Engineering of the Musculoskeletal System and Rehabilitation

2.2 Numerical methods

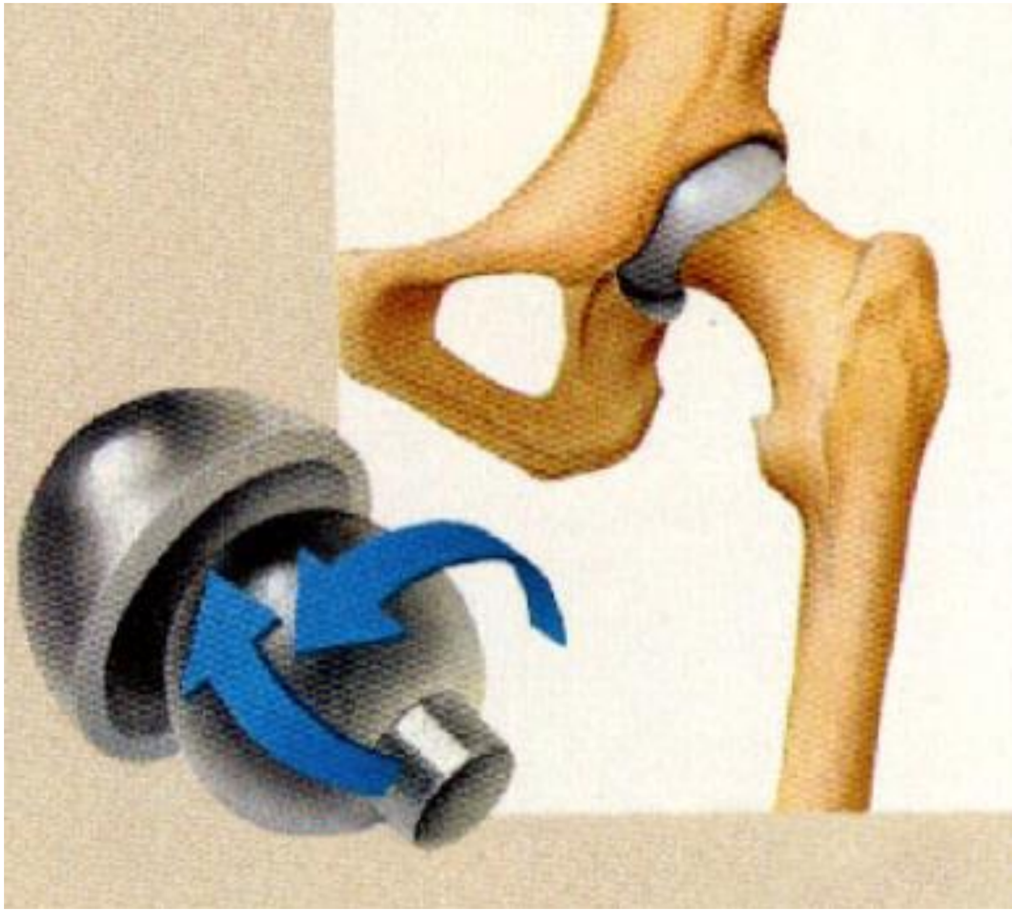
Hip, Knee

Alexandre Terrier

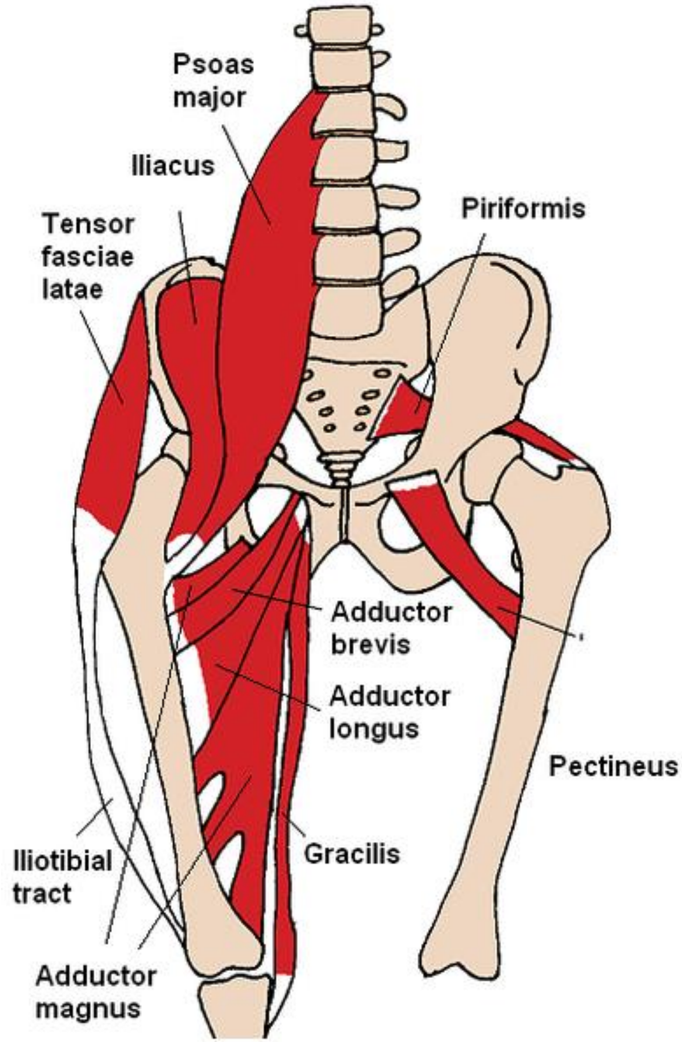
(EPFL-LBO)

Hip anatomy: joint

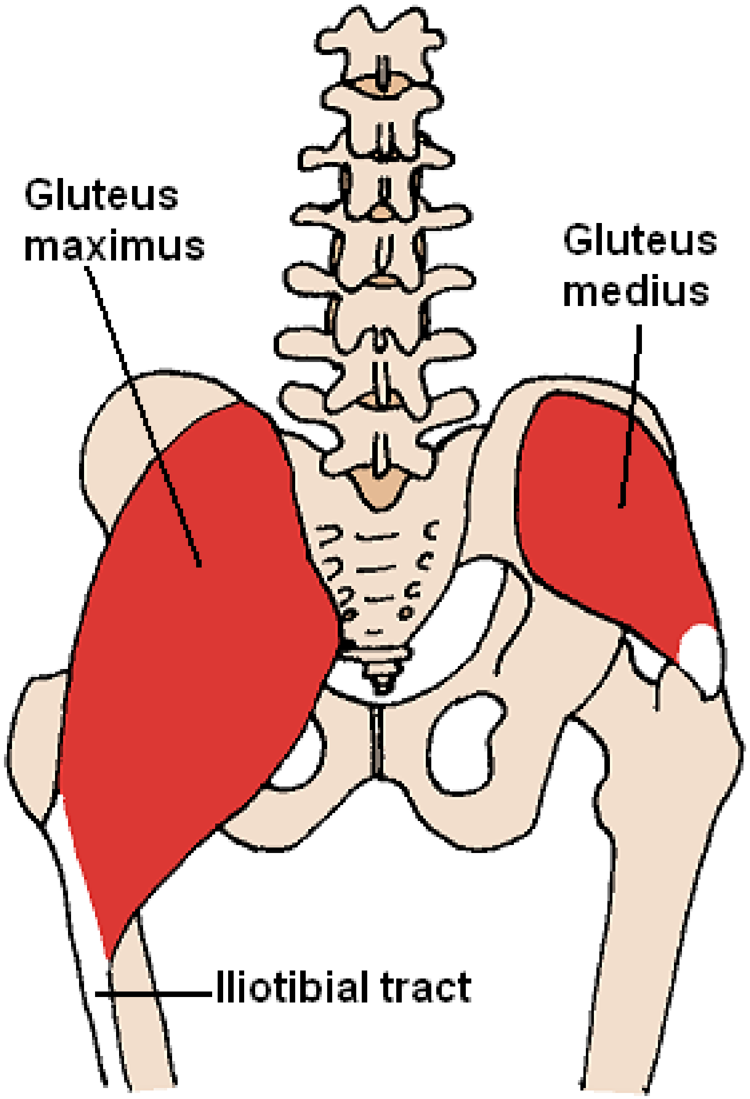
- Ball and socket joint
- Femoral head
- Acetabulum
- Cartilage
- Bone (structure)
- Muscles



Hip anatomy: muscles



Hip anatomy: muscles



Total Hip Arthroplasty (THA)

Total Hip Arthroplasty

- Osteoarthritis, fractures, tumors
- Resurfacing (femoral head) vs. total
- Uncemented vs. cemented
- Shapes of stems (straight, anatomical, custom)
- Materials: polyethylene, ceramics, metal
- Failure rate (Swedish register)
- Failure causes: loosening, infection, fracture, dislocation, technical error

Swedish register

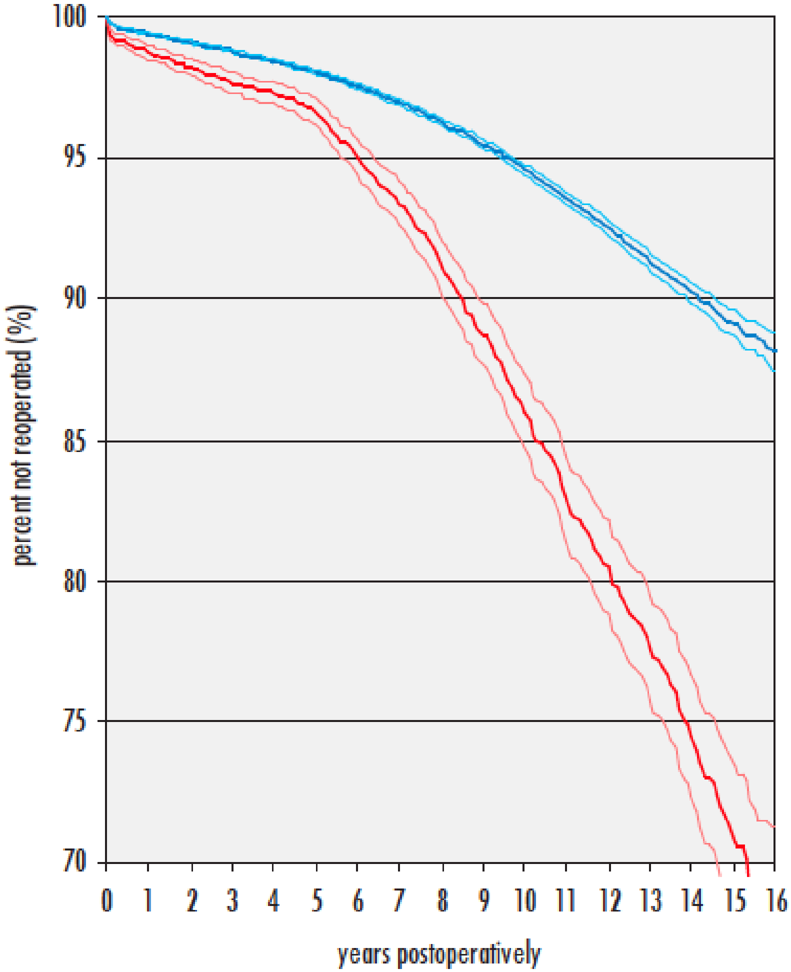
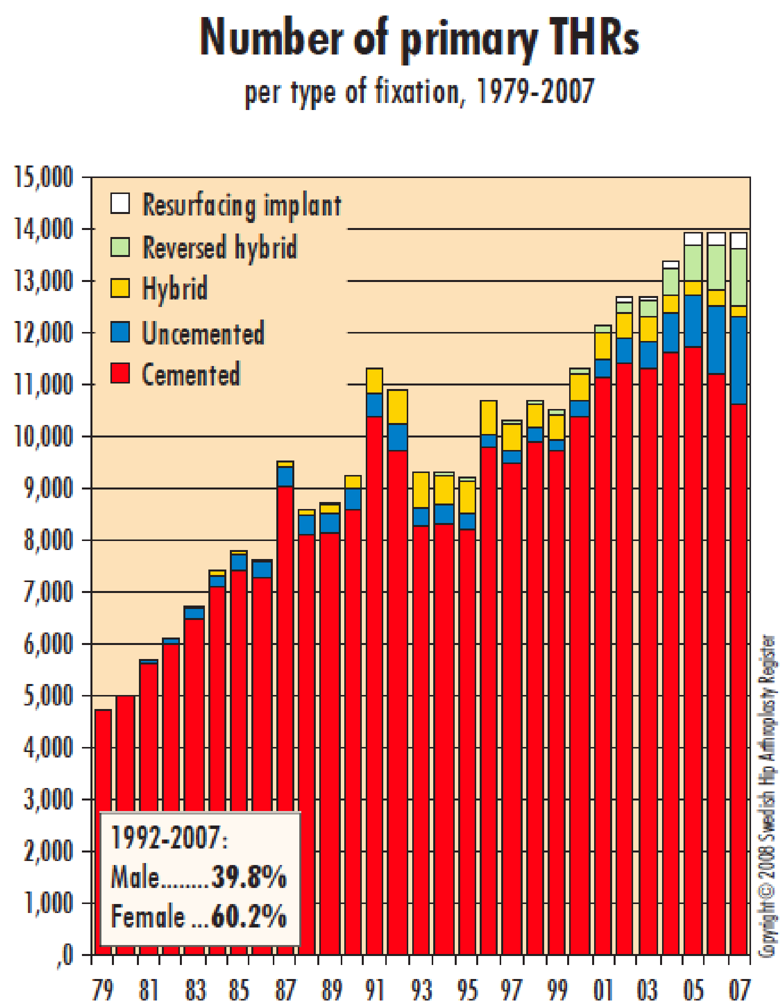
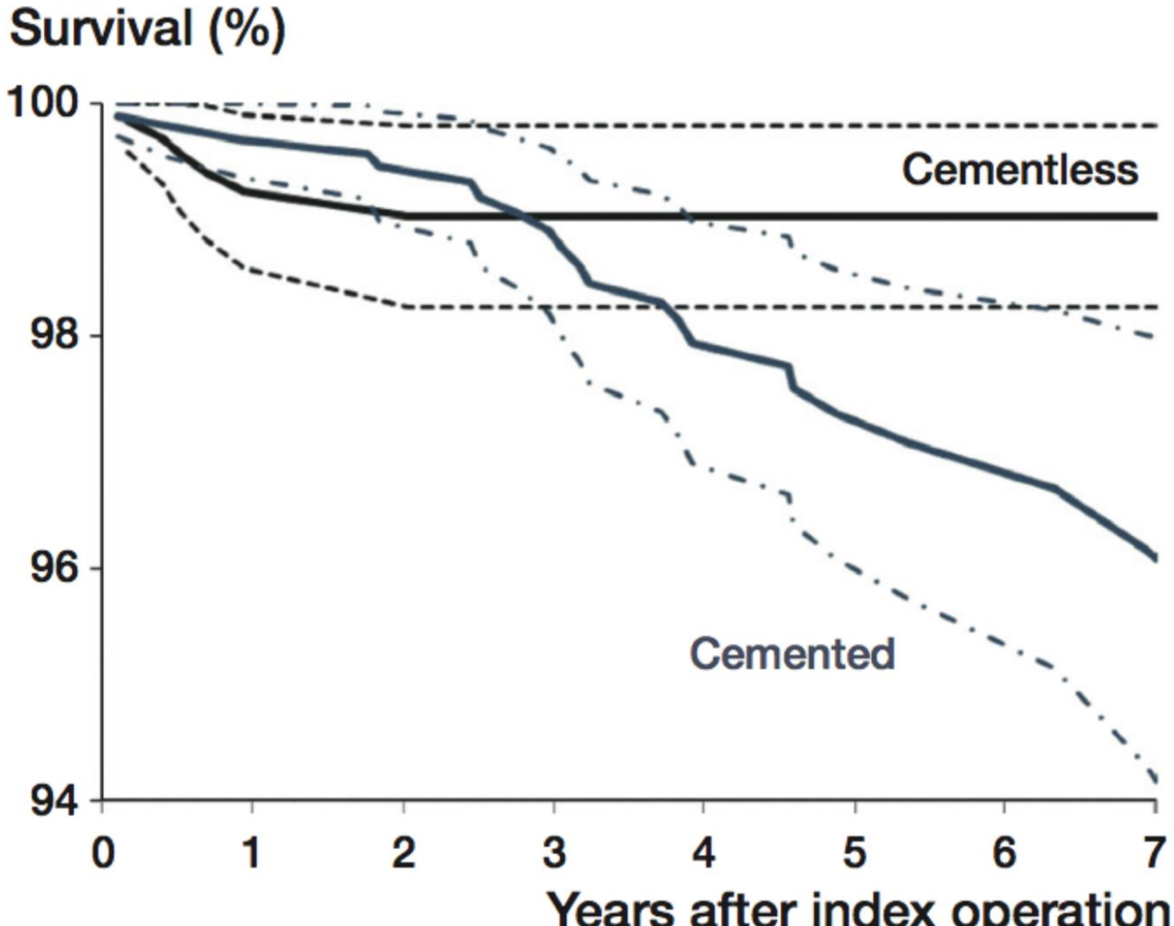


Figure 2a. Implant survival with end-point revision – all causes excluding infection for all-cemented (blue) implants and uncemented (red) implants inserted between 1992 and 2007.



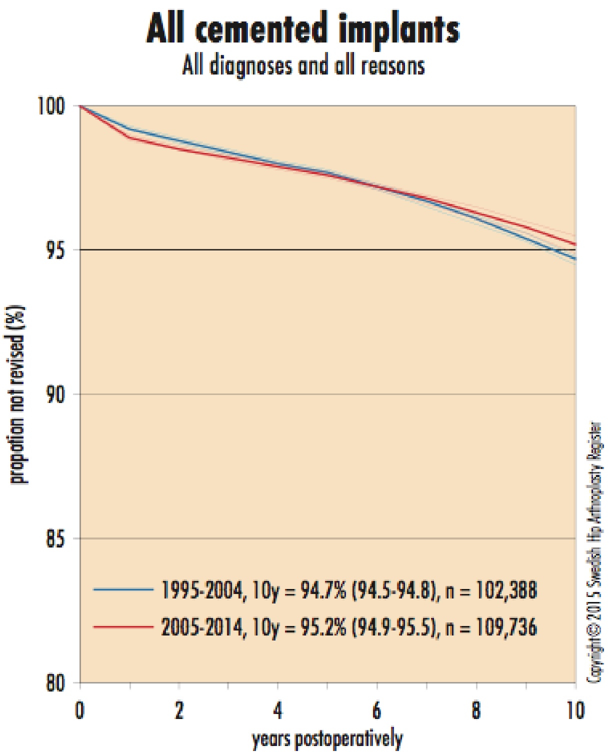
Cementless advantage

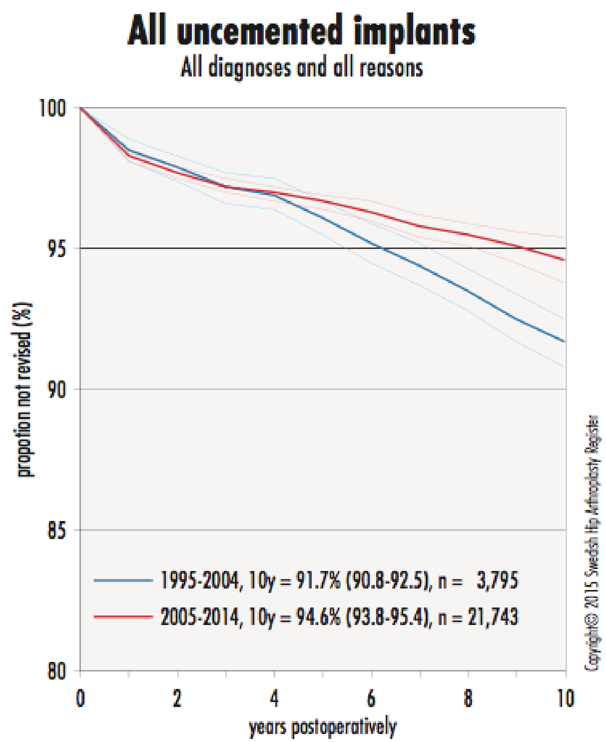


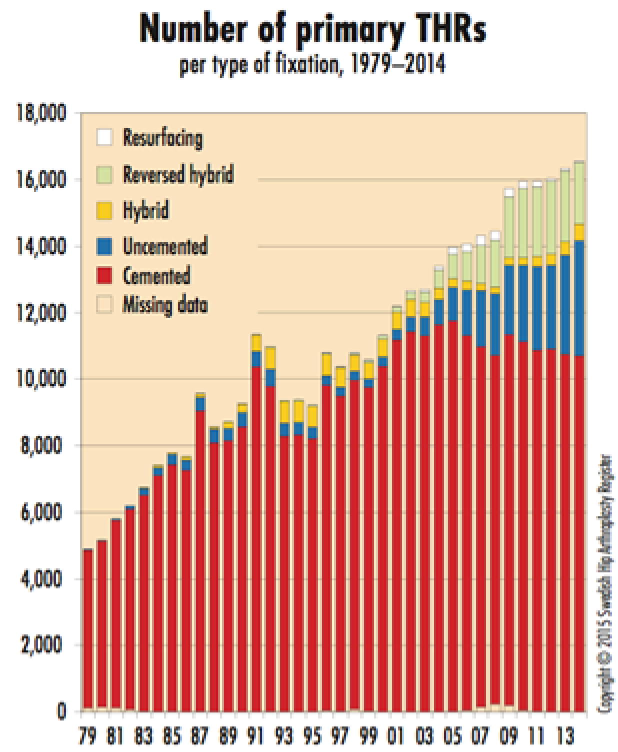
Weiss, et al. *Acta Orthopaedica*, 2011

Total Hip Arthroplasty

The Swedish Hip Arthroplasty Register
Annual Report 2014





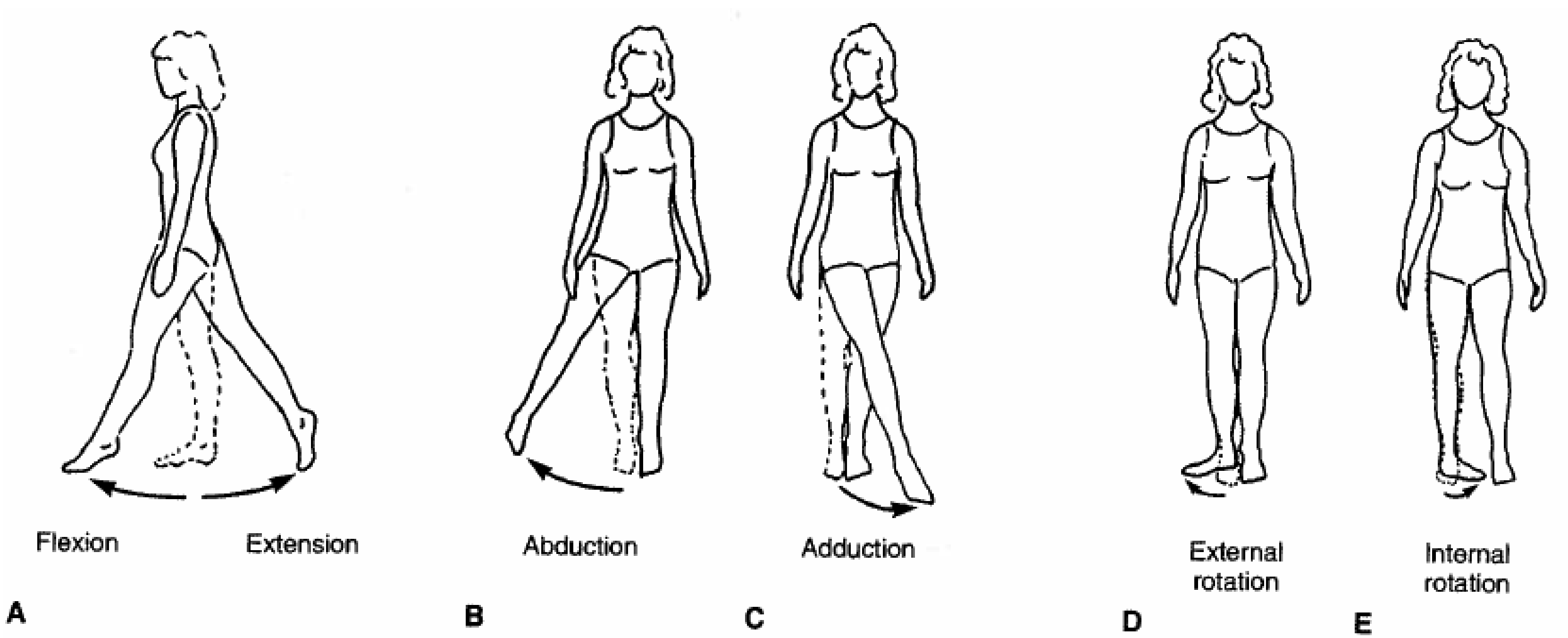


Biomechanics

- Kinematics
  - motion analysis (Camera, Magnetic, Fluoroscopy)
- Biomechanics
  - Force analysis
  - Stress/strain analysis
  - Interface
  - Mechano-biology (cellular response)

Kinematics

- Ball and socket joint (3 rotations)
  - Flexion/extension (120°/30°)
  - Abduction/adduction (40°/20°)
  - Internal/external rotation (40°/50°)



Kinematics

- Activities of Daily Living (ADL)
  - Walking
  - Sitting/standing
  - Stairs climbing/descending


EPFL-LMAM Vicon system

Kinematics

- Kinematics problem associated to THA
  - Impingements
  - Dislocation

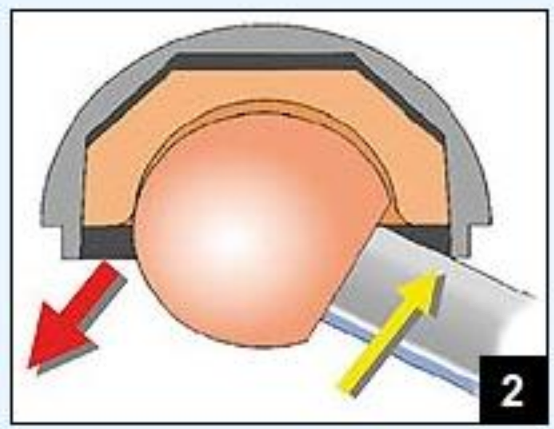


Figure 2: Diagram demonstrating femoral neck impingement on an elevated metal rim resulting in microseparation of the femoral head from the acetabular component.

www.orthosupersite.com

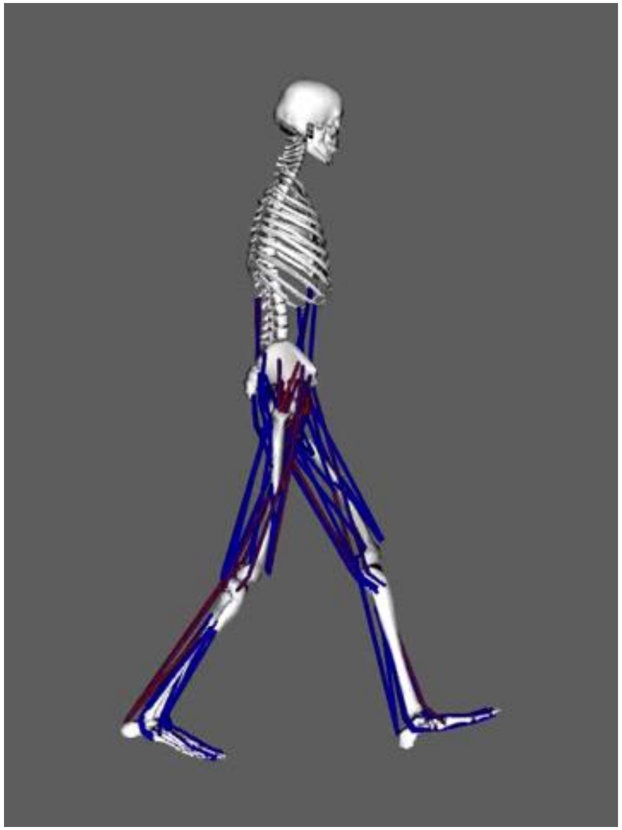
Biomechanics

- Force analysis
  - Indeterminate mechanical system
  - Joint (instrumented prosthesis)
  - Muscles (musculoskeletal models)
  - Body weight (inertia)
  - Ground reaction (force captor plate)

NCSRR NATIONAL CENTER FOR SIMULATION IN REHABILITATION RESEARCH

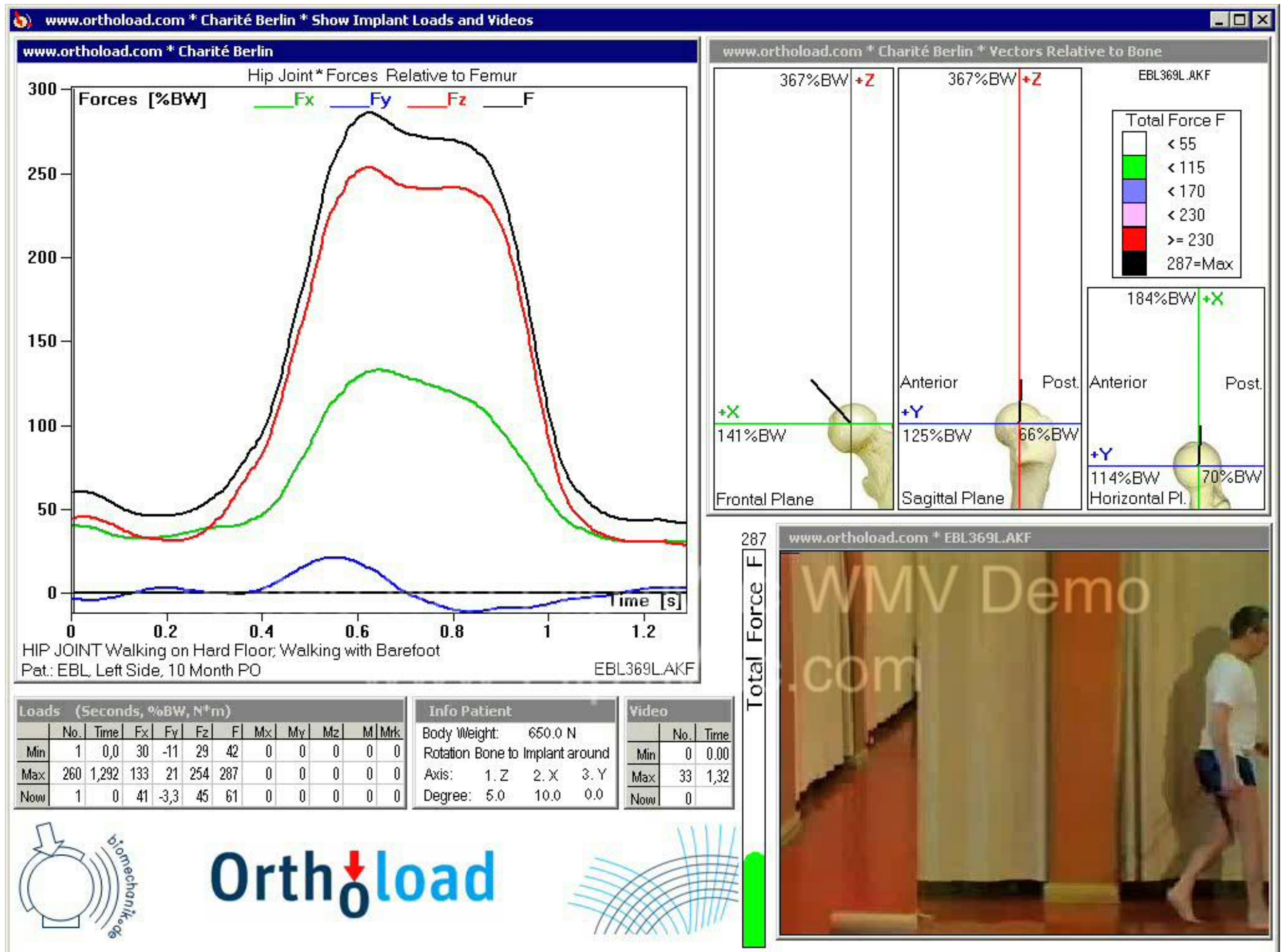
OpenSim Community

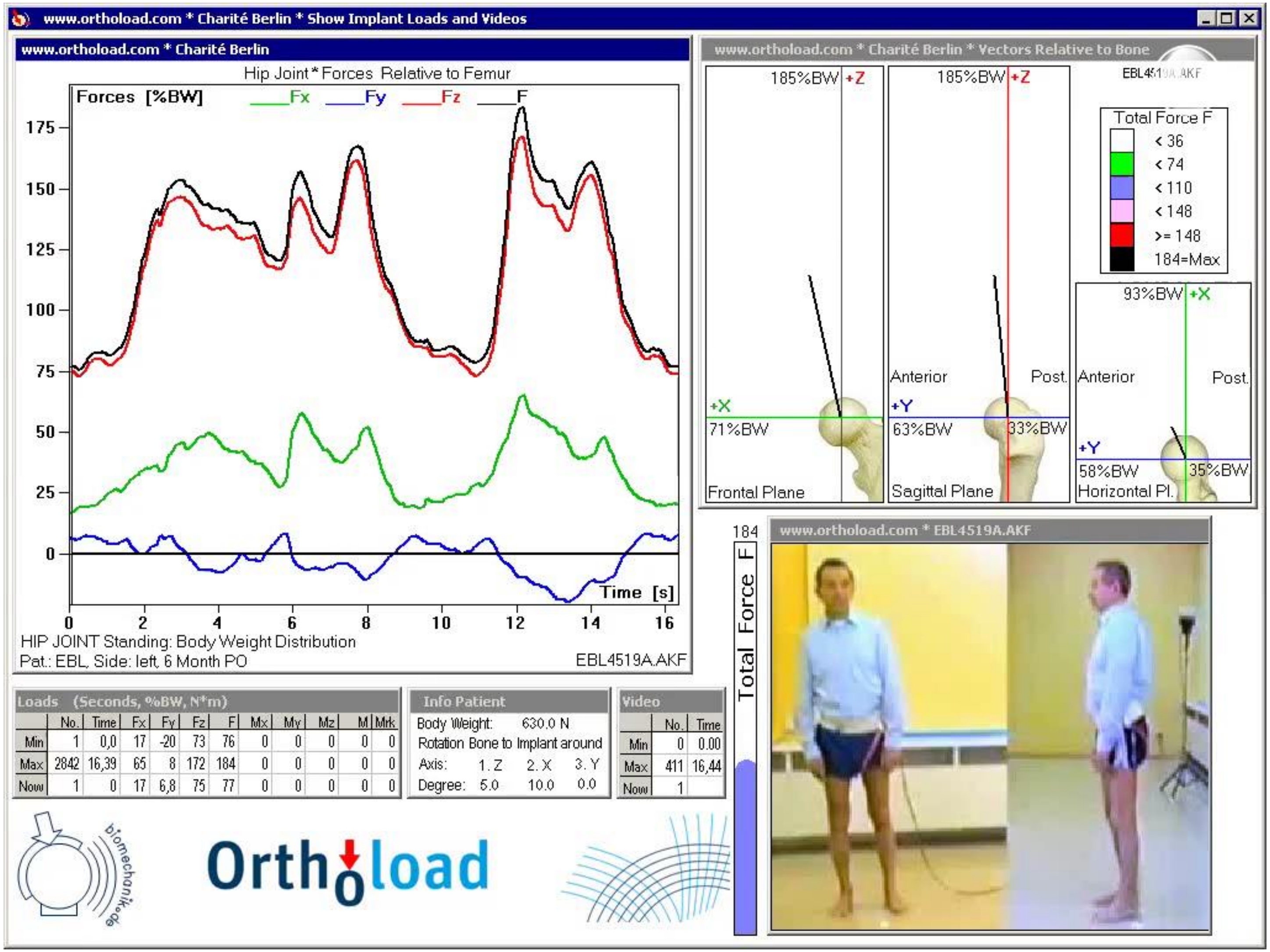
- SEE THE WORK
- JOIN THE COMMUNITY
- FIND SUPPORT, EVENTS, & RESOURCES



Hip force: instrumented prosthesis

http://www.orthoload.com




www.orthoload.com * Charité Berlin * Show Implant Loads and Videos
www.orthoload.com * Charité Berlin
Hip Joint * Forces Relative to Femur
Forces [%BW]
Fx
Fy
Fz
F
Time [s]
HIP JOINT Standing: Body Weight Distribution
Pat.: EBL, Side: left, 6 Month PO
EBL4519A.AKF
www.orthoload.com * Charité Berlin * Vectors Relative to Bone
185%BW +Z
71%BW
Frontal Plane
Anterior
Post.
63%BW
33%BW
Sagittal Plane
Total Force F
< 36
< 74
< 110
< 148
>= 148
184=Max
93%BW +X
58%BW
35%BW
Horizontal Pl.
Loads (Seconds, %BW, N*m)
Info Patient
Body Weight: 630.0 N
Rotation Bone to Implant around
Axis: 1. Z 2. X 3. Y
Degree: 5.0 10.0 0.0
Video
Total Force F
www.orthoload.com * EBL4519A.AKF
Orthoload

Numerical analyses

- Forces (muscles, joint)
- Stress/strain (vs. material/physiological limits)
- Micromotion (interface)
  - Slipping (tangential)
  - Debonding (perpendicular)
- Mechano-biology (remodeling/stress shielding)
- Parametric study
- Patient-specific analyses
- Prosthesis design improvement
- Patient-specific treatment

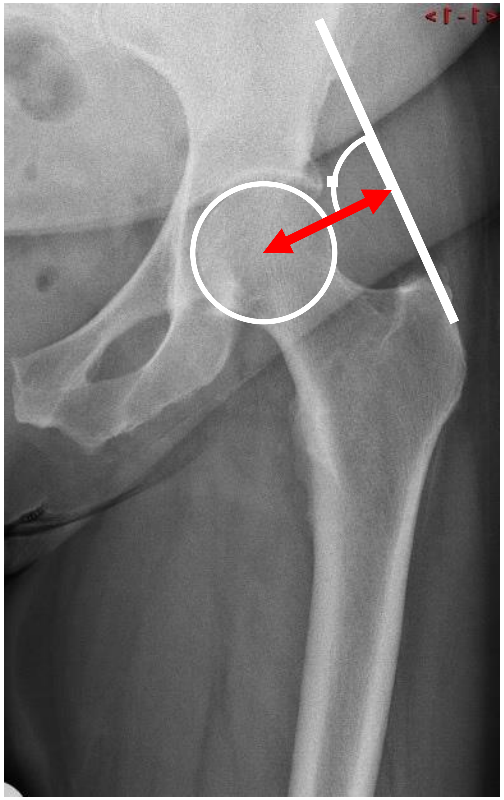
THA: cup medialization

Cup medialization:

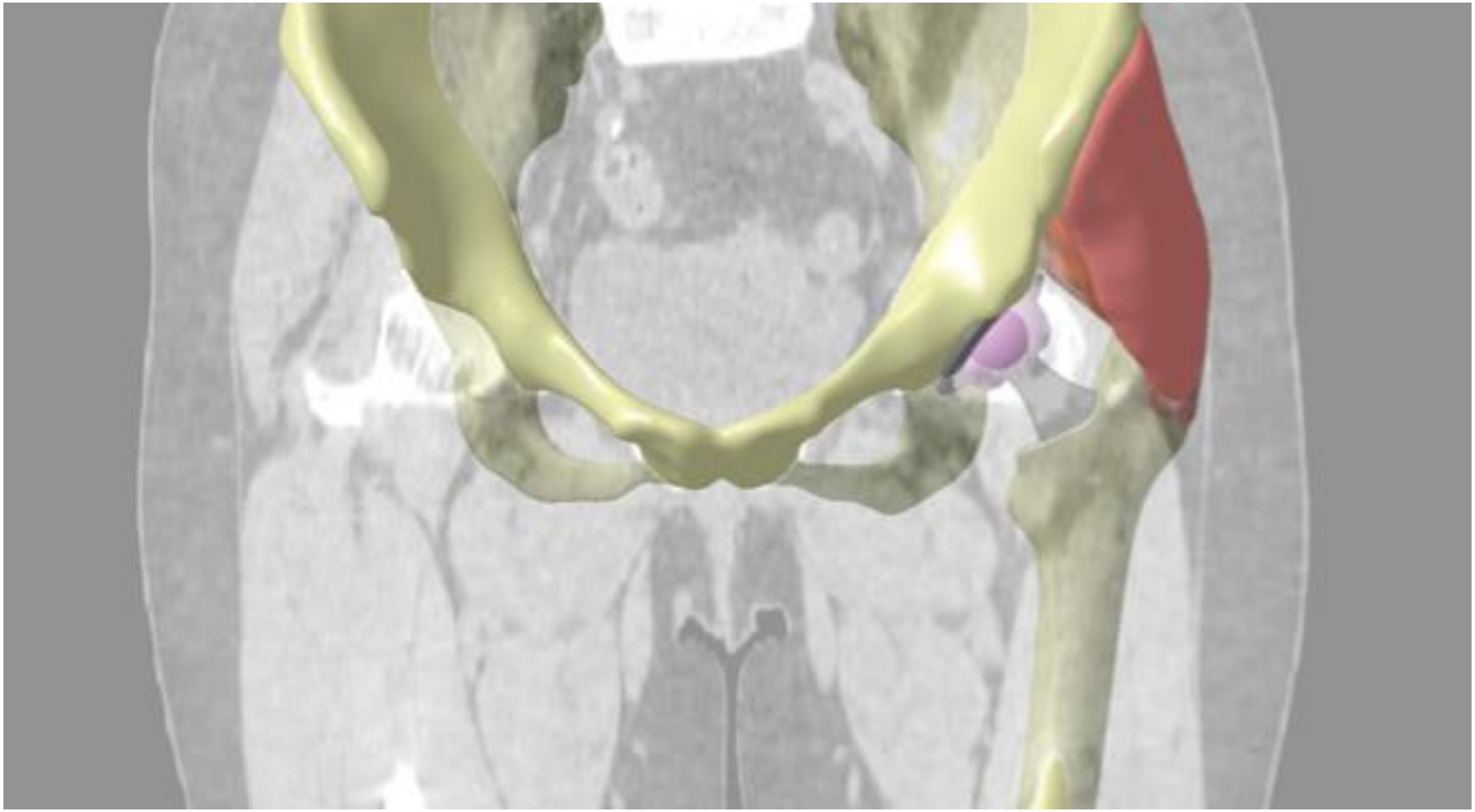
- femoral offset ↑
- acetabular offset ↓
- global offset constant

→ Improved lever arms

→ Loss of bone stock

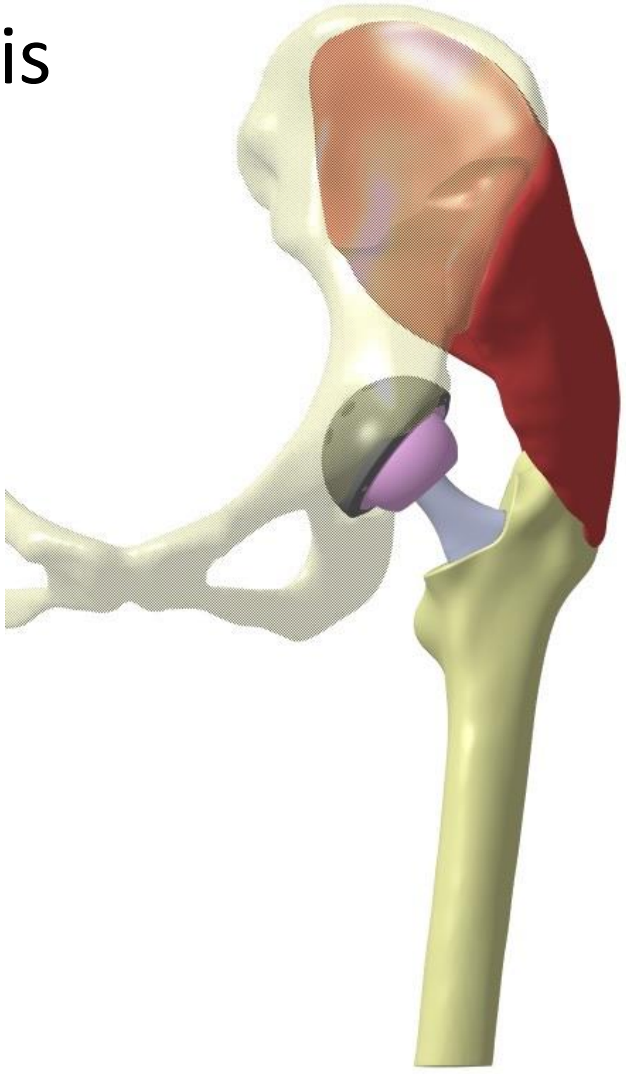


Hip



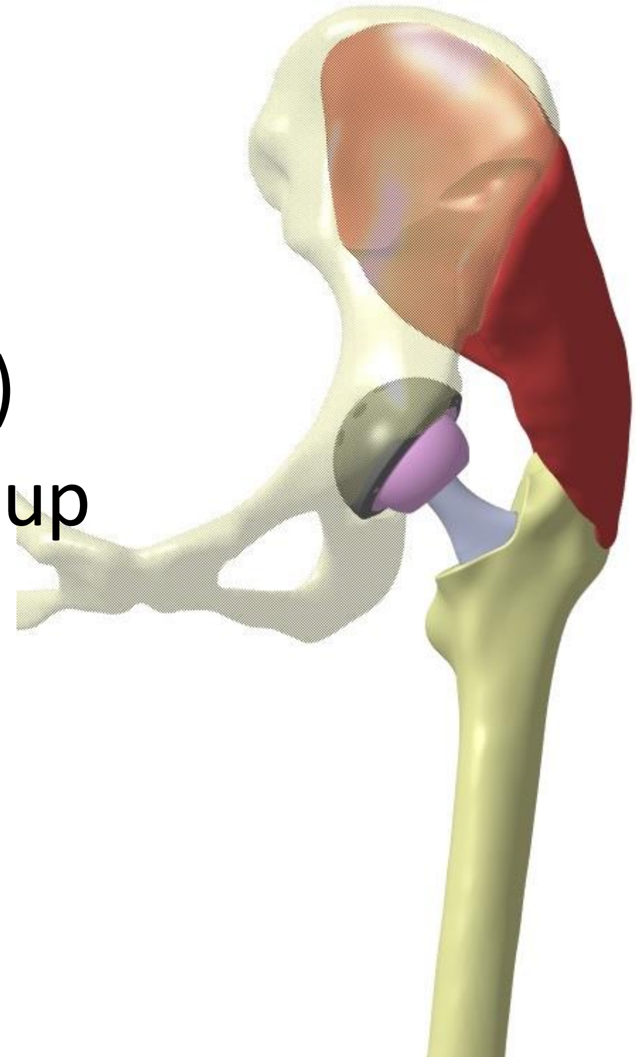
THA: cup medialization

- Limitation of Xray 2D analysis
- Muscle volume
- Muscle fibers
- Gait

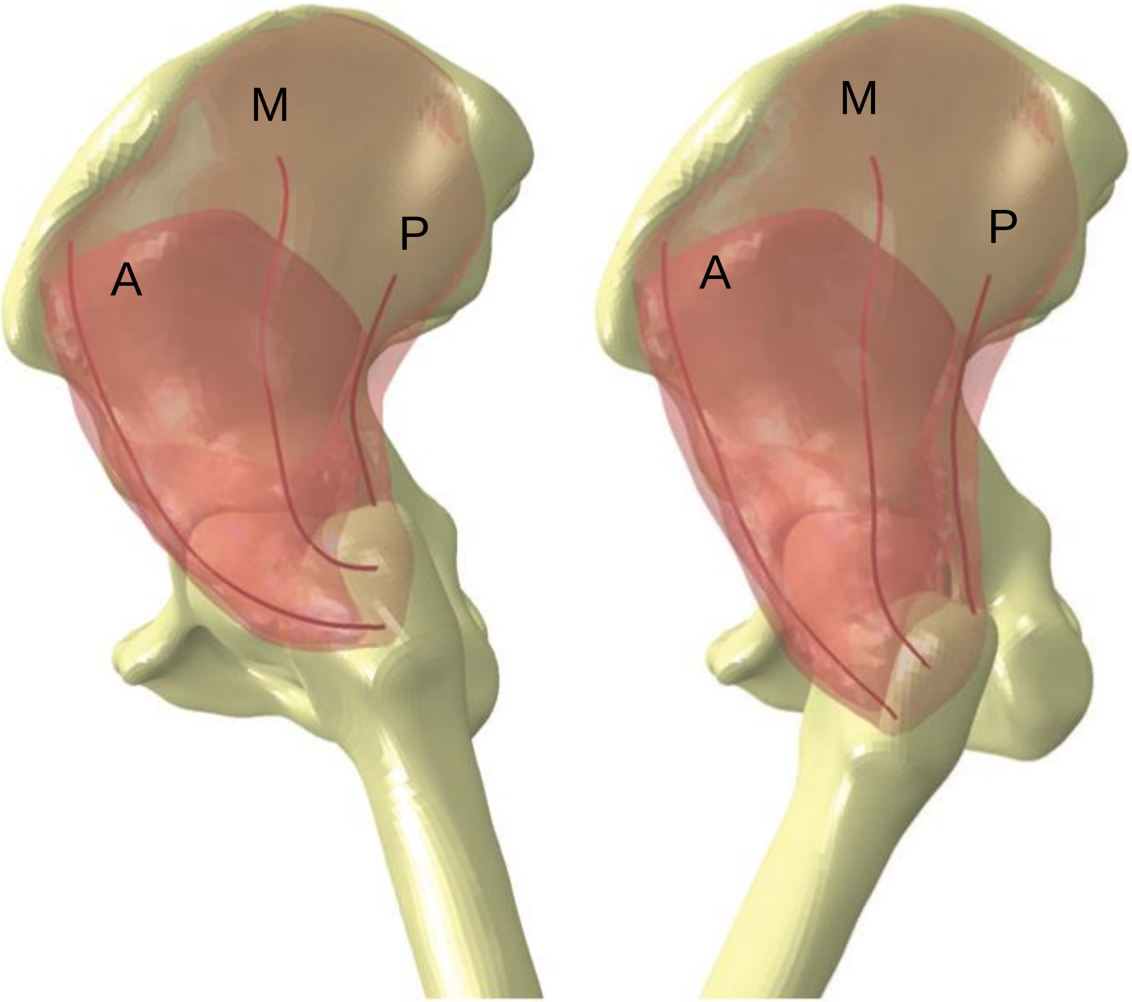


THA: cup medialization

- Numerical model
- 15 patients CT
- Gluteus medius
- 3 fibers (Ant., Middle, Post.)
- Anatomical vs. medialized cup
- Gait
  - Abduction-adduction
  - Flexion-extension



THA: cup medialization



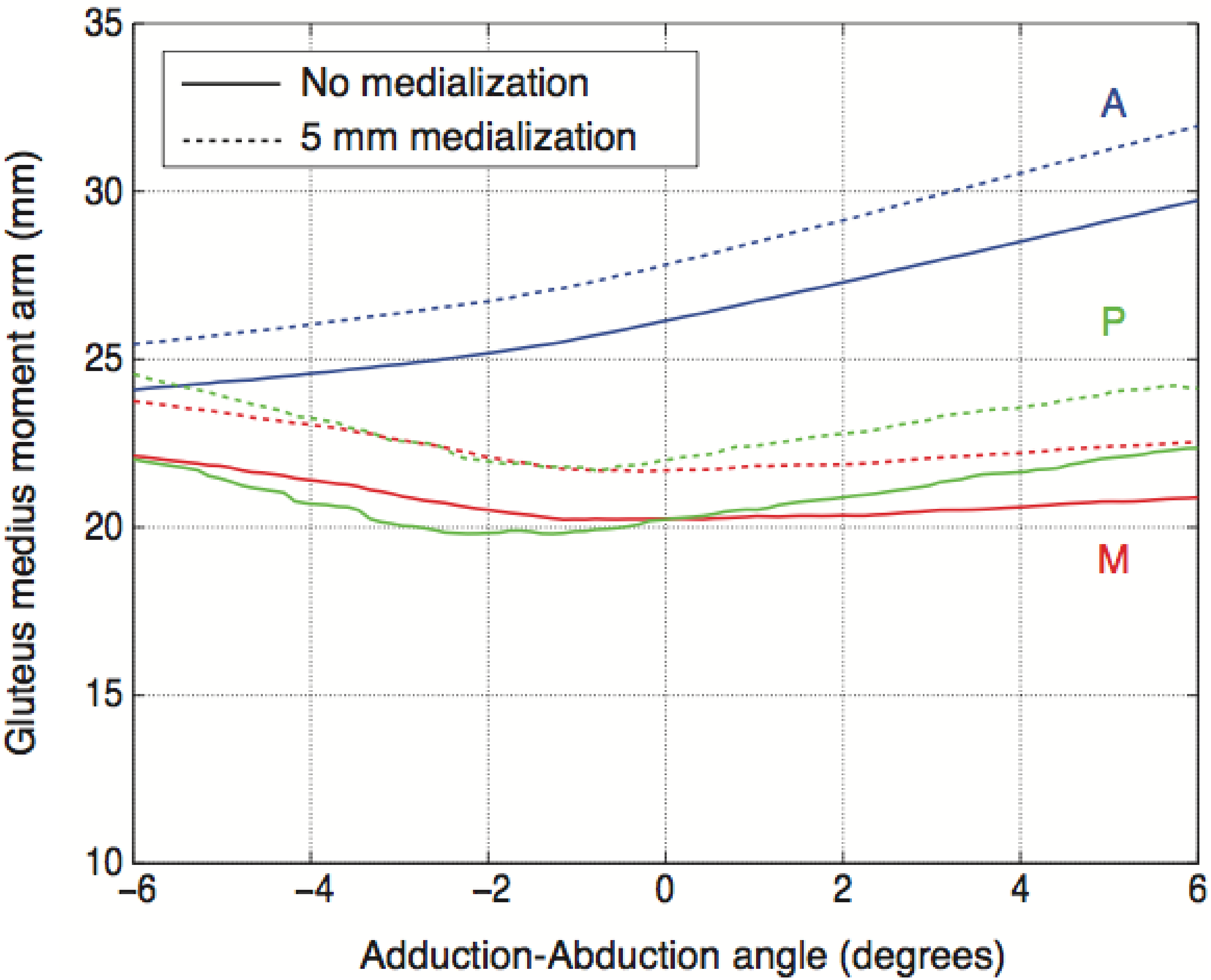
Anterior

Posterior

Extension

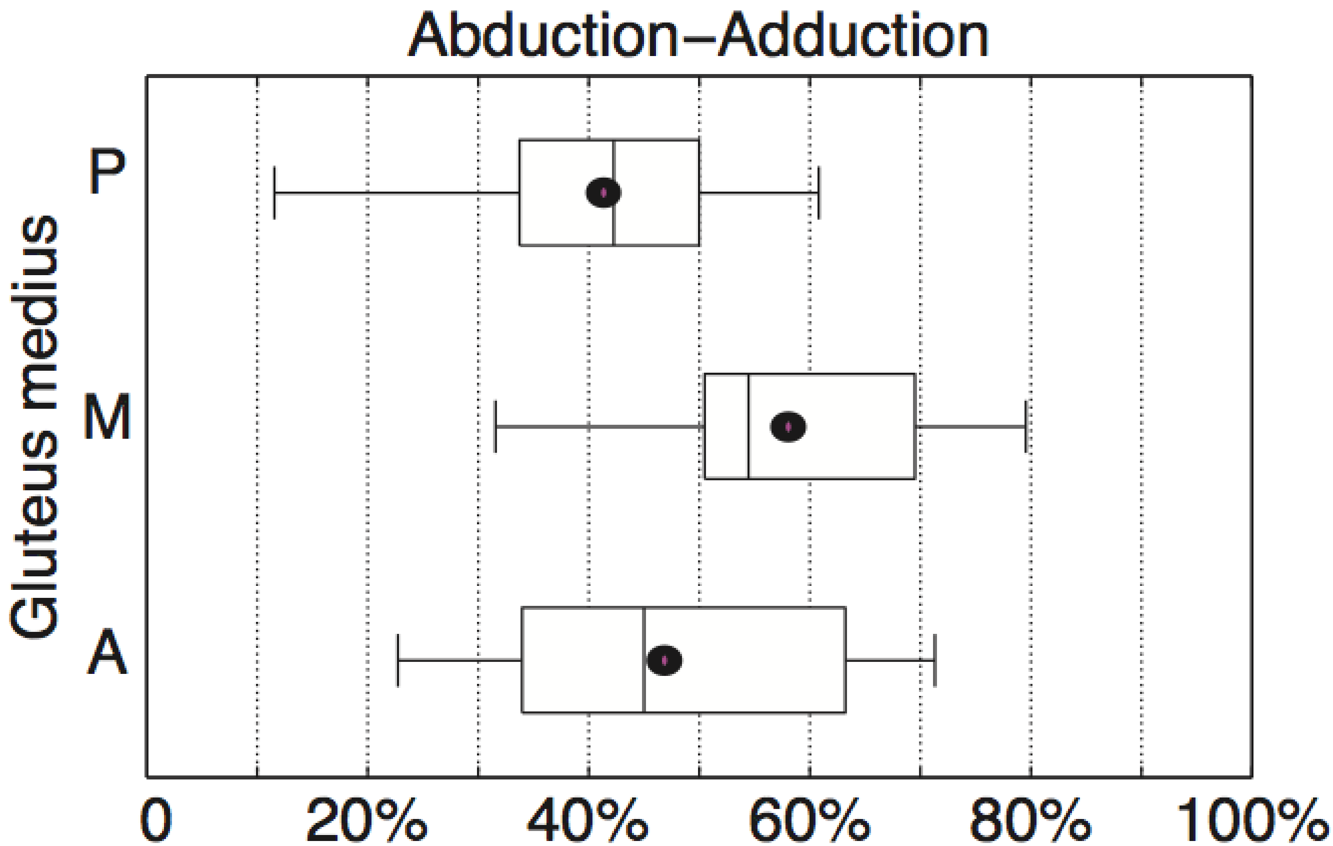
Flexion

THA: cup medialization



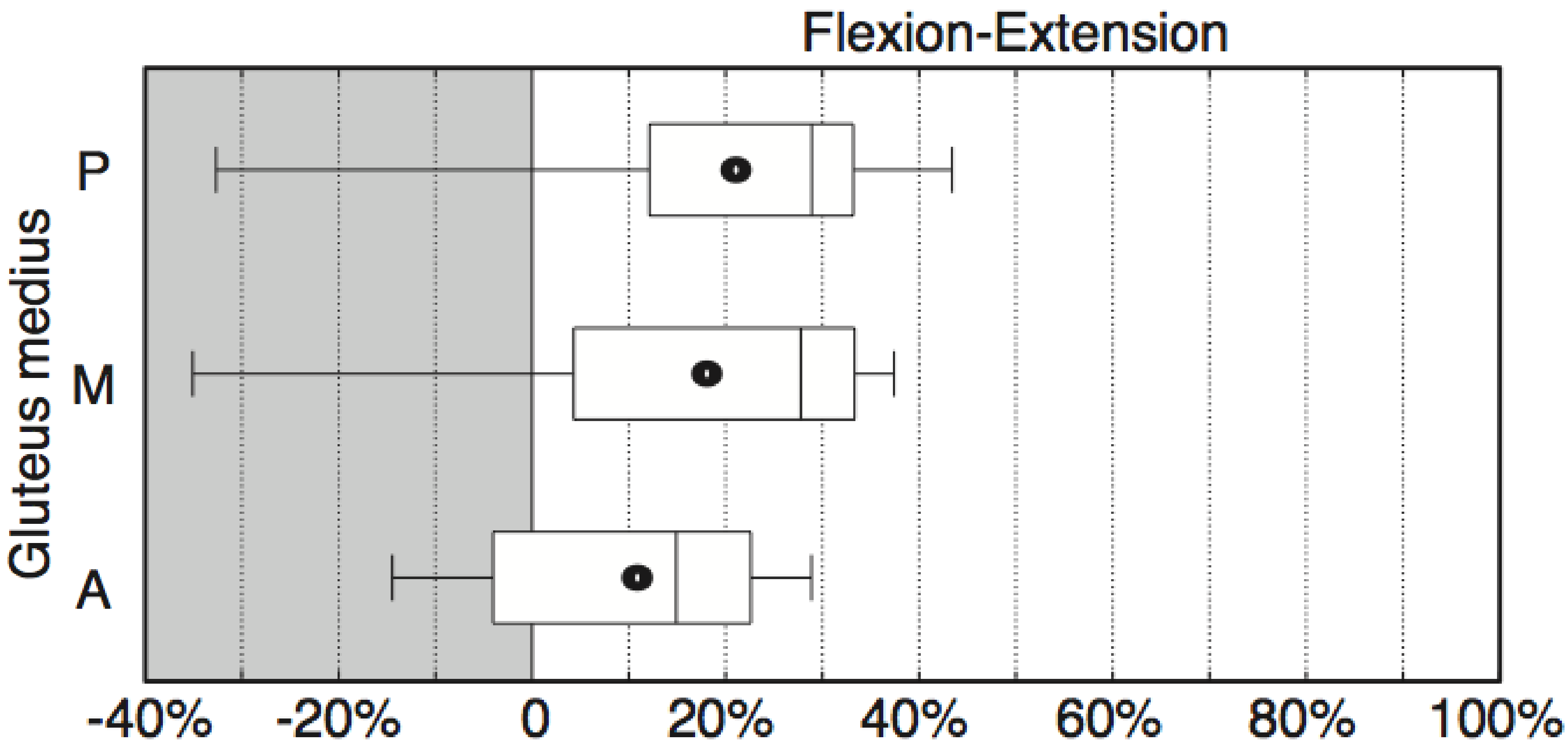
THA: cup medialization

Relative moment arm increase

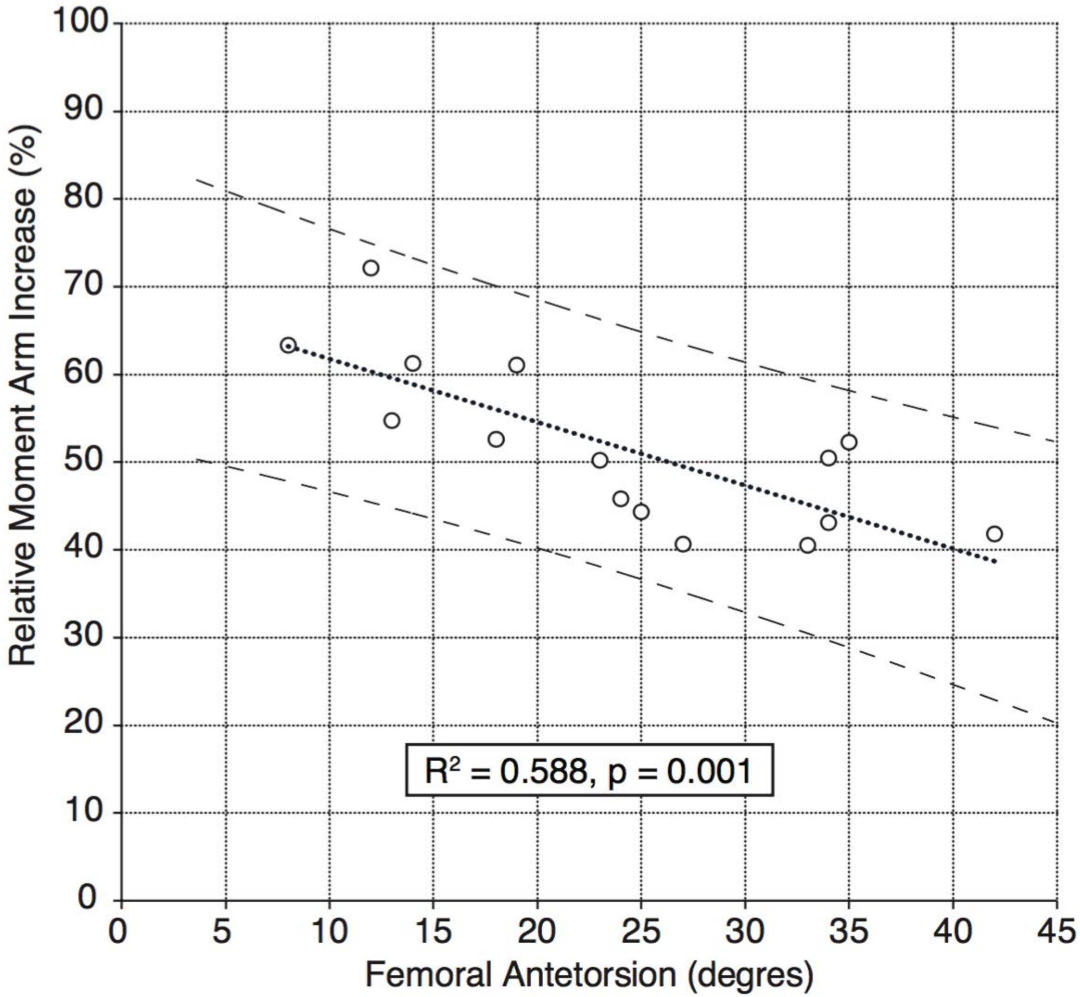


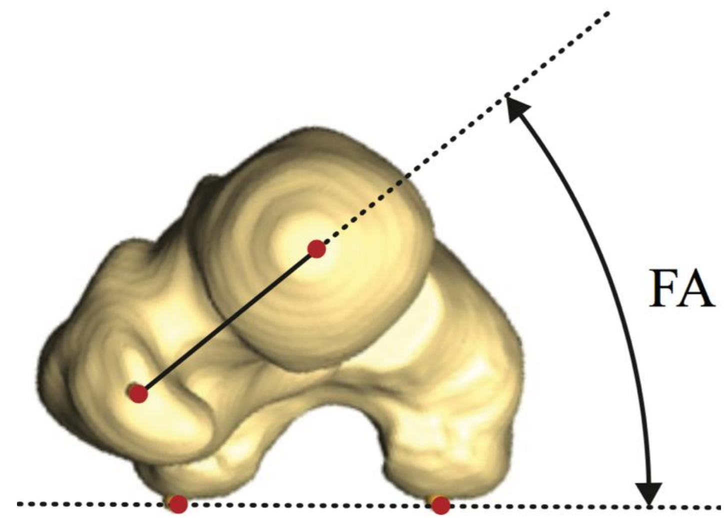
THA: cup medialization

Relative moment arm increase



Correlation with anatomy



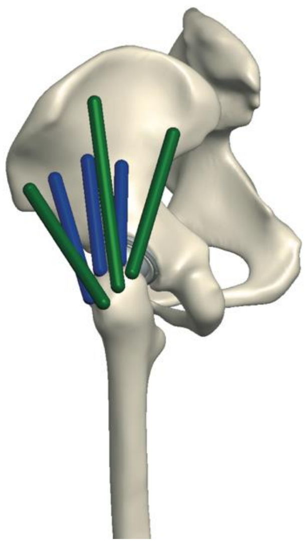


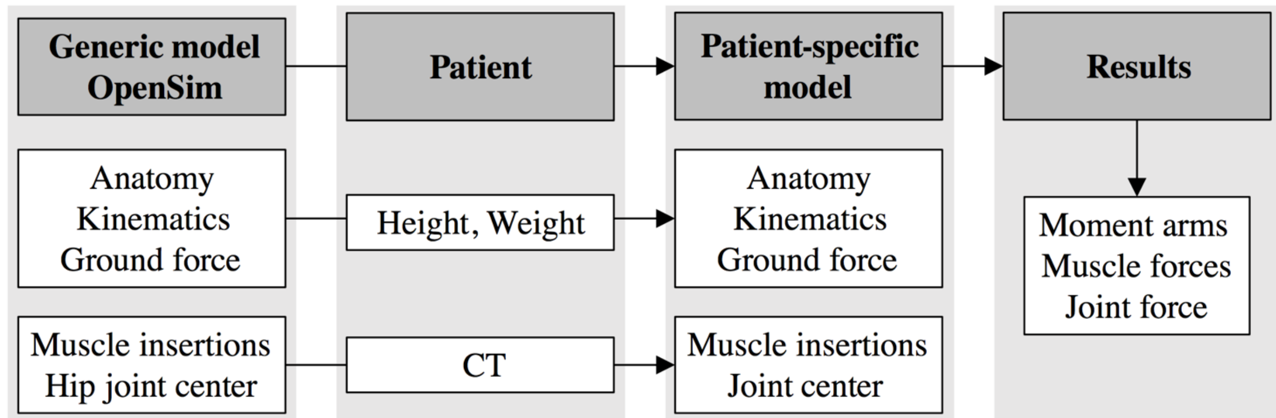
Clin Orthop Relat Res (2014) 472:3159–3165
DOI 10.1007/s11999-014-3787-3

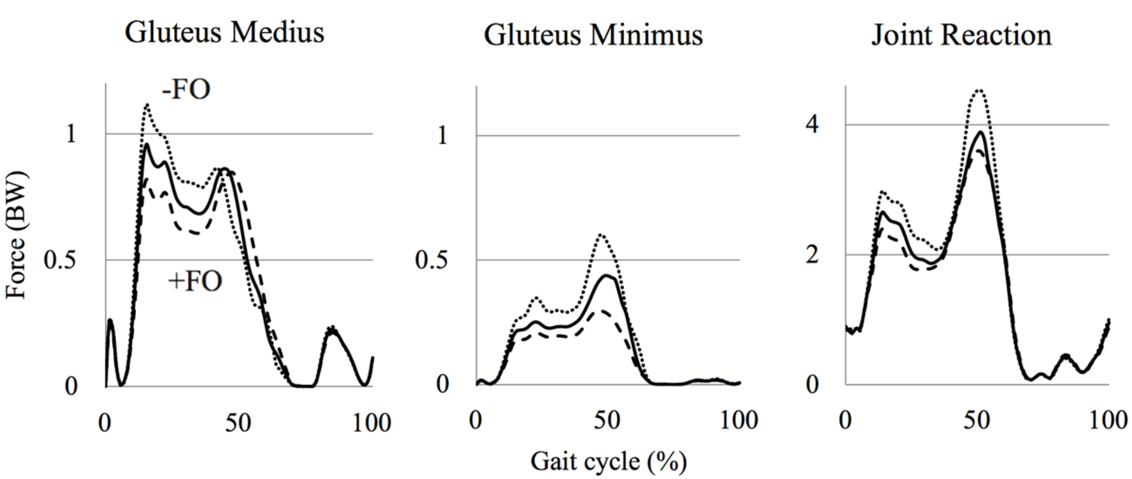
THA: cup medialization

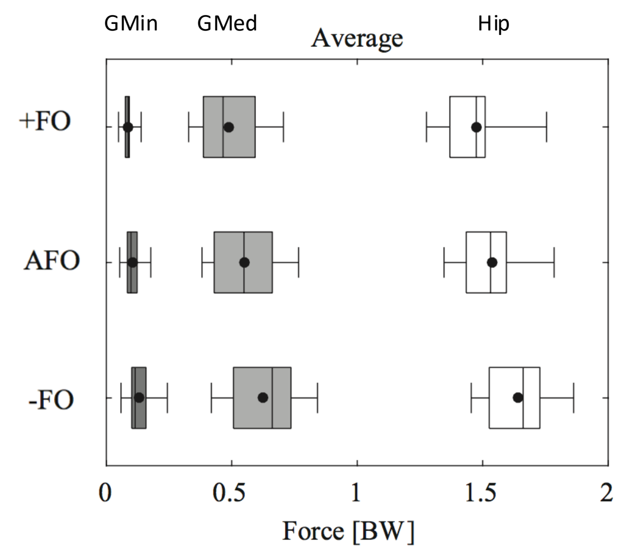
- Advantage of cup medialization quantified
- Statistical analysis on 15 patients
- Variable increase of moment arm
- Dependence of anatomical parameters
- Dependence on surgical technique?
- Surgical technique adapted to the patient
- Effect on forces

Effect of Femoral Offset on Forces





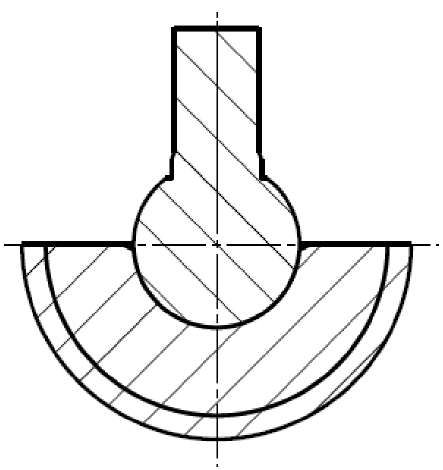




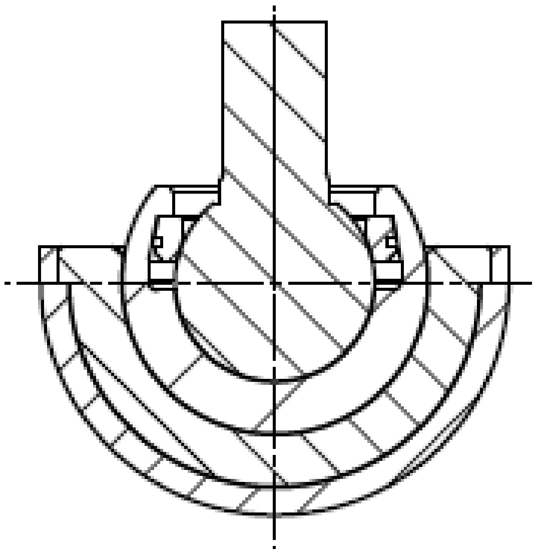
Terrier et al, Arch Orthop Trauma Surg, 2017

THA: Dual mobility

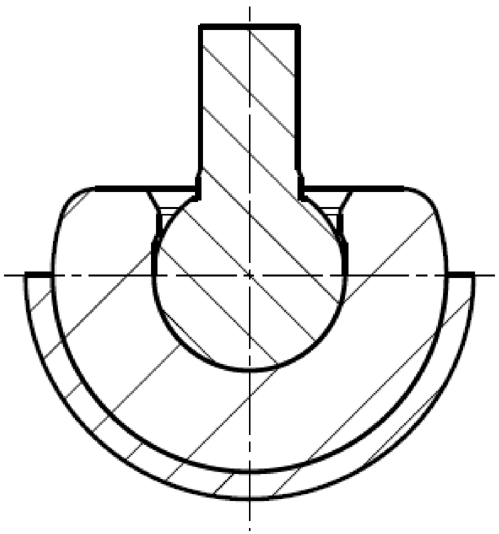
Conventional



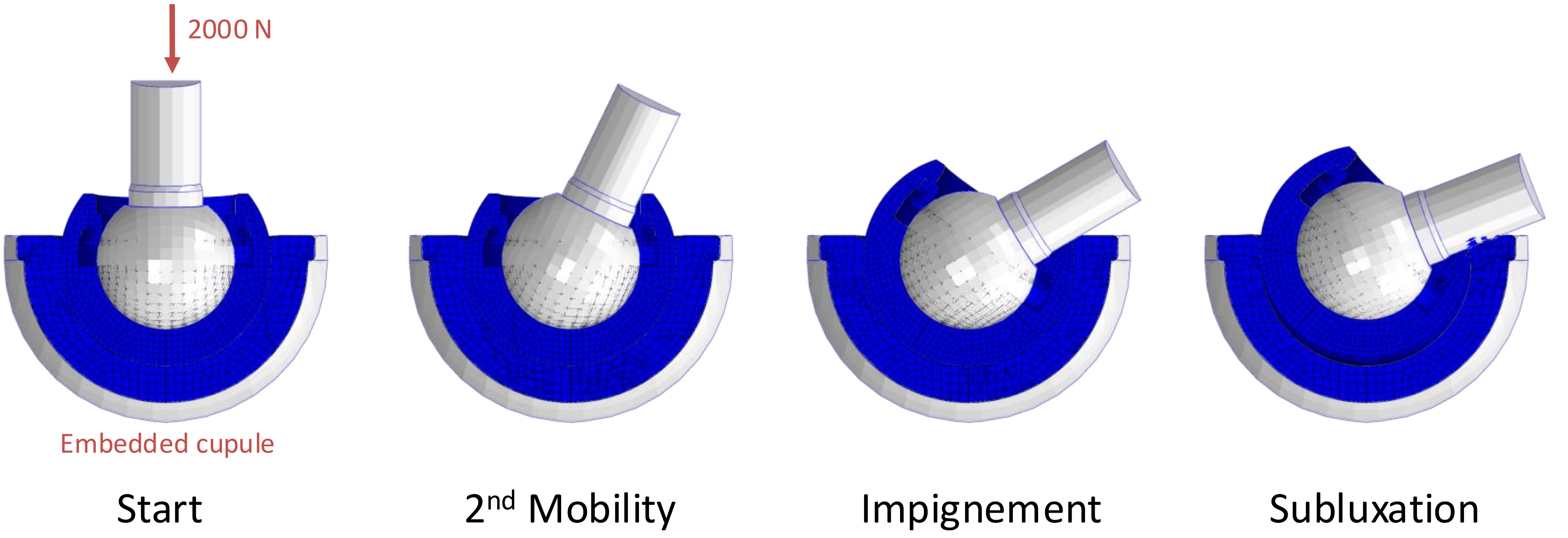
Constraint



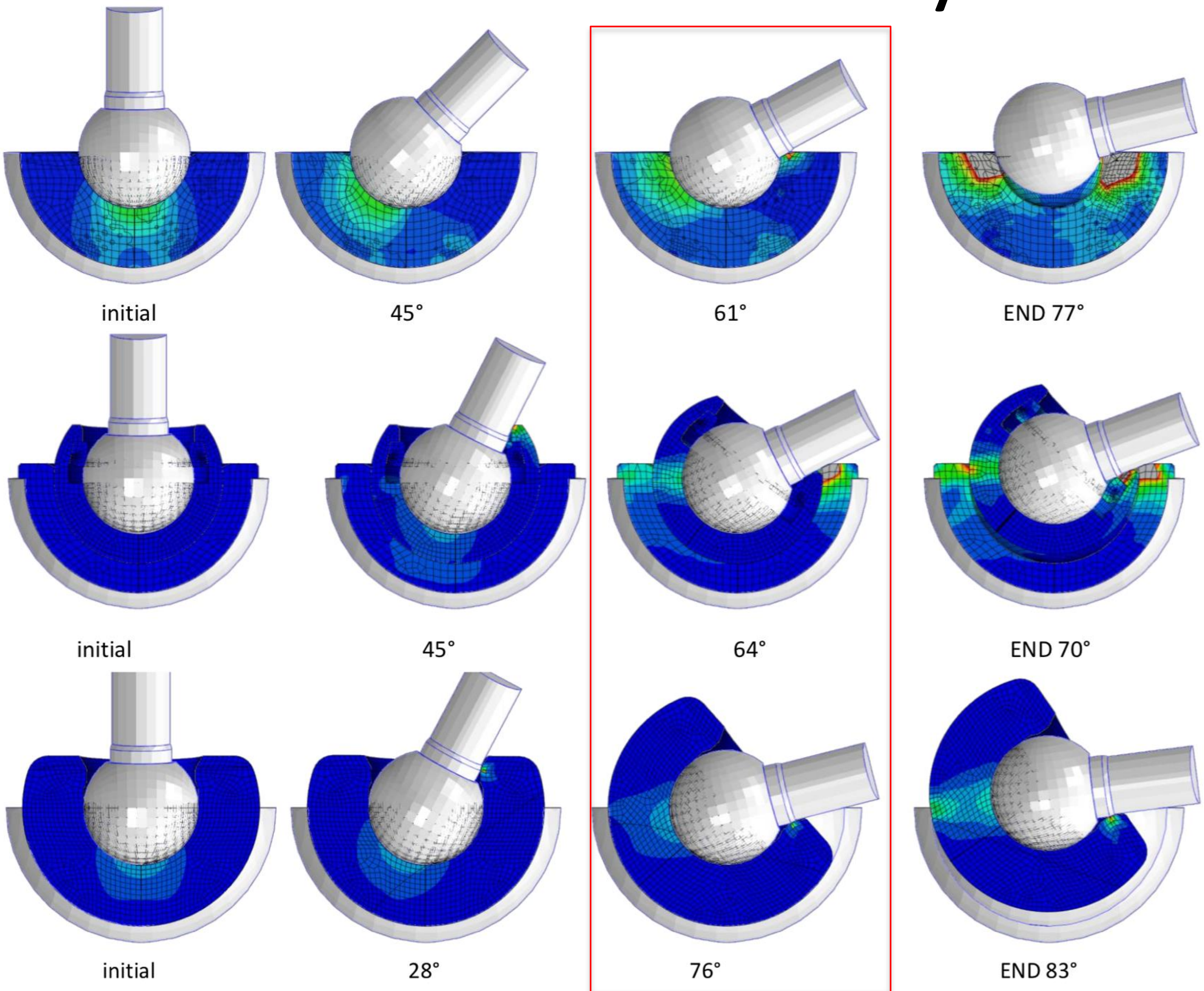
Dual mobility



THA: Dual mobility

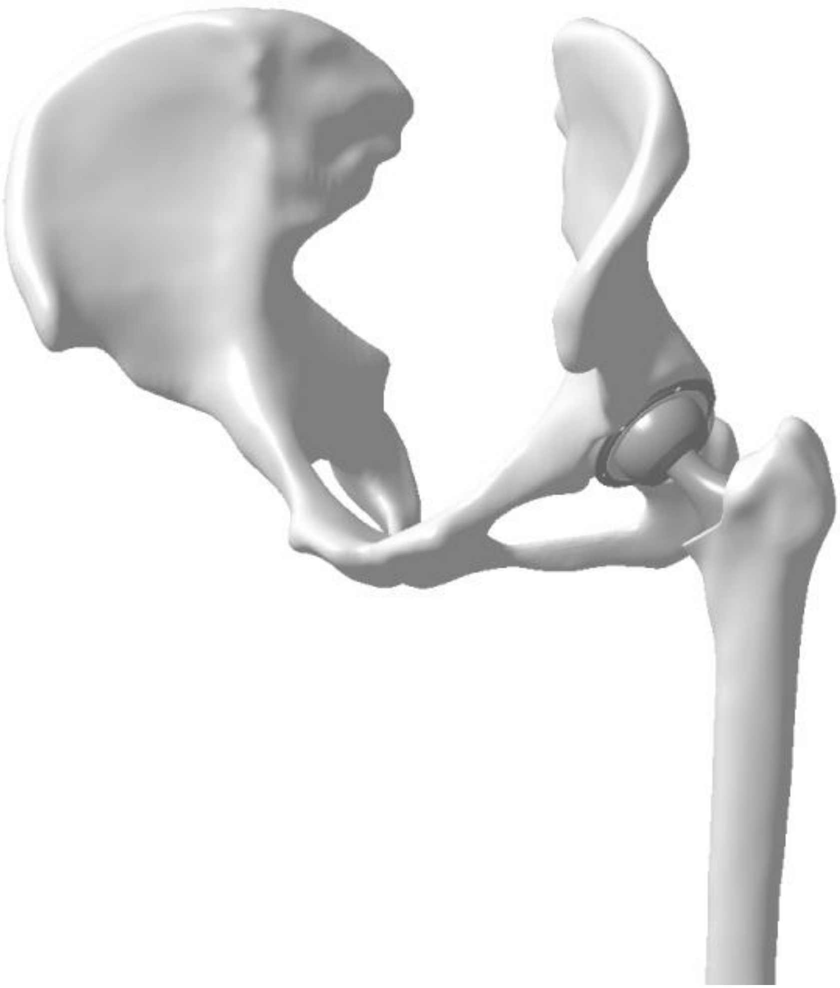


THA: Dual mobility

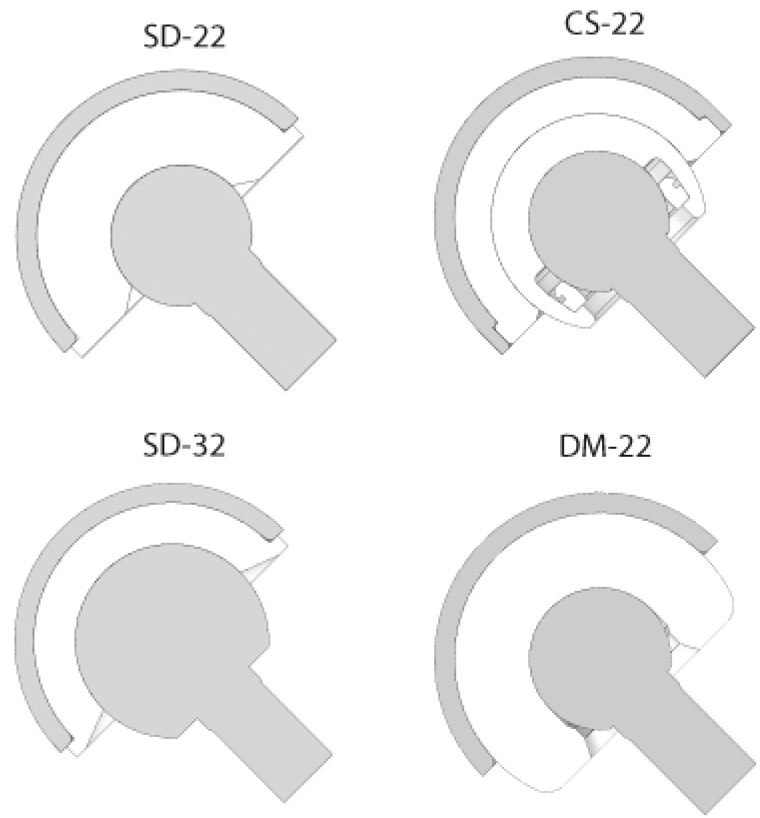


THA: Dual mobility

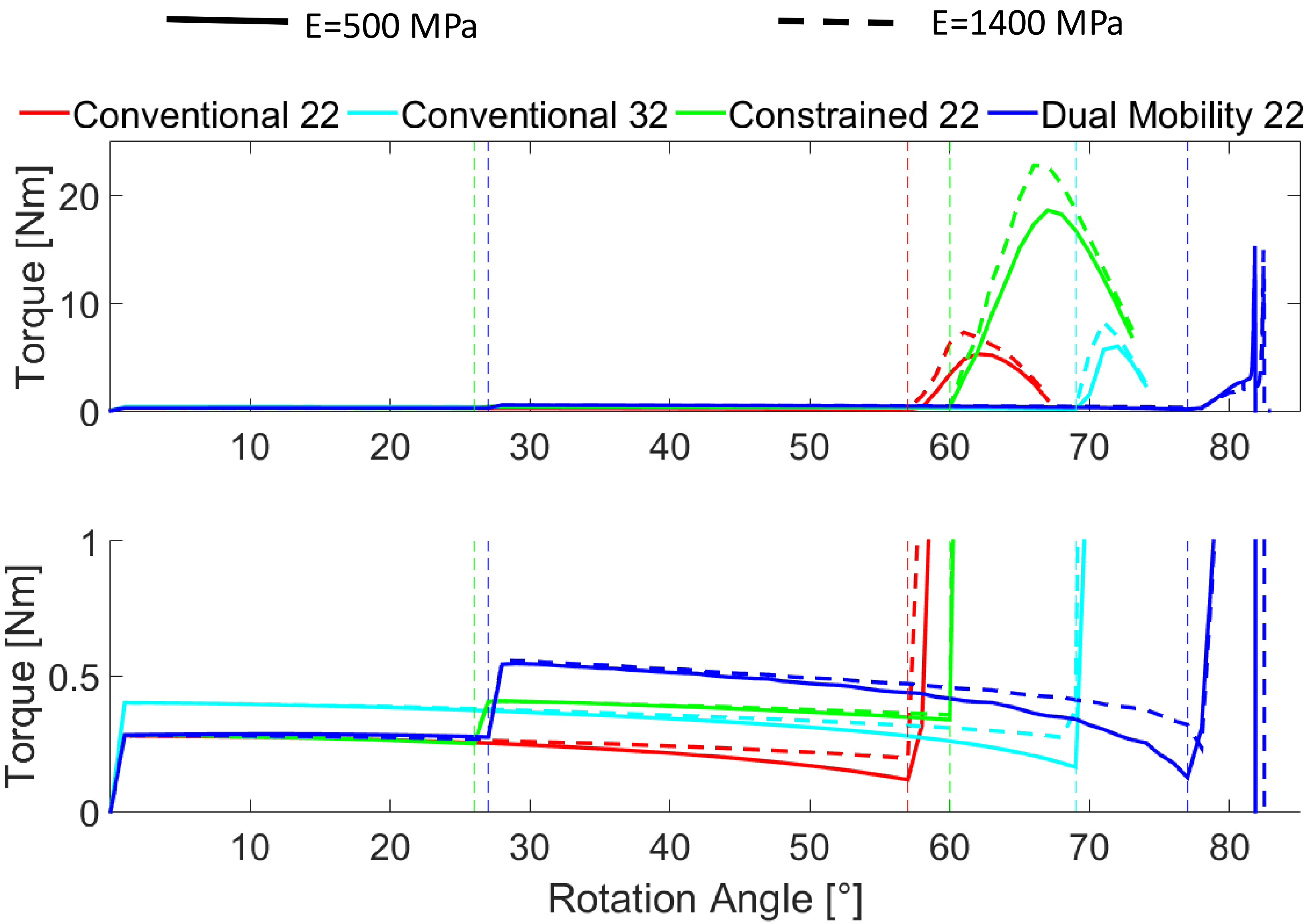
Reconstruction from patient CT



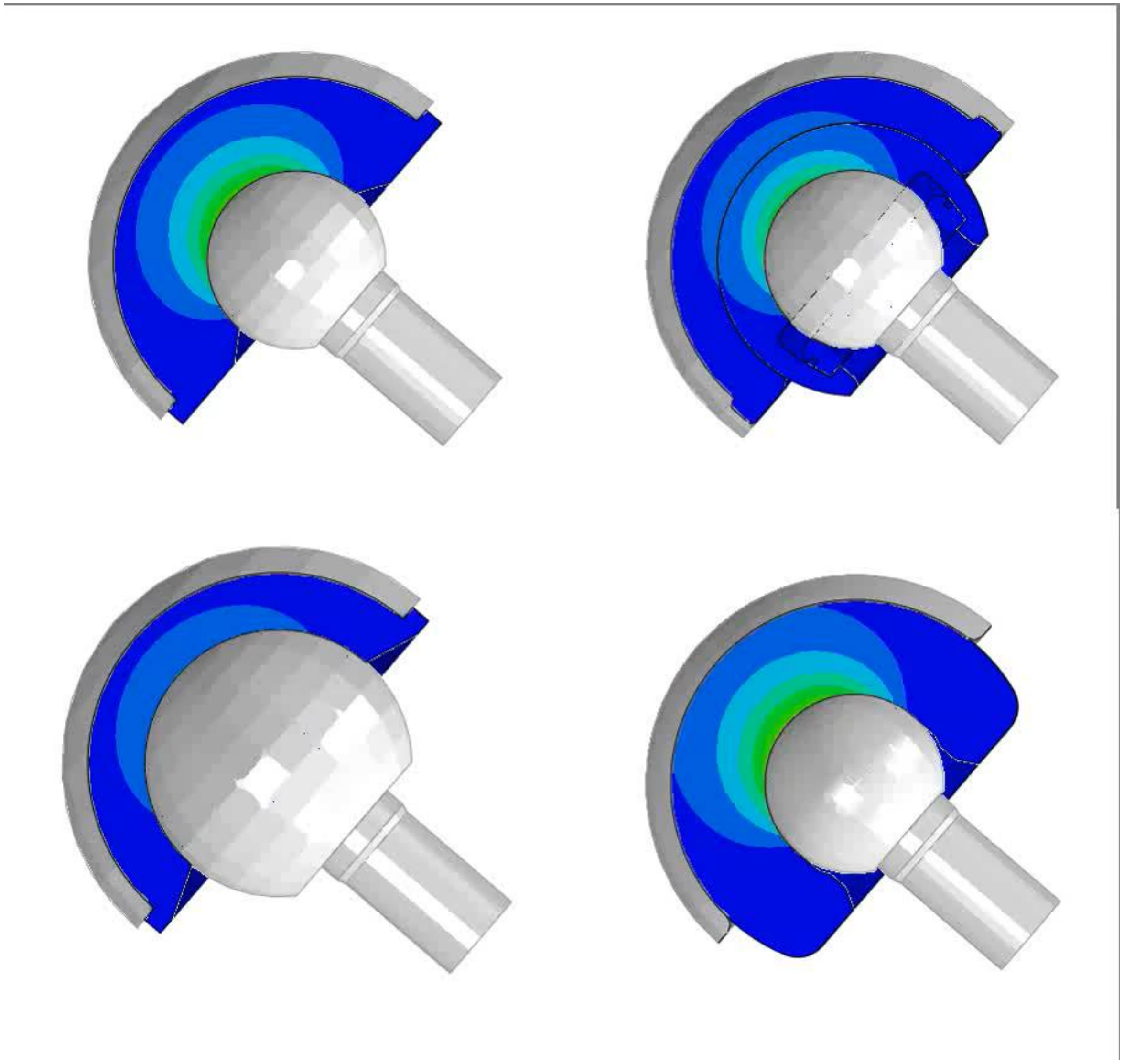
4 types of implants



THA: Dual mobility



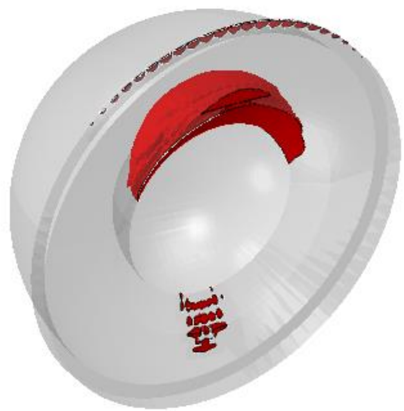
THA: Dual mobility



THA: Dual mobility

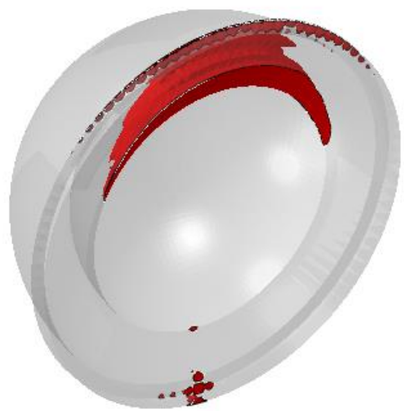
Polyethylene yield stress

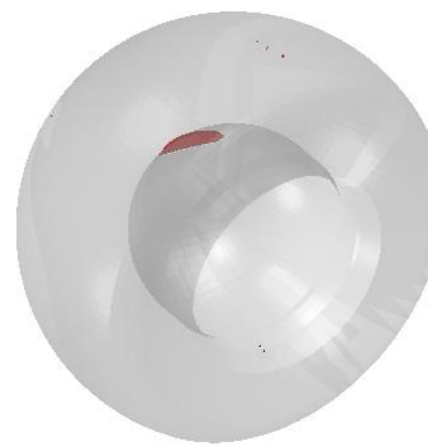
SD-22
(100%)



CS-22
(160%)

SD-32
(130%)



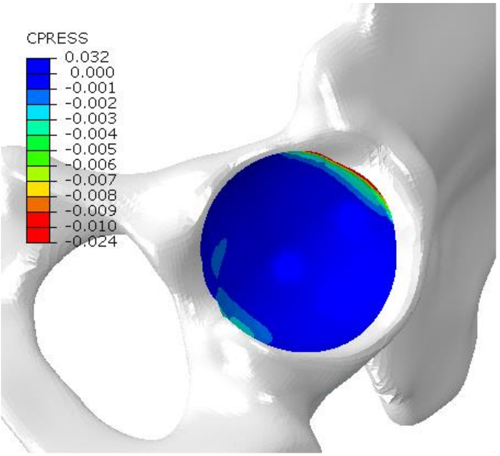


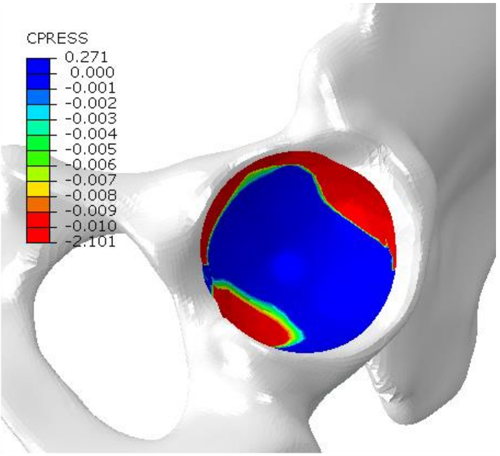
DM-22
(8%)

THA: Dual mobility

Bone-implant tension

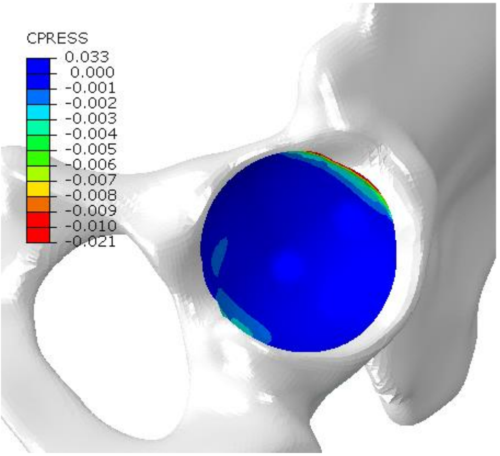
SD-22

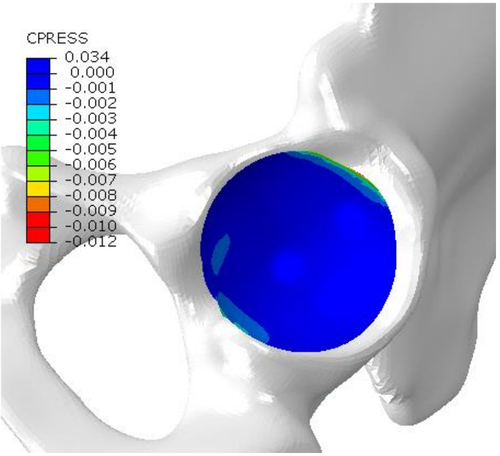




CS-22

SD-32

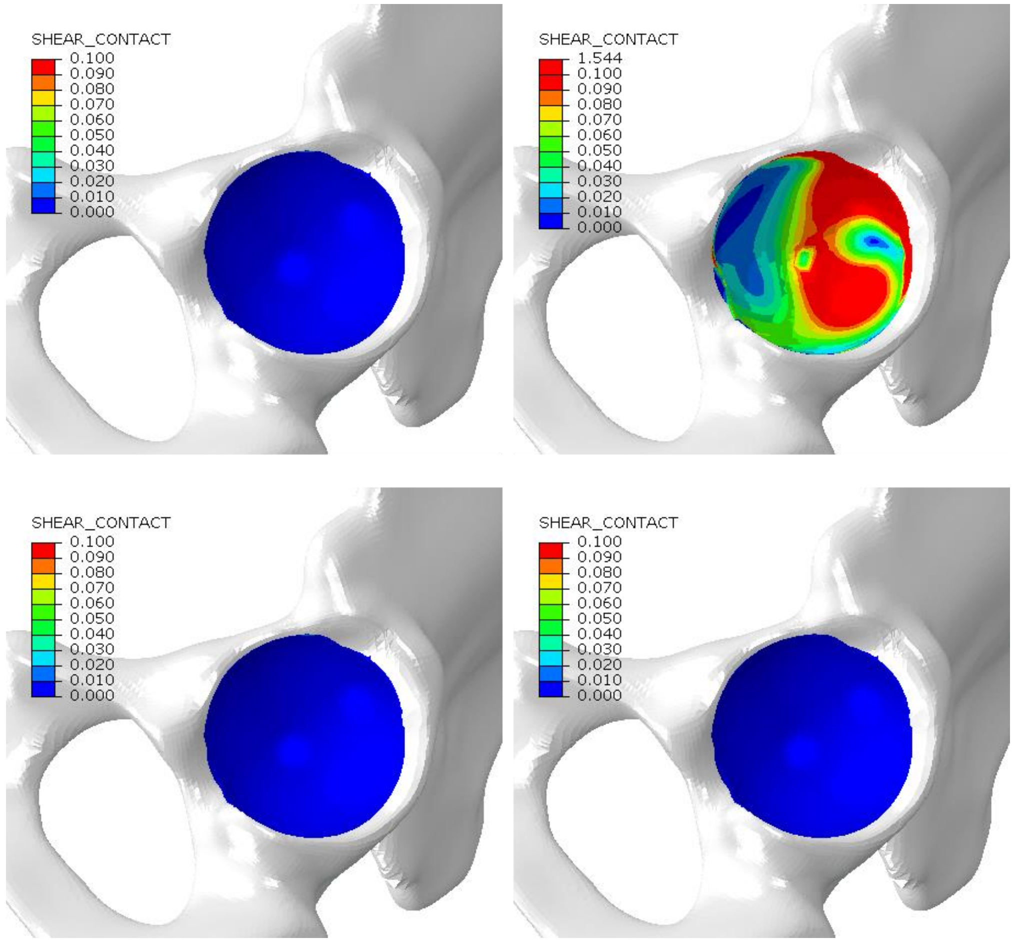




DM-22

THA: Dual mobility

Bone-implant shear



SD-22

CS-22

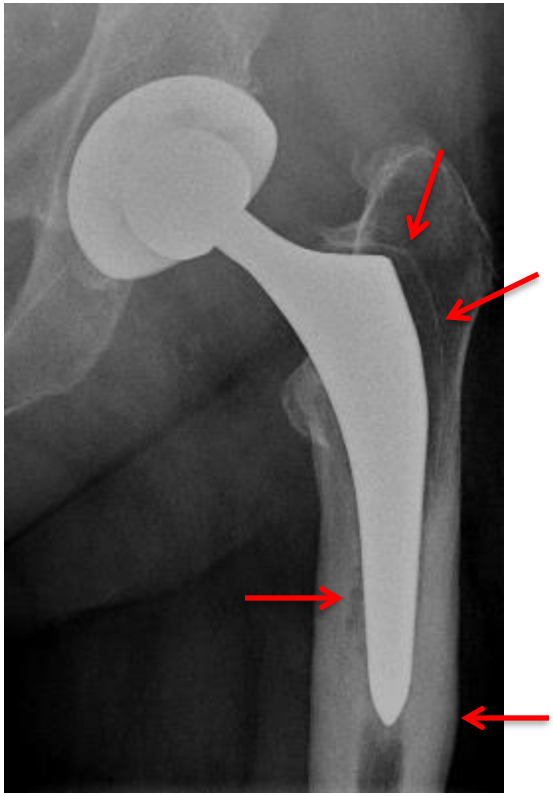
SD-32

DM-22

Primary stability

Clinical Background

- Aseptic loosening is the main cause of revision of cementless THA
- Poor primary stability and excessive micromotions at the bone-implant interface promotes aseptic loosening[1]



[1] Engh et al. CORR 1992;285:13-29.

Reason for Revision

Table HT10: Primary Total Conventional Hip Replacement by Reason for Revision

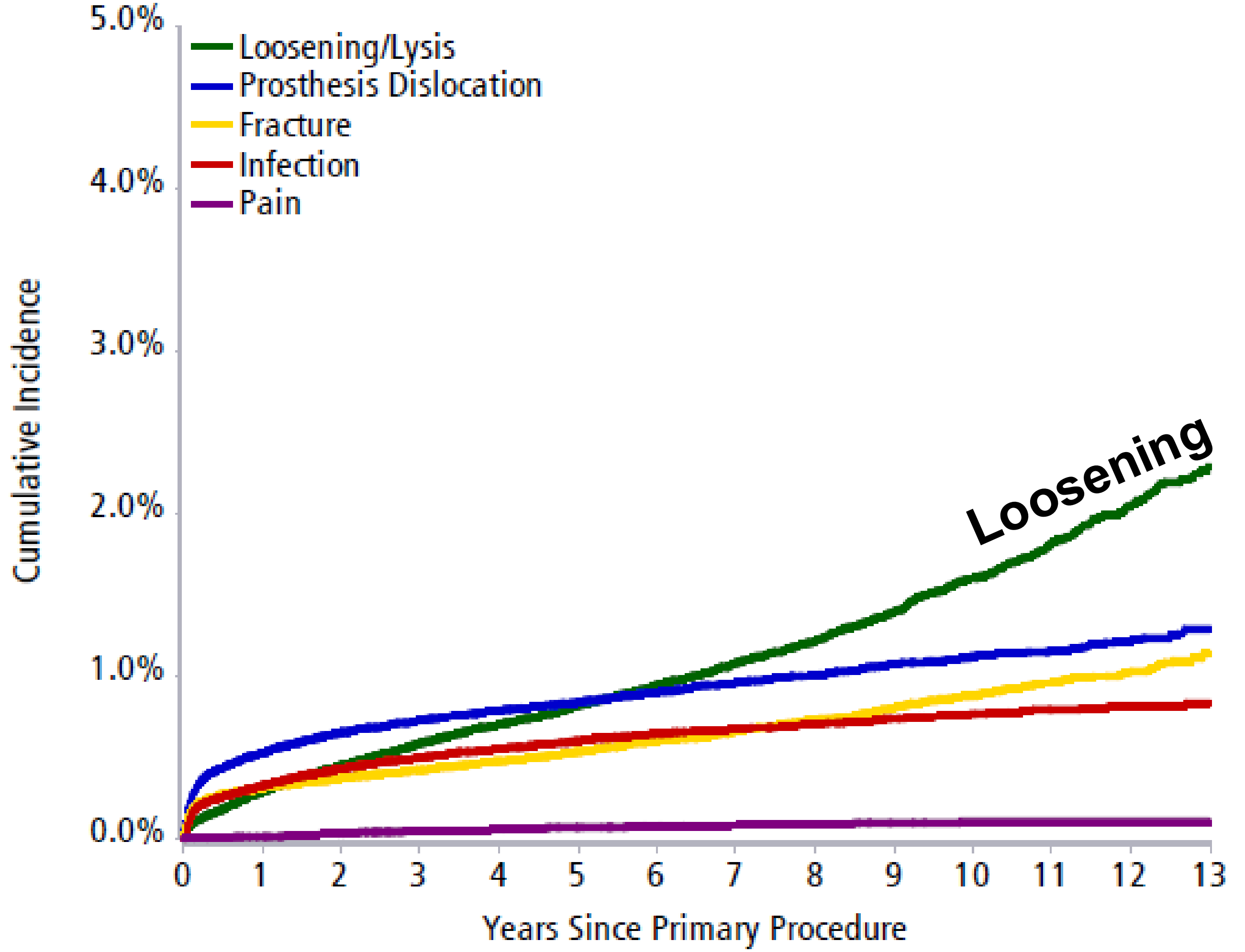
Reason for Revision	Number	Percent
Loosening/Lysis	2550	28.4
Prosthesis Dislocation	2251	25.0
Fracture	1576	17.5
Infection	1534	17.1
Pain	168	1.9
Leg Length Discrepancy	122	1.4
Malposition	108	1.2
Implant Breakage Stem	82	0.9
Instability	77	0.9
Incorrect Sizing	73	0.8
Implant Breakage Acetabular	72	0.8
Implant Breakage Acetabular Insert	69	0.8
Wear Acetabular Insert	58	0.6
Metal Related Pathology	49	0.5
Implant Breakage Head	26	0.3
Other	179	2.0
TOTAL	8994	100.0

Australian Joint Registry – Annual Report 2014

Reason for Revision

Table HT10: Primary Total Conventional Hip Replacement by Reason for Revision

Reason for Revision
Loosening/Lysis
Prosthesis Dislocation
Fracture
Infection
Pain
Leg Length Discrepancy
Malposition
Implant Breakage Stem
Instability
Incorrect Sizing
Implant Breakage Acetabular
Implant Breakage Acetabular Insert
Wear Acetabular Insert
Metal Related Pathology
Implant Breakage Head
Other
TOTAL



Australian Joint Registry – Annual Report 2014

Micromotion, Gap, subsidence

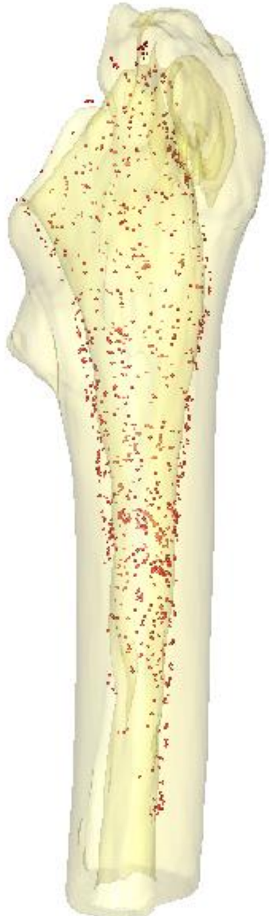
- Micromotion > 150 µm : connective tissue
- Micromotion > 40 µm : bone ingrowth
- Gap > 500 µm : delayed & reduced bone quality
- Subsidence > 5 mm : delayed/no bone ingrowth

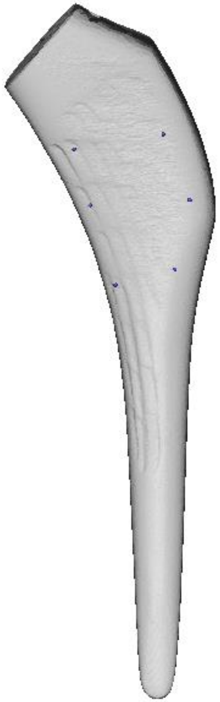
- Pilliar, R.M., J.M. Lee, and C. Maniatopoulos, Observations on the effect of movement on bone ingrowth into porous-surfaced implants. Clin Orthop Relat Res, 1986(208): p. 108-13.
- Jasty, M., C. Bragdon, D. Burke, D. O'Connor, J. Lowenstein, and W.H. Harris, In vivo skeletal responses to porous-surfaced implants subjected to small induced motions. J Bone Joint Surg Am, 1997. 79(5): p. 707-14.
- Soballe, K., E.S. Hansen, H. Brockstedt-Rasmussen, and C. Bunger, Hydroxyapatite coating converts fibrous tissue to bone around loaded implants. J Bone Joint Surg Br, 1993. 75(2): p. 270-8.
- Mavrogenis, A.F., R. Dimitriou, J. Parvizi, and G.C. Babis, Biology of implant osseointegration. J Musculoskelet Neuronal Interact, 2009. 9(2): p. 61-71.
- Engh, C.A., P. Massin, and K.E. Suthers, Roentgenographic assessment of the biologic fixation of porous-surfaced femoral components. Clin Orthop Relat Res, 1990(257): p. 107-28.
- Goodman S, Aspenberg P. Effects of mechanical stimulation on the differentiation of hard tissues. Biomaterials. 1993;14:563–9

In vitro

Bone & Stem markers

Bone
~ 1000 markers
Stainless steal beads
Ø 600 µm

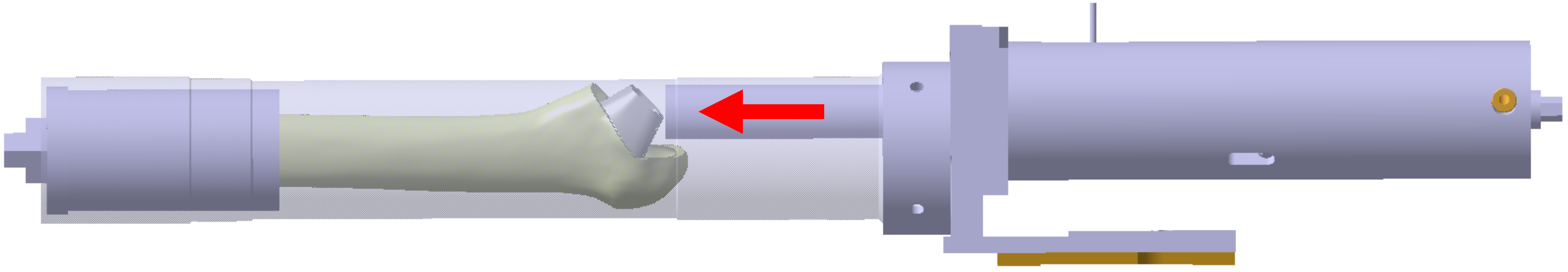




Stem
6 markers
Tantalum beads
Ø 800 µm

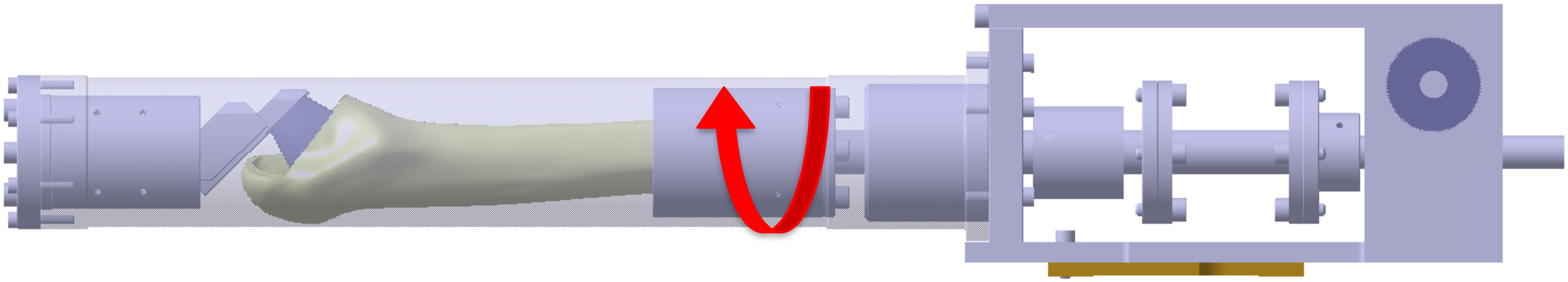
Gortchacow et al., 2011J Biomechanics, 44:557-560

Compression device



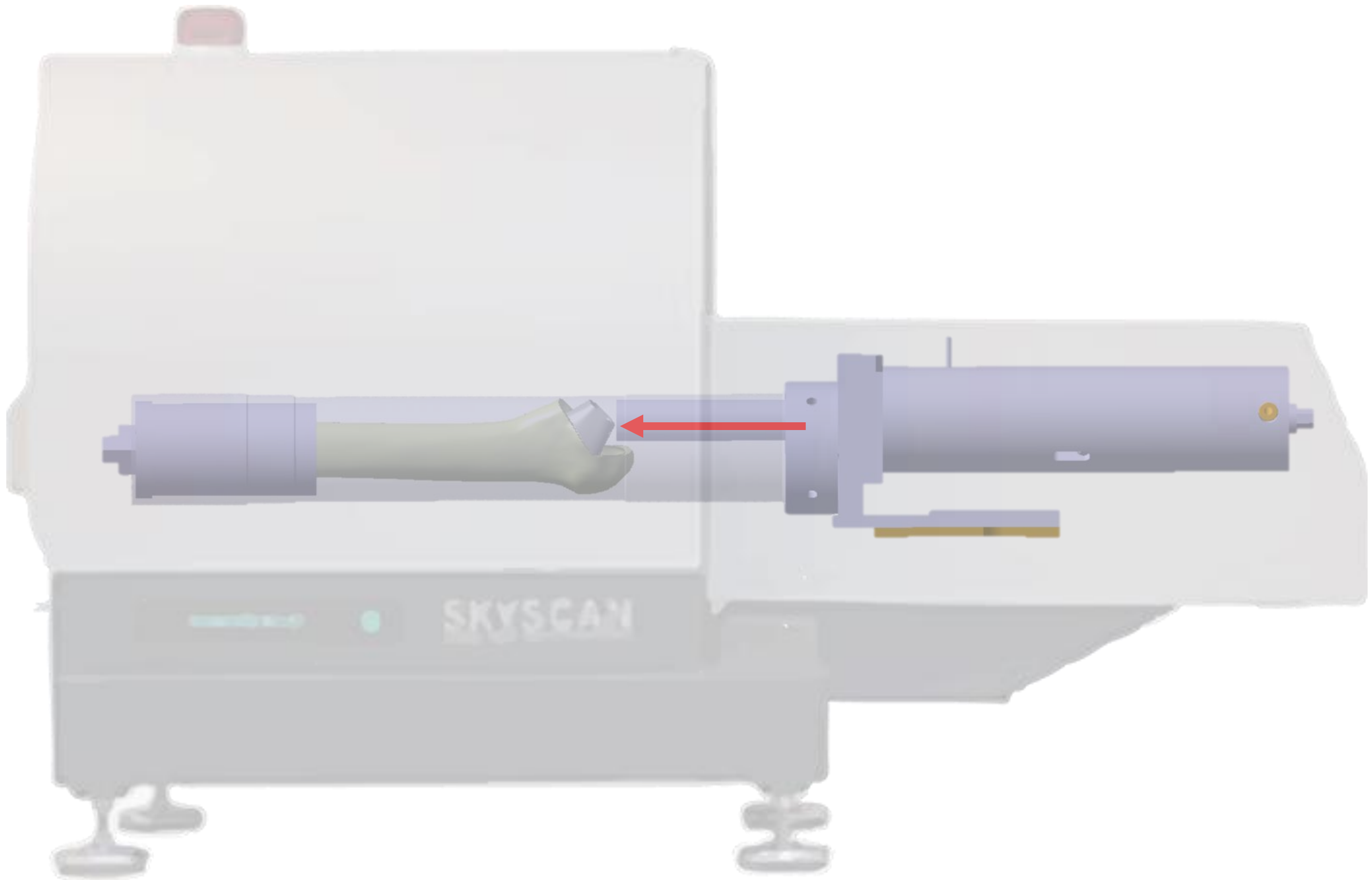
Compression 1800 N

Torsion device



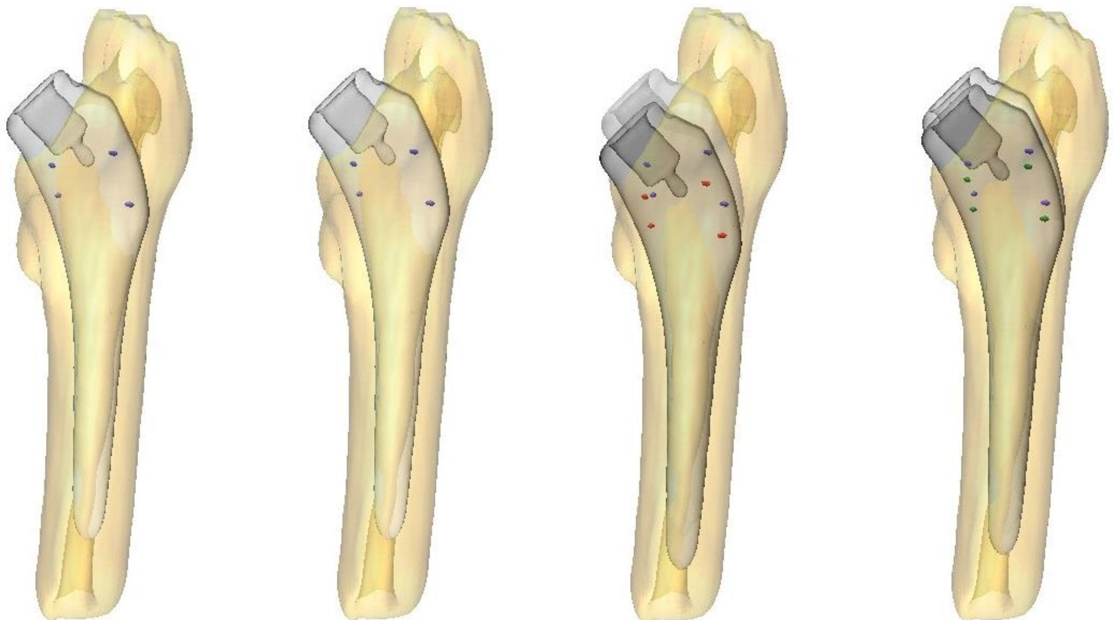
Torsion 14 Nm

Micro-CT



Malfroy Camine V. et al., 2014, ORS 2014 Annual Meeting

4 µCTs



µCT 1: **no load**

µCT 2: **no load**

µCT 3: **load**

µCT 4: **no load**

Error

µCT 2 – µCT 1

Micromotion

µCT 4 – µCT 3

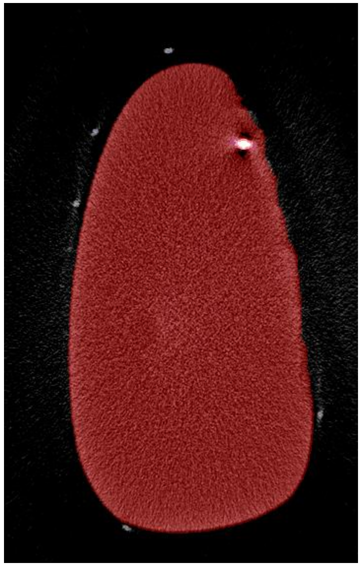
Gap

µCT 4

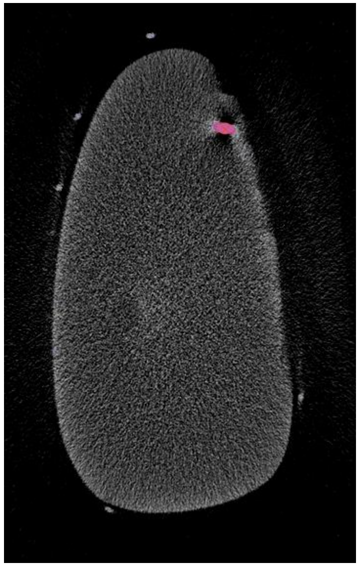
Subsidence

µCT 4 - µCT 2

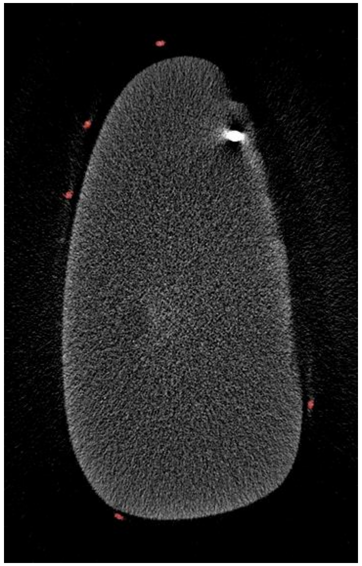
Segmentation



Stem

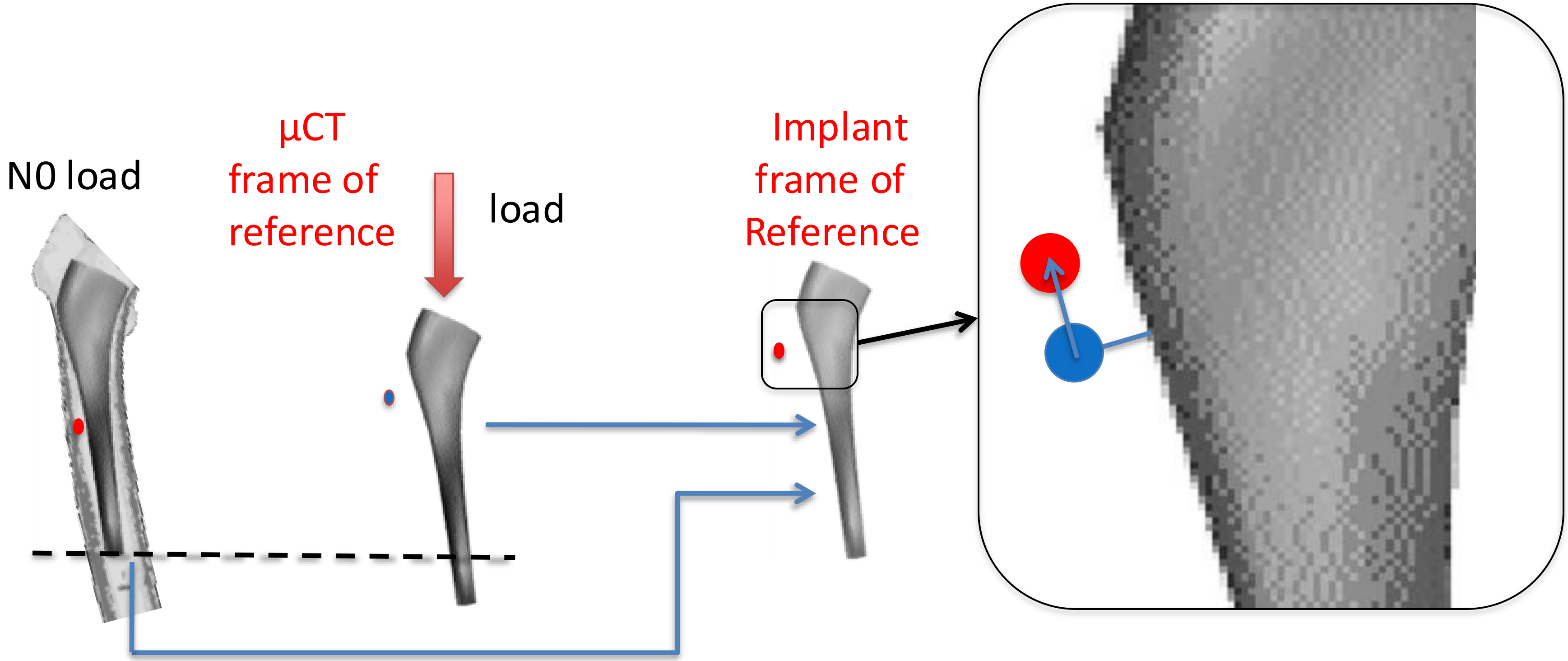


Stem markers

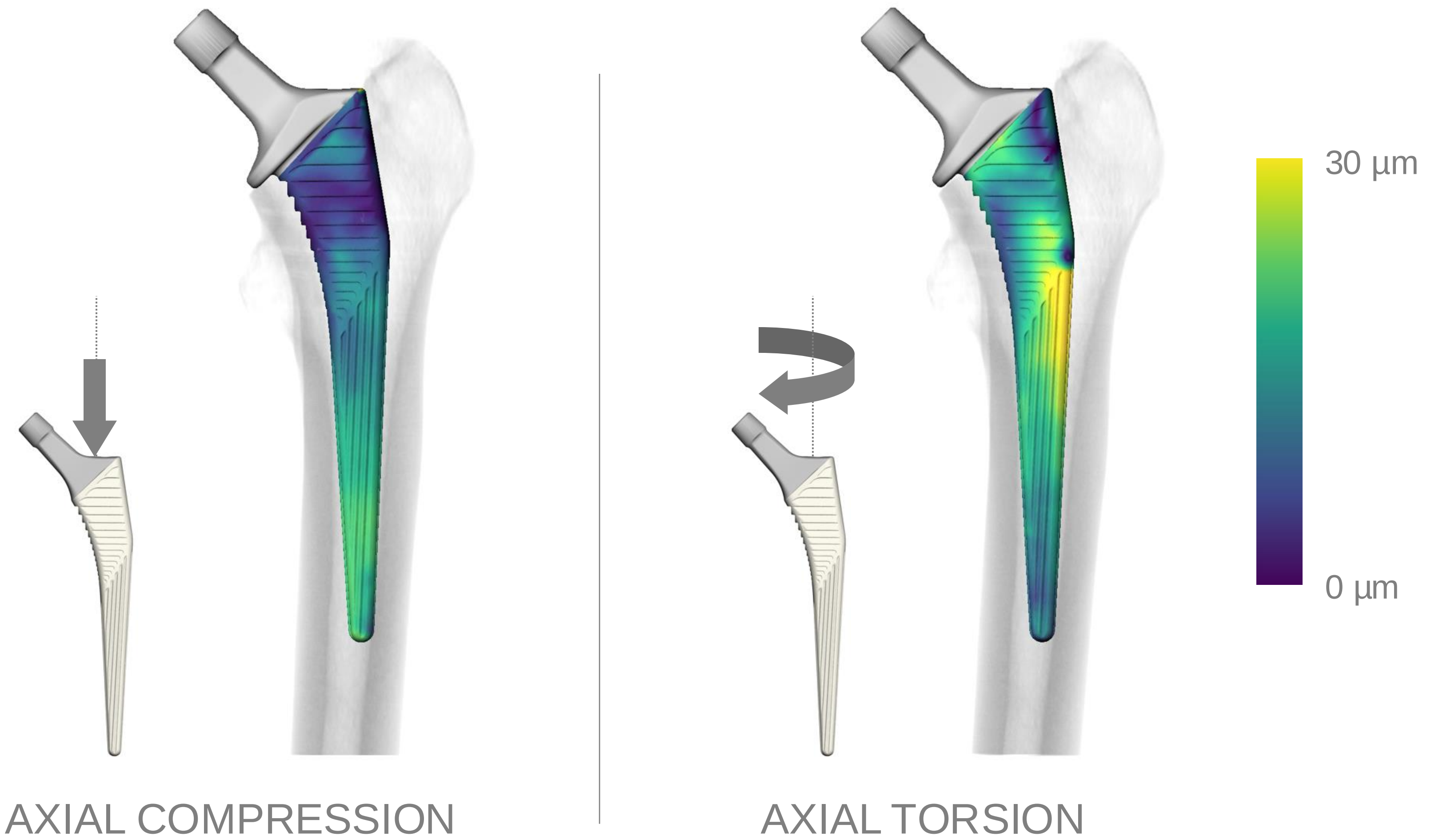


Bone markers

Micromotions



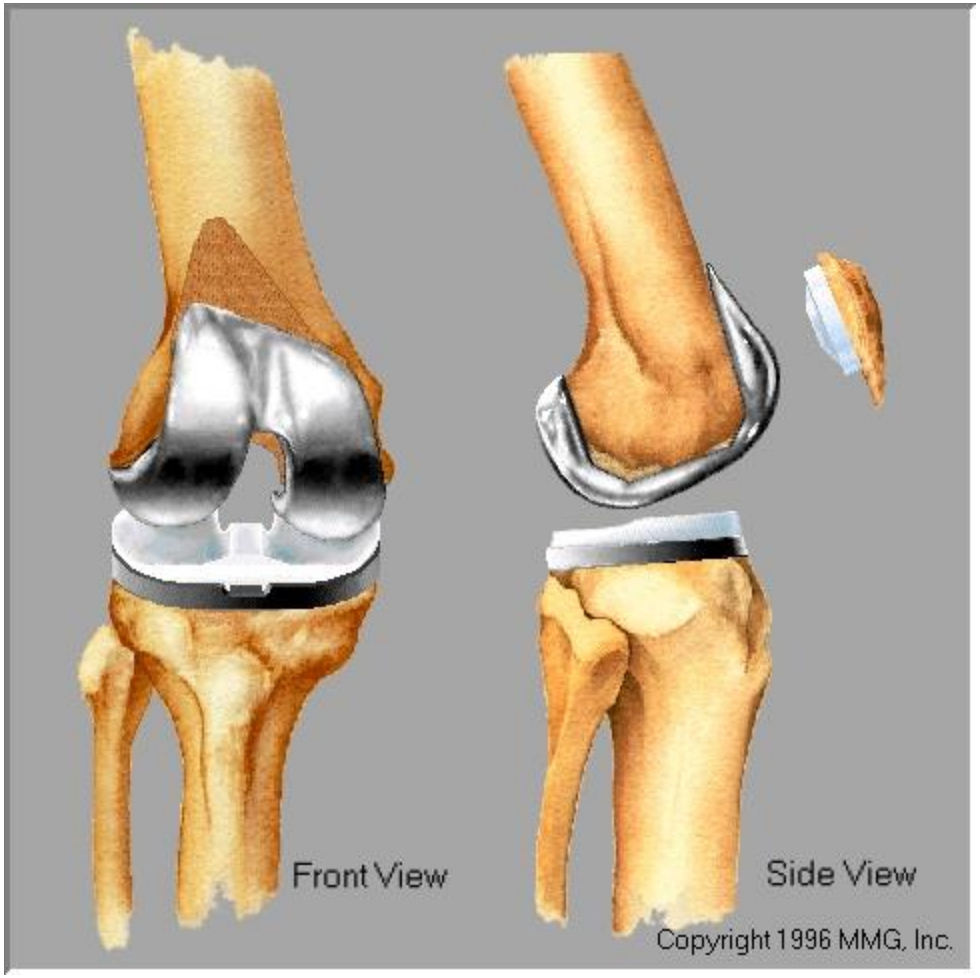
Micromotion



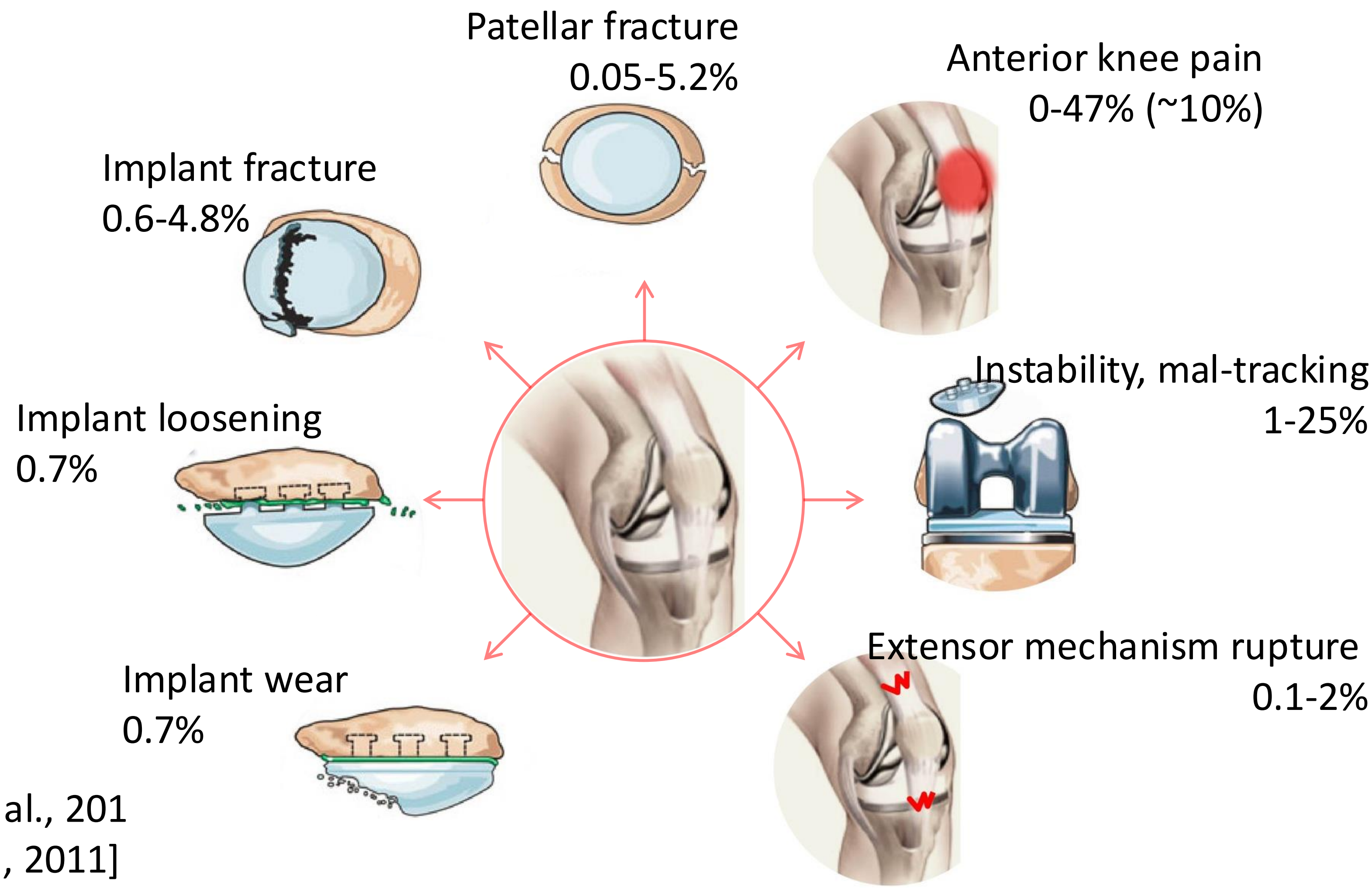
Malfroy Camine et al. International Orthopaedics (2017). https://doi.org/10.1007/s00264-017-3524-0

Comparisons of design philosophies

Total Knee Arthroplasty (TKA)



TKA: patella problem

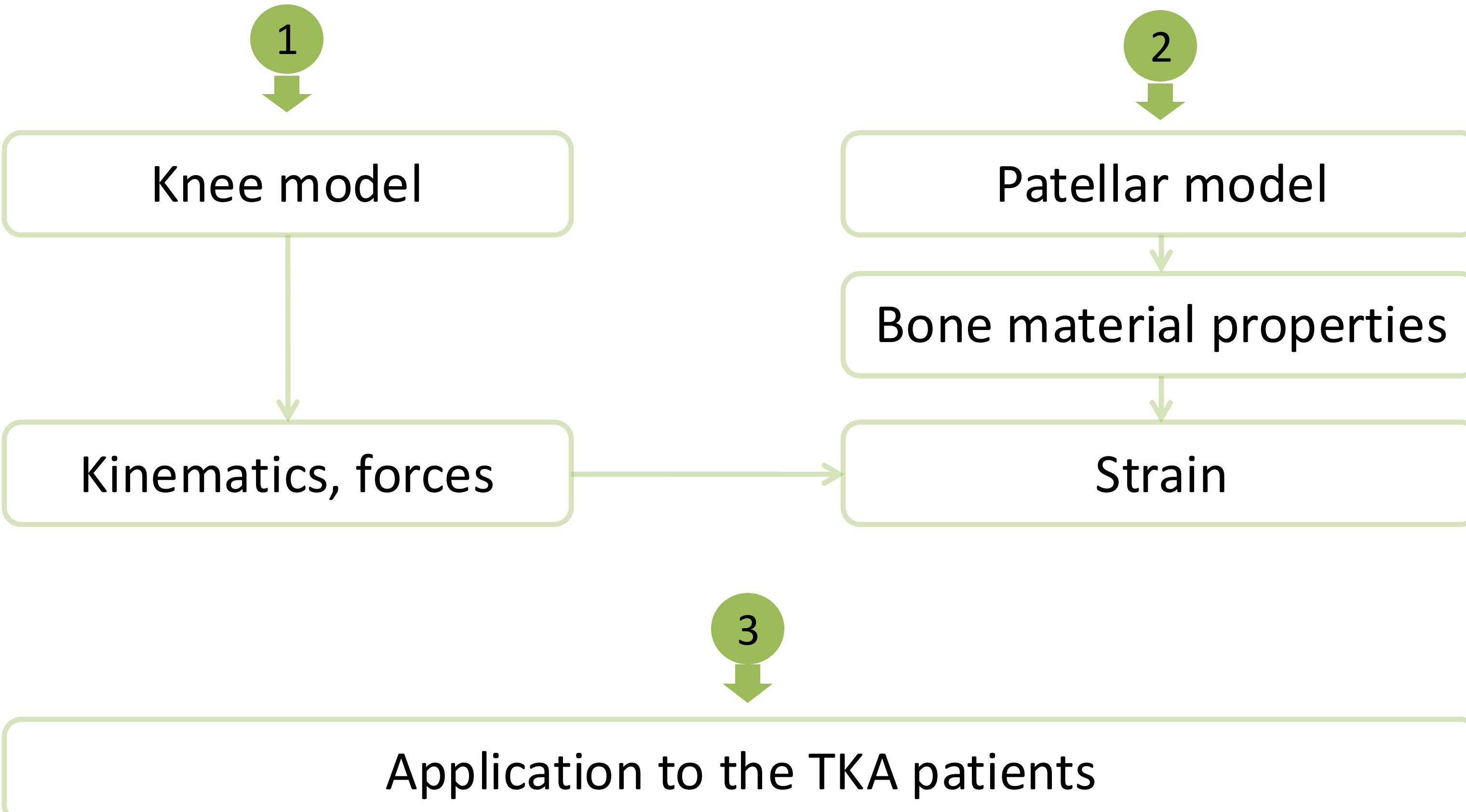


[Bozic et al., 201
[He et al., 2011]
[Schindler, 2012]
[Sundberg et al., 2014]
[Kurtz et al., 2007, 2011]

~ 1.1 million TKA per year in USA and Europe!

↑ number of young and active patients

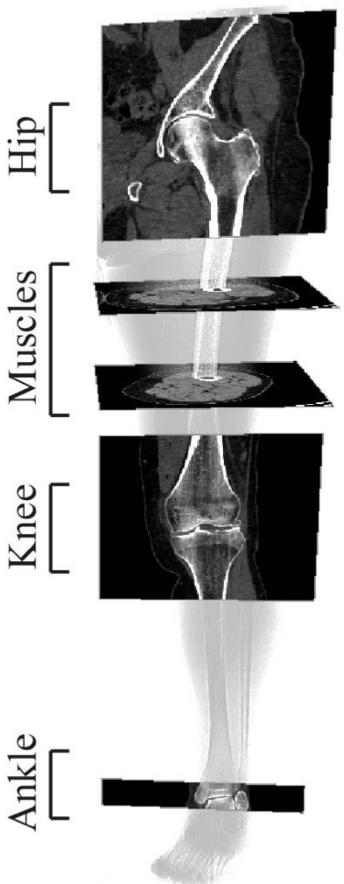
Patient-specific TKA model for patella



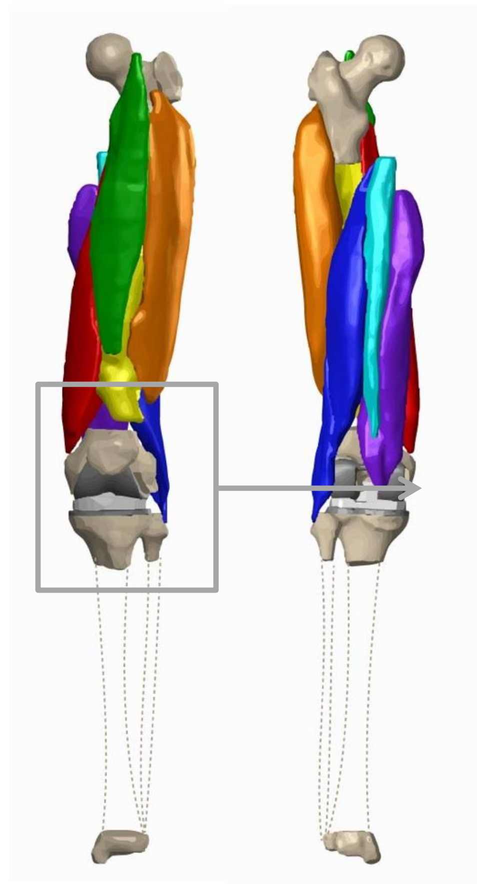
Latypova, 2015

KNEE MODEL: GEOMETRY

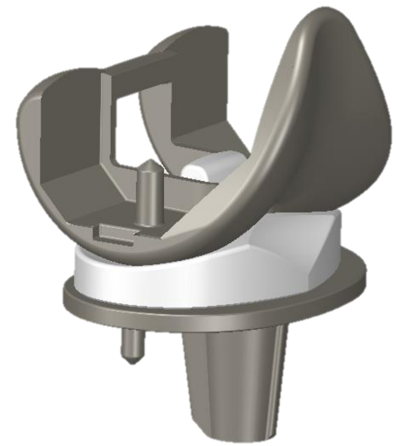
CT protocol



Geometry reconstruction
Implant positioning



SYMBIOS

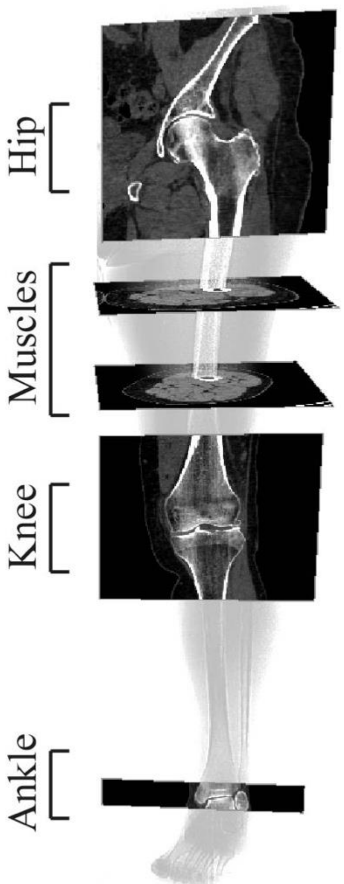


- Ultra-congruent
- Mobile-bearing
- Resurfaced patella

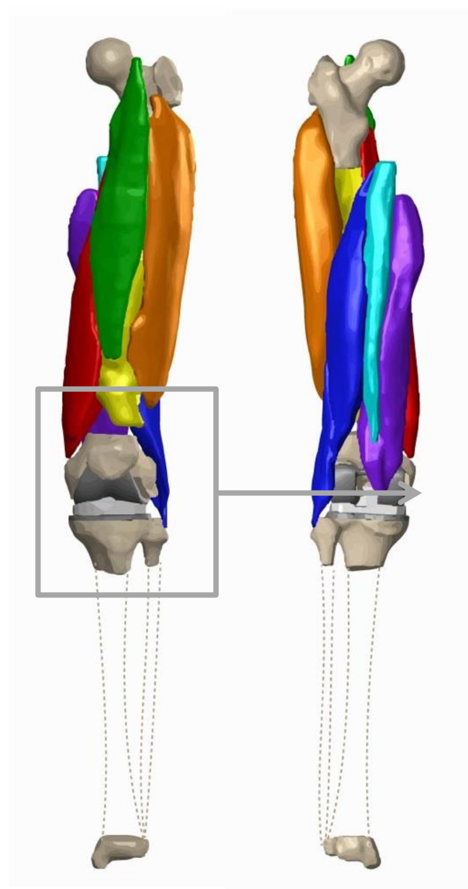
CHUV

KNEE MODEL: GEOMETRY

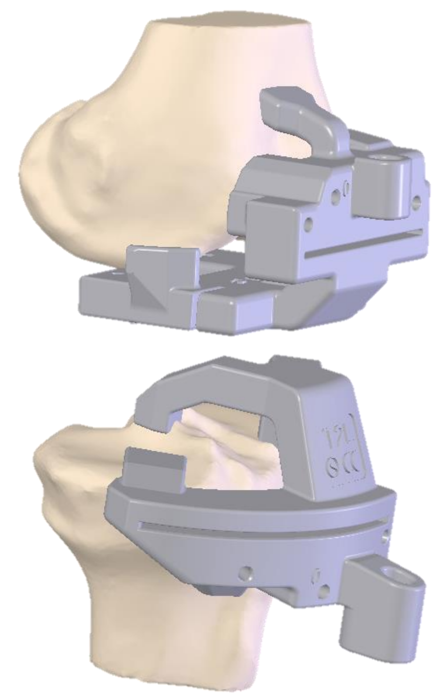
CT protocol



Geometry reconstruction
Implant positioning



SYMBIOS

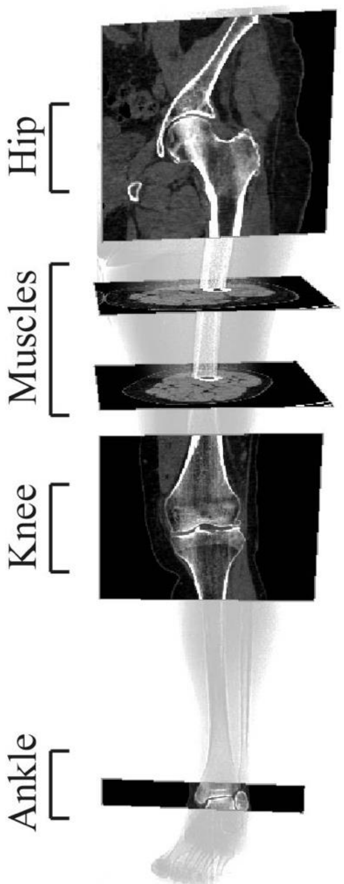


- patient-specific cutting tools

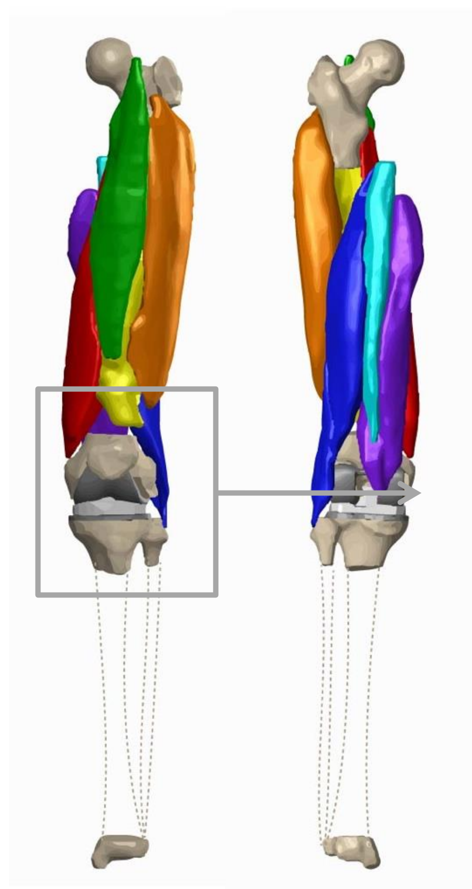
CHUV

KNEE MODEL: GEOMETRY

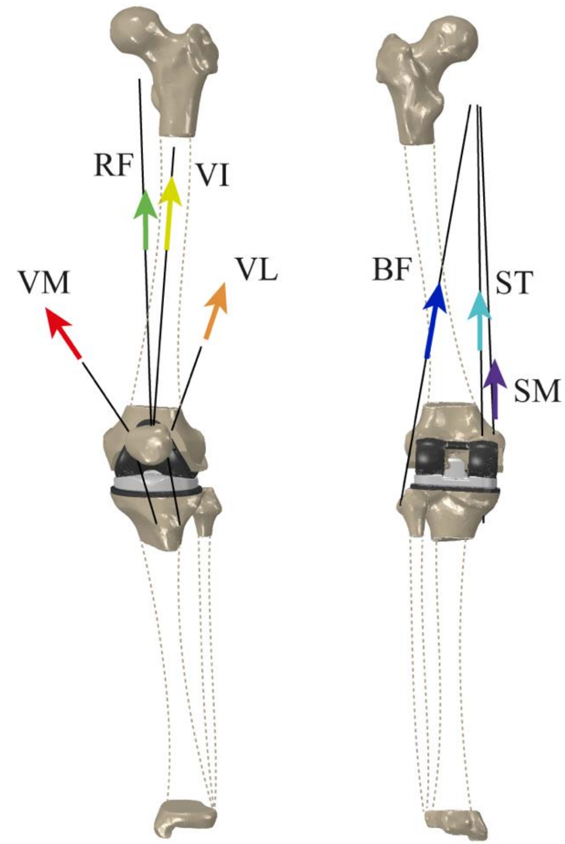
CT protocol



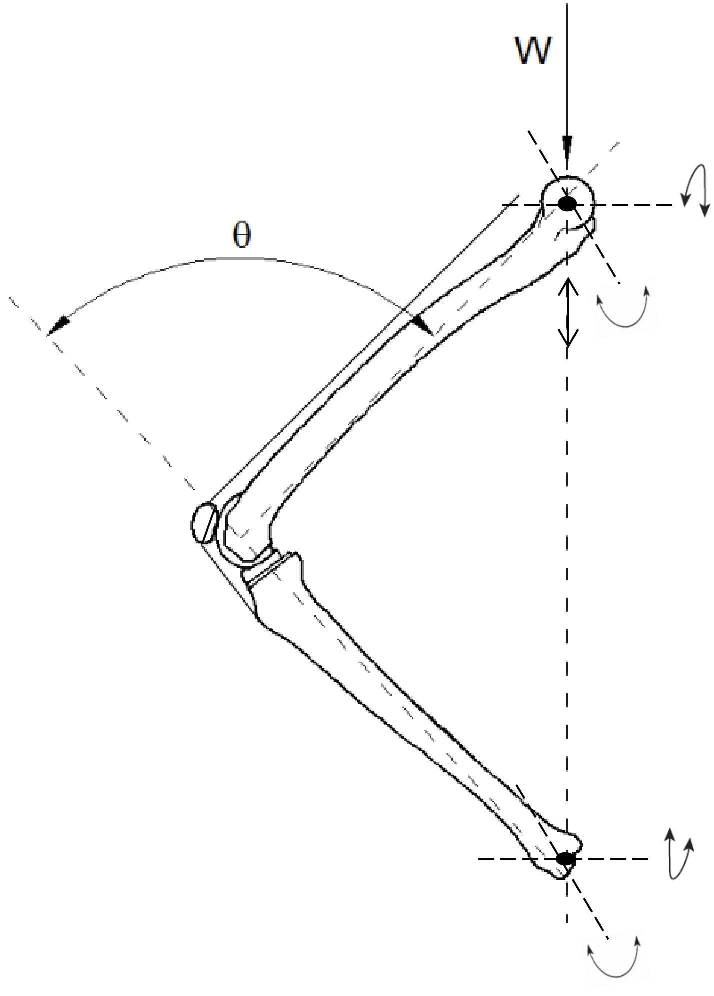
Geometry reconstruction
Implant positioning



SYMBIOS



KNEE MODEL: BOUNDARY CONDITIONS



- Ankle: 2 DoF

  Flexion/extension
  Adduction/abduction

- Hip: 3 DoF

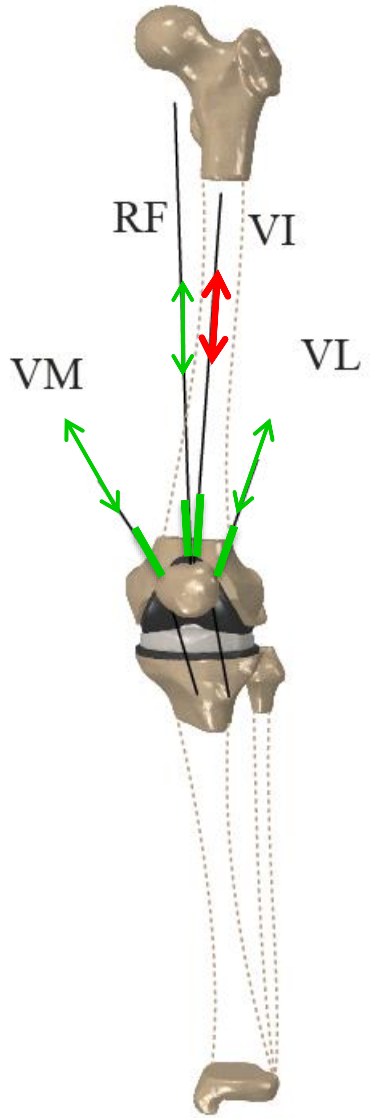
  Superior/inferior translation
  Flexion/extension
  Adduction/abduction

- Patella: 6 DoF

- Contacts:

  Patellofemoral
  Tibiofemoral

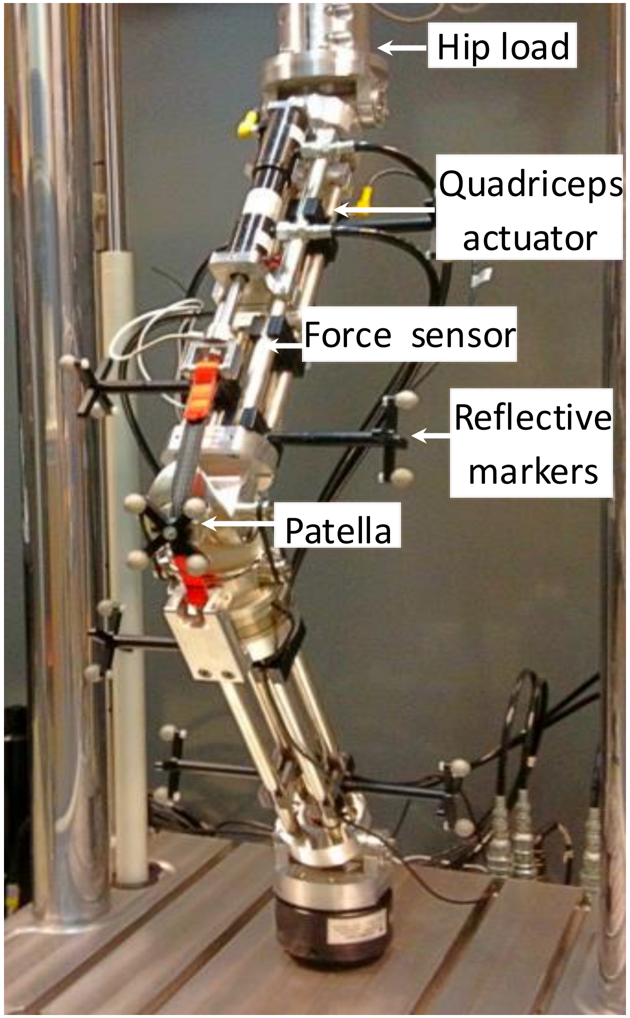
KNEE MODEL: EXTENSOR MECHANISM



- Muscle: passive (tendon) + active (UEL)
- Control: muscle elongation + feedback algorithm[1]
- Force in muscles distributed according muscle ratios
- Constant ratios as product of PSCA (patient) and EMG (literature)[2]
- Patellar tendon: non-linear spring[3]

[1] [Terrier et al., 2007]
[2] [Dionisio et al., 2008; Yavuz et al., 2015]
[3] [Staubli et al., 1996]

KNEE MODEL: VALIDATION



LMAM, EPFL

- Static squat: 10 to 60° (each 5°)
- Body load 300 N
- Self-learning algorithm [1]

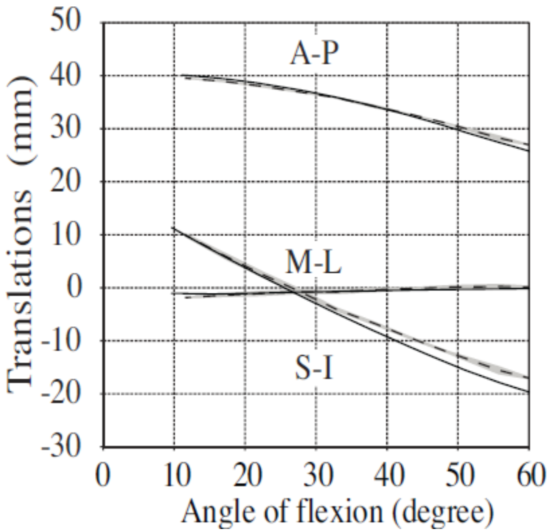
Measurements:

- Quadriceps force
- Patellar kinematics

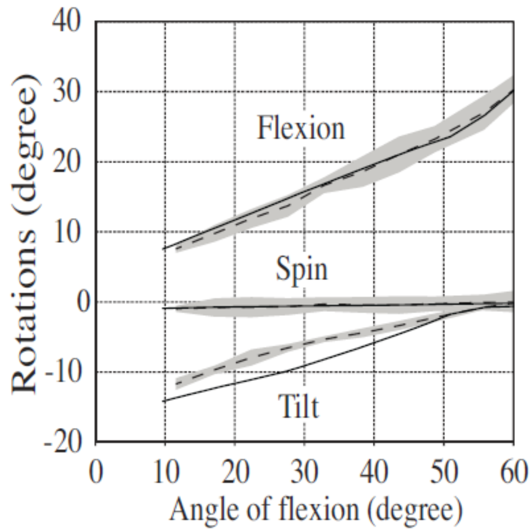
[1] [Arami et al.,2008]

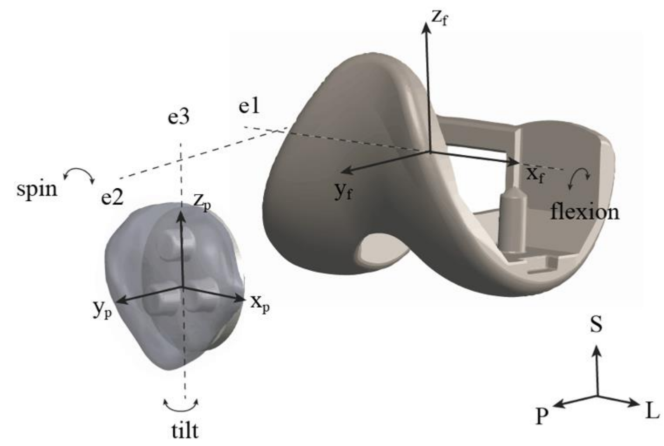
KNEE MODEL: VALIDATION

Average error: 0.6 mm



:1.1 degree

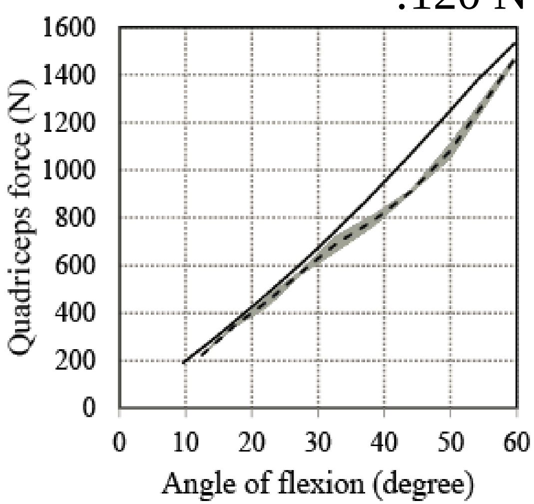




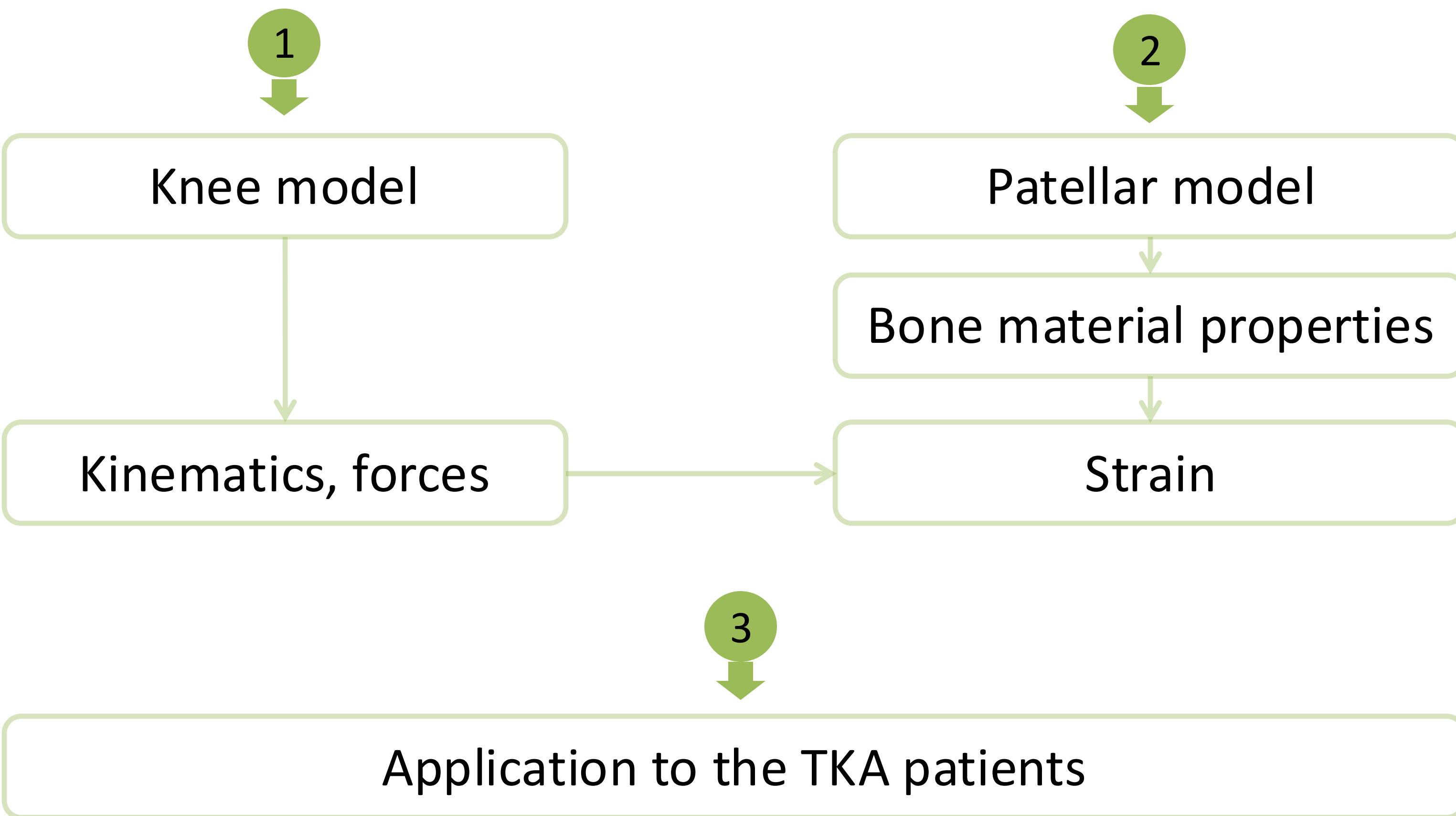
Three-cylinder open-chain system

[Grood and Suntay, 1983]

:120 N



Patient-specific TKA model for patella



Latypova, 2015

Patellar bone model

Anisotropic linear elastic material $\varepsilon = C\,\sigma$

Morphology – elasticity relationship (Zysset – Curnier)[1]

$$C = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & & & \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & & 0 & \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & & & \\ & & & \frac{1}{2G_{23}} & & \\ & 0 & & & \frac{1}{2G_{13}} & \\ & & & & & \frac{1}{2G_{12}} \end{bmatrix}$$

$$E_i = E_0 \rho^k m_i^{2l}$$

$$\frac{E_i}{\nu_{ij}} = \frac{E_0}{\nu_0} \rho^k m_i^l m_j^l$$

$$G_{ij} = G_0 \rho^k m_i^l m_j^l$$

$$\forall\, i \neq j = 1,2,3$$

M : fabric tensor[2]

ρ : BV/TV

E_0, ν_0, G_0, k, l : constants to identify

<u>anisotropic model</u>

$$M = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix}$$

$$m_1 \leq m_2 \leq m_3, tr(M) = 3$$

<u>isotropic model</u>

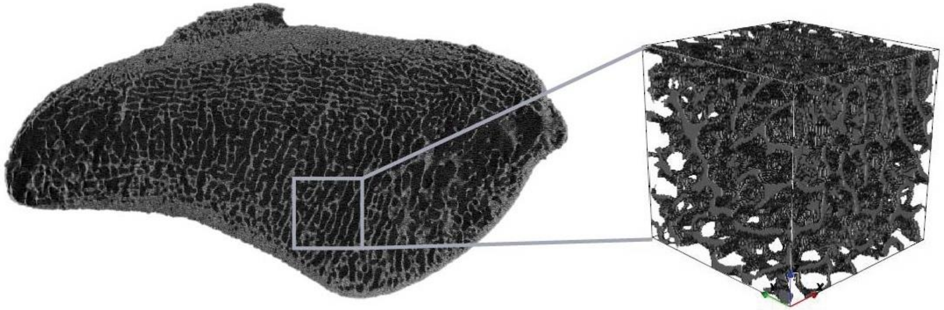
$$M = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

[1] [Zysset , Curnier, 1995]
[2] [Cowin, 1995]

IDENTIFICATION

μCT: 20 patellae

200 cubes (5.3 mm)

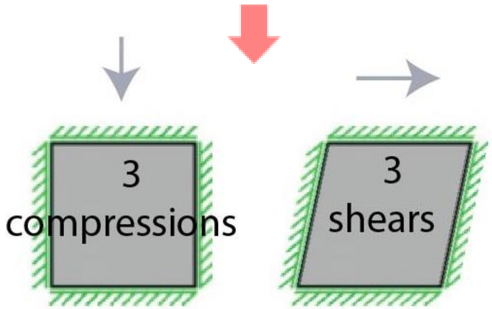


- Each voxel to hex element (E=12 GPa, v=0.3)[1]

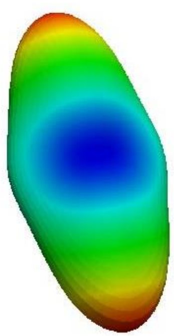
[1][Wolfram, 2010, 2012]

- KUBC[2]

[2][Pahr and Zysset, 2008]

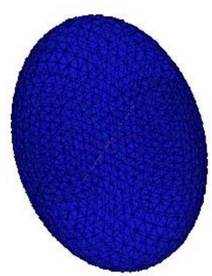


Stiffness



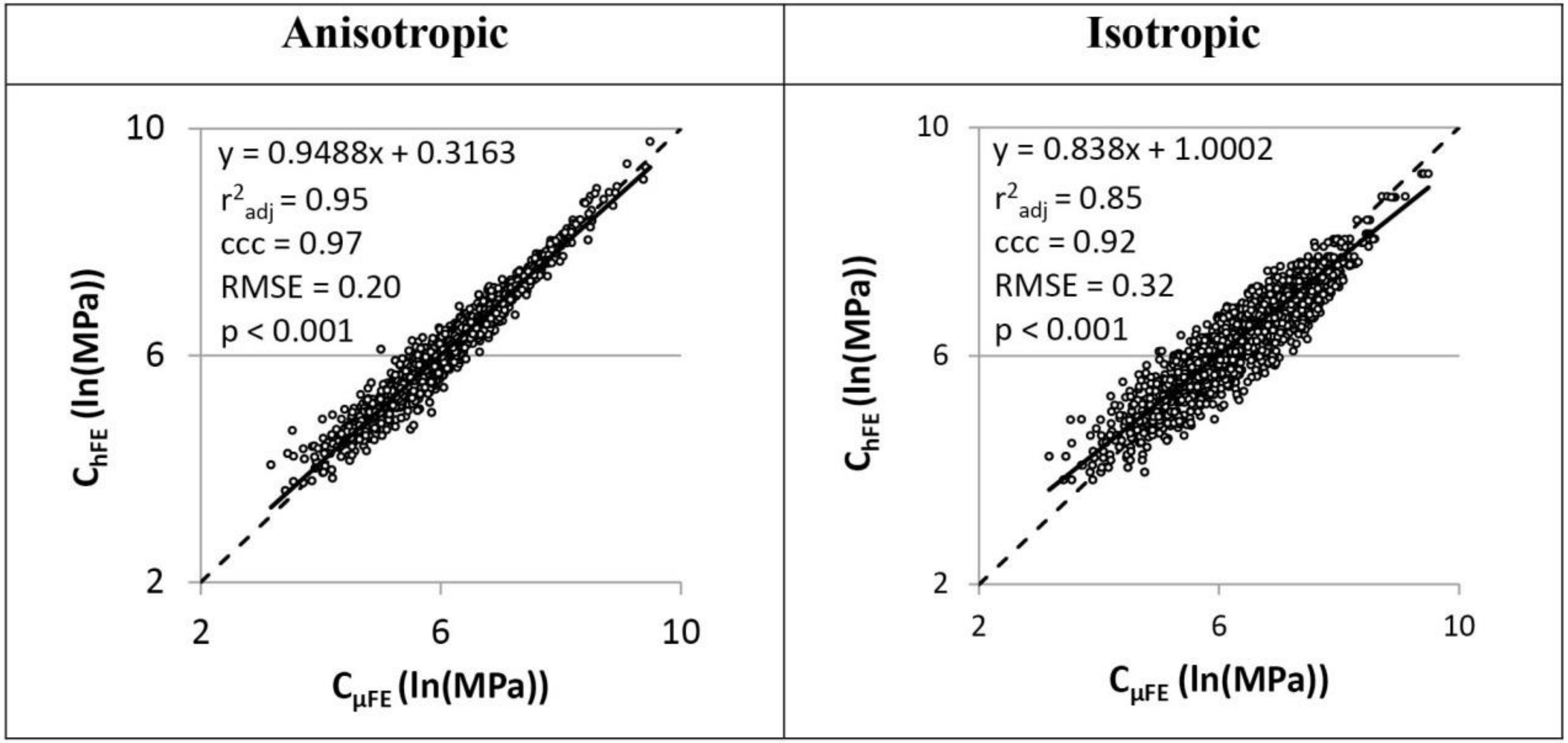
+

Fabric (MIL) + ρ



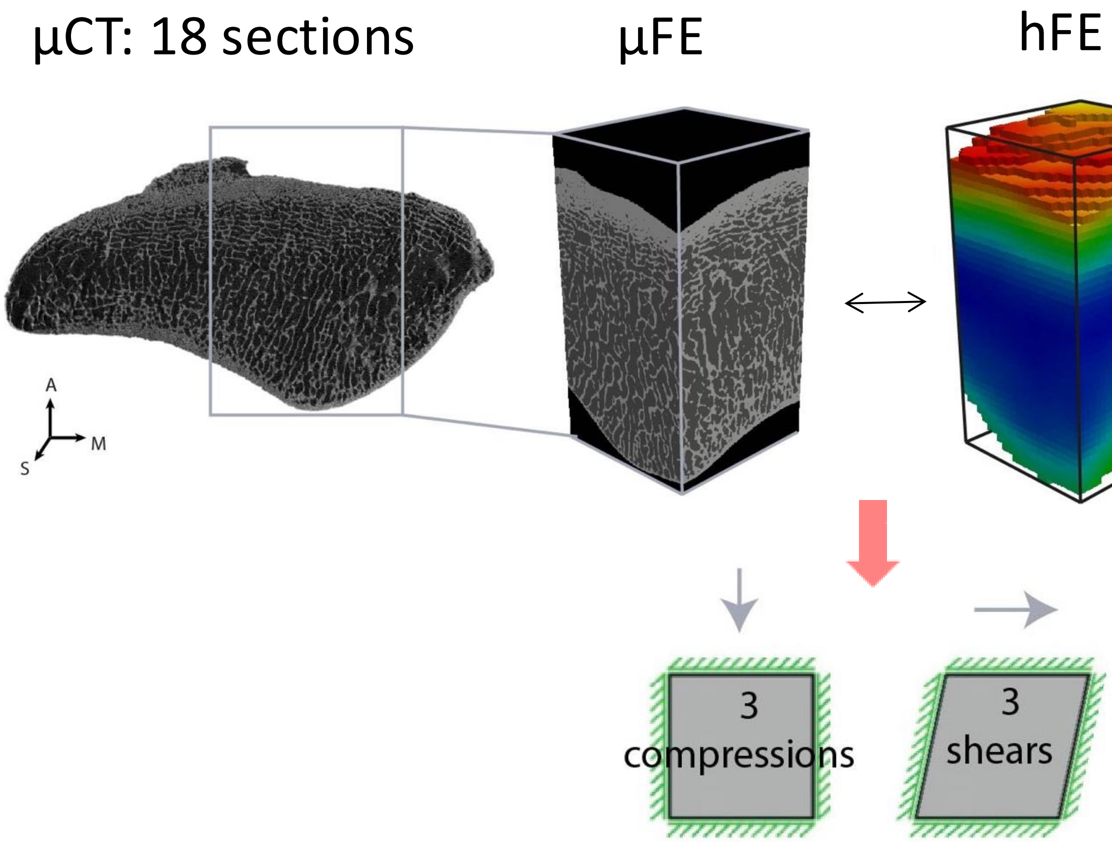
Constants: E_0, v_0, G_0, k, l

IDENTIFICATION



Law	E_0 (MPa)	ν_0	G_0 (MPa)	k	l
Anisotropic	12723.05	0.24	4224.62	2.1	1.02
Isotropic	11035.98	0.26	4395.05	2.13	-

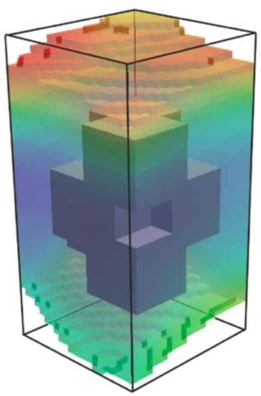
VALIDATION



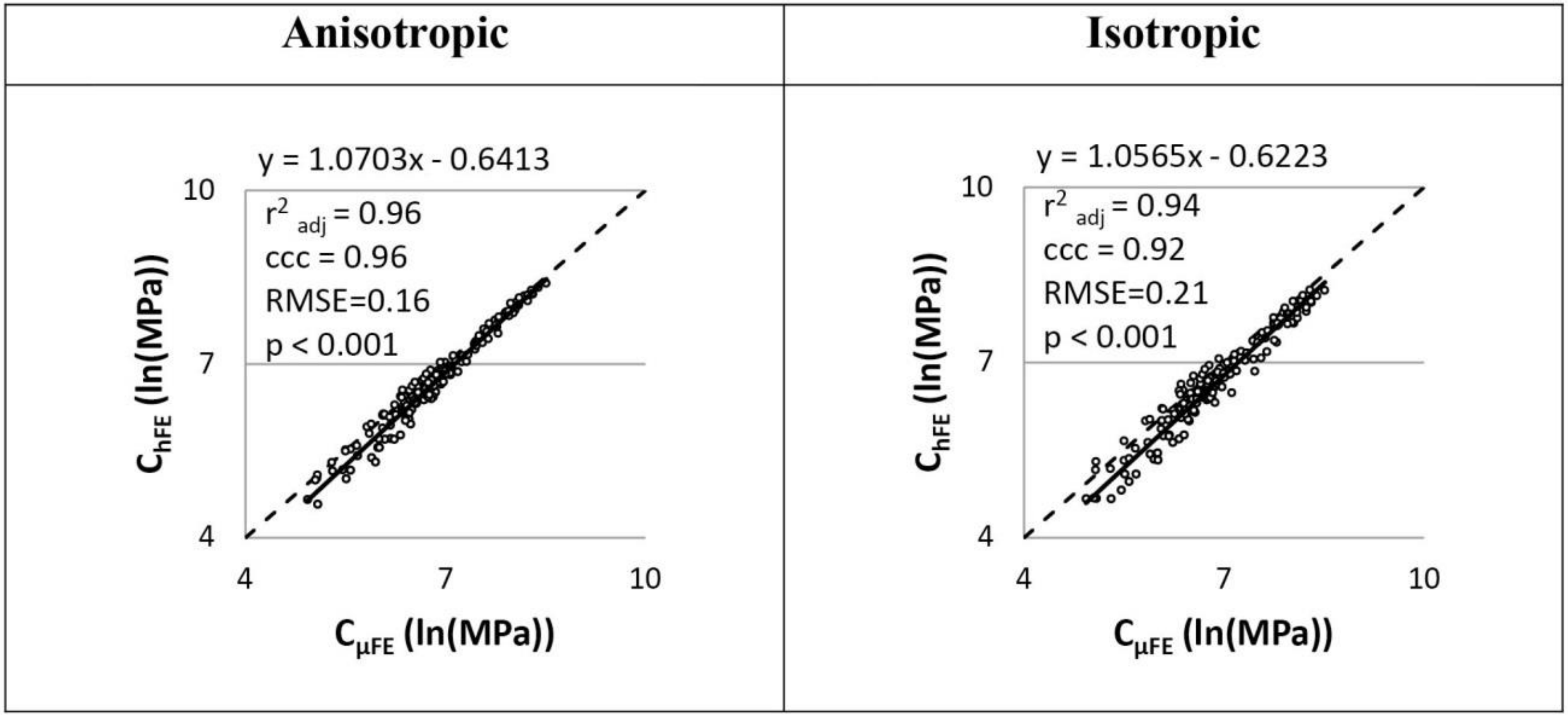
- hFE: anisotropic and isotropic
- KUBC

Global comparison:
Stiffness

Local comparison:
Strain/stress invariants



VALIDATION:GLOBAL STIFFNESS

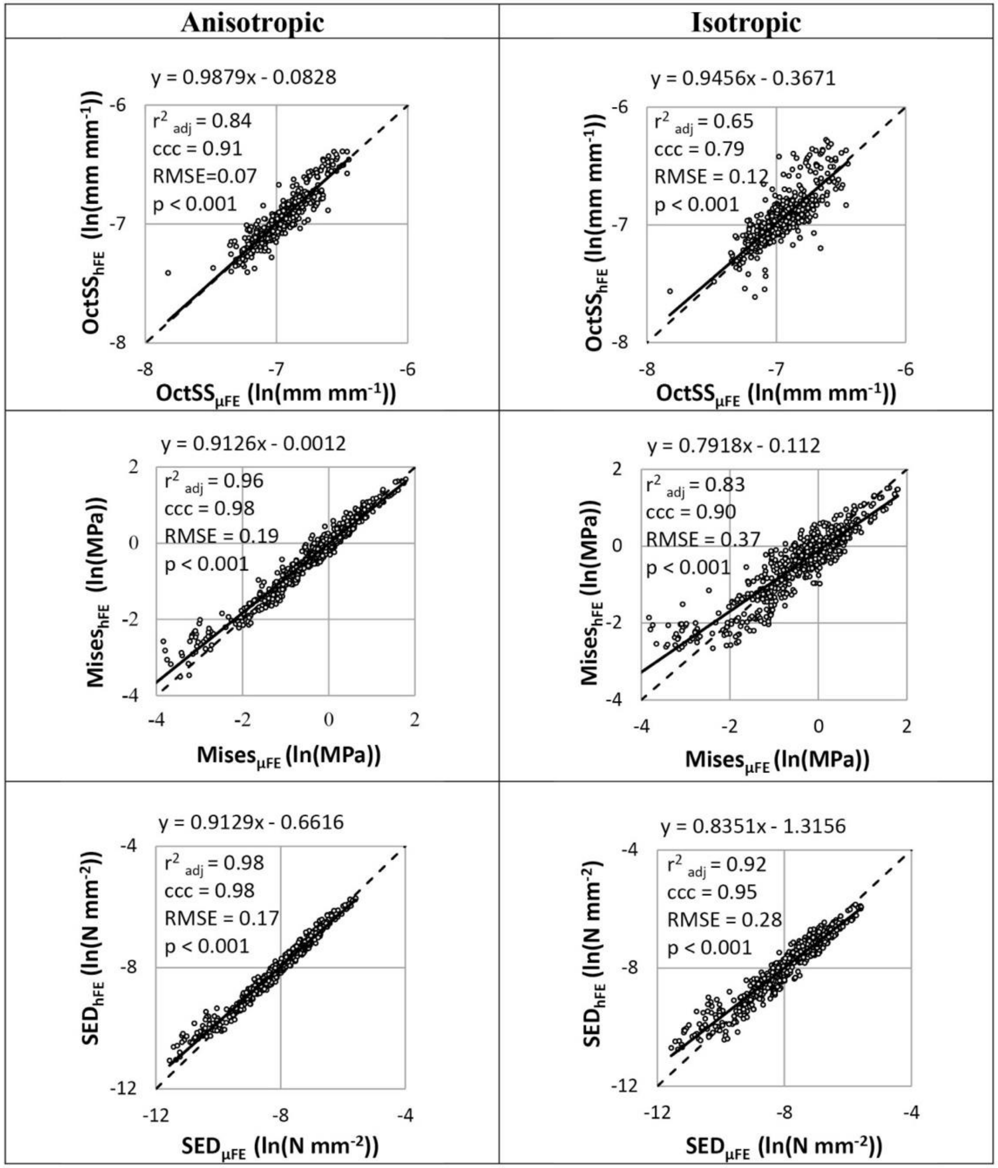


VALIDATION:LOCAL STRESS AND STRAIN

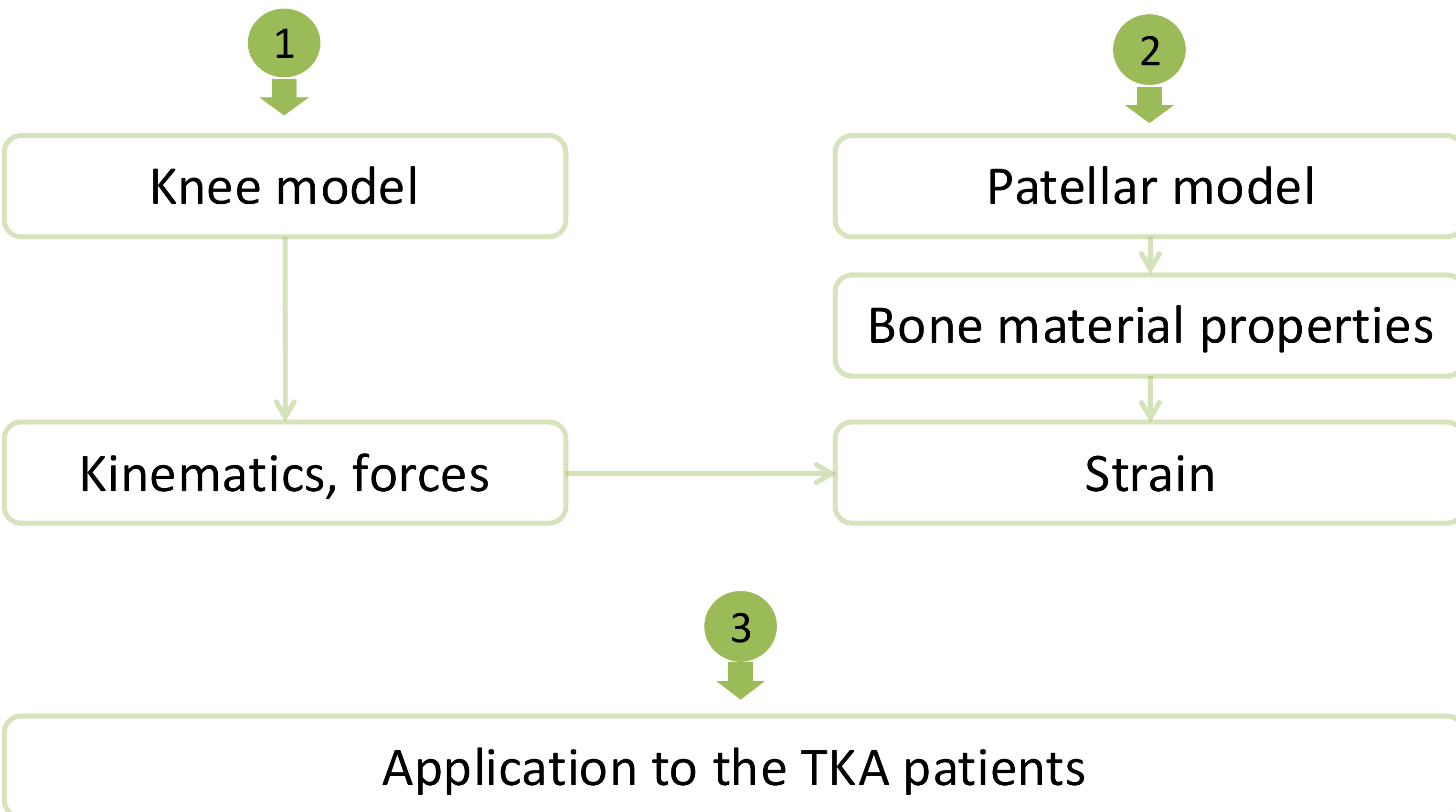
Octahedral shear strain

Von Mises stress

Strain energy density

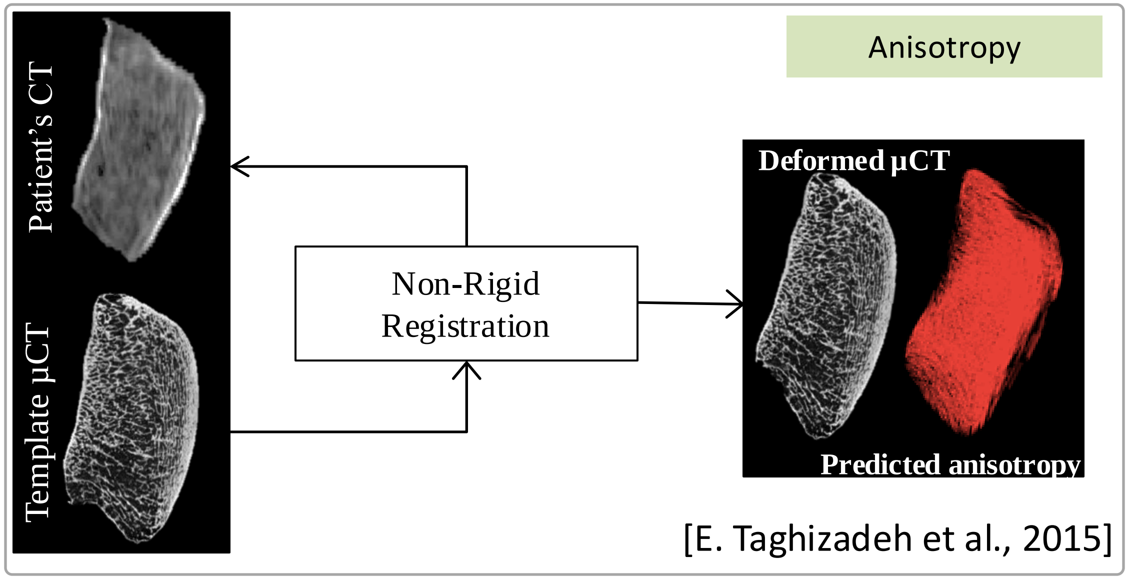


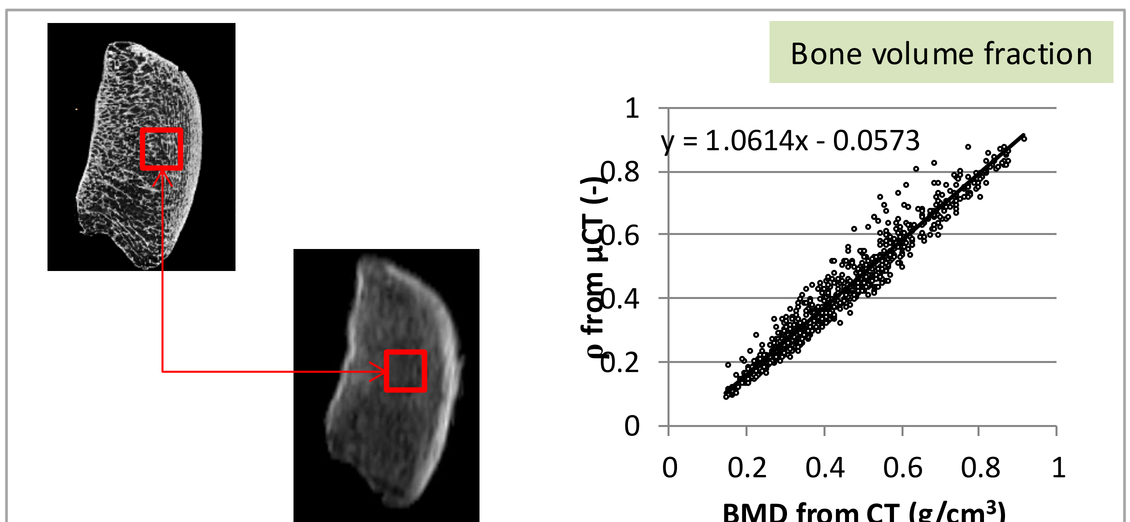
Patient-specific TKA model for patella



Latypova, 2015

MATERIAL PROPERTIES FROM CT

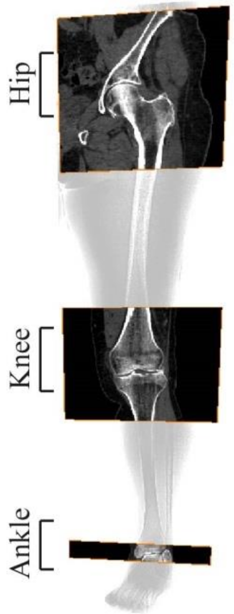




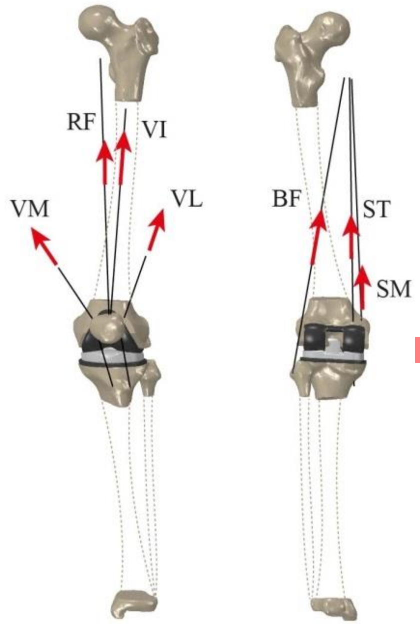
APPLICATION TO PATIENTS

- 14 patients
- Preoperative CT & planning
- 1 year follow-up
- No complications

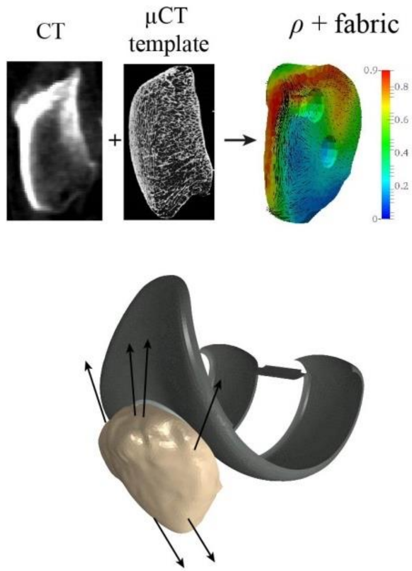
- Patellar cut from post-op X-Ray
- Loaded squat (BW)
- Muscles ratios (PCSA and EMG)
- Strain (octahedral shear) 60° knee flexion



Patient

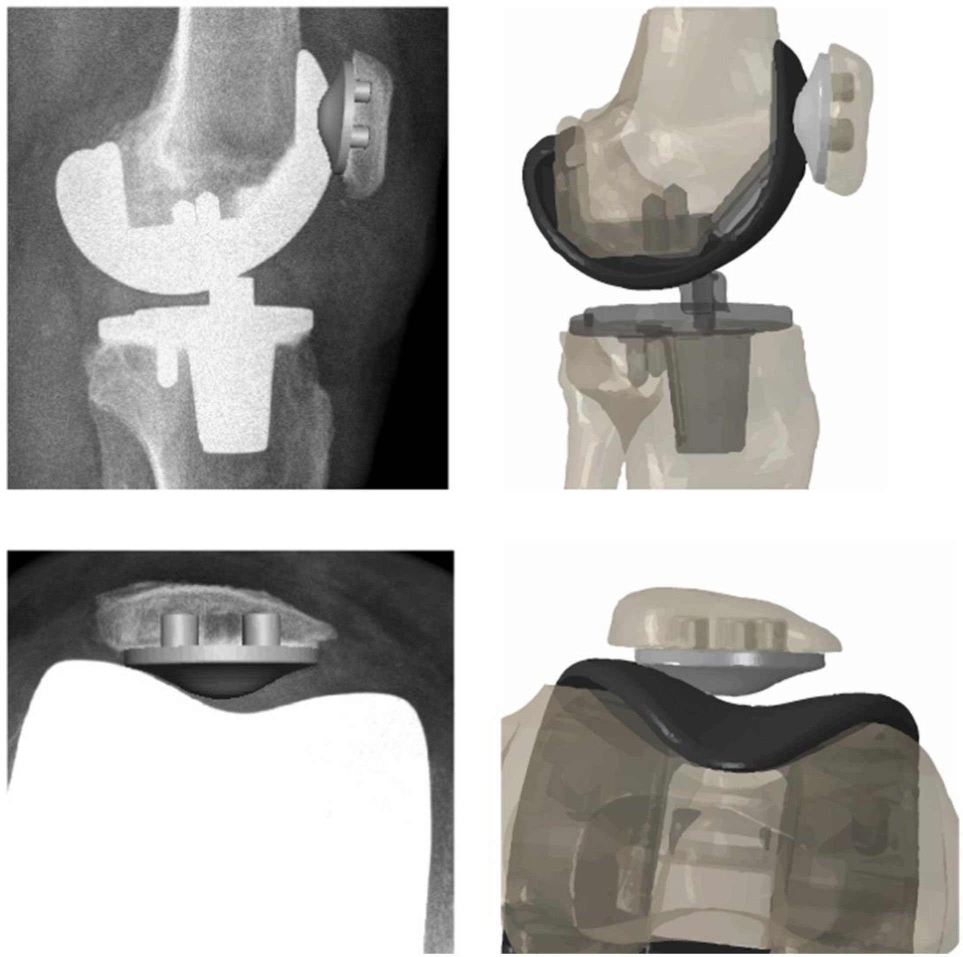


Knee model



Patella model

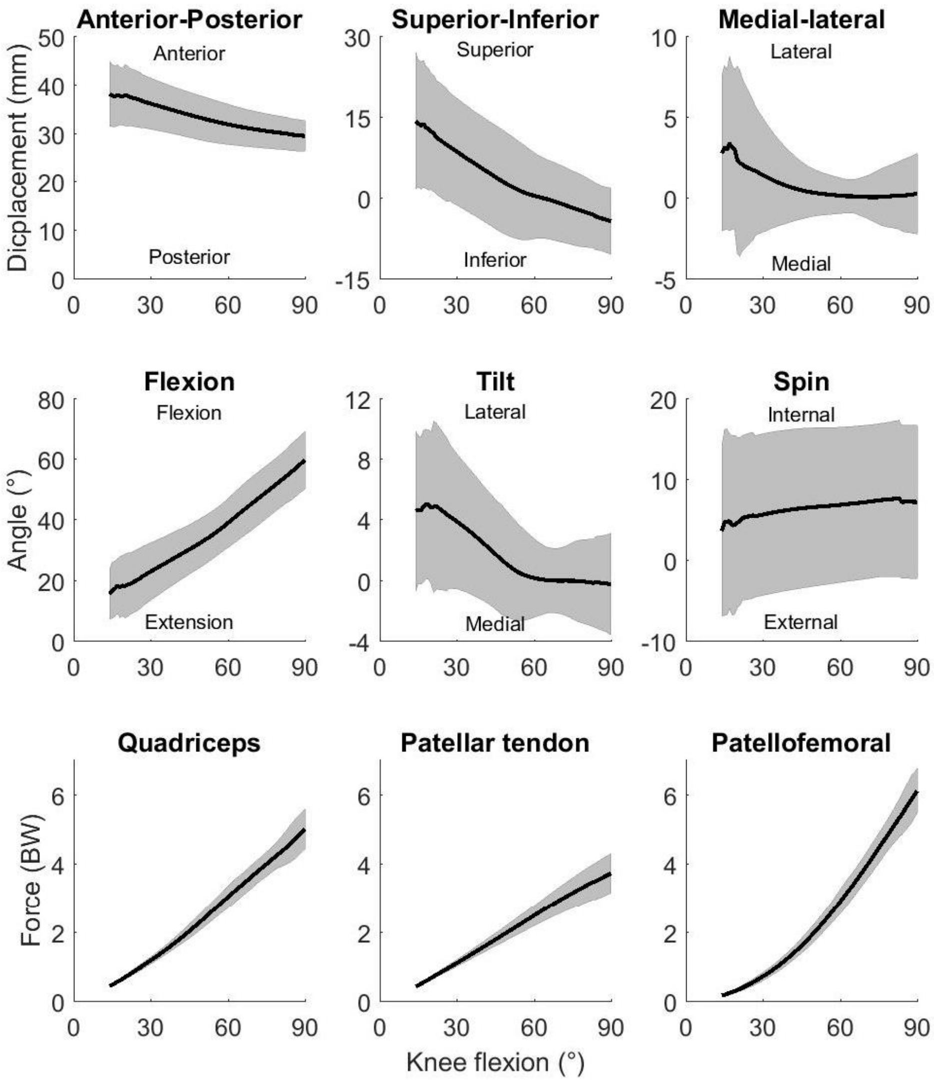
Patient-specific modeling

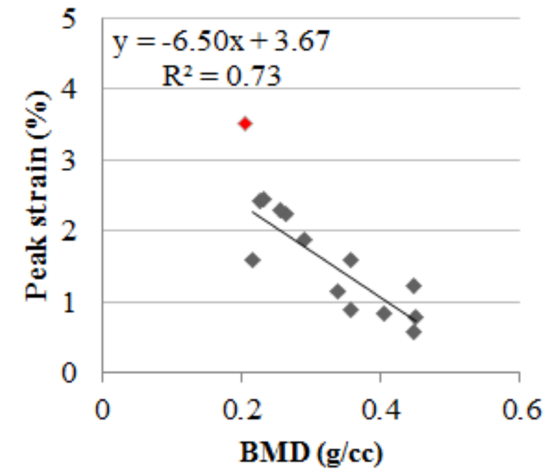


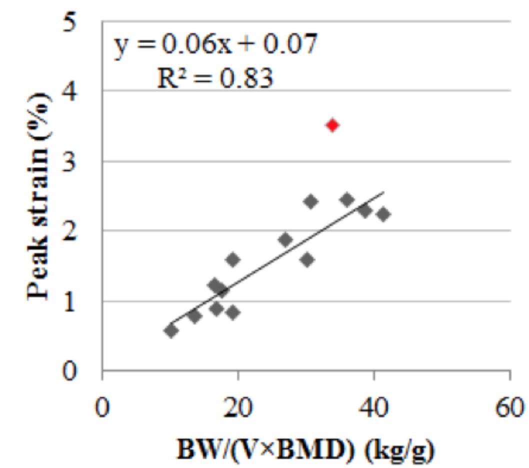
Postoperative X-ray vs model predictions

Patient-specific modeling

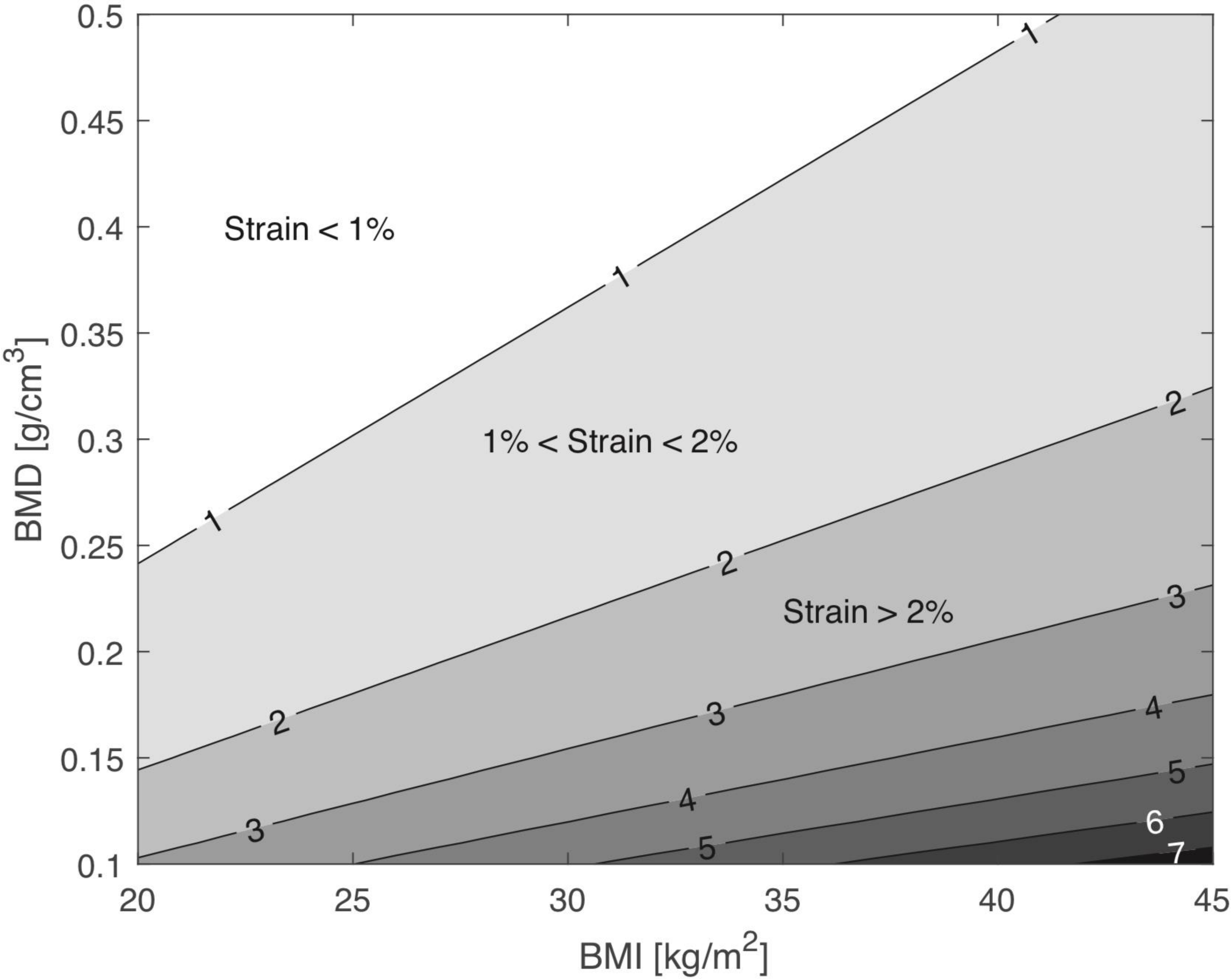
14 patients







Peak strain: maximum strain in 99% bone volume
BMD: average bone mineral density
BW: Body weight
V: patellar bone volume after resurfacing



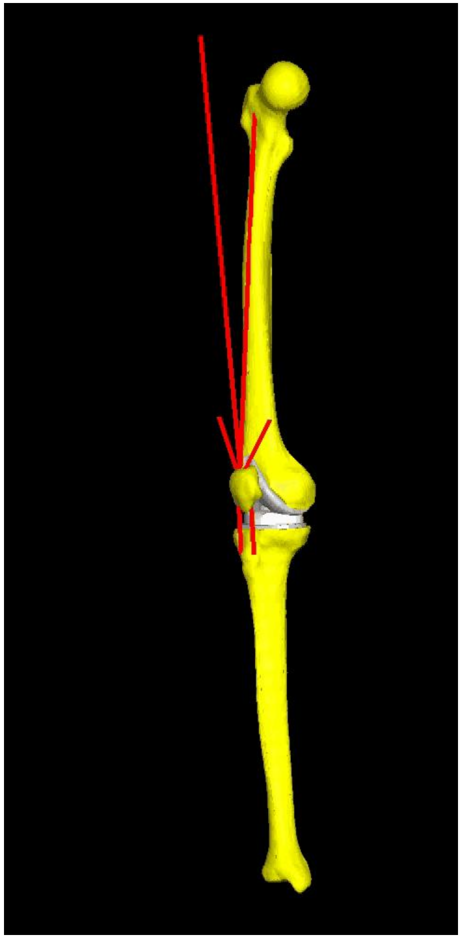
Strain < 1%
1% < Strain < 2%
Strain > 2%
1
2
3
4
5
6
7
BMD [g/cm^3]
BMI [kg/m^2]
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
20
25
30
35
40
45

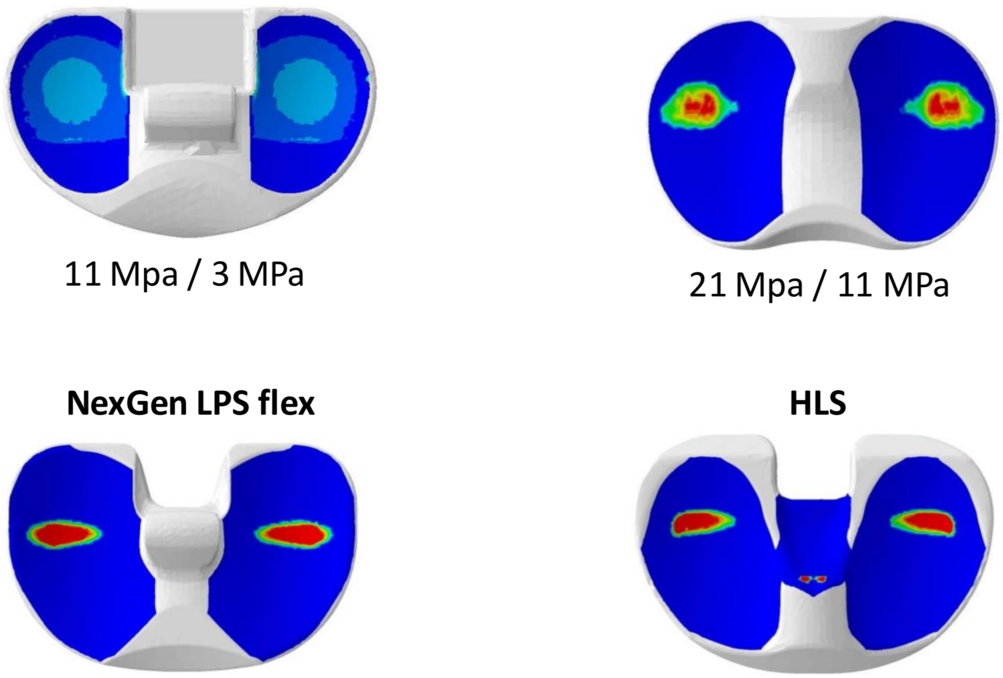
Summary

- Patient-specific TKA model with focus on patella
- Adaptation to anatomy, implant design and position, body weight
- Muscle control
- Identified and validated patellar material properties (anisotropic and isotropic)
- Application to patients
  - Variation between patient
  - Highlighted importance of patellar density and volume, body weight in preoperative planning
- Potential of the model as surgery planning tool
- Application to the patients
  - Two groups of patients (pathologic/control)
  - Other clinical applications (wear, evaluation of new design, etc.)

Knee

Polyethylene contact pattern (max/mean)
at 60° of knee flexion





FIRST

11 Mpa / 3 MPa

PFC

21 Mpa / 11 MPa

NexGen LPS flex

32 Mpa / 17 MPa

HLS

56 Mpa / 18 MPa

EPFL-LBO (A. Terrier)