Image-based Modeling in Orthopaedics

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Overview

- motivation
- image-based FEM
- applications:
  - ligament repair, bone healing
  - component wear
  - imaging under load
  - dynamic imaging
  - future applications

Image-based modeling: motivation

- dynamic load, stress, and strain are important in orthopaedic therapy
- anatomical imaging provides indirect information about underlying biomechanics
- growing desire for functional information about bones and joints during diagnosis and therapy
- MSK applications include OA, arthroplasty, fracture healing, ligament repair

Finite-element modeling

- numerical solution to physical systems (*e.g.* structural analysis, heat transfer, fluid flow)
- system under study is discretized into individual nodal elements
- constitutive equations that govern physical processes are solved as algebraic equations, based on boundary conditions
- common packages include Abaqus, Ansys

Image-based FEM

- advanced biomedical imaging (*i.e.* CT, MRI) can provide material properties and boundary conditions for finite-element models (FEM) to estimate stress, strain, deformation
- 3D image data must be processed to estimate mechanical properties (*i.e.* elastic modulus)
- assumptions are made about material properties (*i.e.* Poisson's ratio, viscoelasticity, anisotropy)

FEM: material properties

	Elastic modulus	Poisson's ratio
Cortical Bone	17 GPa	0.3
Cancellous Bone	350 MPa	0.25
Cartilage	12 MPa	0.45
Meniscus Matrix	10 MPa	0.45
Meniscus Horn	15 MPa	0.45
Anterior Cruciate Ligament	366 MPa	—
AL bundle of Posterior Cruciate Ligament	165 MPa	—
PM bundle of Posterior Cruciate Ligament	98 MPa	—
Medial Collateral Ligament	366 MPa	—
Lateral Collateral Ligament	366 MPa	—

doi:10.1371/journal.pone.0127293.t002

Lai *et al.*, Plos One, May, (2015)

Heterogeneous material properties

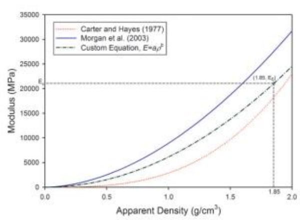
- elastic modulus can be estimated from bone density, which is inferred from CT number
- local modulus assigned from image data

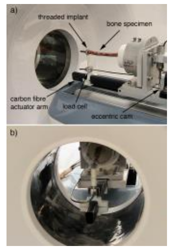
Summary of density–modulus equations used to assign material properties

Study	Density–modulus relationship	Bone site
Carter and Hayes (1977)	$E = 2875\rho_{app}^{3}$	Pooled
Wirtz et al. (2000)	$\rho_{app} < 0.95$: $E = 1904\rho_{app}^{1.64}$ $\rho_{app} > 0.95$: $E = 2065\rho_{app}^{3.09}$	Average of several equations
Morgan et al. (2003)	$E = 8920\rho_{app}^{1.83}$	Pooled
Keller et al. (1994)	$E = 10\,500\rho_{ash}^{2.29}$	Pooled
Snyder and Schneider (1991)	$E = 3891\rho_{app}^{2.39}$	Tibial diaphysis
Lotz et al. (1990, 1991)	$\rho_{app} < 1.04$: $E = 1310\rho_{app}^{1.40}$ $\rho_{app} > 1.04$: $E = 14\,261\rho_{app} - 13\,430$	Femoral neck and metaphysis

Austman *et al.*, J Biomech, 41:3171 (2008)

Heterogeneous material properties





Austman *et al.,* Proc Inst Mech Eng H, 223:787 (2009)

Image-based MSK modeling

Multi-modality imaging for models

- **CT and MRI images can be co-registered to create models of bone and soft tissue**

Image-based MSK modeling

FEM: geometric mesh

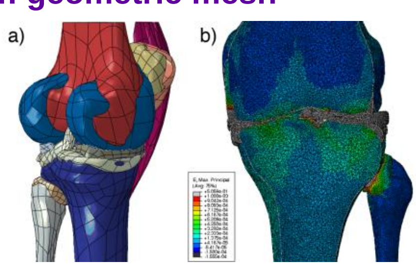


Image-based MSK modeling

Applications: ligament surgery

- ligament rupture in the knee causes knee instability; leads to premature osteoarthritis
- surgical techniques to stabilize the knee with grafts often fail to provide return to previous activities

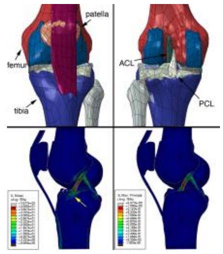


Image-based MSK modeling

Applications: ligament surgery

- FEM model (based on MRI and CT data) shows stress concentration at junction between graft and bone

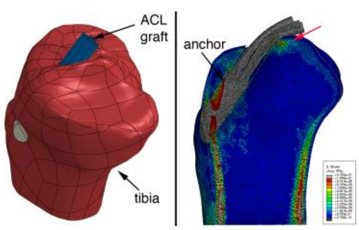


Image-based MSK modeling

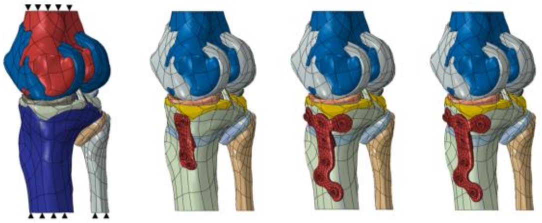
Applications: healing near implants

- assessing the mechanical environment in “medial opening-wedge high-tibial osteotomy”
- subjects imaged with cone-beam CT (bone properties) and co-registered MRI (soft-tissues)
- simulation of various designs of plate hardware
- FEM simulation of loads, strains, stresses in bone and metal hardware

Pauchard *et al.,* J. Biomech. Eng., 137, (2015)

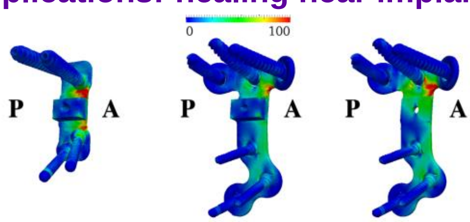
Image-based MSK modeling

Applications: healing near implants



Pauchard *et al.,* J. Biomech. Eng., 137, (2015)

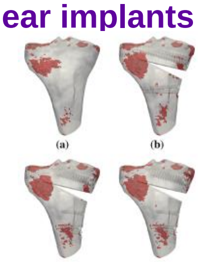
Applications: healing near implants



Pauchard *et al.,* J. Biomech. Eng., 137, 2015)

Applications: healing near implants

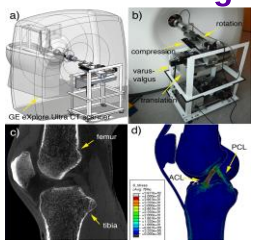
- **finite-element analysis compares bone strain with different hardware options**
- **peak strain occurs in cortex, opposite to plate**
- **simulation can be used to predict optimal surgical technique**



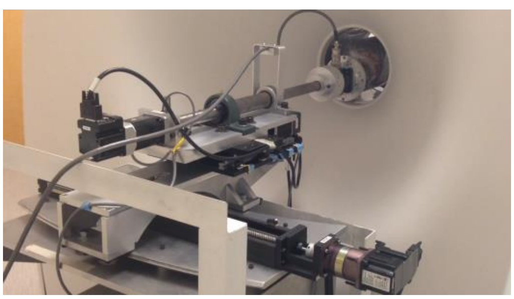
Pauchard *et al.,* J. Biomech. Eng., 137, (2015)

Imaging during mechanical loading

- micro-CT can be combined with dynamic mechanical loading
- provides real-time 3D image data under controlled loading
- optimization of surgical techniques (ACL repair)

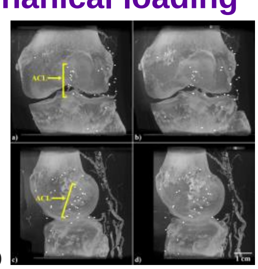


Blokker et al. J. Biomech Eng (2019)

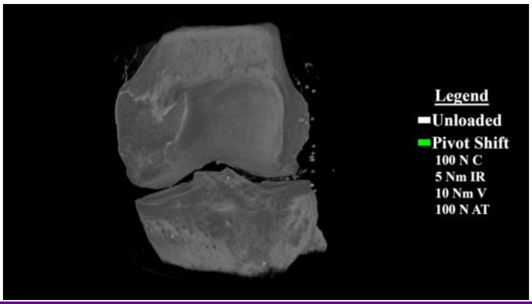


Imaging during mechanical loading

- before (a,c) and after (b,d) application of “pivot shift” loading:
- 100 N compression, 5Nm internal rotation, 10 Nm valgus rotation, 100 N anterior translation

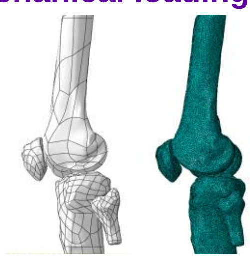


Blokker et al. J. Biomech Eng (2019)



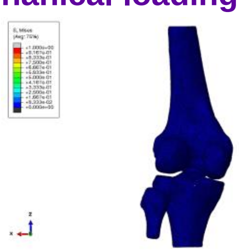
Imaging during mechanical loading

- conebeam micro-CT data provides mesh geometry and heterogeneous elastic modulus information for FEM



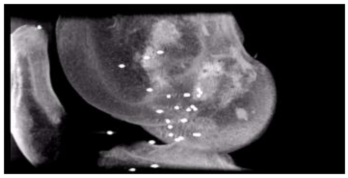
Imaging during mechanical loading

- finite-element model derived from 3D CBCT image data facilitates direct comparison, validation of experimental and FEM data



Dynamic imaging during loading

- also possible to use CT gating techniques (from cardiac imaging) to create fully 3D CT “movies” as basis for dynamic FEM model



Data courtesy Allie Blokker

Imaging during *in vivo* loading

- diagnostic imaging of lower extremities would be more useful under appropriate joint loading
- few options for standing CT or high-field MRI
- possible to obtain CBCT data for FEM modeling using conventional digital radiography system?

Imaging during *in vivo* loading

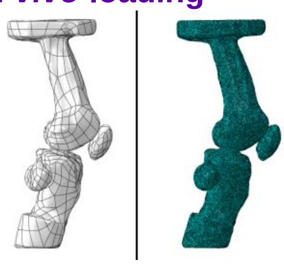
Imaging during *in vivo* loading

- first CBCT images from conventional ceiling-mounted x-ray system
- 270 μm isotropic voxels; 35 cm FOV
- 20 μSv effective dose

Baronette et al., M.Sc. thesis (2018)

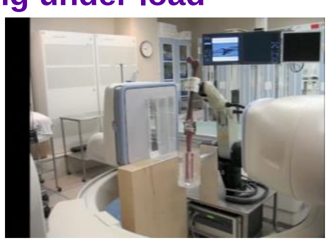
Imaging during *in vivo* loading

- CBCT images from modified ceiling-mounted digital radiography system provide SNR, resolution for FEM models



Dynamic imaging under load

- possible to combine 3D (anatomical) and 2D (dynamic) data
- facilitates 3D models of component wear



Teeter et al., Physiol Med Biol 58:2751 (2013)

Dynamic imaging under load

- integration of dual-belt VR treadmill with ceiling-mounted x-ray
- weight-bearing CT images can be used in combination with real-time fluoroscopy to analyze joint motion; direct comparison with FEM

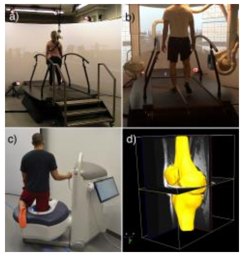
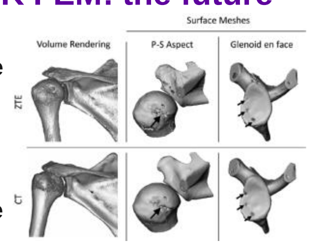


Image-based MSK FEM: the future

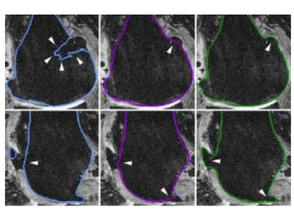
- development of MRI techniques to provide bone and soft-tissue model data from one acquisition
- “zero TE” MRI to provide CT-like image contrast



Breighner *et al.*, Radiology., 286, (2018)

Image-based MSK FEM: the future

- automated segmentation of bone, soft-tissue anatomy from CT and MRI
- application of statistical shape models, convolutional neural networks



Ambellan *et al.*, Med. Image Analysis, 52, (2019)

Image-based MSK FEM: the future

- **MRI-compatible loading systems for functional investigation of the knee**
- **Orthospect Pedal knee (Ergospect) provides axial load (800N), varus-valgus (140 N-m), anterior translation (150 N-m)**

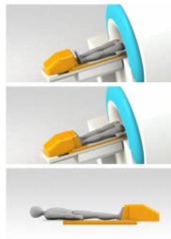


Image-based MSK FEM: the future

- **FEM of complex 3D-printed structures to predict mechanical properties**
- **investigation of porous titanium structures to provide mechanical support of bone**

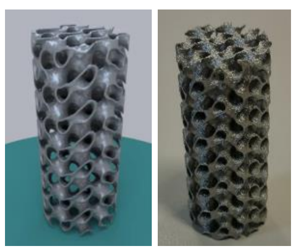
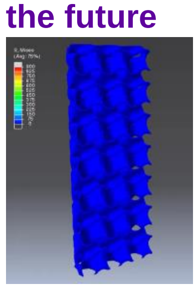


Image-based MSK FEM: the future

- **FEM can predict “effective” modulus of porous structure**
- **finite-element models will identify stress concentrations in advance, allowing design modification**



Summary

- capabilities of FEM have increased dramatically in the past several years
- for orthopaedic applications, advanced imaging provides accurate boundary conditions for FEM
- current applications include investigations of bone stress during healing, soft-tissue reconstruction, dynamic models of joint loading
- future studies will take further advantage of MRI