Biomechanical Effects of Femoral Component Axial Rotation in Total Knee Arthroplasty (TKA)

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- Timothy Wright, PhD receives royalties from and owns stock in Exactech, Inc.
- Michael Cross, MD is a paid consultant for Exactech, Inc.
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Total Knee Replacement (TKR)

Osteoarthritis

TKR

Femoral component

Tibial insert
Patient Dissatisfaction Following TKR

- Anderson (1996): 11%
- Heck (1998): 12%
- Wylde (2007): 15%
- Hawker (1998): 15%
- Bourne (2010): 19%
- Noble (2006): 25%
- Bullens (2001): 27%
- Suda (2010): 39%

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Femoral Component Alignment

Femoral component

Femoral cuts
Femoral Component Rotation

- Tibiofemoral kinematics
- Patellofemoral kinematics
- Articular contact force
- Collateral ligament tension
Excessive Internal Rotation of the Femoral Component

- Qualitatively increases medial collateral ligament (MCL) tension
- Knee pain and stiffness

External Rotation

medial sulcus

3-4°

TEA

lateral epicondyle

PCA
Variability from Patient to Patient
Research Questions

- How does external rotation alter collateral ligament tensions and tibiofemoral contact forces across a subpopulation of knees?

- What anatomic factors of the femoral condyle explain variations in maximum MCL tension among knees?
Computational Model

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A Multibody Knee Model Corroborates Subject-Specific Experimental Measurements of Low Ligament Forces and Kinematic Coupling During Passive Flexion

A multibody model of the knee was developed and the predicted ligament forces and kinematics during passive flexion corroborated subject-specific measurements obtained from a human cadaveric knee that was tested using a robotic manipulator. The model incorporated a novel strategy to estimate the slack length of ligament fibers based on experimentally measured ligament forces at full extension and included multibody representations for the cruciates. The model captured experimentally measured ligament forces ($\leq 5.7$ N root mean square (RMS) difference), coupled internal rotation ($\leq 1.6$ deg RMS difference), and coupled anterior translation ($\leq 0.4$ mm RMS difference) through $130$ deg of passive flexion. This integrated framework of model and experiment improves our understanding of how passive structures, such as ligaments and articular geometries, interact to generate knee kinematics and ligament forces.

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Kia et al. J Biomech Eng 2016
Role of Modeling in Ideation

- **Apply** Forces
- **Control** Ligament Properties
- **Sensitivity** Femoral Component Rotation

Predict
- Loads
  - Contact
  - Ligament

Ideation
- Implant Placement
Model Development

Recipes

1 2 3 4
Bony Geometries

- Three neutrally aligned, non-arthritic, male cadaveric legs
  - Ages: 20, 21, 42
- Obtained from CT scans
  - 0.6 mm slice thickness, 0.6x0.6 mm² in-plane pixel dimensions
Implant Design

- Optetrak Logic™ Posterior Stabilized (PS) Knee
  - Exactech Inc.

![Diagram of implant design with dimensions 8mm and 9mm.]
Implant Placement via Measured Resection

- Proximal tibial cut
  - Perpendicular to mechanical axis
  - Max 9 mm bone resection
- Distal femoral cut
  - Perpendicular to mechanical axis
  - Max 8 mm bone resection
Posterior Femoral Cut

Long axis

3°

PCA
Model of Soft Tissue Envelope
Medial Collateral Ligament (MCL)

Proximal

Transverse

Distal
Ligament Properties

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Contact Force

\[ F_c = A x^b \]
Method to Address Question One

**Input**
Flexion Arc

0-90°

500N

**Femoral component external rotation**

**Output**

- Force
- Collateral ligaments
- Contact
Representative Simulations

0° MCL

9° LCL
Medial Collateral Ligament

Knee 1

Knee 2

Knee 3

MCL tension (N) vs. Flexion (°)
Lateral Collateral Ligament (LCL)

- Knee 1
- Knee 2
- Knee 3

Graphs showing LCL tension (N) vs. flexion (°) for different knees and flexion angles.
Medial Compartment Contact

Knee 1

Knee 2

Knee 3

Flexion (°)

Medial Contact (N)
Lateral Compartmental Contact

Knee 1

Knee 2

Knee 3
Method to Address Question Two

Posterior cut

Distal cut

Medial sulcus

TEA ratio

\[ \frac{r_p}{r_d} \]
Max MCL Tension vs. TEA ratio
Method to Address Question Two

Proximal MCL insertion

Posterior cut

Distal cut

MCL ratio

\[ r_p' \div r_d' \]

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Max MCL Tension vs. MCL ratio
MCL ratio

\[ r'_p \over r'_d \]

Proximal MCL insertion
Clinical Implications

 lords of life

 MCL tension = Subfailure damage

 Difference in compartmental contact forces = Patient satisfaction
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Appendix
Internal/External Tibial Rotation

Knee 1

Knee 2

Knee 3

Flexion (°) - External (°)

0° 3° 6° 9°

0 10 20 30 40 50 60 70 80 90

0 10 20 30 40 50 60 70 80 90

0 10 20 30 40 50 60 70 80 90

0 10 20 30 40 50 60 70 80 90

0 10 20 30 40 50 60 70 80 90
Varus/Valgus Rotation

Knee 1

Knee 2

Knee 3
Ligament property

Toe region  Linear region

\[ F(l, \dot{l}, l_0) = \frac{1}{n} \left\{ \left[ f^*(l) + c_a \dot{l}B_1 \right]B_2 + \left[ K(l - (l_0 + \Delta_t)) + f^*(l_0 + \Delta_t) + c_a \dot{l}B_1 \right]B_3 \right\} \]

\[ B_1 = \text{step}(\dot{l}, 0, 0, \dot{l} + 0.1, 1) \]
\[ B_2 = \text{step}(l, l_0, 0, l_0 + 0.1, 1) \text{step}(l, (l_0 + \Delta_t), 1, (l_0 + \Delta_t) + 0.001, 0) \]
\[ B_3 = \text{step}(l, (l_0 + \Delta_t), 0, (l_0 + \Delta_t) + 0.001, 1) \]
Optimization

\[
\min \sum_{i=1}^{9} \left( \sum_{j=1}^{a} \left[ \vec{F}_{i,j}(l, l_0) \right]^2 \right)^{\frac{1}{2}} - F_i^e \right)^4
\]

\(a = \text{number of fibers for each ligament with 9 ligaments included in the optimization}\)

\(F_i^m = \{\text{ACL, sMCL, LCL, FFL, OPL, POL, MPC, LPC, PCLPM}\}\)

\(F_i^e = \{37, 4, 20, 1, 10, 18, 1, 4, 10\} N\)

\(a = \{6, 6, 1, 1, 2, 3, 3, 3, 4\} \text{ fibers}\)

\(l_0 = l_e(100 - x)\% \quad \text{with} \quad -10 \leq x \leq +10\)
Optimization

- Ligament force at full extension ($F_e$) - from the experiment
- Ligament length at full extension ($l_e$) - from the model
Optimization

- Ligament force at full extension ($F_e$)
- Ligament length at full extension ($l_e$)
Optimization

- Ligament force at full extension ($F_e$)
- Ligament length at full extension ($l_e$)
Lateral vs. Medial Contact Force

Knee 3

Flexion (°)

Lateral Contact (N)

Flexion (°)

Medial Contact (N)

0° 3° 6° 9°

0 200 400 600 800

0 30 60 90

0 200 400 600 800

0 30 60 90
Method to Address Question Two

sTEA ratio = \frac{r_p}{r_d}
Contact Force

Experiment

Power function

$R^2 = 0.995$
Method to Address Question Two

Proximal MCL insertion

MCL ratio

\[ \frac{r_p'}{r_d'} \]
Medial Collateral Ligament (MCL)

Transverse

Proximal

Distal