Biomechanics of Osteoarthritis: Analyzing knee forces and functions

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Anatomy of a Breakdown

Doctors used to think that failing cartilage caused osteoarthritis. Now they know it is a complex process involving muscles, tendons, bones - even genes. *Roll over numbers to see more information.*
Arthritis and Americans

46 million persons
2006

67 million persons
2030
Osteoarthritis (OA)

- Degenerative joint disease involving cartilage deterioration
- Thin cartilage with grooves and fragments
- Debris expedites deterioration
Knee osteoarthritis

- OA severity depends on cartilage thickness, presence of osteophytes
- Scored on Kellgren-Lawrence (KL) scale from x-ray

KL=0  KL=1  KL=2  KL=3
Implications of OA

- Leading cause of disability
- Limits activities of daily living
- >50% of adults with OA are <65 yrs
- No known cause or cure
- Options include total joint replacement (~ 450,000 / year)
Risk factors

- Modifiable
  - Excess body mass
  - Joint injury (sports, work, trauma)
  - Occupation (due to excessive mechanical stress: hard labor, heavy lifting, knee bending, repetitive motion)
  - Structural malalignment, muscle weakness

- Non-modifiable
  - Gender (women higher risk)
  - Age (increases with age and levels around age 75)
  - Race (some Asian populations have lower risk)
  - Genetic predisposition

- Other possible risk factors
  - Estrogen deficiency (ERT may reduce risk of knee/hip OA)
  - Osteoporosis (inversely related to OA)
  - Vitamins C, E and D – equivocal reports
Pathomechanics

In Vivo Function

Variations in Adaptations to Cartilage Degradation
Equilibrium Degradation / Synthesis (Biomarkers)

Cartilage Mechanobiology
Variations in
- Cell metabolism
- Response to mechanical stimuli

Joint Mechanics
Variations in
- Contact Mechanics
- Joint Laxity

Load/Motion at Articular Surface (Gait Analysis)
Cartilage Tissue Level Strains and Morphology (Quantitative MRI)

Andriacchi et al., 2004
Pathomechanics

In Vivo Function

Variations in Functional Mechanics
*Level of Function

Load/Motion at Articular Surface
*Gait Analysis

Joint Mechanics

Variations in
*Contact Mechanics
*Joint Laxity

Cartilage Mechanobiology

Variations in
*Cell metabolism
*Response to mechanical stimuli

Equilibrium
Degradation / Synthesis
*Biomarkers

Cartilage Tissue
Level Strains and Morphology
*Quantitative MRI

Andriacchi et al., 2004
Motivation

- Muscles contribute significantly to joint loads and activity can be modified with non-surgical intervention.
- Response to challenge may identify limiting factors (i.e. what compensatory strategies are used?)
- Loading patterns should be related to cartilage deterioration.
Outline

- Gait analysis
  - Effect of OA severity on hip, knee and ankle contributions
  - Response to challenge
- Modeling and simulation
  - Joint contact forces depend on muscle activity
- Imaging
  - Cartilage geometry vs OA progression
Experimental design

Gait analysis → Musculoskeletal Simulation → Imaging → Cartilage Mapping

JOINT CONTACT FORCES ↔ CARTILAGE GEOMETRY
Subject recruitment

- Goal: 60 OA, 20 healthy subjects
  - Age 30-85
  - Tracked for 2 years
  - No major orthopedic, neuromuscular or cardiovascular conditions
- Bilateral x-ray (KL grade)
- Activity survey
- Strength testing
Gait analysis
Gait analysis

- Instrumented treadmill
- Four walking conditions (30 sec)
  - Self-selected walking speed
  - Control speed (0.8 m/s)
  - Fastest possible walking speed
  - 15% load carriage at SS speed
- Safety harness
- GRFs, Θs, EMG
Quadriceps avoidance?

**Flexion Moment Peaks at 0.80 m/s**

- Minimal
- Moderate
- Severe

[Knee Flexion Moment (Nm/BW)]

OA Severity
**Quadriceps avoidance!**

\[
\text{Quadriceps Effort (QE)} = \frac{\text{Peak Knee Flexion Moment (Nm/BW)}}{\text{Max Quadriceps Volitional Torque (Nm/BW)}} \times 100
\]
Total support moment

Total Support Moment at 0.80 m/s
\( M_s = M_k - M_a - M_h \)

- Minimal
- Moderate
- Severe

Percentage of Gait Cycle

Nm/kg BW
Total support moment

Normalized Total Support Moment at Time of Peak Support
(19% Gait Cycle, Control Walking Speed)

Joint Contributions to Support Moment (% of Total Nm/kg BW)

- Hip
- Knee
- Ankle

OA Severity

- Minimal
- Moderate
- Severe
Response to challenge

Average Difference in External Joint Moments From Self-Selected to Fast Walking Speeds

Change in Moment (Nm/Kg BW)

-0.03
0.00
0.03
0.06
0.09
0.12

Peak Add MOM
Peak Flex MOM

Min
Mod
Severe
Response to challenge

Percent Change of Joint Reaction Force Calculated From Inverse Dynamics

- Min
- Mod
- Severe
From gait analysis...

- Individuals with severe OA exhibit
  - Quadriceps avoidance
  - Reduced contribution of knee extensors to COM support (supplemented by hip)
  - Reduced knee loads (forces and moments) when challenged to walk quickly

What is the role of muscles in compensatory strategies?
Experimental design

- Gait analysis
- Musculoskeletal Simulation
- Imaging
- Cartilage Mapping

Joint Contact Forces

Cartilage Geometry
Musculoskeletal Simulation

- With **inverse dynamics**, we measure position, velocity and acceleration and solve for reaction forces and moments.

- With **forward dynamics**, we estimate and apply internal (muscle) forces to solve for resultant movement patterns.
Generation of movement

- CNS
- e(t)
- activation dynamics
- a(t)
- muscle tendon dynamics
- F(t)
- musculo-skeletal system
- τ(t)

External forces

\[ \dot{\theta}, \dot{\theta}, \theta \]

Movement
Forward dynamics simulation

CNS

activation dynamics

muscle tendon dynamics

musculo-skeletal model

\[ \ddot{\Theta} = M^{-1} [\Theta] \tau \]

equations of motion

\[ \ddot{\theta}, \dot{\theta}, \theta \]
Simulation of OA gait

- Muscle-actuated forward dynamic simulation
- Estimate of muscle forces responsible for observed movement
- Enables study of muscle coordination patterns
- Asymmetry in observed movement and underlying muscle control

www.simtk.org
Simulation results

Predicted reduction in quadriceps excitation and force on more involved side.
Joint contact force

Inverse dynamics
\( (F \approx 100\% \text{ BW}) \)

Forward dynamics
\( (F \approx 200\% \text{ BW}) \)
From simulations...

- Estimates of muscle forces and joint contact force
- Predict muscle coordination patterns
- Highlight muscle compensatory strategies
Experimental design

- Gait analysis
- Musculoskeletal Simulation
- Imaging
- Cartilage Mapping

Joint contact forces

Cartilage geometry
Static weight-bearing MRI

Fonar upright open-MRI

Upright

Tilt 45° Knee 0°

Tilt 45° Knee 15°

Tilt 45° Knee 30°

Image segmentation, cartilage mapping tibio-femoral kinematics
Results – Healthy knees

Cartilage centroid location moves distally with knee flexion
Results – OA knees

Cartilage contact area and centroid location depends on OA severity
From imaging studies...

- Novel weight-bearing MRI
- Cartilage mapping illustrates loss of cartilage area and abnormal contact patterns
- Increased tibio-femoral translations
Experimental design

Gait analysis → Musculoskeletal Simulation → Imaging → Cartilage Mapping

JOINT CONTACT FORCES ↔ CARTILAGE GEOMETRY
Summary

- Abnormal loading patterns for OA knees
- Abnormal cartilage geometry
- Knee forces and functions
  - Depend on muscle coordination
  - Implications for other joints too!
- Muscle coordination patterns can be modified
Research questions

- Do abnormal forces lead to abnormal cartilage geometry?
- Are compensatory strategies beneficial or detrimental to OA progression?
- Do OA copers and non-copers exist?
- Can non-surgical interventions help?

Longitudinal study of OA progression
Multi-disciplinary study funded by NIH to address the mechanisms of OA prevention, progression and treatment

Investigators from mechanical engineering, physical therapy, biology, health and exercise science

Unique focus on mentoring women in science and engineering
OA research at UD

Perlecan and Heparanase in Cartilage Growth and Healing
(PI: Cindy Farach-Carson)

Solute Transport in the Subchondral Bone Plate of Osteoarthritic Joints (PI: Liyun Wang)

Risk Factors for Progression of Knee OA
(PI: Jill Higginson)

Joint Loading and the Progression of Osteoarthritis following Total Knee Arthroplasty (PI: Lynn Snyder-Mackler)

Knee Stiffness, Proprioception and Instability affect Knee Control in OA (PI: Katy Rudolph)
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