Cleveland Clinic

In Silico Biomechanics Without Borders

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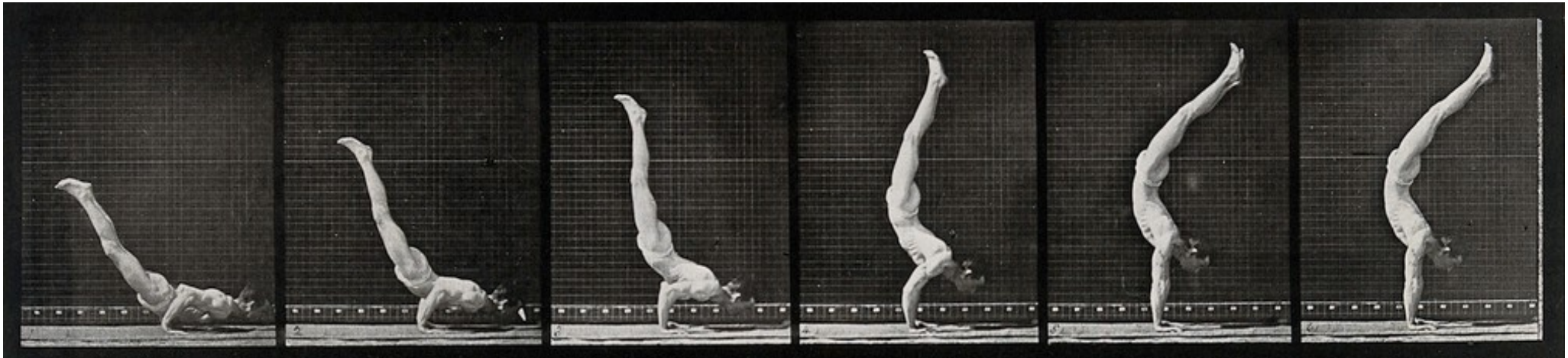
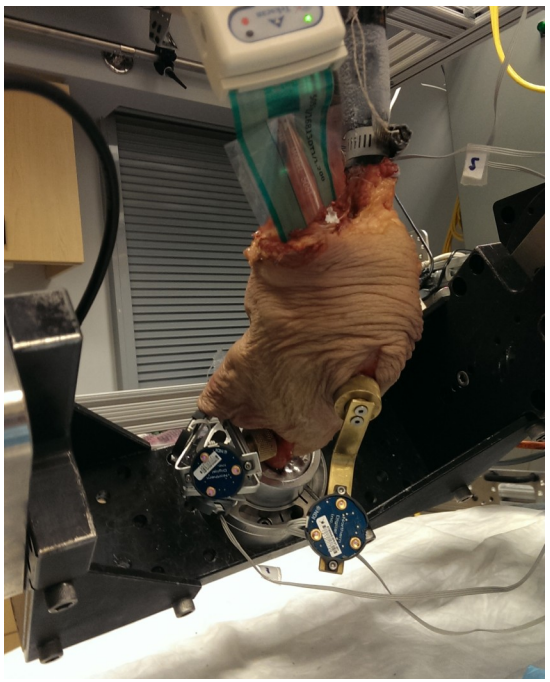
October 2, 2020
Cleveland Clinic – UTEC summit

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

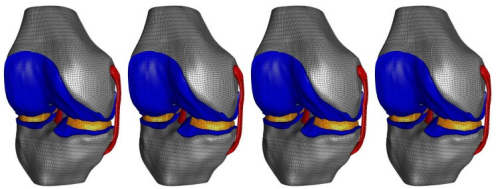
  diagnosis/prognosis

  intervention safety & performance

  medical training

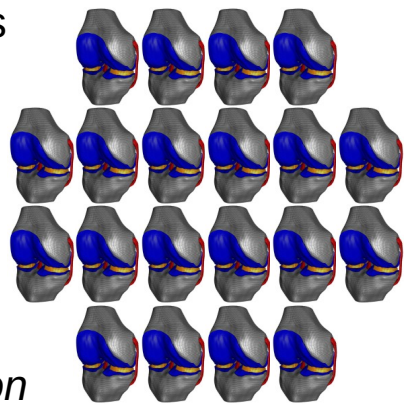
  individualized medicine

virtual experiments

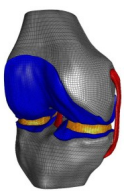


virtual specimen(s) / subject(s)

in silico trials

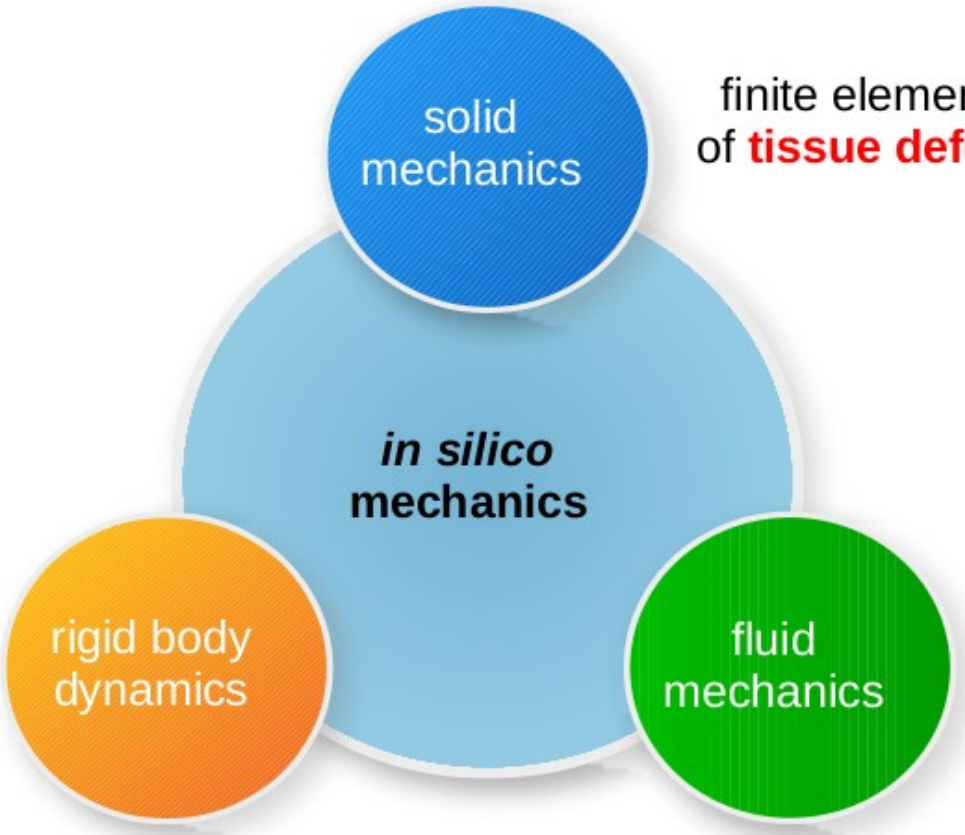


virtual population



virtual patient

In Silico Biomechanics Enterprise

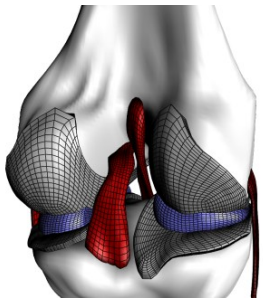


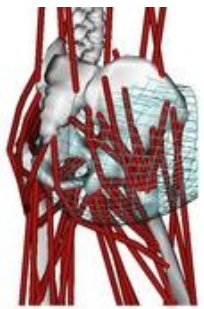
finite element analysis of **tissue deformations**

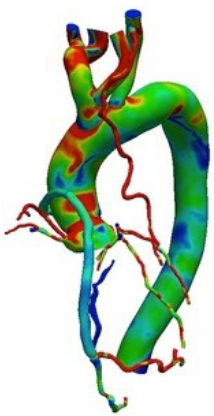
musculoskeletal movement simulations

computational fluid dynamics of **cardiovascular systems**

In Silico Biomechanics Enterprise







simulation software

models

computing hardware

FEBiO
FINITE ELEMENTS FOR BIOMECHANICS

OpenSim

SimVascular

XSEDE
Extreme Science and Engineering Discovery Environment

GPGPU

In Silico Biomechanics Promise

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

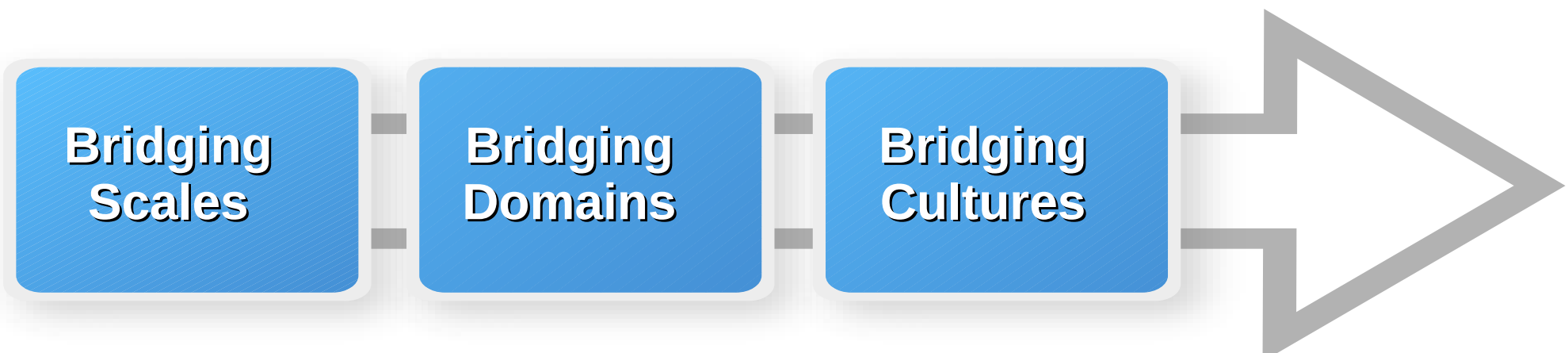
biomechanical response
to support subject/specimen-specific evaluation

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**



Erdemir Laboratory: People

Ariel

Ben

Ellen

Neda

Rici

Sean

Snehal

Current team

Craig

Jason

Scott

Tyler

Alumni

Ahmet

Melissa

Robb

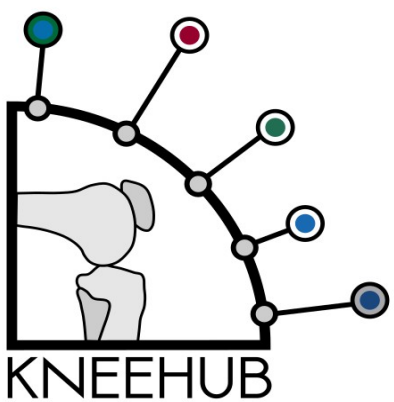
Tammy

Tara

… and many internal and external collaborators

Partners

Erdemir Laboratory: Open Science and Engineering

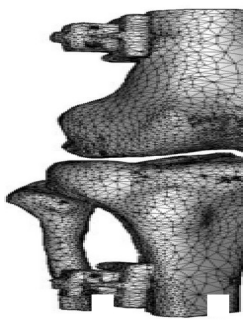


Open Knee(s) as a case study

https://simtk.org/projects/openknee

Modeling and Simulation in Knee Biomechanics

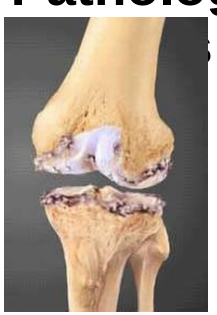
Joint and tissue functions

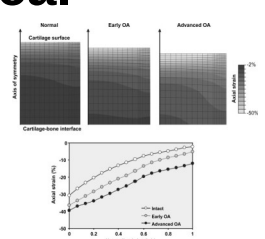


MCL function

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

Pathological





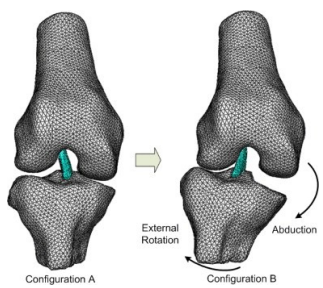
Osteoarthritis

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

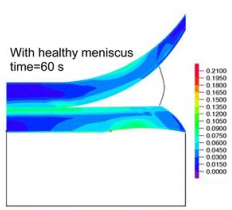
Injury mechanisms

ACL impingement

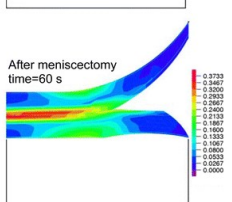
Park et al., J Biomech, 43: 2039-42, 2010.



Surgical interventions

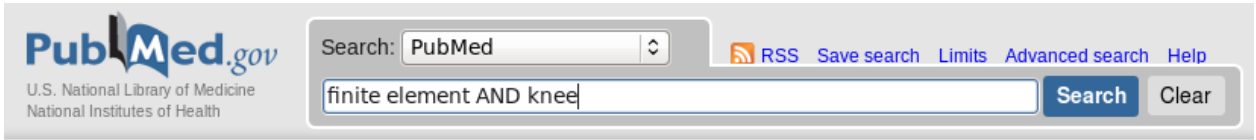


Menisectomy



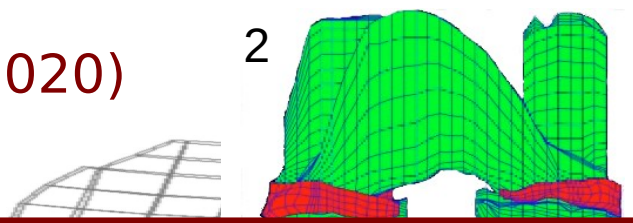
Vaziri et al., Annals of Biomed Eng, 36: 1335-44, 2008.

Modeling and Simulation in Knee Biomechanics



1182 (as of Sept 27, 2020)

1



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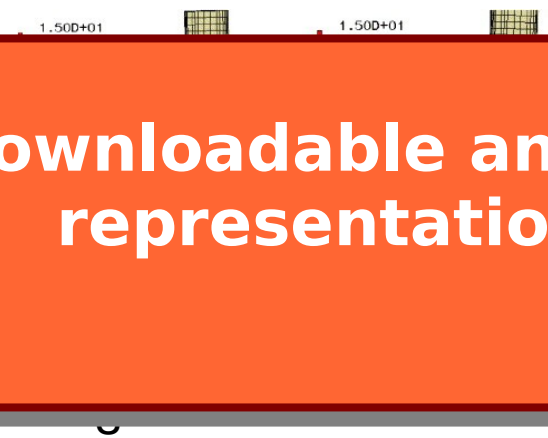
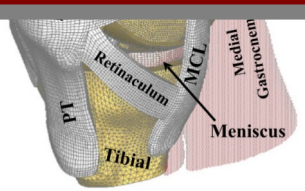


Downloadable and resuable finite element representations of knee models are scarce.



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.*

Open Knee(s) Goals

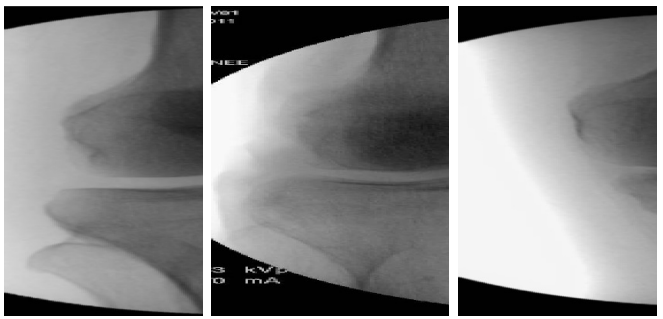
NIH/NIGMS
R01GM104139
9/16/2013- 5/31/2018

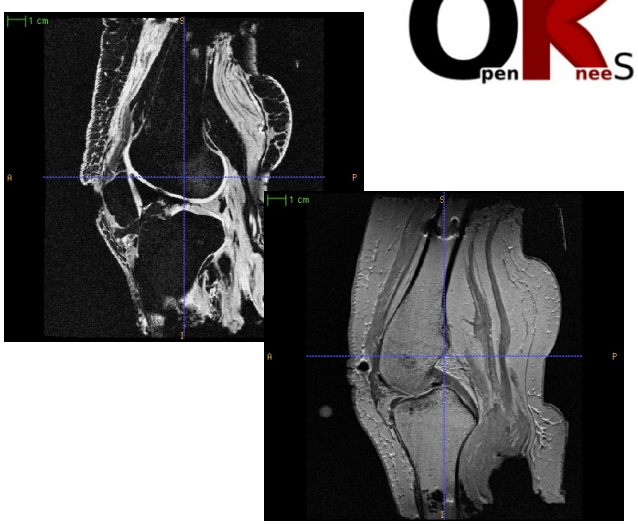
- To provide an open, freely available, and collaborative development, testing, simulation and dissemination platform for in silico exploration of the biomechanics of healthy and diseased knees.

- 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.

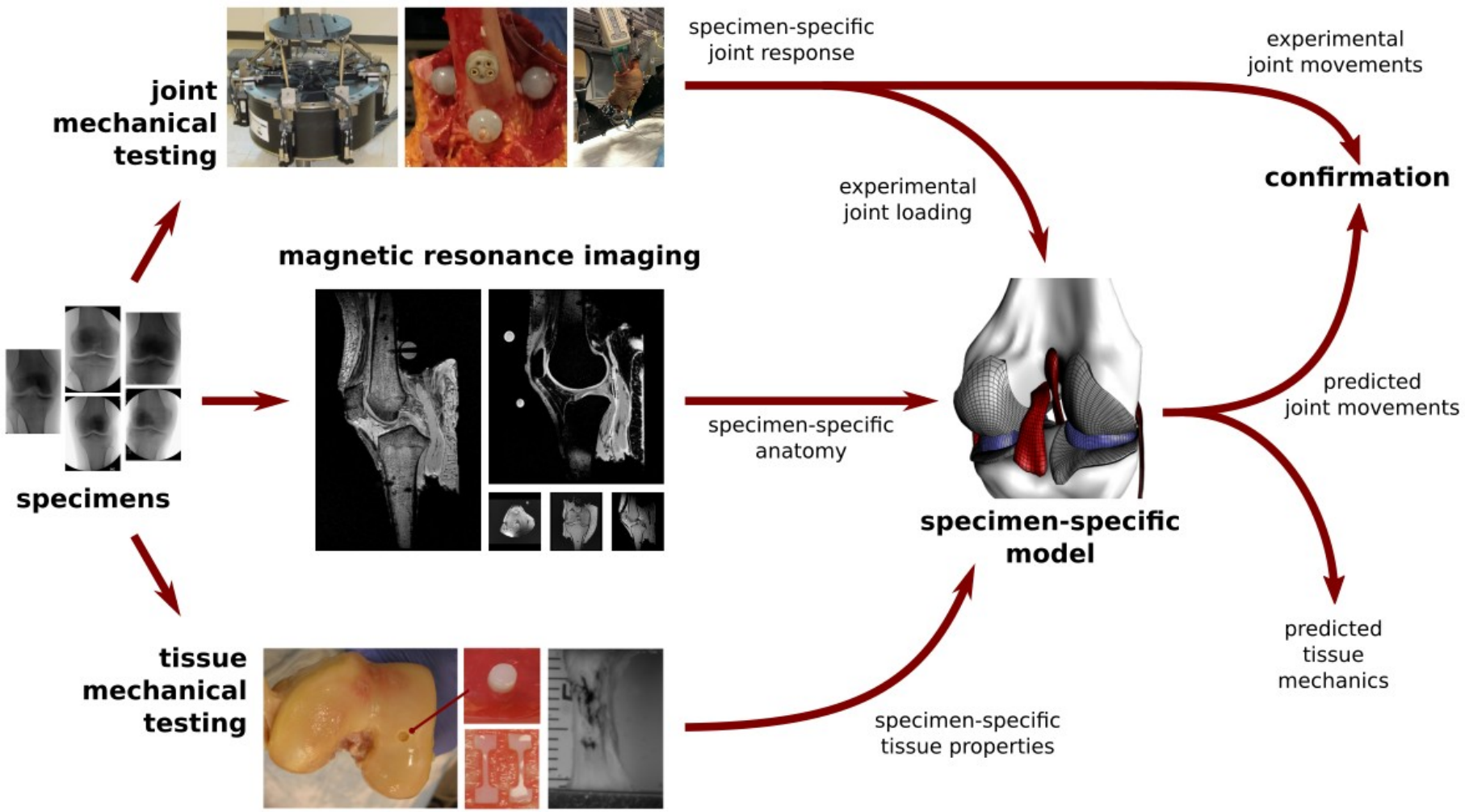
Open Knee(s) Goals

- 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*





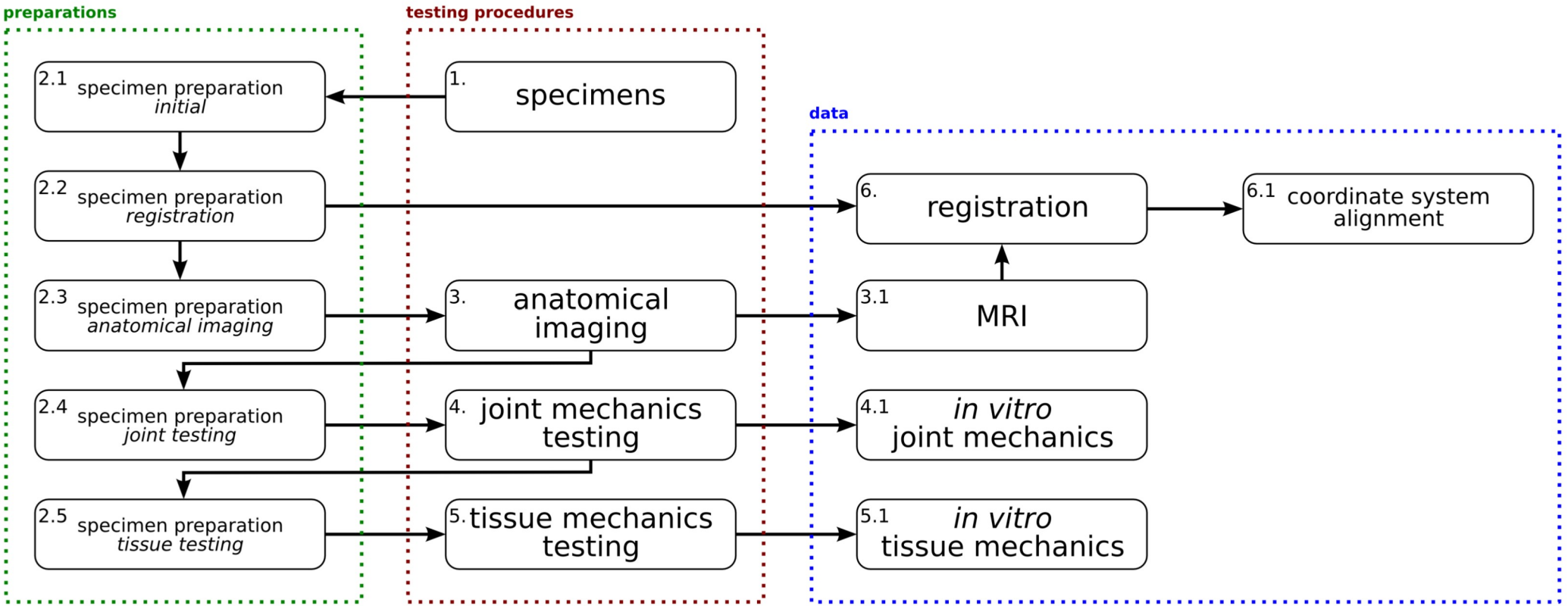
Building Open Knee(s)



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

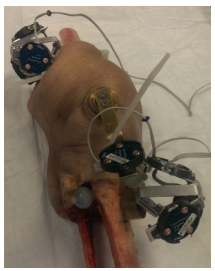
Building Open Knee(s): Experimentation Workflow



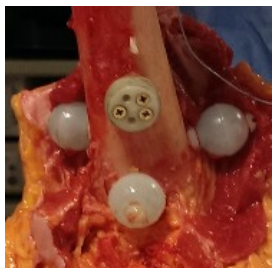
Building Open Knee(s): Preparation

dissection

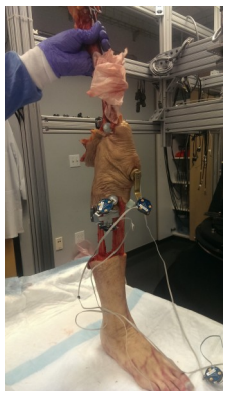
bone plugs



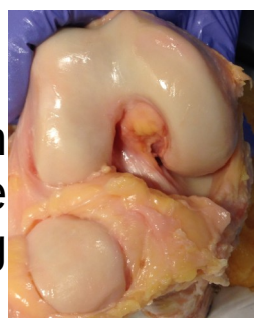
motion capture markers



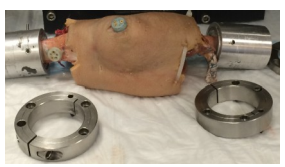
registration markers



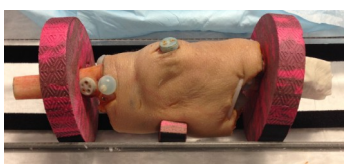
anatomical landmarks



preparation for tissue testing



preparation for joint testing



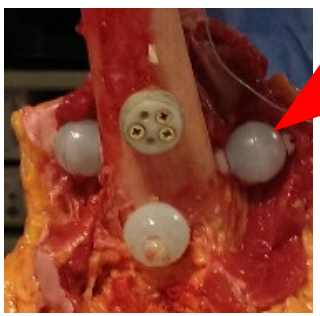
preparation for imaging

to tissue testing

to joint testing

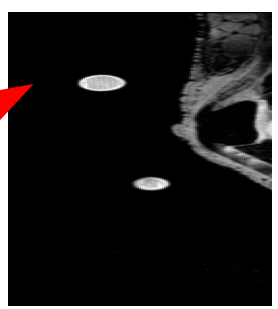
to anatomical imaging

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

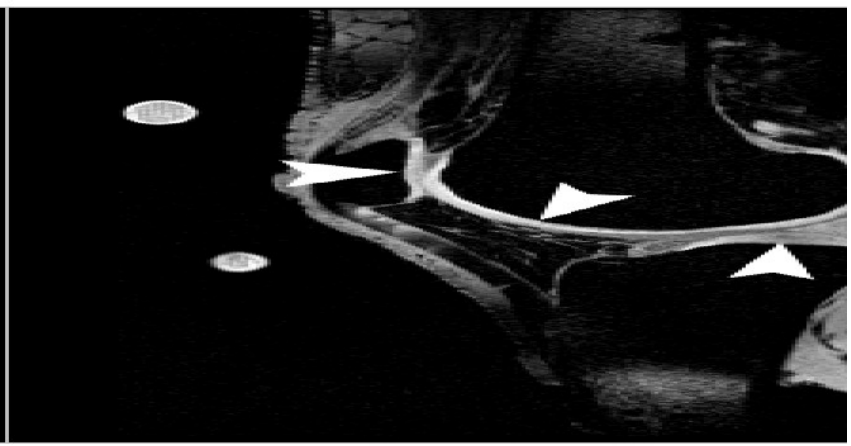
Cartilage

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

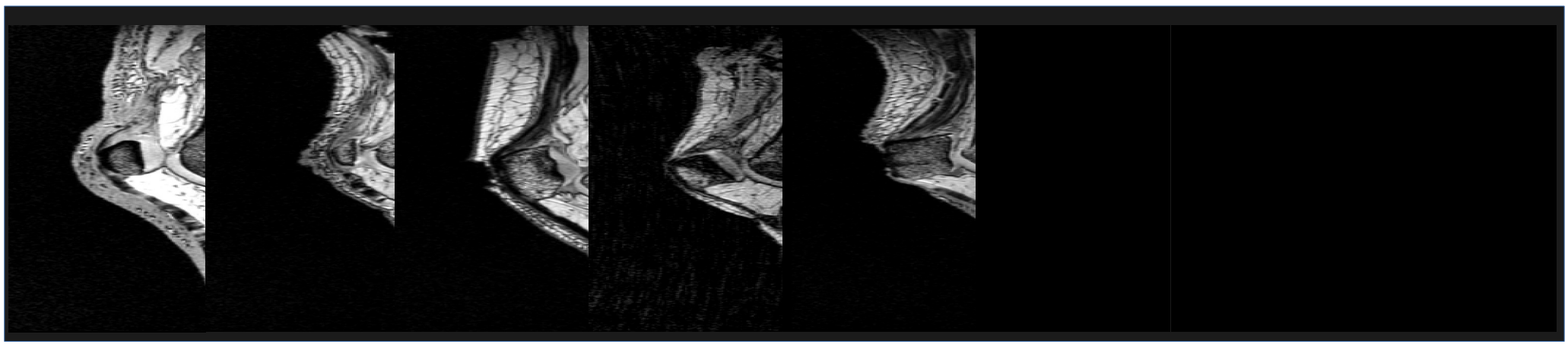
Ligaments

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

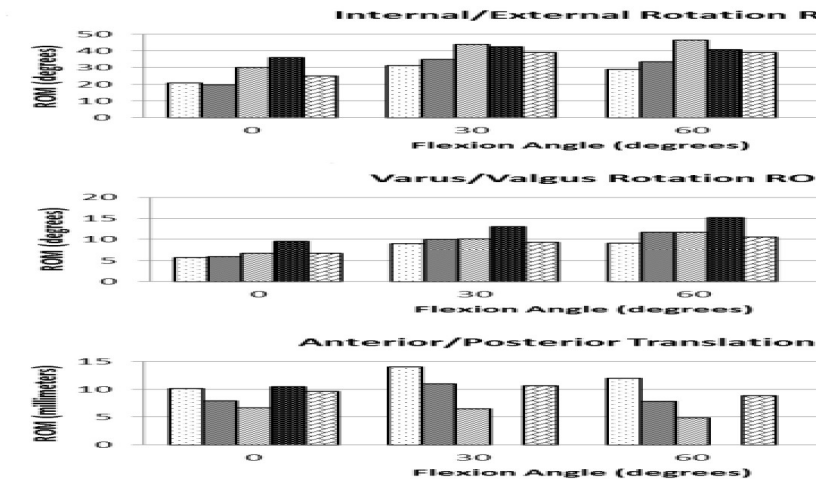
Varus/valgus
- 0 to ±10 Nm
- w/ 2.5 Nm increment

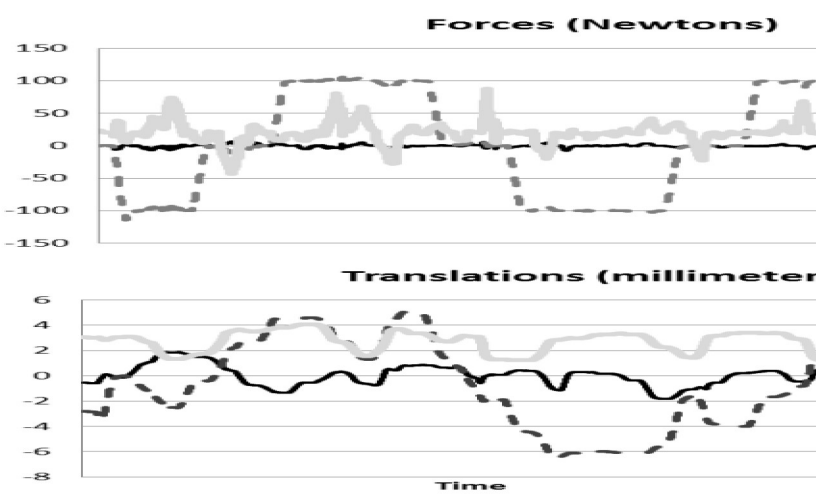
Anterior/posterior translation
- 0 to ±100 N
- w/ 10 N increment

Combined Loading

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

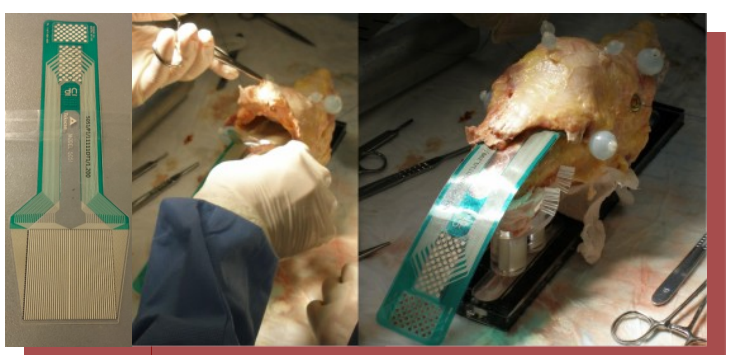
@ 0°, 30°, 60°, 90° flexion
w/ 20 N compression force
measurement of kinematics-kinetics

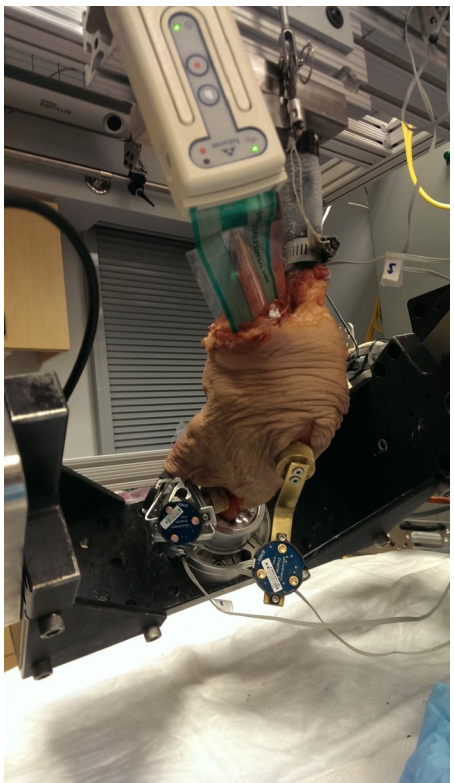


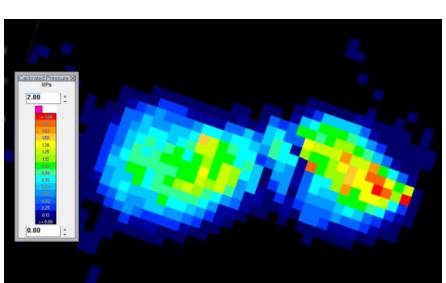


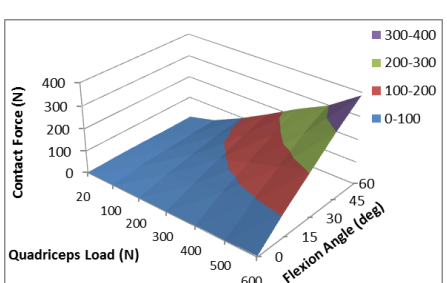
Building Open Knee(s): Patellofemoral Joint Mechanics

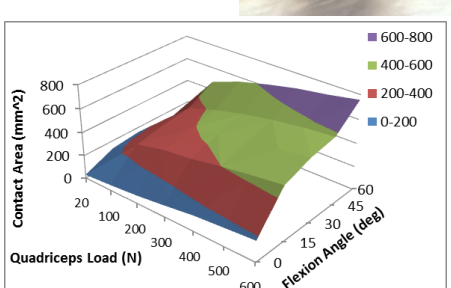
@ 0°,15°,30°,45°,90° flexion
20 N, 100 – 600 N quadriceps force
w/ 100 N increments
measurement of kinematics-kinetics
measurement of contact pressures

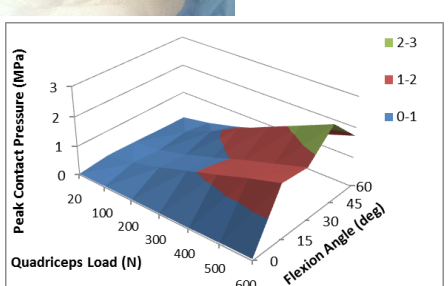












Building Open Knee(s): Tissue Characterization

Cartilage

unconfined compression
confined compression
tension

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

Ligaments and Quadriceps Tendon

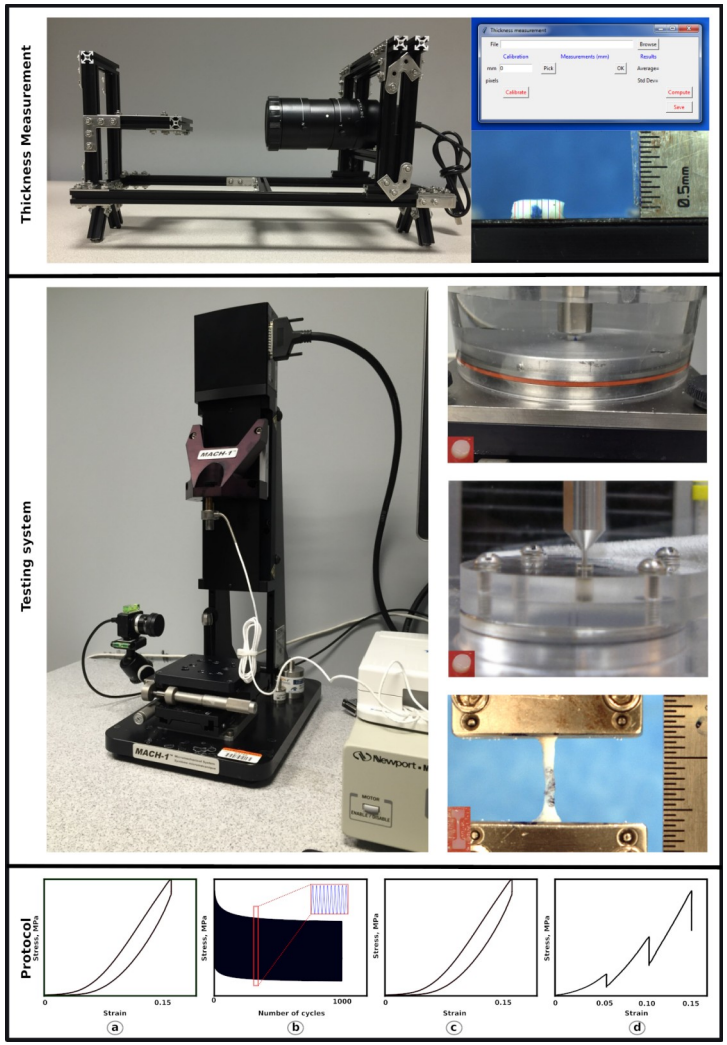
tension

anterior – posterior cruciate
medial – lateral collateral
patellar
transverse

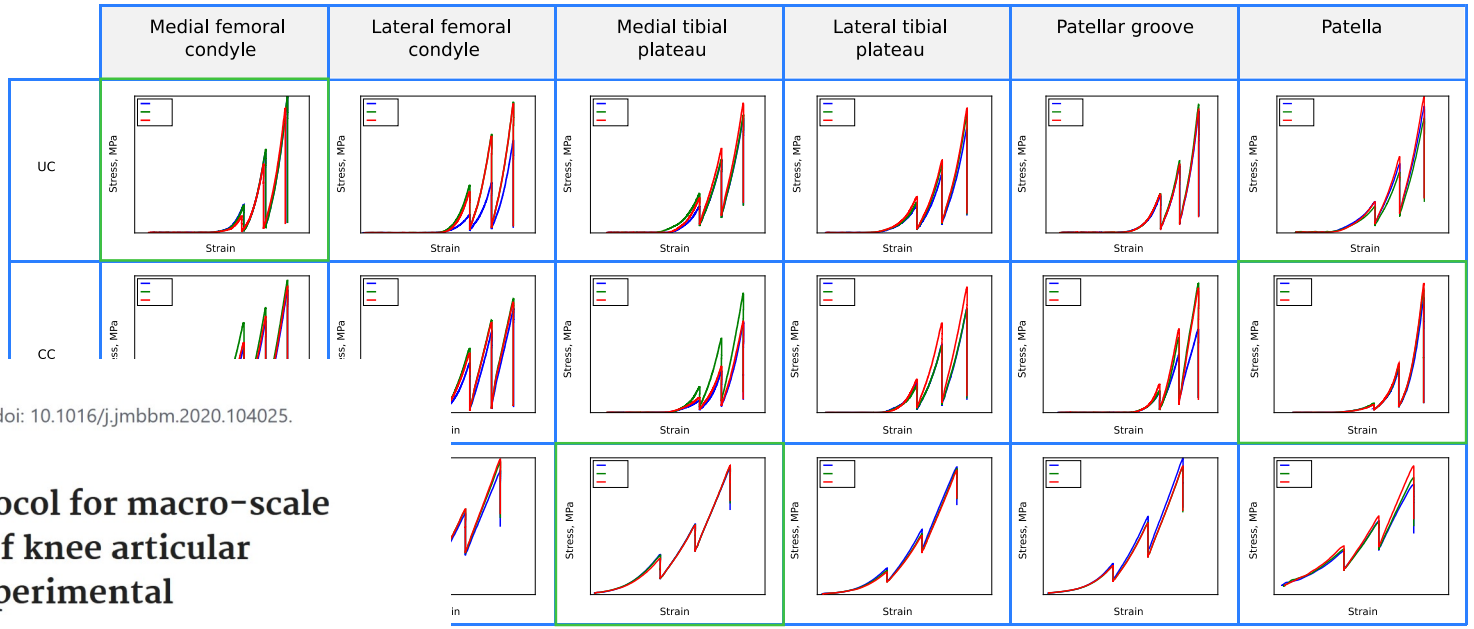
Meniscus

unconfined compression
confined compression
tension

medial – lateral



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]

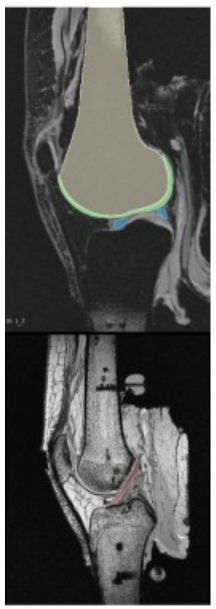
Affiliations + expand

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

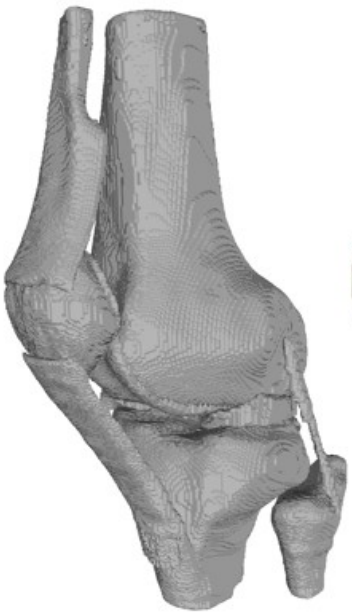
Abstract

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

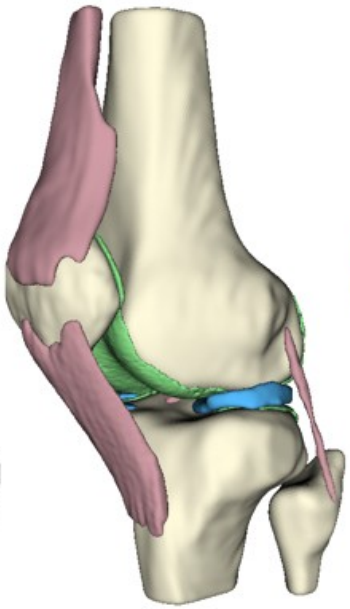
Building Open Knee(s): Modeling Workflow



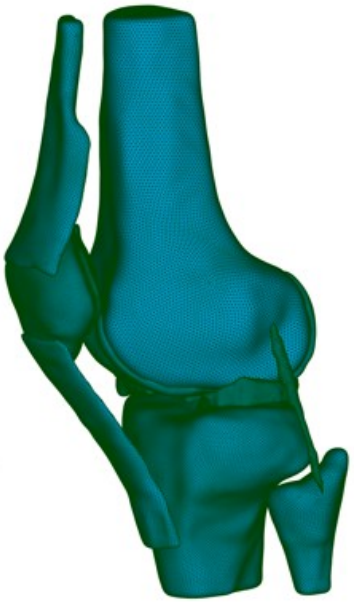
Image



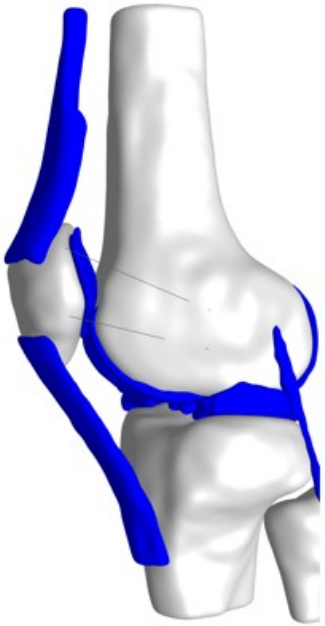
Segmentation



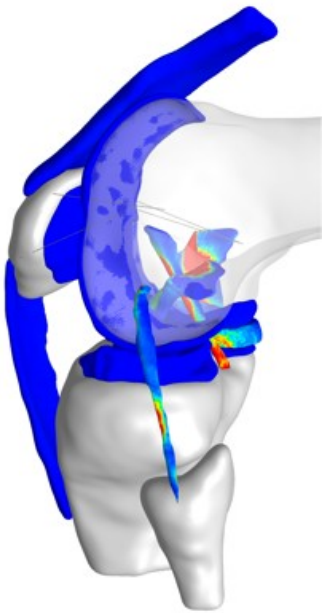
Geometry



Meshing

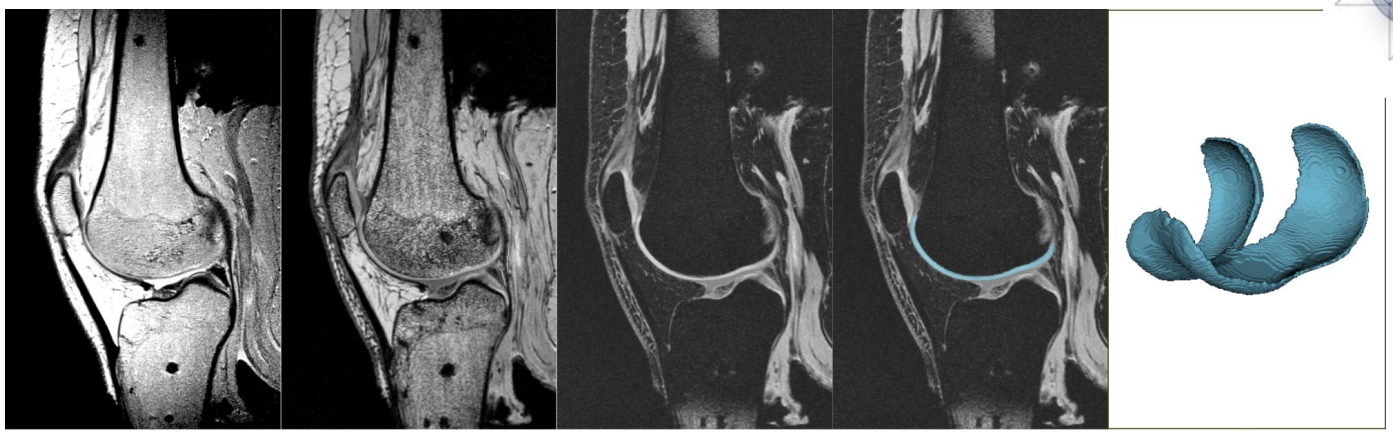


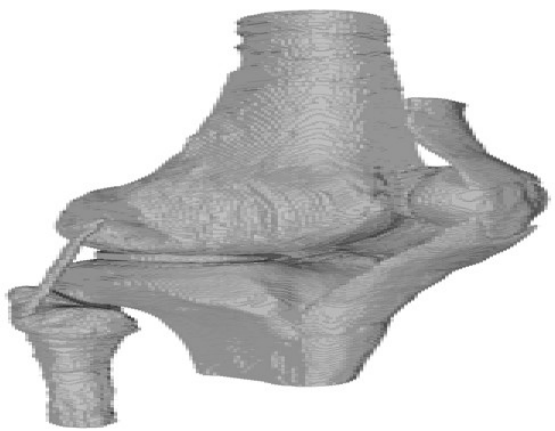
Model

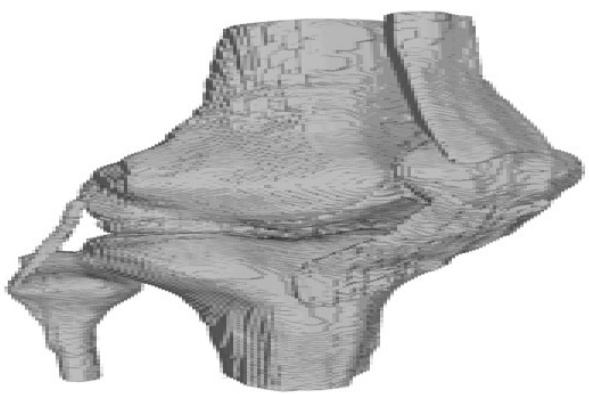


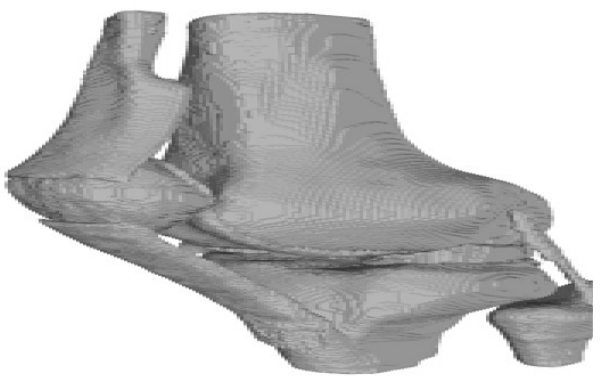
Simulation

Building Open Knee(s): Segmentation



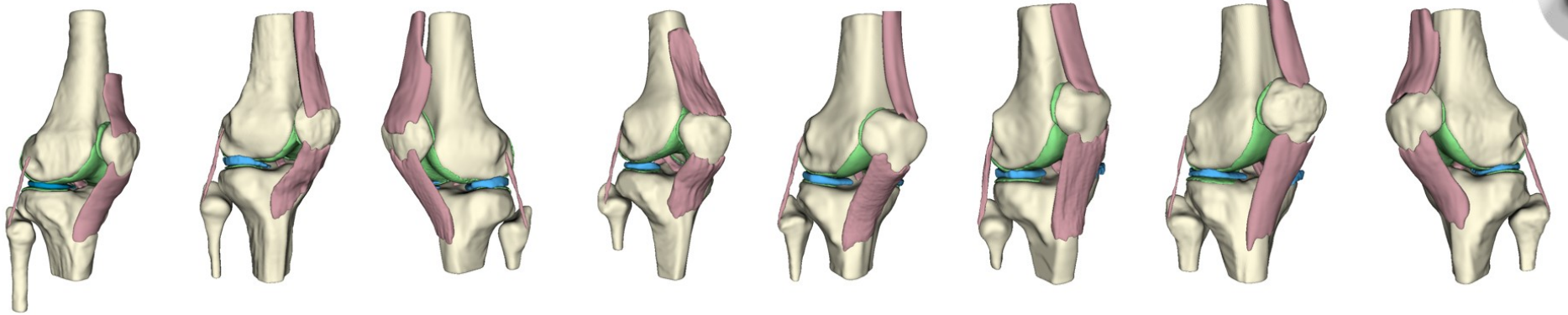




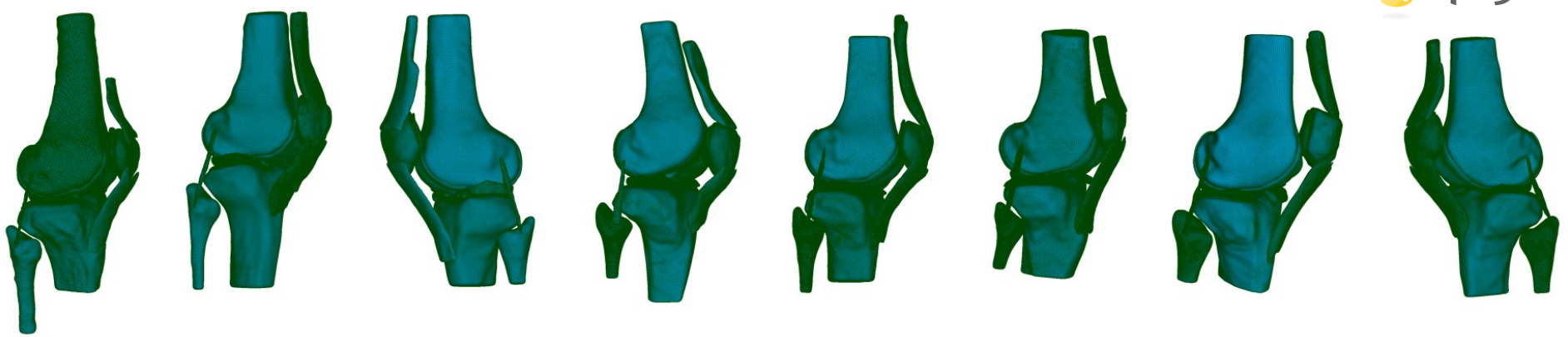


Building Open Knee(s)

Geometry generation

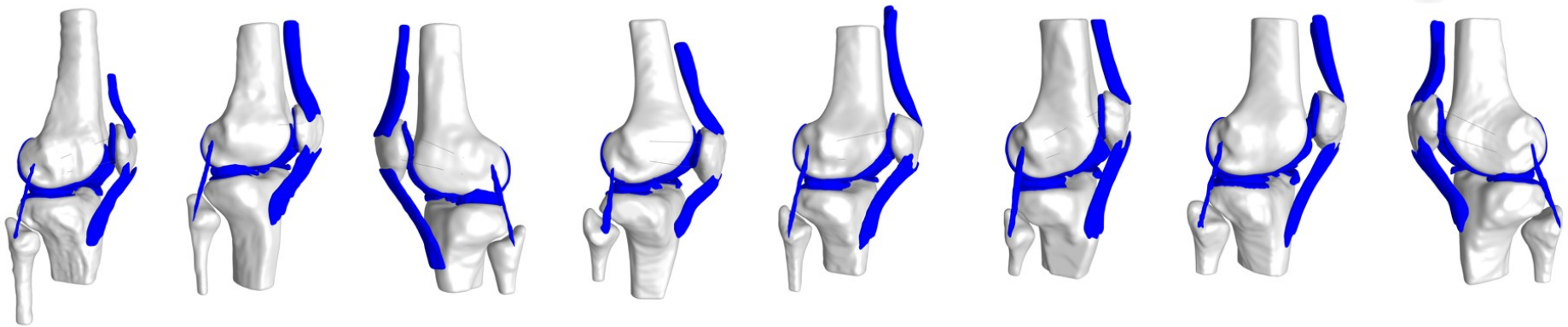


Meshing

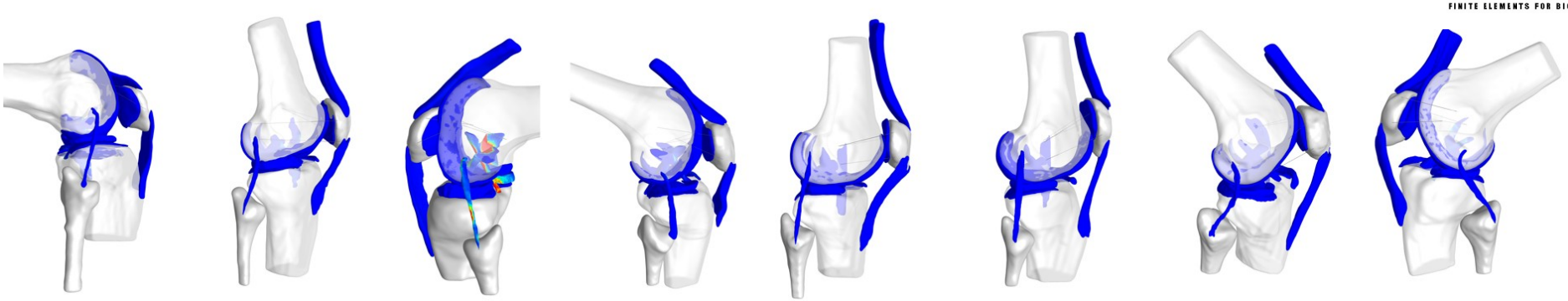


Building Open Knee(s)

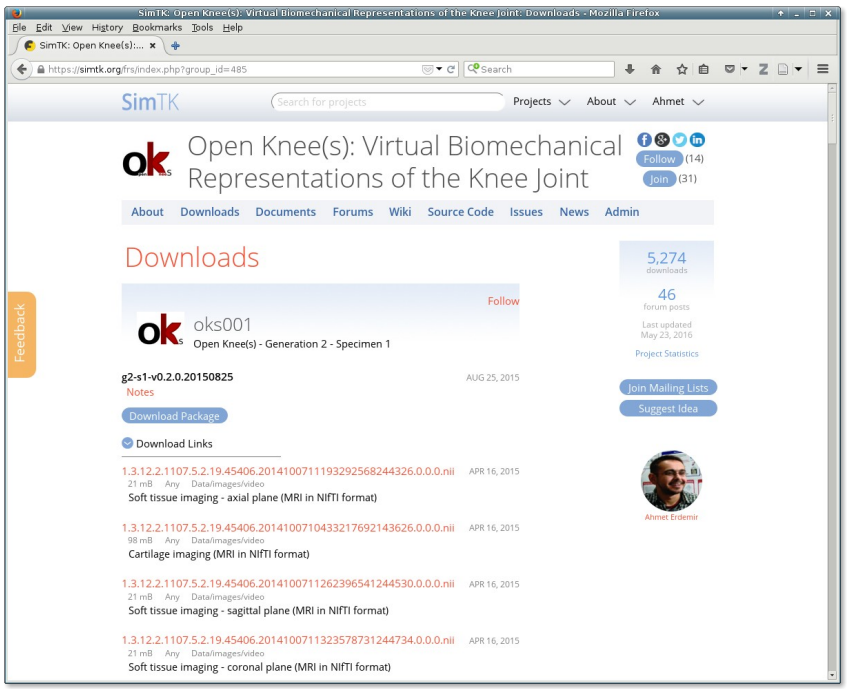
Template Models

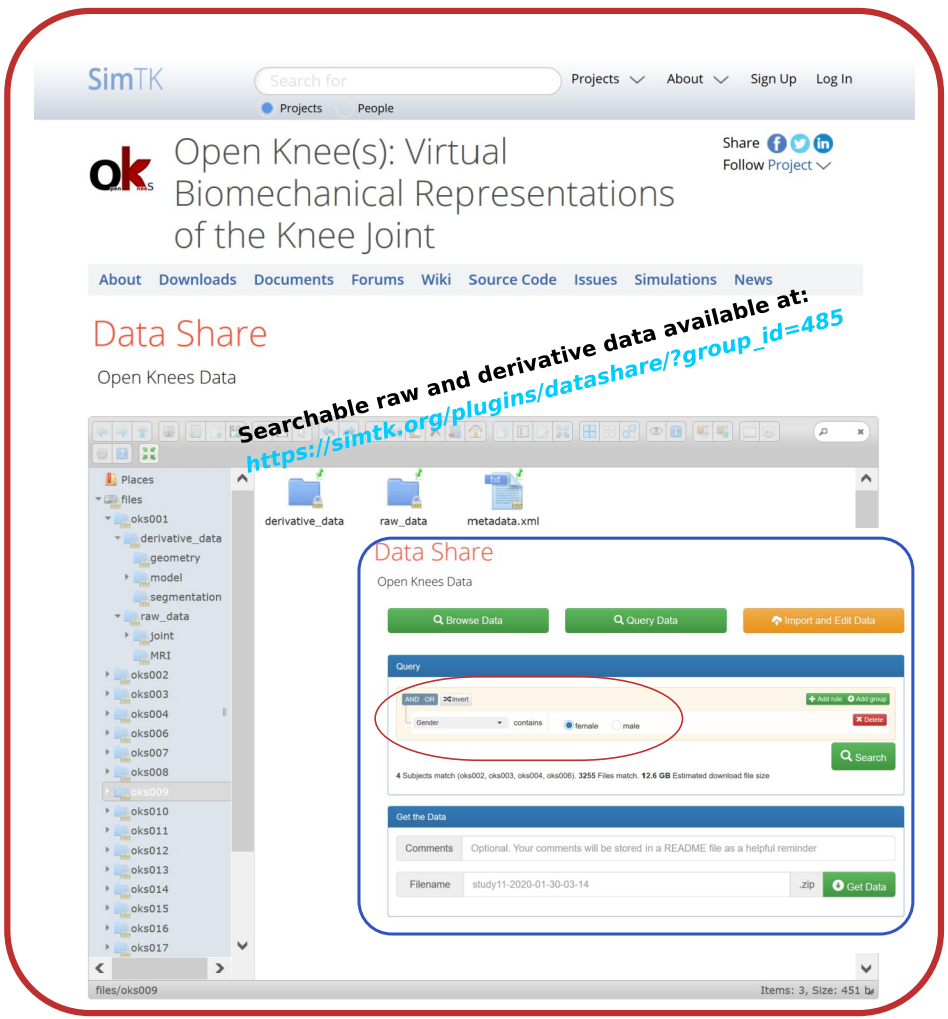


Model customization and simulation



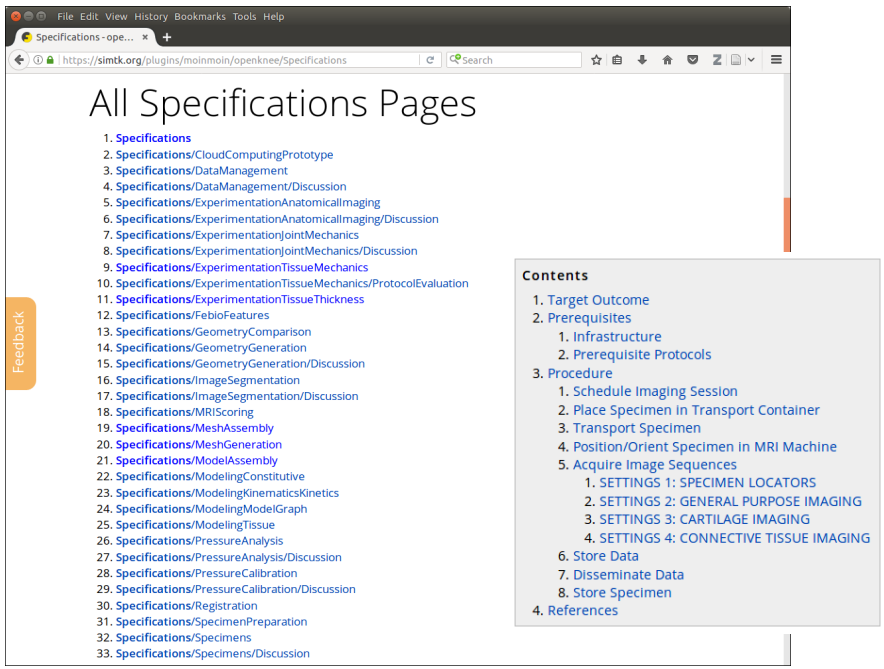
Open Knee(s): Data Management





Comprehensibility

Detailed and transparent documentation of specifications



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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]

[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

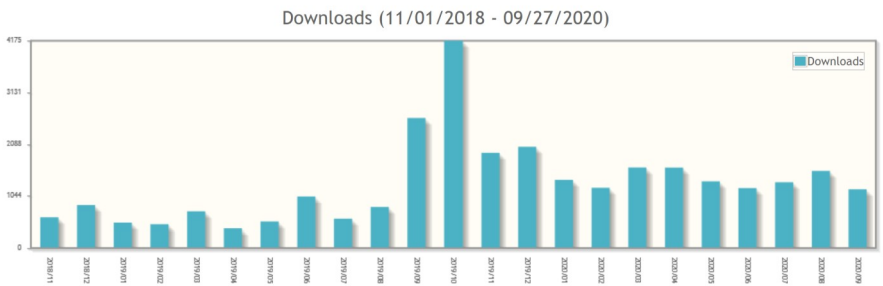
Reporting parameters -

- **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



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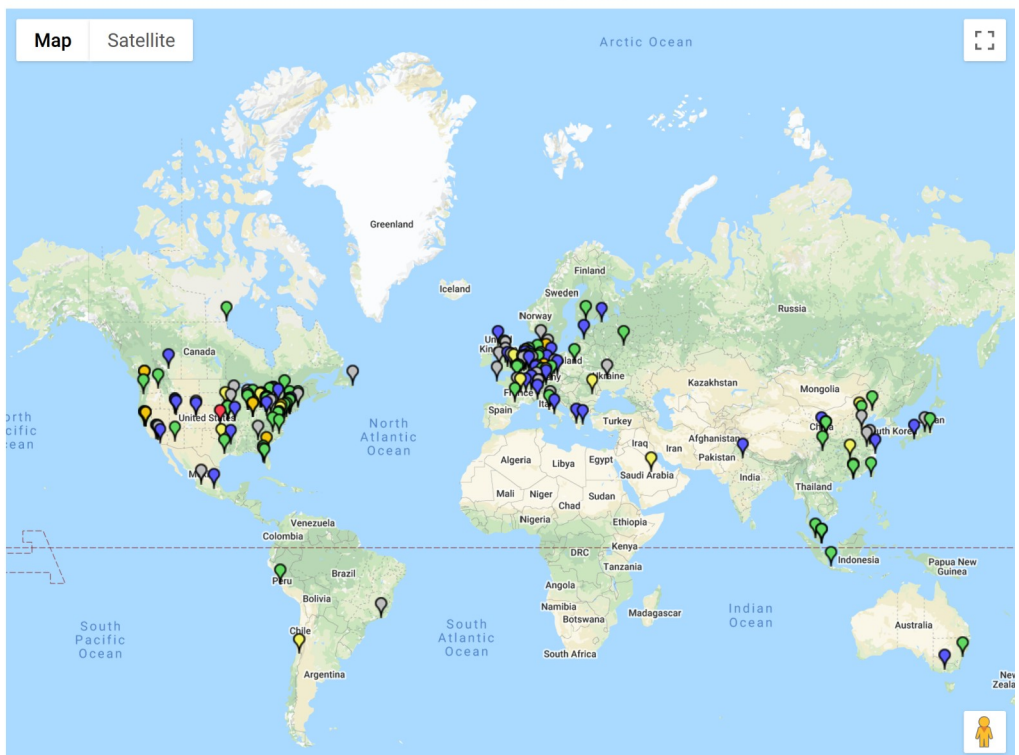
18 Stanford Page Hits (3 Unique Visitors)



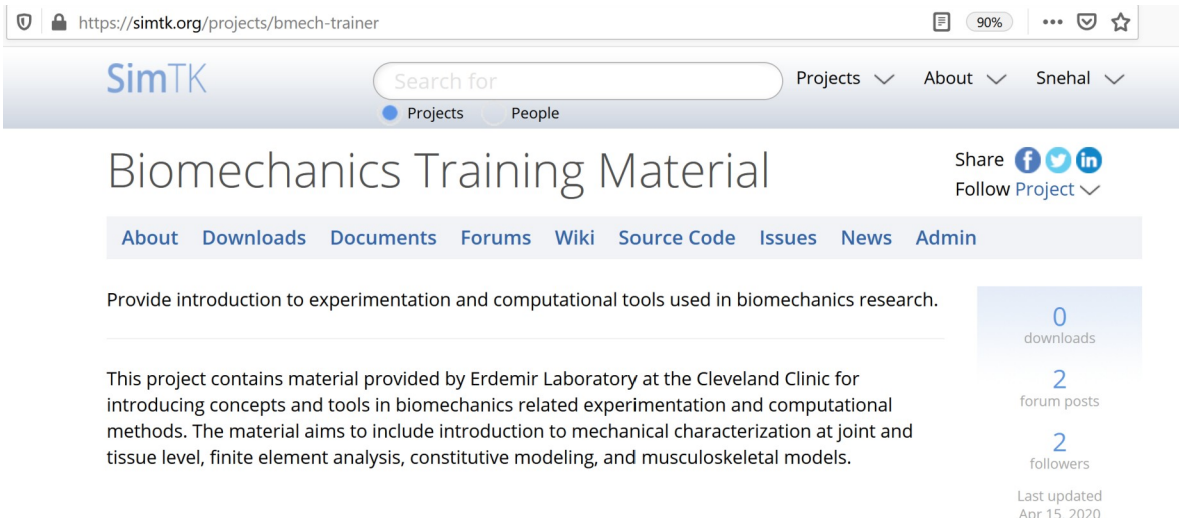
Thus far, 13 studies and 4 text books have referenced the project and 25 studies have utilized Open Knee(s) data in some form

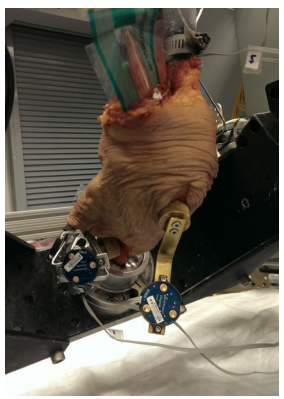
Impact


thesis
collaboration
publication
publication
thesis
origins
publication
thesis
publication
data
contribution
publication
publication
collaboration
collaboration
collaboration

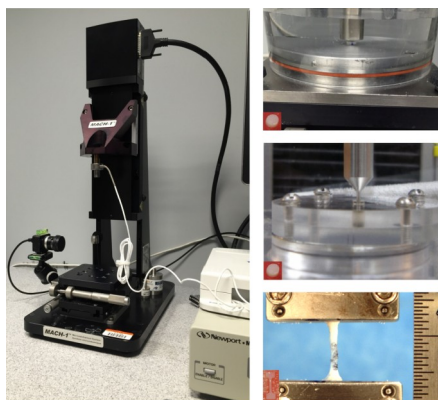
Training and Education

Virtual Labs
UTEC

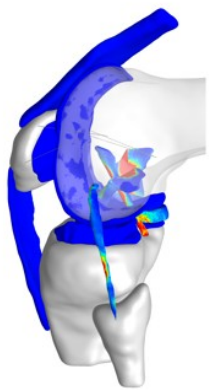




Joint Mechanical Testing



Tissue Mechanical Testing



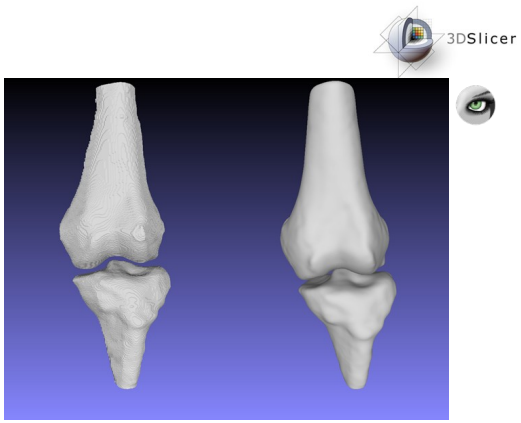
Finite Element Modeling

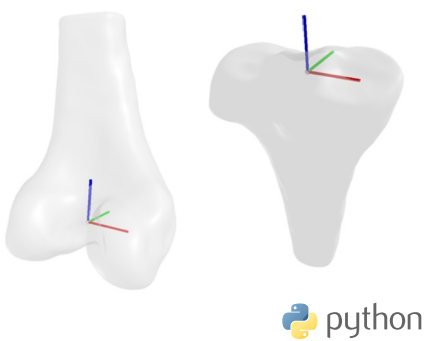
Training and Education

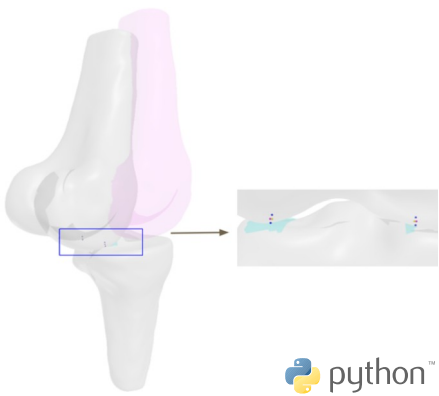
Remote internship

Sebastian Janampa

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







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