

In Silico Biomechanics Without Borders

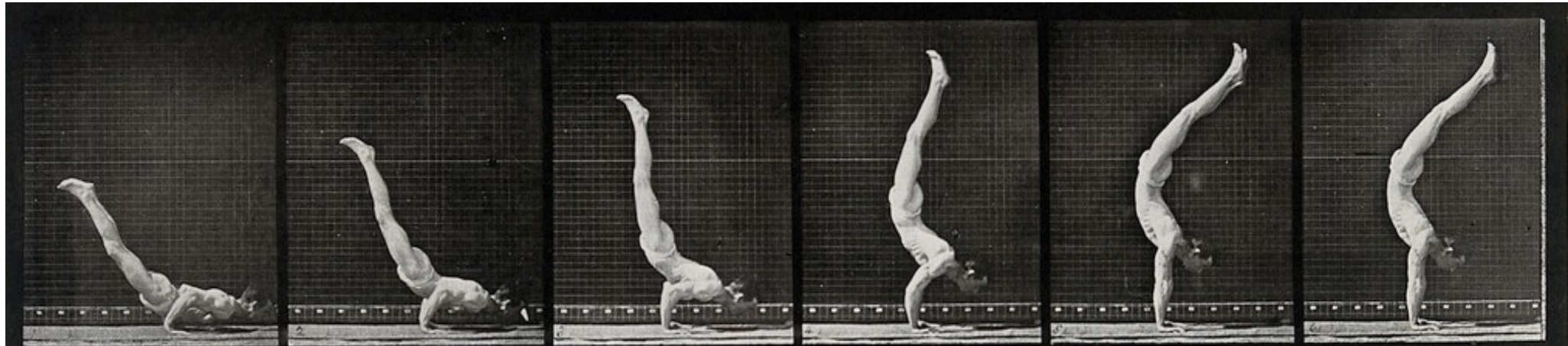
Ahmet Erdemir and Snehal Chokhandre

Department of Biomedical Engineering
Lerner Research Institute
Cleveland Clinic

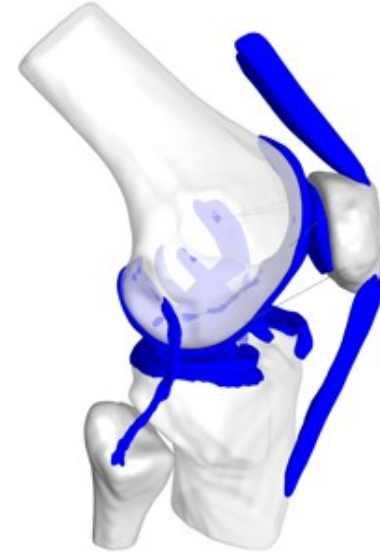
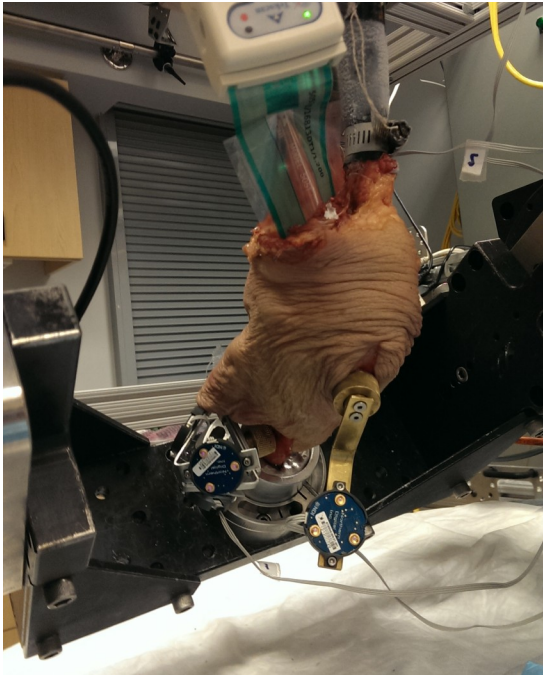
October 2, 2020
Cleveland Clinic – UTEC summit

Biomechanics

Biomechanics deals with **MOTION** and **DEFORMATION** of biological structures as they **interact** with the **environment**



In Silico Biomechanics



In Silico Biomechanics In Healthcare

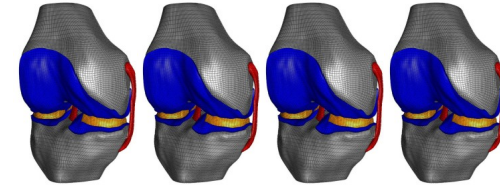
Utility of computational modeling & simulation

For scientific discovery
structure-function relationships in health & disease
mechanistic foundations of data associations

For engineering innovation
intervention design & evaluation

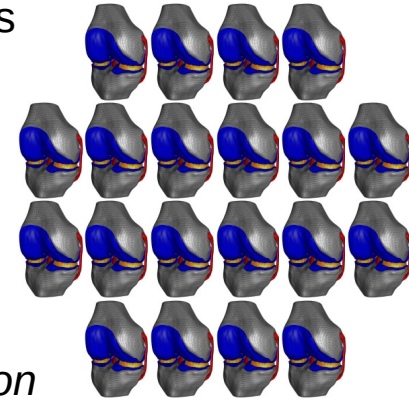
For clinical care
diagnosis/prognosis
intervention safety & performance
medical training
individualized medicine

virtual experiments



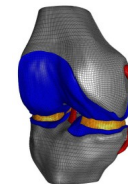
virtual specimen(s) / subject(s)

in silico trials

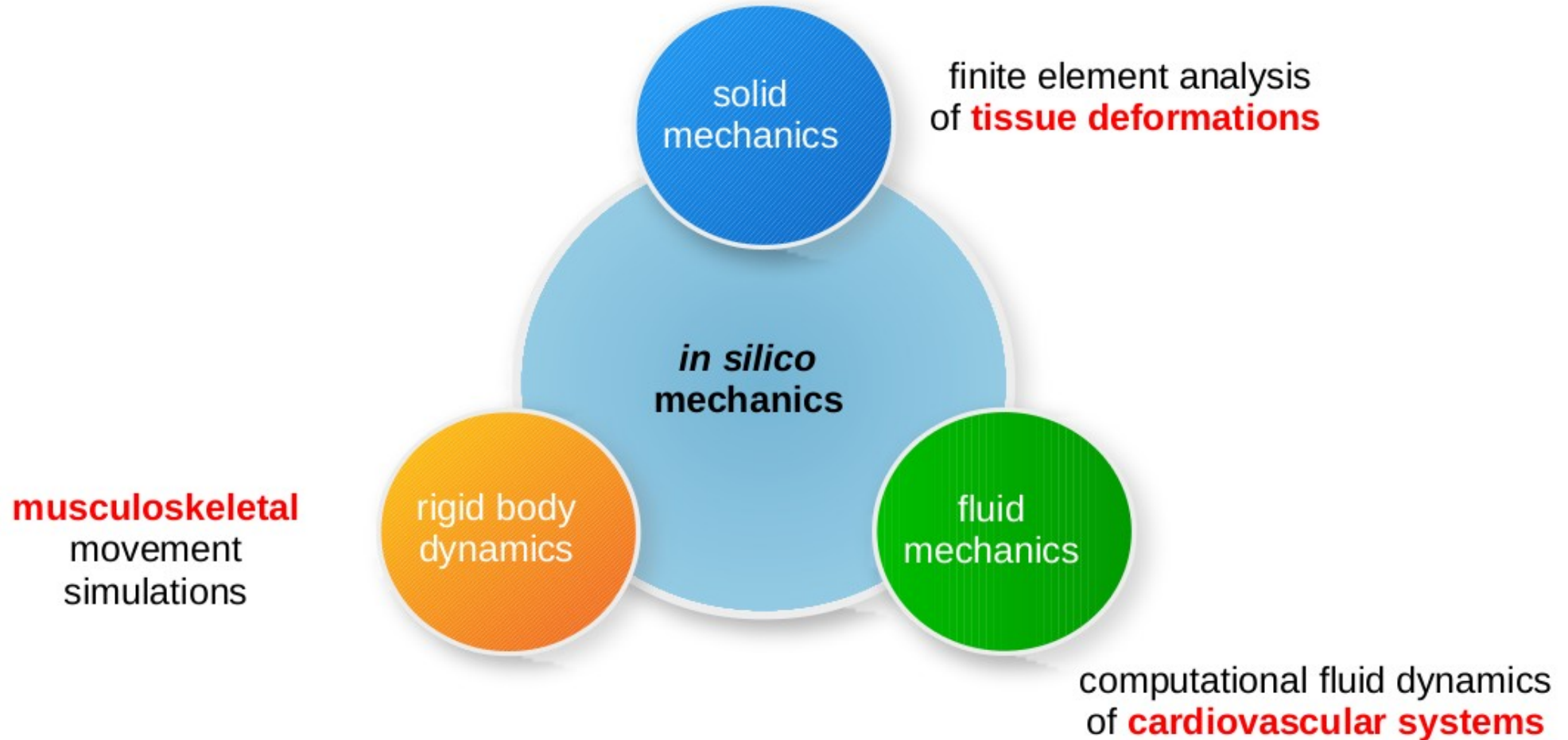


virtual population

virtual patient



In Silico Biomechanics Enterprise



In Silico Biomechanics Enterprise

FEBiO
FINITE ELEMENTS FOR BIOMECHANICS



simulation
software



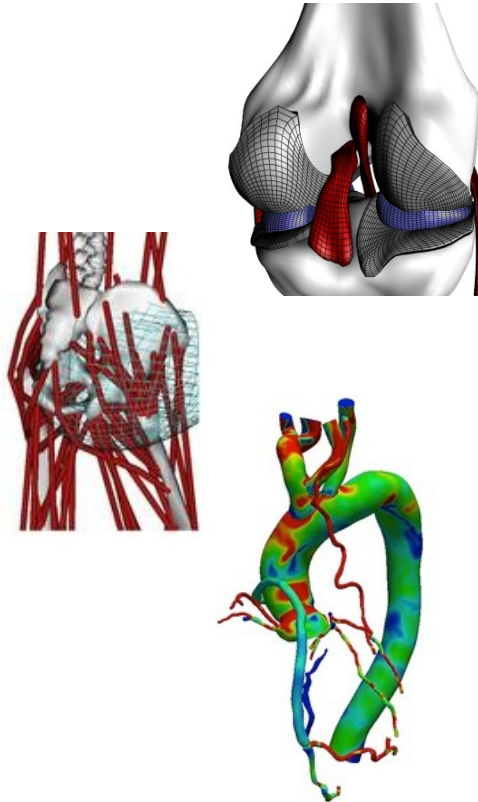
models

computing
hardware

XSEDE

Extreme Science and Engineering
Discovery Environment

GPGPU



In Silico Biomechanics Promise



A STRATEGIC PLAN
AUGUST 2011
www.fda.gov/regulatoryscience

Advancing Regulatory Science at FDA

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

5. *Develop a virtual physiologic patient:*

- Encourage the development of computer models that incorporate radiological imaging data of healthy and diseased anatomy from a range of relevant diseases;
- 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
- Create a library of models so that models validated by FDA are easily accessible to researchers.

FDA U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
U.S. FOOD AND DRUG ADMINISTRATION

Computational models can reduce

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

Need

? 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

Erdemir Laboratory: Mission

Leverage computational modeling as a routine, reliable and efficient **tool** for **healthcare delivery** and **biomedical science**



**Bridging
Scales**

**Bridging
Domains**

**Bridging
Cultures**

Erdemir Laboratory: People

Ariel



Ben



Ellen



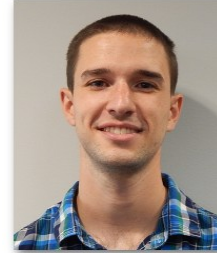
Neda



Rici



Sean



Snehal



**Current
team**

Craig



Jason



Scott



Tyler



Alumni

Melissa



Robb



Tammy



Tara



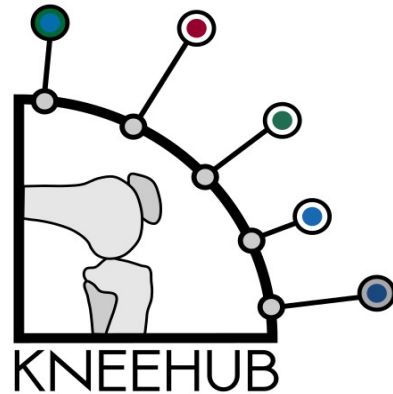
*... and many
internal and
external
collaborators*

Partners



Ahmet

Erdemir Laboratory: Open Science and Engineering



**OPERATION
MULTiS**

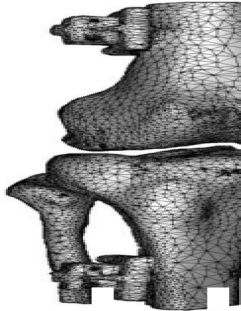


Open Knee(s) as a case study

<https://simtk.org/projects/openknee>

Modeling and Simulation in Knee Biomechanics

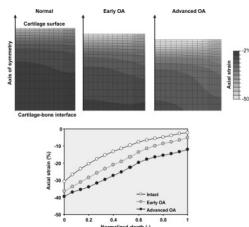
Joint and tissue functions



MCL
function

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

Pathological



Osteoarthritis

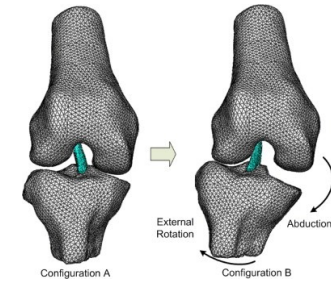
Kalahari et al., Osteoarthritis and Cartilage, 18: 73-81, 2010.

Injury mechanisms

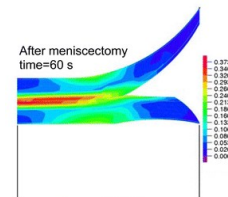
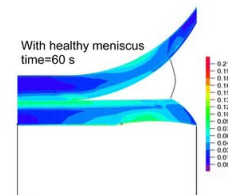


ACL
impingement

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



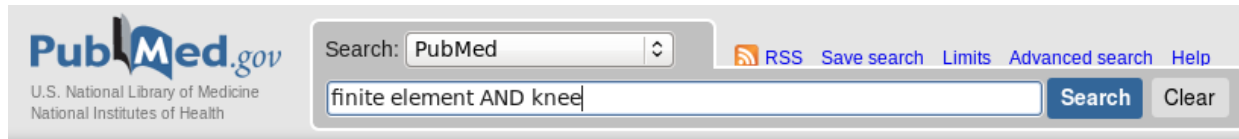
Surgical interventions



Meniscectomy

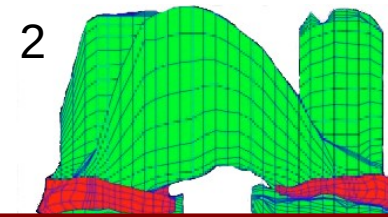
Vaziri et al., Annals of Biomed Eng, 36: 1335-44, 2008.

Modeling and Simulation in Knee Biomechanics



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

Results: 1 to 20 of ~~42~~
1182 (as of Sept 27, 2020)



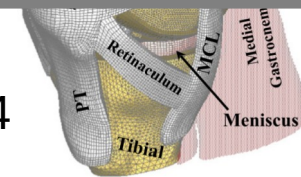
Downloadable and reusable finite element representations of knee models are scarce.

¹Bendjaballah et al., *Clin Biomech*, 12: 139-48, 1997.⁴

²Donahue et al., *J Biomech Eng*, 124: 273-80, 2002.

³Peña et al., *J Biomech*, 39: 1686-701, 2006.

⁴Dhaher et al., *J Biomech*, , 43: 3118-25, 2010.



Open Knee(s) Goals

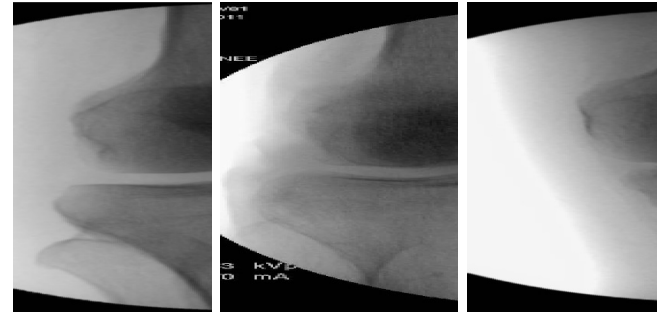


NIH/NIGMS
R01GM104139
9/16/2013- 5/31/2018

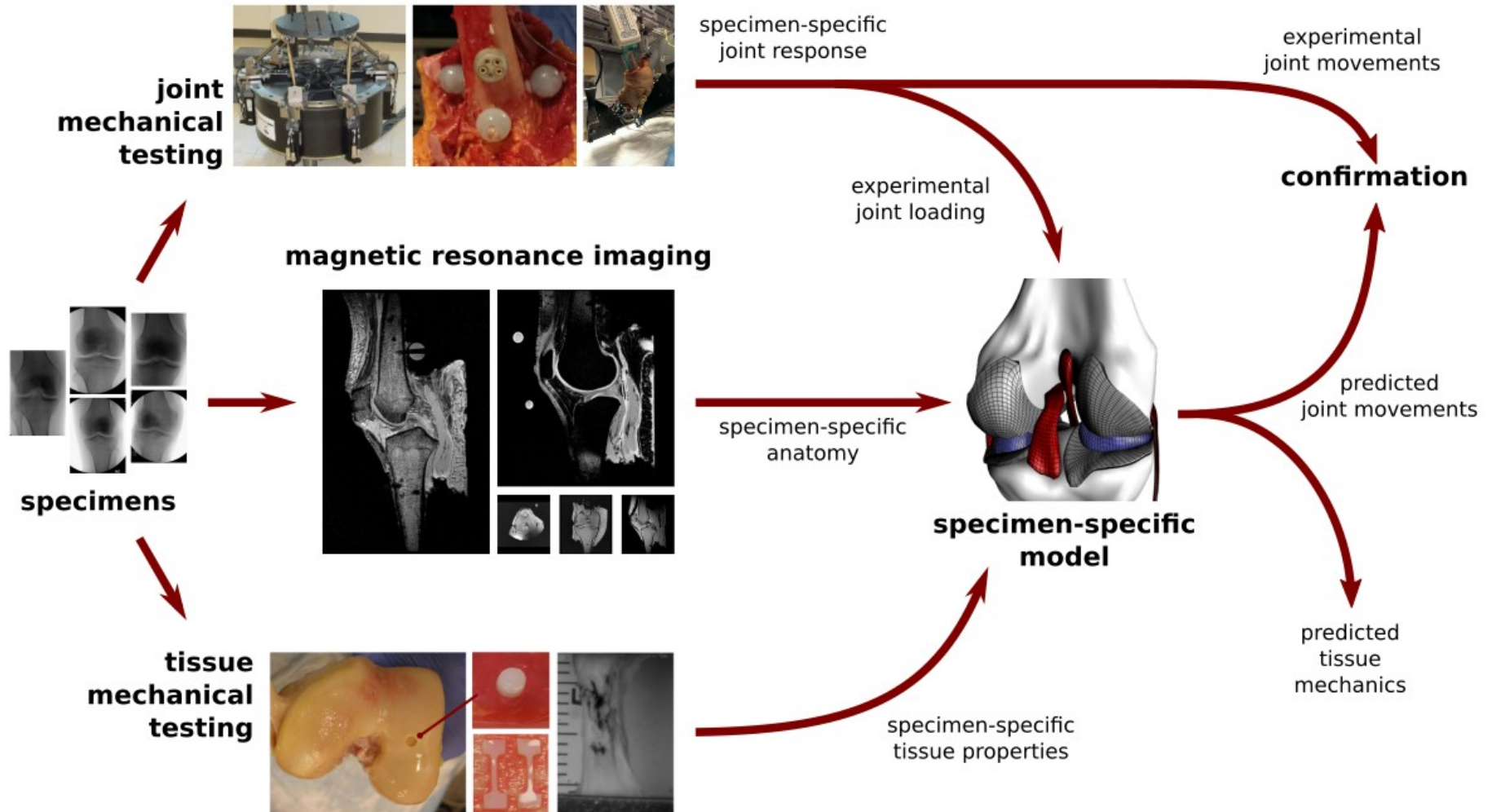
- ❏ To provide an open, freely available, and collaborative development, testing, simulation and dissemination platform for in silico exploration of the biomechanics of healthy and diseased knees.
- ❏ To develop in silico biomechanical ***models of healthy and diseased knee joints*** of different genders and ages, supported by specimen-specific joint and tissue level experimental mechanics.

Open Knee(s) Goals

- ❑ 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*



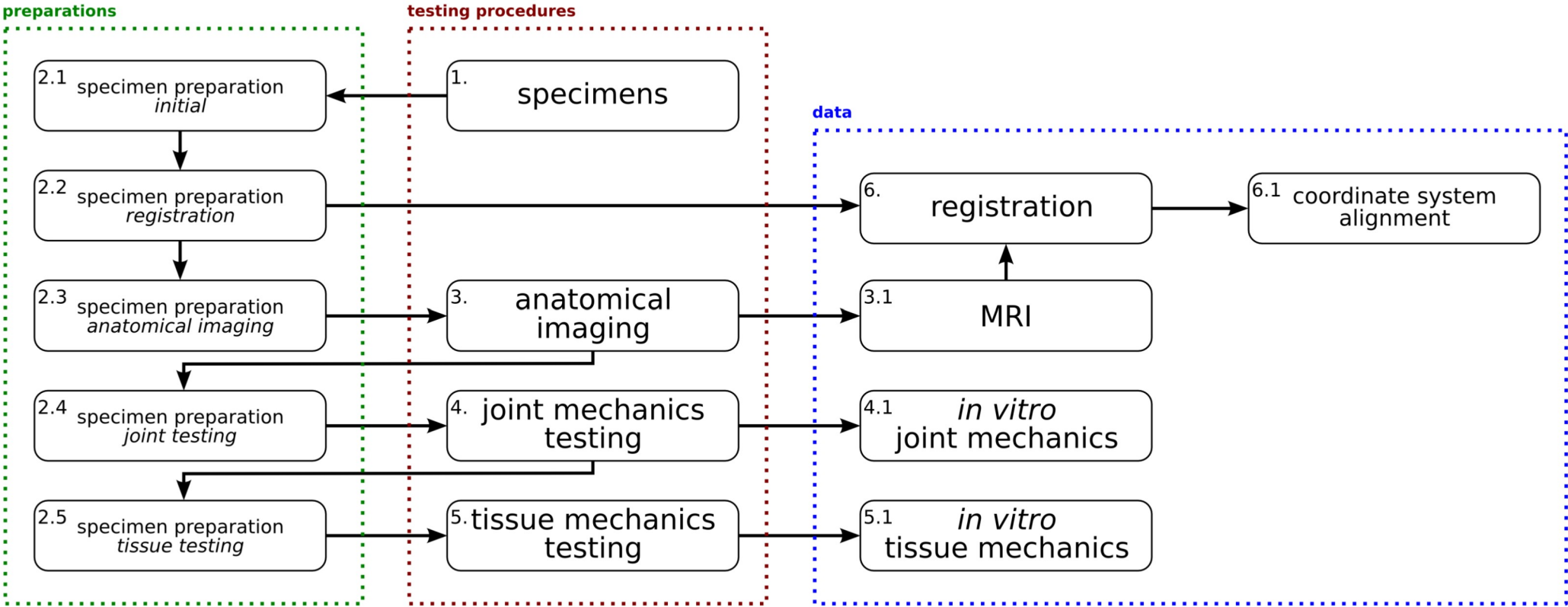
Building Open Knee(s)



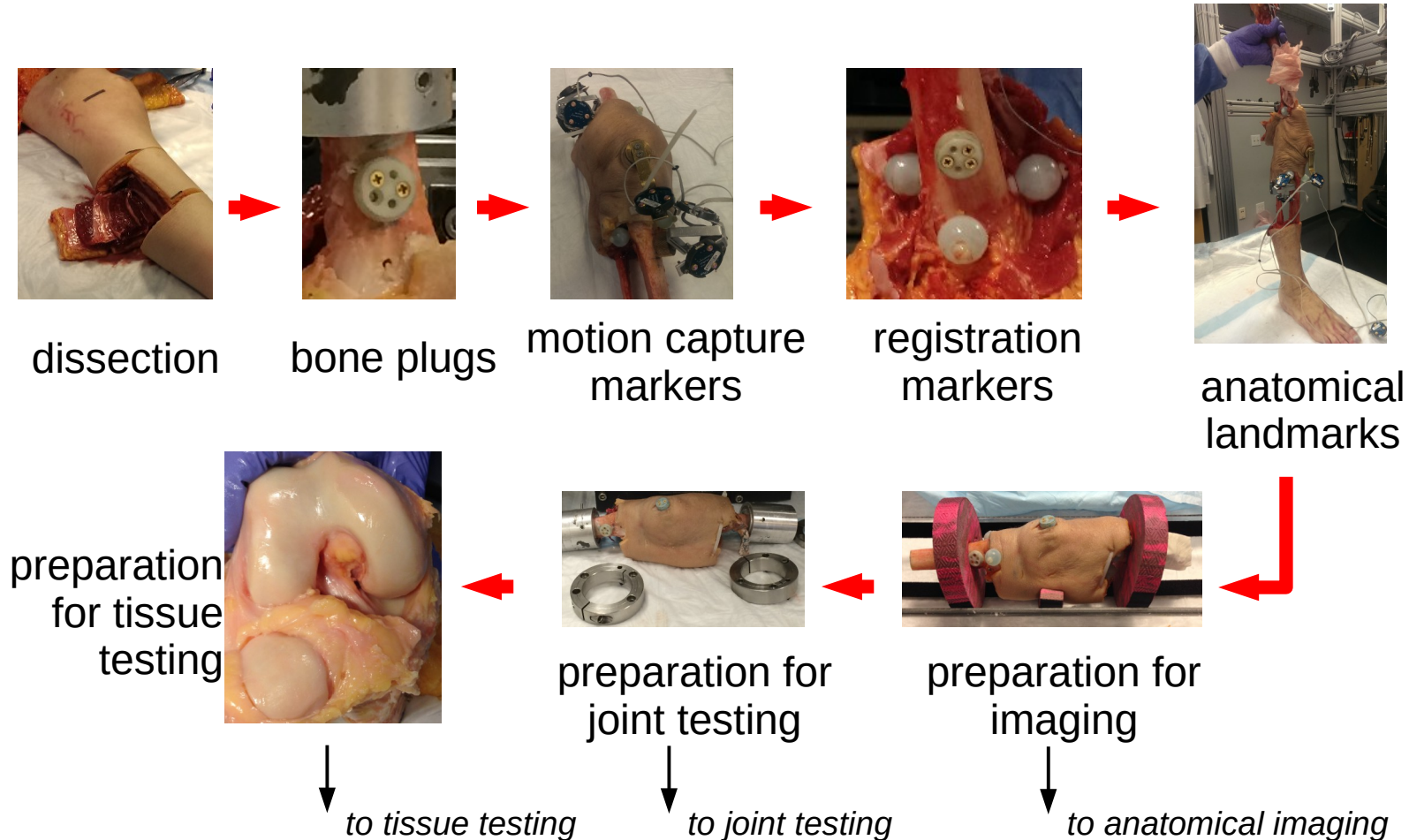
Building Open Knee(s): Specimens

Specimen	oks001	oks002	oks003	oks004	oks006	oks007	oks008	oks009
Side	right	right	left	right	right	right	right	left
Gender	male	female	female	female	female	male	male	male
Age (years)	71	67	25	46	71	71	40	34
Height (m)	1.83	1.55	1.73	1.58	1.52	1.7	1.78	1.8
Weight (kg)	77.1	45.3	68	54.4	49.4	65.8	63.5	68.03
BMI	23.1	18.9	22.8	21.9	21.3	22.7	20.09	20

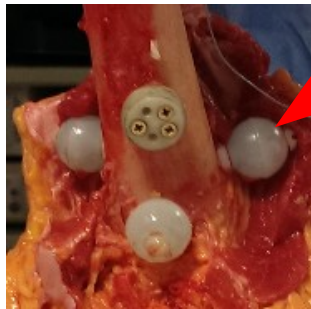
Building Open Knee(s): Experimentation Workflow



Building Open Knee(s): Preparation



Building Open Knee(s): Registration

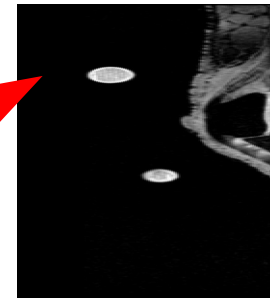
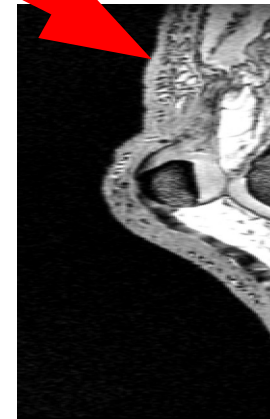


coordinate system transformations
femur – tibia – patella

association of reference states
pose & orientation



joint experimentation



anatomical imaging

Building Open Knee(s): Anatomical Imaging

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

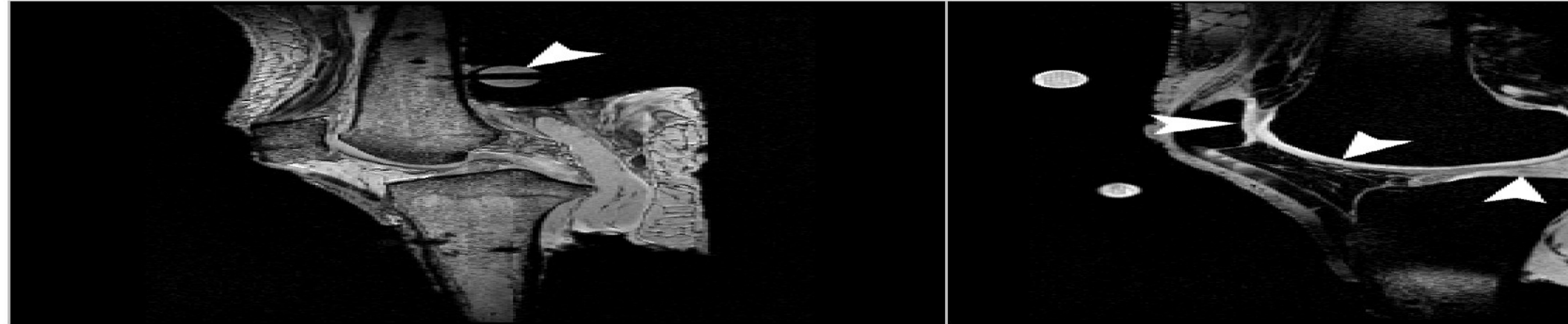
Cartilage

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

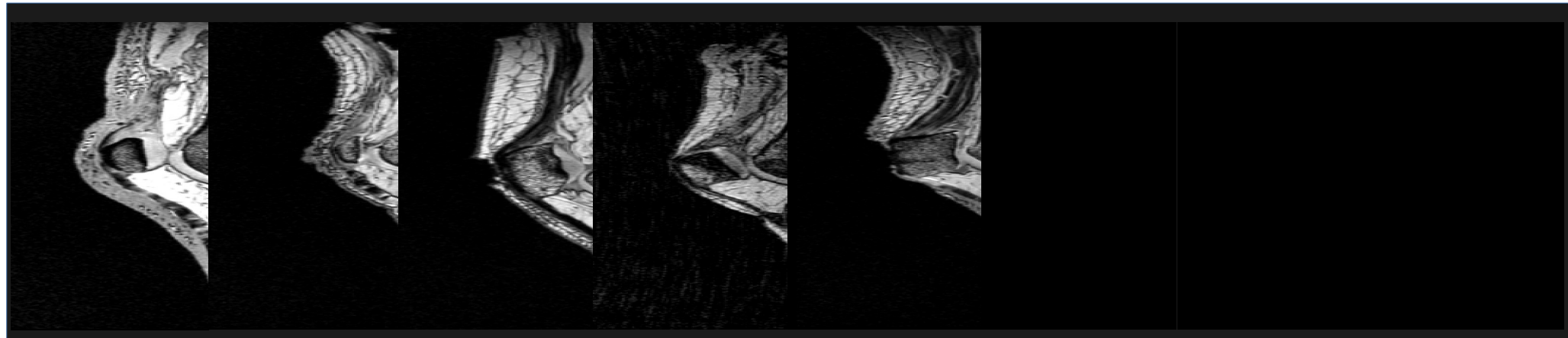
Ligaments

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

Magnetic Resonance Imaging



Building Open Knee(s): Anatomical Imaging



oks001

oks002

oks003

oks004

oks006

oks007

oks008

oks009

Building Open Knee(s): 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

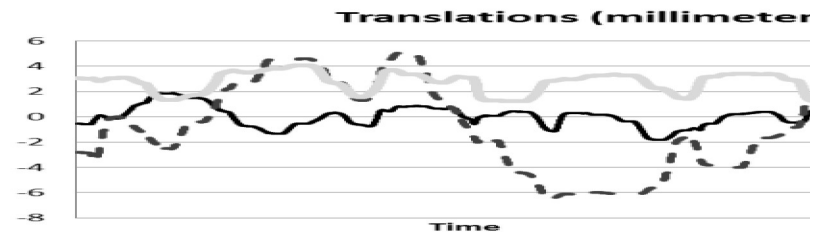
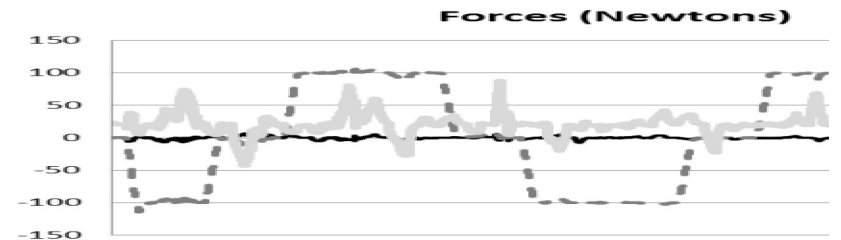
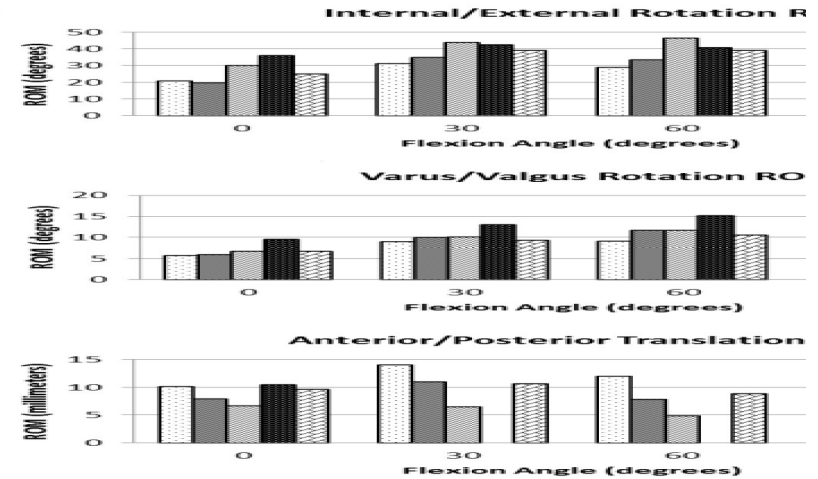
Anterior/posterior translation
0 to ± 100 N
w/ 10 N increment



Combined Loading

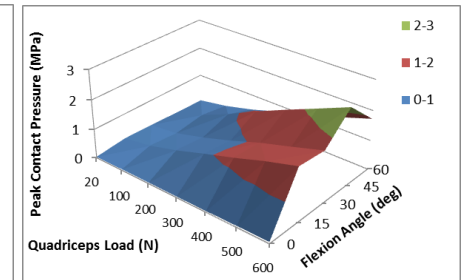
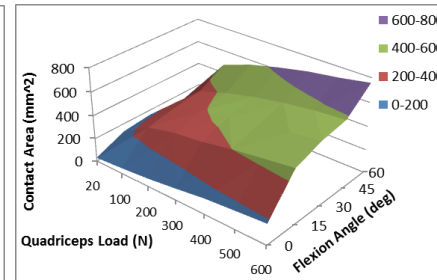
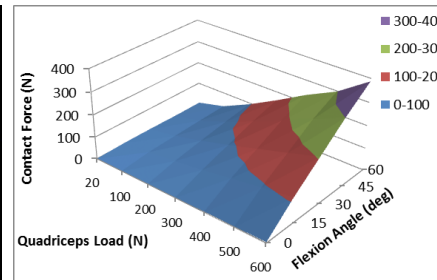
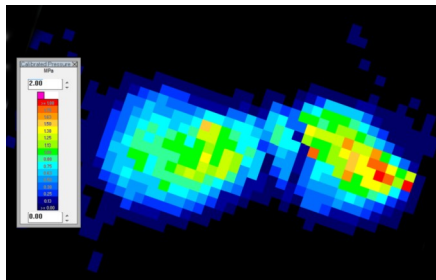
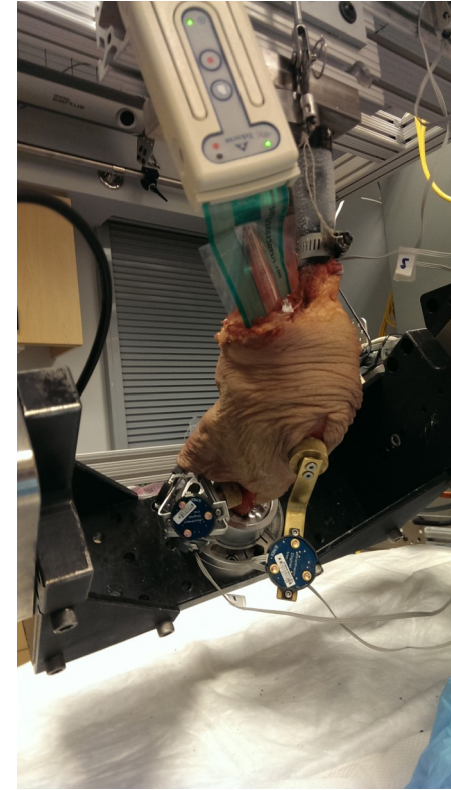
Permutations of
Internal/External rotation – -5, 0, 5 Nm
Varus/valgus – -10, 0, 10 Nm
Anterior/posterior translation – -100, 0, 100 N

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



Building Open Knee(s): 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



Building Open Knee(s): Tissue Characterization

Cartilage

unconfined compression
confined compression
tension

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

Meniscus

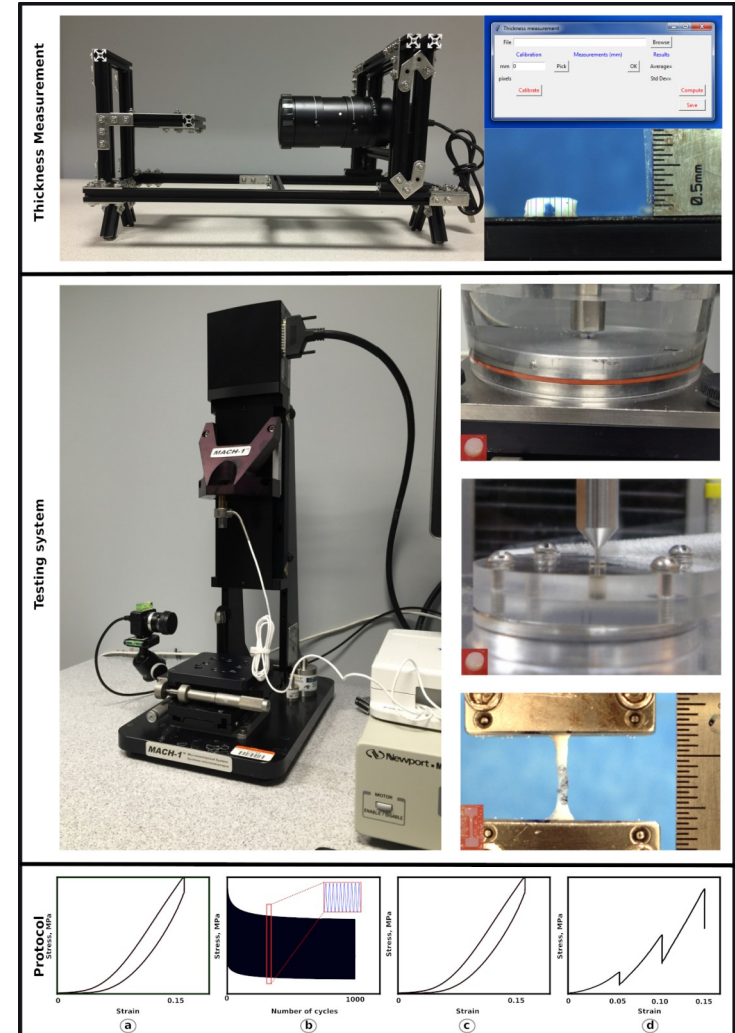
unconfined compression
confined compression
tension

medial – lateral

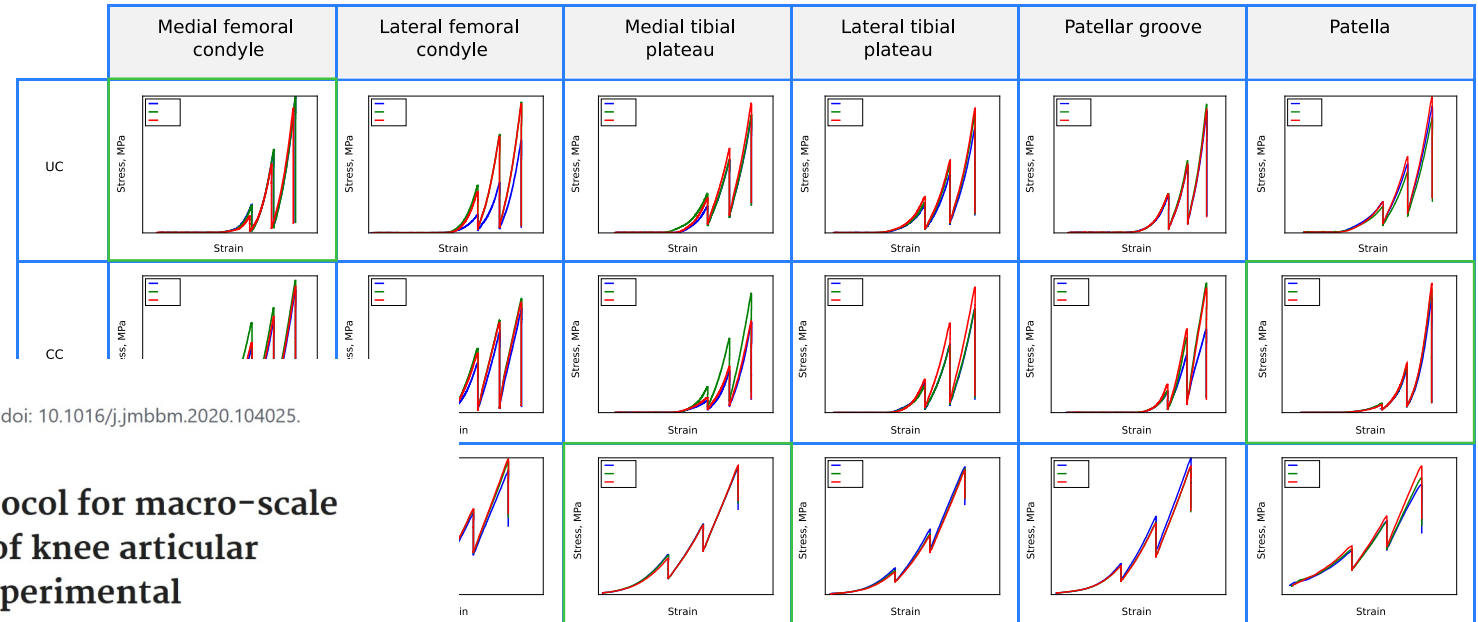
Ligaments and Quadriceps Tendon

tension

anterior – posterior cruciate
medial – lateral collateral
patellar
transverse



Building Open Knee(s): Tissue Characterization



> *J Mech Behav Biomed Mater.* 2020 Aug 8;112:104025. doi: 10.1016/j.jmbbm.2020.104025.
Online ahead of print.

A comprehensive testing protocol for macro-scale mechanical characterization of knee articular cartilage with documented experimental repeatability

Snehal Chokhandre ¹, Ahmet Erdemir ²

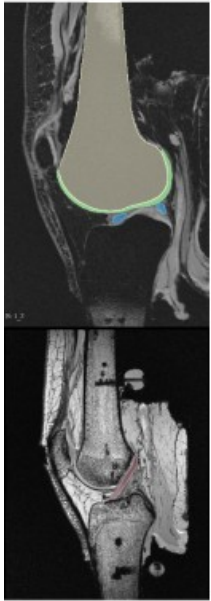
Affiliations + expand

PMID: 32841833 DOI: 10.1016/j.jmbbm.2020.104025

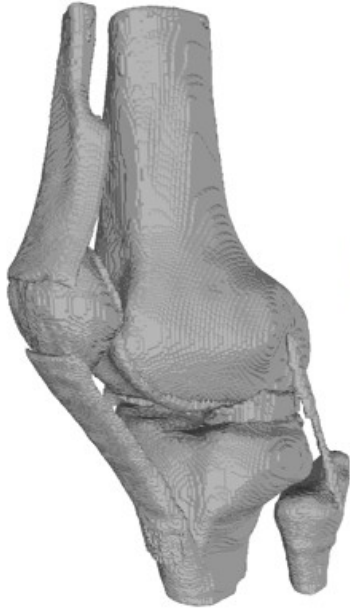
Abstract

Articular cartilage mechanics has been extensively studied with various approaches and mechanical characterization strategies. However testing protocols can be highly varying and difficult to reproduce, particularly for specimen-specific analyses. Detailed knowledge of testing protocols is

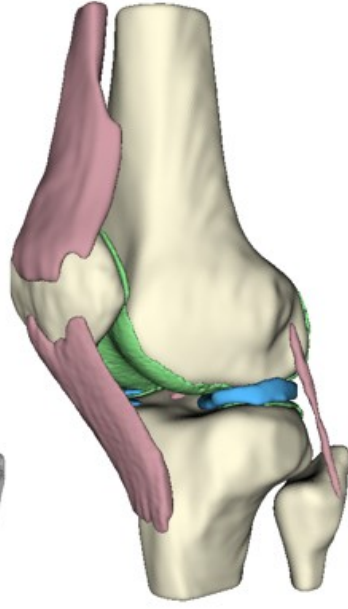
Building Open Knee(s): Modeling Workflow



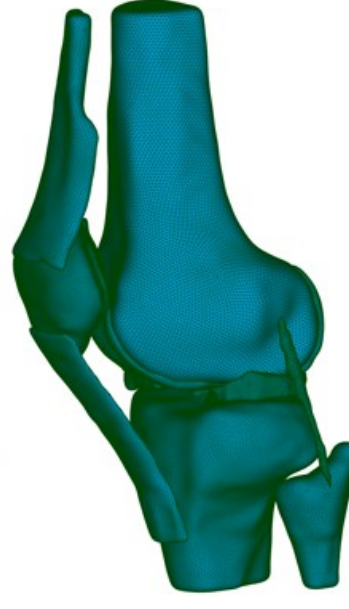
Image



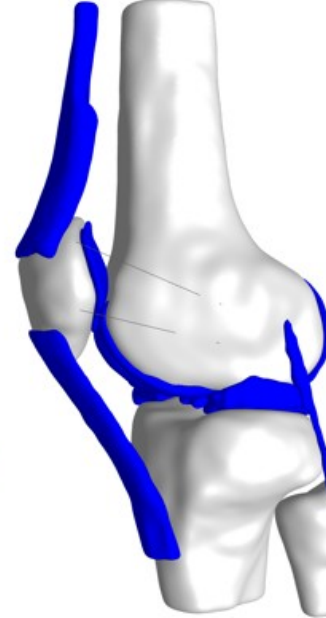
Segmentation



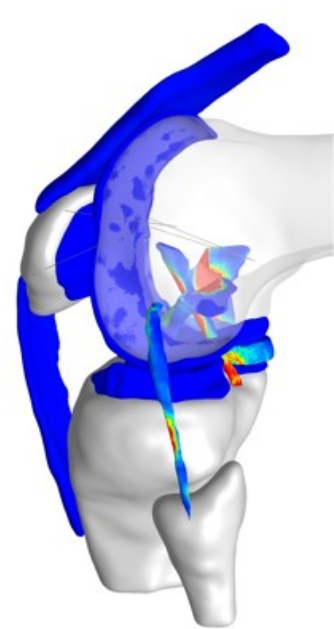
Geometry



Meshing

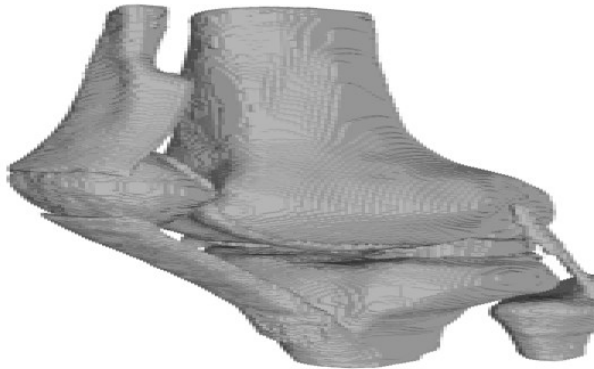
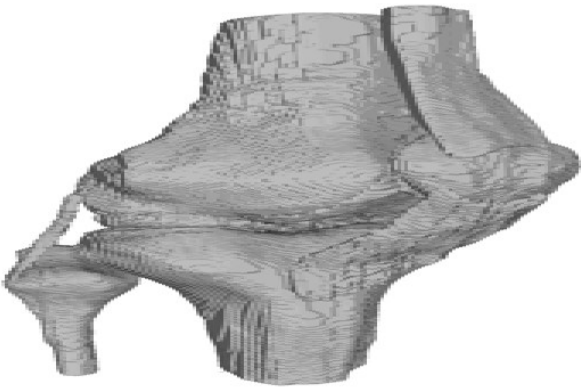
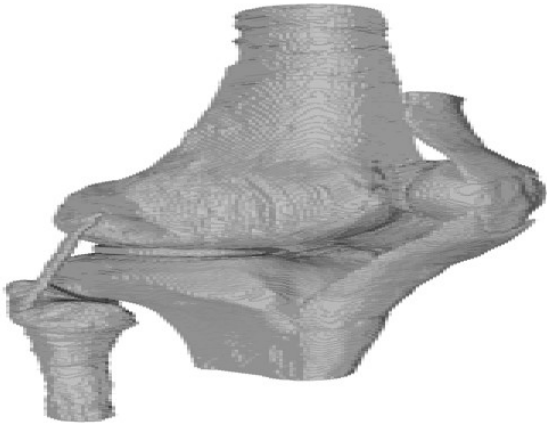
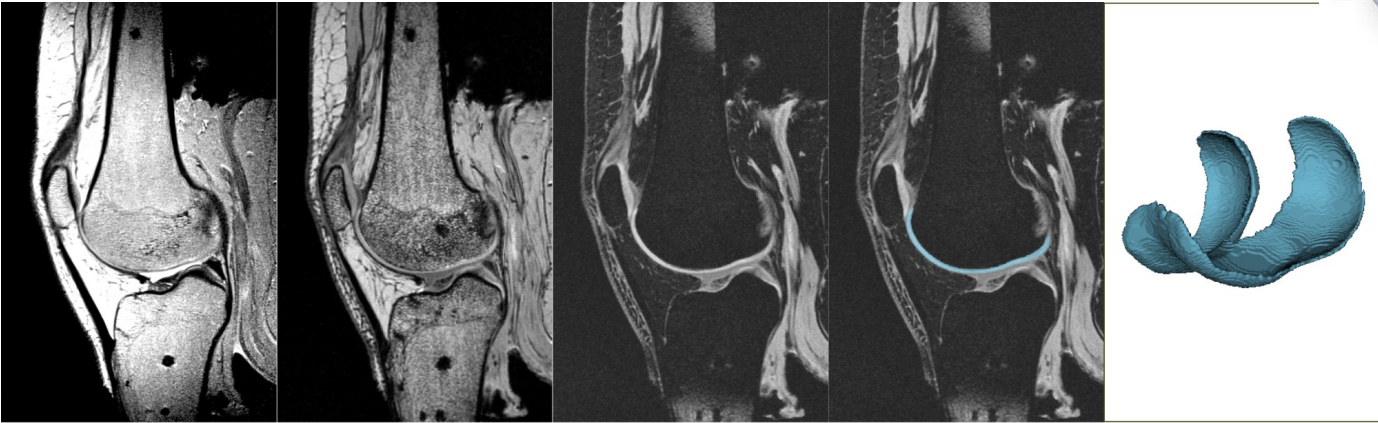


Model



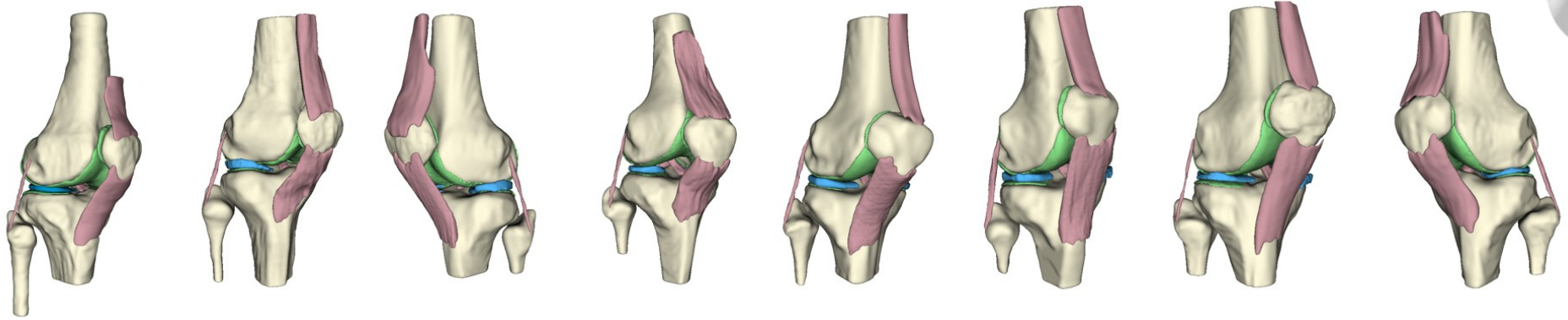
Simulation

Building Open Knee(s): Segmentation

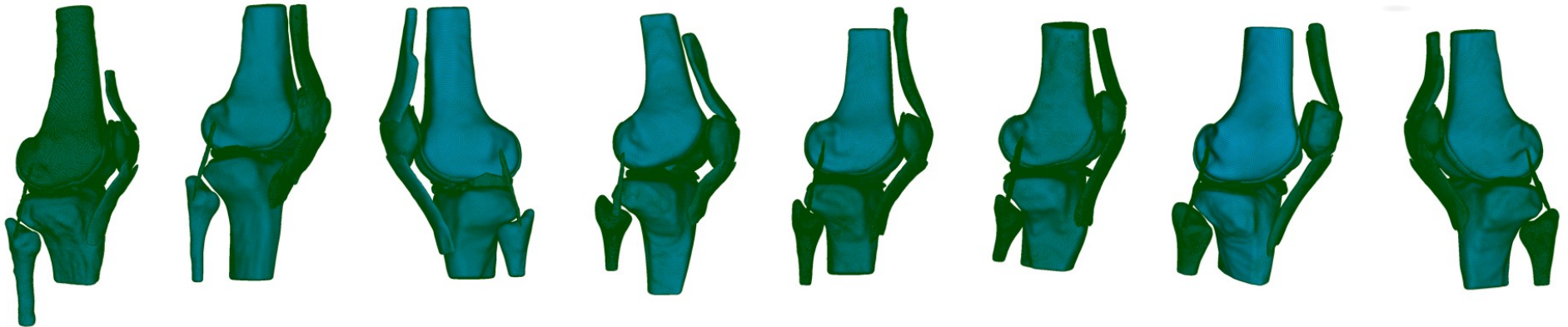


Building Open Knee(s)

Geometry generation

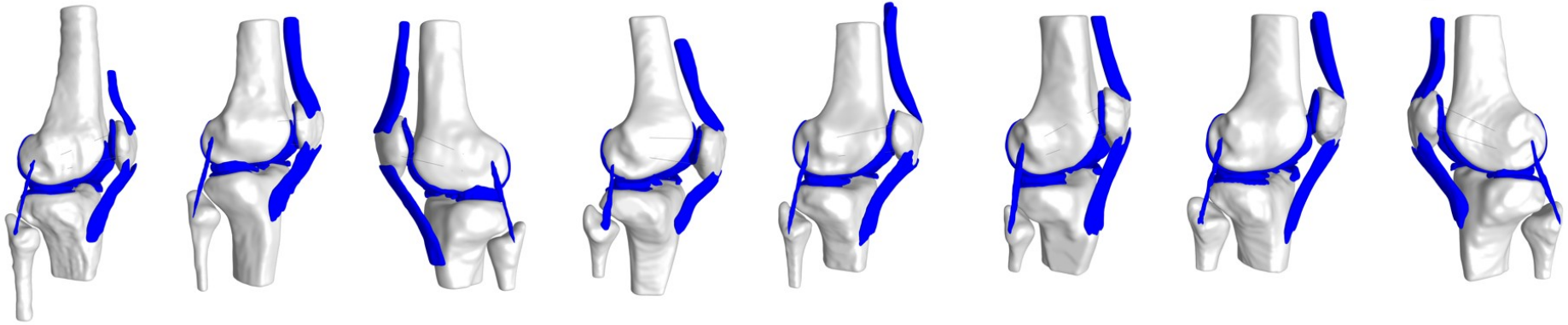


Meshing

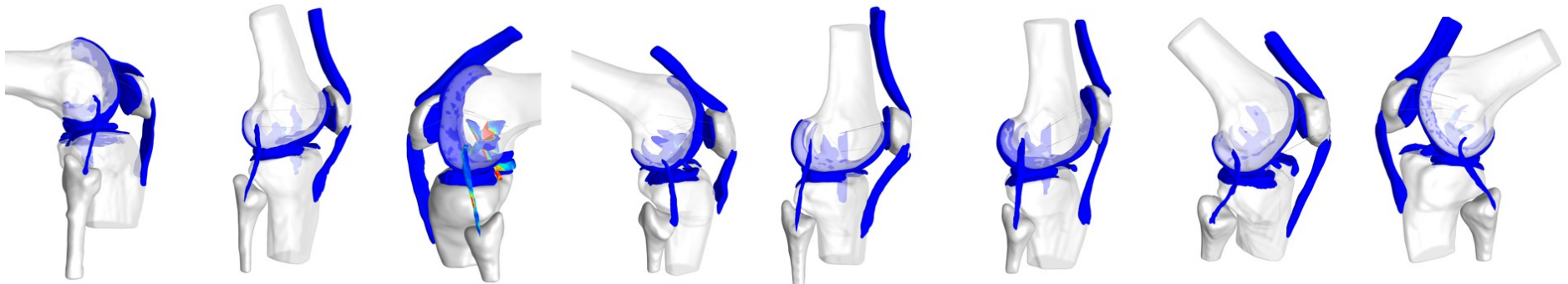


Building Open Knee(s)

Template Models



Model customization and simulation



Open Knee(s): Data Management

SimTK: Open Knee(s): Virtual Biomechanical Representations of the Knee Joint - Downloads - Mozilla Firefox

SimTK Open Knee(s): Virtual Biomechanical Representations of the Knee Joint

Downloads

5,274 downloads

46 forum posts

Open Knee(s) - Generation 2 - Specimen 1

g2-s1-v0.2.0.20150825

1.3.12.2.1107.5.2.19.45406.2014100711193292568244326.0.0.0.nii

1.3.12.2.1107.5.2.19.45406.2014100710433217692143626.0.0.0.nii

1.3.12.2.1107.5.2.19.45406.2014100711262396541244530.0.0.0.nii

1.3.12.2.1107.5.2.19.45406.2014100711323578731244734.0.0.0.nii

https://simtk.org/svn/openknee/

openknee - Revision 3082: /

- [_gen1/](#)
- [app/](#)
- [aux/](#)
- [doc/](#)
- [license.txt](#)
- [oks/](#)
- [readme.txt](#)
- [util/](#)

Powered by [Apache Subversion](#) version 1.9.5 (r1770682).

SimTK Open Knee(s): Virtual Biomechanical Representations of the Knee Joint

Data Share

Open Knees Data

Searchable raw and derivative data available at:
https://simtk.org/plugins/datashare/?group_id=485

derivative_data raw_data metadata.xml

oks001

derivative_data

geometry

model

segmentation

raw_data

joint

MRI

oks002

oks003

oks004

oks006

oks007

oks008

oks009

oks010

oks011

oks012

oks013

oks014

oks015

oks016

oks017

files/oks009

Items: 3, Size: 451 B

Data Share

Open Knees Data

Browse Data Query Data Import and Edit Data

Query

AND OR Invert

Gender contains female male

4 Subjects match (oks002, oks003, oks004, oks006). 3255 Files match. 12.6 GB Estimated download file size

Get the Data

Comments Optional. Your comments will be stored in a README file as a helpful reminder

Filename study11-2020-01-30-03-14 .zip Get Data

Comprehensibility

Detailed and transparent documentation of specifications



The screenshot shows a web browser window with the URL <https://simtk.org/plugins/main/moin/openknee/Specifications>. The page title is "All Specifications Pages". A list of 33 specifications is displayed, including "Specifications", "Specifications/CloudComputingPrototype", "Specifications/DataManagement", "Specifications/DataManagement/Discussion", "Specifications/ExperimentationAnatomicalImaging", "Specifications/ExperimentationAnatomicalImaging/Discussion", "Specifications/ExperimentationJointMechanics", "Specifications/ExperimentationJointMechanics/Discussion", "Specifications/ExperimentationTissueMechanics", "Specifications/ExperimentationTissueMechanics/ProtocolEvaluation", "Specifications/FebioFeatures", "Specifications/GeometryComparison", "Specifications/GeometryGeneration", "Specifications/GeometryGeneration/Discussion", "Specifications/ImageSegmentation", "Specifications/ImageSegmentation/Discussion", "Specifications/MRIScoring", "Specifications/MeshAssembly", "Specifications/MeshGeneration", "Specifications/ModelAssembly", "Specifications/ModelingConstitutive", "Specifications/ModelingKinematicsKinetics", "Specifications/ModelingModelGraph", "Specifications/ModelingTissue", "Specifications/PressureAnalysis", "Specifications/PressureAnalysis/Discussion", "Specifications/PressureCalibration", "Specifications/PressureCalibration/Discussion", "Specifications/Registration", "Specifications/SpecimenPreparation", "Specifications/Specimens", and "Specifications/Specimens/Discussion". A sidebar on the right titled "Contents" lists: 1. Target Outcome, 2. Prerequisites (1. Infrastructure, 2. Prerequisite Protocols), 3. Procedure (1. Schedule Imaging Session, 2. Place Specimen In Transport Container, 3. Transport Specimen, 4. Position/Orient Specimen in MRI Machine, 5. Acquire Image Sequences (1. SETTINGS 1: SPECIMEN LOCATORS, 2. SETTINGS 2: GENERAL PURPOSE IMAGING, 3. SETTINGS 3: CARTILAGE IMAGING, 4. SETTINGS 4: CONNECTIVE TISSUE IMAGING), 6. Store Data, 7. Disseminate Data, 8. Store Specimen, and 4. References. A "Feedback" button is visible on the left side of the page.

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



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

^aComputational Biomodeling (CoBi) Core, Lerner Research Institute, Cleveland Clinic, Cleveland, OH 44195, USA

^bDepartment of Biomedical Engineering, Lerner Research Institute, Cleveland Clinic, Cleveland, OH 44195, USA

^cDepartment of Civil and Mechanical Engineering, University of Missouri – Kansas City, Kansas City, MO 64110, USA

^dDepartment of Orthopaedics and Sports Medicine, University of Washington, Seattle, WA 98195, USA

^eCenter for Devices and Radiological Health, Food and Drug Administration, Silver Spring, MD 20933, USA



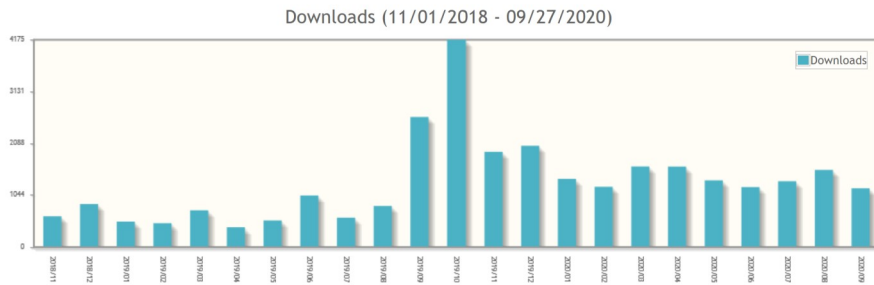
Reporting parameters -

- Model identification
- Simulation structure
- Verification and validation

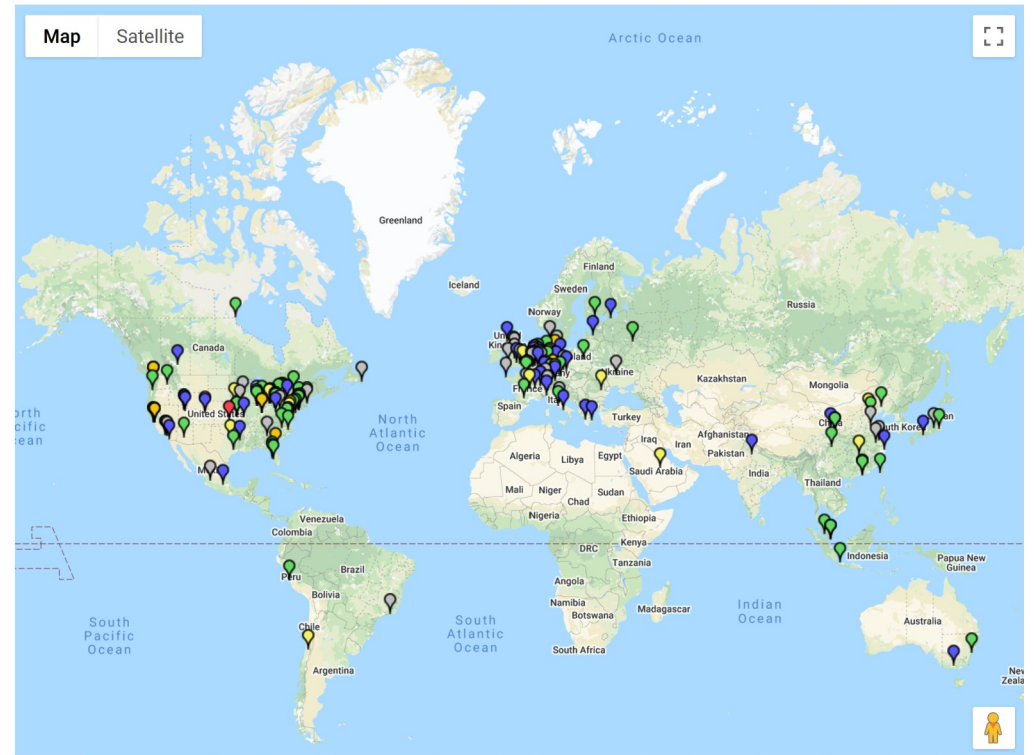
Impact

Summary Statistics

Unique Users ¹	Total Downloads	File Downloads	Links	Unique Downloads ²
1,549	48,154	10,560	37,594	12,432



8054 Page Hits in the past 180 Days (1093 Unique Visitors)
18 Stanford Page Hits (3 Unique Visitors)



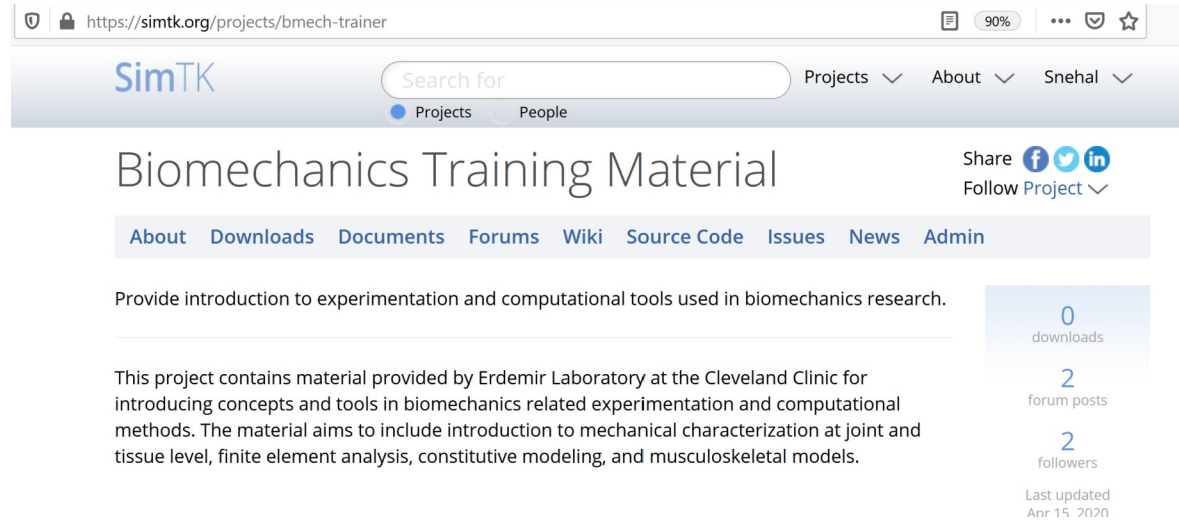
Thus far, 13 studies and 4 text books have referenced the project and 25 studies have utilized Open Knee(s) data in some form

Impact



Training and Education

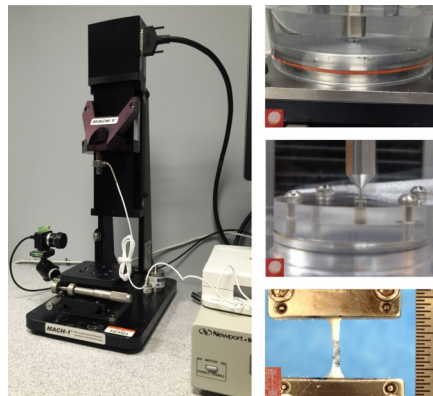
Virtual Labs
UTEC



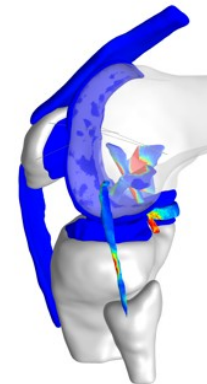
The screenshot shows a web browser window with the URL <https://simtk.org/projects/bmech-trainer>. The page header includes the SimTK logo, a search bar, and navigation links for Projects, About, and Snehal. The main heading is 'Biomechanics Training Material', with social media share buttons for Facebook, Twitter, and LinkedIn, and a 'Follow Project' button. A navigation menu contains links for About, Downloads, Documents, Forums, Wiki, Source Code, Issues, News, and Admin. The main text reads: 'Provide introduction to experimentation and computational tools used in biomechanics research.' Below this, a paragraph states: 'This project contains material provided by Erdemir Laboratory at the Cleveland Clinic for introducing concepts and tools in biomechanics related experimentation and computational methods. The material aims to include introduction to mechanical characterization at joint and tissue level, finite element analysis, constitutive modeling, and musculoskeletal models.' On the right side, a statistics box shows 0 downloads, 2 forum posts, and 2 followers, with a note 'Last updated Apr 15, 2020'.



Joint Mechanical Testing



Tissue Mechanical Testing



Finite Element Modeling

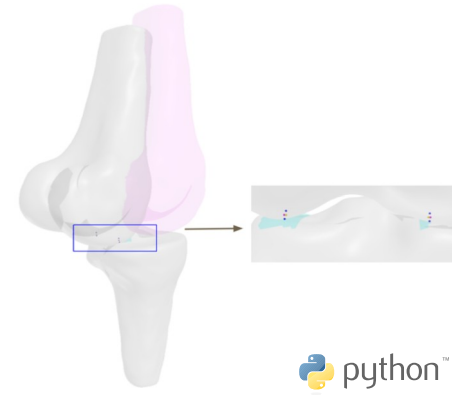
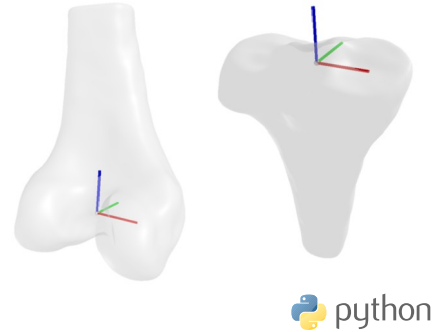
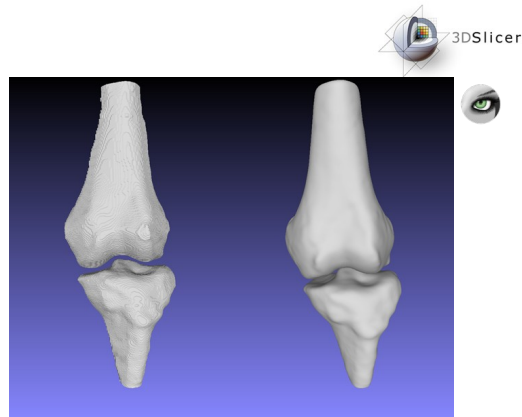
Training and Education

Remote
internship

Estimation of injury kinematics based on
articular surface bruises post noncontact anterior
cruciate ligament injury



Sebastian Janampa



Open Knee(s): In Silico Biomechanics Without Borders

- ❏ 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* *available to all*.

VISIT <http://wiki.simtk.org/openknee>

Acknowledgments



NIH/NIBIB
R01EB009643



NIH/NIGMS
R01GM104139



DOD/USAMRMC
W81XWH-15-1-0232

Reproducibility
in Knee Modeling

NIH/NIBIB
R01EB024573



NIH/NIBIB
R01EB025212

Peripheral
Artery Disease

NIH/NCRR - KL2RR024990
NIH/NIBIB - R01EB018965

Mitral Valve
Mechanics

CC/LRI – Accelerator Award



CC/NI – Innovator
Award



Cleveland Clinic

Lerner Research Institute