Joint Replacement

8.1. Introduction

The well-documented increase in the number of older people is creating an ever increasing demand for total joint replacement. At the same time, the increasing health and activeness of these people creates demand for long-lasting reliable joints minimizing the need for costly revision surgery.

The design and development of new joint replacements is a highly interdisciplinary activity, calling for the combination of sound biomechanical understanding, detailed knowledge of anatomy and surgical experience and insight.

Joint replacement is still one of the major successes of modern medical treatment, transforming the lives of the increasing number of older individuals in the population as well as now offering a realistic return to normality in younger patients with problem joints. The expectations of patients as well as their surgeons continue to rise in terms of the ability to restore function, relieve pain and provide excellent long-term performance. Success in the hip has been followed in fairly short order by similarly good outcomes in the knee, with other joints not so far behind. The position gradually being reached is that restorative implantation surgery will provide answers for those debilitated by disease in the hand and foot, the ankle and the upper limb joints, as well as the spine. Each of these joints has its own unique characteristics in terms of the requirements to be met in achieving a successful replacement device and procedure.

Designers of joint replacements should be familiar with past successes and failures so as to learn the lessons provided by them so as to apply successful features and not to repeat the errors of the past. Designers must also be capable of applying appropriate engineering, scientific and medical principals to the design, or redesign, of joint replacement so as to maximize their performance and minimize their risk.

8.2. Design of Joint Replacements Understanding

8.2.1 -Basic Anatomy such as the understanding of the movements of the human body which that are controlled by its skeletal structure, which is made up of bones, joints, muscles, tendons and nerves. Even in healthy bodies, these parts of the skeletal structure can develop disorders, the symptoms of which can be pain, stiffness, swellings, deformity, loss of function and changes in sensitivity. Of these symptoms, pain is the most common.

8.2.2- properties of materials used in orthopedic implants and instruments is essential in the design and evaluation of such devices. Such understanding involves knowledge of mechanical and corrosion properties, and most importantly the biological reaction to such materials. Biomaterials can be divided according to the chemical composition as follows: Metals, polymers, ceramics and composites

8.2.3- Mechanical properties involve an understanding of the concepts of stress and strain, stiffness, hardness, yielding, fracture and fatigue resistance. Corrosion involves an understanding of surface chemical properties and chemical reactions with the environment surrounding the orthopedics devices. Biological interaction involves the reaction of the body to the release of toxic substances resulting from corrosion and wear in both the short and long term.

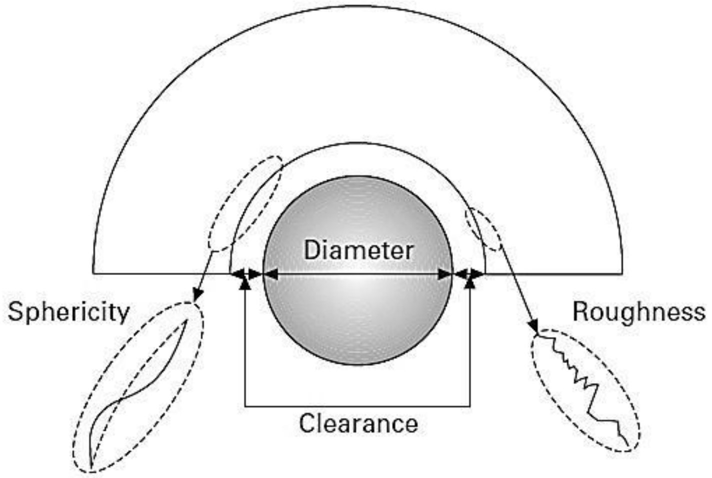
8.2.4- Tribology

Tribology is defined as 'the study of friction, wear and lubrication, and design of bearings, science of interacting surfaces in relative motion' and was formally defined as 'The science and technology of interacting surfaces in relative motion and the practices related thereto'. It encompasses a number of basic engineering subjects such as solid mechanics, fluid mechanics, lubricant chemistry, material science and heat transfer. Important considerations in tribology include surfaces, both microscopic surface topographies and macroscopic bearing geometries, bearing materials, relative motion and loading as well as lubricants. The transient nature of tribological processes should also be pointed out, as the loading and motion involved are often dynamic and the wear of the bearing surfaces can modify the geometry both microscopically and macroscopically.

Tribology plays an important role in the functioning of artificial joints. Hip joints are subjected to a large dynamic load, up to a few times bodyweight during normal walking, and yet this is often accompanied by a large range of motions. Friction played an important role in the design of the original Charnley low-friction arthroplasty. Wear is important, not only from the point of view of the integrity of the prosthetic component, but also from that of wear debris generation which can cause adverse biological reactions. Lubrication can be the most effective means to reduce both friction and wear.

8.2.4.1. Surfaces and roughness

Tribology is mainly concerned with surfaces in relative motion. Therefore the surface profile, texture and topography are all important. For example in an artificial hip joint, the important design parameters include the radii of the femoral head and the acetabular cup, or the diametric clearance between the femoral head and the acetabular cup as shown in Fig.1. The important manufacturing features include sphericity and roughness.



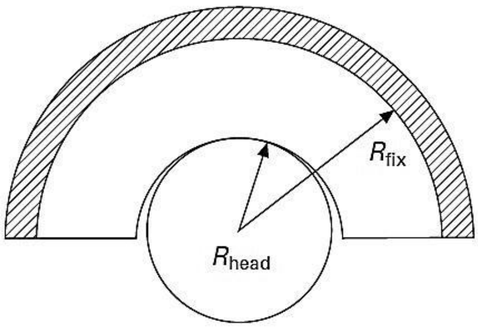
Design and manufacturing parameters associated with the bearing surfaces of artificial hip joints.

8.2.4.2. Contact mechanics

Contact mechanics refers to the mechanics when two bodies are brought into contact. The output from a contact mechanics study generally includes contact stresses, both at the bearing surfaces (also known as the contact pressure) and within the component, and the contact area. The common approach to the study of contact mechanics is either through experimental measurement or computational prediction. The study of contact mechanics in artificial joints is important. The contact parameters are closely linked to the tribology of the bearing surfaces and are often used as input conditions to the overall tribological studies. The contact stresses are important considerations in the design of both hip and knee joint replacements.

8.2.4.3. Friction

Friction generally refers to the resistance to motion. The friction at the bearing surfaces directly affects the stresses transmitted through the fixation interface The frictional force (*S*) at the fixation interface between the outside of the acetabular cup and the underlying support (either cement or bone) is



Schematic diagram of a hip implant with radii of the femoral head (R_{head}) and the outside of the cup (R_{fix}).

$$S = \frac{\mu W R_{\text{head}}}{R_{\text{fix}}}$$

Therefore, to reduce the frictional force transmitted to the fixation interface, it is important not only to minimize the friction coefficient, but also to reduce the femoral head radius and to increase the outside radius of the acetabular cup. These are essentially the design features considered in the Charnley low friction arthroplasty

8.2.4.4. Wear

Wear is defined as progressive loss of substance from the operating surface of a body occurring as a result of mainly relative motion between the articulating surfaces. The importance of wear in artificial joints is manifested not merely by the loss of the accuracy of the bearing geometry, which can subsequently decrease tribological and kinematics functions, but also the biological consequences of the wear debris. The importance of wear in artificial joints has become more evident recently as a result of the recognition of wear debris induced adverse biological reactions. it is now generally accepted that wear particles liberated from artificial joints can cause adverse tissue reactions, osteolysis and loosening.

Different terms are often used to describe the wear phenomenon in artificial joint replacements. These include pitting, scratching, burnishing and delamination on retrieved total condylar knee joint replacements.

However, the following five wear mechanisms are usually used to describe the fundamental wear process.

1. Abrasive – the displacement of materials by hard particles.
2. Adhesive – the transference of material from one surface to another during relative motion by the process of solid-phase welding.
3. Fatigue – the removal of materials as a result of cyclic stress variations.
4. Erosive – the loss of material from a solid surface due to relative motion in contact with a fluid which contains solid particles.
5. Corrosive – a process in which chemical or electrochemical reactions with the environment dominates, such as oxidative wear.

Wear volume (*V*) is generally found to increase proportionally to the normal load (*W*) and the sliding distance (*x*) as follows:

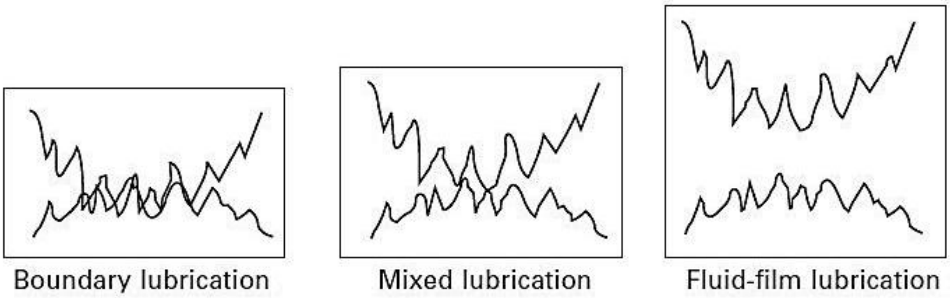
$$V = kWx$$

where *k* is a wear factor, usually with a unit of ^{3}/(Nm).

8.2.4.5. Lubrication

Lubrication generally refers to the presence of a lubricant between the two bearing surfaces of artificial joints. Synovial fluid is generally present in healthy natural joints. Although the viscosity of the lubricant plays an important role in the fluid-film lubrication of artificial joints.

In engineering, lubrication is usually divided into three regimes, fluid-film, mixed and boundary lubrication, as illustrated schematically in Fig. 3. The tribological characteristics associated with each lubrication regime are listed below:



Schematic diagram of three different lubrication regimes.

***Fluid-film lubrication*: ** A complete separation is achieved between the two bearing surfaces. The most important lubricant parameter is viscosity. Under the fluid-film lubrication regime, both friction and wear are minimized. However, a complete elimination of friction and wear is impossible in artificial joints due to the viscous shearing of the lubricant and the breakdown of fluid-film lubrication associated with start-up and stop motions.

***Boundary lubrication*: ** Extensive asperity contacts occur and both wear and friction are significantly increased. Boundary lubricating films play an important role in this lubrication regime, which depend on both the physical and chemical properties of the lubricant.

***Mixed lubrication*: ** This lubrication regime consists of a mixture of both fluid-film and boundary lubrication regions. The tribological characteristics in this lubrication regime depend on the relative contribution of the fluid-film and boundary lubrication.

8.3- The Design

8.3.1. Process

Good design is the key to producing a quality product. The design process should ensure that the design requirements (Design Input) are understood and documented; the design should be continuously reviewed to ensure that the design output matches the design input; and that the design is thoroughly verified and validated before the design is released for production. The resulting final product must meet the requirements for the design, meet all of the design specifications for form and performance, and be introduced in a manner that is in compliance with applicable regulations (Design Input). The device must also be validated after initial production to insure that these requirements are met and will continue to be met.

Good design must be based on sound engineering methods and principles and the applications of such methods and principles by talented, creative designers with a high state of knowledge of the science and practice of orthopaedic implants and instrumentation. Good design involves an understanding and input from several disciplines such as Engineering, Manufacturing, Medical Director, Marketing and Sales.

8.3.2. Procedure

Product design is an iterative process that demands flexibility and the ability to change the design, design inputs and design requirements. The procedure given here is intended to provide a template for guiding the design process. As such, different projects should have different requirements and all parts of this procedure may not fit every project. This should be continually assessed during the project using formal, documented, design reviews. All new designs or significant changes to existing designs should be managed under such a procedure.

8.4. Knee Joint Replacement

8.4.1. Anatomy

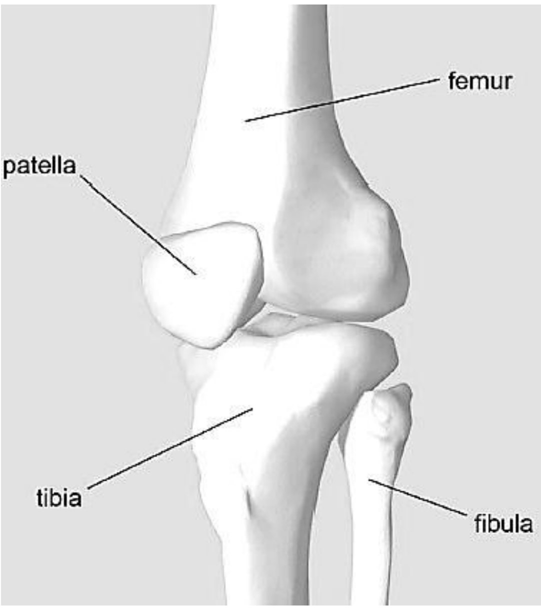
The complex known as the knee joint consists of the femur, tibia, fibula and patella (Fig), articulating to accommodate mainly extension and flexion and to a limited degree of varus-valgus and axial rotation.

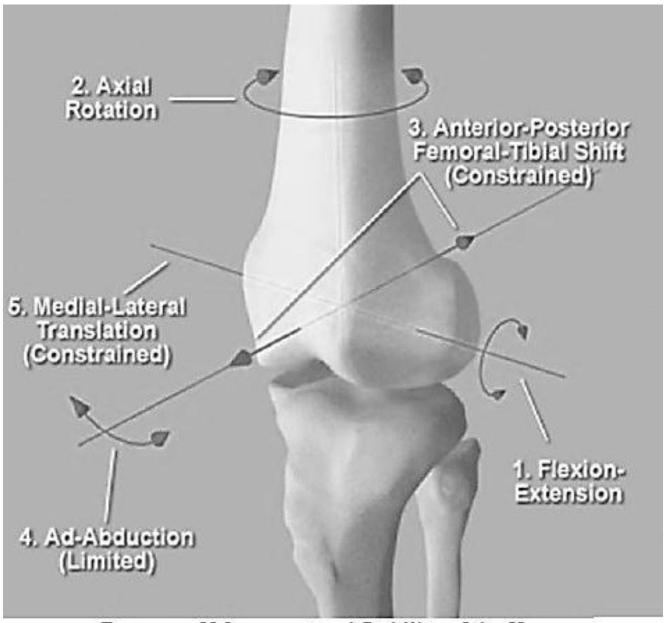
8.4.2. Biomechanics *(Kinematics)*

The five degrees of freedom associated with the knee joint are illustrated in Fig. These are

1. Flexion - Extension; this is the principal motion of the joint.
2. Axial rotation; this motion is limited primarily by the ligaments of the knee.
3. Abduction - Adduction; this motion is limited by the ligaments and the tibiofemoral articulating surfaces.
4. Anterior-posterior (A-P) translation; this motion is limited by the ligaments and the tibiofemoral articulating surfaces.
5. Medial-Lateral (M-L) translation; this motion is limited by the ligaments and the tibiofemoral articulating surfaces.

The first two are associated with primary knee motion and the remaining with secondary knee motion and stability





Degrees of Movement and Stability of the Knee

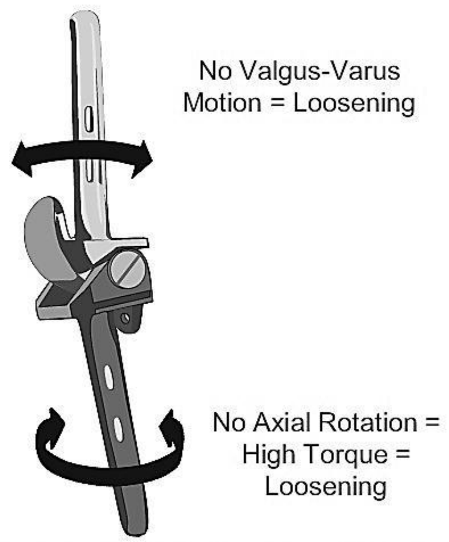
8.4.3. Pathology

Disease processes involving the knee joint are usually classified into congenital, metabolic, neuro-muscular, infectious, autoimmune and post-traumatic.

8.4.4. Knee Replacement

8.4.4.1. First Generation Designs

Early hinge designs of the 1950's, knees restricted motion to a single flexion-extension axis. Although they initially worked reasonably well, when they were simply press-fit into the bone, they showed early loosening when used with cement. This loosening is attributed to over-constraint resulting from lack of axial and ad-abduction rotation producing large axial and varus-valgus. Later resurfacing designs of the late 60's, such as the "Geomedic" and "Geometric", also rapidly failed due to lack of axial rotation, as shown in Fig.



Loosening Resulting from Lack of Axial Rotation in Hinge Type Knees

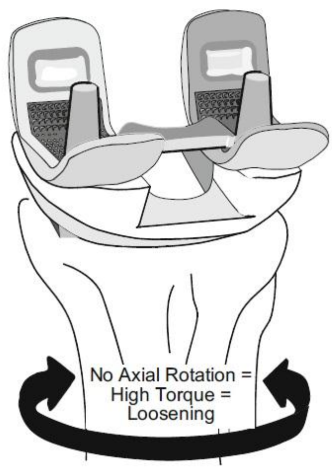
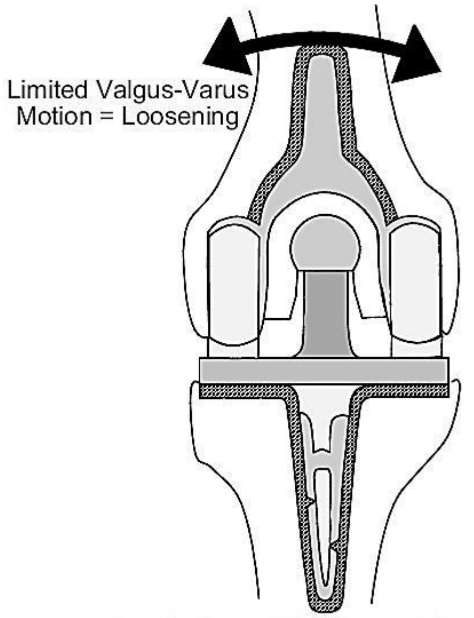


Fig. Loosening Resulting from Lack of Axial Rotation in Resurfacing Knees of the "Geomedic" Type

8.4.4.2 Second Generation Designs

The 1970's saw the introduction of improved resurfacing designs which provided for patellar replacement. The "Total Condylar" and "Townley" designs worked reasonably well. The principal problems were; lack of adequate flexion, patellar wear and loosening, posterior subluxation of the Total Condylar and tibial loosening and excessive pitting type wear with both devices



Loosening Torques in the Spherocentric Knee

8.4.4.3. Third Generation Designs

The mid, and late, 1970's saw the introduction of mobile bearing knee designs.These designs provide mobility and congruency by use of a second bearing surface articulating against a metal tibial platform. The mobile bearing concept solved the dilemma of congruency vs. constraint facing knee designers of the time as illustrated in Fig.

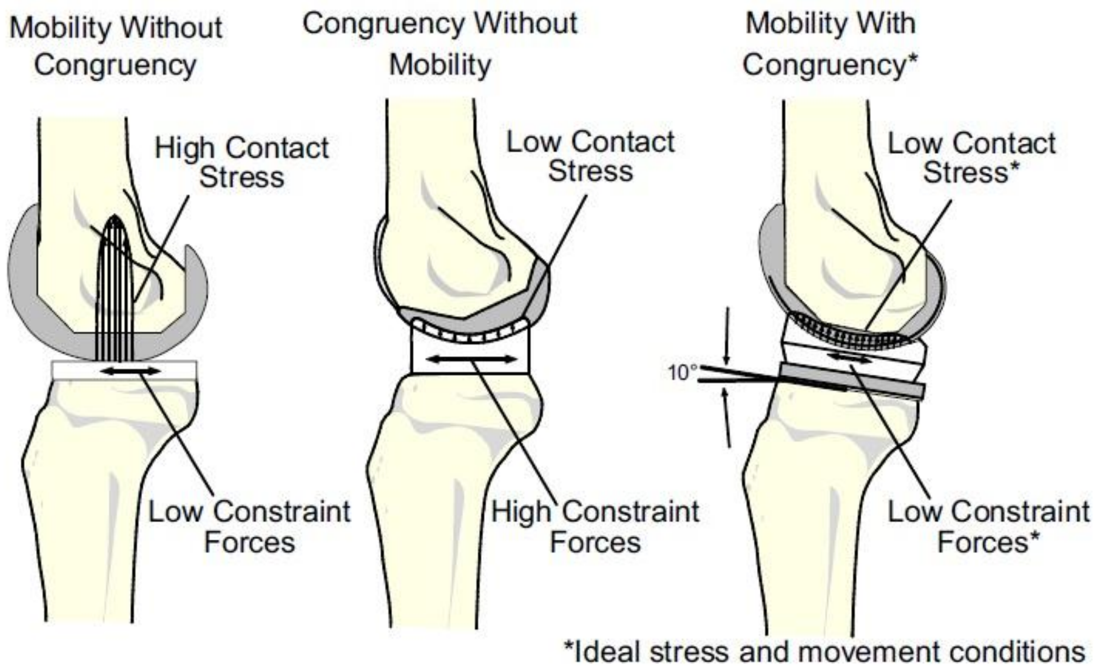


Fig. Mobile Bearing Solution to the Dilemma of Mobility vs Congruity

8.4.4.4. The Fourth Generation

Experience with the LCS and the improved availability of materials and manufacturing process provided information to allow further development and refinement of the LCS, or Buechel - Pappas Mark II mobile bearing knee replacement. A series of new designs were then developed during the period from 1998 through 2009 leading to the B-P Mark V Total Knee Replacement shown in Fig.

The metallic components of this knee are made of wrought titanium alloy coated with a wear and scratch resistant TiN ceramic coating described earlier. Co-Cr versions are available as well. The articulating surfaces have been refined so that the peak contact stress in the Mark V is about half that of the very successful LCS

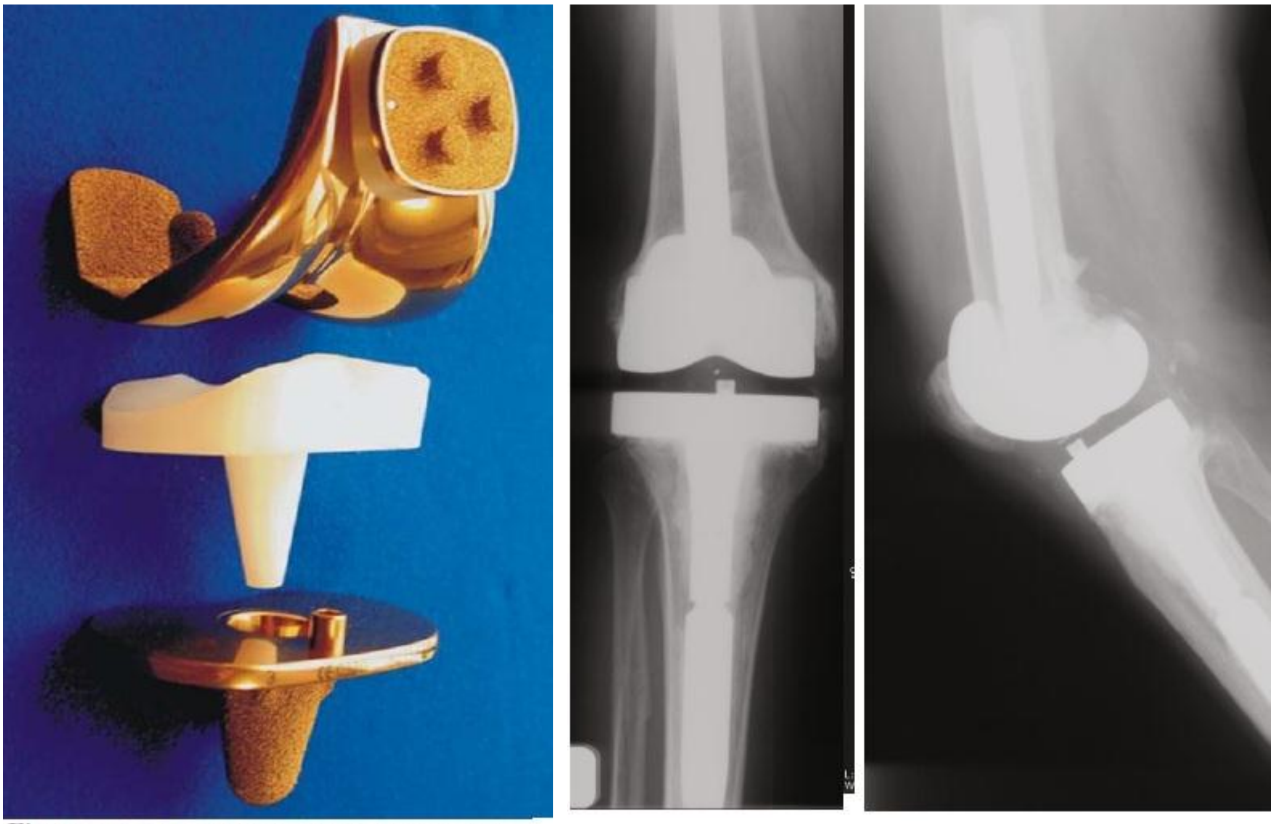


Fig. The B-P Mark V total Knee Replacement

8.5. The Future

Clinical experience and evaluation of the design concepts and materials currently employed in joint replacement devices will provide information needed to refine or abandon existing designs and to develop new ones. The principal means for design improvement, probably will come from the development of new materials rather than new design concepts.

During the last quarter century, after the development of mobile bearing knees, there has been little improvement is knee joint replacement design. The Oxford knee is basically the same as it was a quarter century ago. The B-P design variants are only slightly improved in that time. Posterior stabilization seems unsound based on engineering principles and clinical experience.

The primary improvements have come from the introduction of ceramic coated titanium alloys and the possible improvement of UHMWPe. Even here the advantages of these materials are somewhat controversial and time is needed to more fully evaluate their benefits.

Probably the greatest impact may come in surgical technique, rather than implant design. The application of computer technology to surgery, although in its infancy, has great potential in producing greatly improved prosthetic alignment, an important, if not critical, need for improved knee joint replacement performance. This is particularly true for mobile bearing unicondylar knee replacement where accurate positioning is more important since all the ligaments are retained. The shape and location of the implants must be such that the functioning of these ligaments is not excessively degraded.