Biomechanics of Knee Replacement

Ryan Keyfitz
Rohinton Richard
Biomechanics of the Knee

- Knee Joint
  - Provide mobility
  - Provide stability to the lower extremity
  - Allow flexion and rotation
Anatomy of the Knee

- Modified hinge joint (ginglymus)
  - Tibio-femoral joint
    • Kinematics of flexion, extension, rotation
  - Patello-femoral joint
    • Increases efficiency of extension
Anatomy of the Knee

- Modified hinge joint (ginglymus)
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    - Kinematics of flexion, extension, rotation
  - Patello-femoral joint
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Biomechanics of the Knee

- 6 degrees of freedom
  - 3 translational degrees of freedom
  - 3 rotational degrees of freedom
Biomechanics of the Knee

- Translational Degrees of Freedom
  - Medio-lateral: 1–2 mm
  - Proximo-distal: 2–5 mm
  - Antero-posterior: 5–10 mm
Biomechanics of the Knee

- Rotational Degrees of Freedom
  - Flexion: -15° to 140°
  - Internal / External: -30° to 30° (FLEX)
  - Varus / Valgus: -8° to 8° (EXT)
Biomechanics of the Knee

- Rotational Degrees of Freedom
  - Flexion: -15° to 140°
  - Internal / External: -30° to 30° (FLEX)
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Genu valgum  Normal  Genu varum
Flexion of the Knee:
- 120° during hip extension
- 140° during hip flexion
- 160° during passive knee flexion
Biomechanics of the Knee

Joint Stability (Intrinsic)
- Ligaments
- Shape of the bones
- Menisci
- Capsule
Biomechanics of the Knee

- **Ligaments**
  - Tensile check reins
  - Limits motion based on orientation
  - Cruciates provide sagittal stability
    - Resists anterior / posterior shear
  - Collaterals prevent varus / valgus

- **Bones**
  - Provide physical stability
Biomechanics of the Knee

- Menisci and Capsule
  - Increase contact area
  - Reduce stress on load-bearing surfaces
  - Responsible for low coefficient of friction
  - Articular cartilage and synovial fluid
    - High viscosity at low shear rates
    - Low viscosity at high shear rates
    - Non-newtonian fluid acts as a shock absorber
Joint Stability (Extrinsic)
- Muscles of thigh and calf
- Force to resist abnormal stresses
- Patella “pulley” mechanism
- Screwhome mechanism
  - Automatic rotation of tibia
  - Last 20° of full extension
Biomechanics of the Knee

Joint Stability (Extrinsic)
- Muscles of thigh and calf
- Force to resist abnormal stresses
- Patella "pulley" mechanism
- Screwhome mechanism
  - Automatic rotation of tibia
  - Last 20° of full extension
Static Forces

- **Standing**
  - 43% of body weight on each knee

- **Standing on one leg**
  - More than twice body weight
  - Lateral tension to maintain equilibrium
Dynamic Forces

- **Walking**
  - Compressive: 6x body weight
  - Shear: 2x body weight
  - Resultant force: 7x body weight

Average: 1,900,000 steps per year
Force / Time = ?

DAMAGE!
Causes of Knee Degeneration

- Osteoarthritis
  - Degradation of smooth cartilage lining
  - Development of cysts
  - Erosion of the bone
  - Small bone growths (bone spurs)
  - Increased pain and stiffness
Causes of Knee Degeneration

- Rheumatoid Arthritis
  - Inflammation of tissue surrounding joints
  - Deterioration of the cartilage

- Post-traumatic Arthritis
  - Result of injury to cartilage or ligaments
  - Abnormalities cause excessive wear
Causes of Knee Degeneration

- Avascular Necrosis
  - Inadequate blood supply to end of bone
  - Deterioration of articular cartilage

- Misalignment of the Knee
  - Bowlegs (varus) or knock-knees (valgus)
  - Abnormally high stress on joint
Causes of Knee Degeneration

- Genetics
  - Hereditary
  - Biomechanical Deformities
- Age
- Gender
- Gait
- Shoes
- Physical Activity
Solution?
Early 1940’s: success with vitallium cups in hip replacements

Applied this concept to the knee
- Smith-Petersen prosthesis
- Macintosh / McKeever tibial hemiarthroplasty

Concept of tibial replacement did not emerge until the 1950s with the advent of the new materials
Smith-Petersen Femoral Hemiarthroplasty
Early attempts at arthroplasty = basis for today's unicompartmental knee replacements

- Able to correct for valgus or varus deformity with minimal bone loss during implantation
- Kept soft tissue balance of the knee by not sacrificing collateral ligaments
  - (Important concept later rediscovered for condylar replacements)
History

- 1950’s: hinges become the standard type of arthroplasty
- Supposed ‘need’ for a hinge
  - Primary cause of instability
    - Cartilage and bone loss
    - NOT disruption of collateral ligaments
  - Delayed the introduction of a reliable knee replacement for two decades
Waldius Co–Cr Alloy Roller Bearing. (1958)
Hinged Prostheses

- Some success
- Important stage in development of TKR
  - Taught researchers a great deal particularly from study failures
- R&D in operating theatres not bioengineering laboratory
- Fixed hinge highly subject to symptomatic loosening beginning about two years after insertion
Semi-constrained TKR

- Developed to solve the problem posed by tibial rotation
- Sheehan prosthesis
- High failure rates
  - Too bulky
  - Too complex
  - No understanding of the role of the collateral ligaments
Surface TKR

- First emerged late 1960’s
- Principles underpin the success of today's knee replacements
- Sought to do 2 things
  - Replaced articular surface of femoral and tibial condyles; leave intercondylar zone and cruciate ligaments intact
  - Replaced femoral groove and excision of one or both cruciates with a tibial component which covered the complete tibial surface
- Descendents today are the unicompartmental replacements
- Main weakness is the patello-femoral joint
Articular Surface Replacement

- Effectively 2 unicompartmental knee replacements
- First time metal, polyethylene, and cement used in a TKR
  - Paved way for prostheses used today
- Demonstrated that clinical instability of the rheumatoid knee primarily due to cartilage & bone erosion, not collateral ligament destruction
- Mechanical downfall = minimalism
Condylar Replacement

- Most important development in TKR
- Femoral shell with short peg cemented in place with aid of jigs to ensure accurate centering
- Brought collateral ligaments into tension on extension, relaxation on flexion thus permitting rotation.
- Front of component flat to prevent hyperextension
- Mated with high-density polyethylene tibial tray to allow up to 90° of flexion.
- Concept of a cylinder in a shallow groove provided the potential for excellent medial/lateral stability due to its width
Unicondylar/Duocondylar Prostheses

- Unicondylar and Duocondylar prostheses
- 1974: first Total Condylar Prosthesis
The Patella

- Independent patellar resurfacing procedures
  - Gave way to incorporating patellar surfaces with TKR prostheses during latter part of the 1970’s.
- 1978: TKR’s compared with and without plastic patellar surface
- Patellar resurfacing became standard part of knee replacement surgery
- Problems with metal backed patellar surface prostheses
  - Precipitated return to use of pure polyethylene surface
Attempts at replacement without cement in the 1950s and 1960s

Availability of cement for fixation
- Opened door for successful treatment of arthritic conditions of the knee

Advance of cement fixation

Introduction of porous coating for bone ingrowth

Experience suggests that porous coating can be relied upon for fixation of the femoral component but is less dependable for fixation of the tibial tray
Total Knee Replacement Today

- Large variety of implants available within overall condylar category
- Differences most obvious with instrumentation rather than with the implants themselves
- Each manufacturing firm has its own system
  - Competition provides surgeon with a choice
- Areas of continuing debate:
  - Preservation of PCL
  - Resurfacing of patella
  - Cementing
Components & Materials
Components & Materials

- Majority of TKR’s used today are condylar replacements
- Consist of the following:
  - Cobalt-chrome alloy femoral component replacing femoral condyles and the patella trochlea
  - Cobalt-chrome alloy or titanium alloy tibial tray affixed to the upper tibia.
  - Ultrahigh-molecular-weight polyethylene (UHMWPE) tibial bearing component fixed into the tibial tray
  - UHMWPE patella component
Components & Materials
## Biomechanical Criteria

<table>
<thead>
<tr>
<th>Goals</th>
<th>Biomechanical Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relief of pain</td>
<td>Replacement of all articulating surfaces, interface micromotion &lt;50 um between components and bone.</td>
</tr>
<tr>
<td>Restoration of function</td>
<td>Similar motion characteristics as in the normal knee. Soft tissue lengths within normal range. Similar laxity characteristics as in the normal knee. The same or larger muscle lever arms as normal.</td>
</tr>
<tr>
<td>Durability</td>
<td>Normal stresses at the interface and within the surrounding bone. Minimal wear of the articulating surfaces (&lt;0.05mm depth per year).</td>
</tr>
<tr>
<td>Reliability</td>
<td>Insensitive to misalignment or size mismatch. Function insensitive to different kinetics of patients.</td>
</tr>
</tbody>
</table>
Types of Knee Replacements

- 4 general types:
  - Non-constrained
  - Semi-constrained
  - Constrained or hinged
  - Unicondylar
Non-Constrained Knee Replacement

- Most common type
- Artificial components inserted into the knee are not linked to each other, have no stability built into the system
- Relies on the person's own ligaments and muscles for stability
Semi-Constrained Knee Replacement

- Provides increasing stability for the knee
- Has some stability built into it
- Used if surgeon needs to remove all inner knee ligaments or if surgeon feels new knee will be more stable with this type of implant
Constrained or Hinged Knee Replacement

- Rarely used as a first choice
- Knee joint linked together with hinge
- Used when knee is highly unstable
- Useful in treatment of severely damaged knees
- Disadvantage of this type of knee joint is that it is not expected to last as long as the other types
Unicondylar Knee Replacement

- Replaces only half of the knee joint
- Performed if damage is limited to one side of the joint (with remaining part being relatively spared)
- Some surgeons prefer doing TKR (even with half of knee being undamaged) believing it is a better procedure
Cemented Knee

- Components of the implant are fixed to the bone with grout-like cement (*polymethyl-methacrylate*)
- Allows implants to perfectly fit to the irregularities of the bone
- Reliable procedure
  - Approximately 90 - 95% expected to go pain-free for at least ten years beyond surgery
- Immediately stable → can walk, fully bearing weight, immediately following surgery
- On loosening, some bone may be ground away by loosened cement
  - Potentially making revision more difficult
Non-Cemented Knee

- Components have a roughened porous surface
  - Allows bone to grow into it
  - Eliminates need for cement
- Implants are "press fit" against the bony surfaces that are precisely cut through the use of multiple cutting jigs
- Faultless positioning is necessary for bony attachment to occur with initial fixation by metal pegs and screws of the implant to bone
- Requires good bone to be successful
- Relatively new
- On loosening, less bone loss may occur due to lack of irritant cement
- Weight-bearing status following non-cemented knee replacement will be determined by the surgeon
Hybrid Fixation

- Femoral component is not cemented and the tibial component is cemented
- At present, cemented knee replacements are most commonly used, representing 90% of knee replacement surgery
- Non-cemented replacements are much less common, as are hybrid replacements
Who Is A Candidate?

Criteria

- Quality of Life Severely Affected
- Daily Pain
- Restriction of Ordinary Activities
- Evidence of Significant Destruction of the Knee (eg. X-rays)
Diagnostic Procedures

- Medical History
- Complete Physical Examination
  - Swelling
  - Range of Motion
  - Ligament Stability
  - Knee Alignment
Diagnostic Procedures

- X-rays
  - Shows extent of bone damage
  - Suggest cause of degeneration
Diagnostic Procedures
Diagnostic Procedures

- **X-rays**
  - Shows extent of bone damage
  - Suggest cause of degeneration

- **MRI**
  - Shows ligament and tendon damage
Diagnostic Procedures
Diagnostic Procedures

- **X-rays**
  - Shows extent of bone damage
  - Suggest cause of degeneration

- **MRI**
  - Shows ligament and tendon damage

- **Blood Tests**
  - Inflammatory Arthritis
  - Infection
The Next Step...
Surgical Procedure

- Knee is bent
  - All surfaces of joint are fully exposed
- Incision made between 15 and 30 cm in length,
- Surgeon moves aside kneecap and cuts away damaged joint surfaces
- Surgeon takes measurements to ensure good fit prosthesis, smoothes the bones' rough edges
- Prosthesis is then inserted
- Before closing incision, surgeon ensures proper function
Surgical Procedure
After Surgery

- Typically stay in hospital room for several days before going home
- Under medication to control pain
- During hospital stay, encouraged to move foot and ankle increases blood flow to leg muscles and helps prevent swelling and blood clots
- Blood thinners and support hose or compression boots may be necessary to further protect against swelling and clotting
- The day after surgery, physical therapist demonstrates exercises for new knee
- To help regain movement, a device called a *continuous passive motion machine* may be used → slowly moves knee while in bed
- Physical activity program needs to include:
  - Graduated walking program to gradually increase mobility
  - Slowly resuming other normal household activities, including stairs
  - Knee-strengthening exercises learned from hospital physical therapist should be performed several times a day
After Surgery
As with any surgery, TKR surgery carries risks:
- Infection
- Knee stiffness
- Blood clots in the leg vein (thrombophlebitis) or lungs (pulmonary embolism)
- Heart attack / stroke
- Nerve damage

Risk of serious complications is low
- Less than 2% of people undergoing the surgery experience serious complications

Infection can occur years after surgery
Risks & Complications

- Device failure may also occur
- Subjected to daily stress, even the strongest metal and plastic parts eventually wear out:
  - Wear
  - Loosening
  - Dislocation
- You're at a greater risk of joint failure if you're a young, obese male or you have complicating conditions
Compressive Stress Distribution on Tibial Insert Surface
Results

- 3 - 6 weeks after knee replacement surgery, generally can resume most normal daily activities
- Driving is possible in 4 – 6 weeks if knee can be bent far enough to sit in a car and you have enough muscle control to properly operate the brakes and accelerator
- After recovery, a variety of low-impact activities can be enjoyed, such as walking, swimming, playing golf or biking
- Higher impact activities, such as jogging, skiing, tennis, and sports that involve contact or jumping, may be out
How long will it last?

- 95% success rate for at least 15 years
  - With proper care and use
- Second replacement less successful
  - Bone is weaker
  - Ligaments may be damaged
- Longevity based on activity
Who has them?
Demographics

- 450,000 Worldwide
- 300,000 North Americans
  - 70% Age 65 and over
- Canadians under 55
  - 90% increase between 1994 and 2001
2002 Distribution of Total Knee Replacement Procedures by Patient Age

- 75–84 years: 7,401 (28%)
- 65–74 years: 10,108 (38%)
- 55–64 years: 5,966 (23%)
- 45–54 years: 1,885 (7%)
- 85+ years: 786 (3%)
- <45 years: 354 (1%)

Source: Hospital Morbidity Database, CIHI, Fiscal 2002. N = 26,500
### Demographics

#### Age-Specific Rates (per 100,000 Population) of Knee Replacements, by Gender and Age Group, Canada

<table>
<thead>
<tr>
<th>Age-Group (Years)</th>
<th>Males</th>
<th>10-Year % Change</th>
<th>Females</th>
<th>10-Year % Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 45</td>
<td>1</td>
<td>1.8</td>
<td>1.5</td>
<td>2.4</td>
</tr>
<tr>
<td>45–54</td>
<td>15.7</td>
<td>35.3</td>
<td>21.7</td>
<td>59.5</td>
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<tr>
<td>55–64</td>
<td>103.1</td>
<td>162.5</td>
<td>130.5</td>
<td>242.1</td>
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<tr>
<td>65–74</td>
<td>289.1</td>
<td>456.1</td>
<td>363.7</td>
<td>555.5</td>
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<tr>
<td>75–84</td>
<td>364.5</td>
<td>510.5</td>
<td>392.3</td>
<td>590.4</td>
</tr>
<tr>
<td>85+</td>
<td>121.5</td>
<td>172.5</td>
<td>107.1</td>
<td>172.5</td>
</tr>
<tr>
<td>Total</td>
<td>41.2</td>
<td>74.9</td>
<td>61.1</td>
<td>111.1</td>
</tr>
</tbody>
</table>
### Demographics

#### Number of Total Knee Replacement Procedures Performed in Canada Based on Patient Residence

<table>
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<tr>
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<tbody>
<tr>
<td>Newfoundland and Labrador</td>
<td>177</td>
<td>252</td>
<td>284</td>
<td>60%</td>
<td>13%</td>
</tr>
<tr>
<td>Prince Edward Island</td>
<td>84</td>
<td>111</td>
<td>139</td>
<td>65%</td>
<td>25%</td>
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<tr>
<td>Nova Scotia</td>
<td>674</td>
<td>893</td>
<td>1,079</td>
<td>60%</td>
<td>21%</td>
</tr>
<tr>
<td>New Brunswick</td>
<td>403</td>
<td>695</td>
<td>808</td>
<td>100%</td>
<td>16%</td>
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<tr>
<td>Quebec</td>
<td>2,094</td>
<td>3,314</td>
<td>3,828</td>
<td>83%</td>
<td>16%</td>
</tr>
<tr>
<td>Ontario</td>
<td>6,628</td>
<td>11,301</td>
<td>12,042</td>
<td>82%</td>
<td>7%</td>
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<tr>
<td>Manitoba</td>
<td>574</td>
<td>1,228</td>
<td>1,290</td>
<td>125%</td>
<td>5%</td>
</tr>
<tr>
<td>Saskatchewan</td>
<td>833</td>
<td>1,009</td>
<td>1,072</td>
<td>29%</td>
<td>6%</td>
</tr>
<tr>
<td>Alberta</td>
<td>1,568</td>
<td>2,413</td>
<td>2,701</td>
<td>72%</td>
<td>12%</td>
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<tr>
<td>British Columbia</td>
<td>1,845</td>
<td>2,903</td>
<td>3,203</td>
<td>74%</td>
<td>10%</td>
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<tr>
<td>Territories</td>
<td>11</td>
<td>53</td>
<td>44</td>
<td>300%</td>
<td>-17%</td>
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<tr>
<td>Unknown</td>
<td>222</td>
<td>5</td>
<td>10</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Canada</td>
<td>14,938</td>
<td>24,177</td>
<td>26,500</td>
<td>77%</td>
<td>10%</td>
</tr>
</tbody>
</table>
Mayo Clinic (Rochester, MN)

- “Biomechanical Evaluation of a Microprocessor Controlled Prosthetic Knee Joint - Part I Pilot Study” by K.R. Kaufman
- “Effectiveness of Revision Knee Arthroplasty”
- “A Clinical Study - Incorporating an Oxidized Zirconium Vs. Cobalt Chrome Femoral Prosthesis in Total Knee Replacement”

-by S.P. Scully
NIAMS (Bethesda, MD)

- National Institute of Arthritis and Musculoskeletal and Skin Diseases
- Developing safer and more effective pain relief for osteoarthritis
- Glucosamine and chondroitin
  - Nutritional supplement
  - Reduces the pain of osteoarthritis (not clinically proven)
- Preventative measures against joint injuries
- The role of exercise in protecting the knee
Questions?
References