Probabilistic Simulation of Knee Loading using HTCondor

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Robotic Knee Surgery

Robotic assistance enables precise surgeries

How do you determine the optimal cuts?

https://www.youtube.com/watch?v=QfmLdCHtqWA
Computer Simulation for Surgical Planning

How do surgical factors affect knee function during daily activities?

**Present:** Inform surgical planning

**Future:** Optimize patient-specific treatments
Orthopedic Applications

Total Knee Replacement

Ligament Reconstruction

Pediatric Orthopedics
Uncertainty in Computational Knee Models

Knee Geometries → Cartilage Contact Model → Ligament Model → Musculoskeletal Model

- Cartilage Material Properties?
- Ligament Stiffness?
- Neuromuscular Coordination?

Agenda

Simulation Framework

Validation in Presence of Uncertainty

Surgical Simulation

Future Directions
Knee Model and Movement Simulation Framework
Knee Anatomy and Model

- femur (thigh bone)
- patella (knee cap)
- lateral collateral ligaments
- patellar tendon
- anterior cruciate ligament (ACL)
- fibula
- tibia (shin bone)
Physics-Based Simulation of Movement

Gait Analysis

Musculoskeletal Simulation

Muscle Forces

Knee Movement

Ligament Forces

Cartilage Pressures

Simulation of Knee Mechanics during Movement

Measurements → Musculoskeletal Model → Multi-Body Knee Model → Cartilage Contact Model

gait simulation takes ~0.5 hours

3000 simulations done in series in ~1500 hours
HTC Enables Monte Carlo Analyses

1 simulation in ~0.5 hours

3000 simulations in ~2 hours
Extending Model Validation: Uncertainty and Sensitivity Analysis

Dynamic MRI

Instrumented Knee Replacement
Ligament Parameter Uncertainty

ACL Stiffness

- Stiff
- Nominal
- Compliant

Stiff ACL
Compliant ACL
Dynamic MRI Validation of Simulated Kinematics

Dynamic MRI


Simulation

Lenhart et al, Ann Biomed Eng, 2015
Monte Carlo Simulation

Probabilistic Ligament Stiffness

- LPFL Stiffness
- PT Stiffness
- ACL Stiffness
- LCL Stiffness
Accounting for Ligament Property Uncertainty

Lenhart et al, Ann Biomed Eng, 2015

3000 Simulations
Knee Contact Force Validation

Instrumented Knee Replacement

Subject-Specific Model

Walking Simulation
Ligament Uncertainty Propagation

- ITB Stiffness
- LCL Stiffness
- PFL Stiffness
- MCL Stiffness

Graph showing force vs. gait cycle (%):
- Total
- Medial
- Lateral

Comparison of measured (red) and predicted (blue) forces.

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Ligament Influence on Contact Force

- **dMCL**: Stiffness, Correlation (R) = 0.57
- **LCL**: Stiffness, Correlation (R) = -0.036
- **ITB**: Stiffness, Correlation (R) = -0.30
- **aPCL**: Stiffness, Correlation (R) = 0.28

Medial Force Correlation (R)

- **dMCL**, **sMCL**, **Capsule**, **LCL**, **ITB**, **PFL**, **PCL**

Stiffness
Reference Strain
Surgical Simulation:

Anterior Cruciate Ligament Reconstruction
Clinical Application: ACL Reconstruction

Anterior Cruciate Ligament (ACL)

ACL injury and Osteoarthritis

Monte Carlo Analysis of ACL Femoral Attachment

Tunnel Position
(Attachment Location)

Coronal Angle
60°-90°

Sagittal Angle
40°-70°

2000 Simulations
ACL Forces during Walking

Graft Failure in Intra-Articular Anterior Cruciate Ligament Reconstructions: A Review of the Literature

Anil Vergis, M.B.B.S., M.S., and Jan Gillquist, M.D., Ph.D.

Smith et al, ORS, 2015
Future Direction:

Parametric Knee Model
Stochastic Simulation Framework

Parameterized Inputs
- Anthropometrics
- Constitutive Properties
- Knee Geometry
- Neuromuscular Coordination
- Gait Dynamics

Stochastic Simulation

Probabilistic Cartilage Loading

High Throughput Computing
Subject Specific Modeling

Subject Specific

Population Model

- Anthropometrics
- Constitutive Properties
- Knee Geometry
- Neuromuscular Coordination
- Gait Dynamics

Tibiofemoral Contact Force

2nd Peak
Statistical Shape Modeling

Segmented MRI

20 Healthy Subjects

Statistical Shape Model

Parameterized Geometries
HTC and Stochastic Knee Geometry

How does knee geometry influence cartilage loading?

Sample SSM

Clouthier et al, ORS, 2017
Closing Remarks
Challenges with HTC

- **Programming Difficulties**
  - Linux Compatibility
  - C/C++ Memory Errors

- **Security**
  - Medical Imaging Data
  - HIPAA

- **Big Data Management**
  - 1000 input files = 0.4 GB
  - 1000 results files = 2.6 GB

- **Failed Simulations**
Introducing HTC to the Biomechanics Community

Stochastic Simulation of Knee Mechanics Enabled via Novel Solution Techniques and High Throughput Computing

OpenSim Webinar: http://opensim.stanford.edu/support/event_details.html?id=169
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http://uwnmbl. engr.wisc.edu/