Democratization of Modeling & Simulation in Biomechanics
Our Experience with Open Knee(s)

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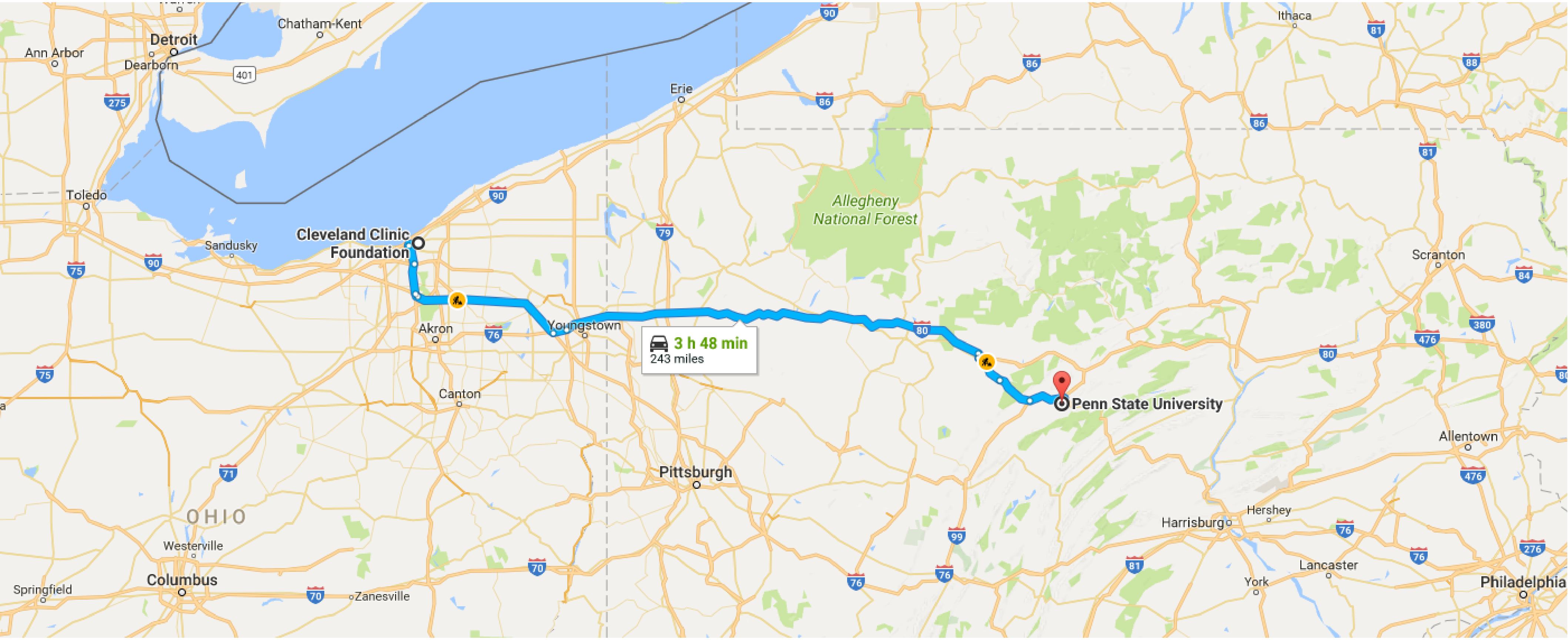
October 26, 2017
Kinesiology Colloquium Seminar
Pennsylvania State University

CLEVELAND CLINIC



CLEVELAND CLINIC

Open Knee(s) Enabled by ...

Craig Bennetts

Snehal Chokhandre

Tara Bonner

Robb Colbrunn

CoBi Core

bioRobotics

Open Knee(s) Enabled by ...

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
Craig Bennetts
Tara Bonner
Snehal Chokhandre
Robb Colbrunn
Ahmet Erdemir
Benjamin Landis

CWRU
Chris Flask
Shannon Donnola

Stanford University
Scott Delp
Joy Ku
Henry Kwong

University of Utah
Ben Ellis
Steve Maas
Jeff Weiss

Community
Dylan Beckler
David Brigati
Elvis Danso
Sam Doerle
Omar Gad
Callan Gillespie
Nicholas Haas
Connor Lough
Raghav Malik
Eryn Merico
Nicole Nassif
Jason Halloran
Katie Stemmer
Diana Suciu
Cara Sullivan
Will Zaylor

Advisory Board
Jack Andrish
Yasin Dhaher
Trent Guess
Morgan Jones
Rami Korhonen
Paul Saluan
Carl Winalski

NIH/NIGMS
R01GM104139

https://simtk.org/projects/openknee

M&S in Healthcare

Utility of computational modeling & simulation

- For scientific discovery

  structure-function relationships in health & disease

  mechanistic foundations of data associations

- For engineering innovation

  intervention design & evaluation

- For clinical care

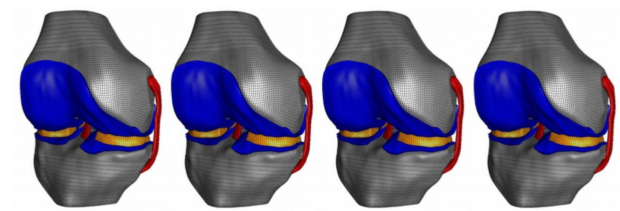
  diagnosis/prognosis

  intervention safety & performance

  medical training

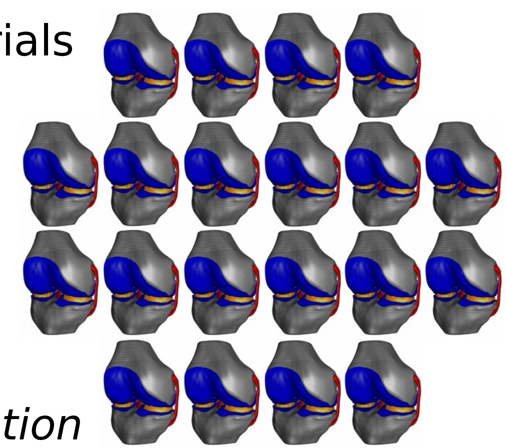
  individualized medicine

virtual experiments



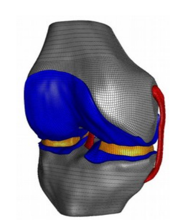
virtual specimen(s) / subject(s)

in silico trials

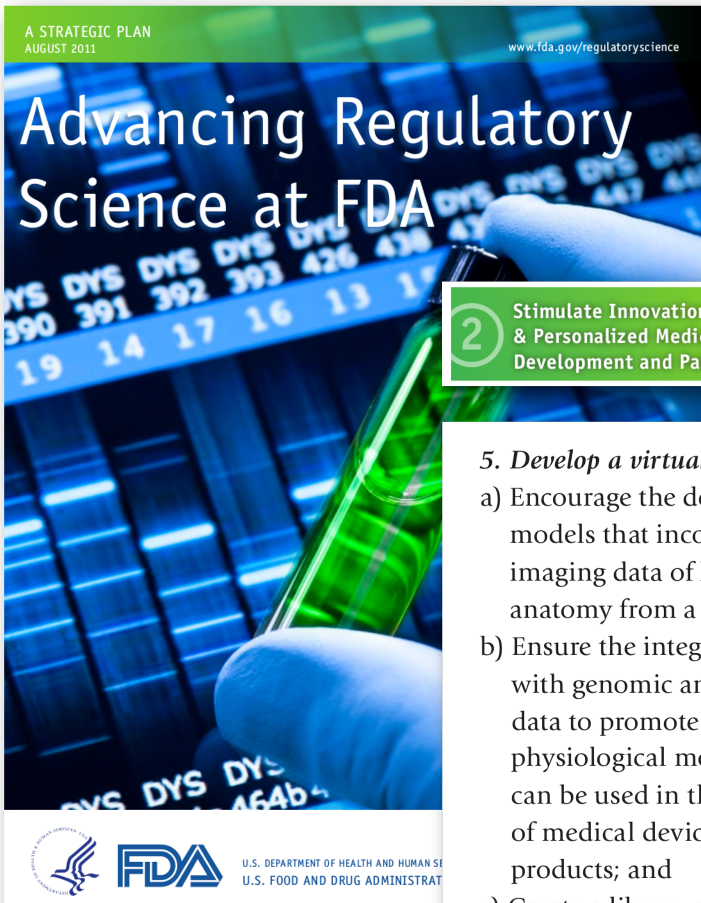


virtual population

virtual patient



Promise of M&S



2 Stimulate Innovation in Clinical Evaluations & Personalized Medicine to Improve Product Development and Patient Outcomes

5. Develop a virtual physiologic patient:

a) Encourage the development of computer models that incorporate radiological imaging data of healthy and diseased anatomy from a range of relevant diseases;

b) Ensure the integration of these models with genomic and other physiological data to promote development of complete physiological models and simulations that can be used in the development and testing of medical devices and other medical products; and

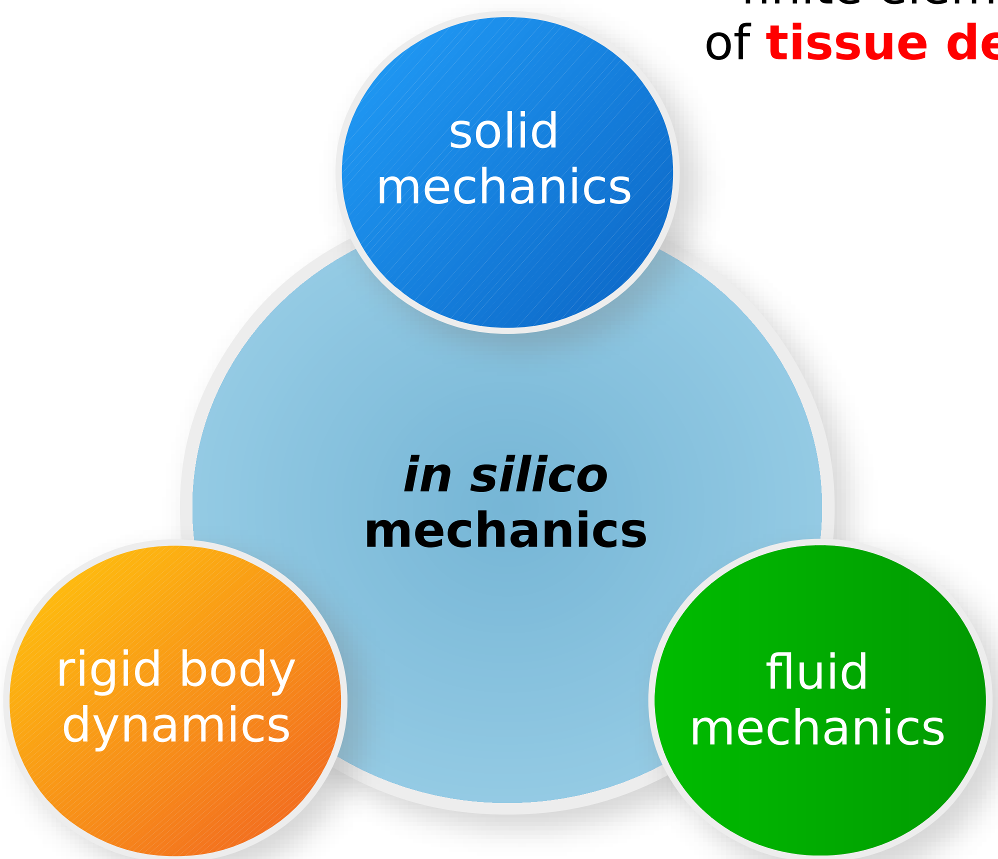
c) Create a library of models so that models validated by FDA are easily accessible to researchers.

Computational models can reduce

- Physical prototyping
- Animal studies
- Human subjects testing
- Cadaver experiments

M&S Enterprise in Biomechanics

finite element analysis
of **tissue deformations**



musculoskeletal
movement
simulations

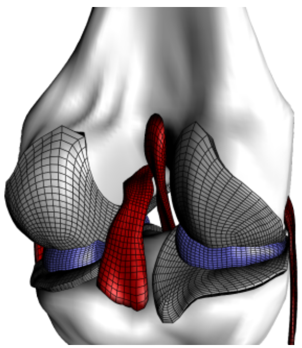
computational fluid dynamics
of **cardiovascular systems**

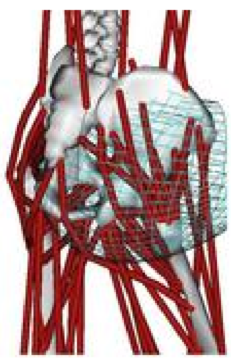
M&S Enterprise in Biomechanics

FEBiO
FINITE ELEMENTS FOR BIOMECHANICS

OpenSim

SimVascular

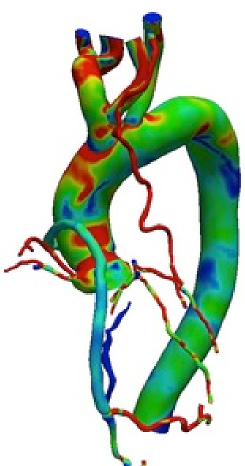




simulation software

models

computing hardware



XSEDE
Extreme Science and Engineering Discovery Environment

GPGPU

Emerging Need

- Simulation **software** – free and open source
- Simulation **hardware** – cost-effective and/or public
- **Models**

anatomical and physiological properties
to support subject/specimen-specific authenticity

biomechanical response
to support subject/specimen-specific evaluation

subject-to-subject variety
to support population diversity

accessibility
to promote wide-spread use

Goals

- To recognize **desirable properties** of democratization in modeling & simulation in biomechanics

- To identify **challenges** to achieve desirable properties

- To demonstrate **strategies** to tackle the challenges

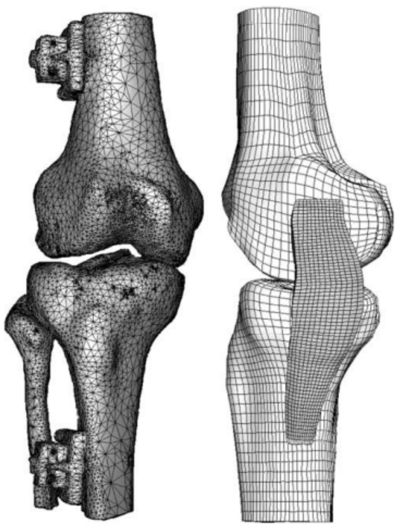
Open Knee(s), modeling & simulation for knee mechanics, as a **case study**

M&S in Knee Biomechanics

- How would this patellar alignment stabilize the movement of the patellofemoral joint? Will it cause increased cartilage contact pressures?
- Should I change the implant design? Will it reproduce natural knee movements? Will it fail? Will the host tissue be safe?
- Will this routing of ACL reconstruction benefit my patient? Will it work for all patients?
- ...

M&S in Knee Biomechanics

Joint and tissue functions



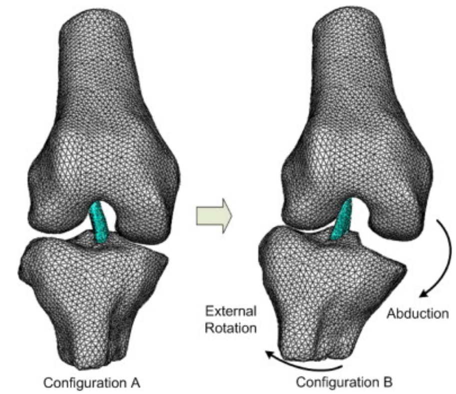
MCL function

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

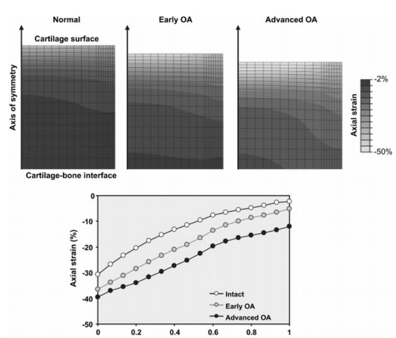
Injury mechanisms

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

ACL impingement



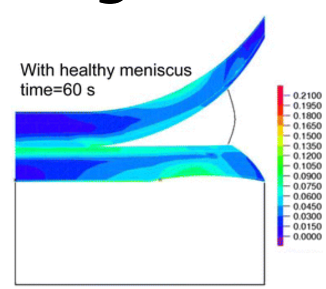
Pathological impacts



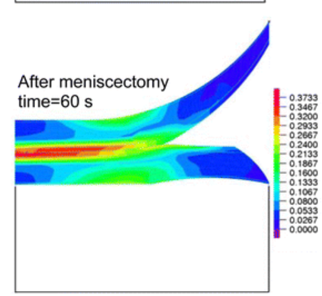
Osteoarthritis

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

Surgical interventions

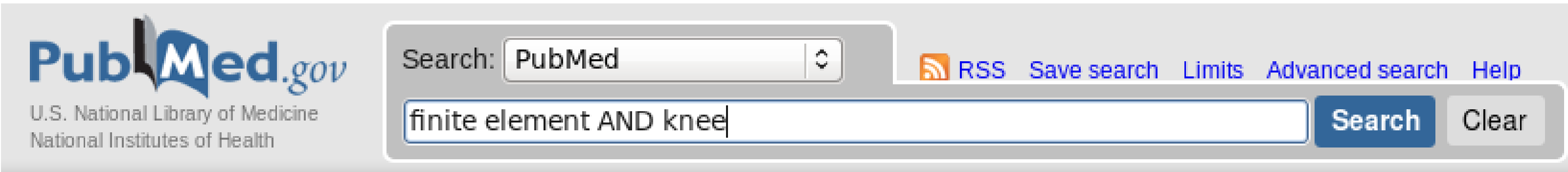


Menisectomy



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

M&S in Knee Biomechanics



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881 (as of Oct 14, 2017)

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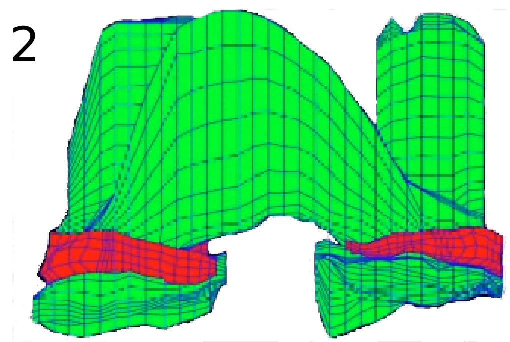

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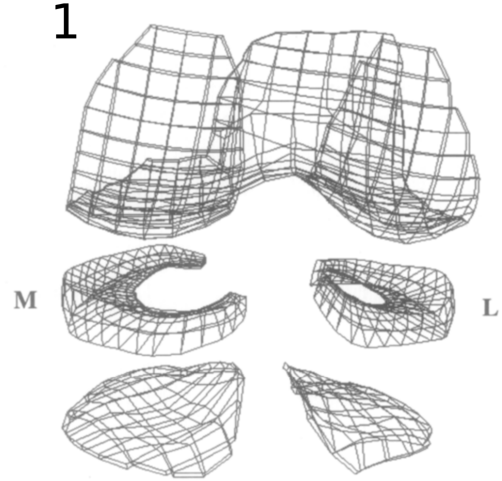
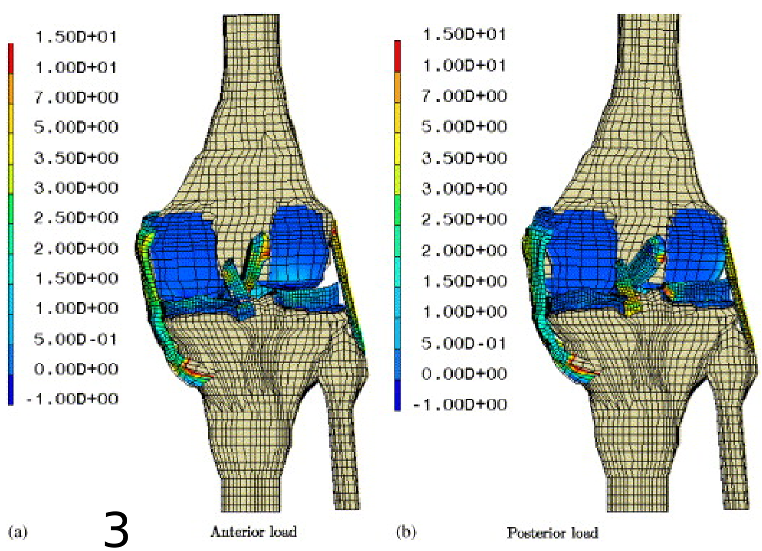
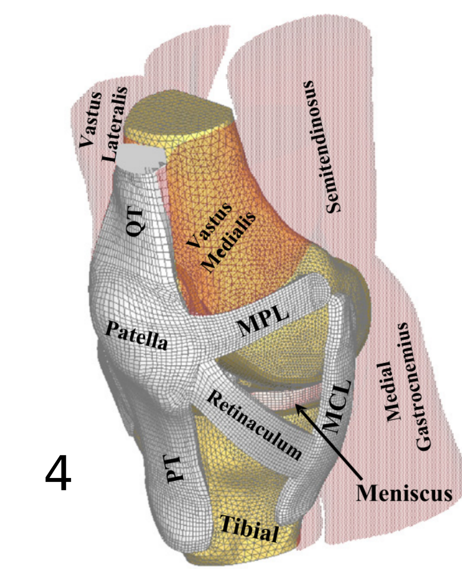




3

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.*

Need for Progress

- How **representative** are the models?
- Are the models **credible**?
- Are the models **accessible**?
- Are the models **usable**?

Open Knee(s) Goals

NIH/NIGMS
R01GM104139
9/16/2013- 5/31/2018

- 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.

- 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.

Open Knee(s) Brief History

Predicting Cell Deformation from Body Level Mechanical Loads – NIBIB, NIH (PI: Erdemir)

2010

Open Knee: First Generation – Dissemination

Open Knee: First Generation – Promotion @ ASB 2010

2012

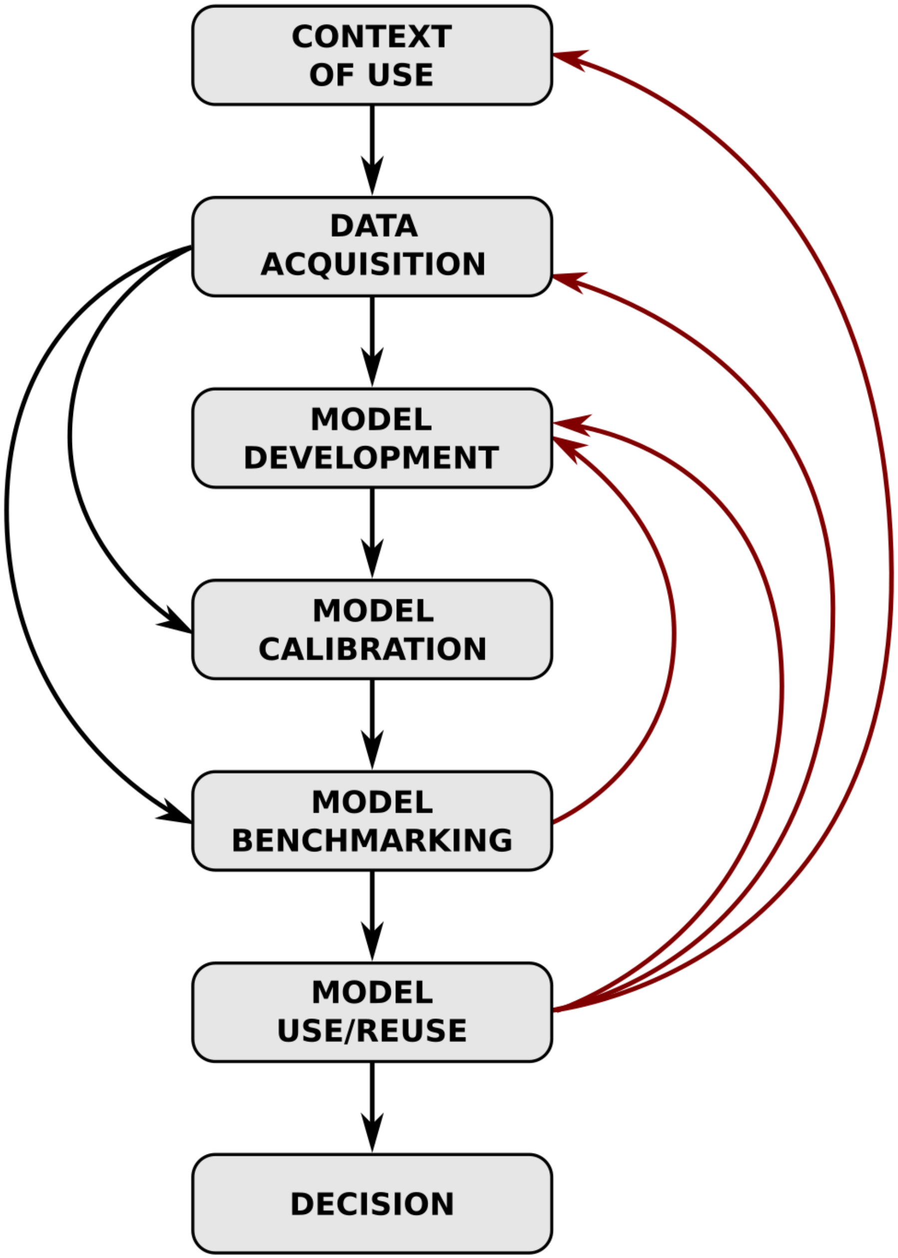
Open Knee(s): Virtual Biomechanical Representations of the Knee Joint – NIGMS, NIH (PI: Erdemir)

2014

Open Knee(s): Second Generation – Data Dissemination

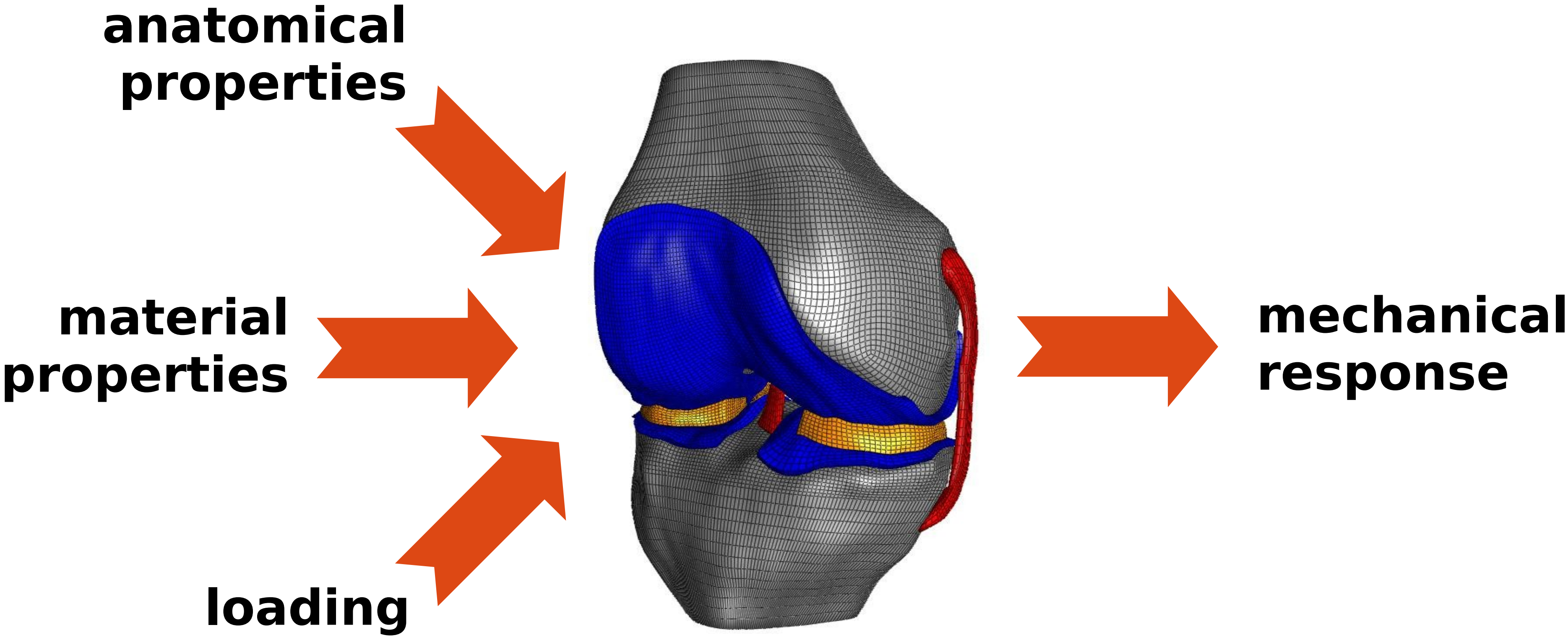
Open Knee: First Generation – Publication @ JKS

Open Knee(s) Lifecycle

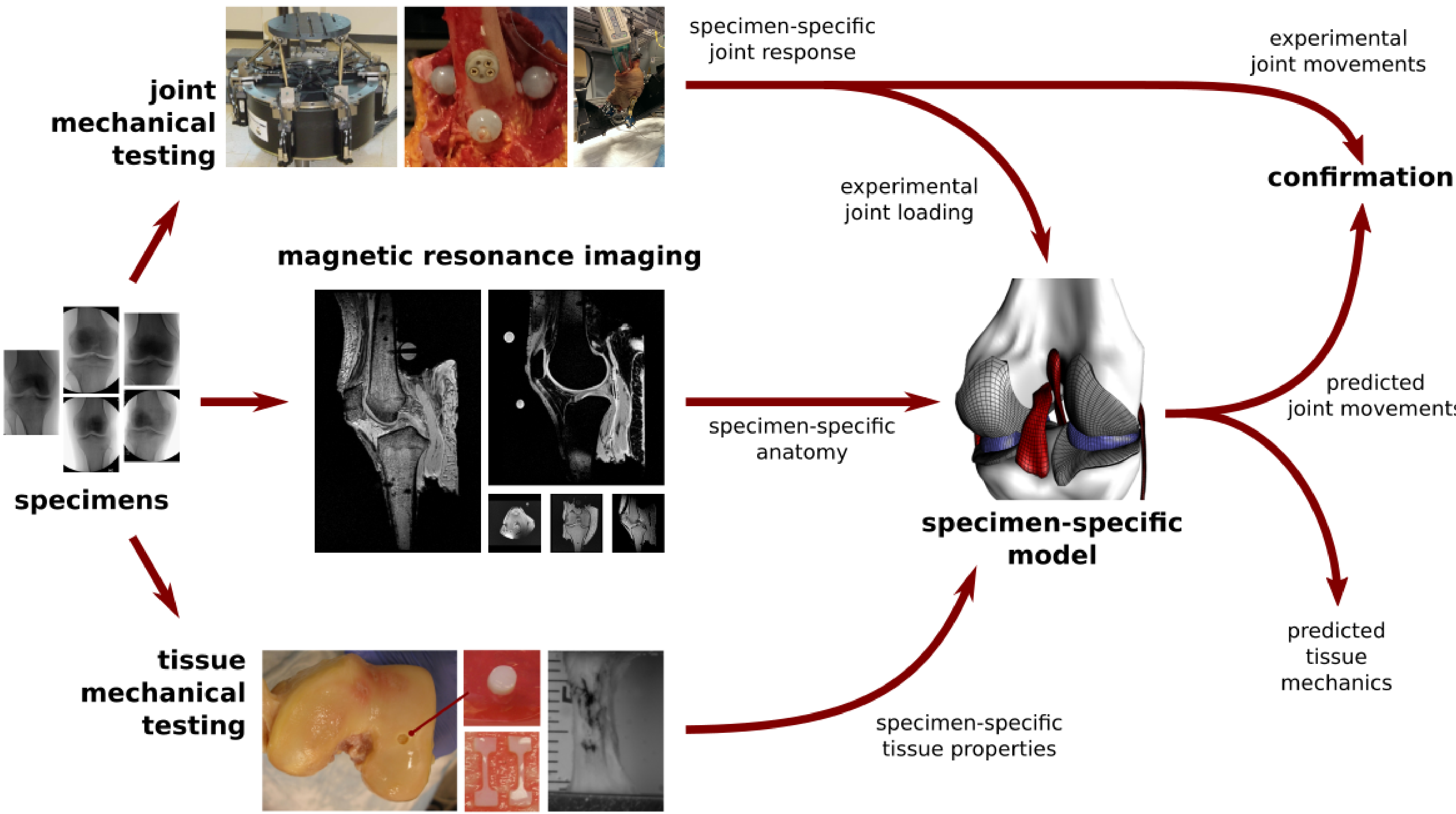


- Context of use targeted for **prediction of joint** and **tissue mechanics** of the knee in health and disease, and after intervention
- **Iterations** are anticipated to establish credibility and to customize for reuse

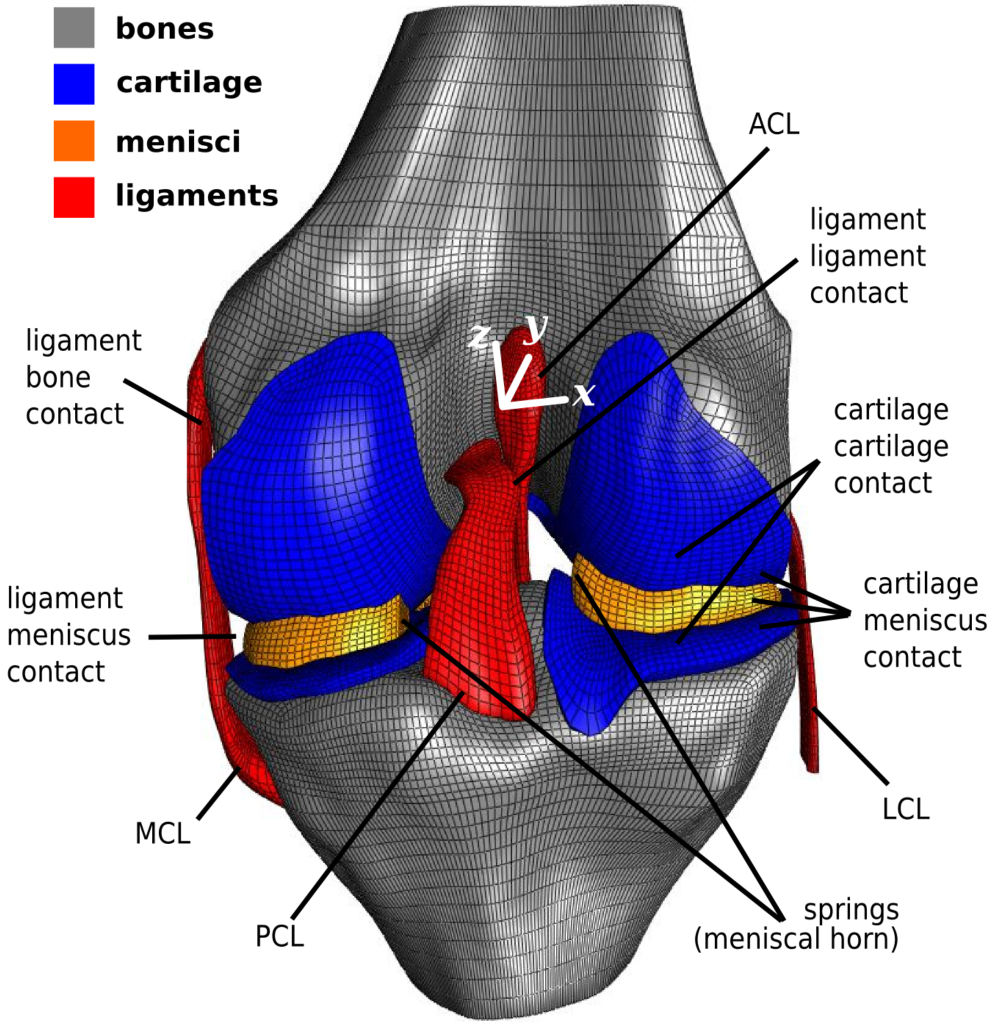
Building Open Knee(s)



Building Open Knee(s)



Building Open Knee(s)



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.

Activities for Democratization

To meet desirable properties of modeling & simulation

- ***Specificity*** – relating to a particular subject
- ***Efficiency*** – achieving maximum productivity
- ***Accessibility*** – easy to obtain
- ***Usability*** – easy to use
- ***Comprehensibility*** – easy to understand
- ***Credibility*** – being trusted

Specificity

Goal to increase the quality of relating to a particular subject

Challenges

lack of comprehensive specimen-specificity

limited availability of sample variations

logistics of data collection

Specificity: Getting Data

Integration of diverse data collection strategies to overcome ***logistical***, ***scientific***, and ***technical challenges*** → **SPECIMEN-SPECIFIC ANATOMICAL & MECHANICAL DATA**

PLOS | ONE

RESEARCH ARTICLE

A Comprehensive Specimen-Specific Multiscale Data Set for Anatomical and Mechanical Characterization of the Tibiofemoral Joint

Snehal Chokhandre[1,2], Robb Colbrunn[2,3], Craig Bennetts[1,2], Ahmet Erdemir[1,2]*

1 Computational Biomodeling (CoBi) Core, Lerner Research Institute, Cleveland Clinic, Cleveland, Ohio, 44195, United States of America, **2** Department of Biomedical Engineering, Lerner Research Institute, Cleveland Clinic, Cleveland, Ohio, 44195, United States of America, **3** BioRobotics and Mechanical Testing Core, Lerner Research Institute, Cleveland Clinic, Cleveland, Ohio, 44195, United States of America

* erdemira@ccf.org

CrossMark
click for updates

adapted from Chokhandre et al. (2015)

Specificity: Getting Data

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

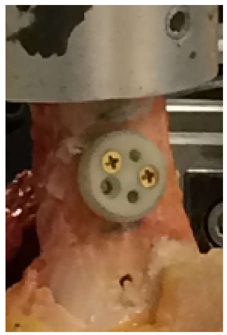
Gender: Male
Age: 71 years
Race: White
Height: 1.7 m
Weight: 65.8 kg
BMI: 22.7

2 more tested; more on the way...

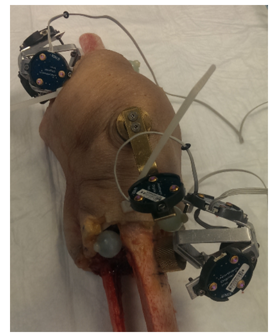
Specificity: Getting Data

Preparation

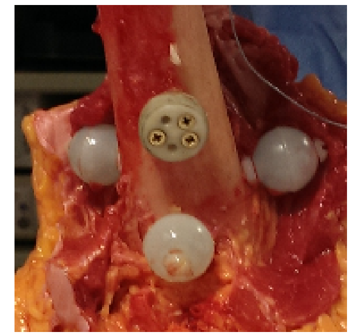
dissection



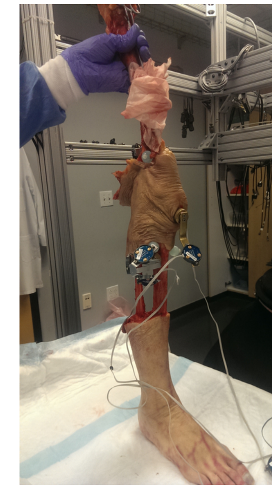
bone plugs



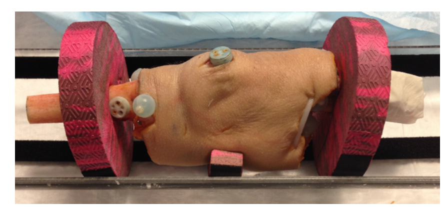
motion capture markers



registration markers

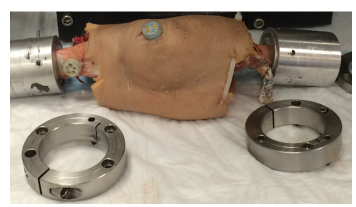


anatomical landmarks



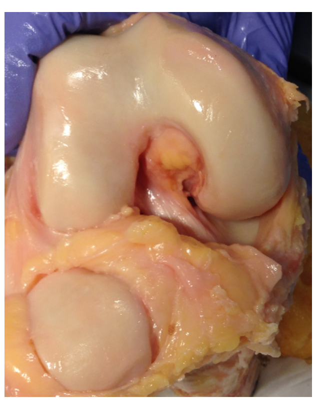
preparation for imaging

to anatomical imaging



preparation for joint testing

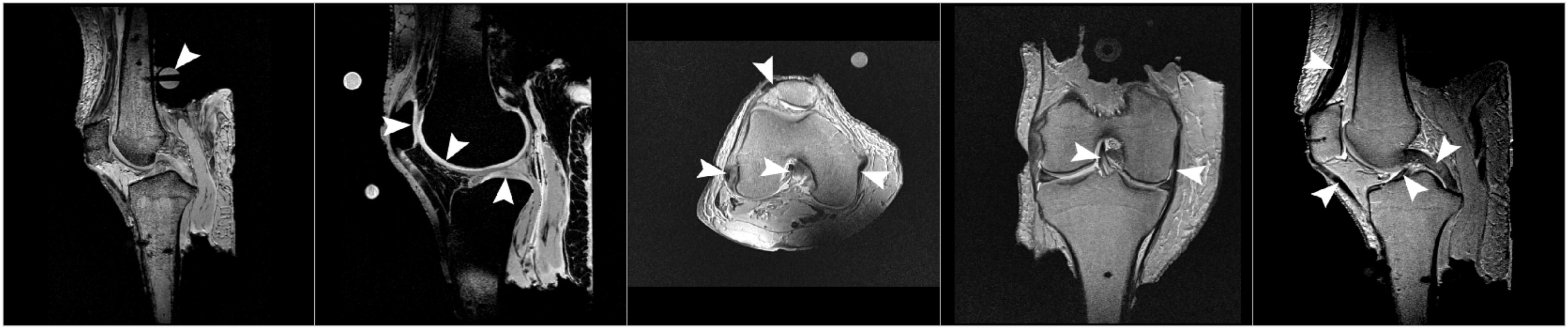
to joint testing



preparation for tissue testing

to tissue testing

Specificity: Getting Data



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

same 8 knee specimens X **Magnetic Resonance Imaging**

Specificity: Getting Data

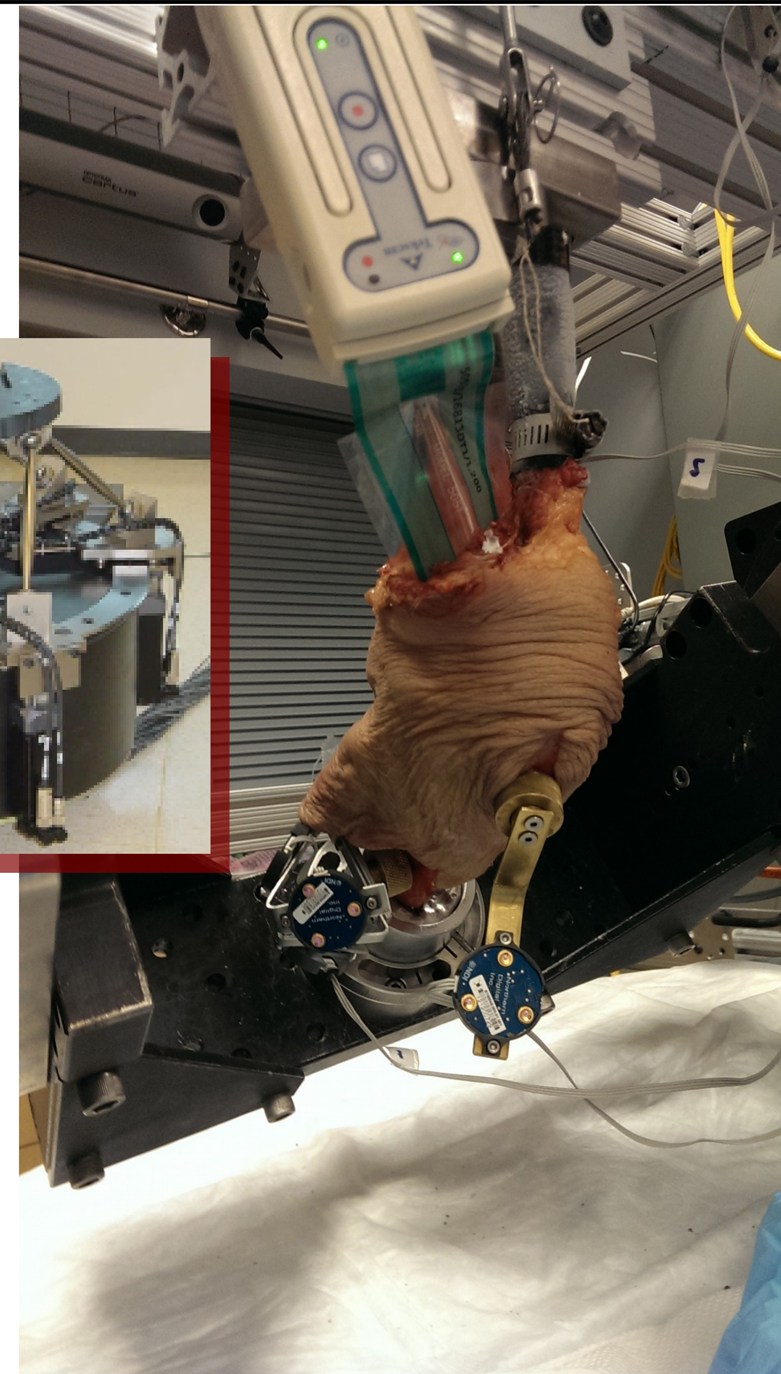
same 8 knee
specimens

X

1 tibiofemoral joint
1 patellofemoral joint

X

Robotics Joint Testing
Kinematics - Kinetics



Specificity: Getting Data

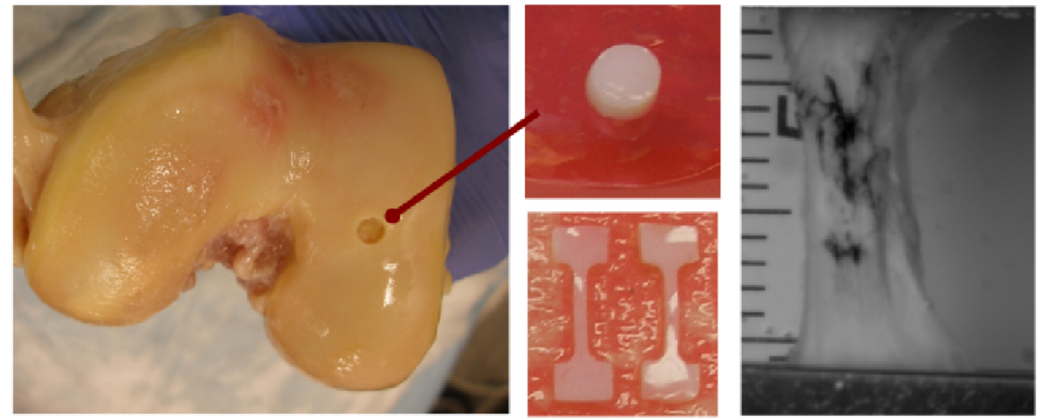
same 8 knee specimens

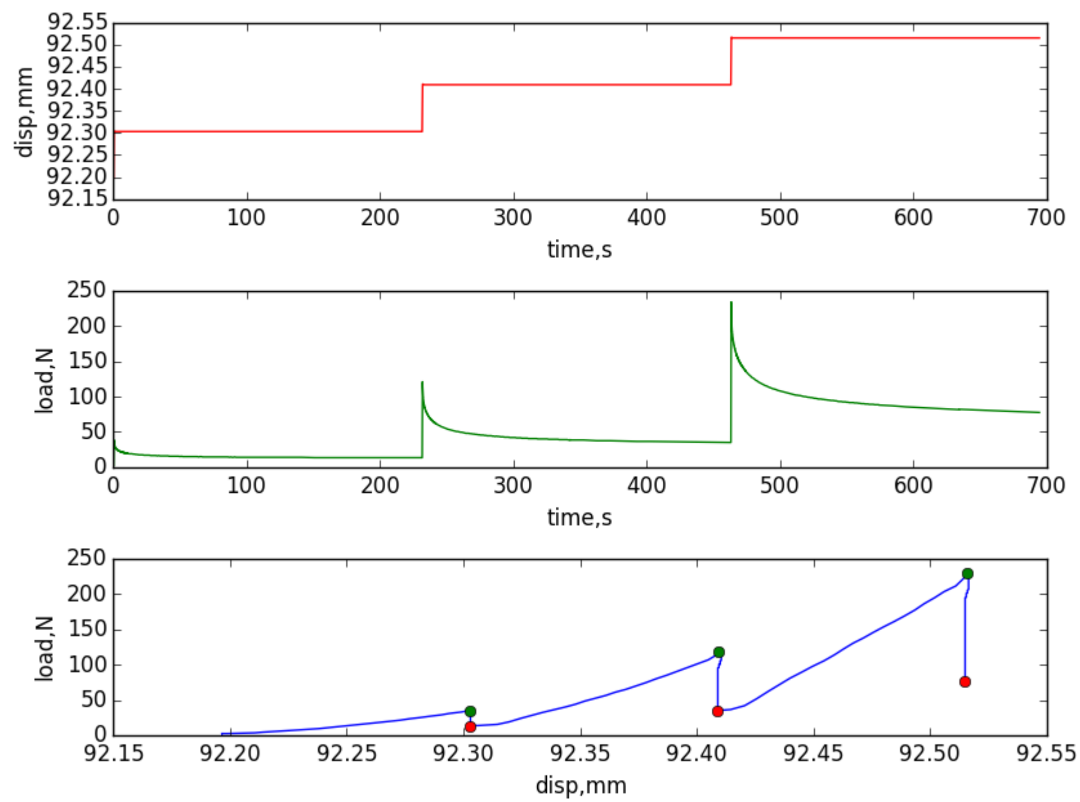
X

12 cartilage samples
4 menisci samples
6 ligament samples

X

Uniaxial Tissue Testing
Tension / Compression



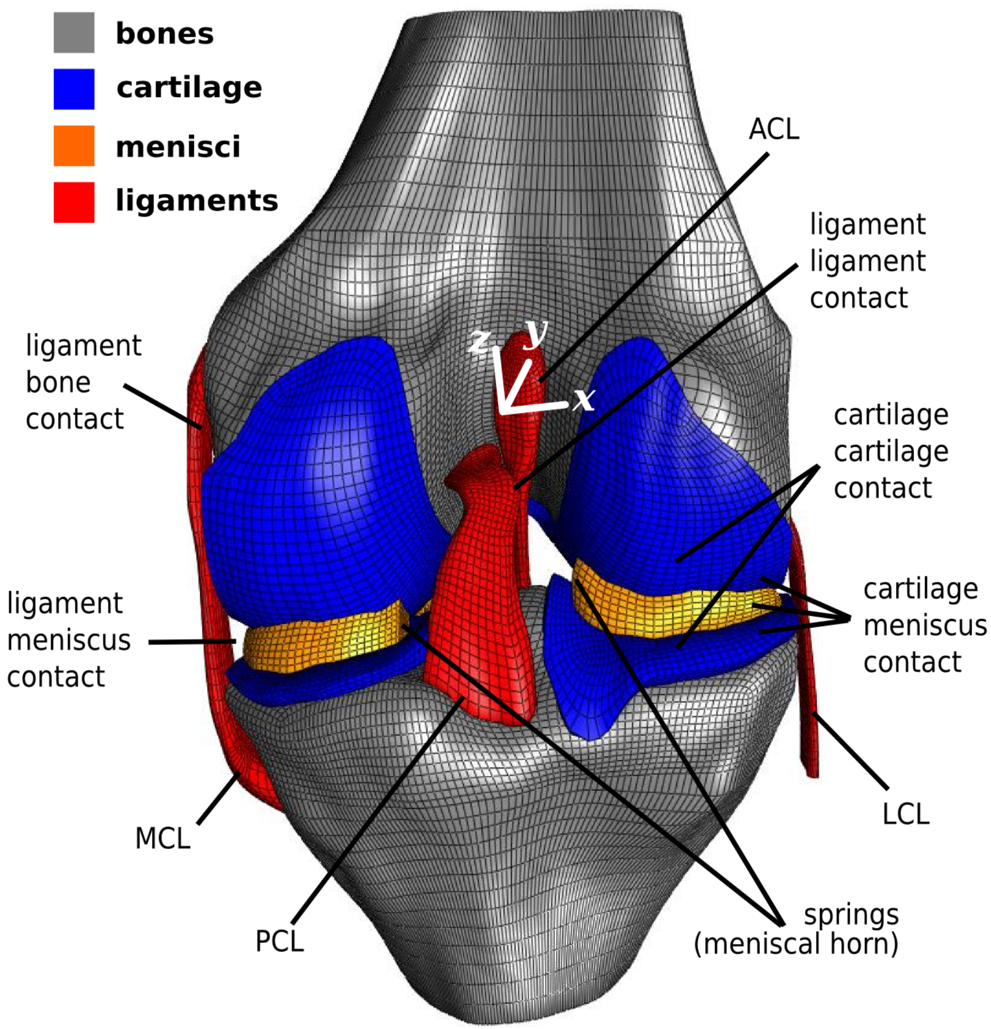


Efficiency

Goal to increase the quality of achieving maximum productivity with minimum wasted effort

Challenges
- manual workflows
- balancing cost and accuracy
- heterogeneous formats
- need for high-throughput analysis

Efficiency: Building Models



Bones
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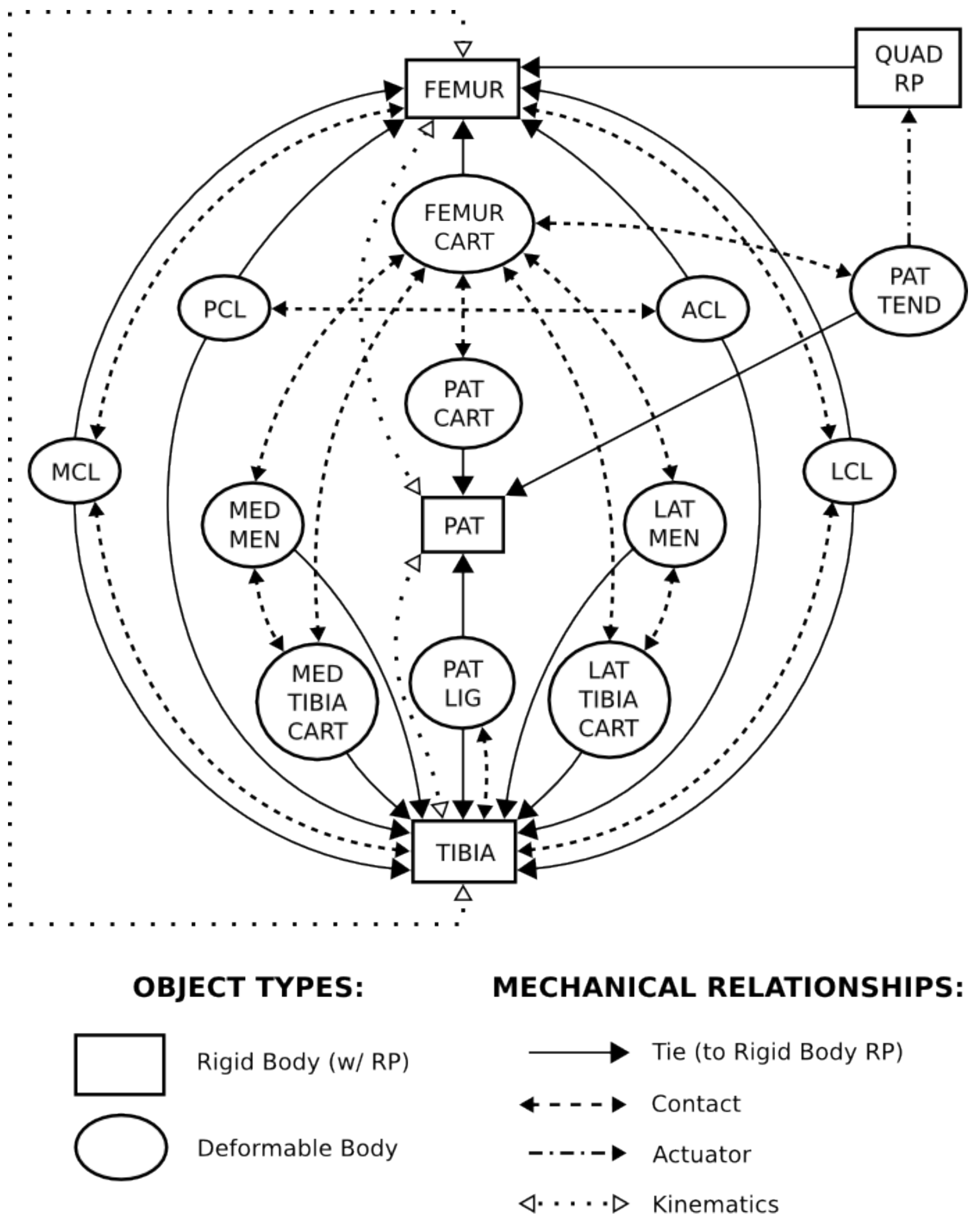
Efficiency: Building Models



Modularity

- Swap components based on

  fidelity of representation

  intervention

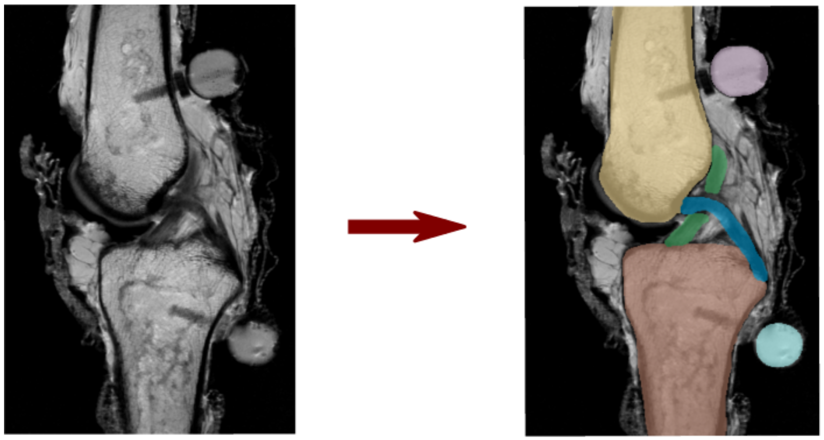
- Compartmental modeling, e.g.,

  cruciate complex

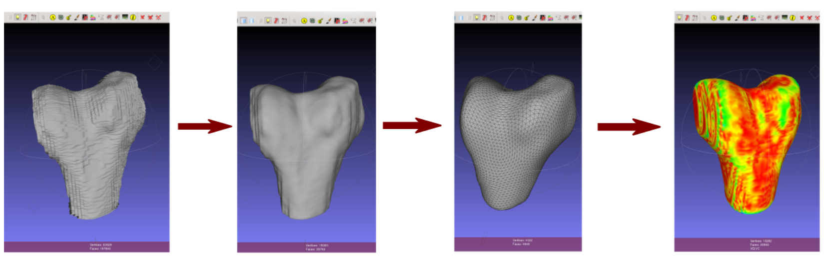
  patellofemoral joint

Efficiency: Building Models

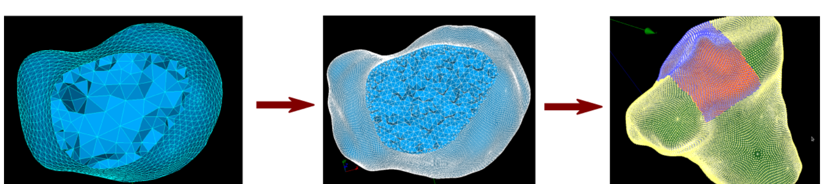
SEGMENTATION

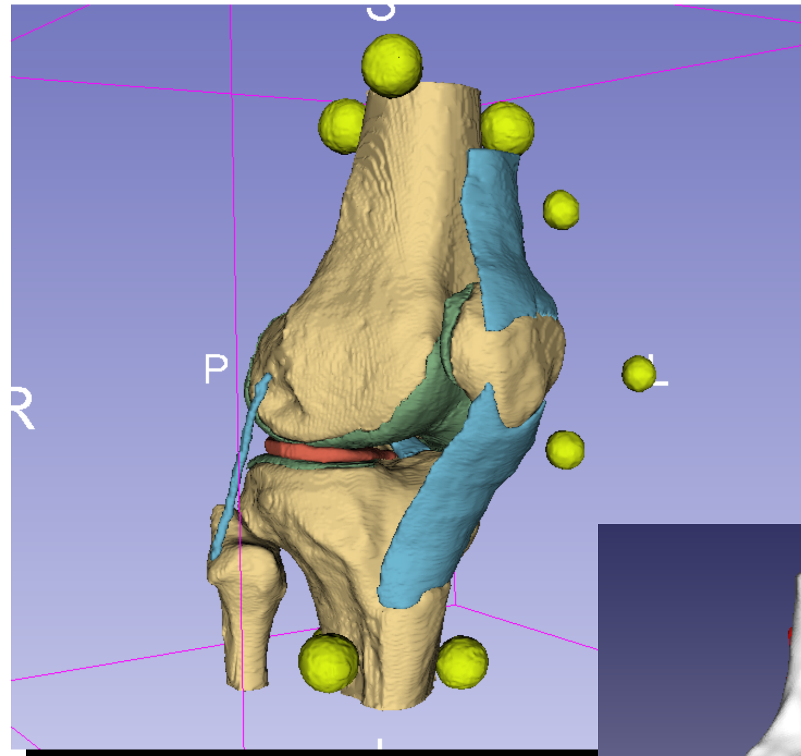


GEOMETRY GENERATION

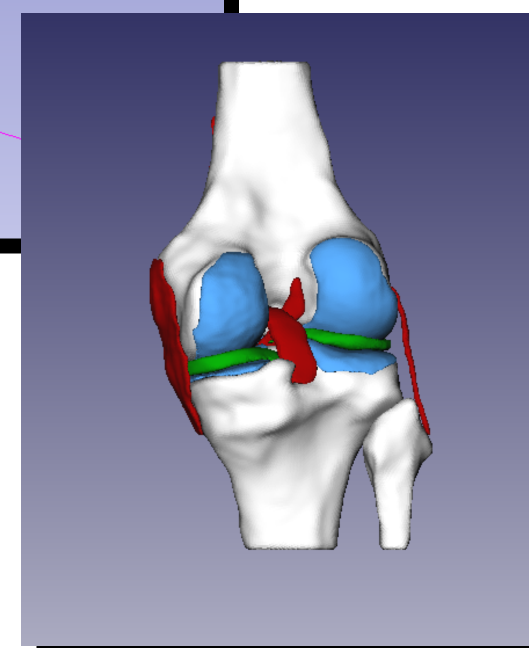


MESH GENERATION

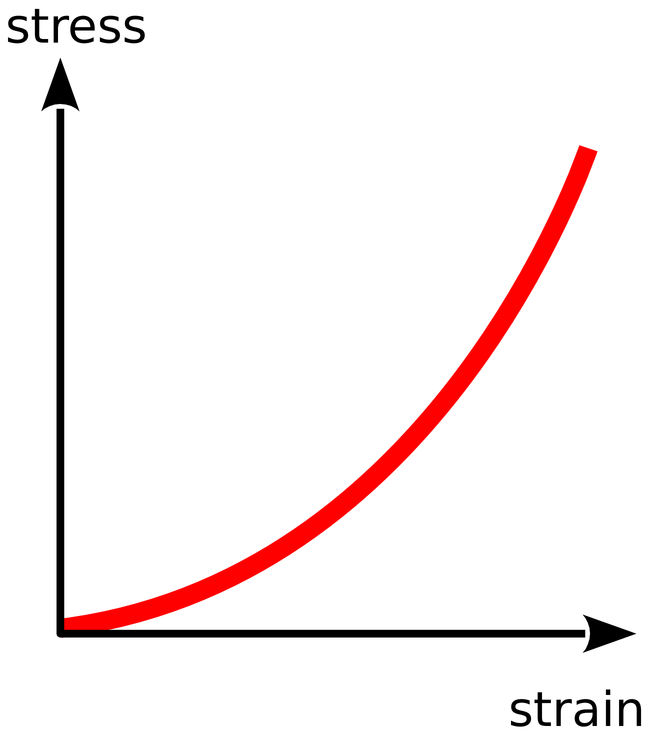




specimen-specific
joint anatomy



Efficiency: Building Models



CONSTITUTIVE MODELING

$$W = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i}\left(\overline{\lambda_1^{\alpha_i}} + \overline{\lambda_2^{\alpha_i}} + \overline{\lambda_3^{\alpha_i}} - 3\right)$$

μ_i , α_i

specimen-specific material properties for cartilage – ligaments - menisci

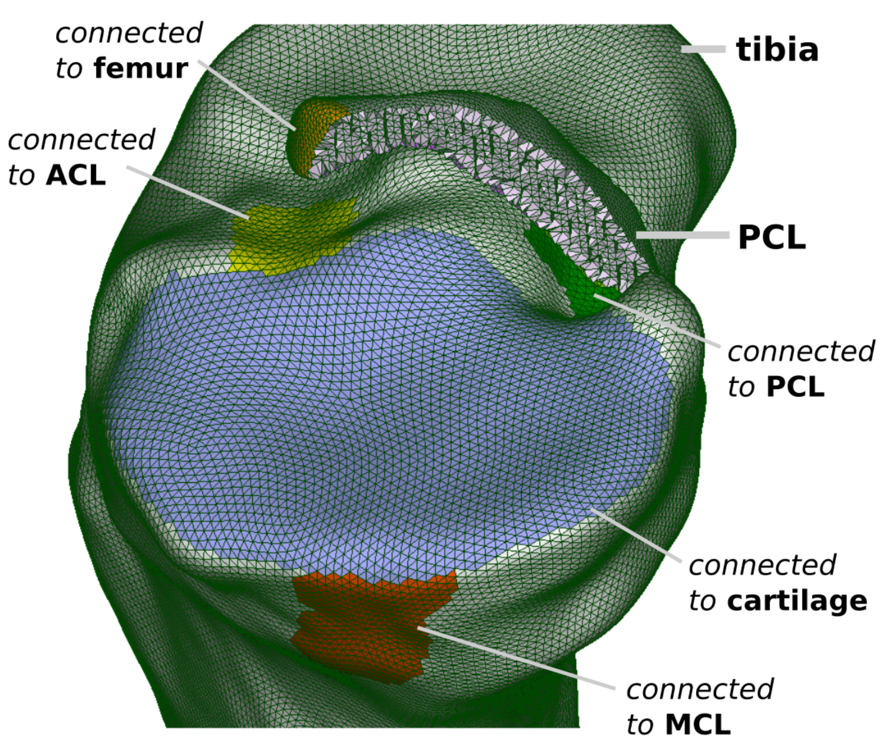
Efficiency: Building Models

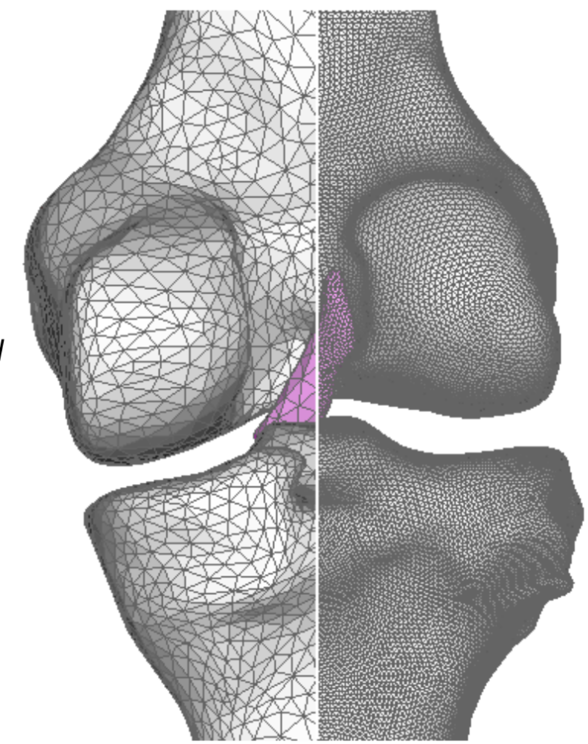
python

SALOME8 PLATFORM

Scripting for **unsupervised** mesh assembly, model generation, multi-format output with support for object replacement

```
<Tibia>
 <file>
  oks001_MRC_TBB_LVTIT_10.stl
 </file>
 <material>
  rigid
 </material>
 <Contact>
  <MCL/>
  <PatellarLigament/>
 </Contact>
 <Tie>
  <TibialMedialCartilage/>
  <TibialLateralCartilage/>
  <MCL/>
  <ACL/>
  <PCL/>
  <PatellarLigament/>
  <MedialMeniscus/>
  <LateralMeniscus/>
  <Fibula/>
 </Tie>
</Tibia>
```





Accessibility

Goal

to increase the quality of being easy to obtain

Challenges

heterogeneous data management

discoverability

completeness of information

tracking origin

licensing

Accessibility

ACCESSIBILITY PROBLEM

BIOMCH-L

Sponsored by the International Society of Biomechanics

12-18-1997, 07:39 PM

Ahmet Erdemir
Guest

Knee kinematics

Dear Subscribers,

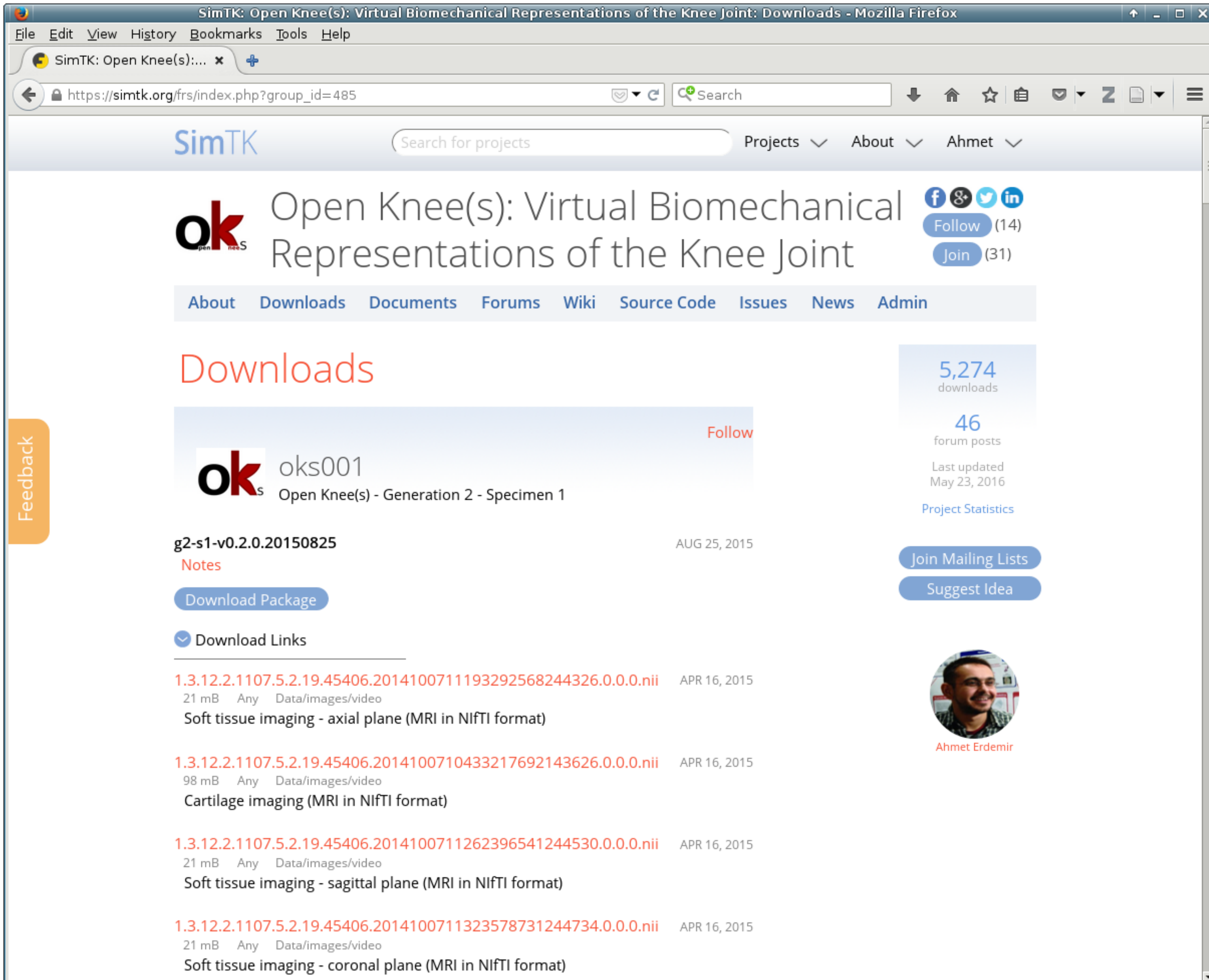
Does any of you know references describing the 3D knee kinematics and change in ligament lengths obtained from in vitro experiments, for full range of flexion?

My aim is to introduce these kinematic results in my three dimensional anatomical model of the human knee to optimize the ligament parameters such as reference strains, stiffness.

The loading conditions and well-defined coordinate systems at these experiments are needed as input to my knee model.

Ahmet ERDEMIR
ODTU, ICHMT
Mak. Muh. Bol., 06531
Ankara, TURKEY
tel: +90 312 210 2541
fax: +90 312 210 1331
e-mail: erdemir@fiesta.me.metu.edu.tr

Accessibility: Data & Models



Adapted from Open Knee(s), refer to ***https://simtk.org/frs/index.php?group_id=485***.

Accessibility: Impact

January 30, 2012

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

October 15, 2017

9 download packages

>10,000 total downloads

>35 enabled studies

Visitor demographics sample

Accessibility: Impact

ACKNOWLEDGEMENTS

The authors would like to express their sincerest gratitude to Dr. Ahmet Erdemir for his generosity in developing the freely-available OpenKnee project (available from https://simtk.org/home/openknee). Finite element model development is a laborious process, often prohibitively so. OpenKnee was a potent springboard for this investigation, greatly facilitating initial model development. The authors would also like to thank Dr.

adapted from Westerman et al. (2013)

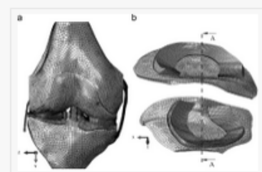
ization method and material model[14–18]. To calculate knee articular osteochondral tissue property, we have to segment meniscus layer and cartilage layer; however it is extremely difficult to segment these two layers from clinical CT data. Fortunately, there is a template of meniscus which can be obtained from the Open Knee(s)[19] at NIH. Thus we can calculate the volume of cartilage layer by subtracting the volume of a template of meniscus from the whole

adapted from Zhang et al. (2016)

Journal of Biomechanics

June 2015

Biomechanics and Mechanobiology of the Meniscus



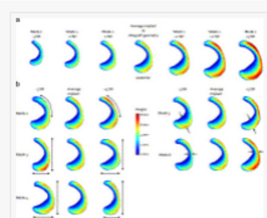
Influence of meniscus shape in the cross sectional plane on the knee contact mechanics

Piotr Łuczkiewicz, Karol Daszkiewicz, Wojciech Witkowski, Jacek Chróścielewski, Witold Zarzycki

p1356–1363

Published online: March 18 2015

Preview | Abstract | Full-Text HTML | PDF



The sensitivity of cartilage contact pressures in the knee joint to the size and shape of an anatomically shaped meniscal implant

M. Khoshgoftar, A.C.T. Vrancken, T.G. van Tienen, P. Buma, D. Janssen, N. Verdonschot

p1427–1435

Published online: February 26 2015

Open Access

Preview | Abstract | Full-Text HTML | PDF

Usability

Goal

to increase the quality of being easy to use

Challenges

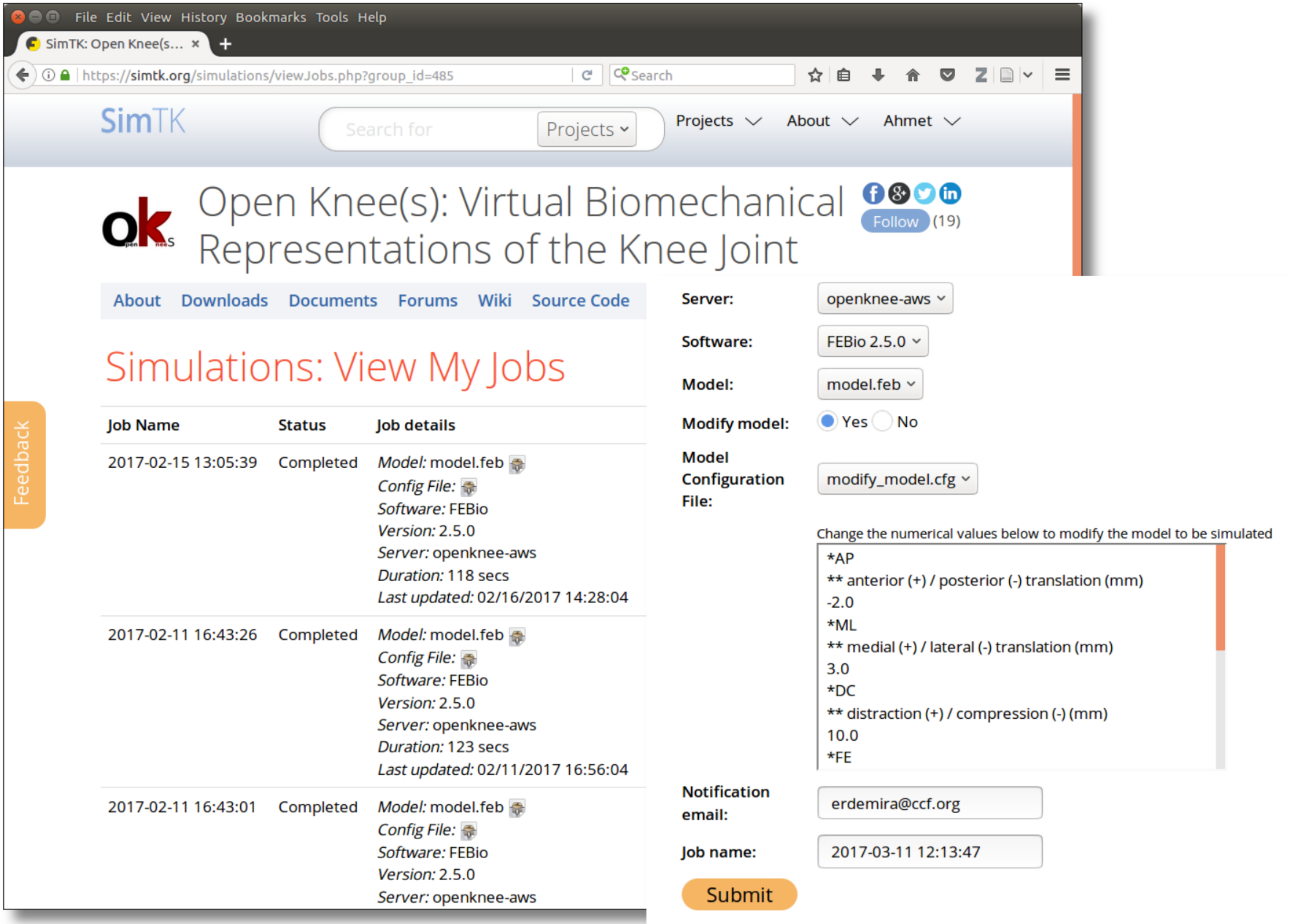
model robustness

lack of tools for utilization

customization for reuse

translation to clinical practice

Usability: Cloud Computing

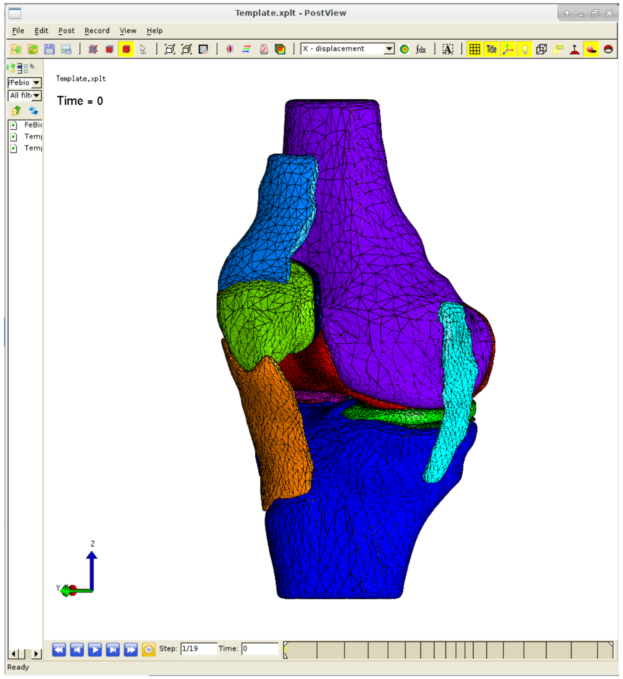


Adapted from Open Knee(s), refer to ***https://simtk.org/simulations/viewJobs.php?group_id=485***.

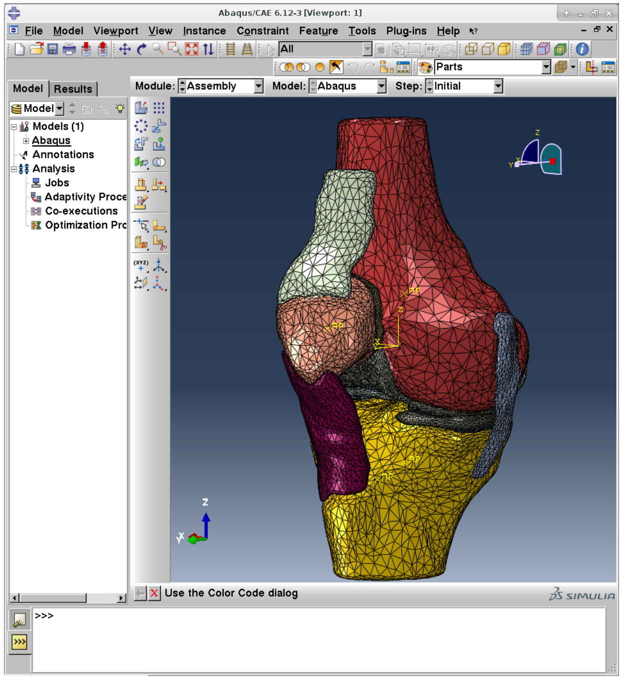
Usability: Different Formats

Capability to push same mesh with template material properties, contact definitions, and constraints to different simulation software

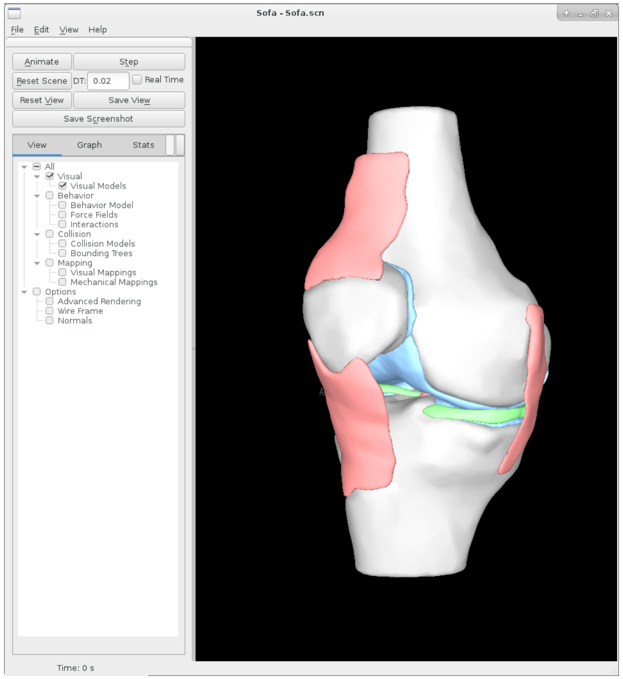
FEBio



Abaqus



SOFA



Usability: Simulation Features

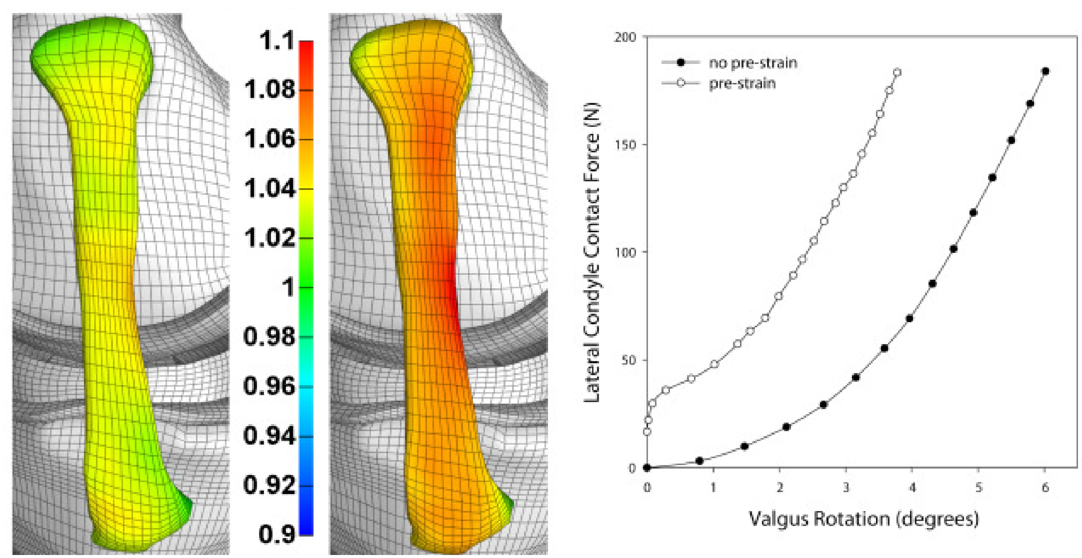
Open Knee(s) is a **driving project** for simulation software development

- In situ strain
- Element, node, surface sets
- Coordinate systems
- Kinematic joints
- Wrapping springs
- Modular file input

FINITE ELEMENTS FOR BIOMECHANICS

http://www.febio.org

Prescribing ligament ***in situ strain***



adapted from Maas et al. (2016)

Usability: Insights


Jack Andrish, MD


Morgan Jones, MD


Paul Saluan, MD


Carl Winalski, MD

Physicians

Trent Guess, PhD


Yasin Dhaher, PhD


Rami Korhonen, PhD


Engineers/Scientists

Open Knee(s)
Advisory Board

Usability: Use Cases

Demonstration of utility through
clinically relevant simulations

ADAPTATION IN SCIENTIFIC AND CLINICAL DOMAINS

Open Knee: Open Source Modeling and Simulation in Knee Biomechanics

Ahmet Erdemir, PhD[1]

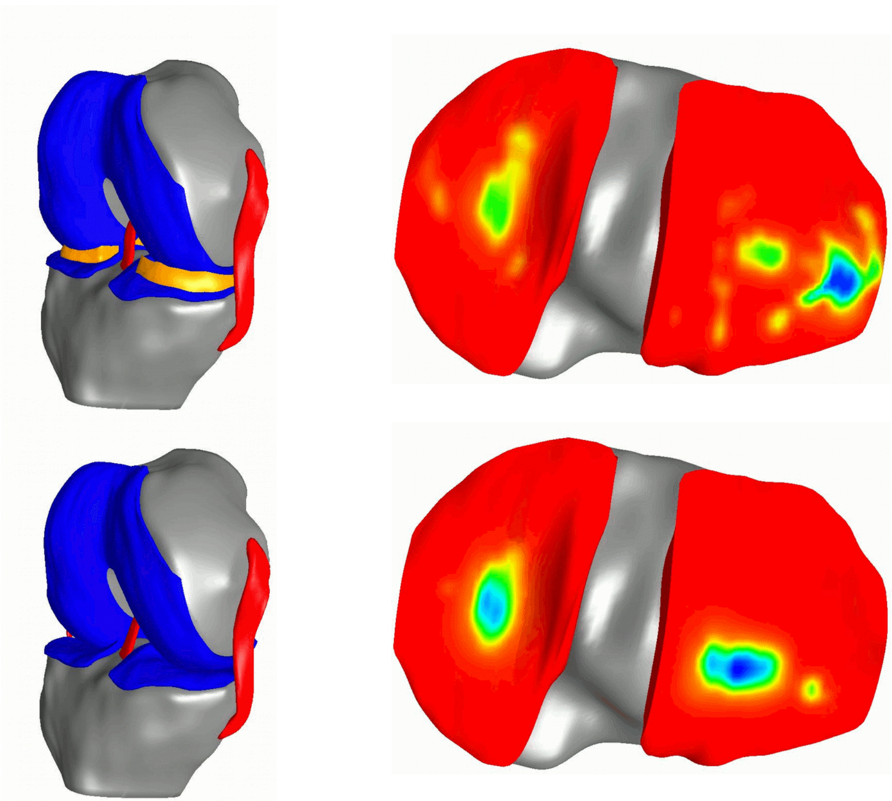
[1] Computational Biomodeling (CoBi) Core and Department of Biomedical Engineering, Cleveland Clinic, Cleveland, Ohio

J Knee Surg 2016;29:107–116.

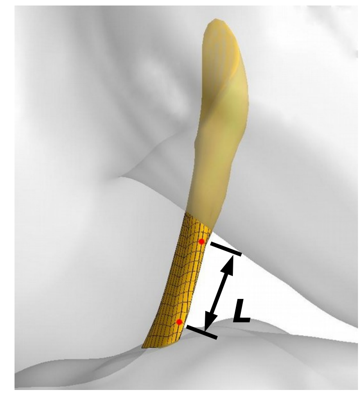
Address for correspondence Ahmet Erdemir, PhD, Computational Biomodeling (CoBi) Core and Department of Biomedical Engineering, Cleveland Clinic, 9500 Euclid Avenue, Cleveland, OH 44195 (e-mail: erdemira@ccf.org).

adapted from Erdemir (2016)

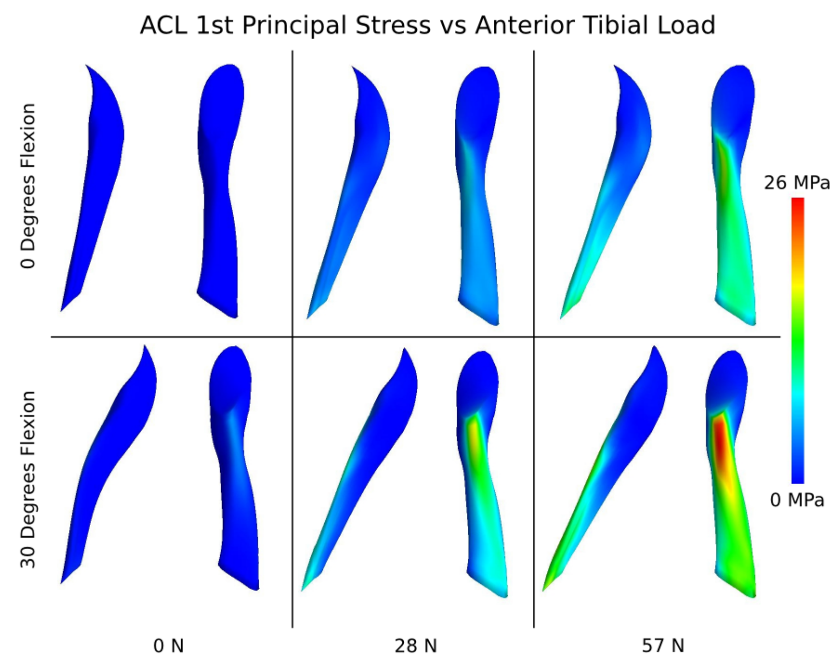
Usability: Use Cases



Influence of **menisectomy** on cartilage loading



ACL mechanics during laxity testing



Open Knee(s) – Generation 1 predictions; adapted from Erdemir (2016)

Comprehensibility

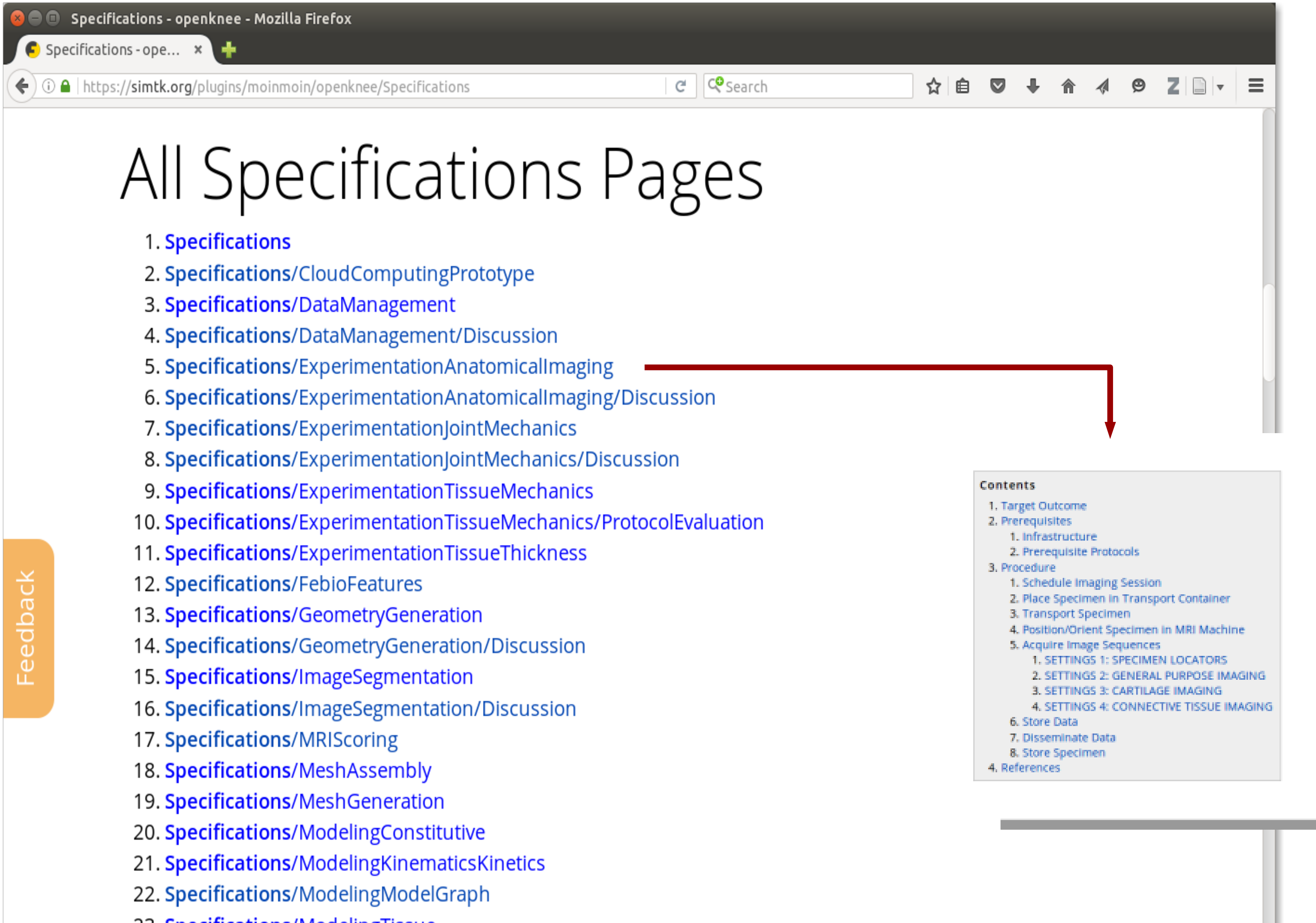
Goal to increase the quality of being easy to understand

Challenges consistency of terminology

specificity of information

correspondence of documentation to reproduction

Comprehensibility: Know-How



Adapted from Open Knee(s), refer to ***https://simtk.org/plugins/moinmoin/openknee/Specifications***.

Comprehensibility: Reporting

Good reporting practice

clarifies uncertainty of **reproducibility**,
promotes **reusability**, and
establishes **accountability**.

→ **CONFIDENCE IN MODELING & SIMULATION**

Journal of Biomechanics 45 (2012) 625–633

Contents lists available at SciVerse ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

ELSEVIER

Perspective article

Considerations for reporting finite element analysis studies in biomechanics

Ahmet Erdemir[a,b,*], Trent M. Guess[c], Jason Halloran[a,b], Srinivas C. Tadepalli[d], Tina M. Morrison[e]

[a] Computational Biomodeling (CoBi) Core, Lerner Research Institute, Cleveland Clinic, Cleveland, OH 44195, USA
[b] Department of Biomedical Engineering, Lerner Research Institute, Cleveland Clinic, Cleveland, OH 44195, USA
[c] Department of Civil and Mechanical Engineering, University of Missouri – Kansas City, Kansas City, MO 64110, USA
[d] Department of Orthopaedics and Sports Medicine, University of Washington, Seattle, WA 98195, USA
[e] Center for Devices and Radiological Health, Food and Drug Administration, Silver Spring, MD 20933, USA

adapted from Erdemir et al. (2012)

Comprehensibility: Reporting

Documented **~80 reporting parameters** classified under:

- Model identification (20)
- Model structure (7 main – 27 subcategorized)
- Simulation structure (6)
- Verification (6)
- Validation (9)
- Availability (5)

adapted from Erdemir et al. (2012)

Credibility

Goal to increase the quality of being trusted

Challenges

lack of unified guidance

uncertainty of reproducibility potential

accountability throughout M&S lifecycle

Credibility: Data Quality

- Anatomical imaging & geometry

  Registration markers

  Segmentation reproducibility

- Joint mechanics

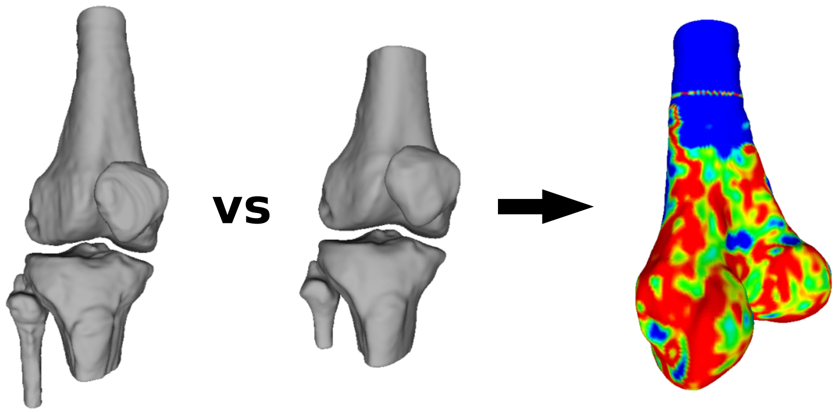
  Registration markers

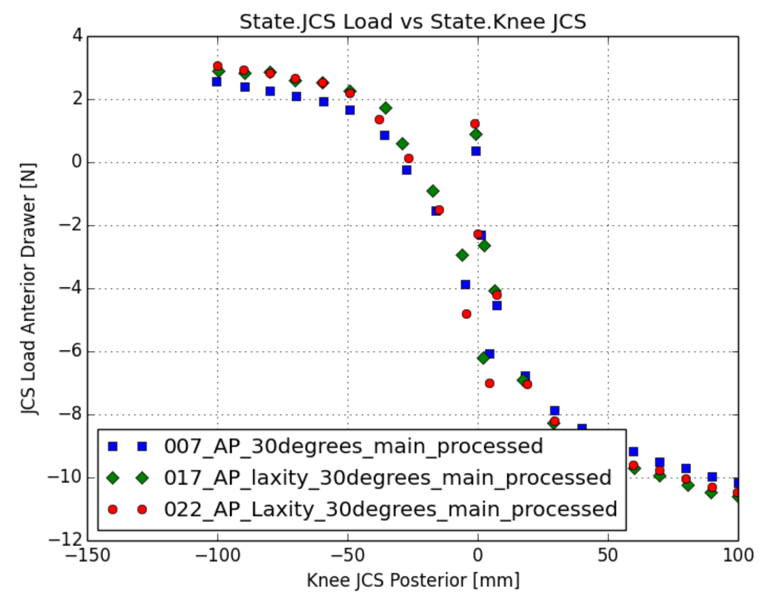
  Surrounding tissue effects

  Repeatability of anterior-posterior laxity response

- Tissue mechanics

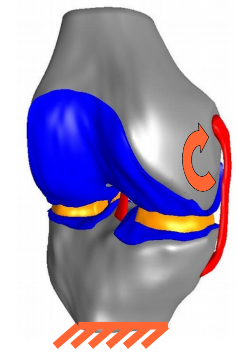
  Reproducibility of uniaxial tissue stress-strain response

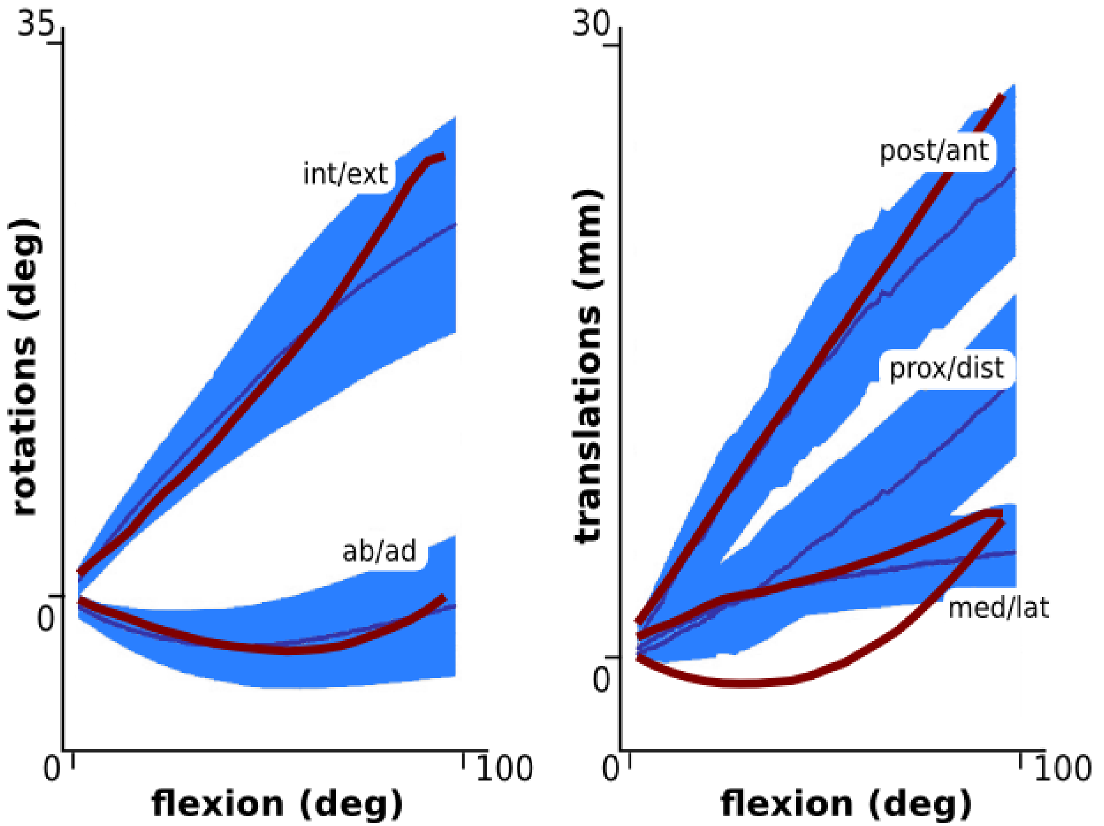




Credibility: Correspondence to Literature

Tibiofemoral joint kinematics during passive flexion
Open Knee(s) – Generation 1 vs data from a sample population





data from Wilson et al. (2000)

Rotations

✓ Internal rotation
(up to ~60° flexion)
✓ Abduction

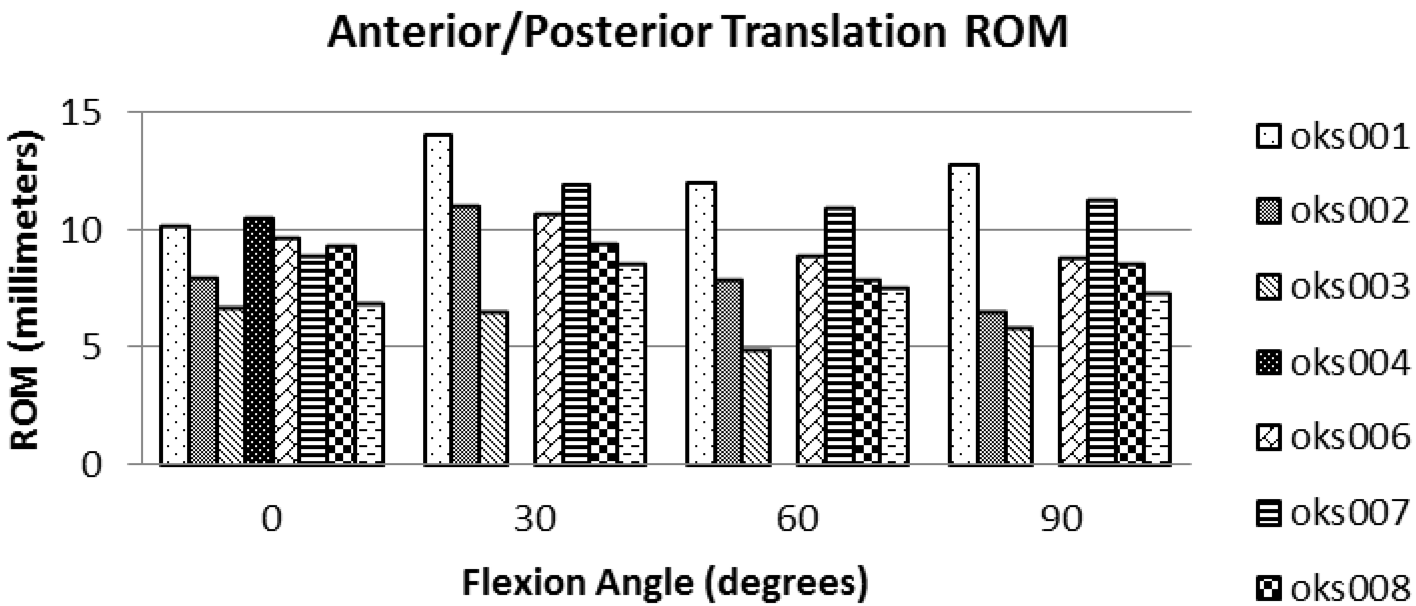
Translations

✓ Posterior
(up to ~50° flexion)
✗ Proximal
✓ Medial
(up to ~50° flexion)

adapted from Erdemir (2016)

Credibility: Specimen-Specificity

Specimen-specific joint response can vary largely.



Credibility: Guidance

Credible Practice of M&S in Healthcare

To establish credible practice guidelines, consistent terminology and a model certification process, as well as to demonstrate workflows and identify new areas of research for reliable development and application of M&S in healthcare practice and research."

CFMS

IMAG **& Multiscale Modeling (MSM) Consortium**

NIH FDA nsf NASA USDA MITACS IARPA

Credibility: Guidance

Ten "Not So" Simple Rules for Credible Practice of Modeling & Simulation in Healthcare

Rule 1 – *Define context clearly.*	Plan and develop the M&S activity with clear definition of the intended purpose or context accommodating end-users' needs.
Rule 2 – *Use appropriate data.*	Use data relevant to the M&S activity, which can ideally be traced back to the source.
Rule 3 – *Evaluate within context.*	Evaluate the M&S activity through verification & validation, uncertainty quantification, and sensitivity analysis faithful to the context/purpose/scope of the M&S efforts, with clear and a-priori definition of evaluation metrics and including test cases.
Rule 4 – *List limitations explicitly.*	Provide an explicit disclaimer on the limitations of the M&S to indicate under what conditions or applications the M&S may or may not be relied on.
Rule 5 – *Use version control.*	Implement a version control system to trace the time history of the M&S activities, including delineation of contributors' efforts.
Rule 6 – *Document adequately.*	Document all M&S activities, including simulation code, model markup, scope and intended use of M&S activities, users' and developers' guides.
Rule 7 – *Disseminate broadly.*	Disseminate appropriate components of M&S activities, including simulation software, models, simulation scenarios and results.
Rule 8 – *Get independent reviews.*	Have the M&S activity reviewed by independent third-party users and developers, essentially by any interested member of the community.
Rule 9 – *Test competing implementations.*	Use competition of multiple implementations to check the conclusions of different implementations of the M&S processes against each other.
Rule 10 – *Conform to standards.*	Adopt and promote generally applicable and discipline specific operating procedures, guidelines, and standards accepted as best practices.

adapted from Erdemir et al. (2015)

Open Knee(s) Summary

- We are building *general purpose*, *publicly accessible*, *reusable*, and *credible* **virtual knees** faithful to specimen-specific anatomy and mechanics.

- Ultimate goal is to enable **virtual experimentation** for cost-effective and prompt explorations in *knee biomechanics*.

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

What's Next for Open Knee(s)?

- **Build** specimen-specific virtual knee(s)

  Generate geometry and meshes

  Characterize tissue properties

  Assemble models

- **Make** virtual knee(s) **credible**

  Evaluate predictions against specimen-specific mechanical response

- **Make** virtual knee(s) **accessible**

  Continue public dissemination

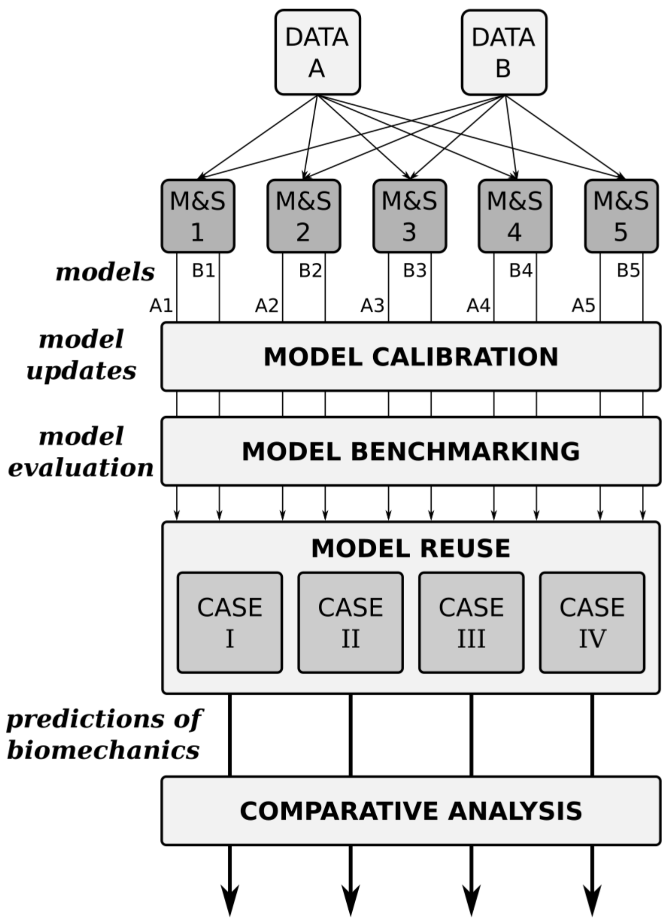
- **Make** virtual knee(s) **usable**

  Expand cloud computing framework

  Launch clinically relevant use cases

What's Next for Open Knee(s)?

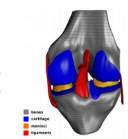
Emphasis on reproducibility and “art” of modeling



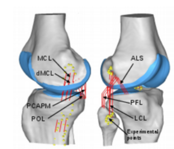
Are M&S predictions influenced by M&S workflow?

Do the predictions of natural knee biomechanics depend on modeling decisions of separate development teams when the target simulation scenarios and the source data to build models remain the same?

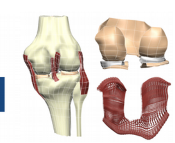
Cleveland Clinic



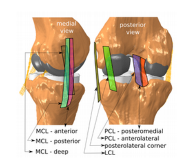
UNIVERSITY of DENVER



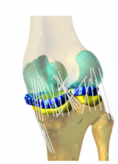
AUCKLAND BIOENGINEERING INSTITUTE
THE UNIVERSITY OF AUCKLAND NEW ZEALAND
Te Whare Wānanga o Tāmaki Makaurau



CLEVELAND STATE UNIVERSITY 1964



HOSPITAL FOR SPECIAL SURGERY

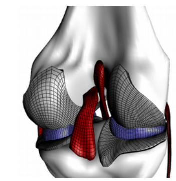


Funding by NIBIB, NIH; refer to ***https://simtk.org/projects/kneehub***.

What's Next for Open Knee(s)?

Emphasis on credibility for translational use

Open Knee(s)
Open source knee joint M&S



confirmation of Open Knee(s) suitability for medical grade simulations

assessment of Open Knee(s) credibility guided by broadly applicable "good practices"

oks

Open Knee(s) as a MDDT

US FDA
Medical Device Development Tools (MDDT)

FDA

CFMS

Community perspectives
Ten "Not So" Simple Rules in Credible Practice of M&S in Healthcare

correspondence between community recommendations for M&S practice and M&S considerations of regulatory agencies

What's Next for M&S in Biomechanics?

- **Promote** principles of democratization in modeling & simulation in biomechanics

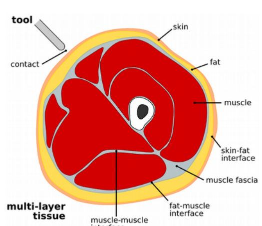
specificity – efficiency – accessibility

comprehensibility – usability – credibility

- **Apply** principles of democratization in other areas of computational biomechanics

OPERATION MULTiS

Reference Models for Multi-Layer Tissue Structures of Musculoskeletal Extremities



https://simtk.org/projects/multis

CONTACT

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erdemira@ccf.org
+1 (216) 445 9523

Laboratory: **http://www.lerner.ccf.org/bme/erdemir/lab**
Open Knee(s): **https://simtk.org/projects/openknee**
Open Knee(s) Wiki: **https://simtk.org/plugins/moinmoin/openknee/**

LICENSING

TRADEMARKS & OWNERSHIPS