# Evaluation of predicted knee kinematics and ligament length changes by force-dependent kinematics in vitro

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# Overview

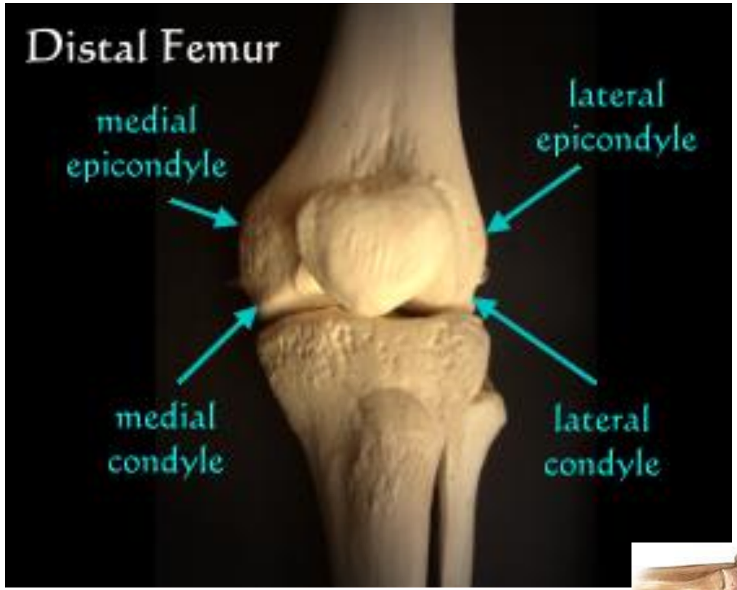
- Motivation of our work
- Modelling workflow
- Results & discussion

# Two strategies to perform a total knee replacement

## Measured resection

Using bony landmarks

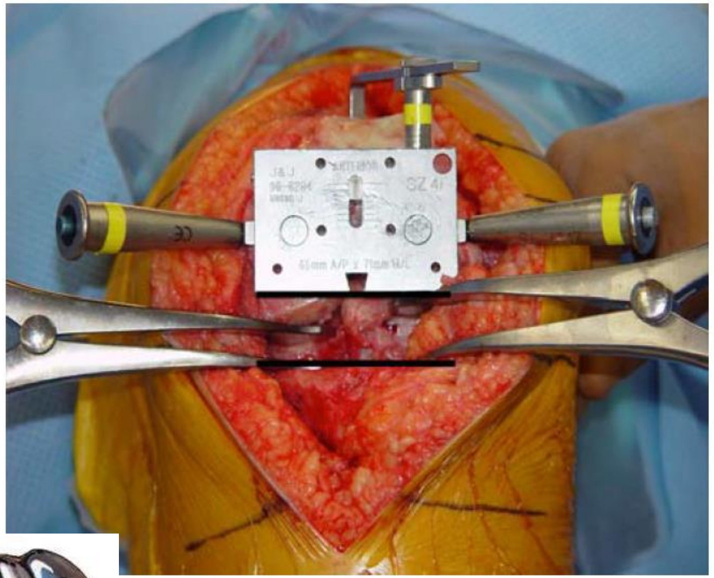
Pre-op planning already used




## Gap balancing

Using ligament tension in flexion

Surgeon expertise required

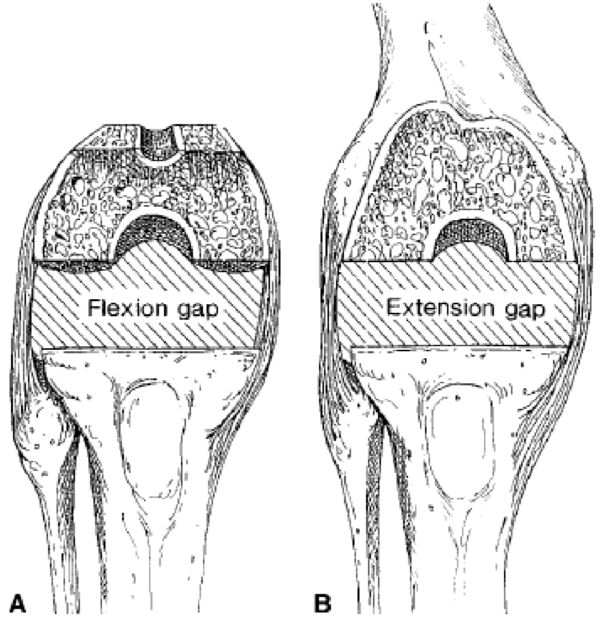


# What is ideal balance?

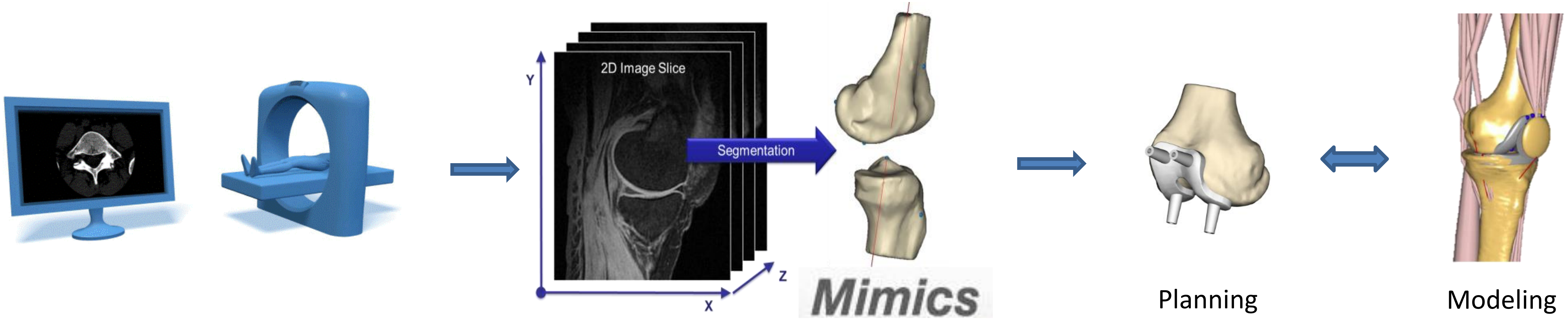
- Not yet been defined

- Current consensus:
  Equal **medial** and **lateral** structure tensions **at full extension** and **at 90° of flexion** are conducive with good clinical outcome

- Unnatural?
- Mid-flexion instability



# Can subject-specific knee models assist in clinical decision-making?

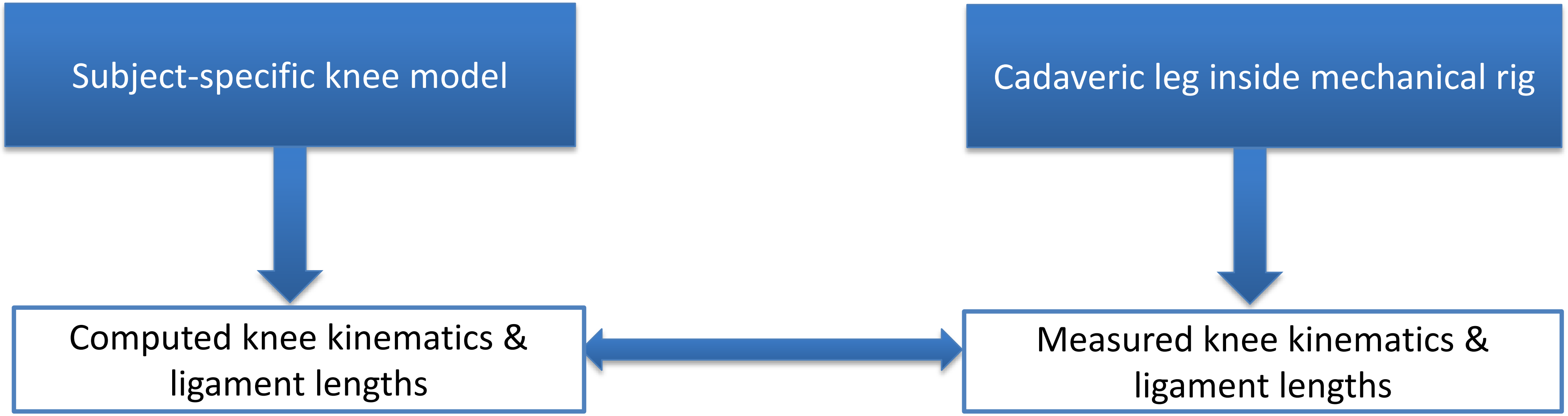



Aim: investigate if musculoskeletal models can be used to determine **optimal implant position** for gap-balanced total knee arthroplasty

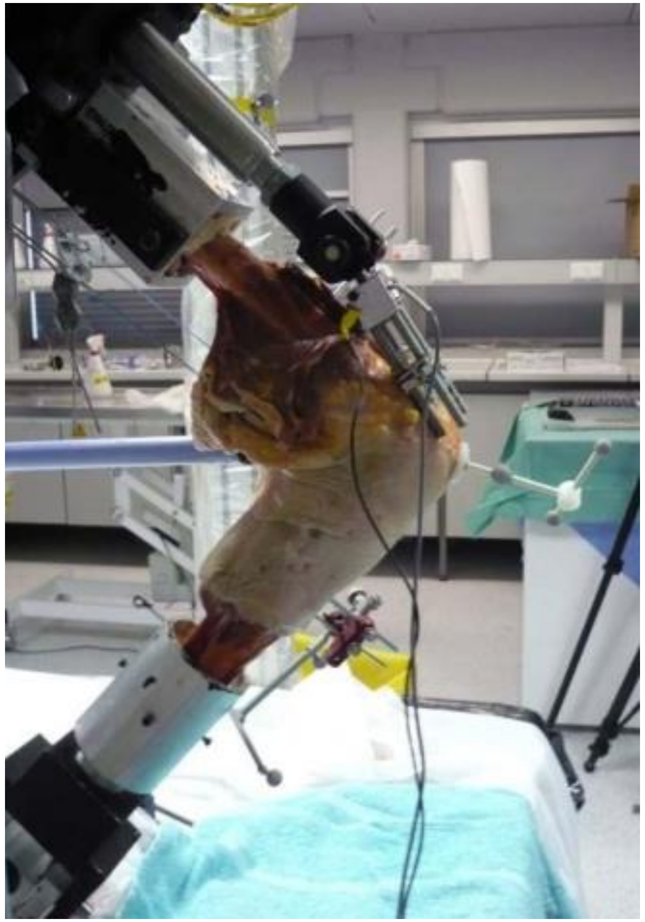
How: Pre-operative modelling of range of motion and ligament behaviour

Validation is essential to transfer numerical models into clinical practice

# Experimental data from a cadaver was used to validate the model

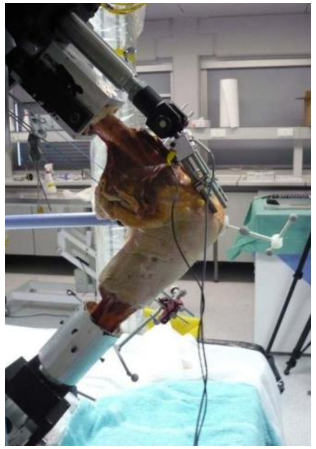
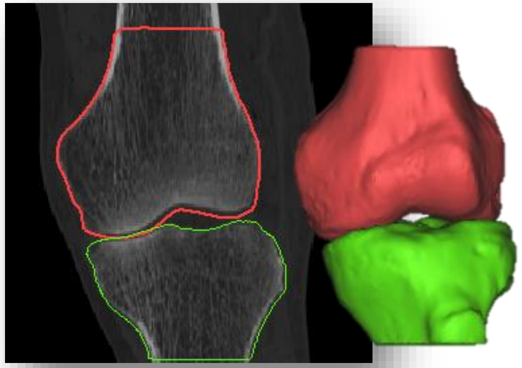
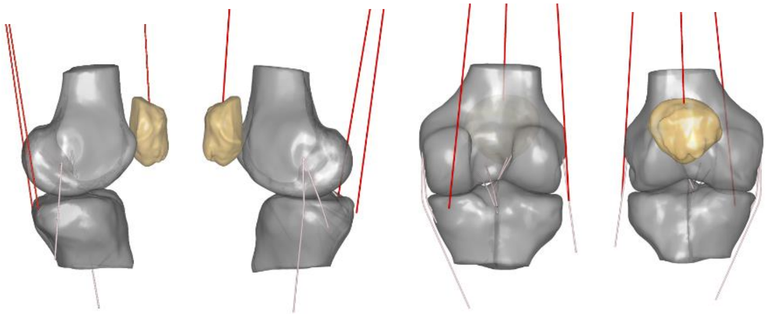
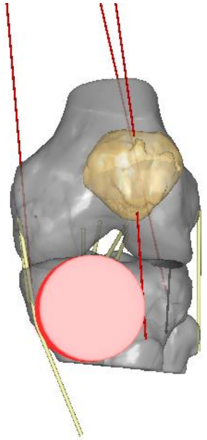


# Simulation of squat motion with the mechanical rig

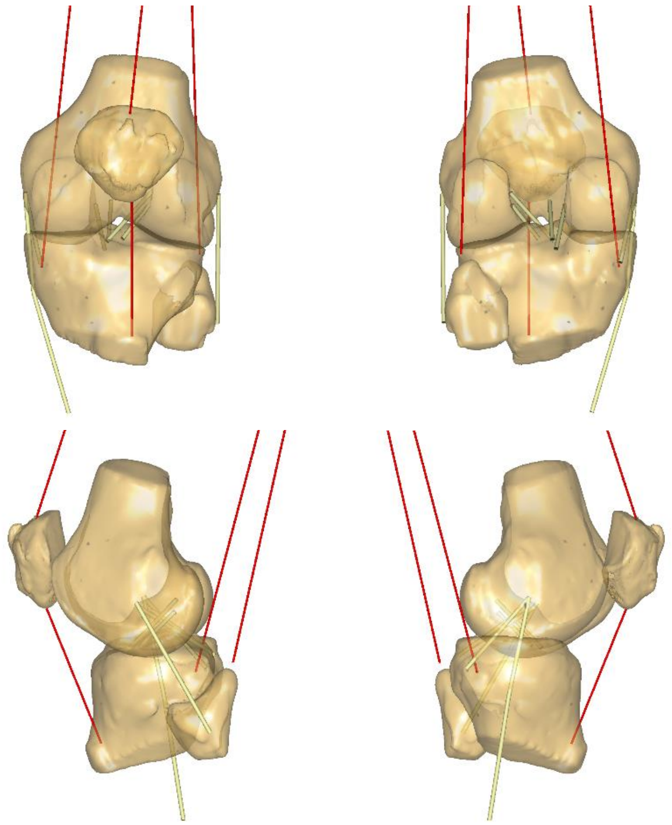


- **Intact** knee from a cadaver
- Simulation of deep knee bend with Oxford Rig:
  - 2 constant force springs load the hamstrings
  - Quadriceps actuator
  - Passive optical markers
    - Experimental knee kinematics
    - Experimental ligament lengths

# Modelling workflow

| Kinematics | Geometry | | |
|---|---|---|---|
|  |  |  |  |
| 1 Oxford rig | 2 Segmentation + Cartilage estimation | 3 Landmarks determine:<br>- Joint axes<br>- Ligament attachments | 4 Wrapping surfaces |

# Modelling of the ligaments



- MCL distal and proximal
- LCL
- ACL anterior and posterior
- PCL anterior and posterior

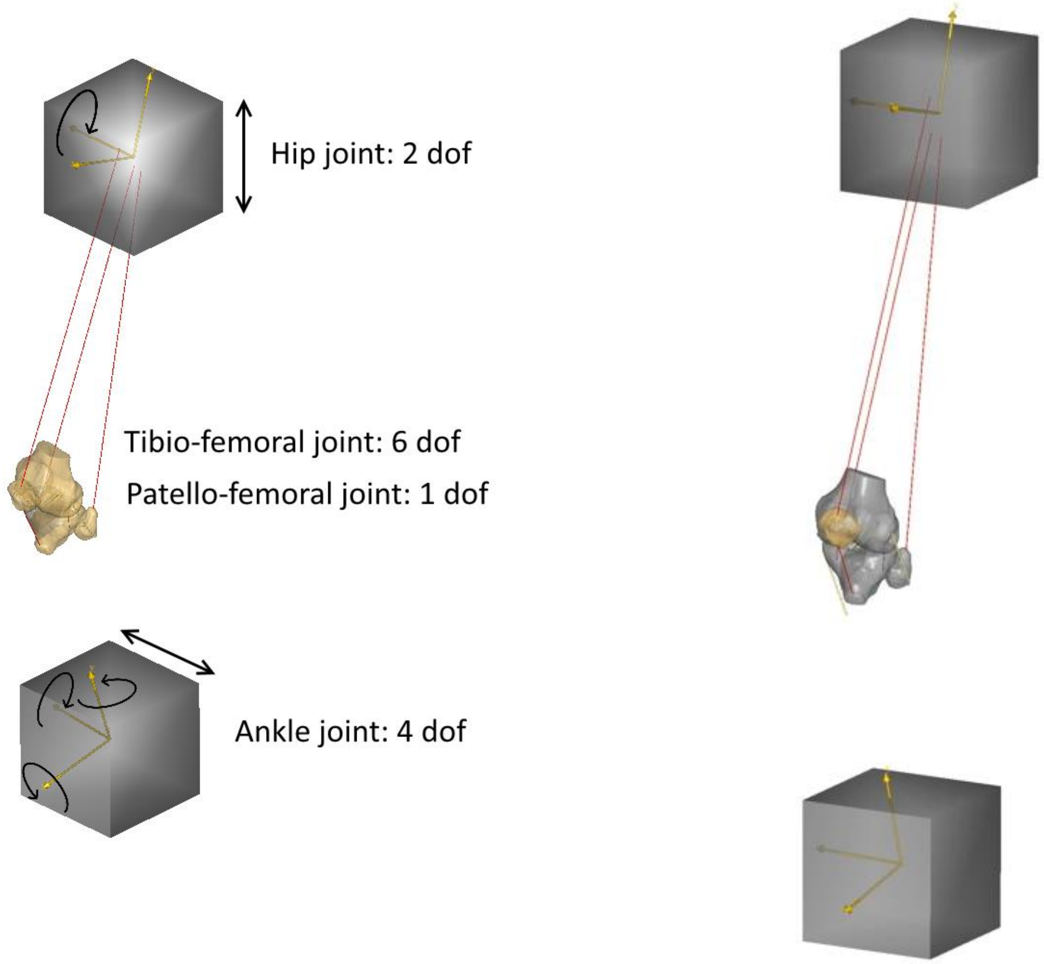
| | MCLprox | MCLdist | LCL | ACL_AM | ACL_PL | PCL_AL | PCL_PM |
|---|---|---|---|---|---|---|---|
| $\epsilon_r$ | 0.04 | 0.04 | 0.08 | 0.06 | 0.1 | -0.24 | -0.03 |
| k | 4125 | 4125 | 6000 | 5000 | 5000 | 9000 | 9000 |

$$L_0 = L_r/(\varepsilon_r + 1)$$

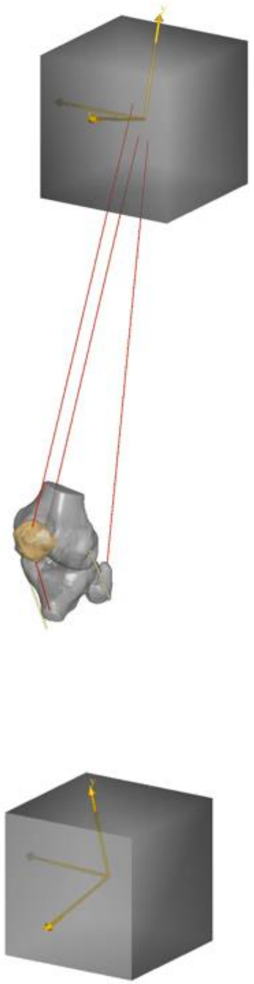
(Blankevoort and Huiskes, 1991)

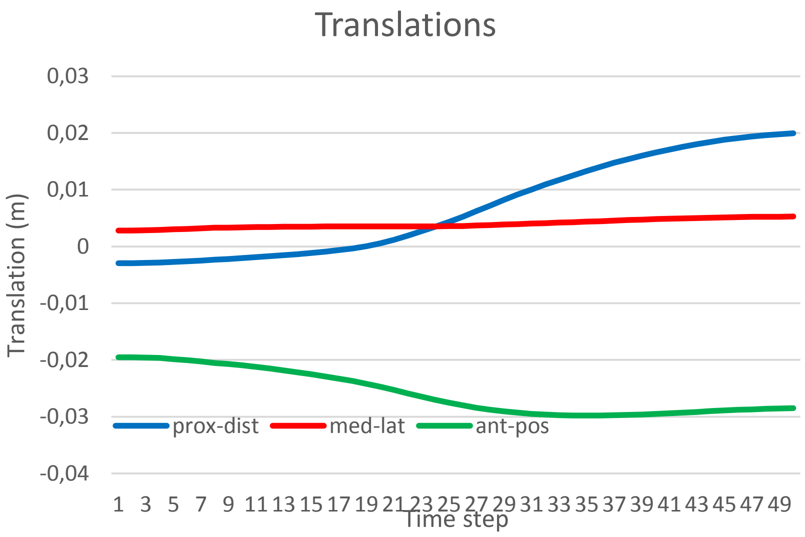
# Simulation in AnyBody Modeling System

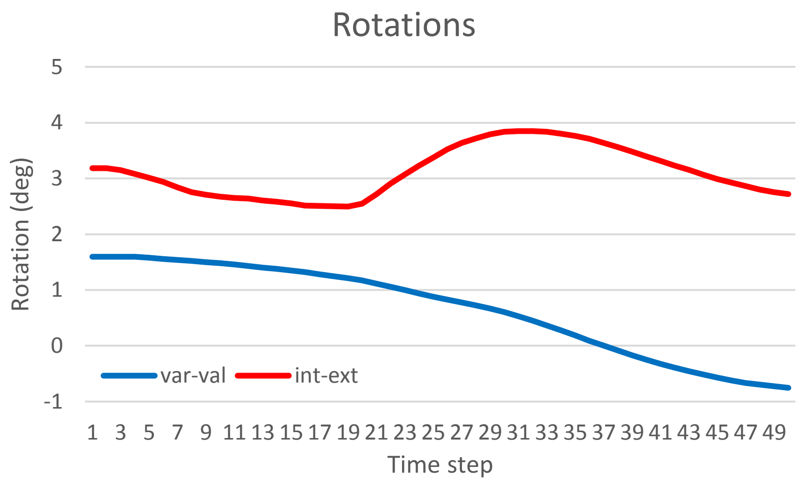
- Force-dependent kinematics
  - Uses inverse dynamics and quasi-static force equilibrium in selected DOFs
- Driver: vertical hip position
- Simultaneously solves muscle, joint and ligament forces and internal joint motion

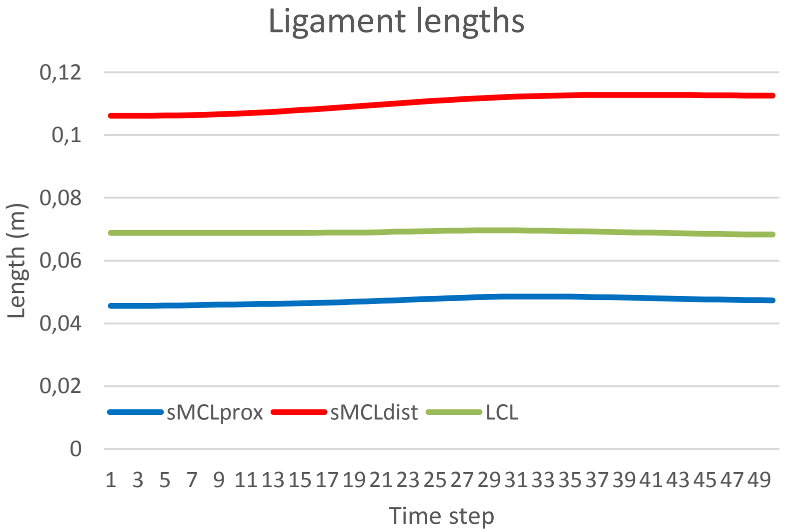


# FDK computes simultaneously kinematics and ligament lengths






Grood and Suntay (1983)

# Sensitivity study

- Variation of reference strain of one ligament bundle at a time
  - 7 ligament bundles
  - 4 pertubations: $\varepsilon_r$ -0.05, $\varepsilon_r$ -0.025, $\varepsilon_r$ + 0.025, $\varepsilon_r$ + 0.05
    - $\varepsilon_r$ +/- 5% (Amiri & Wilson, 2012)
    - $\varepsilon_r$ +/- 4% (Baldwin, 2009)
  - 28 pertubed simulations

| | MCLprox | MCLdist | LCL | ACL_AM | ACL_PL | PCL_AL | PCL_PM |
|---|---|---|---|---|---|---|---|
| $\epsilon_r$ | 0.04 | 0.04 | 0.08 | 0.06 | 0.1 | -0.24 | -0.03 |
| k | 4125 | 4125 | 6000 | 5000 | 5000 | 9000 | 9000 |

$$L_0 = L_r/(\varepsilon_r + 1)$$

- Reported in literature to be a very sensitive parameter

Bloemker, K. H., Guess, T. M., Maletsky, L., Dodd, K., 2012. Computational knee ligament modeling using experimentally determined zero-load lengths. The open biomedical engineering journal 6, 33-41.

Beillas, P., Lee, S. W., Tashman, S., Yang, K. H., 2007. Sensitivity of the tibio-femoral response to finite element modeling parameters. Computer methods in biomechanics and biomedical engineering 10(3), 209-221.

# How can you compare measured values with computed values?

- RMSE $\sqrt{\frac{\sum_{t=1}^{n}(\hat{y}_t - y_t)^2}{n}}.$
- Pearson correlation coefficient ρ

  ρ≤0.35 (weak); 0.35< ρ ≤0.67 (moderate); 0.67< ρ ≤0.9 (strong); 0.9< ρ (excellent) (Taylor, 1990)
- Sprague and Geers metric (Schwer, 2007)

$$\vartheta_{mm} = (t_2 - t_1)^{-1} \int_{t_1}^{t_2} m^2(t)\mathrm{d}t$$

$$\vartheta_{cc} = (t_2 - t_1)^{-1} \int_{t_1}^{t_2} c^2(t)\mathrm{d}t$$

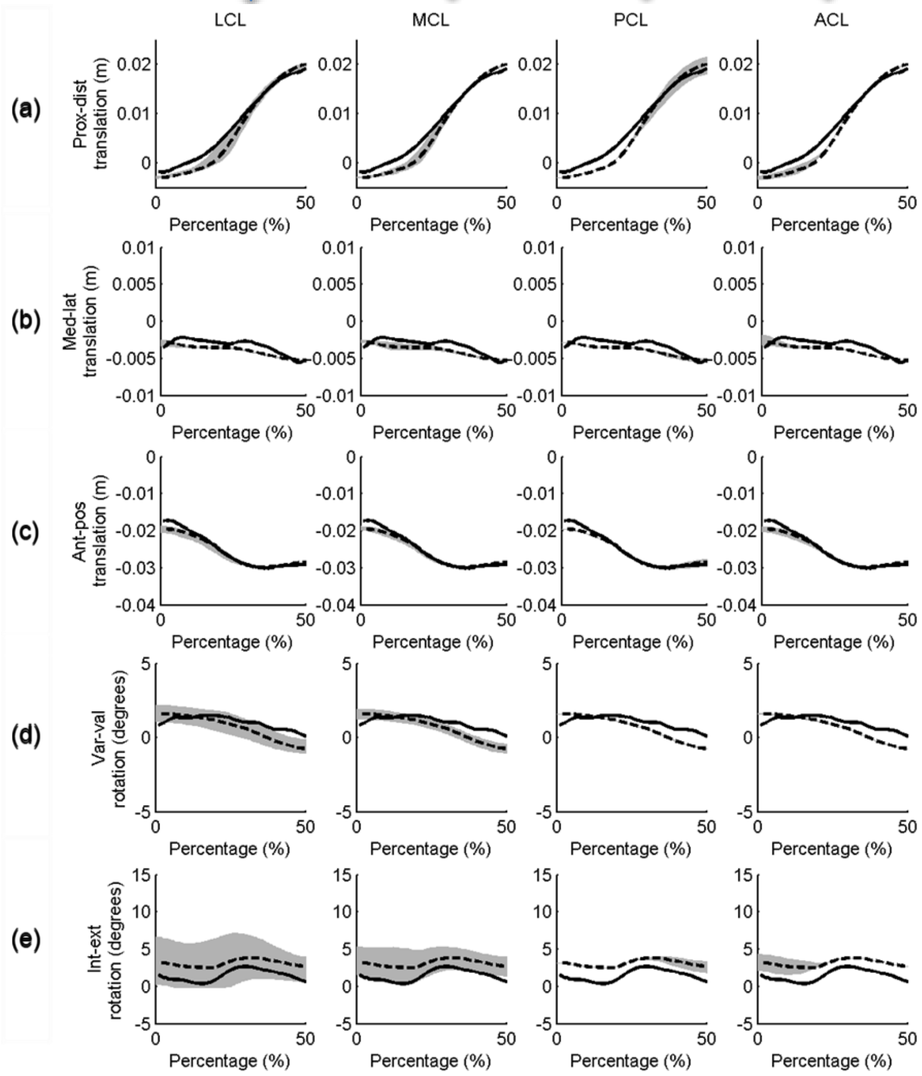
$$\vartheta_{mc} = (t_2 - t_1)^{-1} \int_{t_1}^{t_2} m(t)c(t)\mathrm{d}t$$

Personal reaction of Geers

- <20%: really good
- 20-30%: fair
- 30-40%: rather poor

  - Error in magnitude (insensitive to phase discrepancies): $M_{SG} = \sqrt{\vartheta_{cc}/\vartheta_{mm}} - 1$
  - Phase error (insensitive to magnitude differences): $P = \frac{1}{\pi}\cos^{-1}\left(\vartheta_{mc}/\sqrt{\vartheta_{mm}\vartheta_{cc}}\right)$
  - Comprehensive error Factor: $C_{SG} = \sqrt{M_{SG}^2 + P^2}$

# Kinematic results first specimen

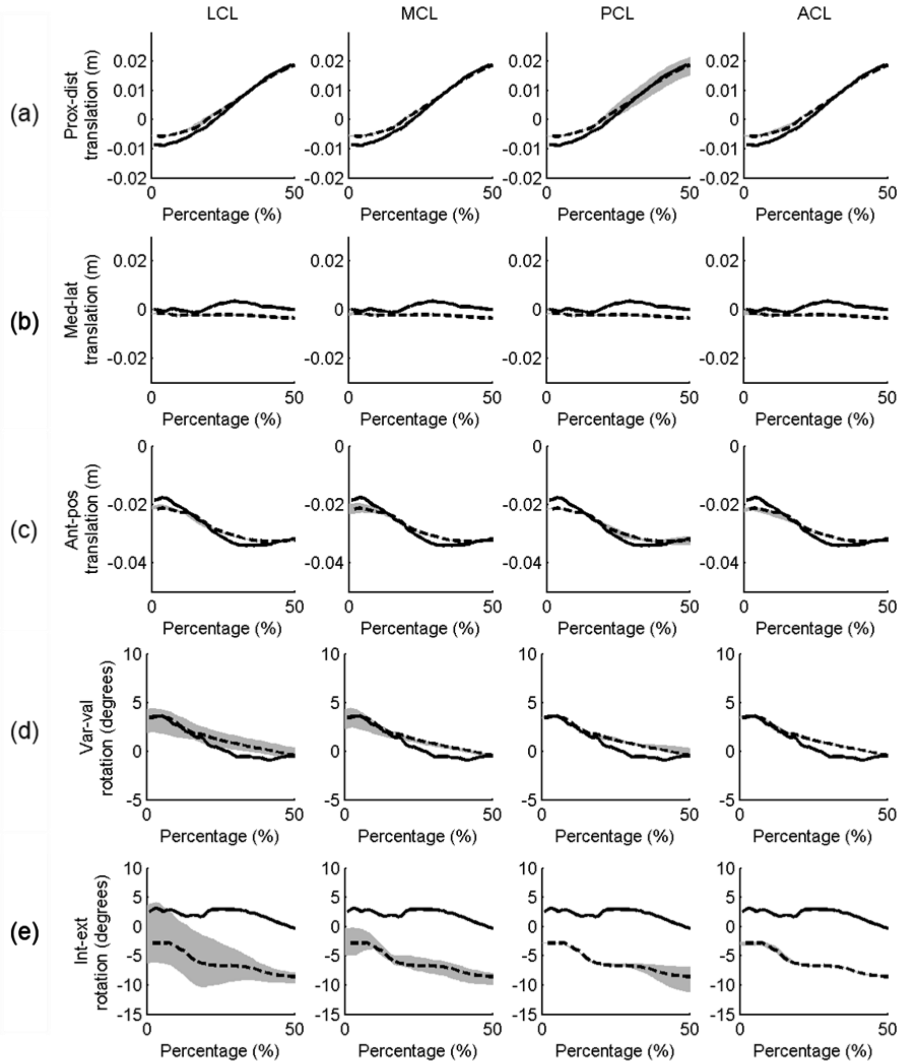



| RMSE | ρ |
|---|---|
| 1,69 mm | 100% |
| 0,82 mm | 87% |
| 0,92 mm | 100% |
| 0,61° | 89% |
| 1,69° | 97% |

—— exp
----- model
pertubations

# Kinematic results second specimen

— exp
----- model
pertubations

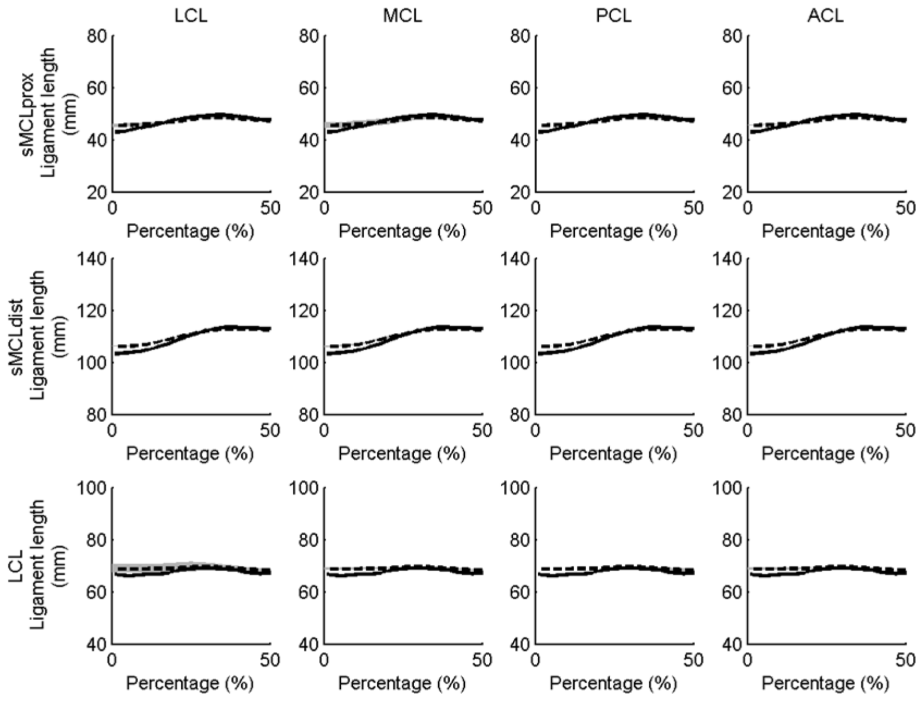



| RMSE | ρ |
|---|---|
| 1,73 mm | 100% |
| 3,67 mm | -4% |
| 1,85 mm | 98% |
| 0,73° | 98% |
| 8,31° | 58% |

# Ligament length changes

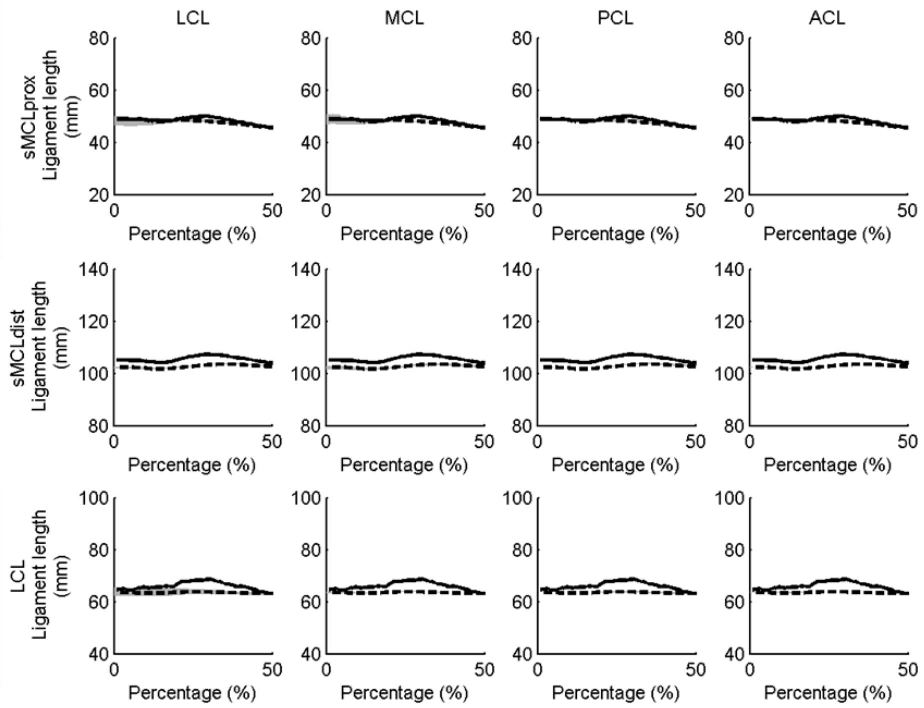
—— exp
----- model
pertubations

## First specimen




| RMSE (mm) | ρ |
|---|---|
| 1,07 | 98% |
| 1,45 | 100% |
| 1,51 | 82% |

## Second specimen




| RMSE (mm) | ρ |
|---|---|
| 0,94 | 83% |
| 2,92 | 73% |
| 2,85 | 92% |

# Limitations

- Patella is represented as a simple hinge joint
- Estimated cartilage and no menisci
- Only 2 specimens

# Lessons learned

- Translations show good agreement
- Rotations are more sensitive to model variations
- Importance of subject-specificity:
  - Slack length and insertions -> laxity test
  - Patella location -> FDK patella model

# Thank you for your attention!

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