Development, validation and clinical applications of patient-specific musculoskeletal knee models

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BioMechTools

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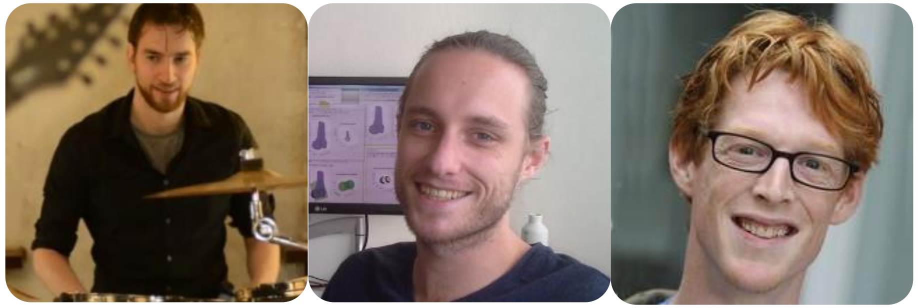
The BioMechTools Project

European Research Council
Established by the European Commission

Biomechanical Diagnostic, Pre-Planning and Outcome Tools to improve Musculoskeletal Surgery

Principal investigator: Prof. Dr. Ir. Nico Verdonschot



TU/e

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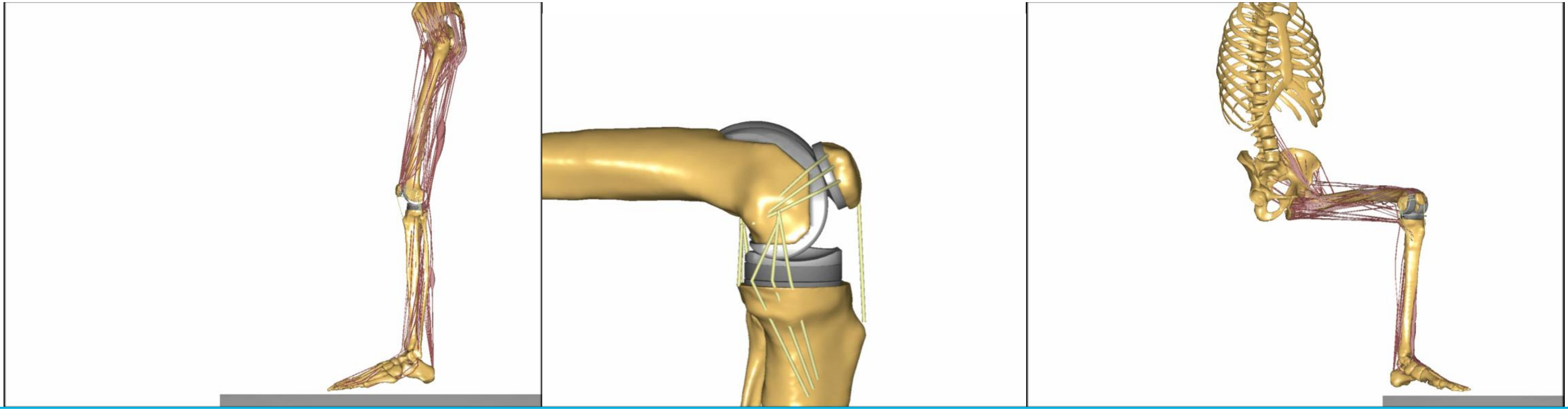
Why musculoskeletal modeling

- Assess musculoskeletal biomechanics
  - *in vivo*, non invasively, under physiological loading
  - potential for diagnostics and pre-planning



Outline

- Development and validation of a subject-specific model of TKA
- Techniques to accelerate the computation of contact mechanics
- Applications
  - effect of different surgical techniques in TKA
  - effect of sagittal alignment in TKA
  - patellofemoral mechanics in trochlear dysplasia

Total knee arthroplasty

- Successful orthopaedic procedure: reliefs pain, restores knee function
- Yet 20 % dissatisfaction

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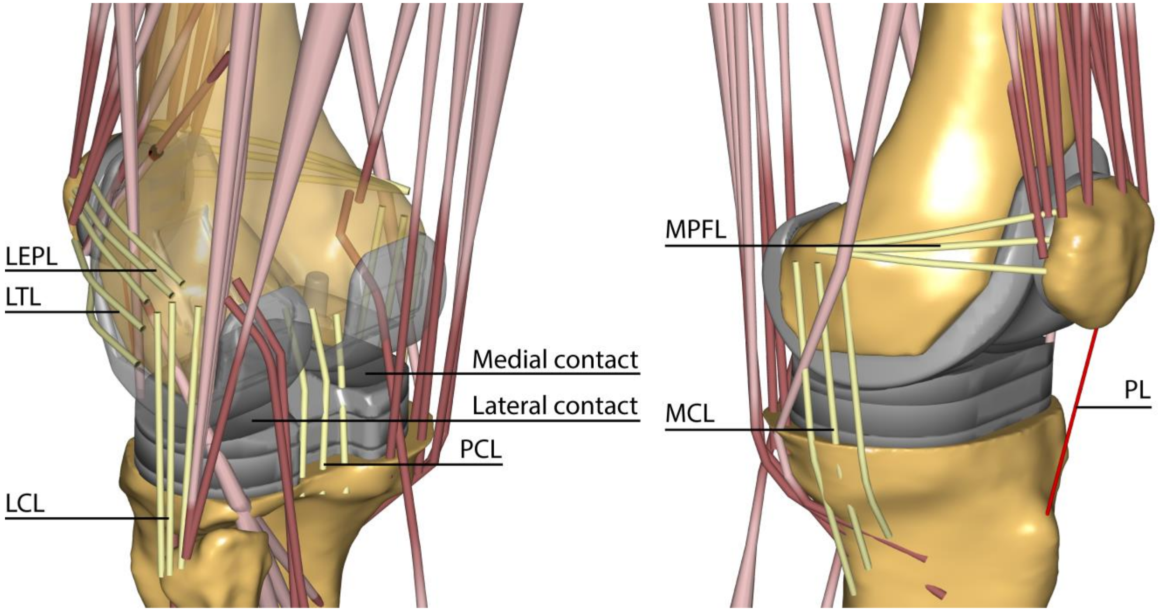
Patient-specific TKA model

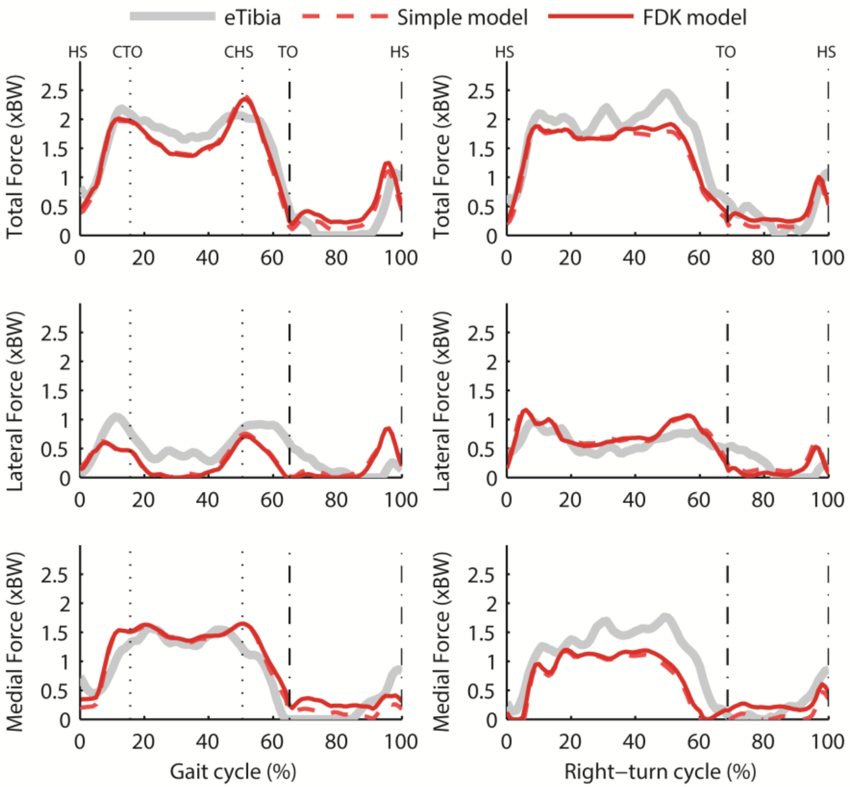
- FDK knee model includes muscles, ligaments, articular contact surfaces

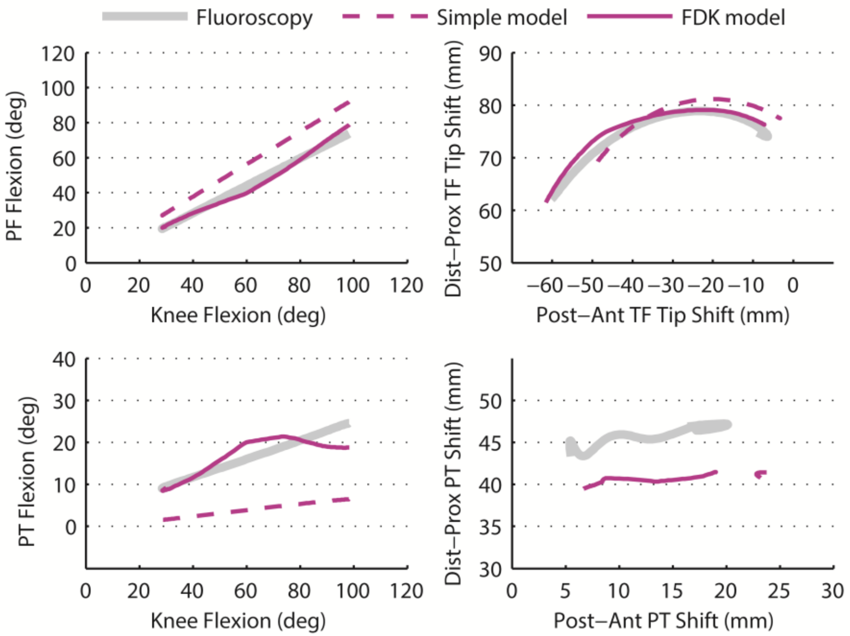


Patient-specific TKA model

- Validation

Fregly and D'Lima[1]

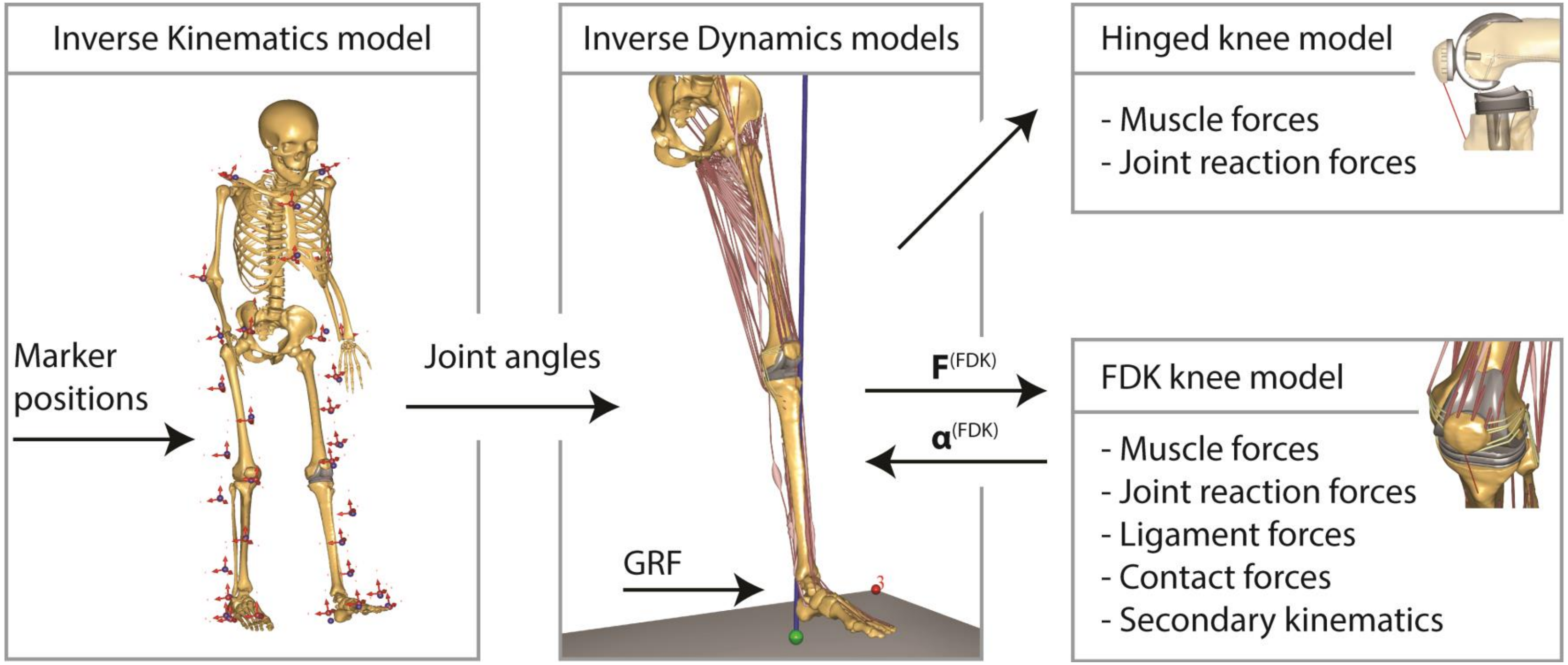




[1]Fregly, B. J., Besier, T. F., Lloyd, D. G., Delp, S. L., Banks, S. A., Pandy, M. G. and D'Lima, D. D. (2012), Grand challenge competition to predict in vivo knee loads. J. Orthop. Res., 30: 503–513. doi:10.1002/jor.22023

Patient-specific TKA model

- Analysis workflow



Patient-specific TKA model

More details…

J Biomech Eng. 2015 Feb 1;137(2):020904. doi: 10.1115/1.4029258. Epub 2015 Jan 26.

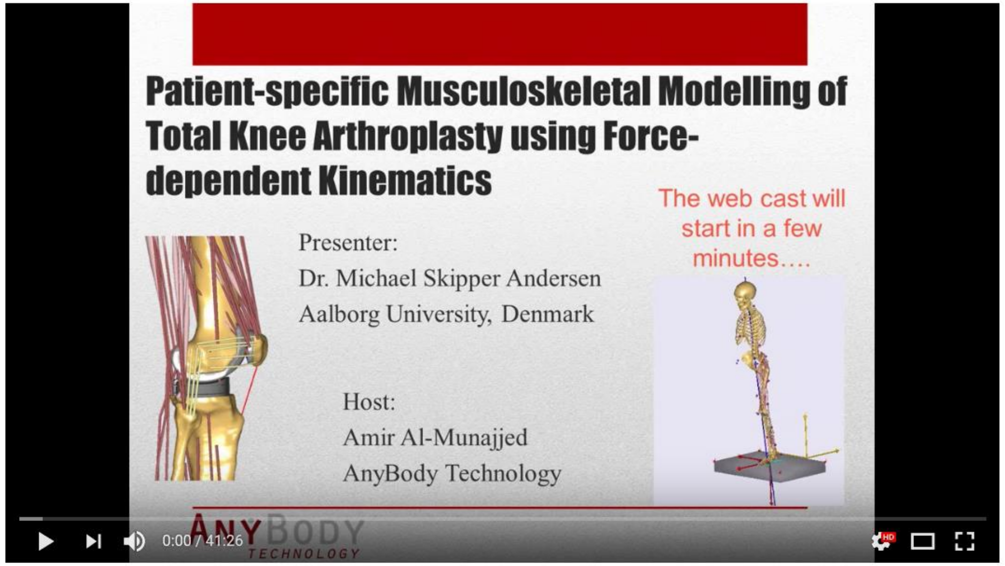
A subject-specific musculoskeletal modeling framework to predict in vivo mechanics of total knee arthroplasty.

Marra MA, Vanheule V, Fluit R, Koopman BH, Rasmussen J, Verdonschot N, Andersen MS.

Abstract

Musculoskeletal (MS) models should be able to integrate patient-specific MS architecture and undergo thorough validation prior to their introduction into clinical practice. We present a methodology to develop subject-specific models able to simultaneously predict muscle, ligament, and knee joint contact forces along with secondary knee kinematics. The MS architecture of a generic cadaver-based model was scaled using an advanced morphing technique to the subject-specific morphology of a patient implanted with an instrumented total knee arthroplasty (TKA) available in the fifth "grand challenge competition to predict in vivo knee loads" dataset. We implemented two separate knee models, one employing traditional hinge constraints, which was solved using an inverse dynamics technique, and another one using an 11-degree-of-freedom (DOF) representation of the tibiofemoral (TF) and patellofemoral (PF) joints, which was solved using a combined inverse dynamic and quasi-static analysis, called force-dependent kinematics (FDK). TF joint forces for one gait and one right-turn trial and secondary knee kinematics for one unloaded leg-swing trial were predicted and evaluated using experimental data available in the grand challenge dataset. Total compressive TF contact forces were predicted by both hinge and FDK knee models with a root-mean-square error (RMSE) and a coefficient of determination (R2) smaller than 0.3 body weight (BW) and equal to 0.9 in the gait trial simulation and smaller than 0.4 BW and larger than 0.8 in the right-turn trial simulation, respectively. Total, medial, and lateral TF joint contact force predictions were highly similar, regardless of the type of knee model used. Medial (respectively lateral) TF forces were over- (respectively, under-) predicted with a magnitude error of M < 0.2 (respectively > -0.4) in the gait trial, and under- (respectively, over-) predicted with a magnitude error of M > -0.4 (respectively < 0.3) in the right-turn trial. Secondary knee kinematics from the unloaded leg-swing trial were overall better approximated using the FDK model (average Sprague and Geers' combined error C = 0.06) than when using a hinged knee model (C = 0.34). The proposed modeling approach allows detailed subject-specific scaling and personalization and does not contain any nonphysiological parameters. This modeling framework has potential applications in aiding the clinical decision-making in orthopedics procedures and as a tool for virtual implant design.

PMID: 25429519 DOI: 10.1115/1.4029258
[Indexed for MEDLINE]



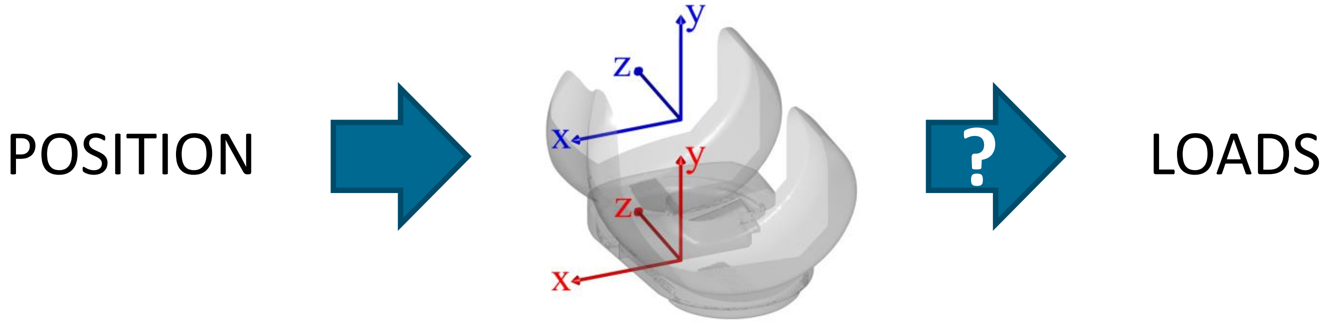
[Webcast] GrandChallenge Knee: Patient-Specific Musculoskeletal Modelling Of Total Knee Arthroplasty

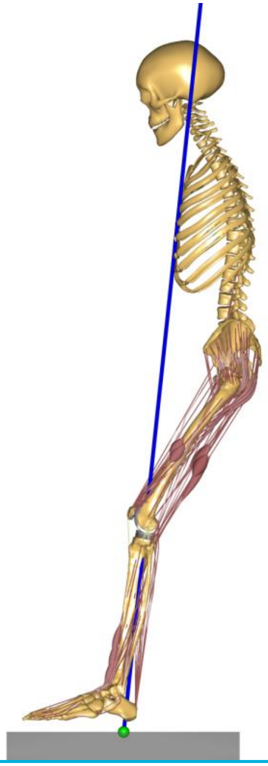
AnyBody Webcast 9 Sep 2014
by Dr. M. Skipper Andersen

Surrogate contact modeling

- Calculation of joint contact forces is time-intensive
  - time spent on closest-point algorithm

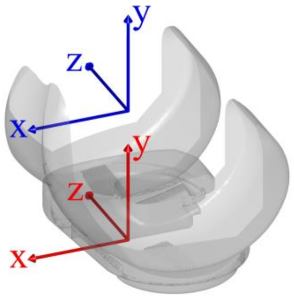
- Can we use a surrogate contact model instead?



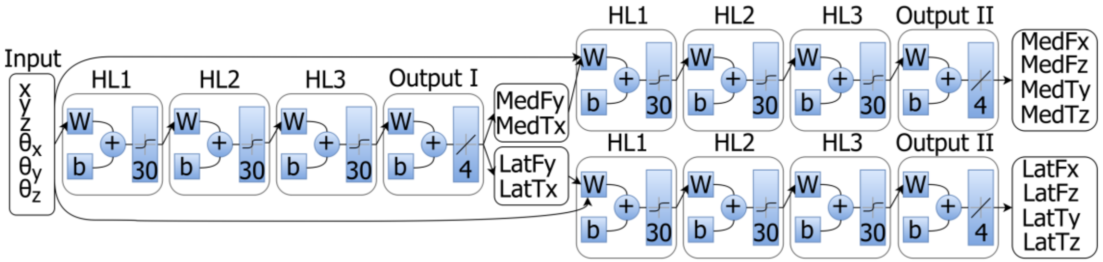


Surrogate contact modeling

Sampling → Training & Testing → Deploy → Evaluation

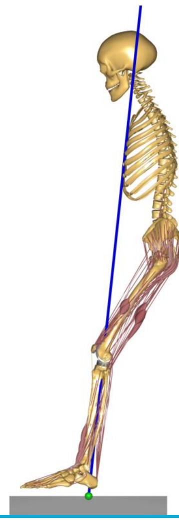


AnyBody



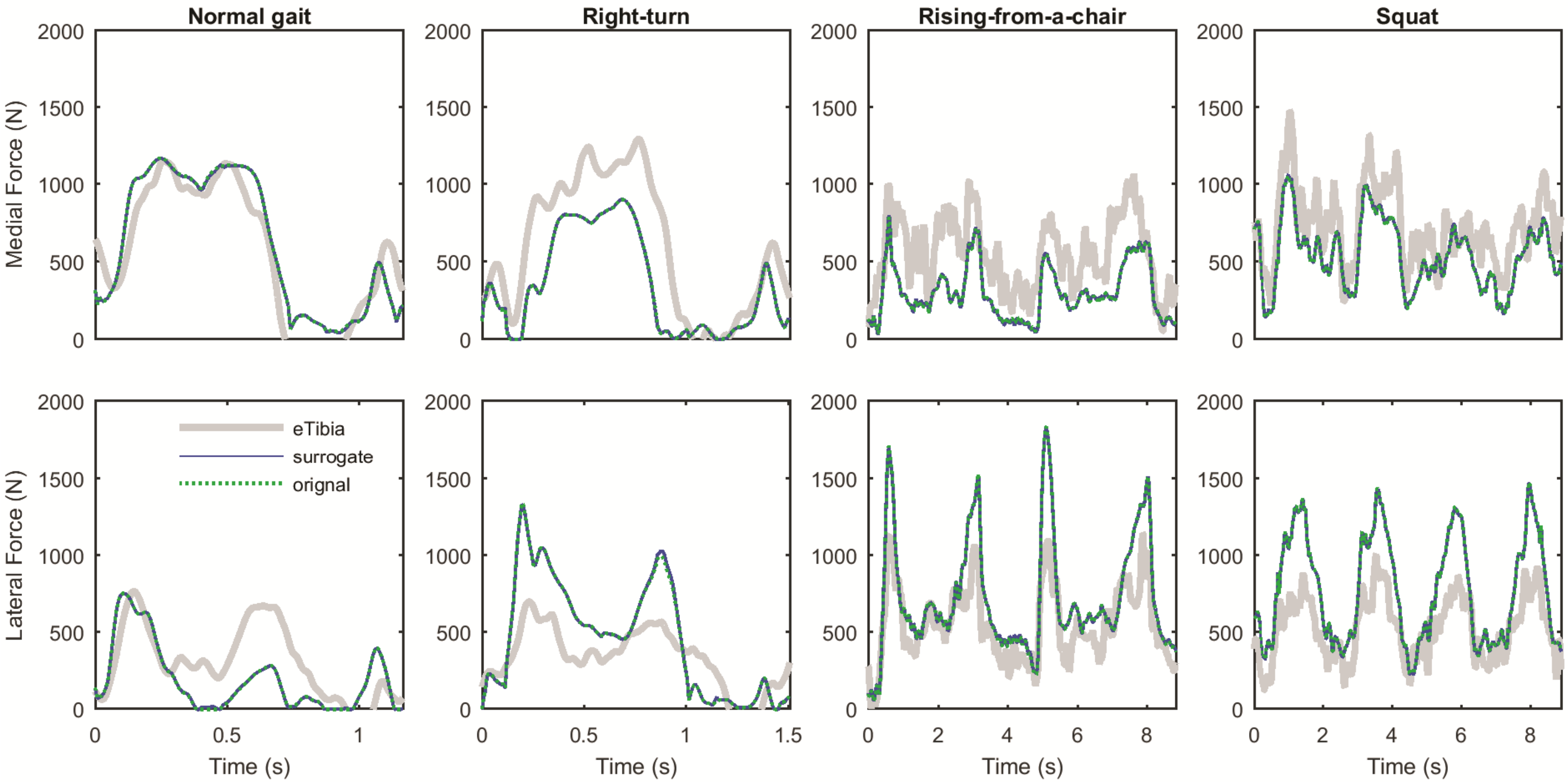
MATLAB Neural Network Toolbox

C++ DLL/
AnyBody
class template



Results

- Accuracy of tibiofemoral forces



Results

- Computation time

	Reference model	Surrogate model	Acceleration
Overground gait	13.6 min	4.5 min	3.0×
Right-turn gait	22.7 min	7.3 min	3.1×
Chair-rising	70.3 min	27.2 min	2.6×
Squat	96.4 min	38.5 min	2.5×

Discussion

- 3× faster FDK analysis w/ surrogate model
- As accurate as reference model

J Biomech Eng. 2017 Aug 1;139(8). doi: 10.1115/1.4036605.

Evaluation of a Surrogate Contact Model in Force-Dependent Kinematic Simulations of Total Knee Replacement.

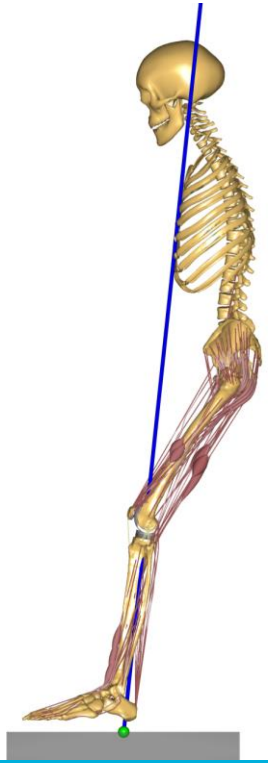
Marra MA[1], Andersen MS[2], Damsgaard M[3], Koopman BFJM[4], Janssen D[5], Verdonschot N[6].

Author information

Abstract

Knowing the forces in the human body is of great clinical interest and musculoskeletal (MS) models are the most commonly used tool to estimate them in vivo. Unfortunately, the process of computing muscle, joint contact, and ligament forces simultaneously is computationally highly demanding. The goal of this study was to develop a fast surrogate model of the tibiofemoral (TF) contact in a total knee replacement (TKR) model and apply it to force-dependent kinematic (FDK) simulations of activities of daily living (ADLs). Multiple domains were populated with sample points from the reference TKR contact model, based on reference simulations and design-of-experiments. Artificial neural networks (ANN) learned the relationship between TF pose and loads from the medial and lateral sides of the TKR implant. Normal and right-turn gait, rising-from-a-chair, and a squat were simulated using both surrogate and reference contact models. Compared to the reference contact model, the surrogate contact model predicted TF forces with a root-mean-square error (RMSE) lower than 10 N and TF moments lower than 0.3 N·m over all simulated activities. Secondary knee kinematics were predicted with RMSE lower than 0.2 mm and 0.2 deg. Simulations that used the surrogate contact model ran on average three times faster than those using the reference model, allowing the simulation of a full gait cycle in 4.5 min. This modeling approach proved fast and accurate enough to perform extensive parametric analyses, such as simulating subject-specific variations and surgical-related factors in TKR.

PMID: 28462424 DOI: 10.1115/1.4036605



Clinical applications

Sint Maartenskliniek

dr. A. Wymenga
dr. P. Heesterbeek

Radboudumc
Orthopaedic Research Lab

Marco Marra
Marta Strzelczak
dr. ir. Dennis Janssen
prof. dr. ir. Nico Verdonschot

Collaboration

Radboudumc
Orthopedie

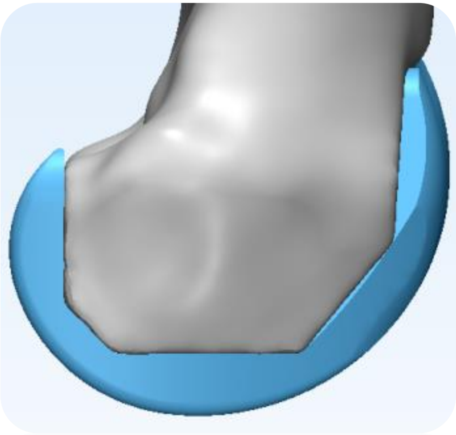
dr. ing. Sebastiaan van de Groes

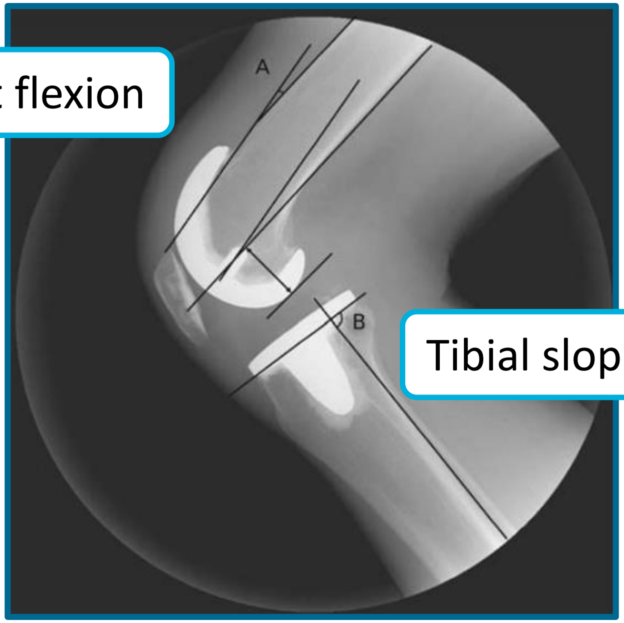
UNIVERSITY OF TWENTE.

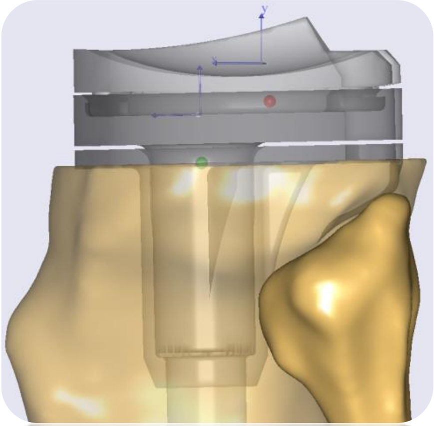
prof. dr. ir. Bart Koopman

Clinical applications

- Sagittal alignment

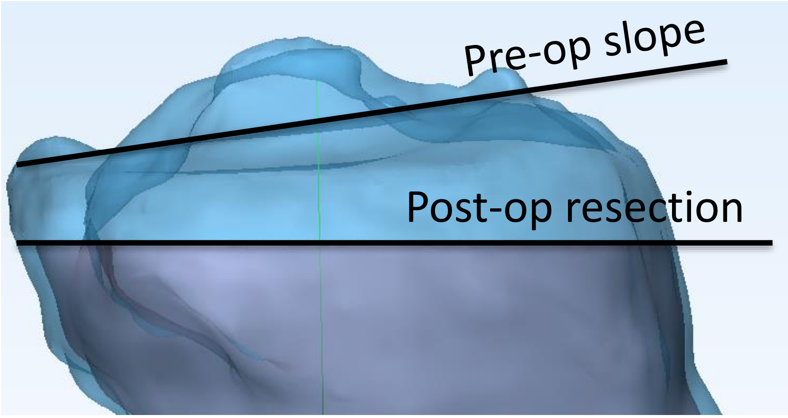


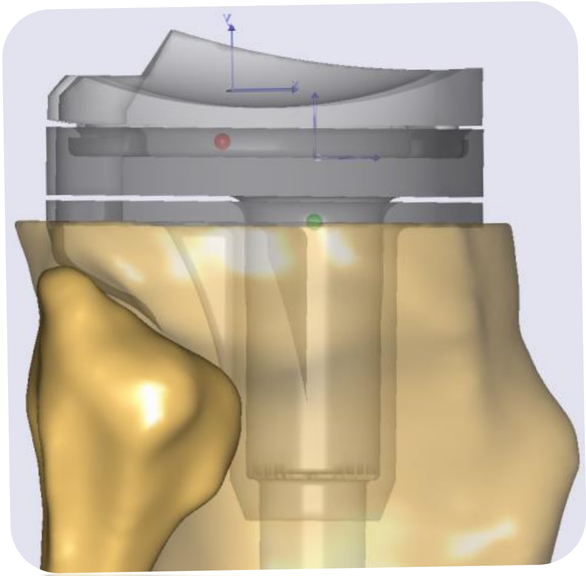




Tibial slope

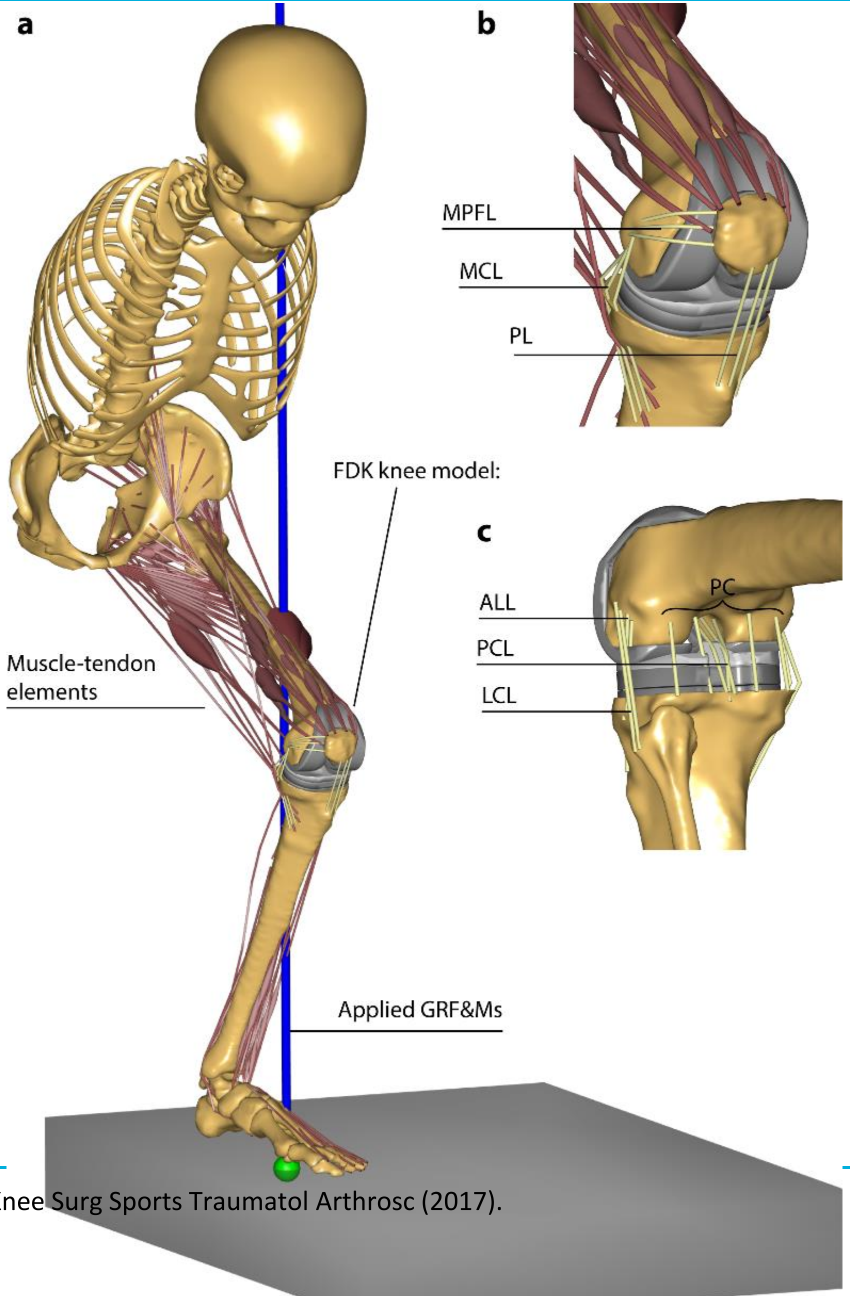
- Insufficient tibia slope often results in tight flexion gap
- What is the effect of increasing slope on flexion gap?





Tibial slope

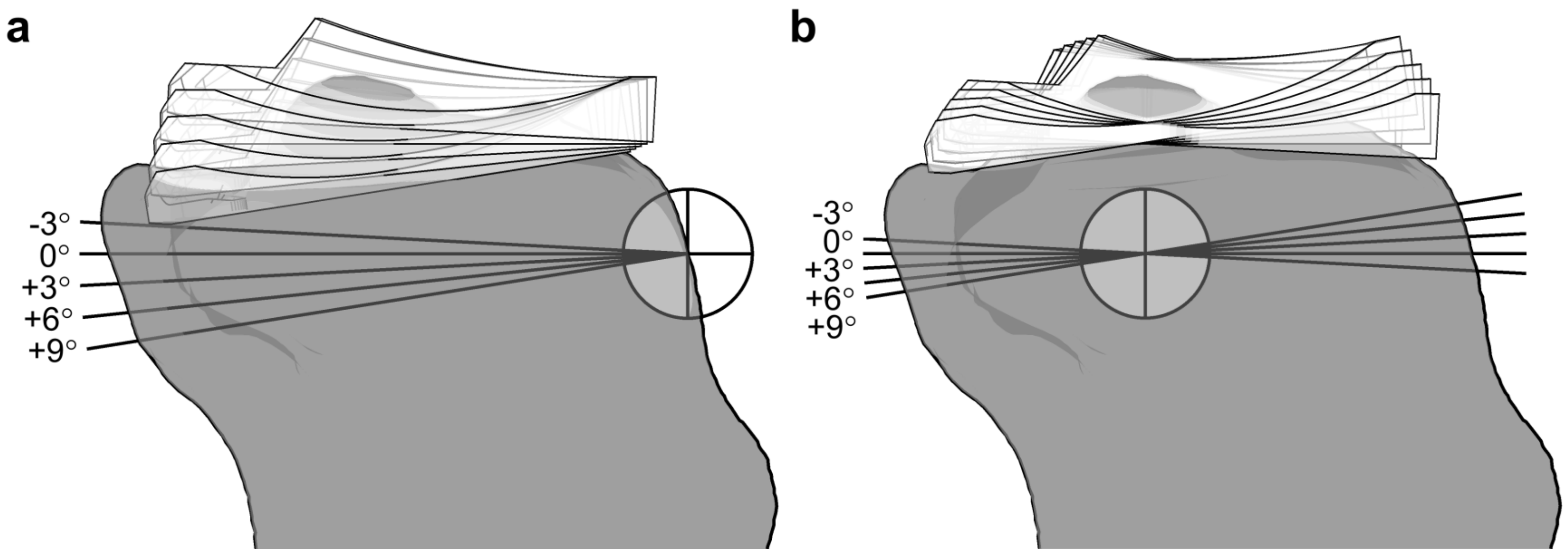
- Patient-specific TKA model



Marra, M.A., Strzelczak, M., Heesterbeek, P.J.C. et al. Knee Surg Sports Traumatol Arthrosc (2017).
https://doi.org/10.1007/s00167-017-4561-3

Tibial slope

- Parametric study



ACR: Anterior tibial cortex-referencing **CPR**: Centre of tibial plateau-referencing

Marra, M.A., Strzelczak, M., Heesterbeek, P.J.C. et al. Knee Surg Sports Traumatol Arthrosc (2017).
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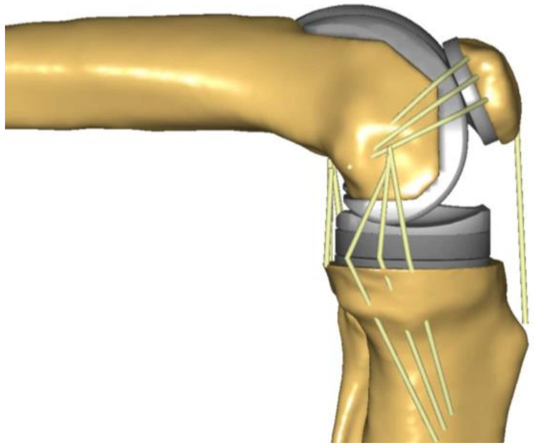
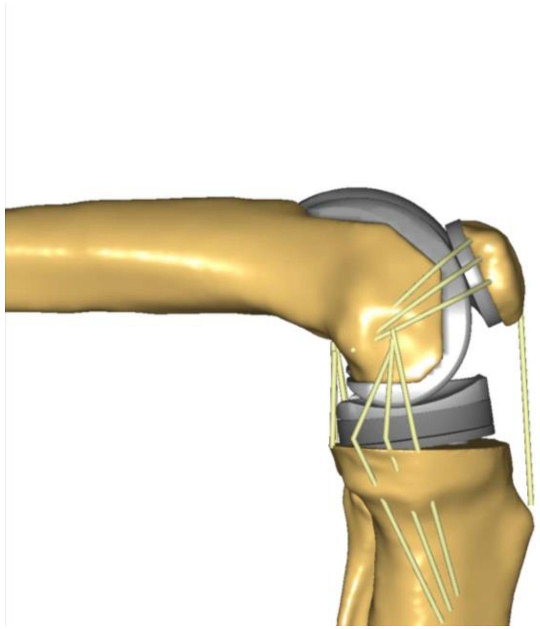
Tibial slope

- Laxity tests 0°-90° knee flexion (A-P 70 N, V-V 15 Nm)

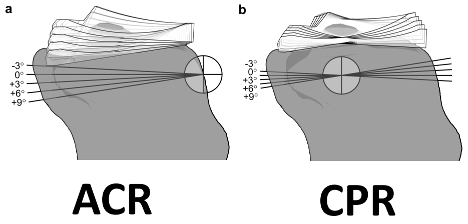


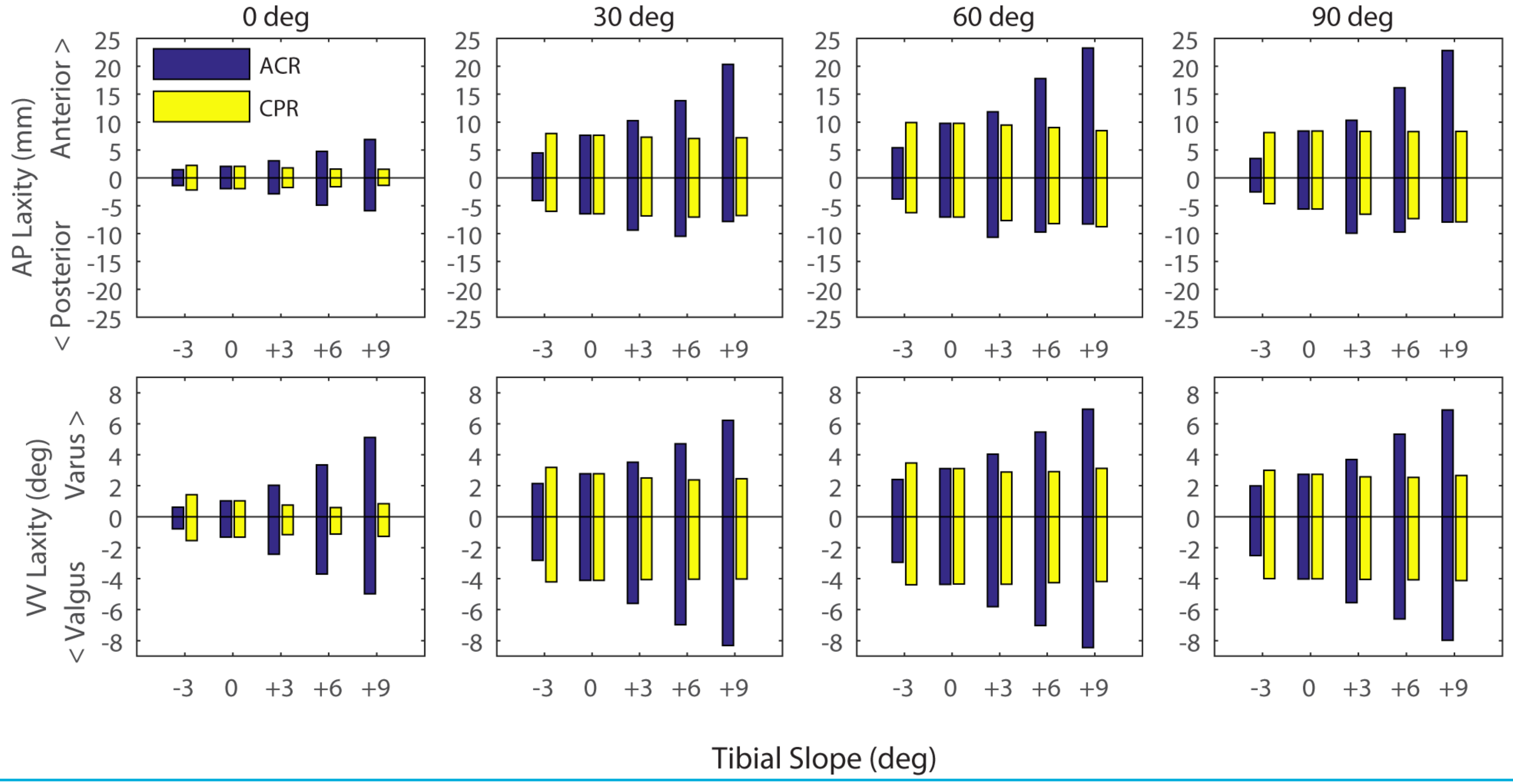
No slope



+9° CPR

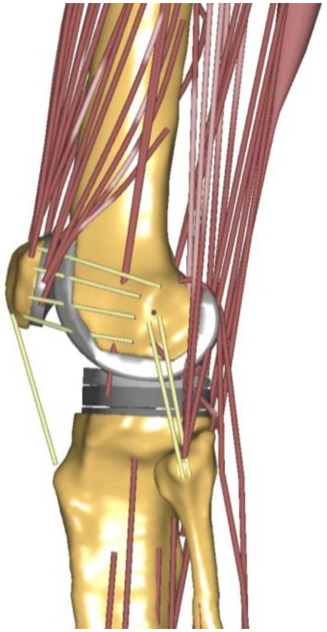
Results


a
b
ACR
CPR


0 deg
30 deg
60 deg
90 deg
ACR
CPR
AP Laxity (mm)
< Posterior
Anterior >
25
20
15
10
5
0
-5
-10
-15
-20
-25
-3
0
+3
+6
+9
VV Laxity (deg)
< Valgus
Varus >
8
6
4
2
0
-2
-4
-6
-8
Tibial Slope (deg)

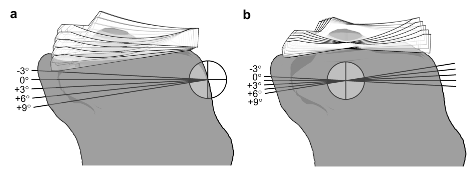
Tibial slope

- FDK analysis of squat[1]

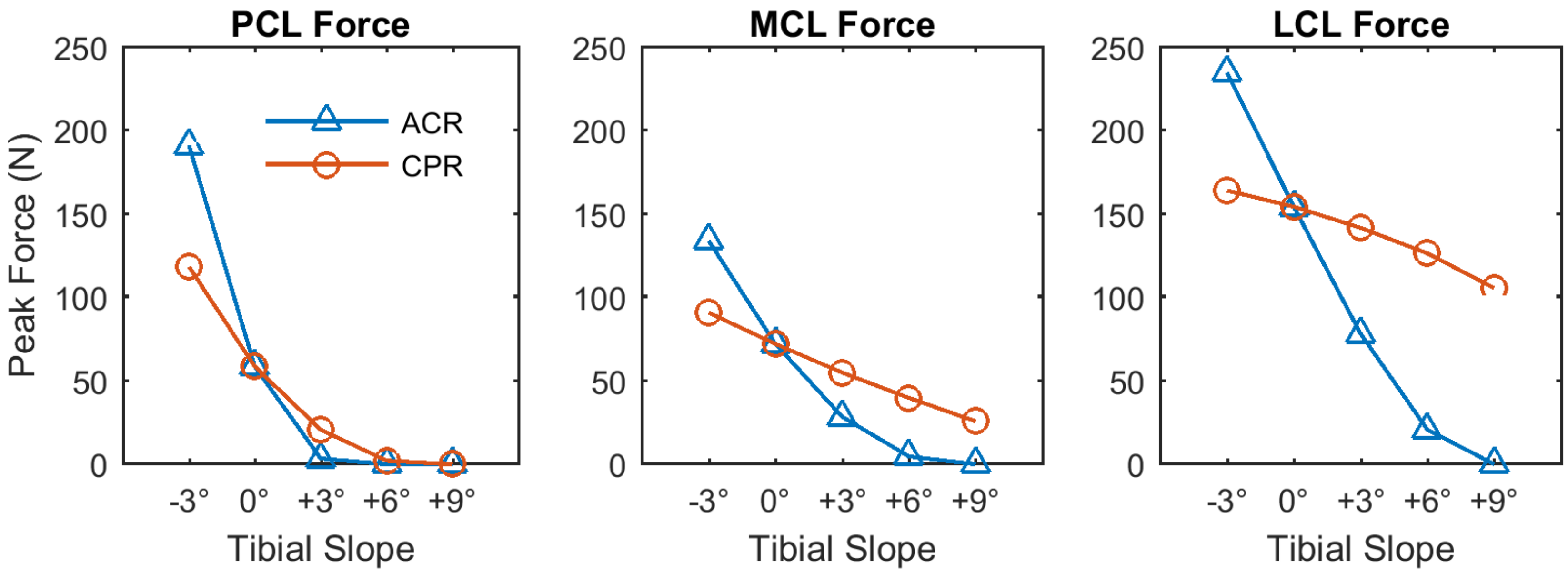


[1]Fregly, B. J., Besier, T. F., Lloyd, D. G., Delp, S. L., Banks, S. A., Pandy, M. G. and D'Lima, D. D. (2012), Grand challenge competition to predict in vivo knee loads. J. Orthop. Res., 30: 503–513. doi:10.1002/jor.22023

Results

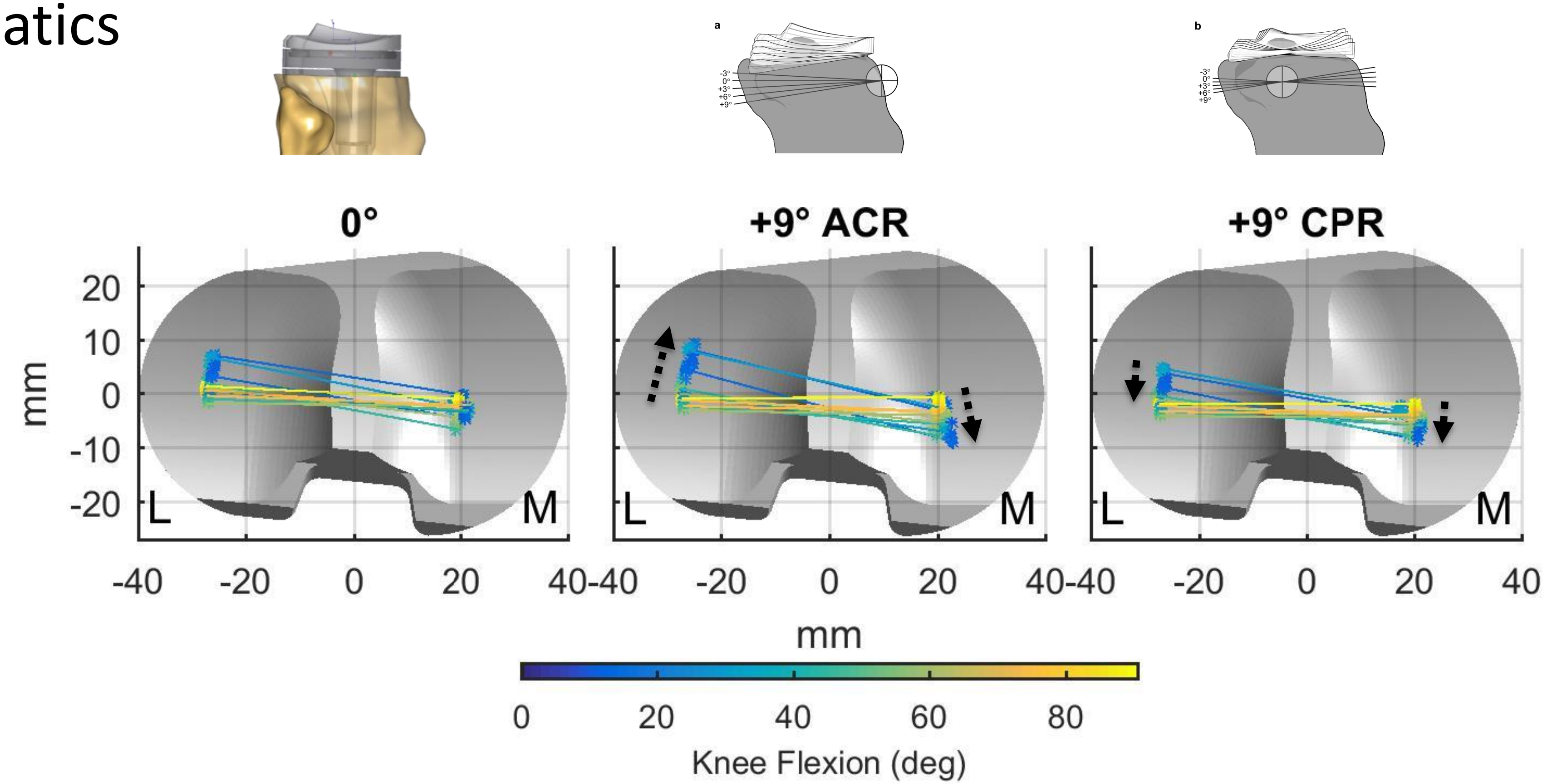


- Ligament forces



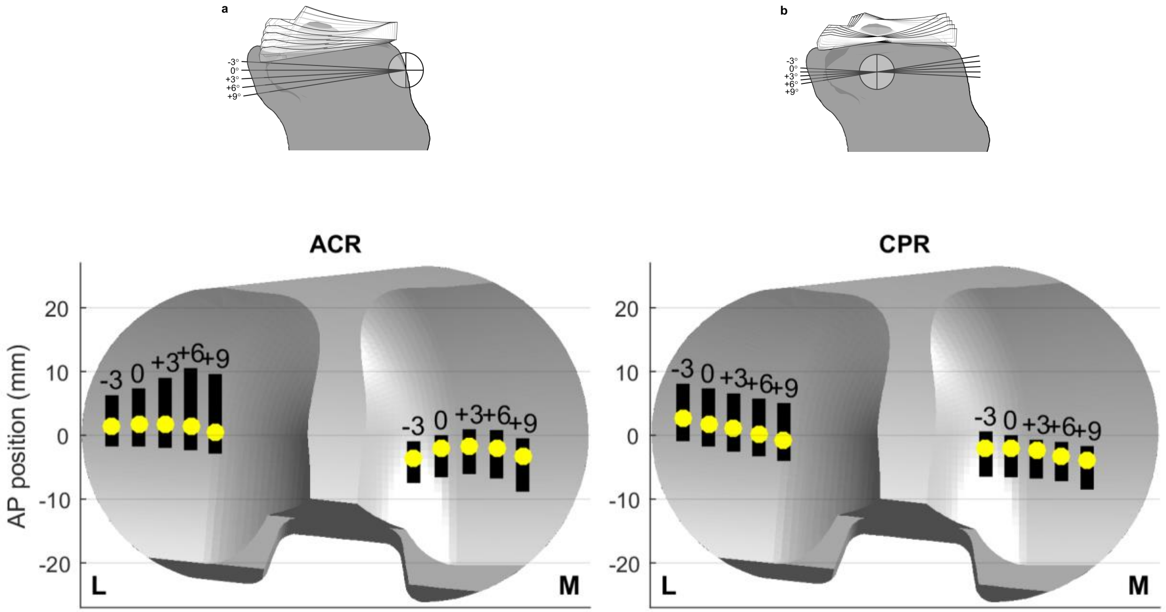
Results

- Kinematics



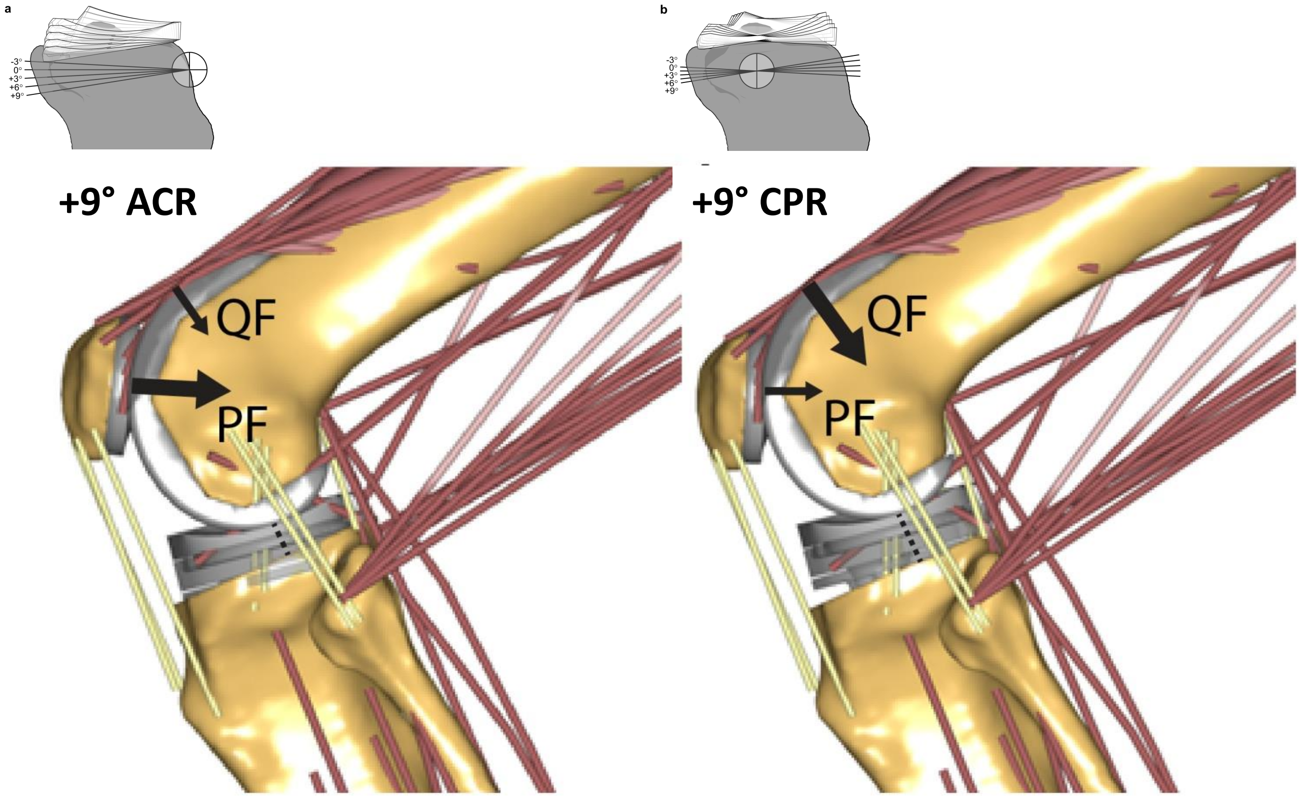
Results

- Kinematics



Results

- Knee loads



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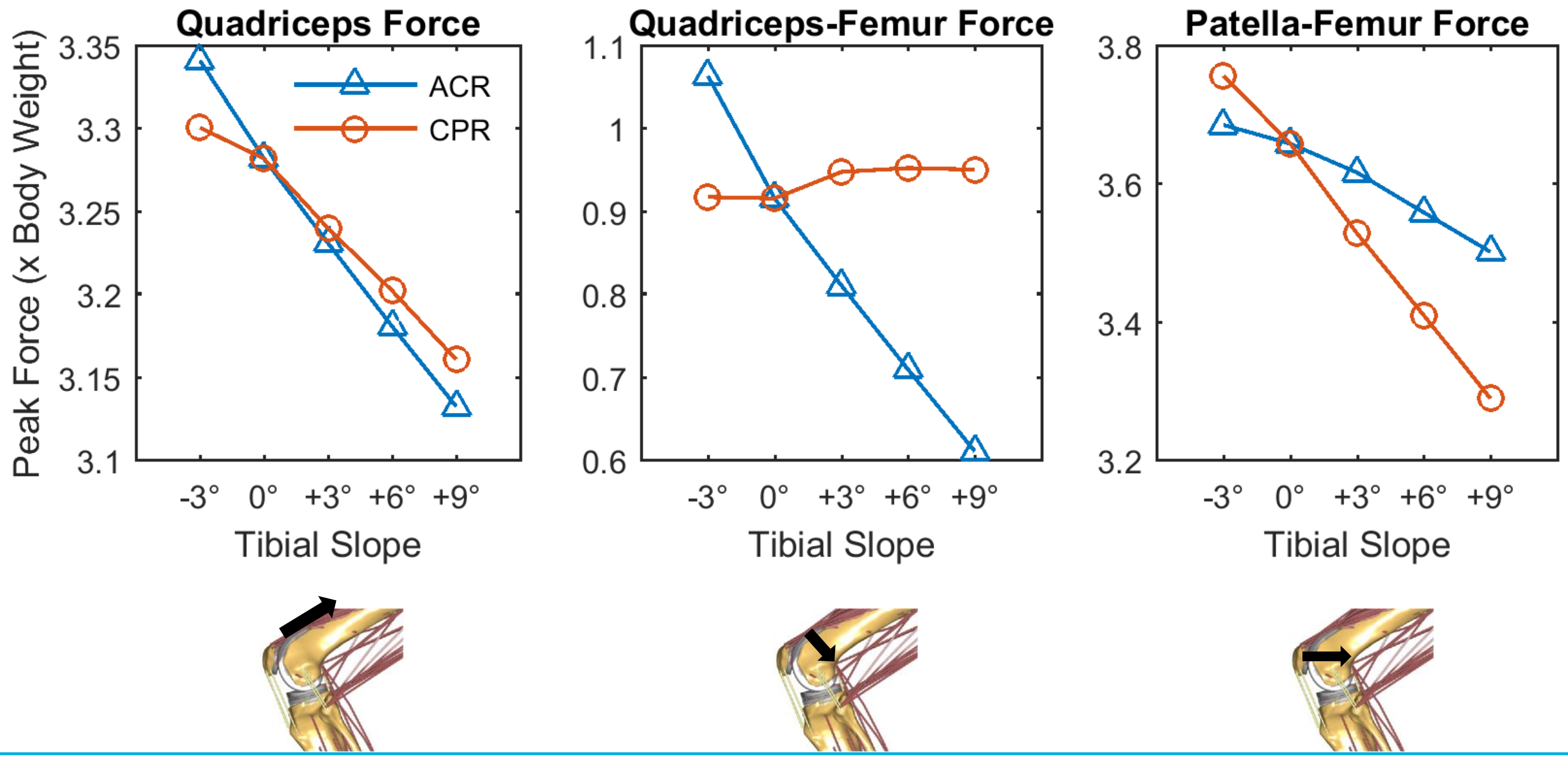
Results

- Knee loads



Discussion

- Large effects of tibial slope with ACR on **laxity** and **kinematics**
- Higher slope with CPR is **more stable** and reduces **PF loads** more
- Tibial slope better planned in advance with CPR

Knee Surg Sports Traumatol Arthrosc
DOI 10.1007/s00167-017-4561-3

KNEE

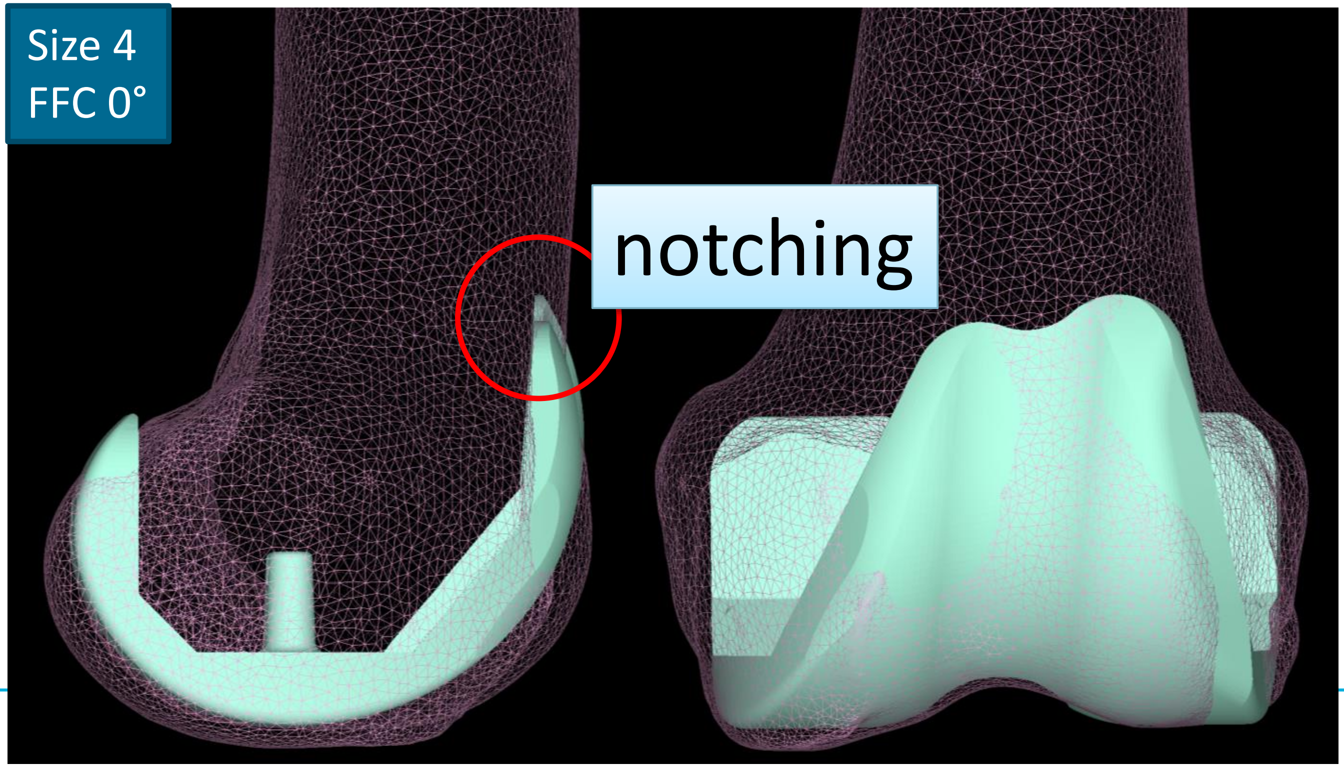
Anterior referencing of tibial slope in total knee arthroplasty considerably influences knee kinematics: a musculoskeletal simulation study

Marco A. Marra[1] · Marta Strzelczak[1] · Petra J. C. Heesterbeek[2] · Sebastiaan A. W. van de Groes[3] · Dennis W. Janssen[1] · Bart F. J. M. Koopman[4] · Ate B. Wymenga[5] · Nico J. J. Verdonschot[1,4]

Received: 2 December 2016 / Accepted: 26 April 2017

Femoral component flexion

- A small femoral component may result in anterior notching
- Can we flex the component to prevent it? What are the effects?



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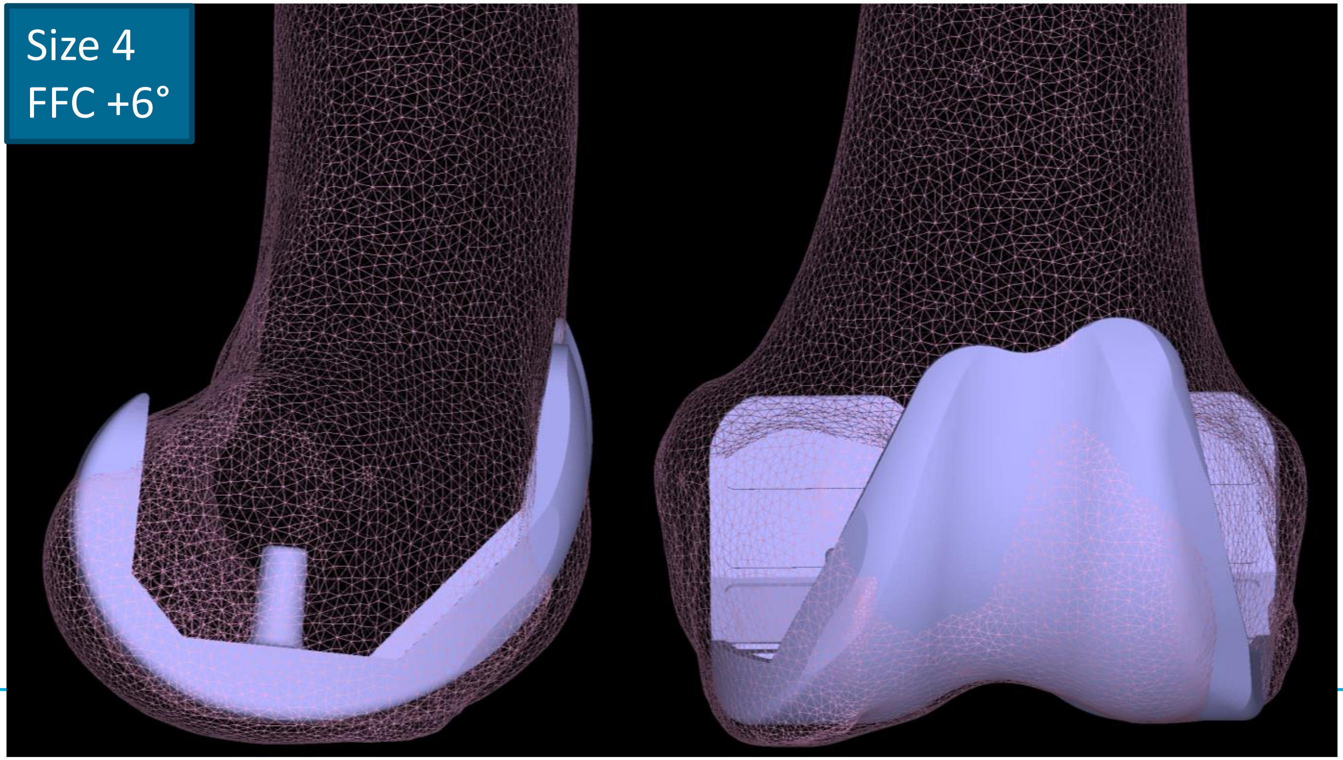
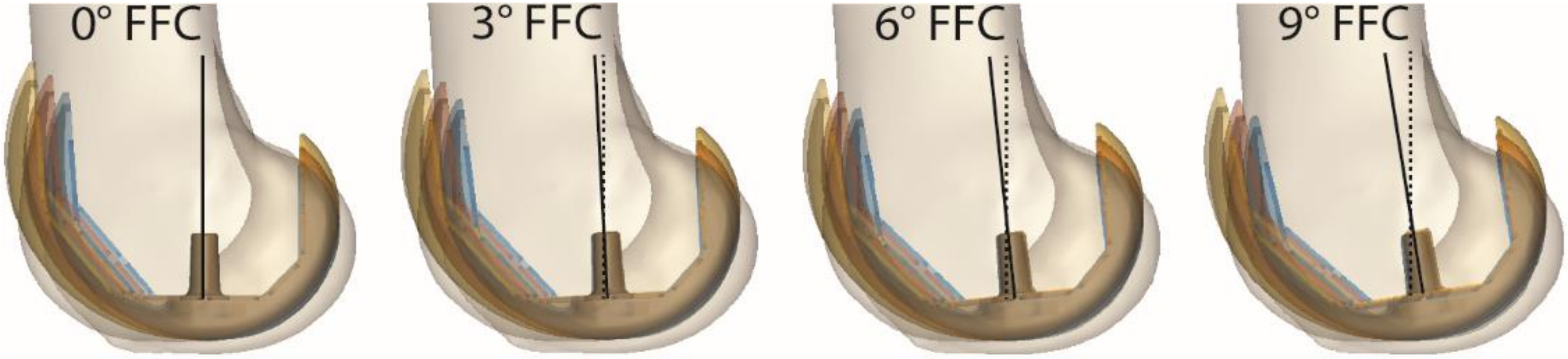


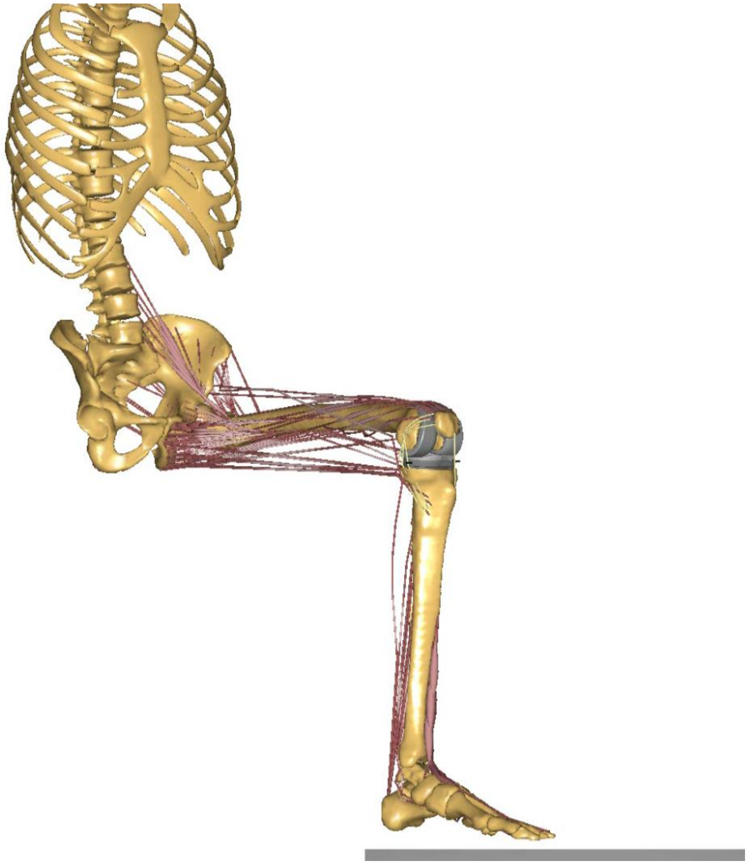
Femoral component flexion

- Parametric study (size + flexion)



Femoral component flexion

- FDK analysis of chair-rising[1]



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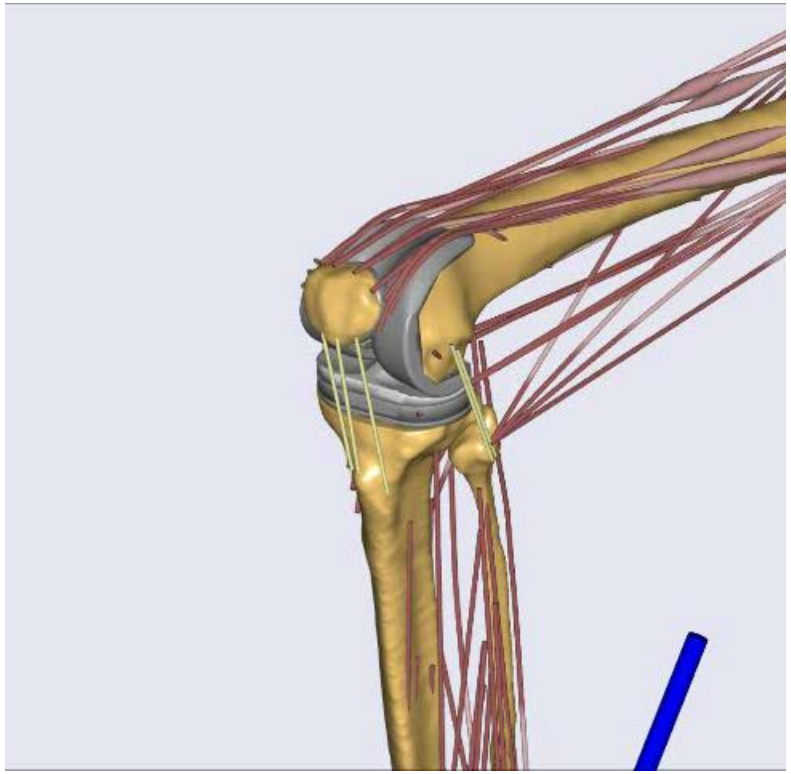
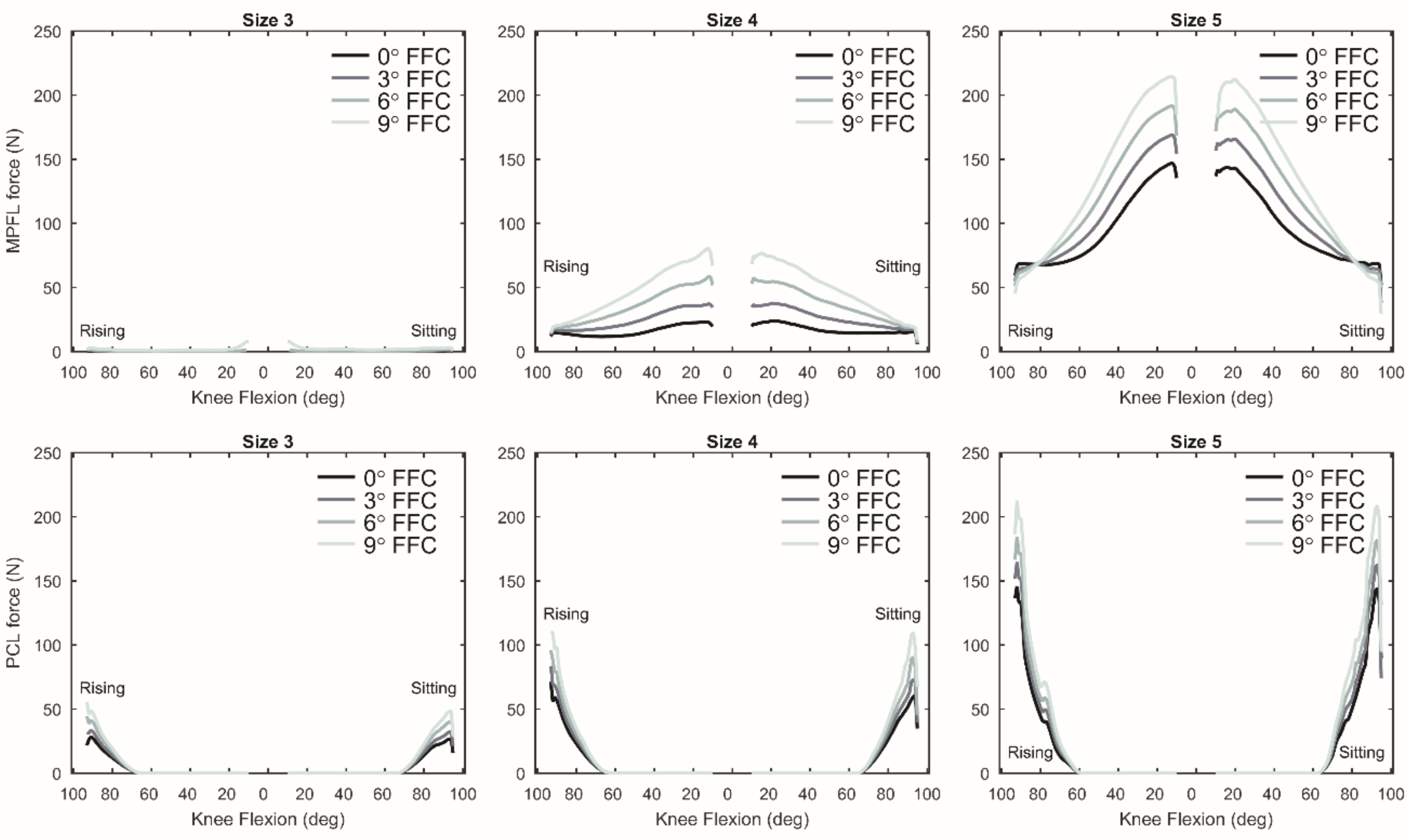
Femoral component flexion



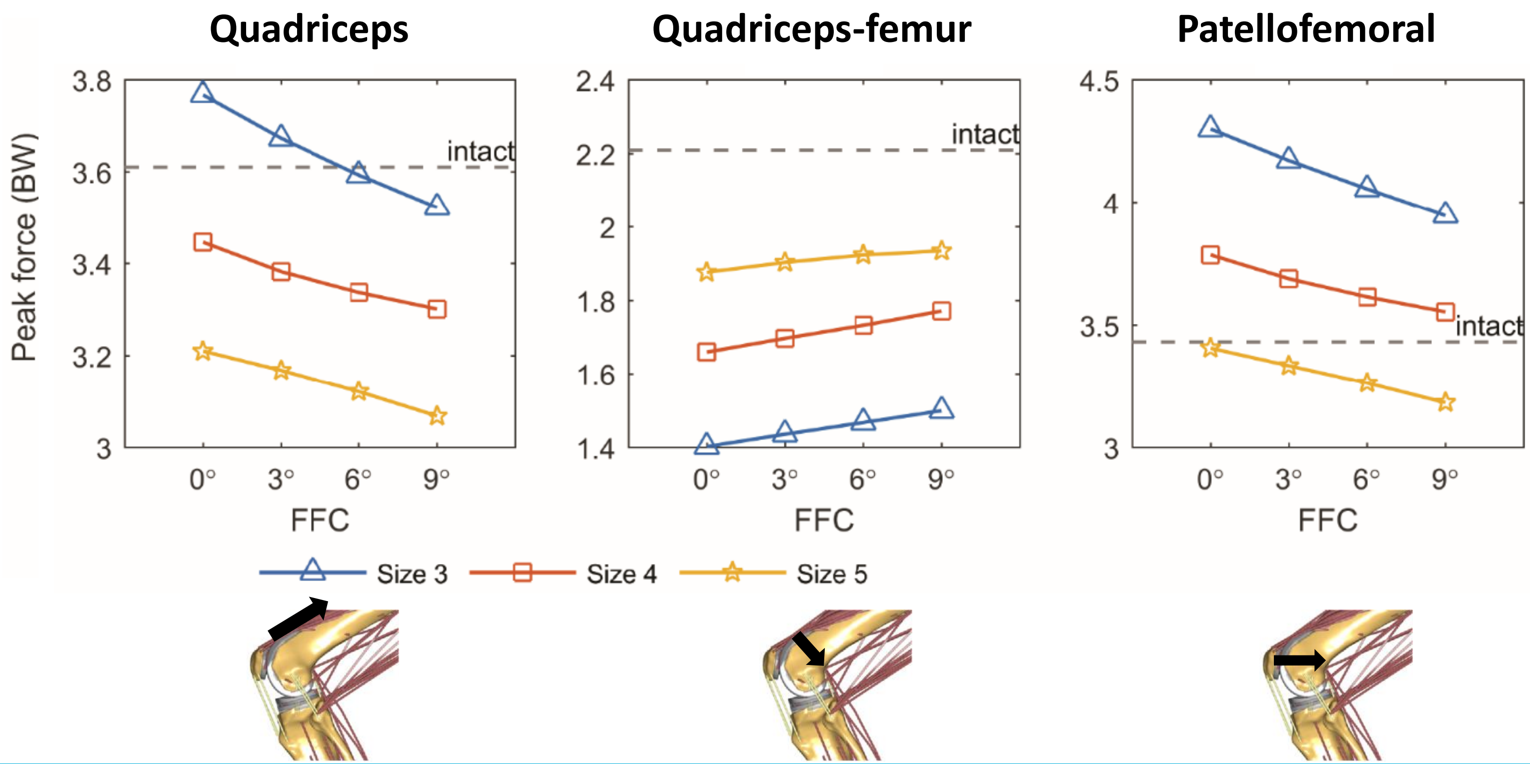
Results

- Ligament forces



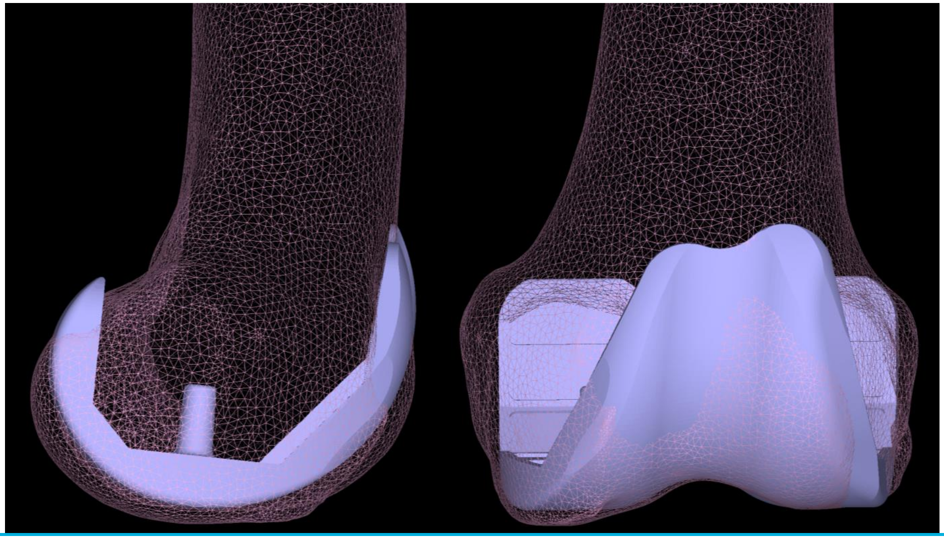
Results

- Knee loads



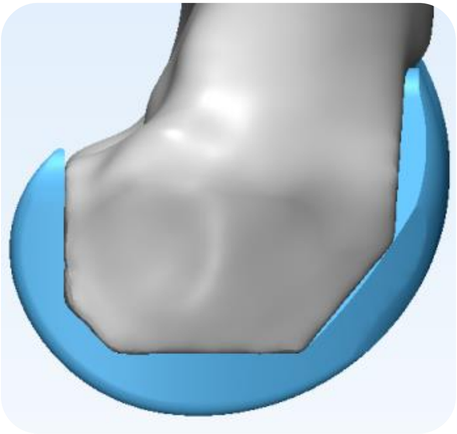
Discussion

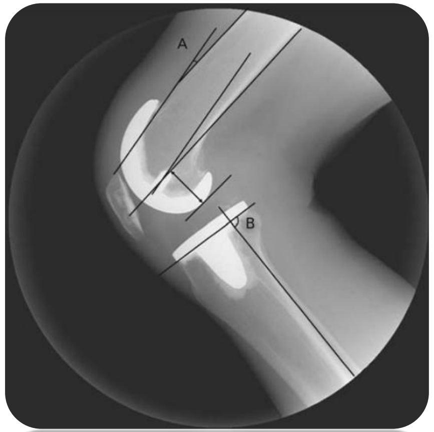
- More flexion leads better **quadriceps-femur load sharing**
  - less stress on the patellofemoral joint → less pain
- Down-sizing + flexing ≈ up-sized no flexion w/o anterior notching!

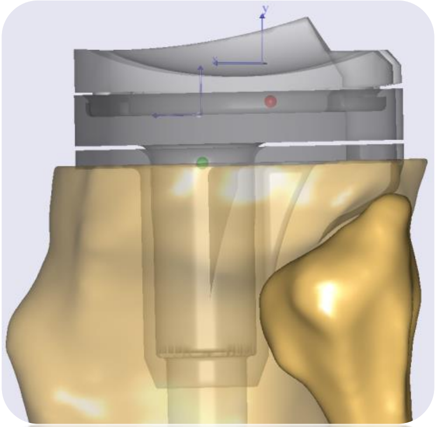


General limitations

- One cruciate-retaining TKA design only
- Does not account for anatomical variability



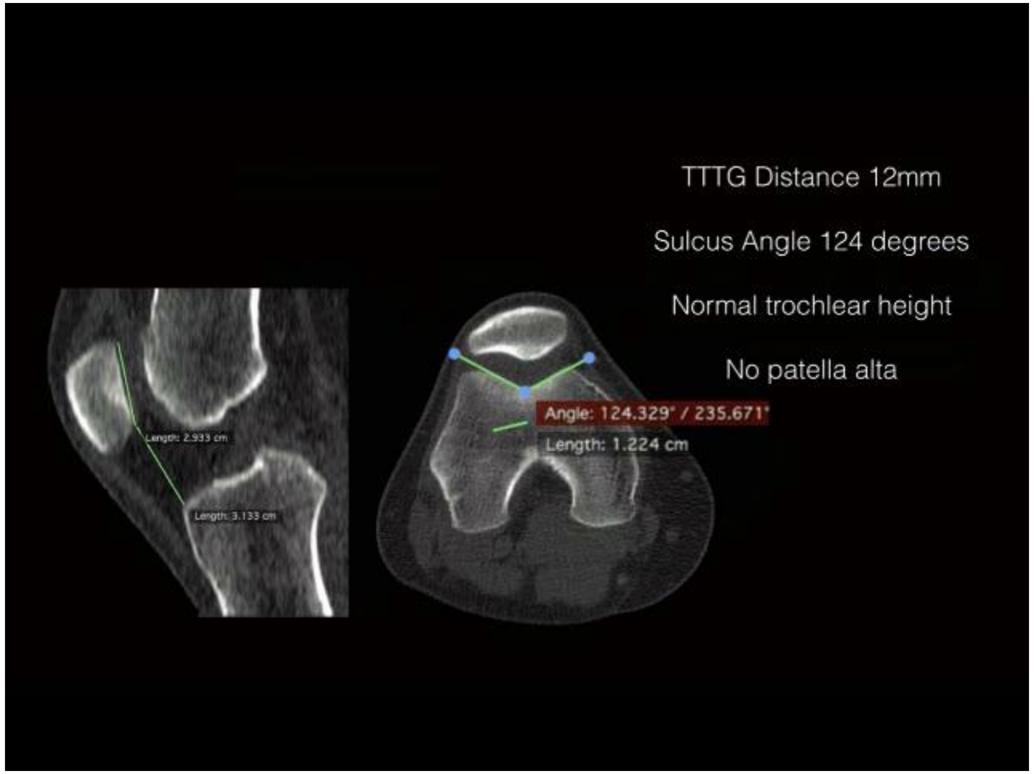




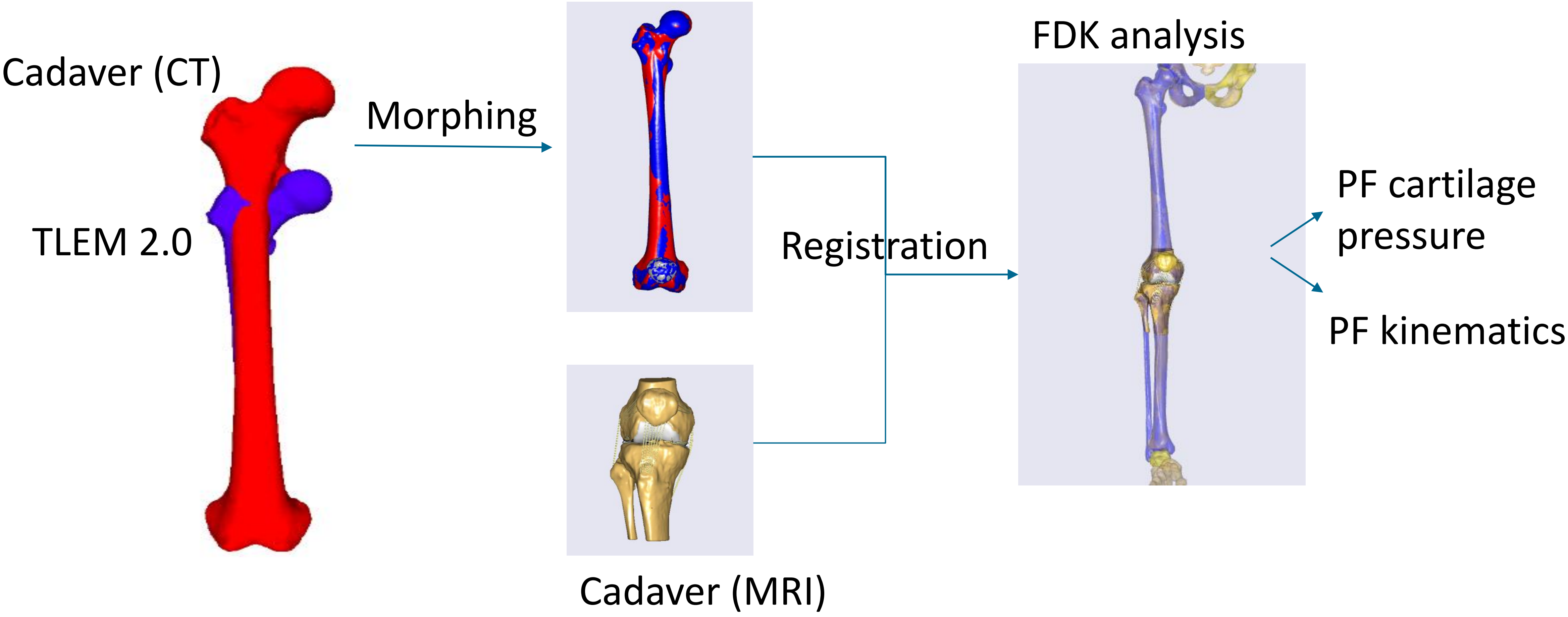
Patellofemoral instability

- Epidemiology
  - 20.000 per year in US
  - 69% in age 10-19

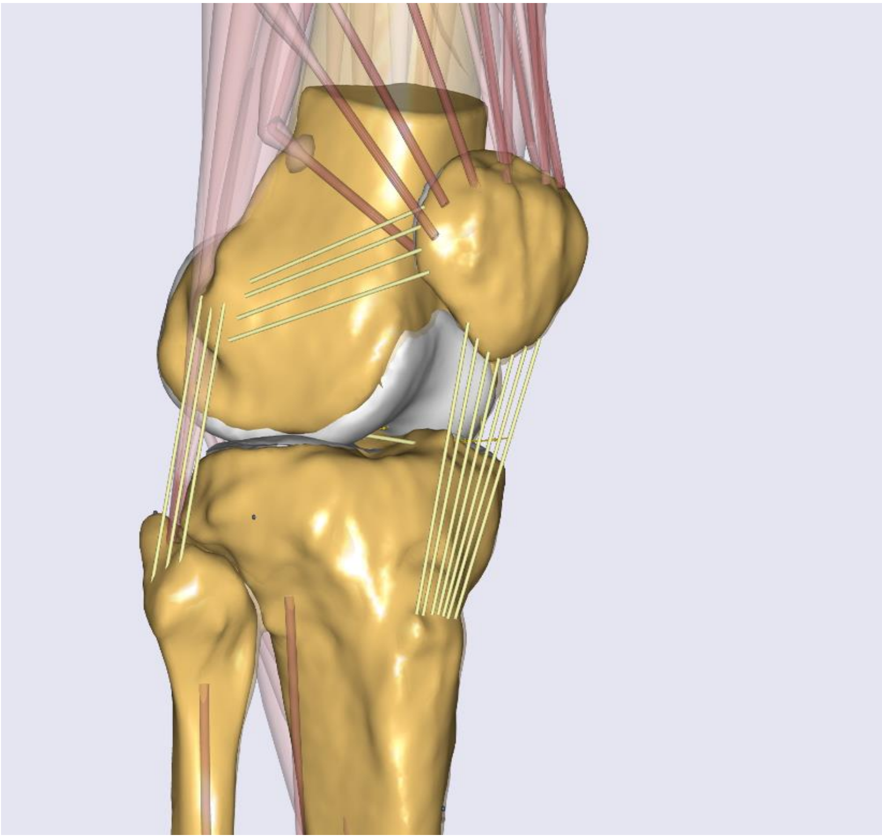
- Risk factors
  - Trochlear dysplasia (TD)
  - MPFL laxity
  - VMO Deficiency
  - Patella Alta
  - Increased Q-angle



Specimen-specific model



Specimen-specific model



Tibiofemoral joint

- 5 DoFs FDK + 1 DoF driven (F/E)

Patellofemoral joint

- 6 DoFs FDK

4 Contact pairs:

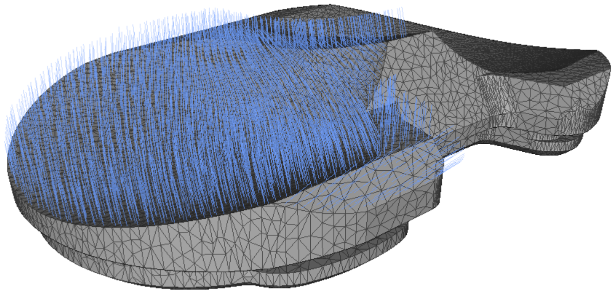
- ACTibiaMed-ACFemur
- ACTibiaLat-ACFemur
- ACPatella-ACFemur
- ACPatella-FEmur

Articular contact model

- Elastic foundation (EF) theory

$$\sigma_n = \sigma_n(u_n) = \frac{(1-\nu)E}{(1+\nu)(1-2\nu)} \frac{u_n}{b}$$

$$\varepsilon_n = \varepsilon_n(u_n) = \frac{u_n}{b}$$



σ_n normal surface stress
u_n normal surface displacement

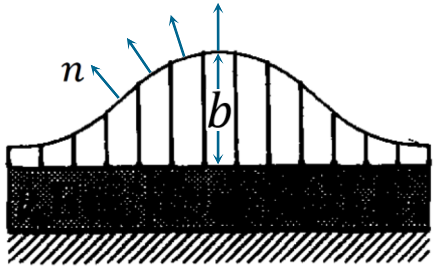
ε_n normal surface strain

<u>Material parameters</u>

ν Poisson's ratio
E Young modulus

<u>Geometrical parameters</u>

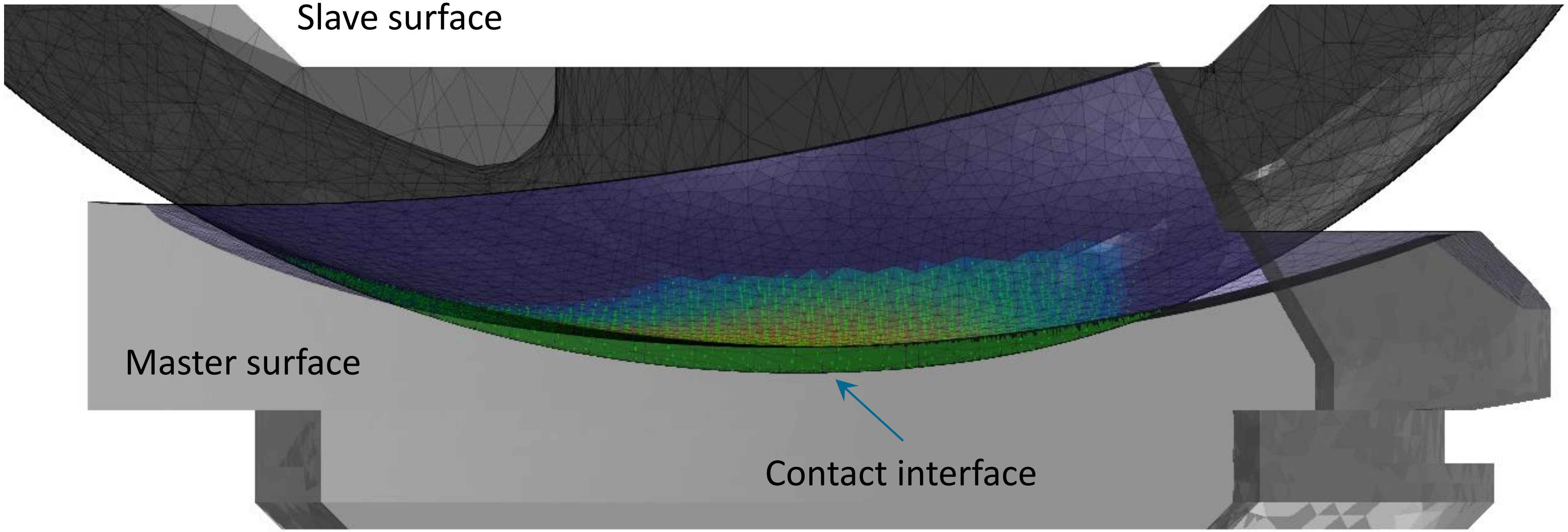
b surface thickness



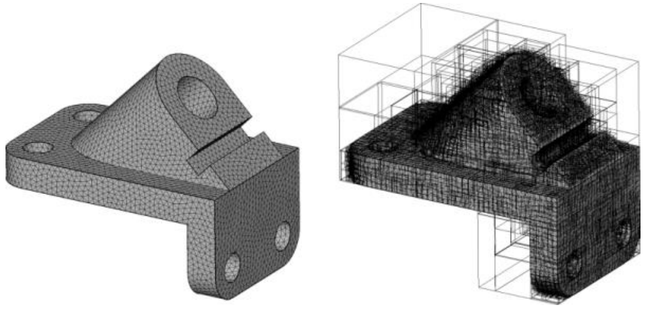
L. Blankevoort, J.H. Kuiper, R. Huiskes, H.J. Grootenboer (1991), Articular contact in a three-dimensional model of the knee, Journal of Biomechanics, Volume 24, Issue 11, 1019-1031, https://doi.org/10.1016/0021-9290(91)90019-J

Proof of concept

- Example: tibial insert in contact with femoral component

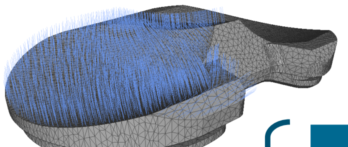


Proof of concept

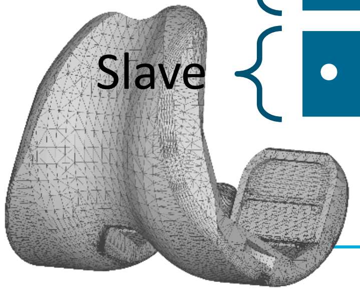


- Implemented using AABB Tree CGAL
  - 3D Fast Intersection and Distance Computation

Load-time



Master
- Compute thickness — b
- Compute area — A



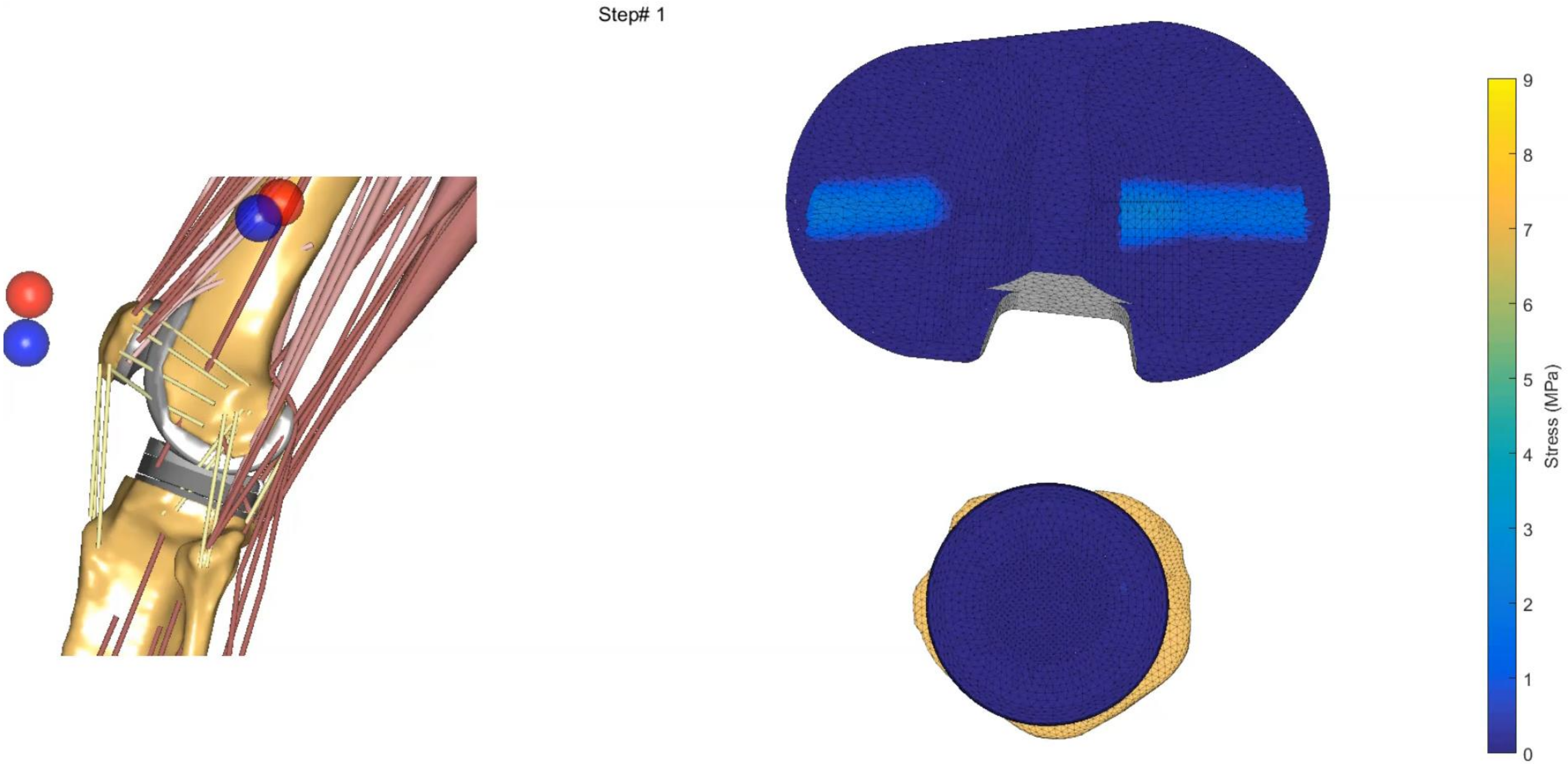
Slave
- Build AABB tree

Run-time

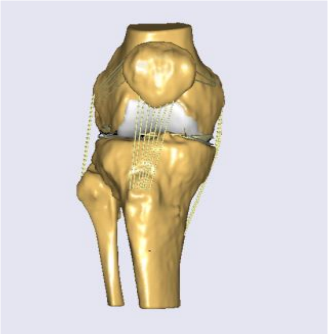
$$\sigma_n = \sigma_n(u_n) = \frac{(1-\nu)E}{(1+\nu)(1-2\nu)} \frac{u_n}{b}$$

$$\int \sigma_n \, \mathrm{d}A$$

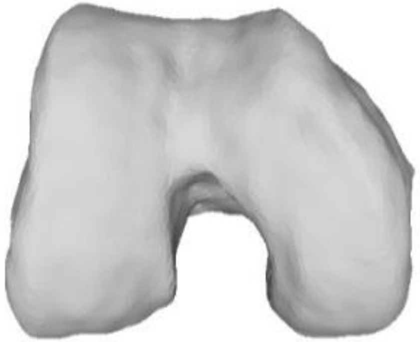
Distance query (u_n) → Contact pressures (σ_n) → Net contact forces (F)


Step# 1
9
8
7
6
5
4
3
2
1
0
Stress (MPa)

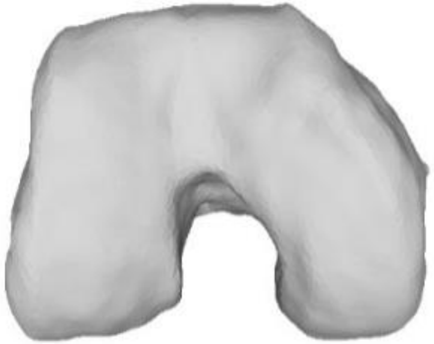
Trochlear dysplasia model



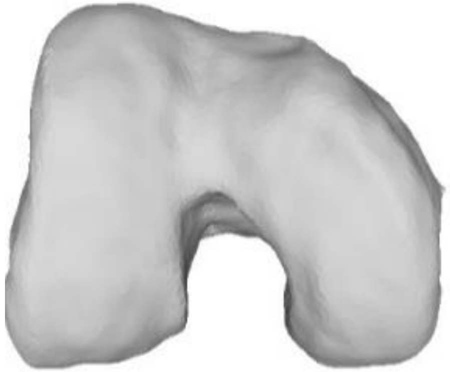
TypeA



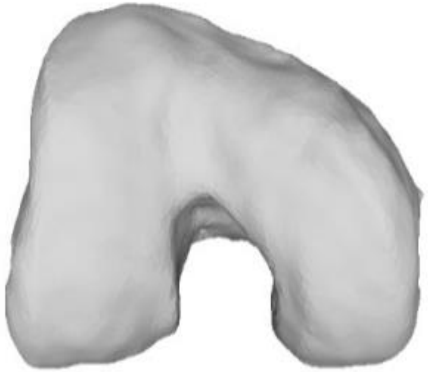
TypeB

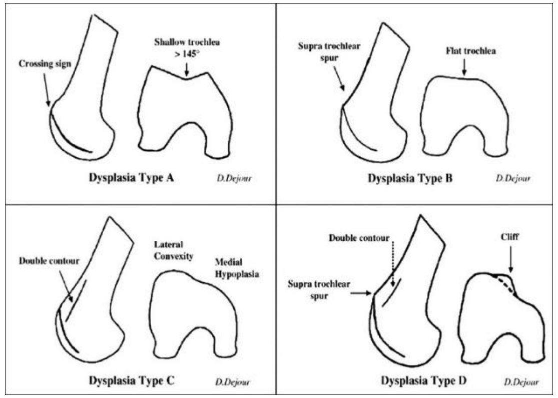


TypeC



TypeD





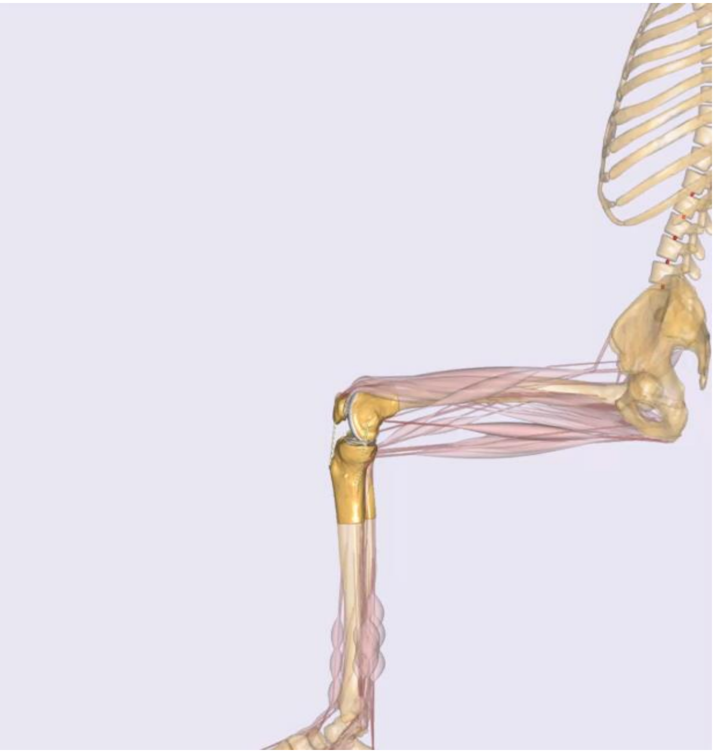
DeJour, D., & Saggin, P. (2010). The sulcus deepening trochleoplasty—the Lyon's procedure. *International Orthopaedics*, *34*(2), 311–316. http://doi.org/10.1007/s00264-009-0933-8

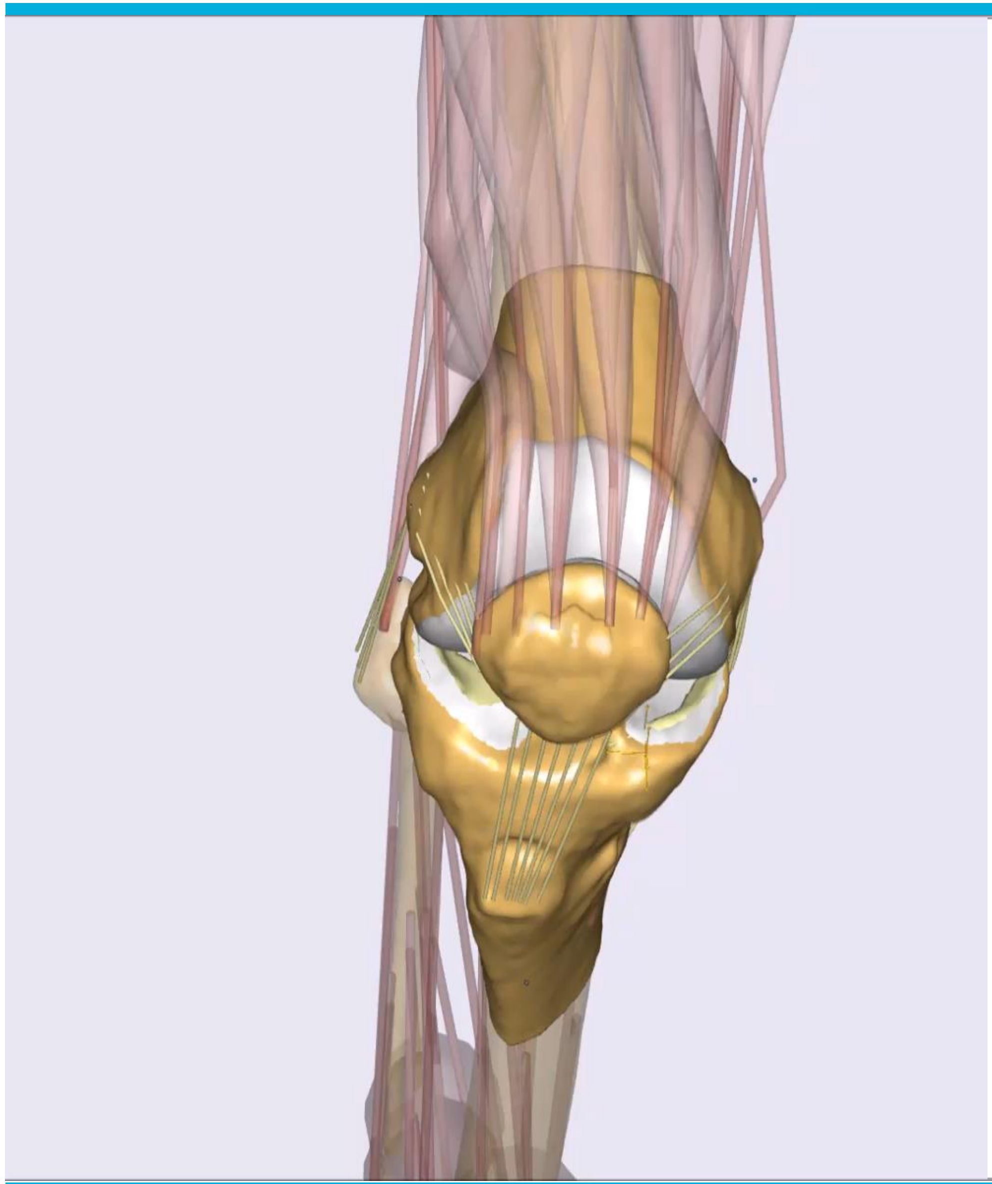
Methods

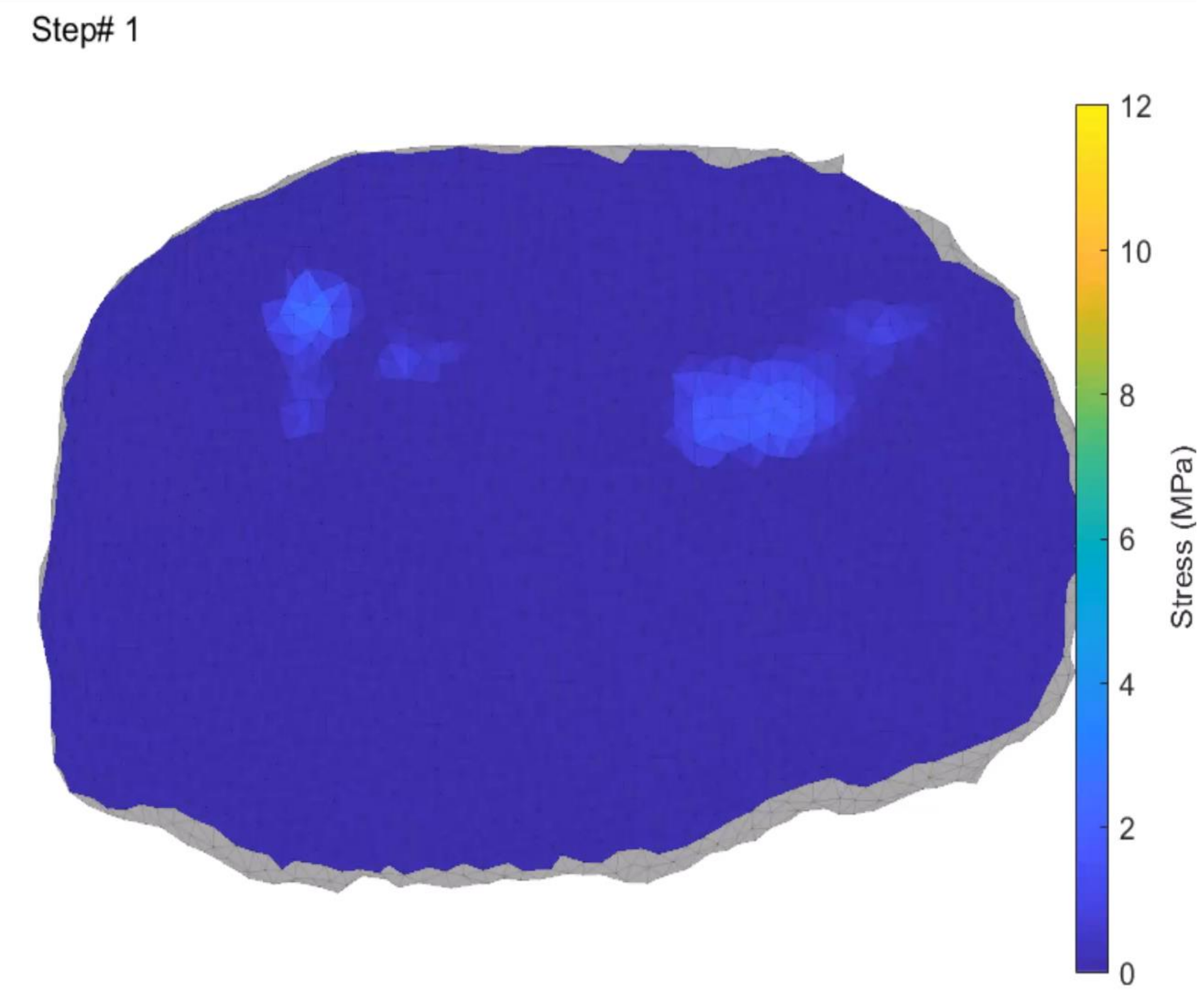
- Leg extension (90°-0°)

- Contact parameters
  - E = 10 Mpa
  - ν = 0.45

- Cases
  - Healthy
  - TD type A, B, C, D



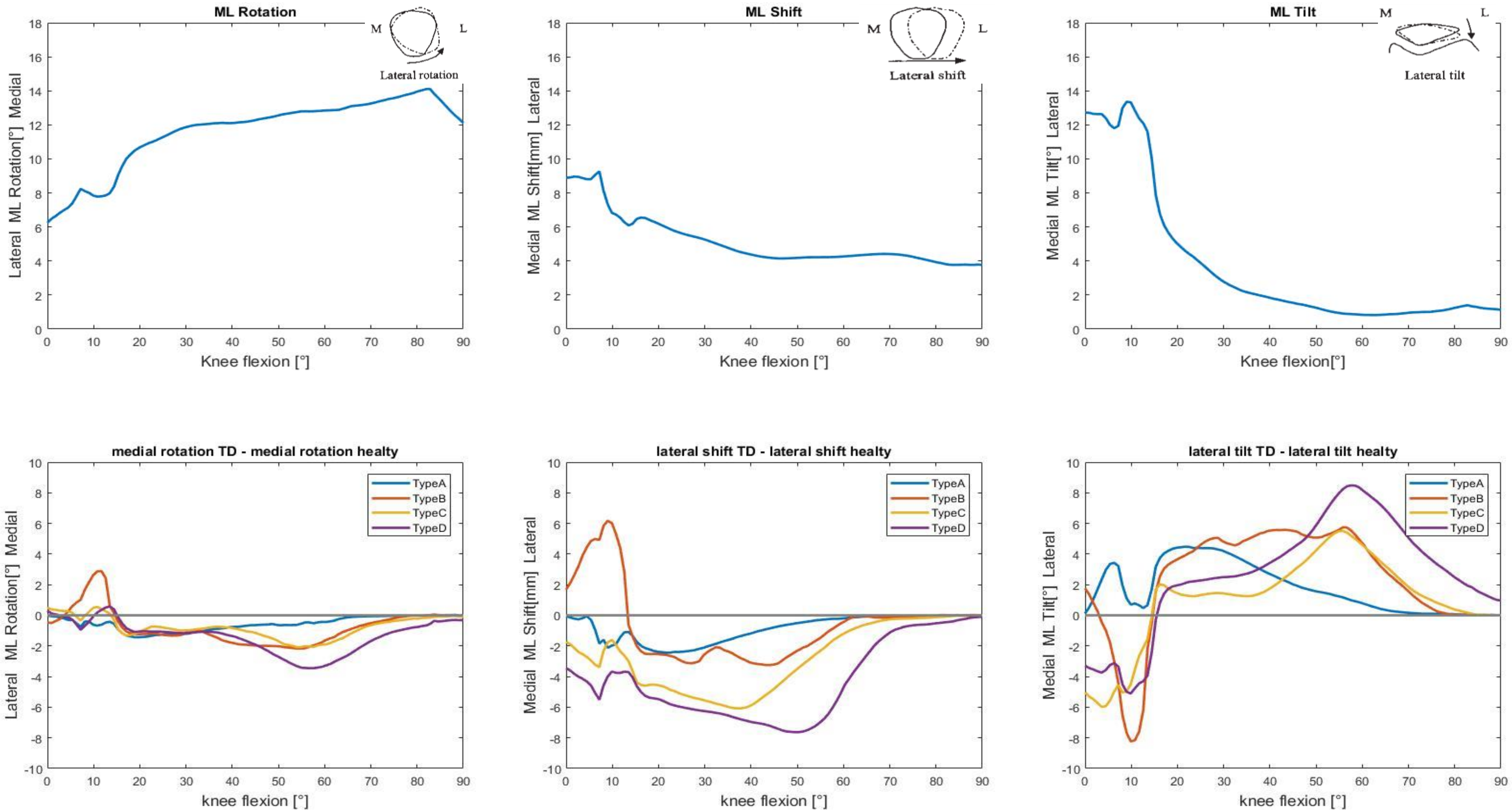



Step# 1
Stress (MPa)
12
10
8
6
4
2
0

Patellofemoral kinematics

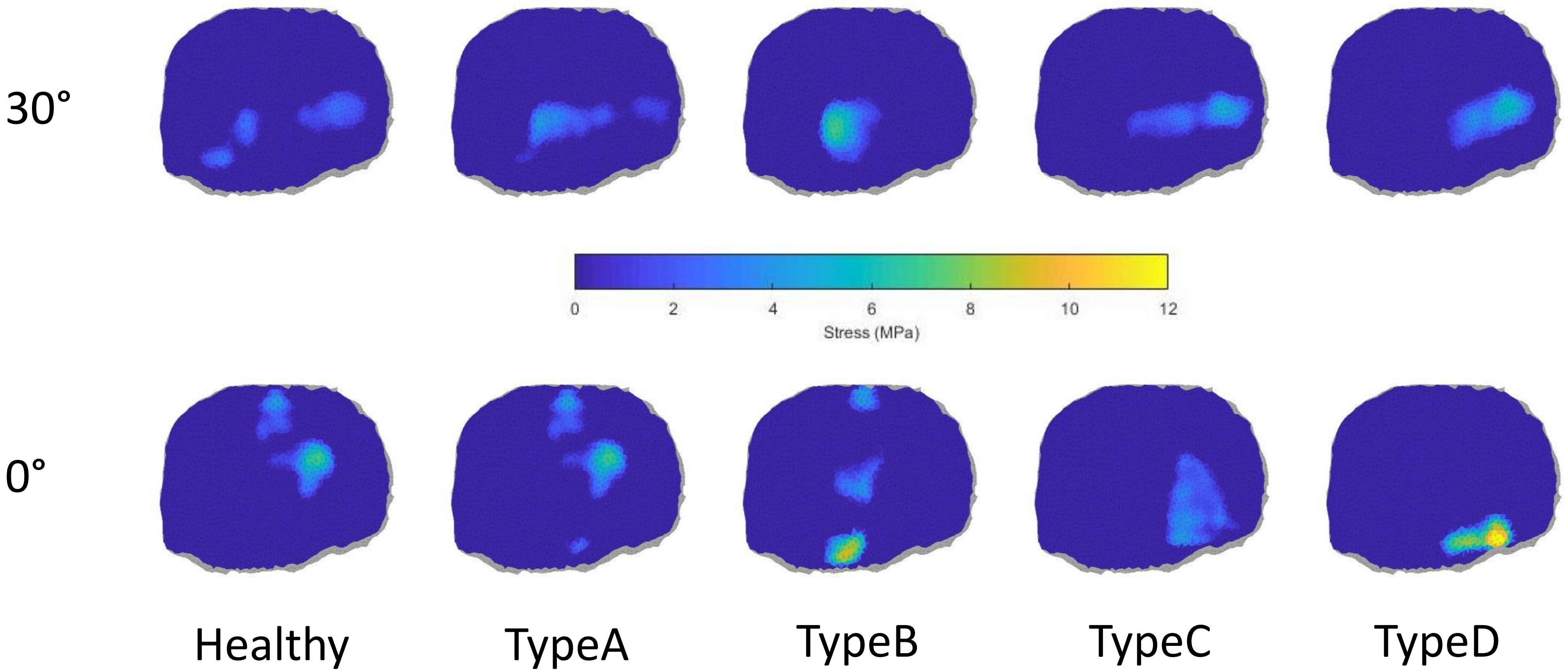
Healthy

TD



Radboudumc

Patellofemoral contact pressure

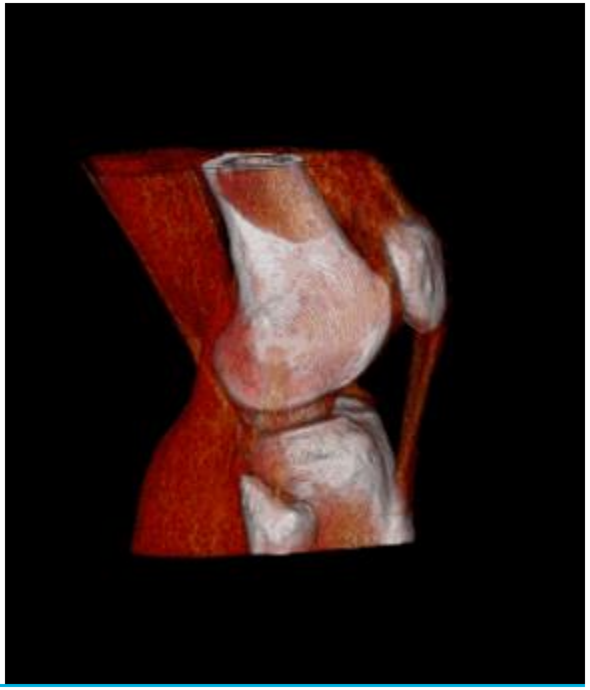


Discussion

- PF cartilage pressure is sensitive to TD type
- Efficient EF model for cartilage contact

- Limitations
  - Synthetic TD models
  - Viscoelastic behaviors neglected

- Future work
  - validate PF kinematics using 4D-CT



Thank you

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