Computational Biomechanics Laboratory

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Simulation-Based Treatment Development for Knee Osteoarthritis

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Introduction

Let's visit the shoe store . . .

Analogy

Student = Patient

Shoe salesman = Orthopedic surgeon

Shoes = High tibial osteotomy surgery

Size 7 to 10 shoes = Rotation 7 to 10 deg

Knee Implant Design Process

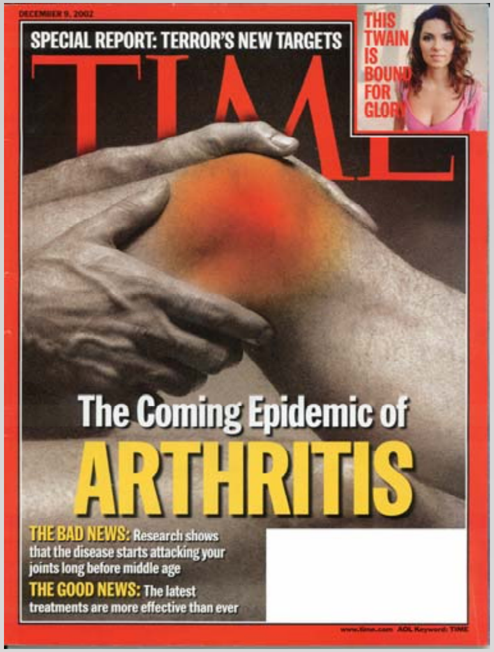
1. Focus group of surgeons
2. Geometric design development
3. Static computational testing
4. Dynamic physical testing
5. Clinical trials

But no functional simulation!!!

Why Should We Care?

According to statistics from the Arthritis Foundation:

- Roughly 1 in 6 Americans currently suffer from arthritis.
- Arthritis costs the U.S. economy close to $65 billion annually.
- Arthritis is the second leading cause of work disability in the U.S.
- The majority of arthritis suffers have osteoarthritis (OA).
- The knee is the joint most commonly affected by OA.



Standard Treatment Planning

1. Observe what has worked well for previous patients.
2. Create implicit, mental model of patient.
3. Guess best treatment parameters for current patient.
4. Apply treatment and iterate if possible/necessary.

Subjective treatment planning
based on a trial-and-error foundation,
so outcome can be variable for different patients.

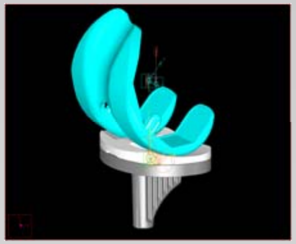
Customized Treatment Planning

1. Observe what has worked well for previous patients.
2. Create explicit, computational model of patient.
3. Perform virtual treatments on patient-specific model.
4. Apply optimized treatment to patient.

Objective treatment planning
based on a theoretical foundation,
so outcome can be optimized for different patients.

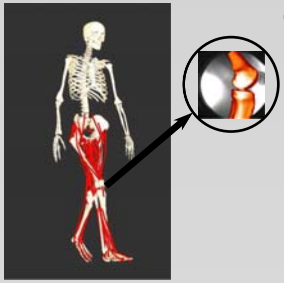
Vision

To design patient-specific clinical interventions for knee osteoarthritis using computer simulation of:



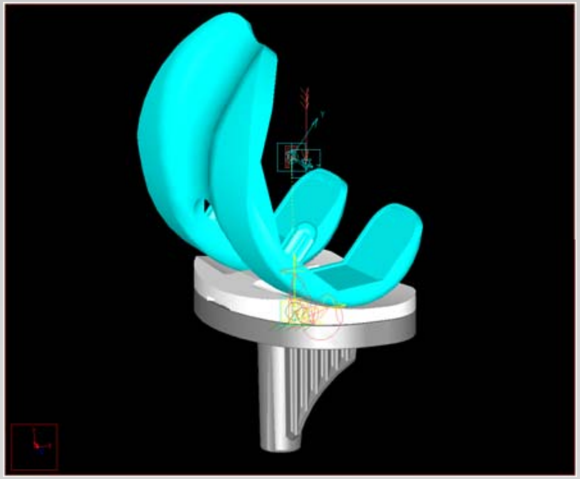
1. Joint mechanics

2. Human movement



3. Joint mechanics during movement

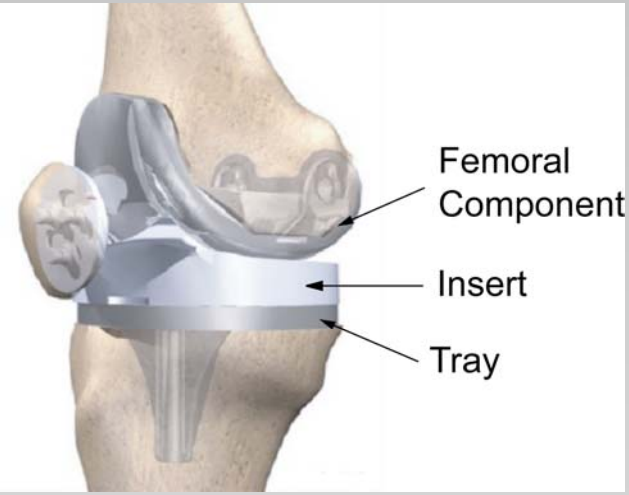
Joint Mechanics



How can we design better joint replacements for patients with knee osteoarthritis?

Collaborators: Scott Banks, Ph.D., Greg Sawyer, Ph.D., Darryl D’Lima, M.D., and Cliff Colwell, Ph.D.

Background



- Wear remains a major concern for total knee replacement (TKR) longevity.
- Younger patients are getting TKRs and demanding more functionality.

Background

Knee simulator machines are:

- Useful for screening new designs
- Useful for comparing different designs

but they are also . . .

- Expensive (~$10s of thousands)
- Time intensive (~months)
- Sometimes inconsistent

Objective

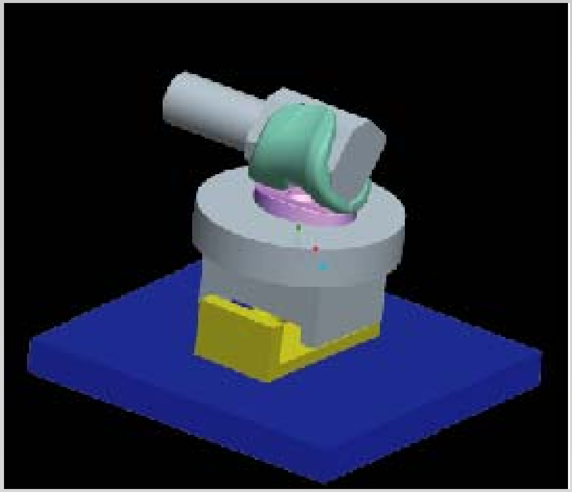
To predict accurately knee replacement wear generated by testing on a simulator machine.

Follow on to encouraging results for an *in vivo* wear prediction generated using fluoroscopically measured kinematics (Fregly *et al*., *Journal of Biomechanics*, 2005).

Approach

1. Measure the wear of the implant material pair using a pin-on-plate tribometer

Approach



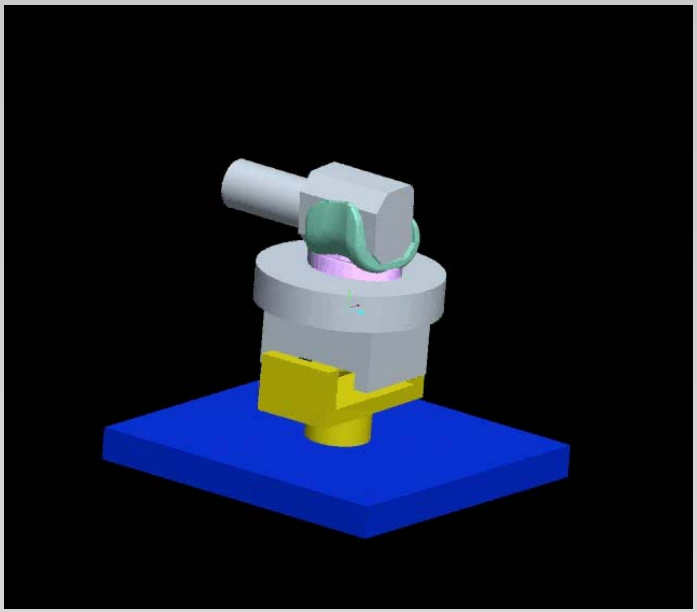
1. Measure the wear of the implant material pair using a pin-on-plate tribometer
2. Predict insert surface wear with a computational model that uses the material pair wear properties

Approach

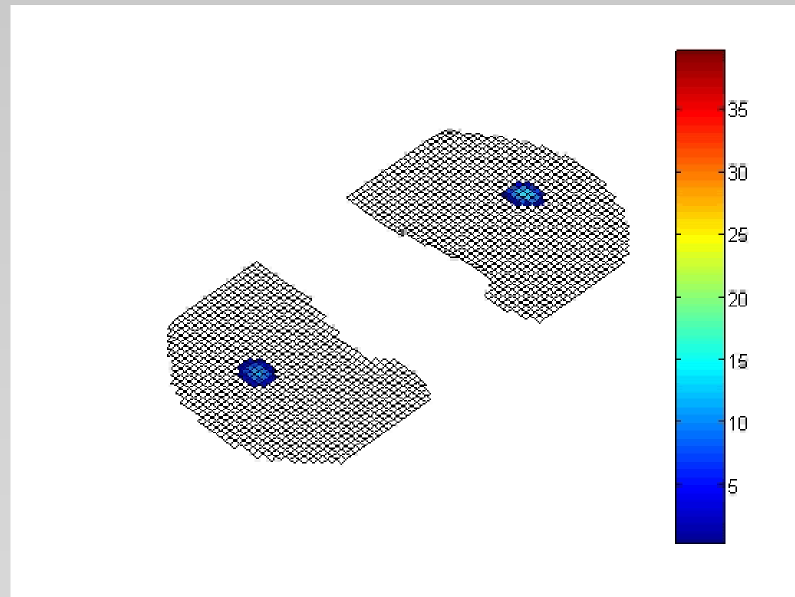
1. Measure the wear of the implant material pair using a pin-on-plate tribometer
2. Predict insert surface wear with a computational model that uses the material pair wear properties
3. Compare predictions with wear measured on same implant during testing on a simulator machine

Machine Simulations

Predicted Motion

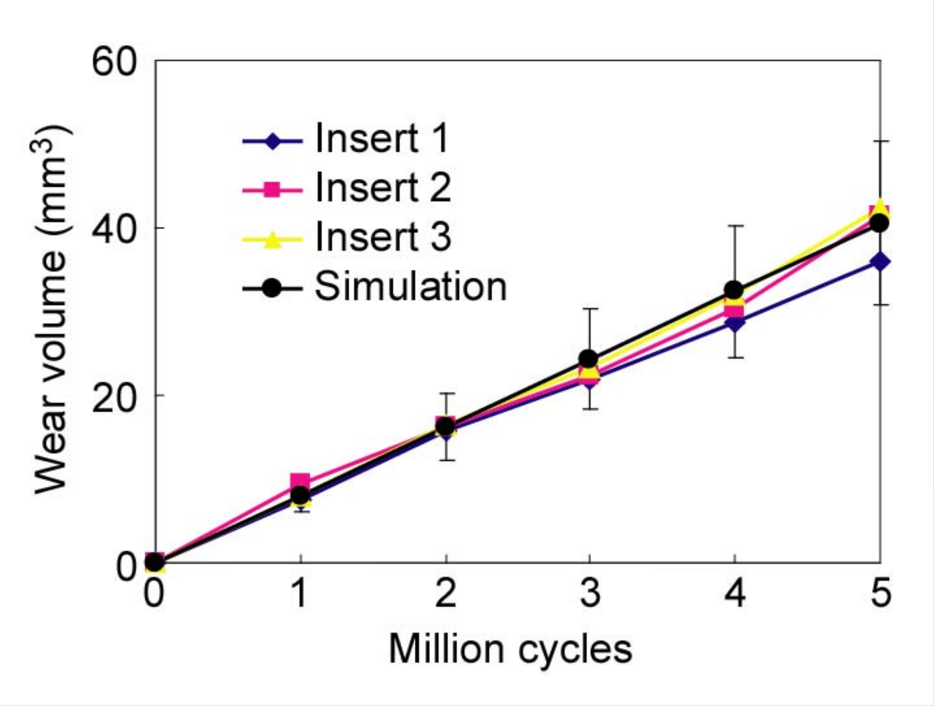


Predicted Pressures

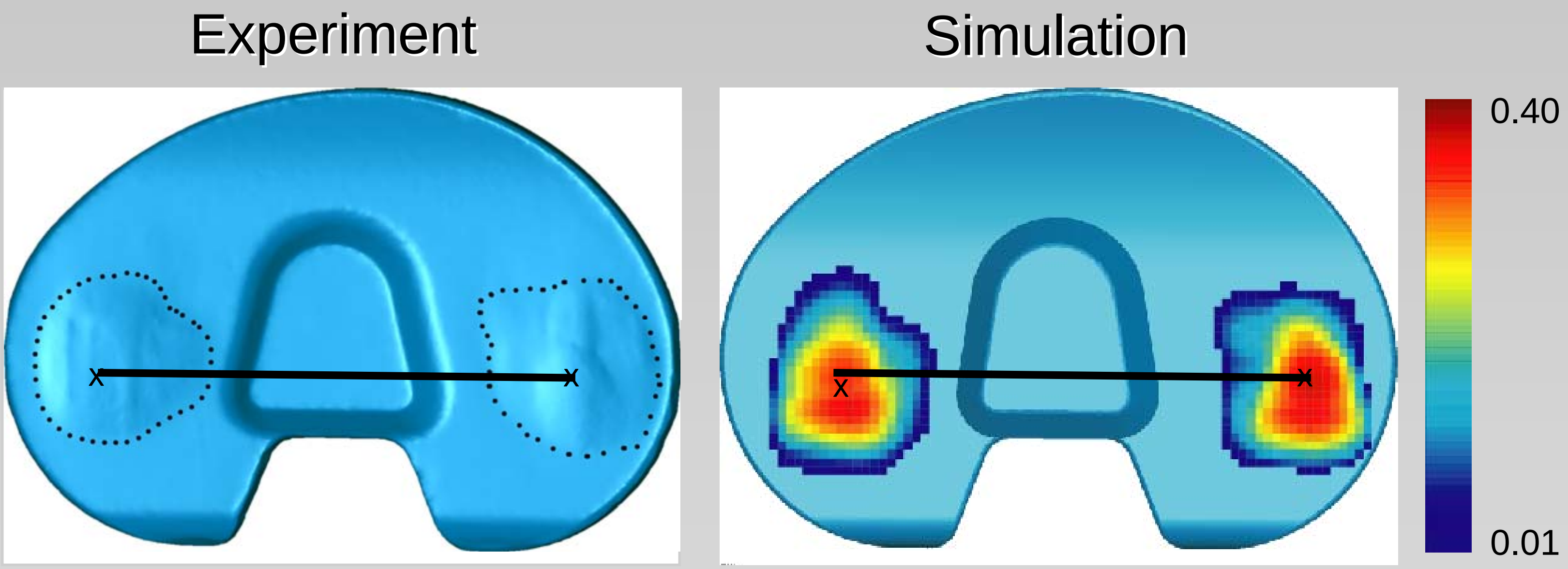


Update Geometry

Predicted Wear Volume



Predicted Wear Scars

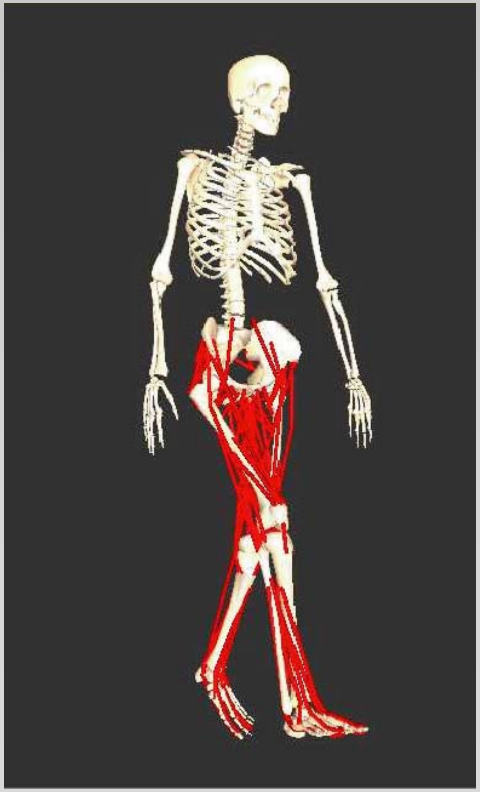


Zhao *et al.*, *Journal of Biomechanical Engineering*, in press

Next Steps

- Design a “clean sheet” next generation knee replacement for a start-up company in Florida.
- Refine a novel surrogate modeling approach for creating “lightning fast” contact models.
- Develop a cartilage adaptation model to predict changes in cartilage thickness over time (osteoarthritis development and progression).

Human Movement



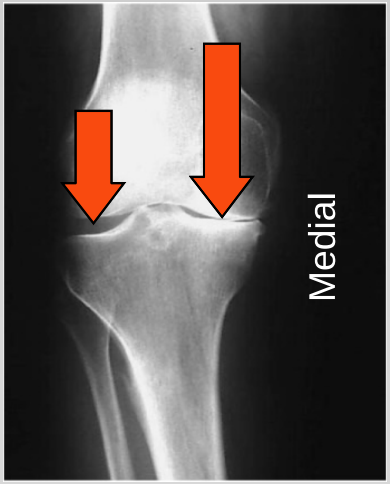
How can we design better rehabilitation treatments for patients with knee osteoarthritis?

Collaborators: Raphael Haftka, Ph.D., Terri Chmielewski, Ph.D., Kay Crossley, Ph.D., Rana Hinman, Ph.D., Anthony Schache, Ph.D., and Marcus Pandy, Ph.D.

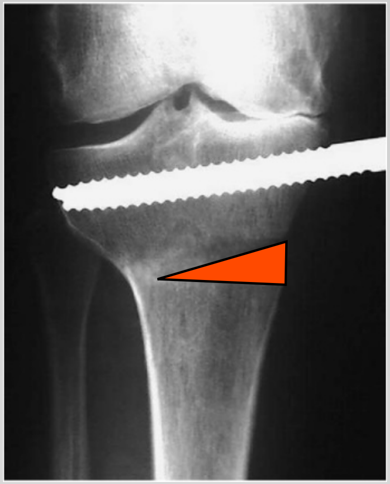
Background

High Tibial Osteotomy Surgery

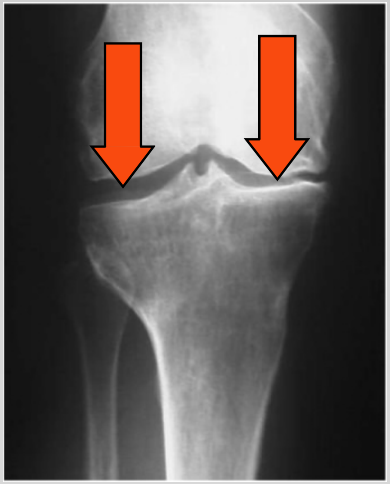
Pre-operative



Three weeks post-operative

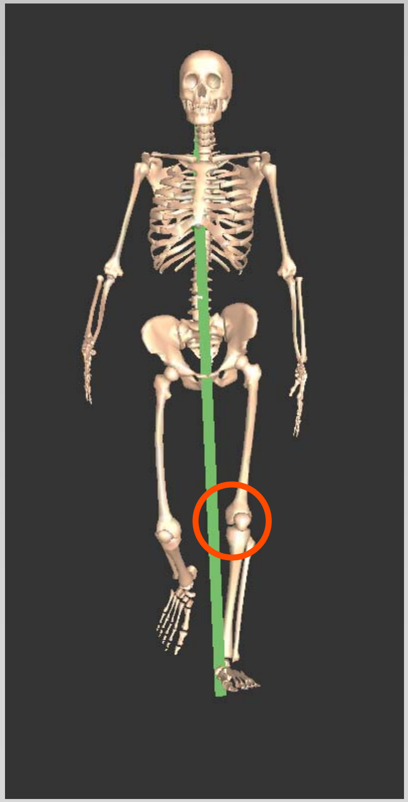


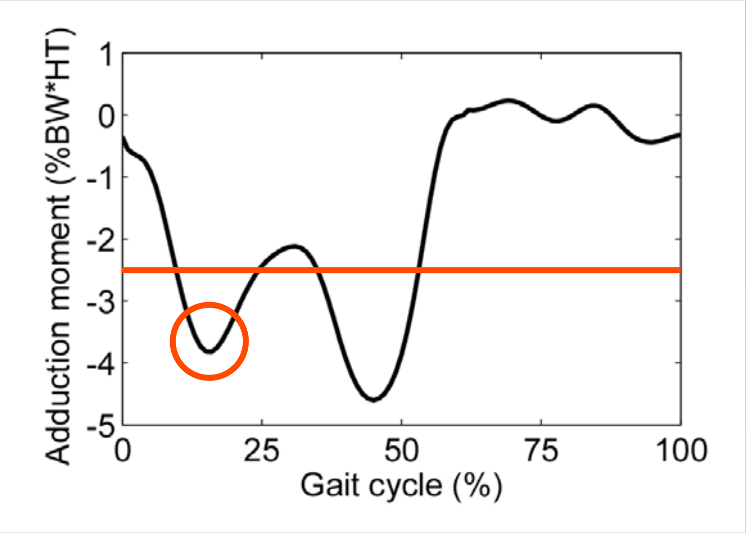
Two years post-operative



Miller and Sterett, *Techniques in Knee Surgery*, 2003

Background





Andriacchi, *Ortho Clin North Am*, 1994.

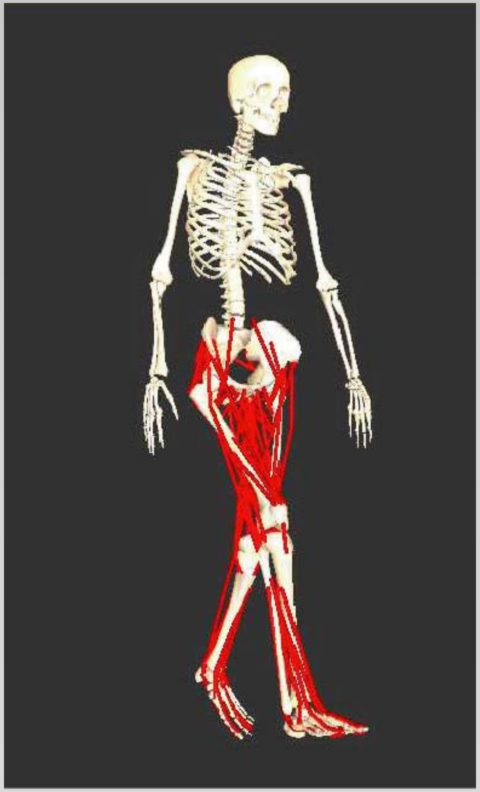
Low knee adduction moment = best clinical outcome

Prodromos *et al*., *Journal of Bone & Joint Surgery*, 1985.

Objective

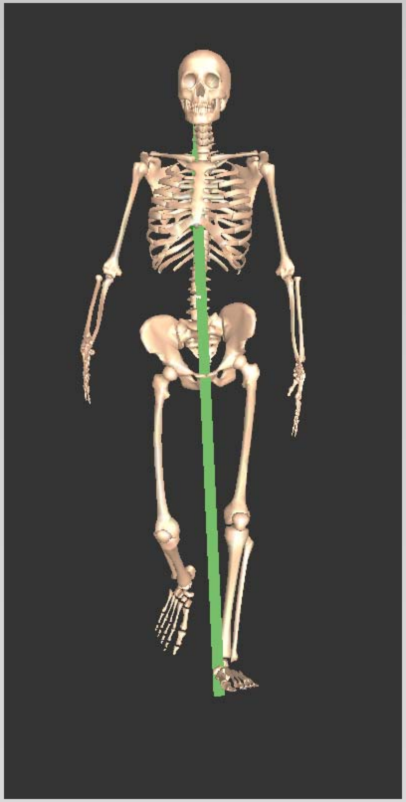
To design a customized walking motion that achieves the same knee load changes as HTO surgery.

Approach



- Create a dynamic model of the patient's normal walking motion

Approach



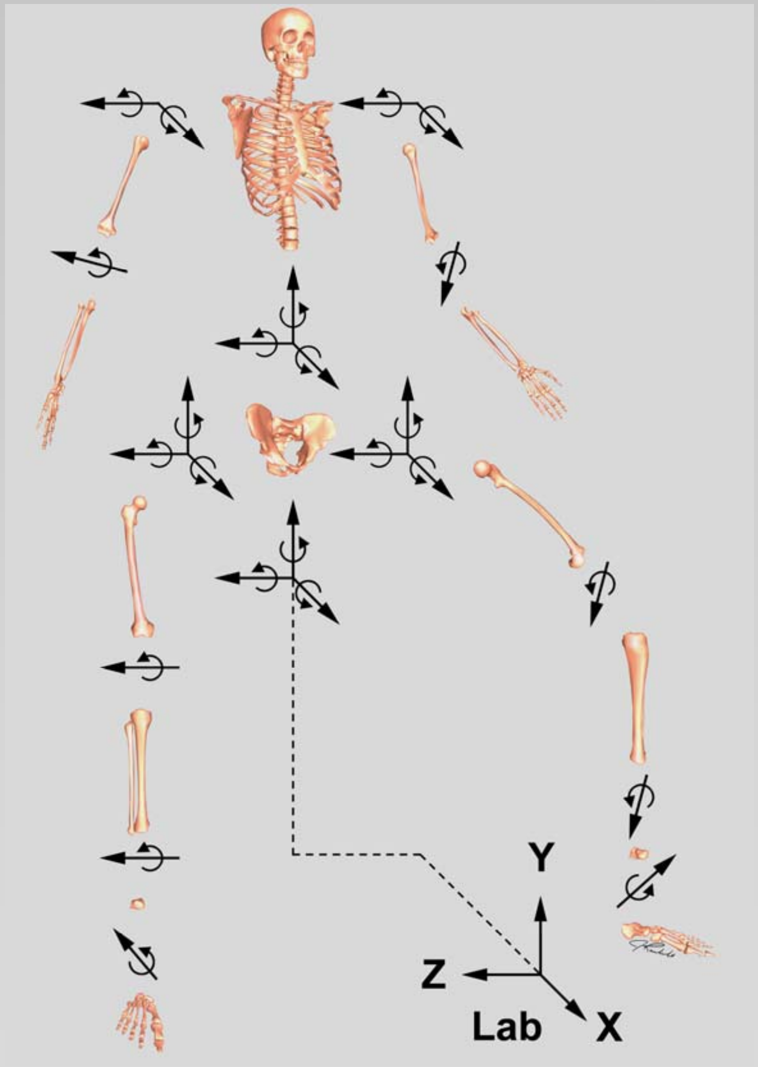
- Create a dynamic model of the patient's normal walking motion
- Predict walking changes that reduce both knee adduction moment peaks

Approach

- Create a dynamic model of the patient’s normal walking motion
- Predict walking changes that reduce both knee adduction moment peaks
- Test predictions in the gait lab after training the patient to walk differently

Patient-Specific Model

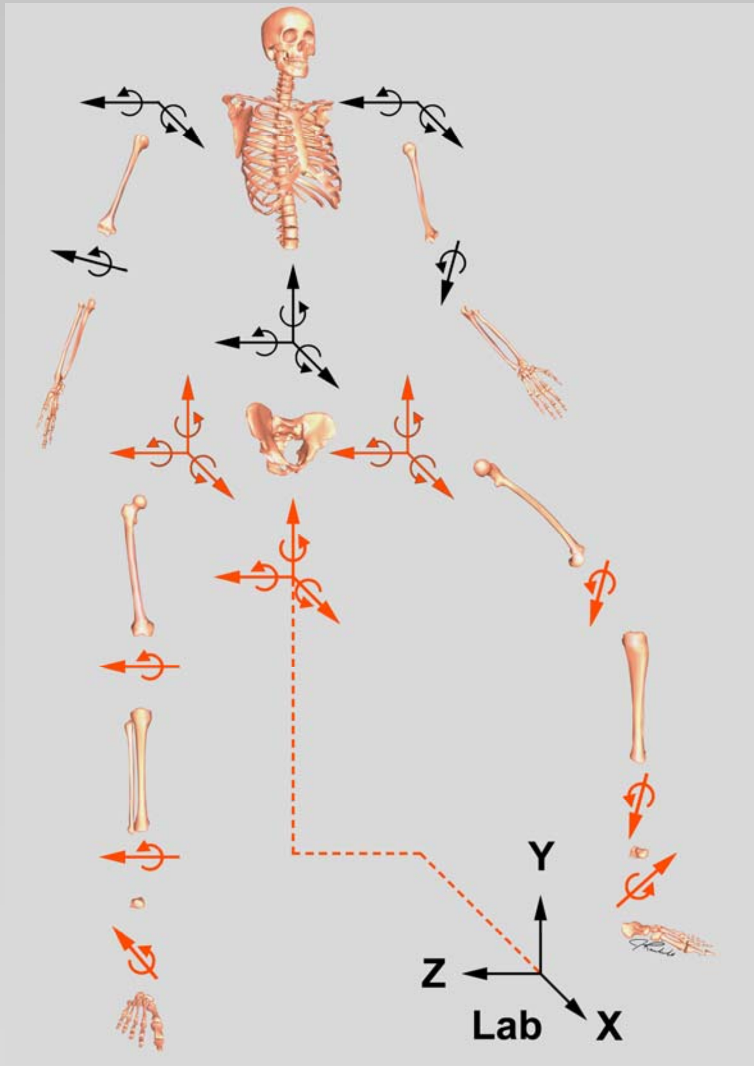
- Full-body walking model
- Three-dimensional
- Engineering joints



Human Movement

Patient-Specific Model

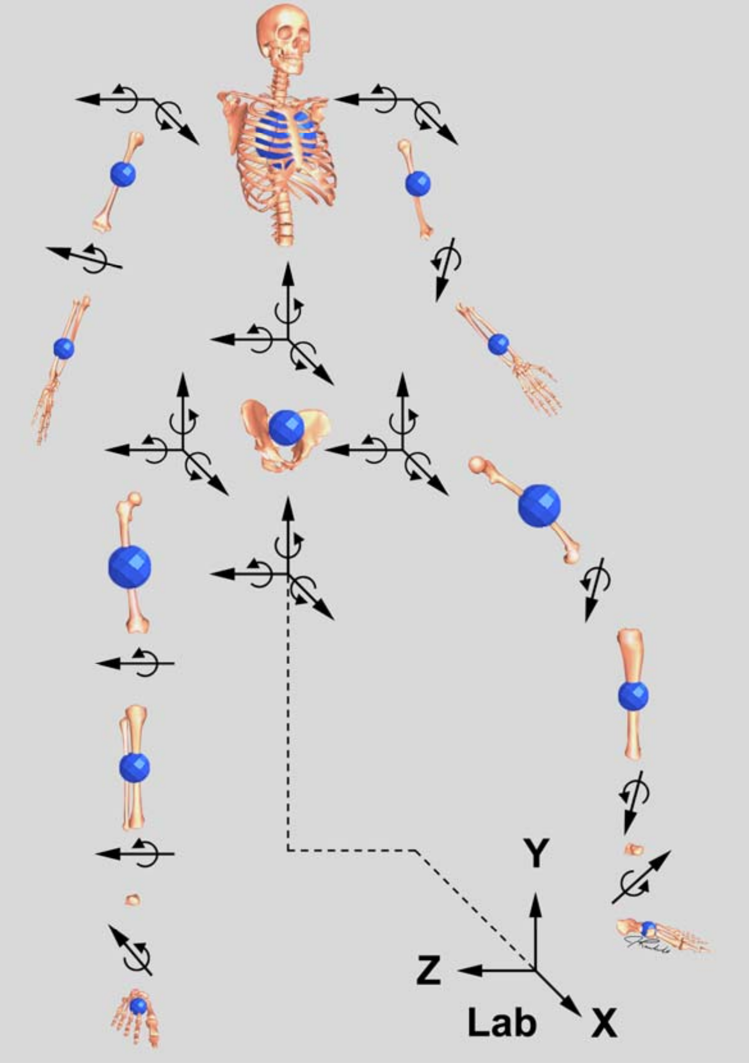
- Full-body walking model
- Three-dimensional
- Engineering joints
- Calibrated lower body joints



Human Movement

Patient-Specific Model

- Full-body walking model
- Three-dimensional
- Engineering joints
- Calibrated lower body joints
- Calibrated full body masses



Human Movement

Data Collection

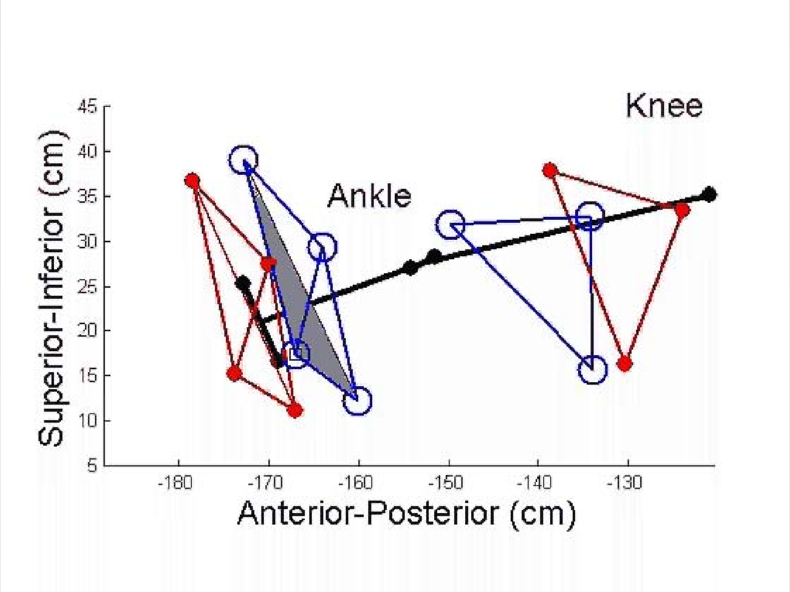
- Motion of links measured using reflective markers placed on the skin
- Forces between feet and ground measured using special plates in floor

Model Calibration

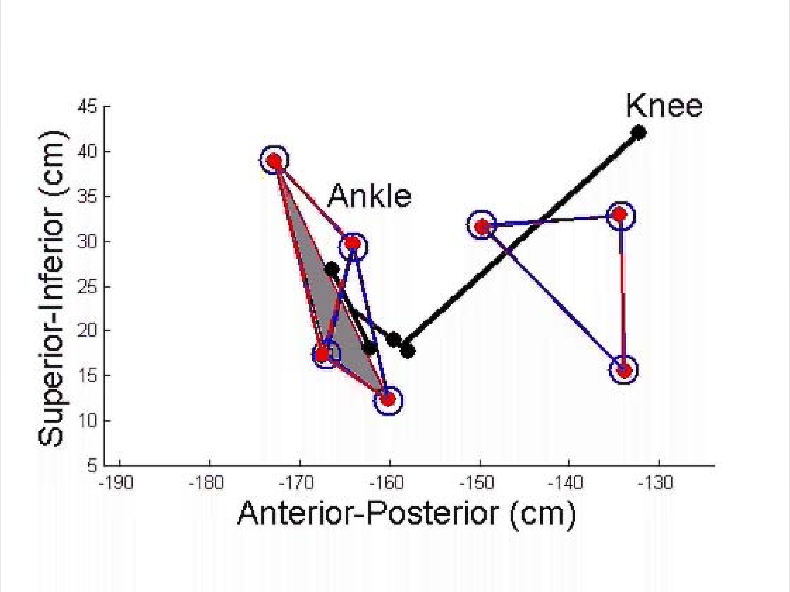
Ankle Joint Trials

Model Calibration

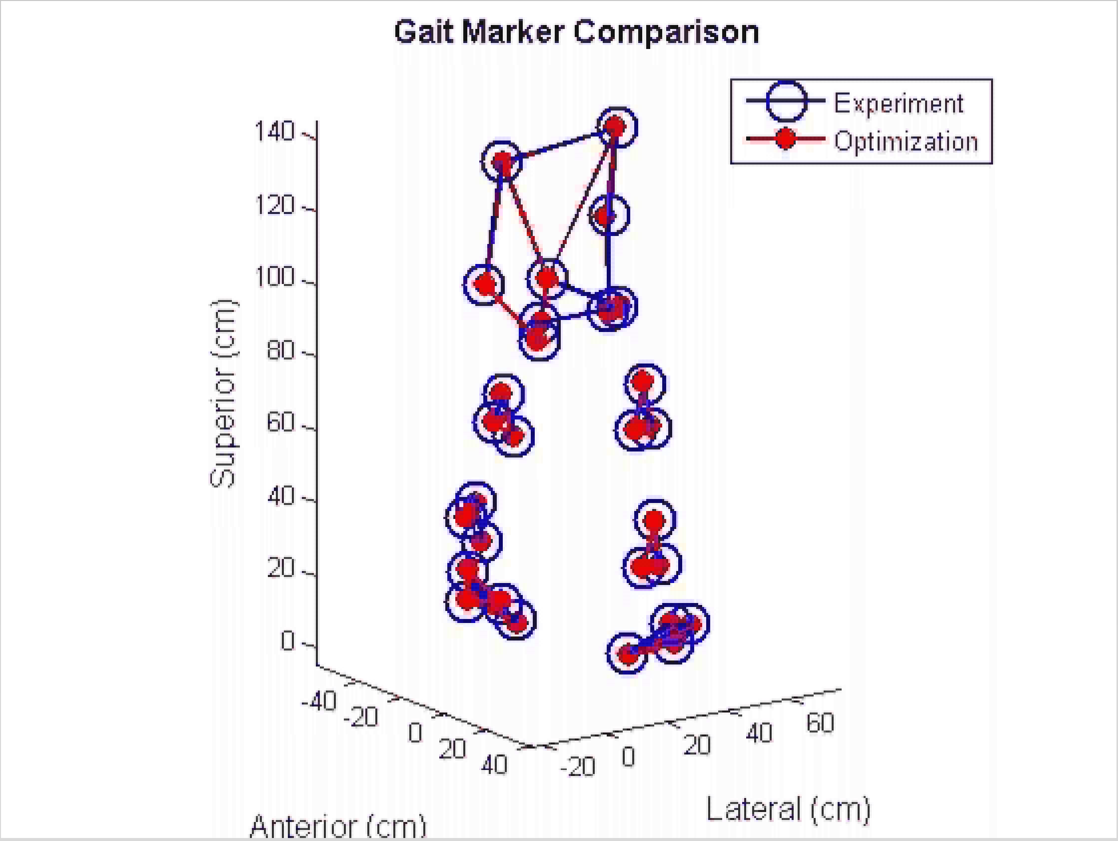
Unoptimized



Optimized



Model Calibration



Optimization Development

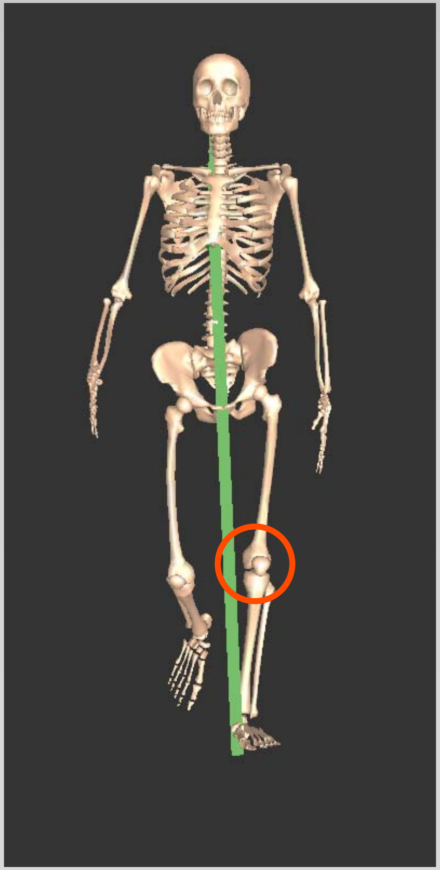
Goal: Predict a new walking motion that is close the patient’s normal walking motion but reduces the knee adduction moment.

Approach: Guess a new motion, calculate the resulting knee loads, and iterate until the knee adduction moment is minimized.

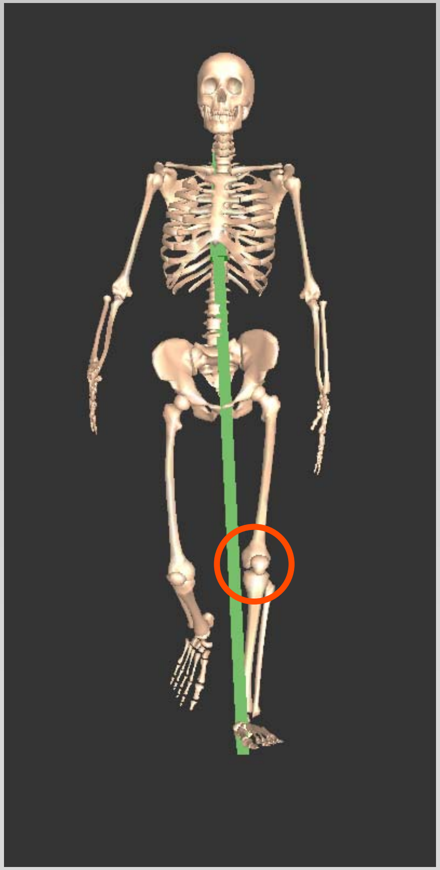
Constraints: No change in arm swing, trunk rotation, pelvis translation, or foot motion.

Predicted Gait Motions

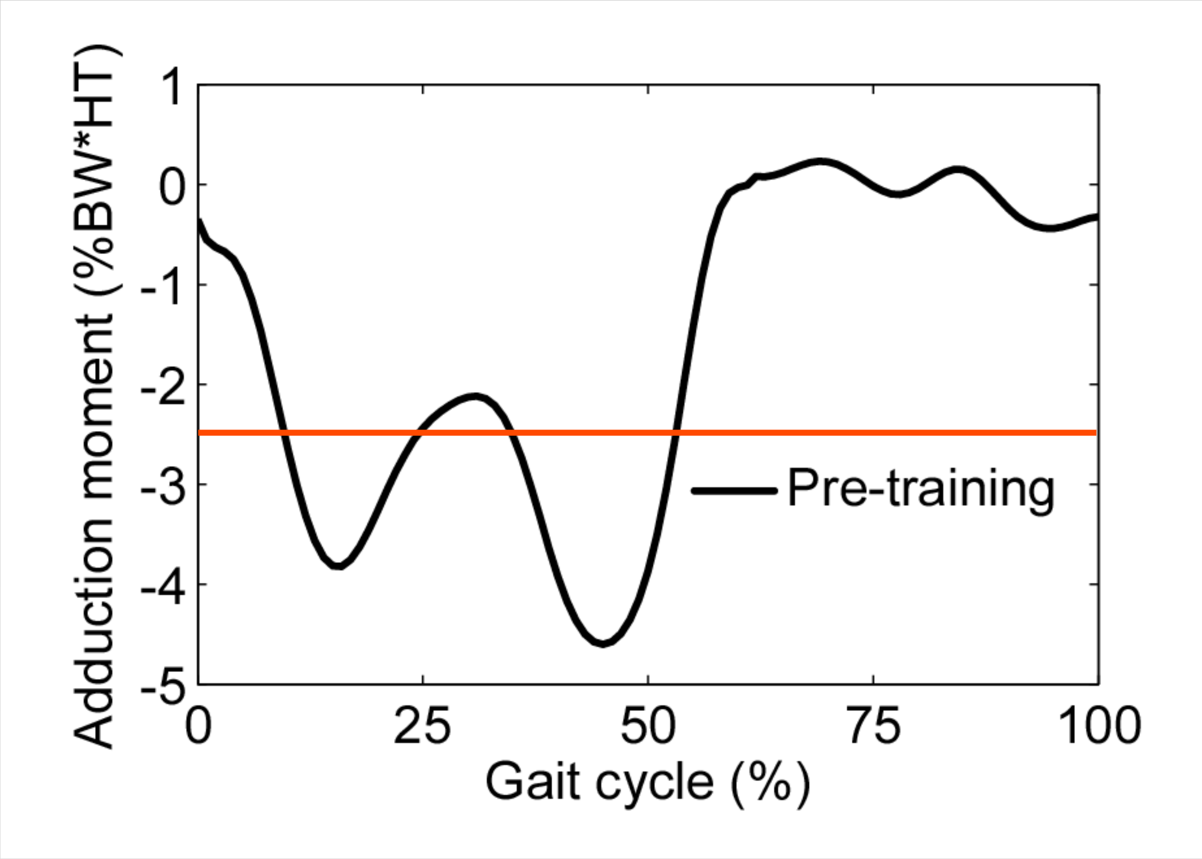
Experiment



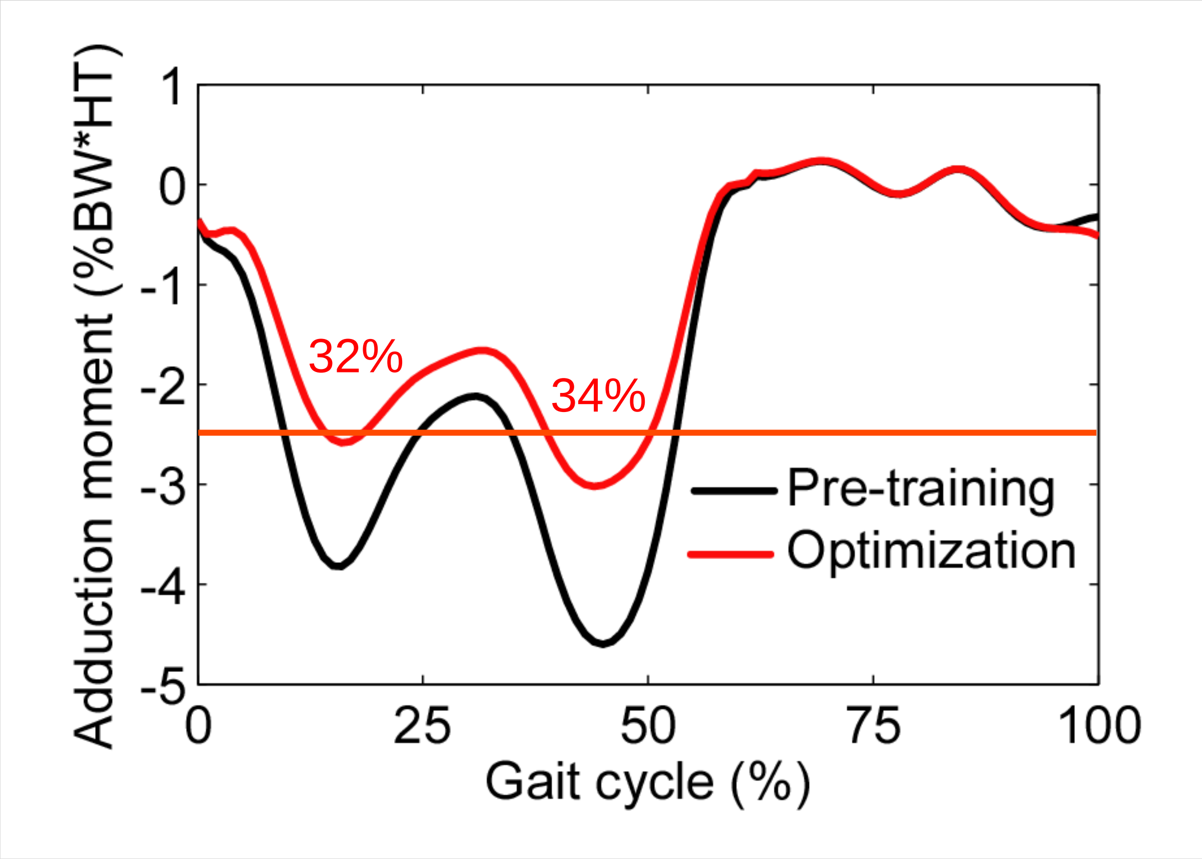
Optimization



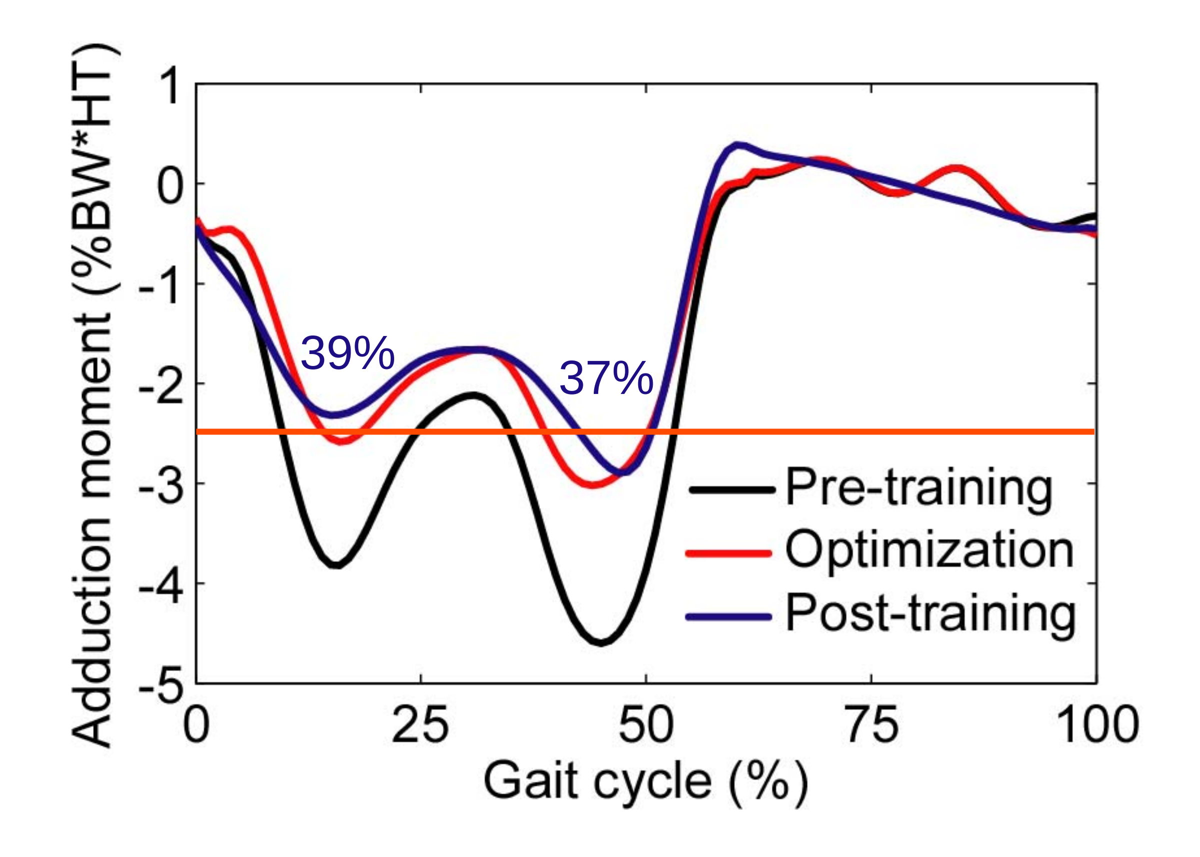
Adduction Moment Changes



Adduction Moment Changes



Adduction Moment Changes



Fregly *et al.*, *IEEE Transactions on Biomedical Engineering*, 2007

Observations

The risk of osteoarthritis progression increases by a factor of 6.5 for each 1% BW*HT increase in peak knee adduction moment (Miyazaki *et al*., *Ann Rheum Dis*, 2002).

Our patient reduced both knee adduction moment peaks by between 1.5 and 2.7% BW*HT.

Observations

Percent Decrease in Peak Knee Adduction Moment

HTO (highest peak)[1]	< 50%

[1]Wada *et al*., *Clinical Orthopaedics*, 1998

Observations

Percent Decrease in Peak Knee Adduction Moment	
HTO (highest peak)[1]	< 50%
Toe out gait (second peak only)[2]	< 40%

[1]Wada *et al*., *Clinical Orthopaedics*, 1998
[2]Guo *et al*., *Gait and Posture,* 2007

Observations

Percent Decrease in Peak Knee Adduction Moment

HTO (highest peak)[1]	< 50%
Toe out gait (second peak only)[2]	< 40%
Medial thrust gait (both peaks)[3]	< 50%

[1]Wada *et al*., *Clinical Orthopaedics*, 1998
[2]Guo *et al*., *Gait and Posture,* 2007
[3]Fregly *et al*., *IEEE Trans Biomed Eng*, 2007

Recent Developments

- The effectiveness of “medial thrust gait” has since been verified in three other labs (University of Melbourne, University of Delaware, and Stanford University).
- Two studies have recently been initiated to investigate “medial thrust gait” further (University of Melbourne and University of Florida).
- A third study is currently being planned for the Durham VA/Duke.
- Changes in foot path do not appear to have a significant synergistic or detrimental effect on “medial thrust gait.”

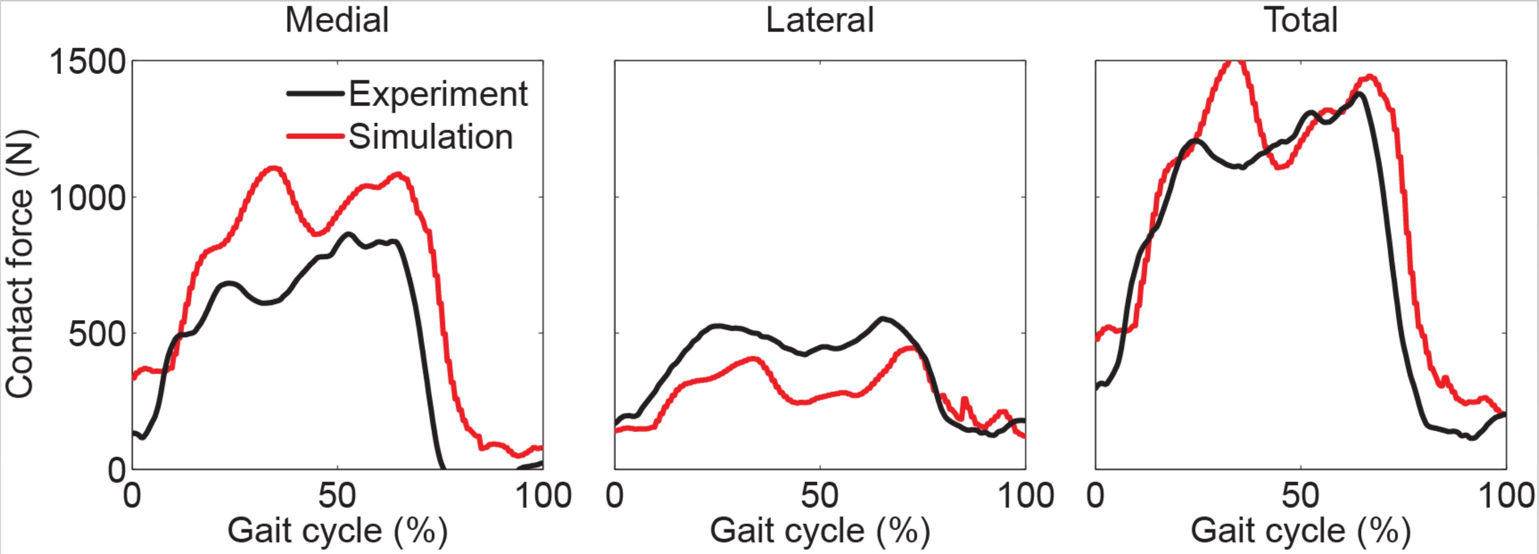
More Recent Developments

- We have recently shown that the knee adduction moment is highly correlated with *in vivo* medial contact force ($R^2 = 0.77$, Zhao *et al*., *Journal of Orthopedic Research*, 2007).
- We evaluated medial thrust gait with an instrumented knee replacement last month and found it reduced medial contact force by 18%.
- We are working to evaluate *in vivo* muscle force predictions using the instrumented knee replacement data.

Collaboration with Darryl D'Lima, Cliff Colwell, Scott Banks, and Marcus Pandy

Human Movement

"Hot off the Press" Results



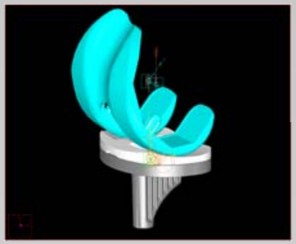
Next Steps

- Extend model-based surgical and rehabilitation planning to other clinical problems:

  Surgical: high tibial osteotomy, cerebral palsy

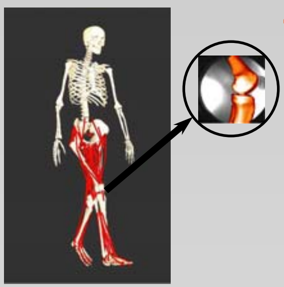
  Rehabilitation: patellofemoral pain, bone loss in space
- Combine full-body walking model with detailed joint models to evaluate in vivo muscle force predictions using instrumented implant data.

Conclusion



1. Joint mechanics

2. Human movement



3. Joint mechanics during movement

This is an exciting time to be combining engineering mechanics and computer simulation to address clinical problems in orthopedics and rehabilitation.

Acknowledgments

Computational Biomechanics Laboratory

The Whitaker Foundation

United States
National Library of Medicine
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WHERE DISCOVERIES BEGIN

National Institutes of Health
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