Open Knee(s)

A Path Towards Open Source Virtual Musculoskeletal Joints

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DISCLOSURES

UNLABELED USE

INVESTIGATIONAL PRODUCTS

AFFILIATIONS WITH COMMERCIAL FIRMS

FUNDING PROVIDED BY

National Institute of General Medical Sciences
National Institute of Biomedical Imaging and Bioengineering (partially)
National Inst. of Arthritis and Musculoskeletal and Skin Diseases (partially)
National Institutes of Health

WHY MODELING?

"... a **representation** of the **essential aspects** of an existing system (or a system to be constructed), which presents knowledge of that system **in a usable form**."

Eykhoff (1974) System Identification: Parameter and State Estimation.

WHY MODELING?

Computational **modeling & simulation** provides **medicine** the tools of **modern engineering**.

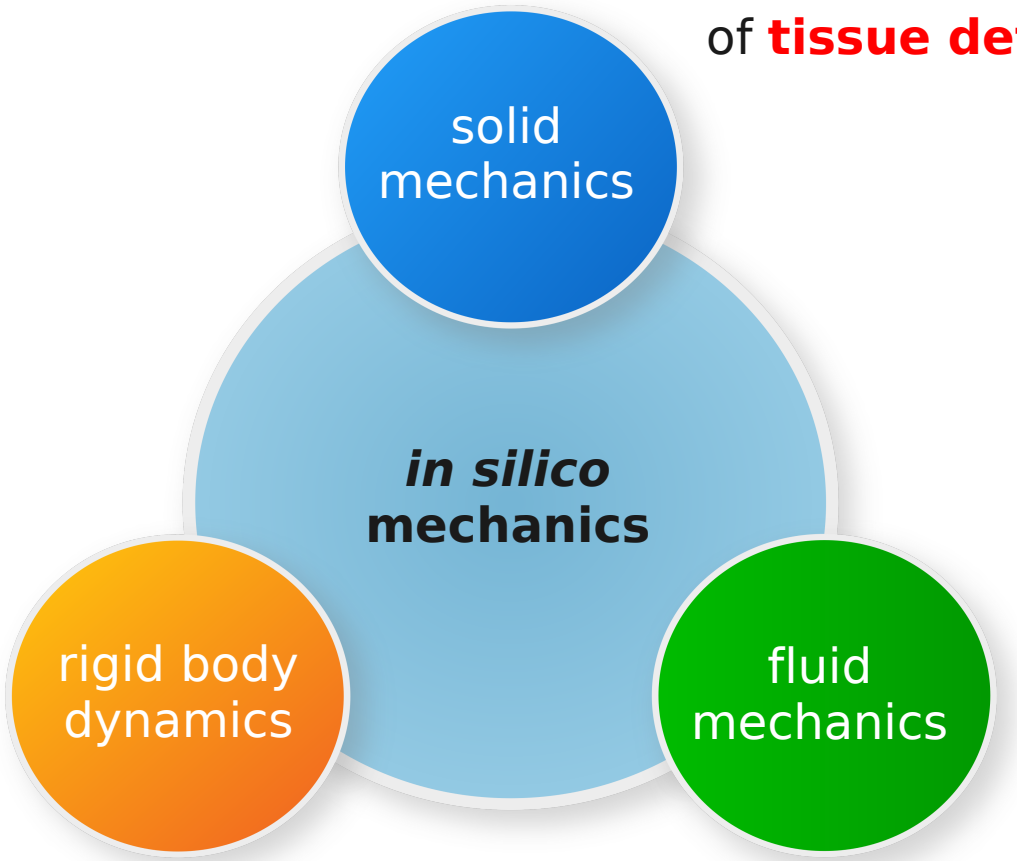
> "... For example, doctors will be able to use simulations – initialized with patient specific anatomic and physiologic data – *to predict* the outcomes of procedures and thereby *design* optimal treatments for individual patients. ..."
>
> "... manufacturers could use SBES methods to predict the performance of their medical devices in virtual patients. ..."

adapted from NSF Blue Ribbon Panel Report on SBES (2006)

***In silico* approaches** provide many **opportunities** in scientific **research**, **technology** development, and clinical **translation**.

MODELING MODALITIES

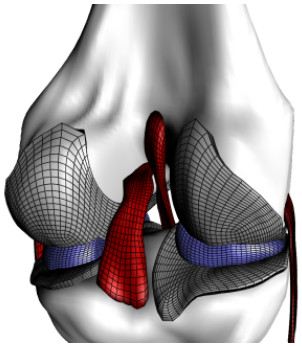
finite element analysis
of **tissue deformations**

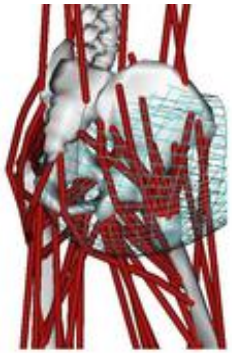


musculoskeletal
movement
simulations

computational fluid dynamics
of **cardiovascular systems**

MODELING & SIMULATION ENTERPRISE





simulation software

models

computing hardware

FEBiO
FINITE ELEMENTS FOR BIOMECHANICS

OpenSim

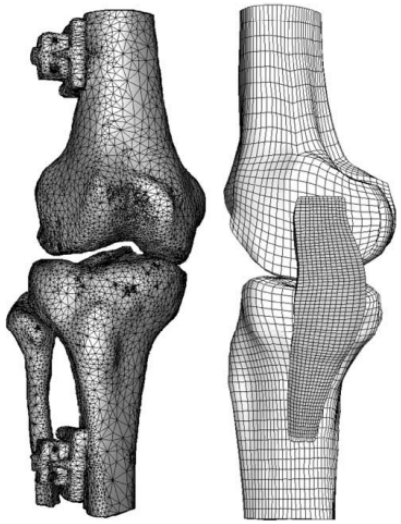
SimVascular

XSEDE
Extreme Science and Engineering Discovery Environment

GPGPU

WHY KNEE MODELING?

Joint and tissue functions



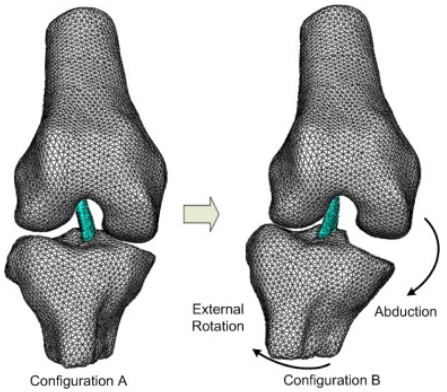
MCL function

Gardiner and Weiss, J Orthop Res, 21: 1098-106, 2003.

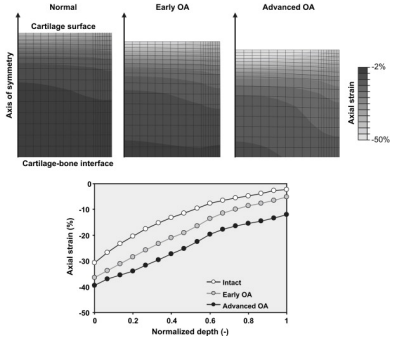
Injury mechanisms

Park et al., J Biomech, 43: 2039-42, 2010.

ACL impingement



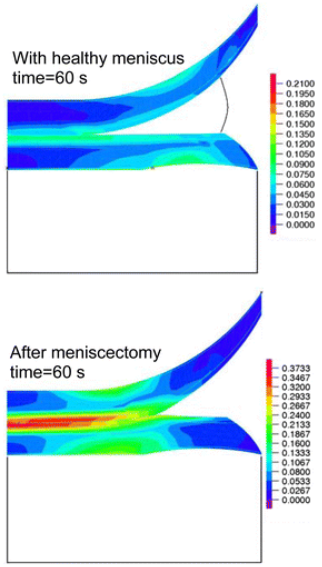
Pathological impacts



Osteoarthritis

Kalahari et al., Osteoarthritis and Cartilage, 18: 73-81, 2010.

Surgical interventions



Menisectomy

Vaziri et al., Annals of Biomed Eng, 36: 1335-44, 2008.

STATE OF KNEE MODELS

PubMed.gov
U.S. National Library of Medicine
National Institutes of Health

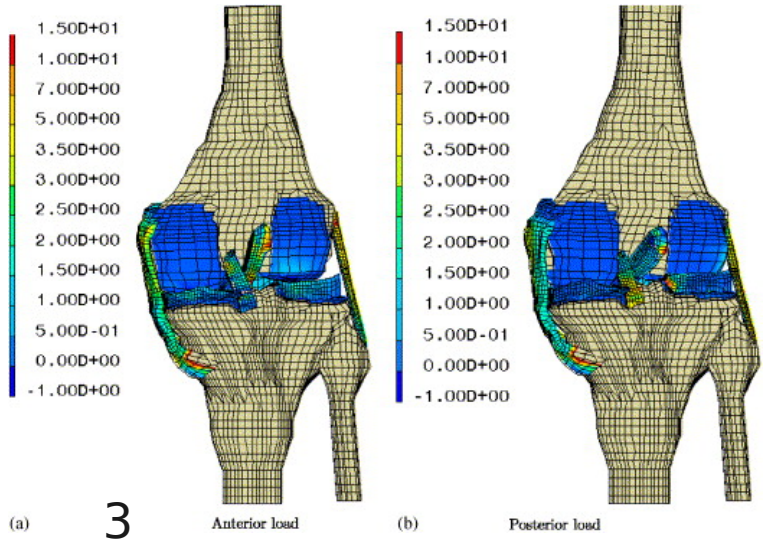
Search: PubMed RSS Save search Limits Advanced search Help

finite element AND knee Search Clear

Display Settings: Summary, 20 per page, Sorted by Recently Added

Results: 1 to 20 of ~~412~~

699 (as of Mar 15, 2015)



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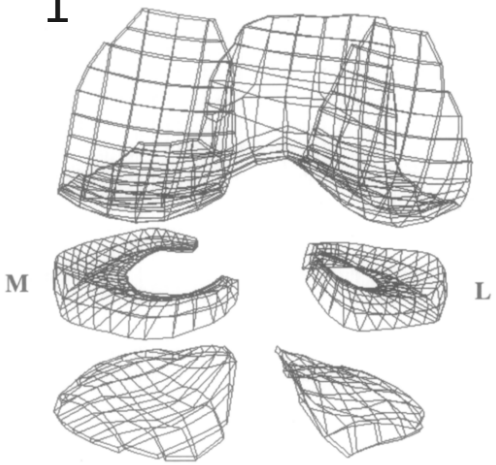
1



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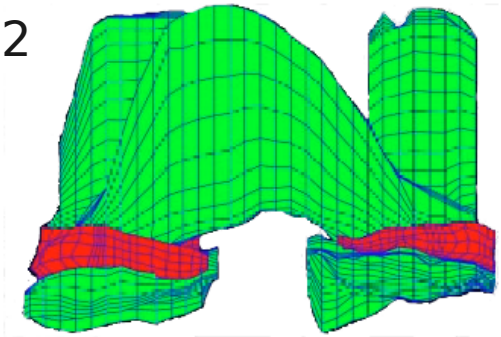

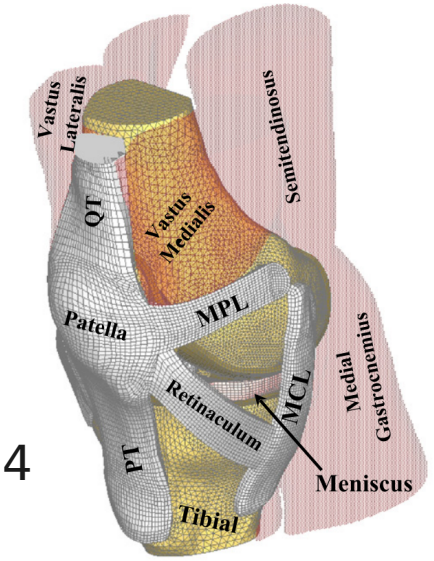

4

[1] *Bendjaballah et al., Clin Biomech, 12: 139-48, 1997.*
[2] *Donahue et al., J Biomech Eng, 124: 273-80, 2002.*
[3] *Peña et al., J Biomech, 39: 1686-701, 2006.*
[4] *Dhaher et al., J Biomech, , 43: 3118-25, 2010.*

STATE OF KNEE MODELS

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finite element AND knee | Search | Clear

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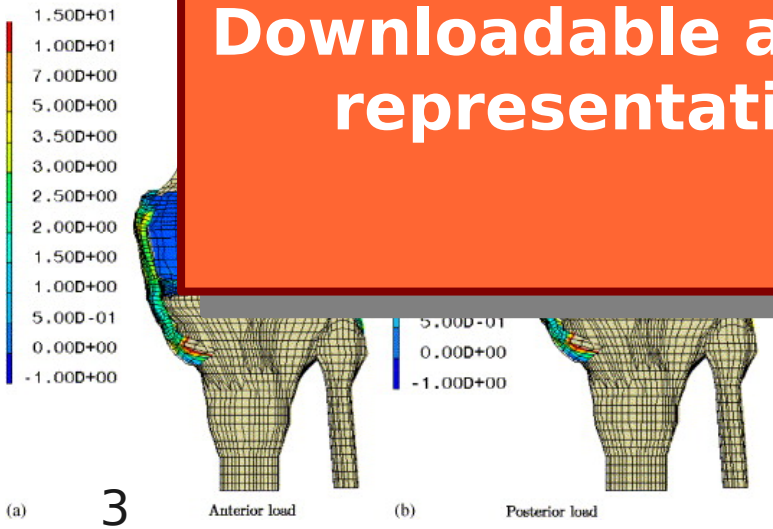
699 (as of Mar 15, 2015)

Downloadable and resuable finite element representations of knee models are scarce.



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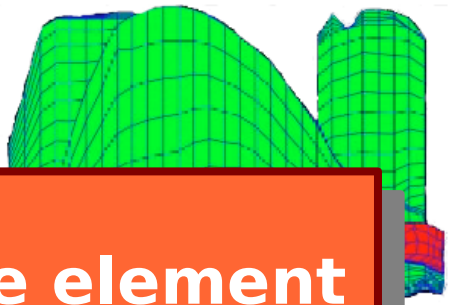

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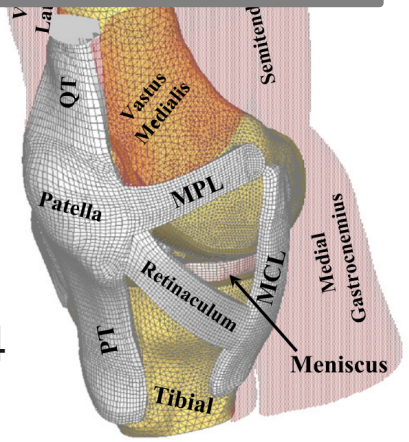

4

[1] *Bendjaballah et al., Clin Biomech, 12: 139-48, 1997.*
[2] *Donahue et al., J Biomech Eng, 124: 273-80, 2002.*
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[4] *Dhaher et al., J Biomech, , 43: 3118-25, 2010.*

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finite element AND knee Search Clear

Display Settings: Summary, 20 per page, Sorted by Recently Added

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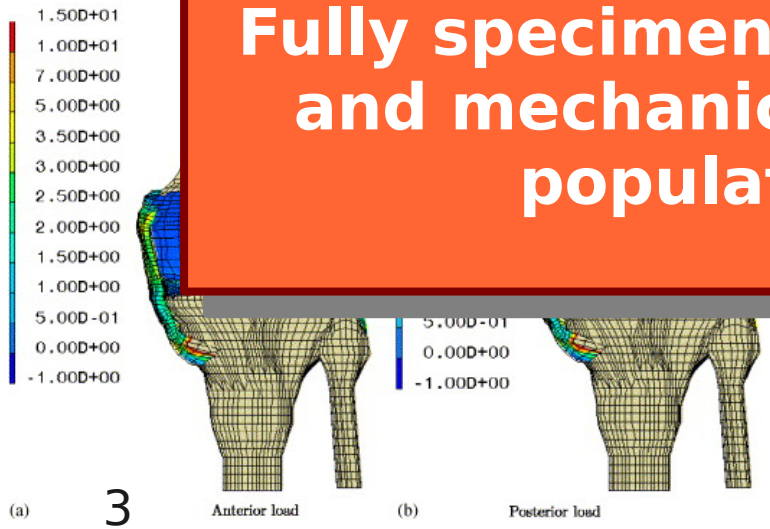
699 (as of Mar 15, 2015)

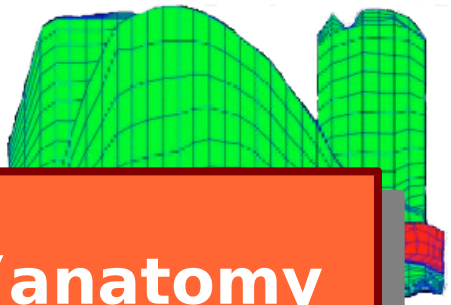
Fully specimen-specific models (anatomy and mechanical properties) of diverse populations do not exist.

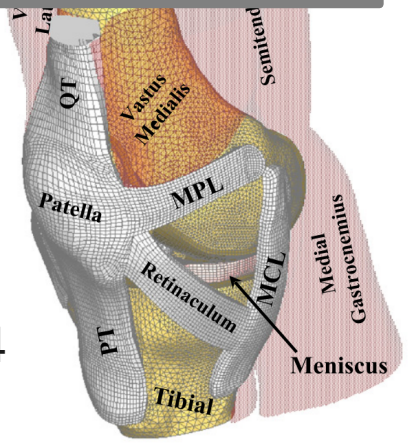
1



3

2





4

[1] *Bendjaballah et al., Clin Biomech, 12: 139-48, 1997.*
[2] *Donahue et al., J Biomech Eng, 124: 273-80, 2002.*
[3] *Peña et al., J Biomech, 39: 1686-701, 2006.*
[4] *Dhaher et al., J Biomech, , 43: 3118-25, 2010.*

WHY OPEN SOURCE?

- Benefits **users** of models

  disruption of barriers to entry to modeling & simulation

- Benefits **developers** of models

  opportunity for crowd-sourcing

- Benefits **community** and scientific enterprise

  collaboration possibilities

  expedited translation of models to practice

  promotion of reusability, accountability, reproducibility

OPEN KNEE(S) GOALS

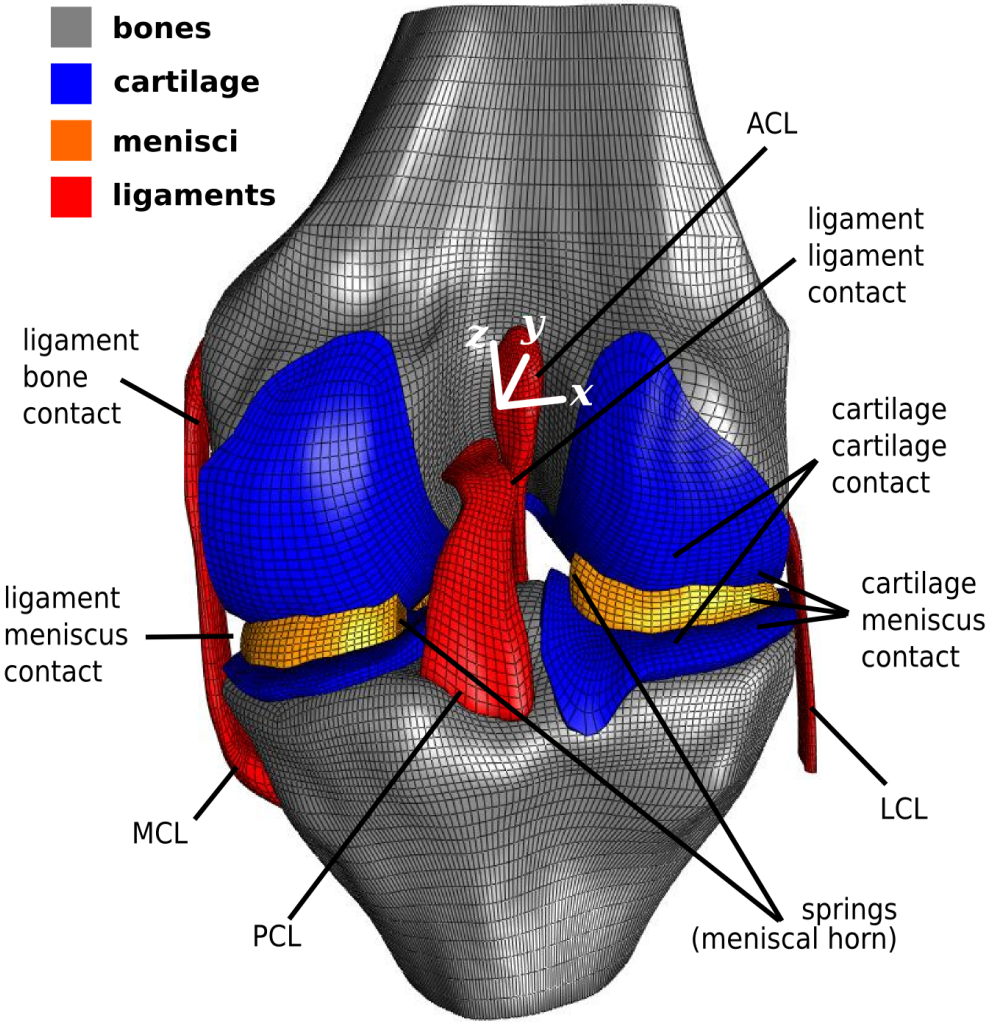
- To provide an open, freely available, and collaborative development, testing, simulation and dissemination platform for in silico exploration of the biomechanics of healthy and diseased knees.

→ Platform for community driven modeling & simulation

- To develop in silico biomechanical models of healthy and diseased knee joints of different genders and ages, supported by specimen-specific joint and tissue level experimental mechanics.

→ General purpose models of healthy and diseased knees

GENERATION 1 (G1)



Bones
rigid body

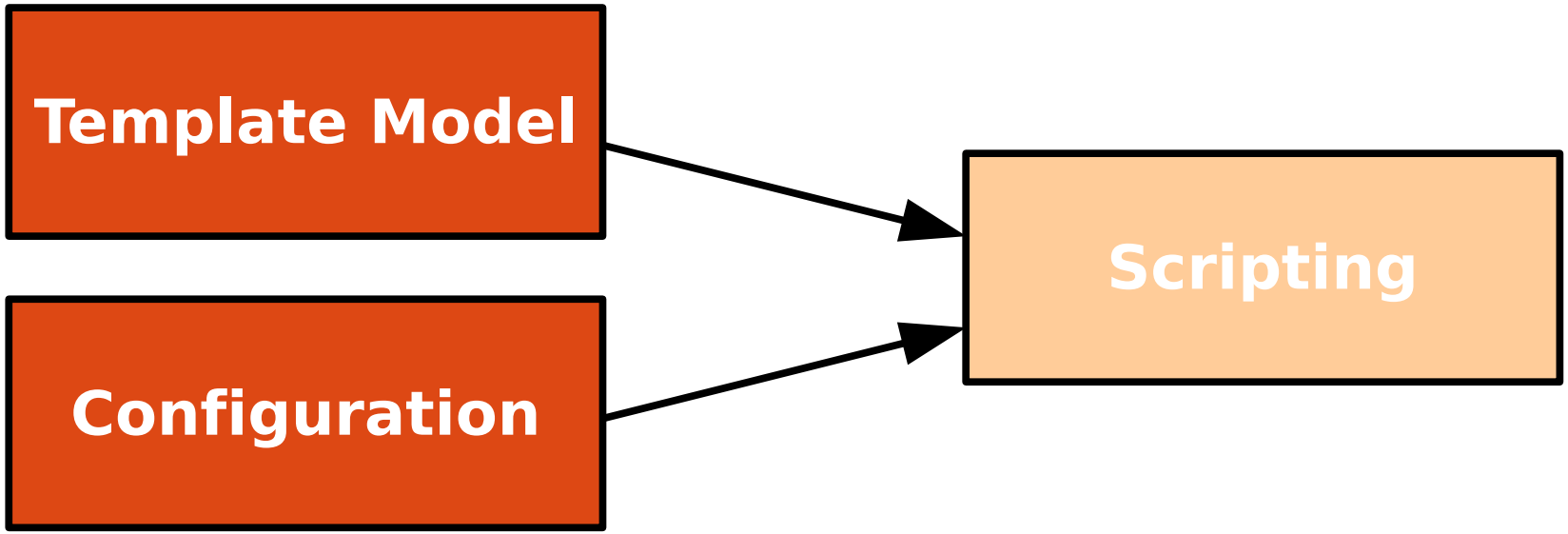
Cartilage
nearly incompressible Neo-Hookean

Menisci
Fung orthotropic hyperelastic
horn attachments as springs

Ligaments
transversely isotropic hyperelastic

Erdemir and Sibole, Open Knee User's Guide, Version 1.0.0, 2010.

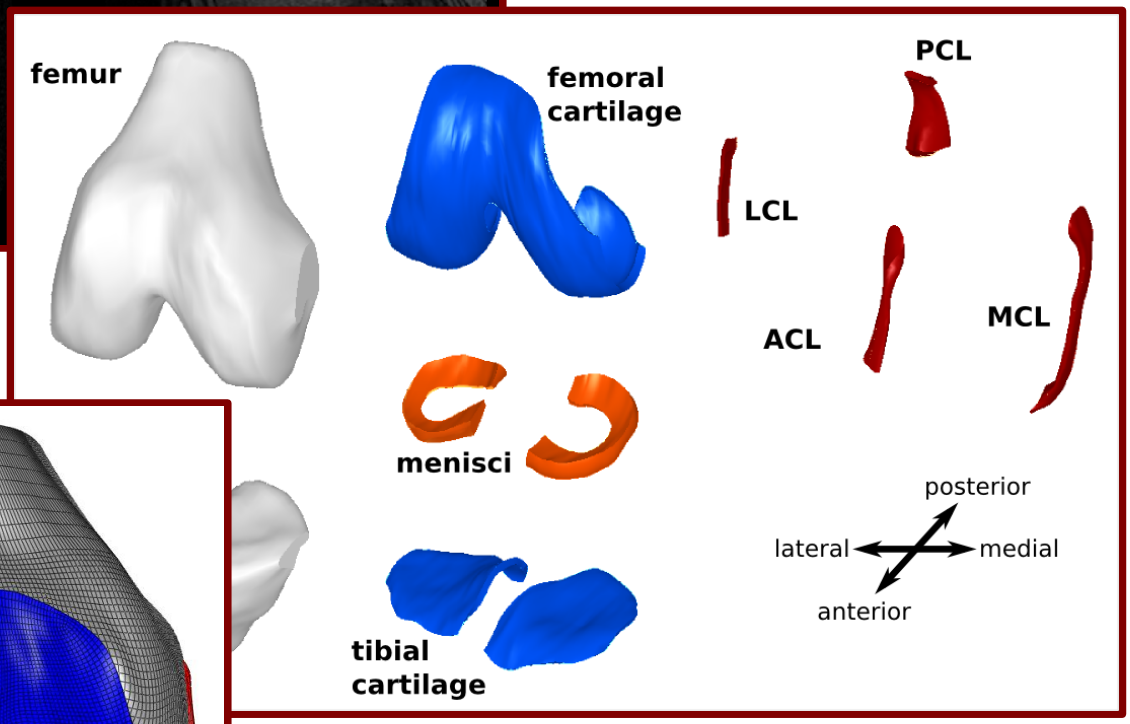
G1 SCRIPTING



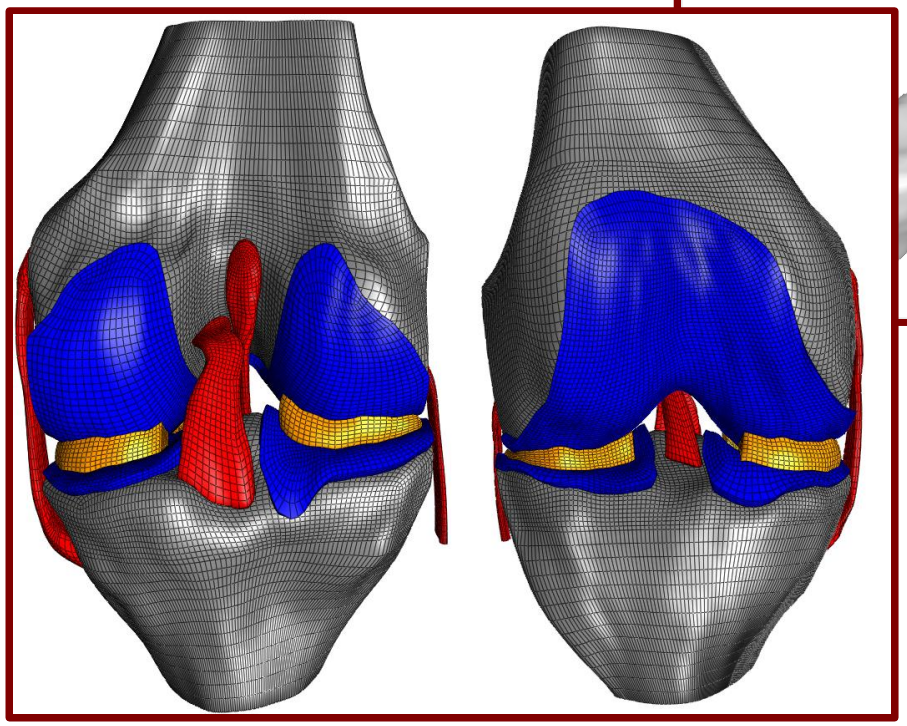
- Customization
  - *loading & boundary conditions*
  - *material properties*
  - *output metrics*
- Iterative analysis
  - *inverse problems*
  - *sensitivity analysis*
  - *probabilistic simulations*

G1 INTERMEDIATE PRODUCTS

Imaging data



Geometry



Mesh

G1 DISSEMINATION

Open Knee Statistics (January 30, 2012)	
Project site	https://simtk.org/home/openknee
Project launch date	February 18, 2010
Page hits	19525 (past 180 days)
Unique visitors	902 (past 180 days)
Team members	8 total 3 active 2 original, 1 from community
Documentation	1 user's guide 3 conference abstracts
Development	248 repository commits
Releases	v.1.0.0.199 (major) December 17, 2010 v.1.0.1.202 (minor)
Release downloads	207 total 162 unique
Expected use of downloads (feedback provided by users)	56 research 54 training 24 reference for other models 14 evaluation 9 anterior cruciate ligament 9 instrumentation/implants/ orthotics/prosthetics 6 cartilage/osteoarthritis 5 potential contributions 4 impact biomechanics 4 knee loads 2 knee movements 2 knee geometry 1 meniscal injury 1 femur biomechanics Rest unspecified/unsure

as of March 15, 2015

138,290 page hits past 180 days

26,789 unique visitors past 180 days

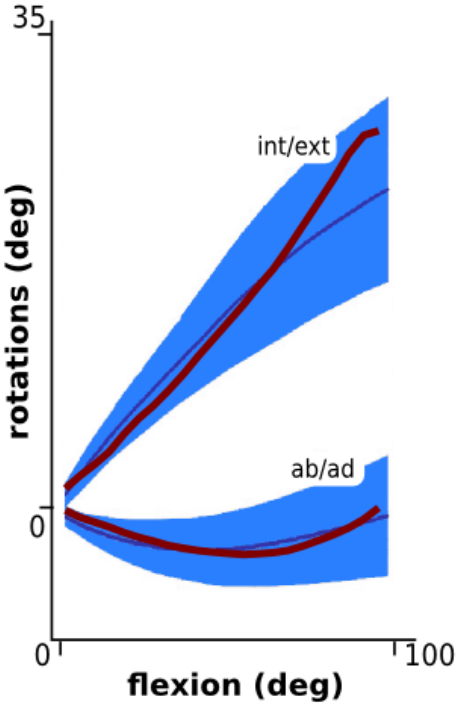
453 repository commits

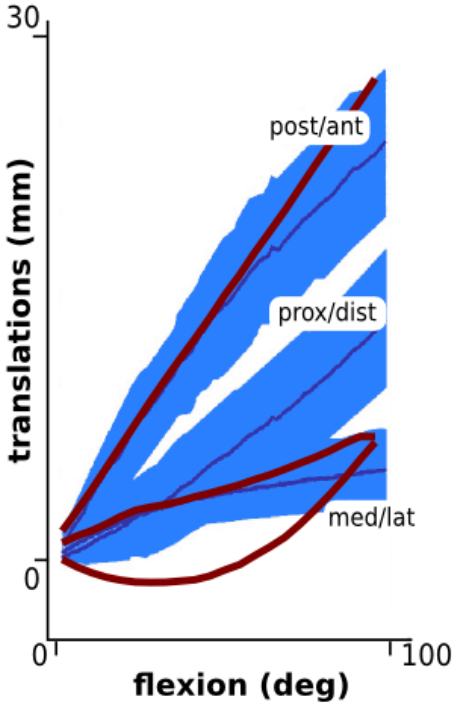
777 total downloads

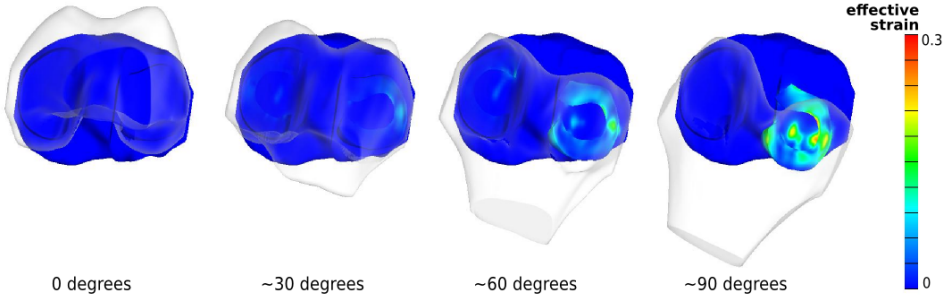
565 unique downloads

G1 DEVELOPER STUDIES

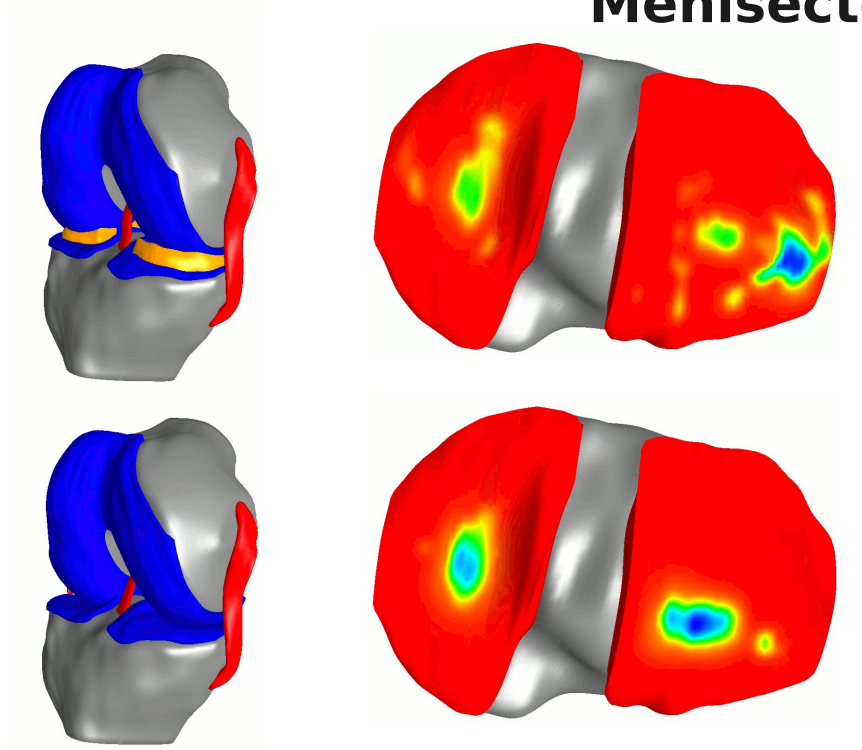
Passive flexion



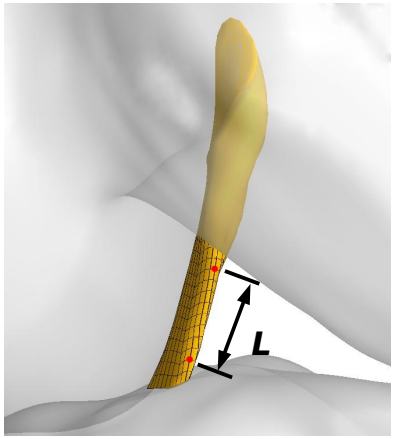


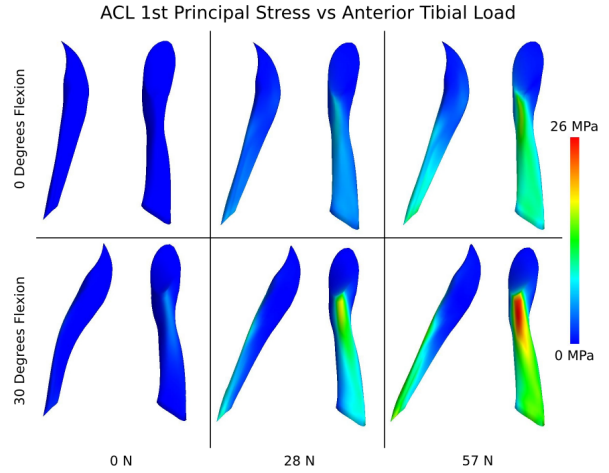


Menisectomy



ACL mechanics





G1 ENABLED STUDIES

Peer-Reviewed Articles (3 out of 4 shown)

Sibole, S. C. and Erdemir, A. (2012) Chondrocyte deformations as a function of tibiofemoral joint loading predicted by a generalized high-throughput pipeline of multi-scale simulations, PLoS ONE, 7, e37538.

Westermann, R. W., Wolf, B. R. and Elkins, J. M. (2013) Effect of acl reconstruction graft size on simulated lachman testing: a finite element analysis, Iowa Orthop J, 33, 70-77.

Guo, H. and Spilker, R. L. (in press) An augmented Lagrangian finite element formulation for 3D contact of biphasic tissues, Computer Methods in Biomechanics and Biomedical Engineering.

Thesis (3)

Heydon, R. (2011) Finite element analysis of knee articular cartilage, M.A.Sc. Thesis, Ryerson University, Toronto, Ontario, Canada.

Tichon, D. J. (2011) Finite element analysis of the effect of low-speed rear end collisions on the medial meniscus, M.Sc. Thesis, University of Connecticut, Storrs, Connecticut, USA.

Wangerin, S. (2013) Development and validation of a human knee joint finite element model for tissue stress and strain predictions during exercise, M.Sc. Thesis, California Polytechnic State University, San Luis Obispo, California, USA.

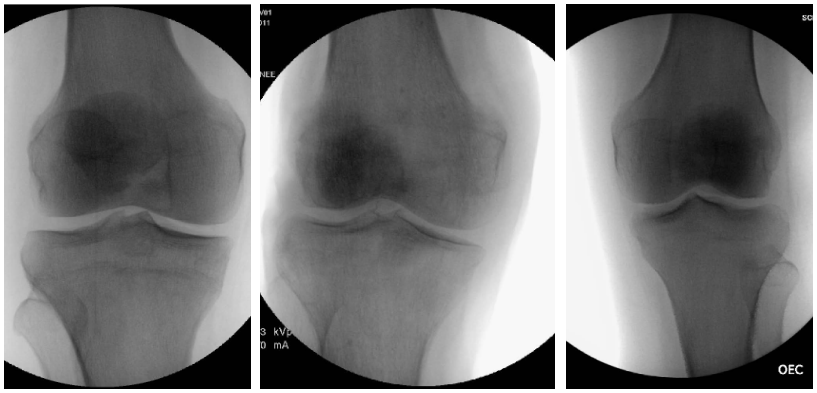
Conference Abstracts (2 out of 7 shown)

Tichon, D. J. and Peterson, D. R. Effect of rear end low-speed collisions on the meniscus, IEEE 37th Annual Northeast Bioengineering Conference, April 1-3, 2011, Troy, NY.

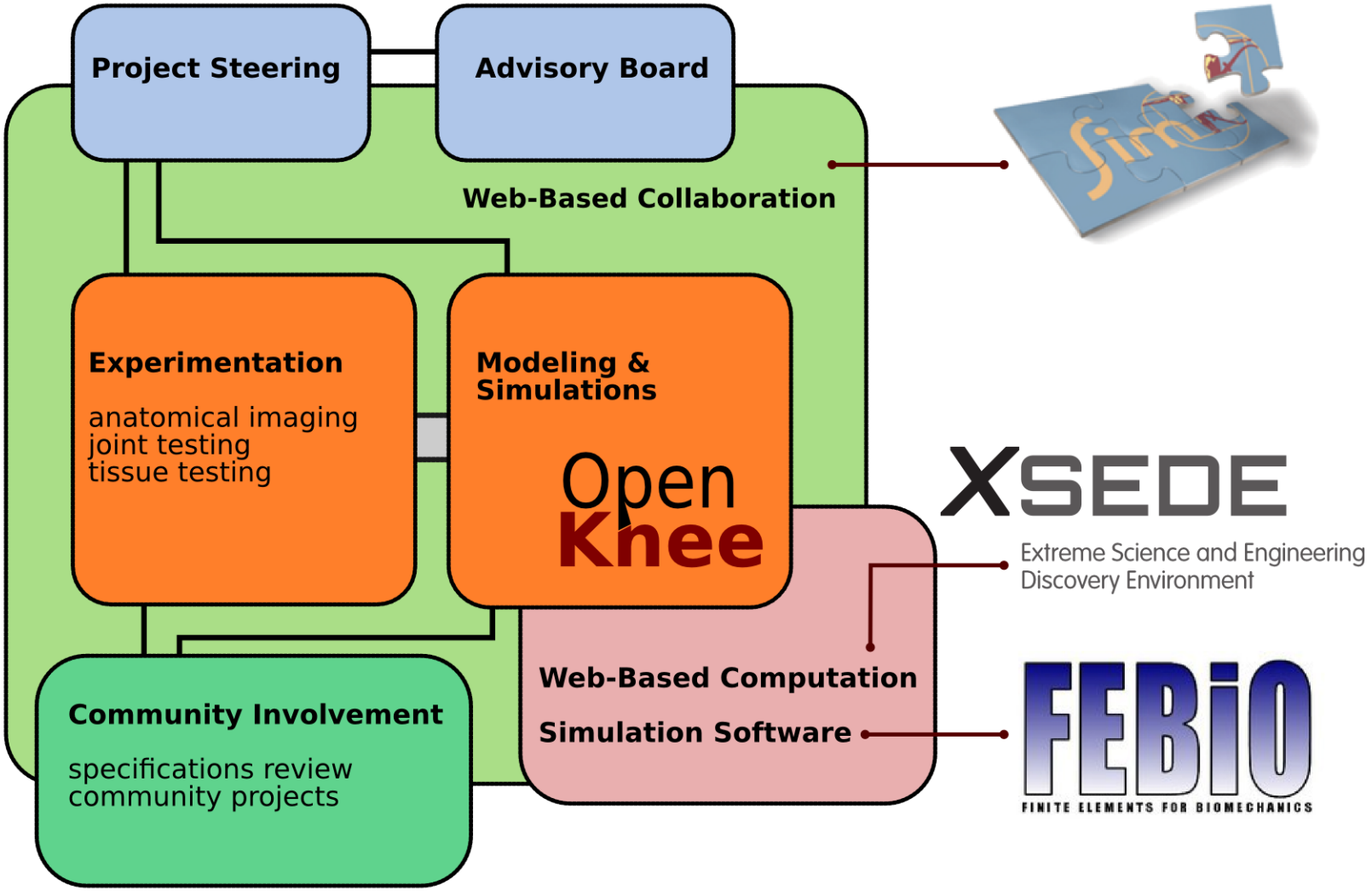
Valkeapää, A., Kłodowski, A., Rantalainen T. and Mikkola A. Knee cartilage surface loading during stationary bicycling, Computer Methods in Mechanics, May 9-12, 2011, Warsaw, Poland.

GENERATION 2 (G2) PROGRESS

- Full knee models
  - *tibiofemoral joint*
  - *patellofemoral joint*
- Complete specimen-specificity
  - *geometry*
  - *material*
- Comprehensive data
  - *magnetic resonance imaging*
  - *joint kinematics/kinetics*
  - *tissue stress/strain*
- Multiple knees
  - *young/elderly*
  - *male/female*
  - *healthy/osteoarthritic*



G2 INFRASTRUCTURE



G2 ADVISORY BOARD


Jack Andrish, MD


Morgan Jones, MD


Paul Saluan, MD


Carl Winalski, MD

Physicians

Trent Guess, PhD

Yasin Dhaher, PhD

Rami Korhonen, PhD

Engineers/Scientists

G2 KNEES





oks001

Right knee

Gender: Male
Age: 71 years
Race: White
Height: 1.83 m
Weight: 77.1 kg
BMI: 23.1

oks002

Right knee

Gender: Female
Age: 67 years
Race: White
Height: 1.55 m
Weight: 45.3 kg
BMI: 18.9

oks003

Left knee

Gender: Female
Age: 25 years
Race: White
Height: 1.73 m
Weight: 68 kg
BMI: 22.8

oks004

Right knee

Gender: Female
Age: 46 years
Race: White
Height: 1.58 m
Weight: 54.4 kg
BMI: 21.9

oks006

Right knee

Gender: Female
Age: 71 years
Race: White
Height: 1.52 m
Weight: 49.4 kg
BMI: 21.3

oks007

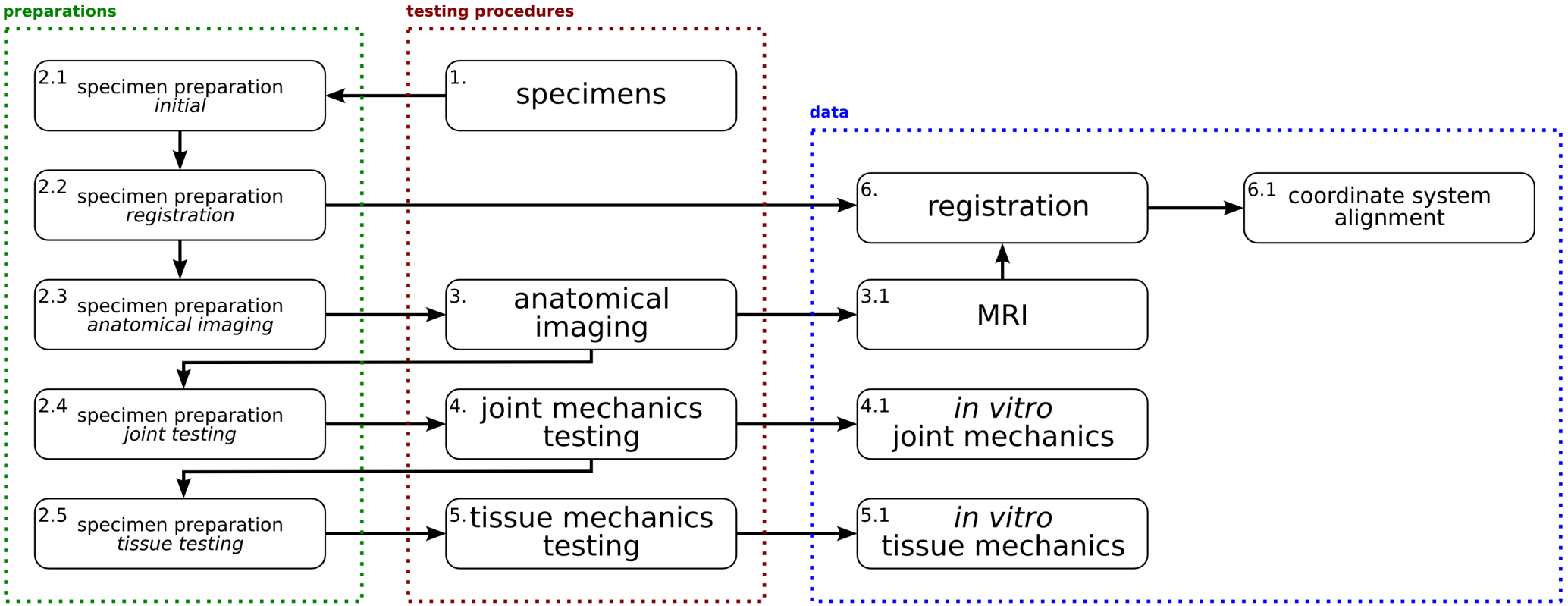
Right knee

Gender: Male
Age: 71 years
Race: White
Height: 1.7 m
Weight: 65.8 kg
BMI: 22.7

4 more on the way...

G2 EXPERIMENTATION

Workflow



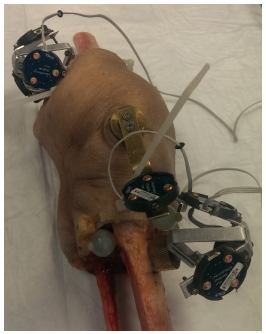
For mature and developing standard operating procedures, refer to ***http://wiki.simtk.org/openknee/Specifications*****.**

G2 EXPERIMENTATION

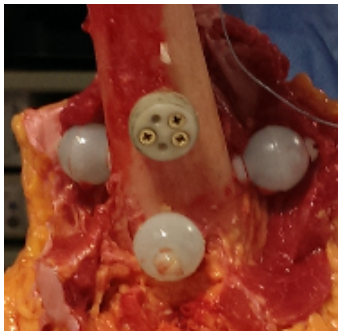
Preparation

dissection

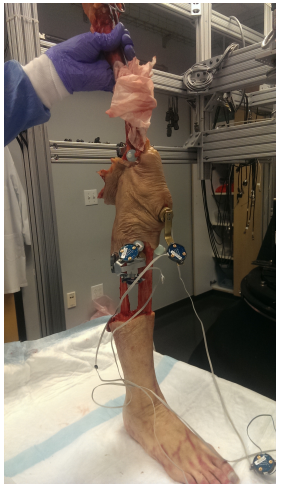
bone plugs



motion capture markers

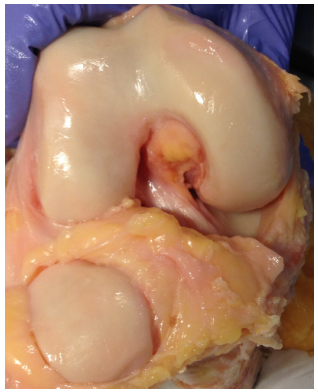


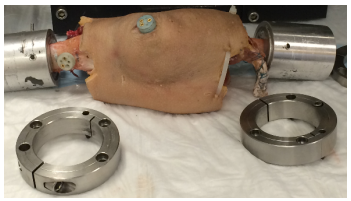
registration markers



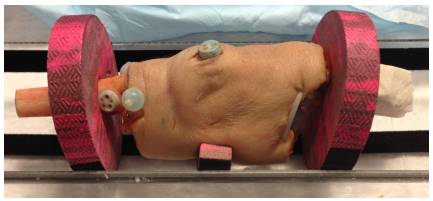
anatomical landmarks

preparation for tissue testing





preparation for joint testing



preparation for imaging

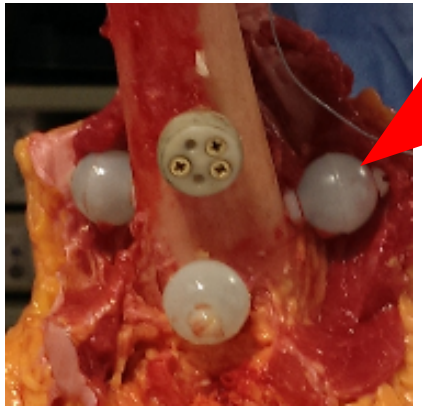
to tissue testing

to joint testing

to anatomical imaging

G2 EXPERIMENTATION

Registration



coordinate system transformations
femur – tibia – patella

association of reference states
pose & orientation

joint experimentation

anatomical imaging

G2 EXPERIMENTATION

General Purpose

3D T1-weighted
w/o fat suppression
0.5 x 0.5 x 0.5 mm
TE = 6.01 ms
TR = 20 ms

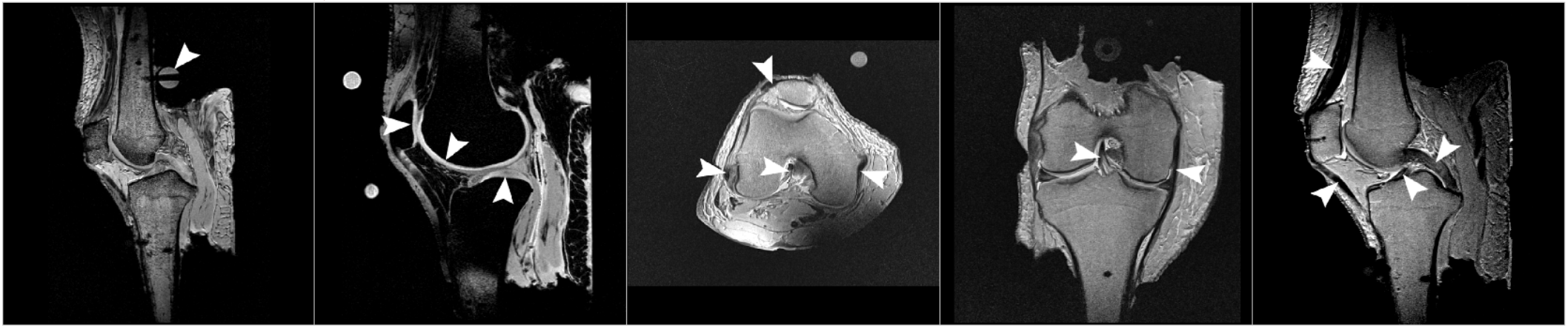
Cartilage

3D T1-weighted
w/ fat suppression
0.35 x 0.35 x 0.7 mm
TE = 5.34 ms
TR = 29 ms

Ligaments

Proton density
Turbo spin echo
0.35 x 0.35 x 2.8 mm
TE = 9.7 ms
TR = 10,000 ms

Anatomical Imaging



G2 EXPERIMENTATION

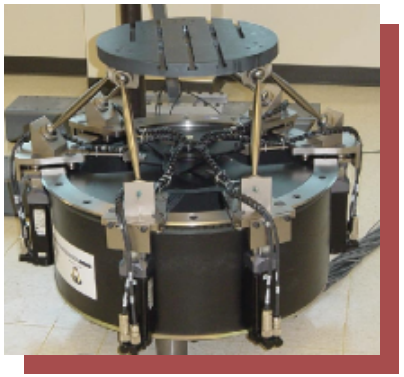
Tibiofemoral Joint Mechanics

Laxity Testing

Internal/external rotation
- 0 to ±5 Nm
- w/ 1 Nm increment

Varus/valgus
- 0 to ±10 Nm
- w/ 2.5 Nm increment

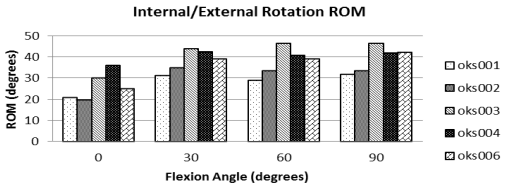
Anterior/posterior translation
- 0 to ±100 N
- w/ 10 N increment

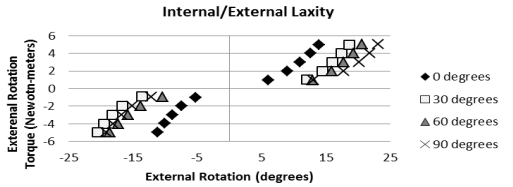


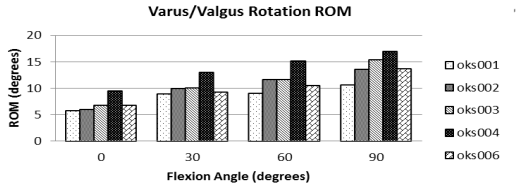
Combined Loading

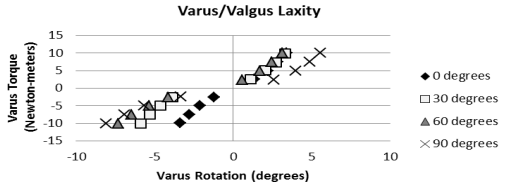
Permutations of
- Internal/External rotation – -5, 0, 5 Nm
- Varus/valgus – -10, 0, 10 Nm
- Anterior/posterior translation – -100, 0, 100 N

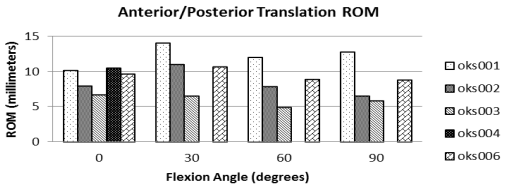
@ 0°,30°,60°,90° flexion
w/ 20 N compression force
measurement of kinematics-kinetics

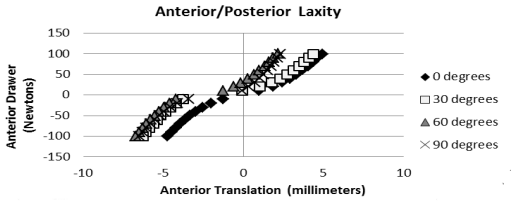


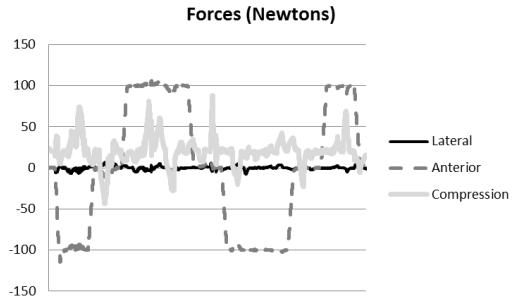


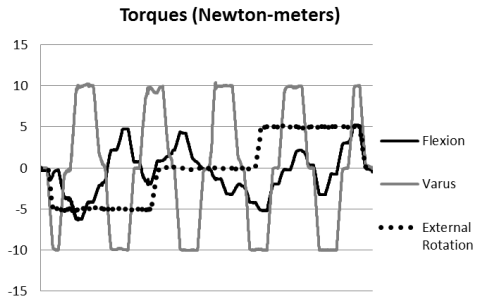


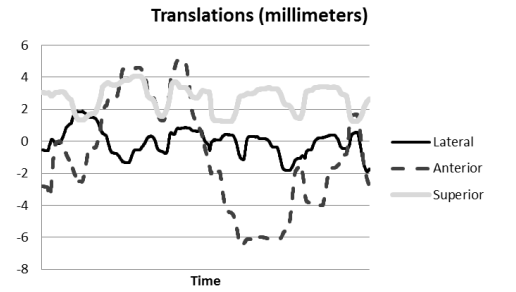


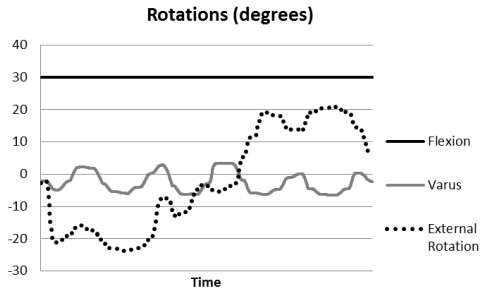








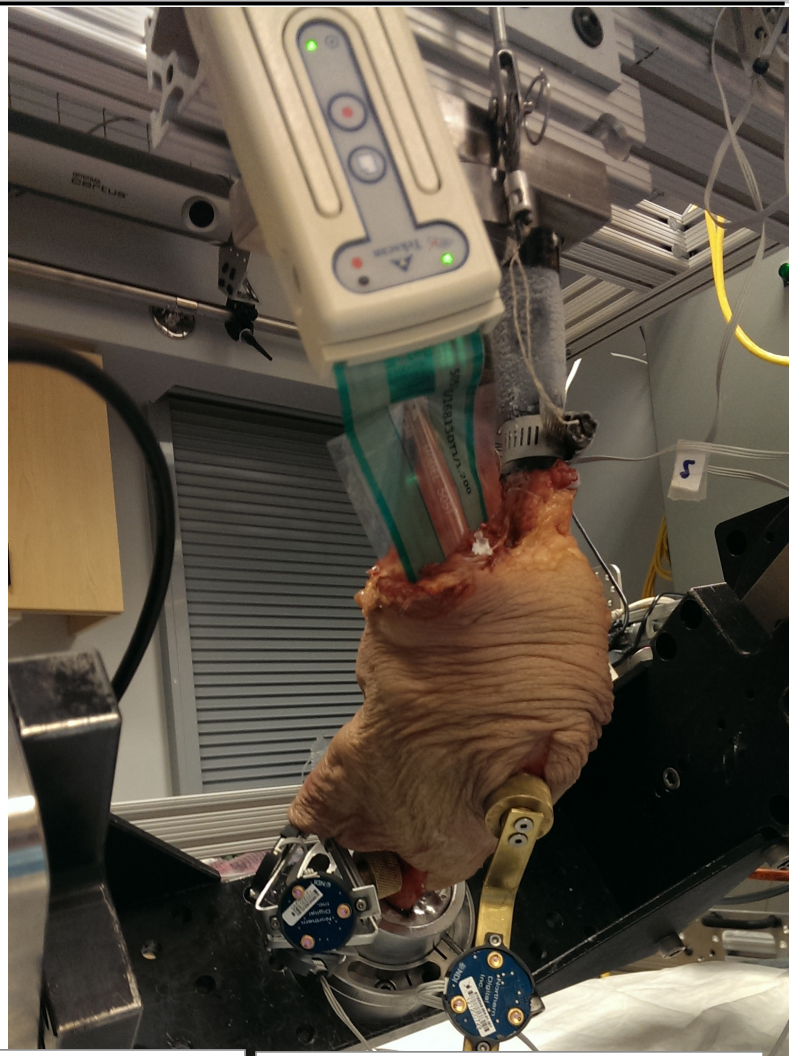


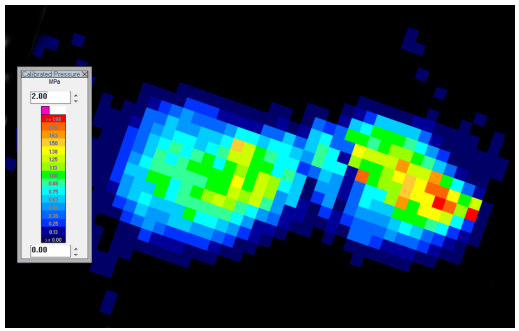


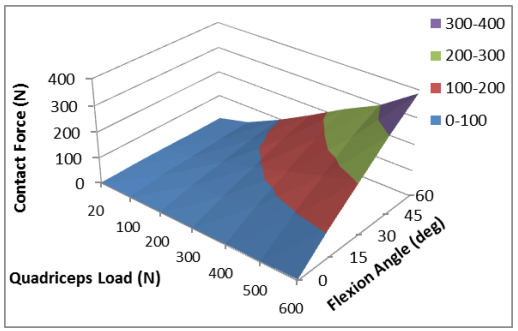
G2 EXPERIMENTATION

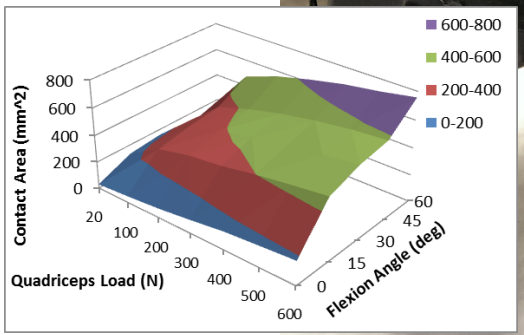
Patellofemoral Joint Mechanics

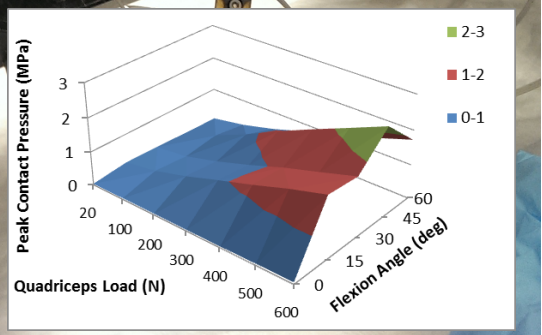
@ 0°,15°,30°,45°,90° flexion
20 N, 100 – 600 N quadriceps force
w/ 100 N increments
measurement of kinematics-kinetics
measurement of contact pressures











G2 EXPERIMENTATION

Tissue Mechanics

Cartilage

unconfined compression
confined compression
tension

medial – lateral femoral condyle
medial – lateral tibial plateau
femoral groove - patella

Meniscus

unconfined compression
confined compression
tension

medial – lateral

Ligament

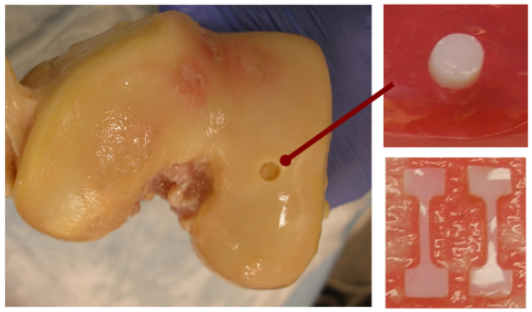
tension

anterior – posterior cruciate
medial – lateral collateral
patellar
transverse

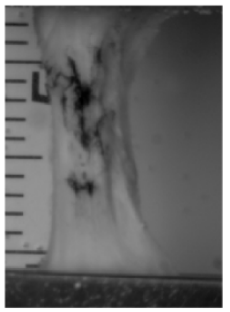
Tendon

quadriceps

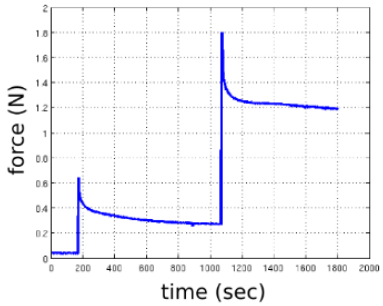
Tissue Sampling



Uniaxial Testing



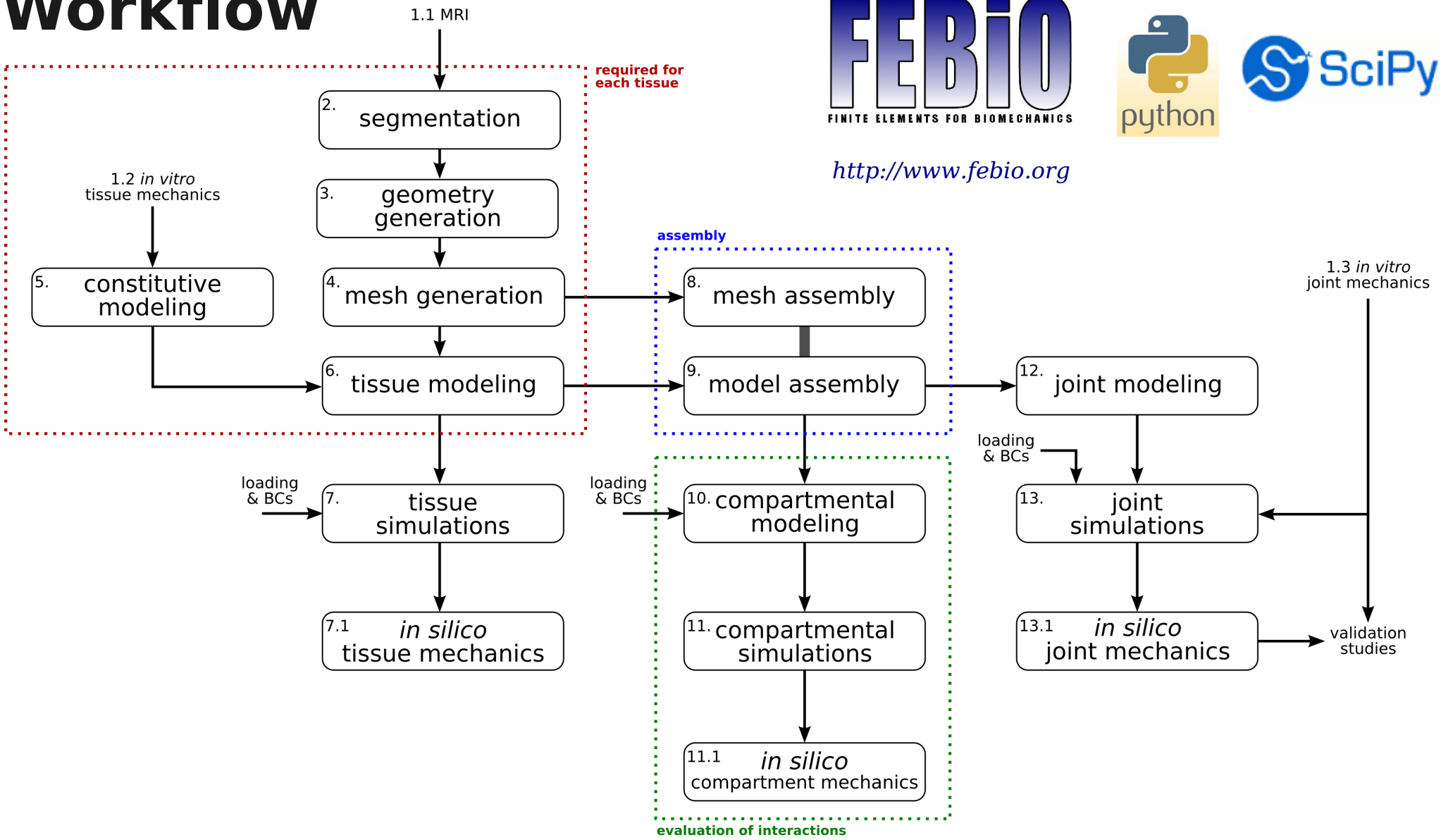
Stress Relaxation



multi-step stress relaxation tests
measurement of displacement – force
measurement of sample size
image capture (tension samples)

G2 MODELING

Workflow



FEBiO FINITE ELEMENTS FOR BIOMECHANICS

http://www.febio.org

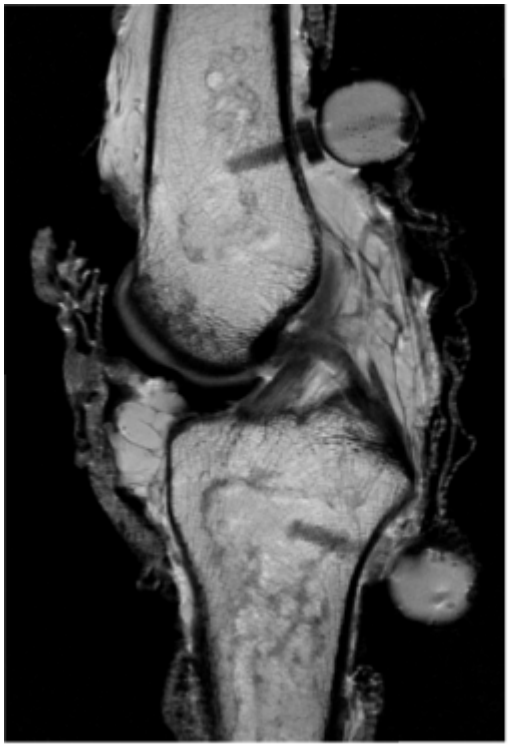
python

SciPy

For mature and developing standard operating procedures, refer to ***http://wiki.simtk.org/openknee/Specifications*****.**

G2 MODELING

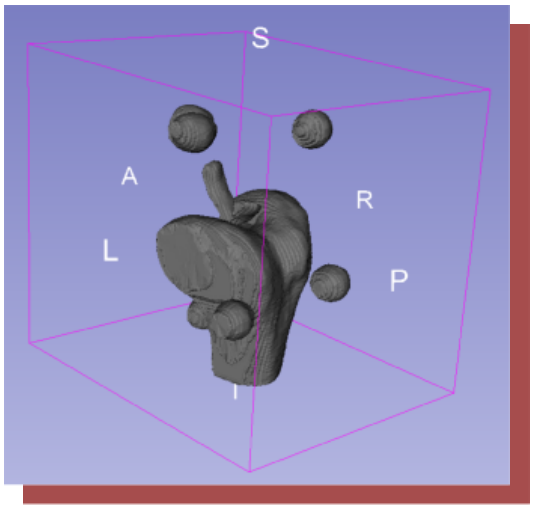
Segmentation



image

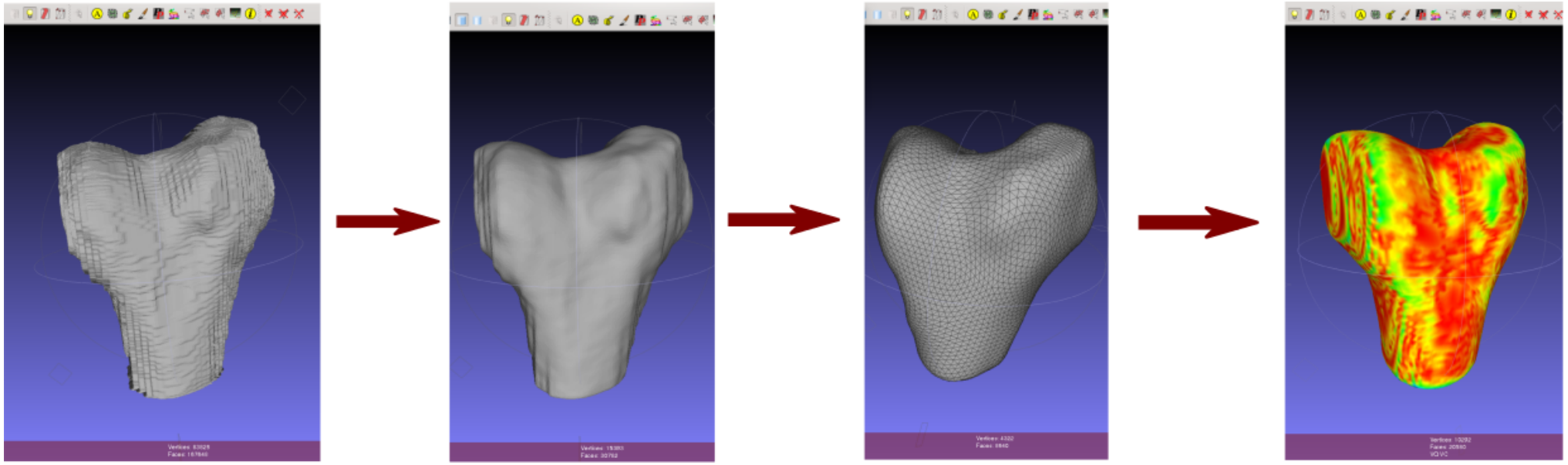
segmented volume

3DSlicer



G2 MODELING

Geometry Generation



raw volume

smoothing

isoparametric surface

error estimation

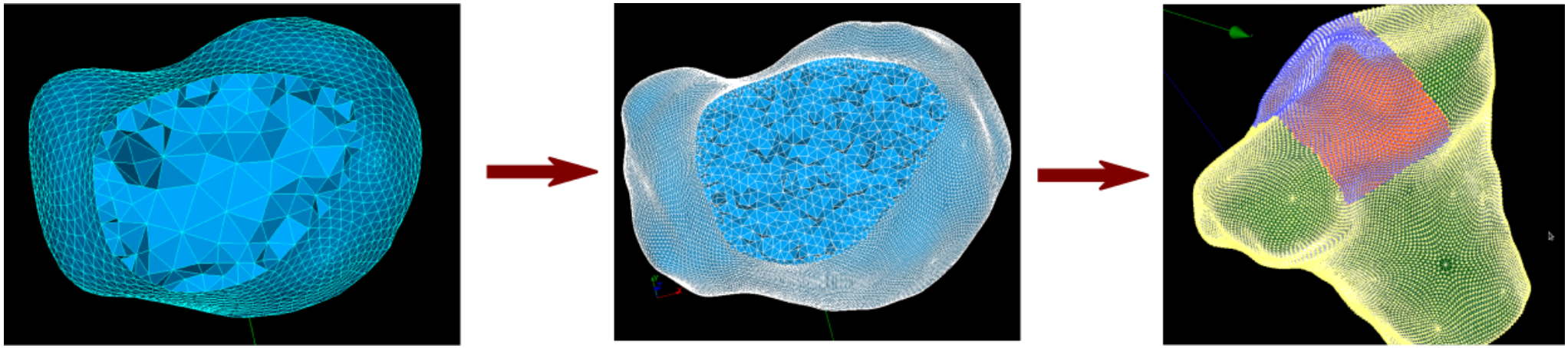
MeshLab

pyformex

G2 MODELING

Meshing

Relying on open source tools



coarse tetrahedral mesh

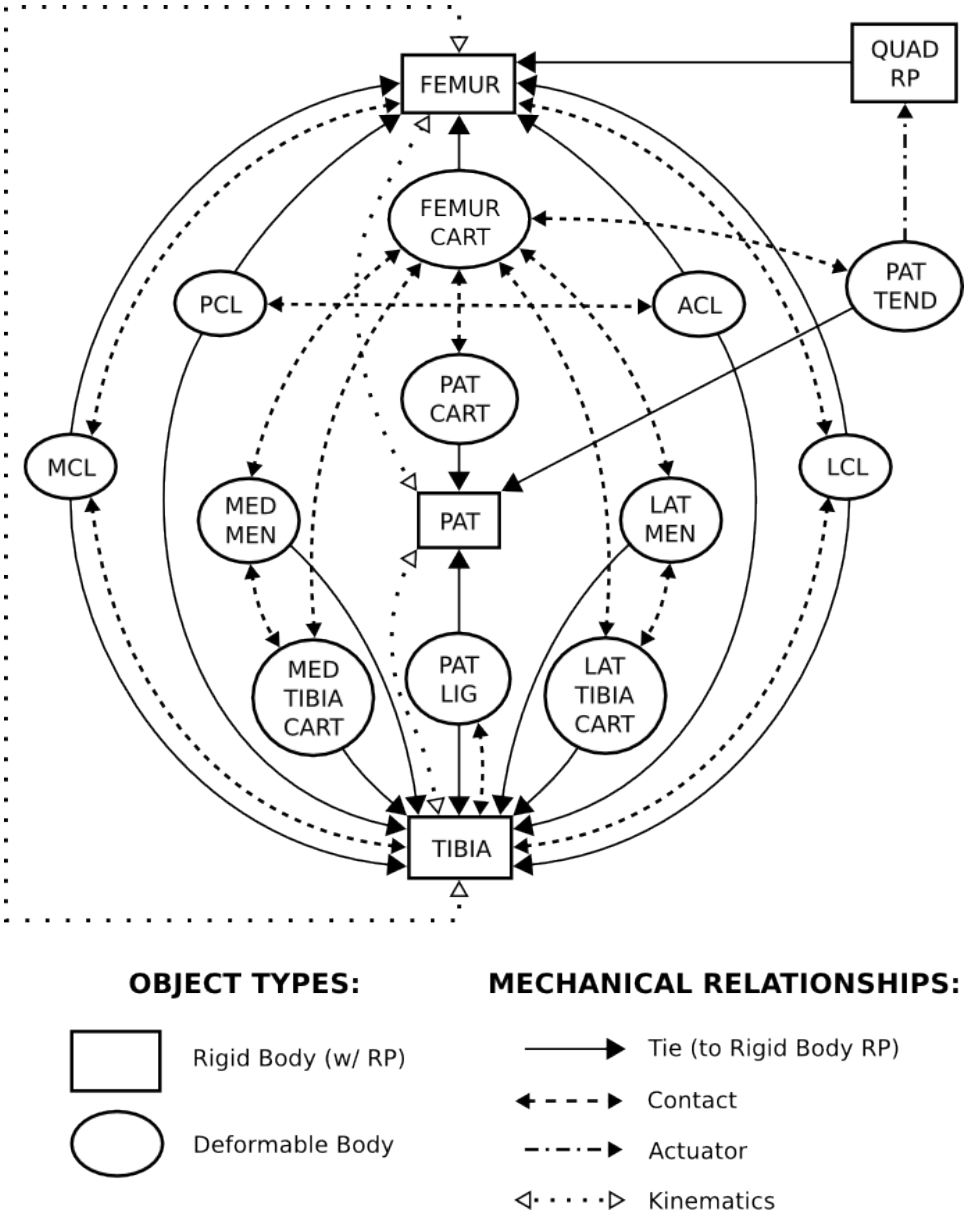
mesh refinement

set definitions

SALOME7 PLATFORM

IA-FEMesh for hexahedral meshing

G2 MODELING

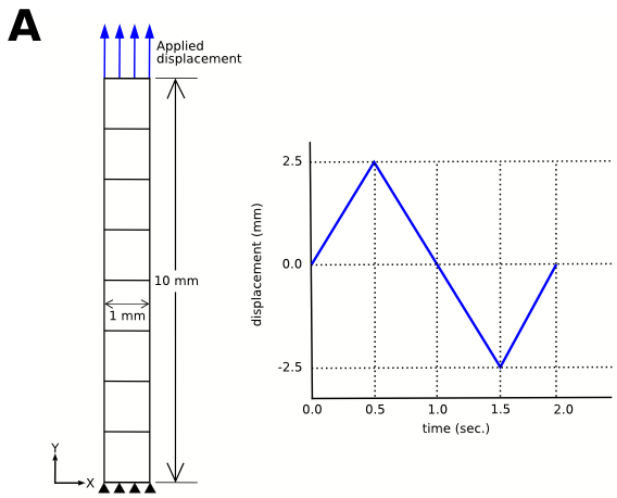


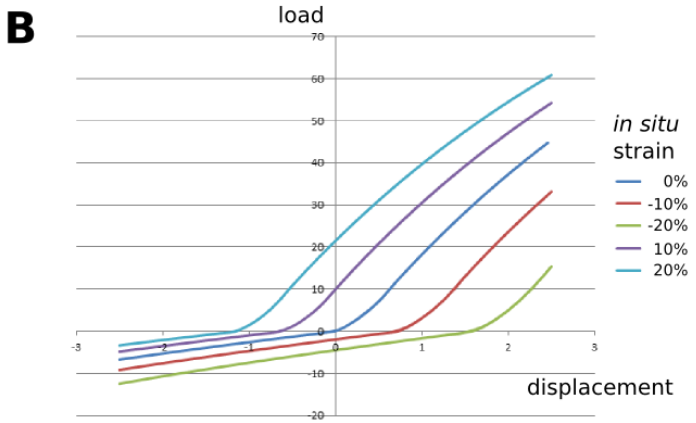
Customization

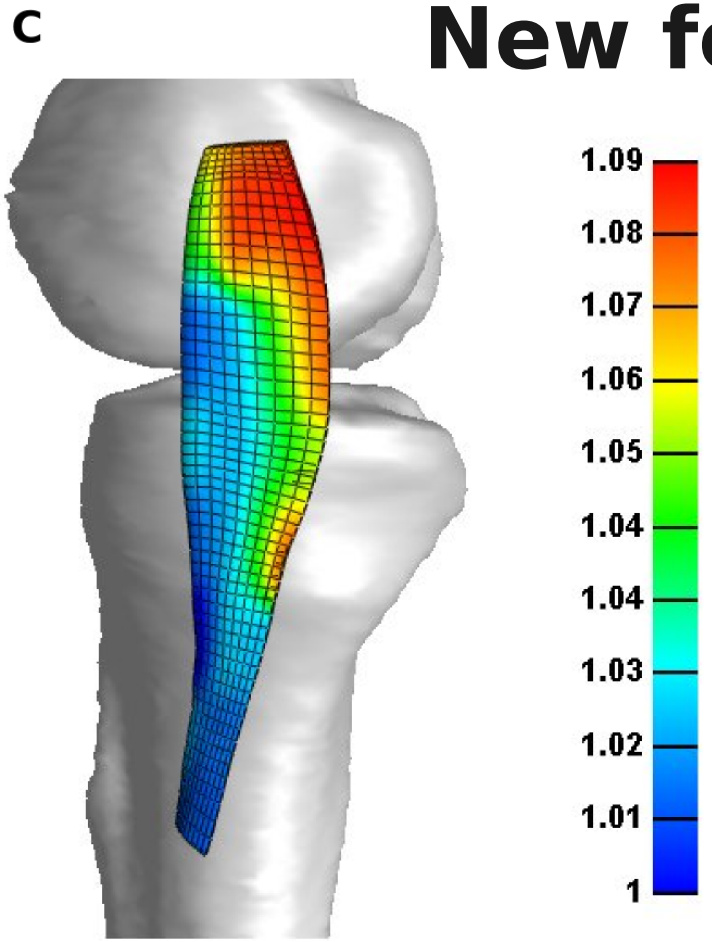
- Swap components based on
  - *fidelity of representation*
  - *intervention*
- Compartmental modeling, e.g.,
  - *cruciate complex*
  - *patellofemoral joint*

G2 SIMULATION SOFTWARE

New features





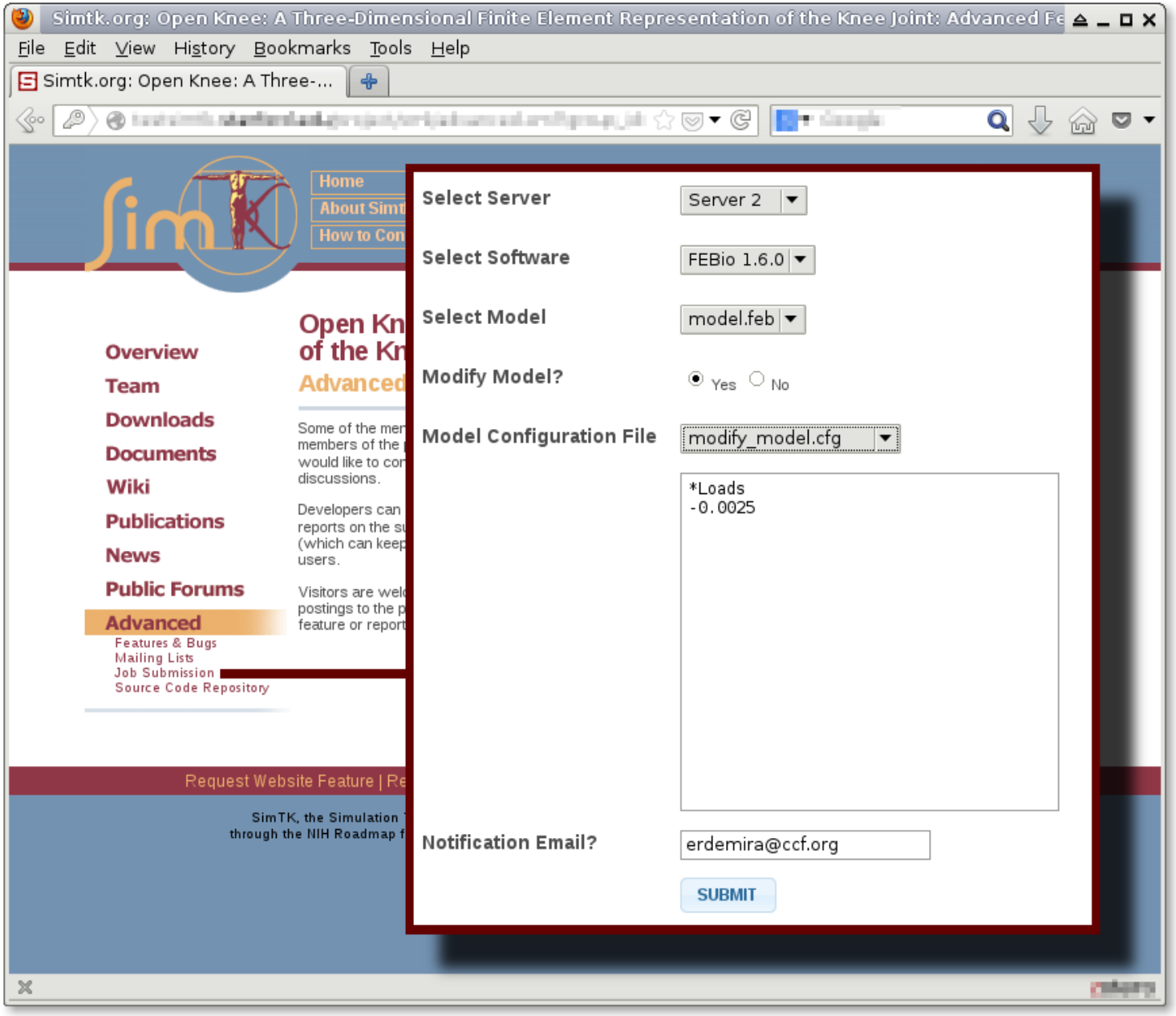


FEBiO
FINITE ELEMENTS FOR BIOMECHANICS

http://www.febio.org

A. In situ strain test problem
B. Ligament load with different in situ strain
C. In situ strain field applied to medical collateral ligament

G2 CLOUD COMPUTING



G2 COMMUNITY INVOLVEMENT

- USERS
  - *trainees – experts*
  - *engineers – scientists – physicians*
- POWER USERS
  - *of intermediate products*
    - *images - mesh - geometry*
  - *model customization*
  - *new simulation cases*
- DEVELOPERS
  - *of derivative models*
  - *contributors to Open Knee(s) roadmap*

SUMMER INTERNSHIPS ARE AVAILABLE

CONCLUDING REMARKS

- Open access models can **bridge the gap** between finite element analysis software and practical applications.
- Customization opportunities can enhance **broad utility** of open access models.
- Access to intermediate products of modeling workflow can facilitate **wide spread adaptation**.
- **Building communities** for direct translation of finite element analysis into scientific and clinical practice can be enabled.

POTENTIAL BENEFITS

- To knee biomechanics community

  Accessible training to understand knee function

  Customization for hypothesis generation

  Customization for intervention testing

  Evaluation of required fidelity for patient-specific modeling

  Enhanced repeatability & reproducibility of simulations

POTENTIAL BENEFITS

- To knee biomechanics community
  - *Accessible training to understand knee function*
  - *Customization for hypothesis generation*
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  - *Evaluation of required fidelity for patient-specific modeling*
  - *Enhanced repeatability & reproducibility of simulations*
- For experimentation and modeling of other musculoskeletal joints
  - *Transfer of standard operating procedures to other joints*

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  Enhanced repeatability & reproducibility of simulations

- For experimentation and modeling of other musculoskeletal joints

  Transfer of standard operating procedures to other joints

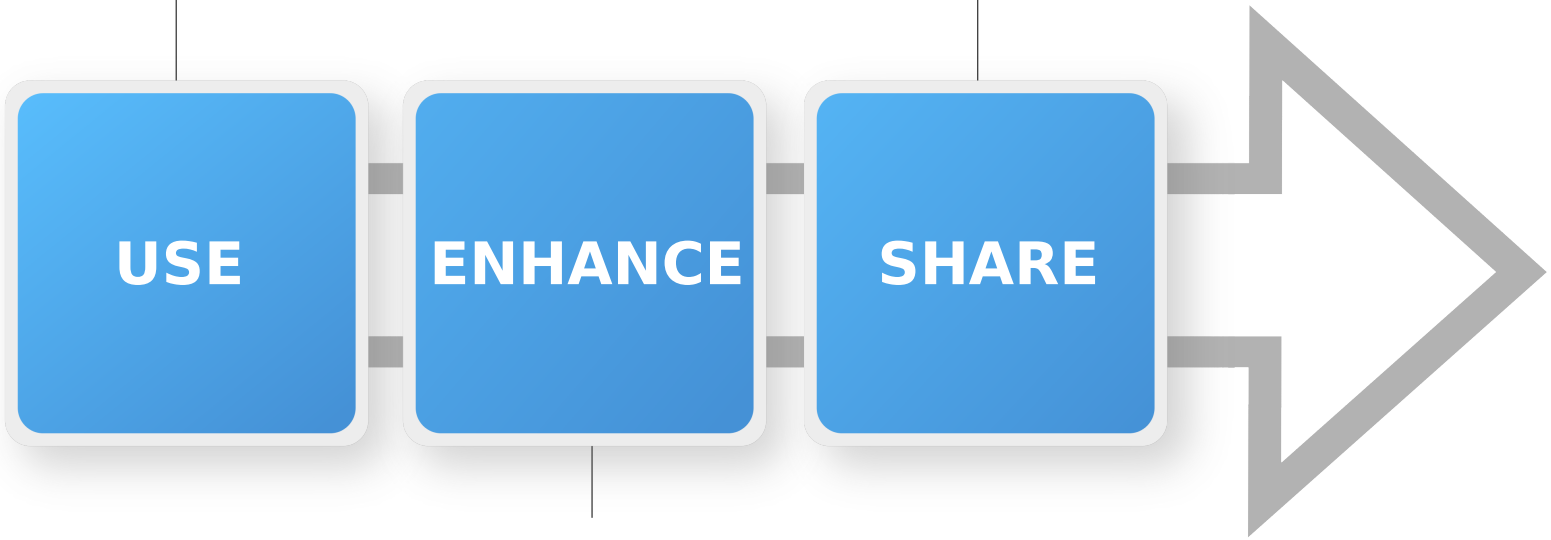
- To other subdisciplines of biomechanical modeling

  Illustration of open development and community involvement

HOW CAN YOU CONTRIBUTE?

models – meshes – geometries
images – mechanics data
usability issues – bugs - errors

your own data – models
customizations – derivative models



provide feedback on specifications
customize models for your needs

follow Open Knee(s) roadmap
analyze data – develop models
run simulations – document

VISIT **http://wiki.simtk.org/openknee**

ACKNOWLEDGMENTS

OPEN KNEE – GENERATION 1

Modeling
Craig Bennetts
Ahmet Erdemir
Randy Heydon
Scott Sibole

Data
Bhushan Borotikar
Antonie J. van den Bogert

Simulation Software
Ben Ellis
Steve Maas
David Rawlins
Jeff Weiss

NIH/NIBIB R01EB009643
NIH/NIGMS R01GM083925
NIH/NIAMS R01AR049735
Simbios

OPEN KNEE(S) – GENERATION 2

Cleveland Clinic
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Snehal Chokhandre
Robb Colbrunn
Ahmet Erdemir
Jason Halloran

Stanford University
Scott Delp
Joy Ku
Henry Kwong

University of Utah
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Steve Maas
Jeff Weiss

CWRU
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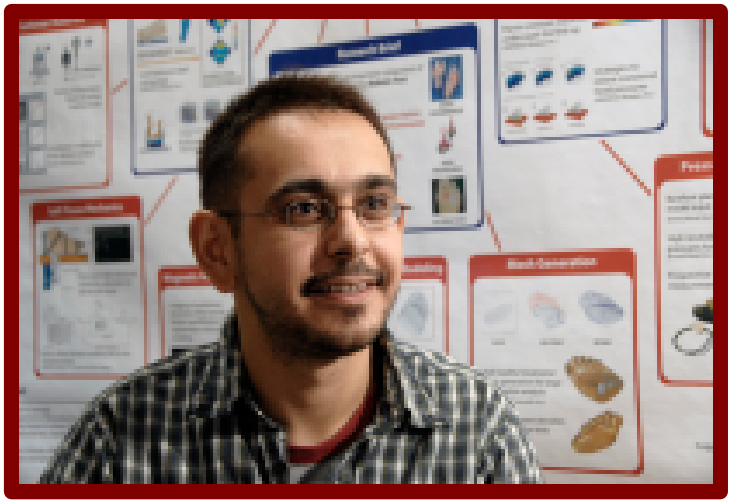
NIH/NIGMS
R01GM104139

https://simtk.org/home/openknee

CONTACT



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Open Knee(s): https://simtk.org/home/openknee
Open Knee(s) Wiki: http://wiki.simtk.org/openknee

LICENSING

TRADEMARKS & OWNERSHIPS