Biomechanics of Total Knee Replacements

By: Melissa Perri and Niki Efantis
Anatomy of the Knee

**Major Bones:**
- Femur
- Patella
- Tibia

**Ligaments:**
- Posterier cruciate ligament (PCL)
- Anterior cruciate ligament (ACL)
- Lateral collateral ligament (LCL)
- Medial collateral ligament (MCL)

**Meniscii:**
- Medial meniscus
- Lateral meniscus

**Other components:**
- Articular cartilage
- Synovial Lining

Movement of the Knee Joint

- Major movements of the knee are flexion and extension; also some rotation
- Shape of the articulating surfaces of the tibia and femur as well as the 4 ligaments of the knee all play a role in movement of the knee
- Rollback mechanism of flexion
  - As knee bends in flexion femur glides over and rolls back on tibia
  - PCL prevents femur from gliding/rolling too far back on tibial plateau
**Unhealthy Knees**

**CONDITIONS:**

1.) Arthritis

2.) Infection

3.) Injury

4.) Aging

5.) Articular Cartilage wear

6.) Insufficient Synovial fluid
Types of Arthritis

1.) **Osteoarthritis**
   - at the age of 50; hereditary
   - Cartilage wears away, bone rubs on bone

2.) **Rheumatoid Arthritis**
   - synovial membrane thickens and becomes inflamed produces too much synovial fluid causing internal pressure
   - can cause cartilage loss and pain

3.) **Post Traumatic Arthritis**
   - Caused by serious knee injuries
   - knee fracture or severe tears of ligaments causing articular cartilage damage over time
   - limits knee function
Healthy Vs. Unhealthy knees

Joint Space

Lost Joint Space
Who is a good candidate for Total Knee Arthroplasty?

- People with severe knee pain
- Knee deformity (e.g., Bow legged or knock kneeed)
- Inability to tolerate pain medications
- Failure of other non-operative procedures such as cortisone injections and physical therapy

- Usually performed on patients 60-80 yrs of age. Can be performed on younger or older patients but unlikely candidates.
History of Knee Replacements

- Knee surgery carried out by ancient Egyptians
- The first knee replacement surgeries began just after WWII
- In the late 1960’s use of plastic on metal became more common
- By the 1970s engineers and scientists designed total condylar prosthesis
- Improved instrumentation used to install replacement during surgery was developed
- Modern designs compromise between stability and freedom of movement while trying to minimize stress in the joint.
Implant Design

Artificial Knee Components

- Femoral Component
- Plastic Spacer
- Tibial Tray
- Patella Button
Materials

1.) strong and high resistance to wear
2.) low coefficient of friction
3.) biocompatibility

- Metal components: titanium alloys or cobalt chromium alloy
  - durable, lightweight, inert in body

- Plastic components: ultra high molecular weight polyethylene (UHMWPE)
  - used for its very low coefficient of friction

<table>
<thead>
<tr>
<th>Materials</th>
<th>Coefficient of friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tire/road</td>
<td>1</td>
</tr>
<tr>
<td>Nylon/steel</td>
<td>0.2</td>
</tr>
<tr>
<td>PTFE/PTFE</td>
<td>0.07</td>
</tr>
<tr>
<td>PTFE/PTFE (in water)</td>
<td>0.04</td>
</tr>
<tr>
<td>CoCr/CoCr (in water)</td>
<td>0.38</td>
</tr>
<tr>
<td>CoCr/UHMWPE (in water)</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Surgery

- Damaged portion of femur and tibial bone are removed and replaced with prosthetic components
Alignment during surgery

- Alignment is critical to ensure minimal stress and strain to the prosthesis.
- Mechanical axis is restored as much as possible.
- Special instruments are used to ensure proper cutting and alignment.
Biomechanics

Kinematics:

- **Walking cycle:**
  - represented by 2 steps
  - 4 states: swing through, heel strike, weight transfer, toe-off
  - motion of leg during each step has 2 phases:
    - stance (support) phase
    - swing (nonsupport) phase

- **Lubrication of knee**
  - *Swing phase:* a thick film is pushed into space between cartilage
  - *Heel strike:* load on knee increases, so film squeezed out to reduce thickness
  - *Toe-off:* load is maximum, but there is still film present to avoid surface-to-surface contact

Fig. 17 Lubrication mechanism illustrated for the right knee.
**Three Dimensional (3D) Static Analysis**

- Force at the knee joint 10% into the stance phase of climbing the stair.
- Forces at knee are dependent on position of the tibia.

Let:
- $R = \text{ground reaction force}$
- $Q = \text{quadriceps (primary muscle acting on the sagittal plane)}$
- $L = \text{ilio-tibial band (varus movement in frontal plane)}$
- $V = \text{joint force, perpendicular to tibial surface}$
- $H = \text{joint force, parallel to tibial surface}$

**Vertical force balance, sagittal plane**

$$R + L \cos 14 + Q \cos 20 + H \sin 8 - V \cos 8 = 0$$

**Horizontal force balance, sagittal plane**

$$L \sin 14 + V \sin 8 - H \cos 8 - Q \sin 20 = 0$$

**Moment balance, sagittal plane**

$$8L + 53Q - 49R + 19H = 0$$

**Moment balance, frontal plane**

$$8Q \cos 21 + 47L \cos 14 - 42R = 0$$

Setting $R$ equal to body weight, $W$:
- $V = 2.42W$
- $H = 0.28W$

Resultant joint force = $2.44W$
- $Q = 0.70W$
- $L = 0.80W$
Design Considerations

Load Transfer:

- components of prosthesis are designed to transfer joint loads directly to the underlying cancellous bone
- this property is similar to load distribution in a healthy knee

Engineering solutions:

*design goal*: distribution of joint loads to underlying cancellous bone as uniformly as possible over as large an area as possible.
a) **Metal Backing:**

**Advantages:**
- helps to distribute applied loads uniformly over a large area (mod of elasticity)
- reduces maximum compressive stresses and increases maximum tensile stresses

**Disadvantages:**
- UHMWPE has to be attached securely
- polyethylene must be thinner (creates more wear)
- dimensional changes occur because of wear particles

b.) **Maximum contact area of plateau**

- *goal:* distribute load over as large an area as possible
- Cannot extend the plateau
- Coverage of the entire plateau is important
- This minimizes stress on bone and ligaments as
  Stress = F/A
- In a normal knee joint pressures vary from 3kg/cm^2 to 19.3kg/cm^2
**Pegs and Screws for Support**

<table>
<thead>
<tr>
<th>Model</th>
<th>Central Peg (A)</th>
<th>Short Peripheral Peg or Screw (B)</th>
<th>Bladed Cruciate Form (C)</th>
<th>Bladed Central Peg (D)</th>
<th>Long Uncemented Intramedullary Stem (E)</th>
</tr>
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<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td>Most widely used</td>
<td><em>Pegs:</em> Improved rotational resistance</td>
<td><em>- Resistance to bending, rotation, or shear stress</em></td>
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<td>Appropriate for sinkage of tibial component</td>
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<td><em>Screws:</em> - reduce micromotion and enhance ingrowth process</td>
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<td>- transfers load directly to lateral cortex</td>
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<td></td>
<td></td>
<td>- suitable for patients with bony defect</td>
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<td><strong>Disadvantages</strong></td>
<td>- Unsuitable for uncemented application</td>
<td><em>Pegs:</em> Minimal support to varus-valgus bending</td>
<td><em>- Instrumentation must be accurate</em></td>
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<td>- Invasive technique</td>
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<td><em>Screws:</em> pressure is localized</td>
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**Fixation:**

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**Advantages:**
- Most widely used
- Does not stress protect the proximal cancellous bone
- Carries some varus-valgus bending

**Pegs:**
- Improved rotational resistance

**Screws:**
- Reduce micromotion and enhance ingrowth process

**Disadvantages:**
- Unsuitable for uncemented application
- Minimal support to varus-valgus bending
- Sometimes stress protect the proximal cancellous bone
- Pressure is localized

**Instrumentation must be accurate**

**Invasive technique**

**Appropriate for sinkage of tibial component**
- Transfers load directly to lateral cortex
- Suitable for patients with bony defect
Prosthetic Models

3 widely used types:

1.) **Condylar replacement**
   - Simplest form
   - Kinematics are similar to that of the normal of knee
   - Main problem is wear in polyethylene

2.) **Hinged or linked prosthesis**
   - Very constrained design
   - Much of the force transferred to fixation stems and surrounding bone
   - Mostly used for older people with serious knee instability, damaged ligaments and bone loss

3.) **A/P stabilized prosthesis**
   - PCL is removed
   - Post in tibial plateau prevents femur from rolling too far back
   - In addition to wear in polyethylene disc, post is also susceptible to wear
Testing Procedure

- Two types of failure modes:
  - Fatigue
  - Wear-deformation
- Testing for 10 years of usage takes approximately 3 weeks

- **Axial loading**: offset leading could lead to failure of metallic parts, excessive deformation of plastic

- **Shear force**: only 10% of vertical force component, lead to severe plastic wear through metal tray

- **Combination**: combined stresses can be much higher than for one load condition alone.
Problems Arising from Implants

Adverse Effects of Any Surgery

- Scarring
- Nerve injury (temporary/permanent numbness in localized area)
- Blood vessels injury
- Slow healing (especially for diabetics, or patients with long-term steroid use)
- Infection
Adverse Effects of TKA

**Infection**
- Symptoms may appear early after surgery, or may not appear for months, or even years after the operation
- Infection of the hematoma (collection of blood)

**Stiffness**
- Usually caused by scar tissue formed near the prosthesis, limiting the range of motion
- Preventive methods: use of Constant Passive Motion (CPM) machine and physical therapy
Loosening

- **Fibrous Tissue:** a soft fibrous tissue develops permitting more relative motion between implant and bone loading.

- **Bone necrosis (death)**

- **Mechanical damage during surgery**

- **Wear debris:**
  - Foreign body wear
  - Sub-surface fatigue

- **Mechanical loosening from fatigue**
  - Debonding: metal stem from cement, and cement from bone
Advancements

- Minimally invasive surgery (MIS) of the knee is a new development
  - Advantages: - needs only a small incision
    - better cosmetic results
  - Disadvantages: - surgeon has limited visibility when placing components

- As a result Computer Aided Orthopedic Surgery (CAOS) is becoming more common
  - uses infrared cameras, sensors and tracking devices
  - a patient specific digital image of the knee is created

- Computer tracks surgeon’s instruments and provides information about where to cut bone for proper alignment
Mobile bearing prosthesis – UHMWPE discs slide along inside of tibial plate - increases contact area at all points of flexion and extension

<table>
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<tr>
<th>Type</th>
<th>Contact area (square mm)</th>
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<tbody>
<tr>
<td>Stable</td>
<td>200-300</td>
</tr>
<tr>
<td>Mobile</td>
<td>1000-1500</td>
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Increased wear of polyethylene due to increased sliding since

\[ V = k(Wx)/3H \]

where \( k = \) wear coefficient

\( H = \) hardness/softness of material
References

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