WORKSHOP
The Evolution of Total Joint Arthroplasty: A Historical Review of Hip, Knee, and Shoulder Prosthesis Design Advances

(Organized by the ORS Industry Engagement Committee and ORS Orthopaedic Implants Section)

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Speakers:
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John Callaghan, MD
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ORS 2018 Annual Meeting Workshop: March 11, 2018 from 7-8:15am

The evolution of total joint arthroplasty: a historical review of hip, knee, and shoulder prosthesis design advances

Organized by ORS Industry Engagement Committee (IEC) & ORS Orthopaedic Implants Section
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Speakers:
Historical Overview of Shoulder Arthroplasty Prosthesis Design
Evan Flatow, MD, Mt. Sinai School of Medicine

Historical Overview of Hip Arthroplasty Prosthesis Design
John Callaghan, MD, University of Iowa

Historical Overview of Knee Arthroplasty Prosthesis Design
Michael Mont, MD, Cleveland Clinic

Abstract: Total joint arthroplasty is one of the most cost-effective and clinically successful medical procedures ever devised, with highly predictable outcomes for many different indications in the hip, knee, shoulder, and other diarthrodial joints. Prosthesis designs for each application have evolved over the past 50 years in an effort to improve long-term survivorship and patient satisfaction while also reducing the occurrence and severity of complications. Furthermore, expanding clinical usage and indications, and utilization of novel materials and manufacturing technologies have driven numerous prosthesis innovations that offer the potential to improve clinical outcomes. Thought leaders will describe the design lineages of hip, knee, and shoulder arthroplasty prosthesis designs, describing the ever-changing surgical, patient, engineering, and business factors that have influenced device requirements and led to the contemporary prosthesis designs. Finally, future advances in prosthesis design which offer the potential to improve clinical outcomes will be discussed.
Historical Overview of Shoulder Arthroplasty Prosthesis Design
Evan Flatow, MD
Lasker professor of Orthopedic Surgery
President of Mount Sinai West Hospital

- Early History
  - Themistocles Gluck designed first arthroplasties in late 1800s
  - First shoulder arthroplasty credited to Jules-Émile Péan in 1893
  - Many attempts at acrylic and polyethylene prostheses in 1950s
  - Little progress until Neer designed first prosthesis for proximal humerus fractures in 1951
  - First modern total shoulder introduced by Neer in 1974

- Anatomic shoulder replacements
  - Long-term outcomes:
    - Glenoid wear and loosening has compromised long-term outcomes of anatomic total shoulders
    - Manufacturers have tried to address these issues by modifying glenoid components
  - Metal-back glenoids have had higher revision and early failure rates than standard all-poly glenoids and should not be used on a routine basis
  - Cemented vs uncemented humeral fixation
    - Both alternatives have produced good results but there may be a benefit to cementing certain implants in men
  - Managing Glenoid Bone Loss
    - Outcomes have been less favorable in patients with Walch glenoid B2 deformity
      - Companies have developed posteriorly augmented implants to address the B2 deformity
      - Having a posterior wedge implant allows to preserve the most bone while insuring stable support
    - In patients with severe bone loss or significant retroversion, inset glenoids may provide an option

- Reverse Shoulder arthroplasty
  - Term “Cuff Tear Arthropathy” coined by Neer in 1981
  - Noticed that patients with rotator cuff tears did more poorly and required a different type of implant to restore function
  - Designed the Mark I, Mark II and Mark III reverse total shoulders that produced poor results
  - In the 1970s, many different surgeons designed implants based on a fixed fulcrum system dependant on glenoid cementing and were fully-constrained
    - Led to premature failure of the glenoid component and high-revision rates
Some later designs shifted toward cementless glenoid fixation but still produced poor results with high complication rates

- In 1985, Paul Grammont revolutionized the design of reverse shoulder arthroplasty
  - New design based on 4 key features:
    - Inherently stable prosthesis
    - Convex weight-bearing surface, concave supported part
    - Center of the sphere at or medial to glenoid rim
    - Center of rotation distalized and medialized to improve deltoid lever arm
  - First modern reverse was Delta III that had ½ sphere to further medialize center of rotation in order to improve deltoid mechanical advantage.
  - Modern reverses face new challenges
    - Inferior and posterior notching
    - Instability
    - Limited active ROM and strength
    - Glenoid component loosening and wear
    - Acromial Stress Fractures
  - New designs are focusing on these issues
  - Biomechanics of lateralizing glenoid component and reducing humeral neck-shaft angle
    - Lateralization of glenosphere produced higher loads and increased the deltoid force required to produce abduction
    - Lateralization of the humerus required less force from the deltoid to produce abduction
    - Lateralization of the humerus from 15mm to 35mm improves rotator cuff torque
    - Lateralizing glenosphere and reducing the neck-shaft angle produced significantly more impingement-free motion in all planes
  - Clinical Studies
    - Both lateralized and standard implants provided similar clinical outcomes at 2 years follow-up although the lateralized short-stemmed implant had more favorable radiological outcomes in terms of notching, glenoid lucency and bone resorption.
    - In a 2016 systematic review, there was a clinically and statistically significant difference in external rotation favoring the lateralized group

- Stemless Shoulder Designs
  - Resurfacing implants were introduced as alternatives to standard hemiarthroplasty in hopes of preserving bone for future revisions
  - Preserves the head so very difficult to expose glenoid for total shoulder arthroplasty
    - According to the Danish registry, revision rates have been higher in resurfacing hemiarthroplasties than in stemmed hemiarthroplasties
  - Stemless implants
    - Theoretically retain the same advantages of resurfacing implants (i.e. preservation of humeral shaft, easier revision, possibility of implantation in patients with post-traumatic deformity)
- Involve making are similar head cut as for a stemmed implant making glenoid preparation and implantation much easier
- Not yet FDA approved
- Encouraging initial results showing similar short-term outcomes than traditional stemmed implants

- Patient-Specific Instrumentation and custom implants
  - Patient specific instrumentation systems have been developed by many manufacturers in order to improve accuracy among surgeons
  - Initial results have shown that the patient-specific instrumentation systems require more work to better control reaming and rotation of components
  - Vault reconstruction systems and custom implants are now being developed for patient who have severe deformity

- Thinking outside the box
  - Pyrocarbon interposition arthroplasty is a novel implant that has been designed for very young patients with osteoarthritis or osteonecrosis
  - Pyrocarbon has favorable tribologic and elastic properties minimizing joint wear
    - Pyrocarbon interposition arthroplasty has similar patient reported outcome scores to hemiarthroplasty but inferior to total shoulder arthroplasty
    - However, high-revision rates, high rates of bony erosion and lack of long-term data leaves significant questions about using this implant as an alternative to hemiarthroplasty

References:
I. Early Development of Hip Replacement

A. Precursors to successful total hip replacement
   1. Cup arthroplasty (Smith-Petersen)
   2. Endoprosthesis i.e. Austin Moore

B. The initial breakthrough: Charnley low-friction arthroplasty
   1. Why the Charnley total hip replacement was clinically successful
      a. Use of cement to anchor the prosthesis to bone
      b. Use of a metal-on-plastic articulation

C. One step backwards before moving forward
   1. The rapid failure of Polytetrafluoroethylene (PTFE – aka Teflon)

D. The second breakthrough
   1. The story of finding a new bearing surface
   2. Polyethylene for the acetabular component

II. Development of Cemented Femoral Components

A. Femoral component designs which protected cement (no sharp corners and were torsionally stable) Charnley design, T-28, HD-2

B. Collar, collarless controversy to preserve bone quality

C. Torsionally stable designs vs a taper wedge philosophy (Exeter)

D. Improvement in metallurgy to prevent stem fracture

E. Evolution of stem surface finish from satin to grit to polish

III. Development of Improved Cementing Technique

A. Hand packing cement

B. Cement gun to introduce cement

C. Cement pressurization

D. Porosity reduction

IV. Understanding the Biology of Component Failure

A. Cement disease

B. Particle disease (wear became the main culprit)
C. Mechanical vs biological mechanisms

V. The Move to Cementless Fixation from Cemented Fixation

A. Porous coated devices

VI. Development of Durable Bearing Surfaces

A. Recognition of polyethylene as the limitation to total hip arthroplasty durability (late 1990's)
   1. Oxidation
   2. Crosslinking

B. Development of options to traditional gamma in air polyethylene
   1. Crosslinked polyethylene
   2. Ceramic-on-ceramic
   3. Metal on metal

C. The results of the change in bearing surface (late 1990's) at 15 years (2017)
   1. Crosslinked polyethylene, minimal wear, minimal osteolysis, minimal failure
   2. Metal-on-metal: relatively high failure from adverse local tissue response (ALTR)
   3. Ceramic-on-ceramic, excellent durability, squeaking and liner chipping from impingement

D. Understanding the need for circumferential coating and the effective joint space: the gasket effect

E. Variations in femoral design
   1. Fully coated vs proximally coated designs
   2. Porous coating vs Hydroxyapatite vs textured titanium surfaces
   3. Straight vs anatomic vs tapered
   4. Use of modularity

VII. Cementless acetabular devices and fixation

A. Technique and designs providing stable fixation
   1. Press-fit of the components
   2. Screws and spikes for augmentation
   3. Improvement in porous surface technology
      a. Trabecular metal coatings
      b. 3-D printing

VIII. Development of Optimal Femoral Head Size

A. Issue with stability vs wear

B. Smaller head size, less wear
   1. Sliding distance (short)
   2. Polyethylene thickness

C. Larger head sizes
1. Greater motion to impingement and dislocation (dropout distance)
2. Thinner polyethylene and longer sliding distance

IV. Future Challenges Providing 50 Year Durability in Active Patients and the Ultimately Stable Hip

A. Obstacles to 50 year durability
   1. Wear at bearing surfaces
   2. Wear of modular connection
      a. Femoral head tapers
      b. Modular acetabular liners

B. Improvement in Stability
   1. Robotic and computer assisted technology for optimal patient specific component positioning
   2. Newer designs including dual mobility bearings

References:
Historical Overview of Total Knee Arthroplasty Prosthesis Design
Michael A. Mont, MD
Department of Orthopaedic Surgery
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Early prosthetic models:
- Soft tissue interposition for construction
- Resection arthroplasty
- Hinged arthroplasty
- Campbell metallic interposition femoral mold
- Massachusetts General Hospital interposition prosthesis

Resurfacing and condylar protheses:
- Macintosh: acrylic then later metallic tibial plateau prosthesis
- Mckeever prosthesis: similar concept and wider utilization
- Gunston modifications: polycentric prothesis

Evolution of modern total knee arthroplasty (TKA):
- Freeman-Swanson prosthesis: pioneering the technique and design and introduction of the concept of ligament balancing and soft tissue releasing
- The Hospital for Special Surgery duocondylar knee (1971)
- Duopatella knee (Ranawat, 1974)
- Total condylar knee (Insall, 1974)
- The anatomic vs. functional protheses
- Modularity and Eftekhar Mark knees
- David Murray’s variable axis

Early cruciate retention design:
- Yamamoto and Kodoma prosthesis: the first cementless condylar cruciate-sparing total knee
- Townley’s design with cruciate retention, patellar resurfacing
- Geomedic/metric knee and posterior cruciate ligament (PCL) retention
- Porous coated anatomical knee (PCA) and cementless fixation

Current prosthesis design:
- Fixed-bearing, surface replacement prostheses:
  - Traditional cruciate-retaining and posterior-stabilized prosthesis
- Guided motion prostheses
- High-flexion and gender-optimized prostheses
- Cementless fixation
- Mobile-bearing prostheses
- Constrained prostheses
  - Constrained unlinked prostheses
  - Constrained rotating hinge prostheses

Evolution of design features:
- Articular geometry
- Design and fixation of the tibial component
- Modular augments and stems
- Patellar resurfacing and configuration
Future perspectives:
- Robotic and navigation technology
- Cementless fixation
- Conclusion

References: