The Biomechanics of Knee Osteoarthritis

The Predisposition of Varus Knee Alignment

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Osteoarthritis (OA)

Mechanical & biological events $\rightarrow$ imbalance between cartilage synthesis & degradation \cite{Mollenhauer2002}

The most common type of arthritis

Diagnosed US cases \cite{CDC2009}
- Now: 46 million
- 2030: 67 million

Economic impact
- $60 \text{ billion/year} \; \text{(Buckwalter et al., 2004)}
Knee OA

Lifetime risk of symptomatic knee OA (Murphy et al., 2008)
1/2 people at risk
2/3 obese people at risk

Prevalence of symptomatic knee OA
16% of adults aged 45+ years (CDC, 2009)

Within the knee joint
TF > PF (Davies et al., 2002)
Medial > Lateral (Dearborn et al., 1996)

In comparison
3x hip
8x ankle
Knee OA - risk factors

Risk → Interaction between systemic & local factors

**Local (mechanical) factors**
- Static alignment *(Brouwer et al., 2007)*
- Knee adduction moment *(Miyazaki et al., 2002)*
- Ligamentous laxity *(Schmitt et al., 2007)*
- Joint injury *(Gelber et al., 2000)*
- Muscle weakness *(Slemenda et al., 1998)*

Abnormal alignment and high knee adduction moments = *‘malalignment effect’* *(Cerejo et al., 2002)*

Can we influence the *‘malalignment effect’* to deter disease?
Overview

Project 1 – Compare gait mechanics between 2 groups
  Healthy, varus-aligned vs healthy normally-aligned

Project 2 – Predictors of knee adduction moment
  LE frontal plane joint kinematics (dynamic)
  LE clinical findings (static)

Conclusions/Future directions/Significance
Project 1

Gait mechanics of individuals with healthy varus-aligned knees
Varus knee alignment

Individuals with medial knee OA
4x risk – radiographic disease progression in 18 months (Sharma et al., 2001)
4:1 ratio – MRI medial:lateral tibiofemoral cartilage loss over 26 months (Eckstein et al., 2008)

Healthy individuals
2x risk – radiographic disease development in 6-7 years (Brouwer et al., 2007)
Knee adduction moment (KEAM) in OA

↑ KEAM in medial knee OA cohorts?

↑ in medial knee OA (0.45 Nm/kg*ht) vs controls (0.33 Nm/kg*ht) (Gok et al., 1993)

↑ in medial knee OA vs controls (Baliunas et al., 2002)

↑ KEAM & disease state?

6.5x ↑likelihood of progression in 6-7 years (Miyazaki, et al. 2002)

No data on disease development

KEAM \approx \text{GRF} \times \text{moment arm to KJC}
OA gait: frontal plane

Beyond the KEAM

↓ Peak hip external adduction moment
  ↓ Peak hip adduction
  alignment-related

↑ Peak knee adduction
  alignment-related

↑ Peak rearfoot eversion
  compensatory for tibial axis

↑ Peak lateral ground reaction forces
  alignment-related

(Mundermann et al., 2005; Kaufmann et al., 2001; Gok et al., 2002; Weidow et al., 2006; Astephen et al., 2005)
OA gait: sagittal plane

Stiffer, more extended gait pattern

↓ Peak hip extension
↓ Peak hip external extension moment
   weakness, tightness, stride length
↓ Peak knee flexion during midstance
↓ Peak knee external flexion moment
↑ Dynamic knee stiffness
   pain, weakness, lessen joint forces
↑ Knee extension at footstrike
↑ Peak vertical GRF load rate

(Mundermann et al., 2005; Kaufman et al., 2001; Gok et al., 2001; Al-Zahrani & Bakheit, 2002; Weidow et al., 2006; Zeni et al., 2008)
Project 1: purpose

To evaluate if healthy individuals with varus knee alignment demonstrate similar mechanics to those with normal alignment

Variables of interest

- Previous literature: medial knee OA
- Theory: structure-mechanics
Hypotheses: frontal plane

Individuals with varus knees will demonstrate:

↓ Peak hip external adduction moment
↓ Peak hip adduction
↑ Peak knee external adduction moment
↑ Peak knee adduction
↑ Peak rearfoot eversion
↑ Peak lateral ground reaction forces
Hypotheses: sagittal plane

Varus-aligned & normal subjects similar in:

- Peak hip extension
- Peak hip external extension moment
- Peak knee flexion during midstance
- Peak knee external flexion moment
- Dynamic knee stiffness
- Knee extension at footstrike
- Peak vertical GRF load rate
Methods: subjects

1. A priori power assessment = 17 subjects/group
2. Age: 18-35 years old
3. No history of ligamentous/meniscal/chondral pathology or other condition affecting gait
4. Knee Injury and Osteoarthritis Score Knee Survey (KOOS), Sports and Recreational Activities subscale
   Appropriate for young, healthy population
   Squatting, running, jumping, twisting/pivoting, kneeling
   5-point Likert scale: (0=no symptoms, 4=severe symptoms)
   Score range: 0-20
   Exclusion criteria: > 2/20
Group assignment

Caliper-inclinometer method (Hinman et al., 2006)

Tibial tuberosity → neck of talus
Axis relative to vertical

Normative data: 30 healthy individuals

Mean = 8°, SD = 2°
Normal (± .5 SD) = 7-9°
Varus (+ 1.5 SD) ≥ 11°

Studied knee
Greater deviation, or chosen at random
Data Collection

27 retroreflective spherical markers
13 anatomical markers removed after standing calibration
Hip trial (sphere-fit algorithm)
23m walkway @ 1.46 m/s (± 2.5%)

Processing in Vicon and Visual 3D
- Marker data low-pass filtered @ 8 Hz, analog data @ 50 Hz
- Variables of interest extracted & averaged from 5 trials

Descriptive data: means & standard deviations
Statistical analysis: independent samples t-tests
Results: Demographic data

<table>
<thead>
<tr>
<th></th>
<th>Age (years)</th>
<th>Gender (M/ F)</th>
<th>BMI (kg/m²)</th>
<th>KOOS-SR Score</th>
<th>TMA (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal (n=17)</td>
<td>23.8 (4.6)</td>
<td>14/3</td>
<td>25.4 (5.0)</td>
<td>0.3 (0.6)</td>
<td>7.7 (0.6)</td>
</tr>
<tr>
<td>Varus (n=17)</td>
<td>23.6 (3.6)</td>
<td>15/2</td>
<td>23.2 (2.4)</td>
<td>0.2 (0.5)</td>
<td>11.5 (0.7)</td>
</tr>
</tbody>
</table>

Varus subjects mostly males
Results: Frontal plane hip mechanics

No difference

No difference
Frontal plane knee mechanics

Knee External Adduction Moment x Group

Knee Adduction Angle x Group

$p < 0.001$
Rearfoot eversion & ML GRF

\[ p < 0.001 \]

\[ p = 0.022 \]
Sagittal plane hip mechanics

No difference

No difference
Sagittal plane knee mechanics

Knee External Flexion Moment x Group

- Normal
- Varus

Moment (Nm / kgm) (flexion +)

Stance

p = 0.067

Knee Flexion Angle x Group

- Normal
- Varus

Angle (degrees) (extension +)

Stance

No difference

p < 0.001
Vertical load rate & dynamic stiffness

No difference (0-10%)

No difference
Discussion

Frontal plane

Varus mechanics similar to OA gait mechanics

Similar KEAM magnitudes to established disease \( (Gok \text{ et al.}, 2002; Butler \text{ et al.}, 2007) \)

Supports notion that mechanics contribute to disease development

Increased pronation compensatory: achieve plantigrade foot

Sagittal plane

Varus mechanics did NOT resemble OA gait mechanics

More extended, stiffer gait results from disease \( (Mundermann \text{ et al.}, 2005) \)

Onset of patterns - indicates disease?

Actually: greater knee flexion

Medial loading higher, correlates/predictors?
Lower Extremity Walking Mechanics of Young Individuals with Asymptomatic Varus Knee Alignment

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ABSTRACT: Varus knee alignment is associated with an increased risk for developing medial knee osteoarthritis (OA). Medial knee OA is commonly associated with altered walking mechanics in the frontal and sagittal planes, as well as altered ground reaction forces. It is unknown whether these mechanics are present in young, asymptomatic individuals with varus knees. We expected that varus-aligned individuals would generally present with frontal plane mechanics that were similar to those reported for individuals with medial knee OA. The gait mechanics of 17 asymptomatic individuals with varus knees and 17 healthy, normally aligned controls were recorded. Gait parameters associated with medial knee OA were compared between groups. The individuals with varus knees exhibited greater knee external adduction moments, knee adduction, eversion, and lateromedial ground reaction force than the normally aligned individuals. In addition, those with varus knees also demonstrated increased knee flexion and external knee flexor moments during midstance. These results suggest that individuals with varus knees exhibit some, but not all, of the altered mechanics seen in medial knee OA. © 2009 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 27:1414–1419, 2009

Keywords: varus; gait; knee osteoarthritis
Project 2

Relationship between static and dynamic alignment-related variables to the KEAM
Relationships with KEAM

Andrews et al., 1996; Hunt et al., 2006; Hurwitz et al., 2002; Hunt et al., 2008

**Radiographic**
- Frontal plane knee alignment ($r = 0.14 - 0.79$)
- Joint space narrowing ($r = 0.48$)
- Kellgren-Lawrence grade ($r = 0.30$)
- Sclerosis ($r = 0.43$)

**Kinematic**
- Foot progression angle ($r = 0.20 - 0.30$)
- Ipsilateral trunk lean ($r = 0.33$)
- Frontal plane lever arm ($r = 0.47 - 0.77$)
- Vertical+frontal plane GRF ($r = 0.19 - 0.53$)
- LE frontal plane joint kinematics ($r =$ ?)

**Clinical measures ($?$)**
Purpose & Hypotheses

Three predictive models (KEAM variation)

Static
Rationale: simple, clinical tools can be informative about medial knee joint loading
Hypothesis 2.1: Significant $R^2$

Dynamic
Rationale: dynamic LE alignment should relate well to medial knee loads
Hypothesis 2.2: Greater $R^2$ than static measures

Static + Dynamic
Rationale: static and dynamic predictors are unique contributors
Hypothesis 2.3: Greatest $R^2$
Expected correlations

Clinical findings
With ↑ KEAM
  ↓ hip abduction strength
  ↑ tibial mechanical axis
  ↑ distance between medial knee joint lines
  ↑ medial arch height lowering

Frontal plane kinematics
With ↑ KEAM
  ↑ hip abduction
  ↑ knee adduction
  ↑ rearfoot eversion
Methods: Static measures

Tibial Mechanical Axis

Knee Joint Line Distance
Methods: Static measures

Sit-Stand Arch Height Index Lowering

Hip Abduction Strength
Dynamic measures

Knee External Adduction Moment

Hip Frontal Plane Angle

Knee Frontal Plane Angle

Rearfoot Frontal Plane Angle
Methods

37 subjects
Used data from Project 1, collected data on 3 additional subjects

Pearson’s/Spearman’s rank correlation coefficients
Correlate static and dynamic variables to peak KEAM

Stepwise multiple linear regressions
$p_{in} < 0.05, p_{out} > 0.10$
Determine best predictors of KEAM variance
### Demographic data

<table>
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<tr>
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<th>Age (years)</th>
<th>Gender (M/ F)</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
<th>KOOS-SR Score</th>
<th>TMA (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N=37</td>
<td>23.6 (4.0)</td>
<td>32/5</td>
<td>1.78 (0.09)</td>
<td>76.9 (18.0)</td>
<td>0.2 (0.5)</td>
<td>9.9 (2.0)</td>
</tr>
</tbody>
</table>

Young, fit, asymptomatic
Mostly male
Results: Static measures

- **TMA vs KEAM**
  - $r = 0.74$

- **Knee Joint Distance vs KEAM**
  - $r = 0.64$

$p < 0.001$
Results: Static measures

- Hip Strength vs KEAM
  - Correlation coefficient: \( r = 0.20 \)
  - Significance: \( p = 0.122 \)

- Arch Lowering vs KEAM
  - Correlation coefficient: \( r = 0.09 \)
  - Significance: \( p = 0.299 \)
Results: Dynamic measures

Knee Adduction Angle vs KEAM

r = 0.68

p < 0.001
Results: Dynamic measures

- Rearfoot Eversion Angle vs KEAM
  - $r = 0.60$
  - $p < 0.001$

- Hip Adduction Angle vs KEAM
  - $r = -0.14$
  - $p = 0.203$
### Stepwise regressions KEAM

<table>
<thead>
<tr>
<th>Static model (1)</th>
<th>Adjusted $R^2$</th>
<th>$R^2$ Change</th>
<th>F Change p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tibial mechanical axis</td>
<td>0.532</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

$p < 0.001$ for all models
Discussion

Static measures

Tibial mechanical axis accounts for 53% of variation
Similar to HKA, lever arm (Hurwitz et al., 2002; Hunt et al., 2006)
Suggests clinical utility

Dynamic measures

Knee adduction – 47%
Not as high as TMA (or HKA)
Dynamic evaluation NOT superior to static (Sharma et al., 2007)
Knee adduction + rearfoot eversion – 53%
Knee and foot uniquely contribute to observed KEAM

Static + Dynamic measures

Tibial mechanical axis + knee adduction angle – 59%
Both variables directly reflect alignment
Dynamic – modest improvement (6%)
Static and dynamic correlates of the knee adduction moment in healthy knees ranging from normal to varus-aligned

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ABSTRACT

Background: Individuals with medial knee osteoarthritis often present with varus knee alignment and ambulate with increased knee adduction moments. Understanding the factors that relate to the knee adduction moment in healthy individuals may provide insight into the development of this disease. This study aimed to examine the relationships between static and dynamic lower extremity measures with the knee adduction moment. We hypothesized that the dynamic measures would be more closely related to this moment.

Methods: Arch height index, hip abduction strength and two static measures of knee alignment were recorded for 37 young asymptomatic knees that varied from normal to varus-aligned. Overground gait analyses were also performed. Correlation coefficients were used to assess the relationships between the static and dynamic variables to the knee adduction moment. Hierarchical regression analyses were then conducted using the static measures, the dynamic measures, and the static and dynamic measures together.

Results: Among the static measures, the tibial mechanical axis and the distance between the medial knee joint lines were correlated with the knee adduction moment. The best predictive static model \( R^2 = 0.53 \) included only the tibial mechanical axis. Among the dynamic variables, knee adduction and rearfoot eversion angles were correlated with the knee adduction moment. Knee adduction and rearfoot eversion, together, were the best dynamic model \( R^2 = 0.53 \). The static and dynamic measures together created the strongest of the three models \( R^2 = 0.59 \).

Conclusions: These results suggest that dynamic measures slightly enhance the predictive strength of static measures when explaining variation in the knee adduction moment.

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Summary

Project 1

Confirm/quantify ↑KEAM (40%) in healthy varus knees
Stiffened gait patterns do not appear to precede medial knee OA due to varus knee malalignment

Project 2

Simple, clinical tools: useful predictors of knee loading
Dynamic assessment ≈ static assessment
Ongoing agenda

Comprehensive reliability analysis and normative database of TMA measure

Gait mechanics of varus-aligned females

Muscle activation patterns in healthy malalignment

Clinical and biomechanical utility of load-reducing mechanisms in knee OA treatment and prevention
Connecting with UD

Open House – Motion Analysis Laboratory
209F, College Center Park
Tuesday, November 30, 1-4

Collaborative research
  Mechanical engineering
  Exercise science
  Others??
Questions?