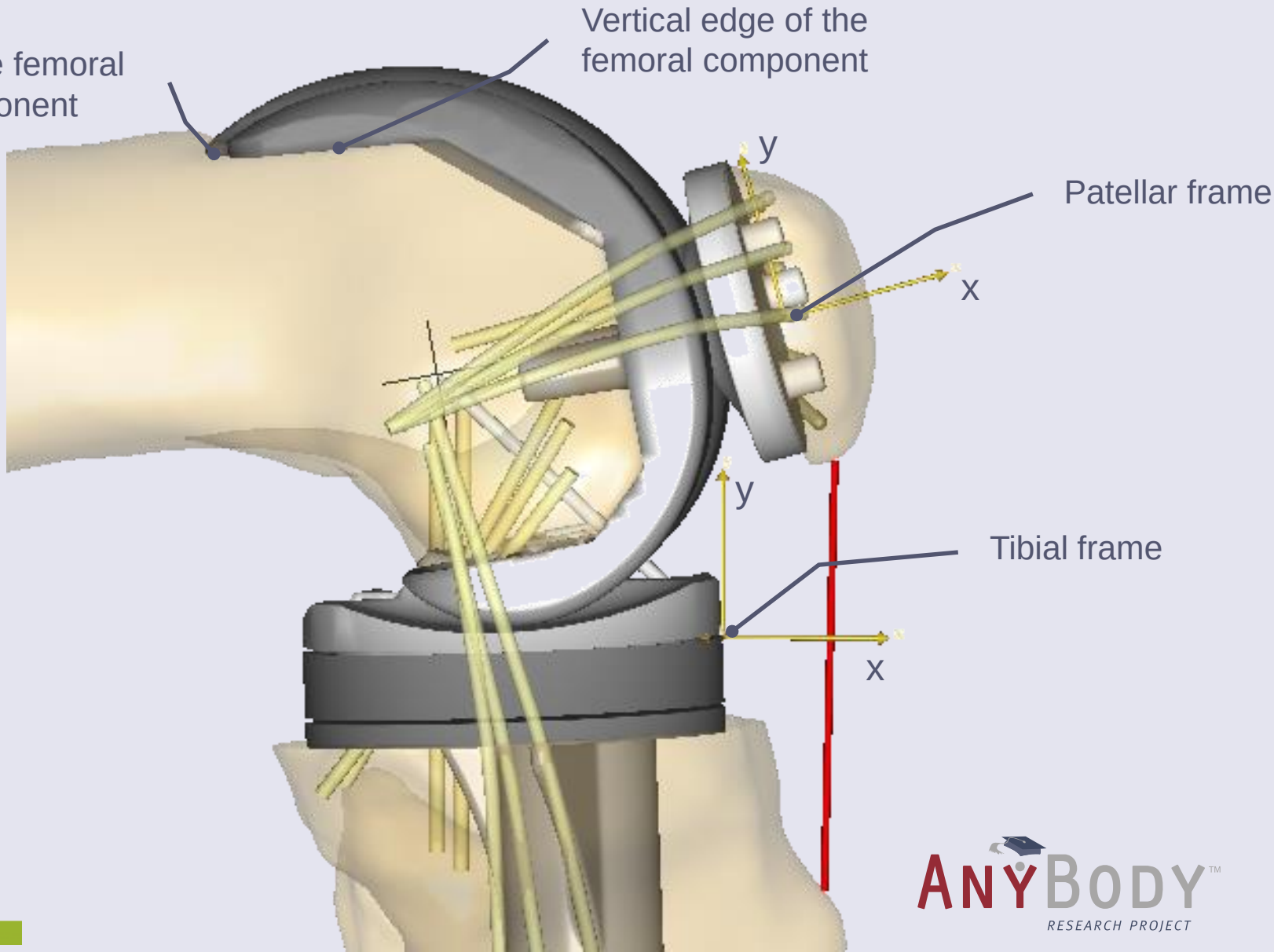
Fluoroscopy



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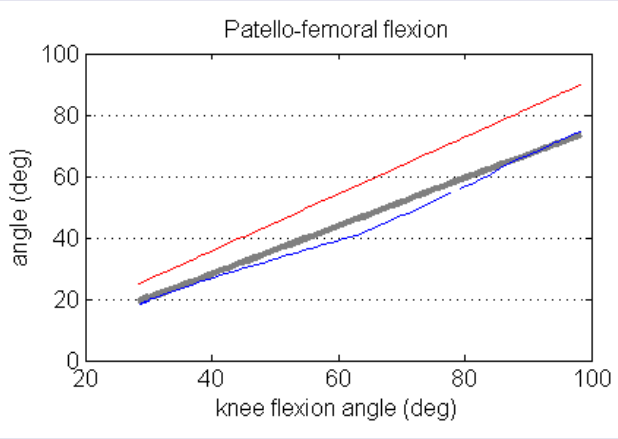
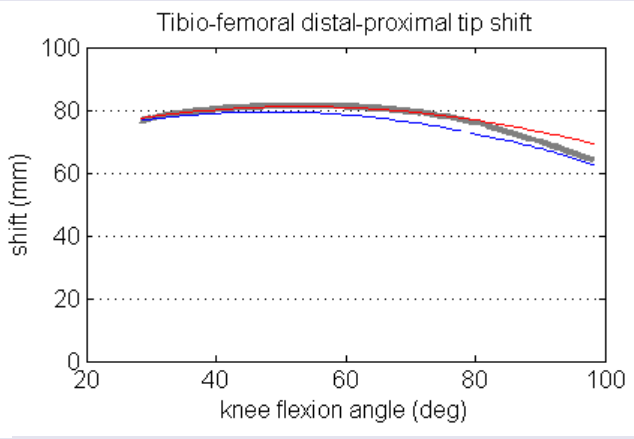
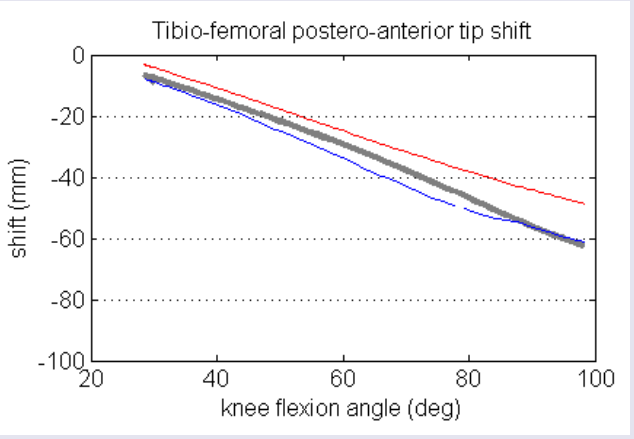
Fluoroscopy

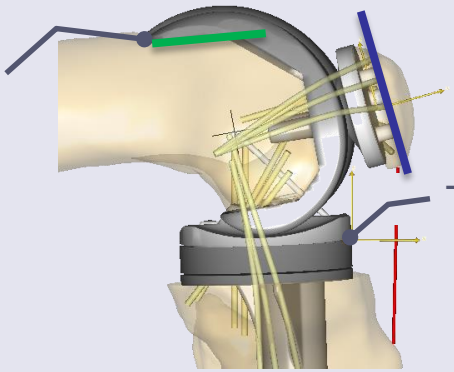
Red: Revolute joint-based knee.
Blue: FDK knee.
Grey: Fluoroscopy.



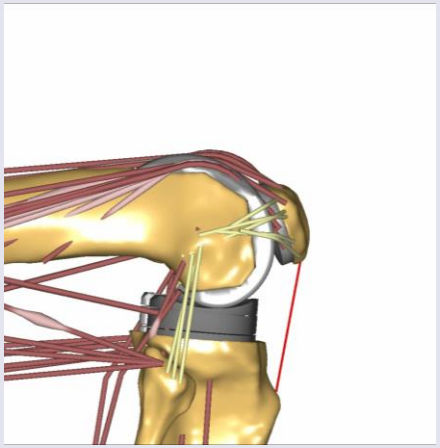




Tip of the femoral component



Tibial frame



Camera attached to tibia

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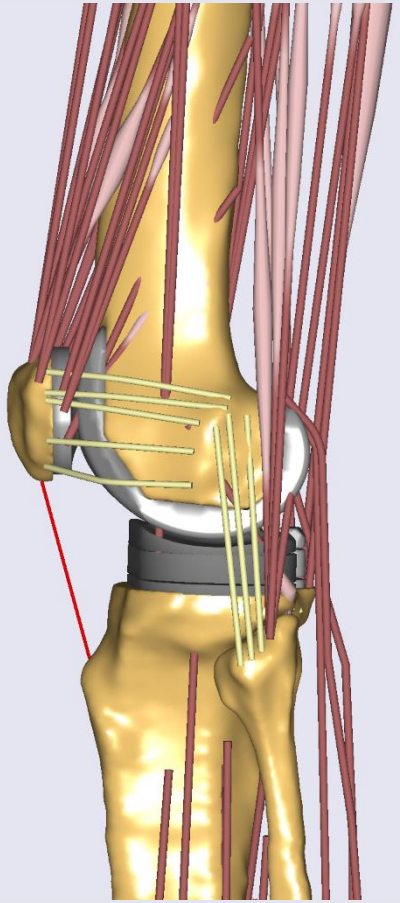
Lessons learned

- 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.



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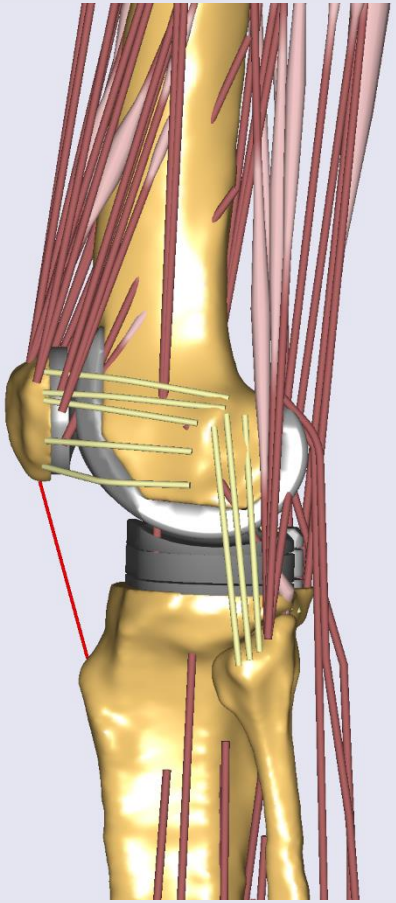
Future work

- 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).



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Thank you!

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