

BIOTRIBOLOGY CONSIDERATIONS OF TOTAL KNEE REPLACEMENT

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ABSTRACT

The knee joint is a complex system of bones, cartilage, tendons and other soft tissue, that, in a healthy state, work together to provide mobility and support to the body. However, in severe states of osteoarthritis, total replacement of the knee joint is essential not only to relieve the pain, but most importantly to restore the mobility lost due to the degeneration of the cartilage and also to protect the surfaces of the articulating bones from further wear. In total knee replacement systems available today, a major cause of implant failure is wear of the articulating materials. It is therefore essential to study the modes of wear in order to understand better how to resolve this critical problem. In this paper, a brief overview of the anatomy of the knee was provided as well as the loading conditions on the joint, during walking, that can cause wear of the bones and/or cartilage. This information was then used to examine choices of past, current and future materials and to analyze how each of the components, with their material properties, restore the function of the knee.

1. Introduction

The knee is a complex system of tissues that provide mobility and support to the body. It experiences different types of motion as a whole system or relative to its parts and is therefore subjected to a variety of loading conditions as a person walks, runs, or performs any other type of load-bearing activity. In the knee joint, a set of muscles and ligaments joins three bones (the tibia, the patella and the femur) and controls the range of motion of the knee. Cartilages assist the articulation of the knee by providing cushion to the joint as well as a smooth and lubricated surface. For a healthy knee, the cartilage minimizes the wear on the bones. However, in cases of osteoarthritis where the cartilage is degraded, the bones of the knee rub against each other causing both wear of the bones, and extreme pain to the person. In mild cases of osteoarthritis, over-the-counter or prescription non-steroidal anti-inflammatory drugs may be taken. In severe cases, however, surgery to replace the joint may be the only option. There are several types of knee replacements that range from partial to total knee replacements (TKR). The type of replacement a patient receives depends on the severity of the condition requiring the replacement.

In 2005, it was estimated that over 400,000 TKRs were performed in the US. Not considering infection, the major reasons for implant failure are aseptic component loosening (defined as the production of microscopic particulate debris produced at the bearing articulating surfaces) and macroscopic component wear [1]. In this paper, the problem of wear in total knee replacements will be explored as they are exposed to loading conditions during walking. To do this, a background on the anatomy of the knee will be presented. A detailed description of the kinematics of the knee during walking will also be provided to gain a better understanding of the loading conditions on the joint, and thus provide further insight into what causes wear and its specific location on the joint. This information will be used to evaluate current knee replacements on the market, to evaluate suggested designs to improve weaknesses of the current systems, and to formulate further recommendations on reducing the problem of wear.

2. Problem Statement

Despite the astounding biomechanical performance of the healthy knee, roughly 400,000 patients each year will receive a TKR as a result of osteoarthritis. While advances have been made to improve performance and lifespan of the artificial joint, the artificial joint fails to mimic

the performance of a healthy knee. Several materials make up an artificial knee joint that are designed to work together to mimic the natural state of the joint. Part of this condition must allow for motion of two surfaces while minimizing wear, which currently is one of the major reasons for implant failure. While 85% of joint implants will last 20 years before failure, roughly 17,000 knee replacements fail annually because of problems surrounding wear in the materials [2]. Therefore, it is important to investigate how well different articulating materials (polymer, ceramic and/or metal), currently on the market and under research and development, mimic a healthy articulating joint and to look closely at what happens at the surface of these materials.

3. Background

3.1 Knee Biomechanics

The knee is an important consideration in the study of biomechanics because it is one of the most commonly injured areas of the body and is susceptible to degenerative joint diseases. The knee joint joins the femur, tibia, and surrounding supportive muscle and ligament groups [3]. The inferior femur has lateral and medial femoral bulbs, or condyles, that rest on the concave tibial condyles of the superior tibia. Cruciate ligaments hold the femur and tibia together, and additional muscles and ligaments serve to stabilize the knee [3].

Anatomical considerations for this report will be limited to bone and cartilage components of the knee, as those are the main players in the occurrence of wear. Both the superior tibia and inferior femur have a covering of cartilage. This layer of cartilage, known as the meniscus, separates the bone surfaces. Motion in joint is supported on a thin fluid film that sits atop the cartilage layer, which leads to low wear and friction in the healthy knee [3]. The most identifiable component on knee anatomy, the patella (or kneecap), is connected with patellar ligaments that aid in extension of the knee joint.

3.2 Total Knee Replacement

3.2.1 Indication

Integrity of the cartilage is a vital component of the healthy knee's performance. Any damage to joint surface can cause osteoarthritis, a type of degenerative arthritis brought on by the breakdown of cartilage. Softening, splitting, and fragmentation of the cartilage surface occur and compromise integrity of the cartilage layer. When this happens, the bones of the femur and tibia

rub against each other causing extreme pain. Often, parts of the knee joint can be replaced. However, in severe cases of osteoarthritis, TKR is required to restore full function of the knee.

3.2.2 Knee Replacements and Implant Design

There are various types of knee replacement surgery, which range from partial procedures that treat one or two compartments in the knee to total knee replacements that address all three compartments. Knee implants, shown below, serve as replacement for removed portions of the femur, patella, and tibia.

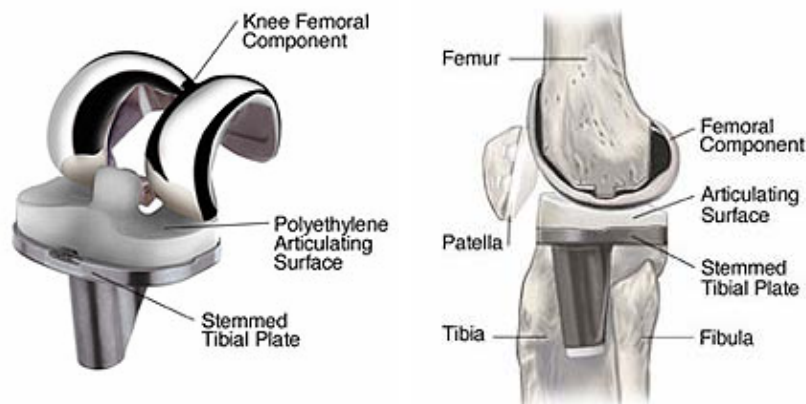


Figure 1: Total Knee Replacement- Implant Diagrams [22]

There are over 150 knee implant designs on the market today, so implant design can vary significantly from one manufacturer to the next [2]. All knee replacements, whether partial or total, are designed so metal components articulate against plastic components, resulting in minimal wear. The metal components consist of titanium or cobalt/chromium-based alloys while the plastic components consist of an ultra-high molecular weight polyethylene. The metal femoral component curves around the condylar surfaces of the femur. The interior groove enables the kneecap to move up and down when the joint bends and straightens [2]. The tibial component is a cushioned platform that is stemmed for implant stability. The metal stem is topped with a polyethylene cushion that acts as the articulating surface.

3.2.3 Surgery, Complications, and Recovery

To perform a total knee reconstruction, the worn surfaces of the femur and the tibia are first reshaped. The end of the femur is then capped with a curved metallic component that is set in place either with bone cement or with screws. The end of tibia is also capped, but with a metallic

tray that will hold a plastic spacer. The metallic tray is set in place using the same cement, and the spacer set in place by press-fitting the component into the tray. The plastic insert is used to mimic the articular cartilage and is either fixed into the tray or is designed to allow rotation relative to the tibial tray. Finally, the surgeon will resurface the back of the patella with a plastic material, after which time the bones are realigned and tested for motion. Advances in modern medicine have allowed for knee replacement surgeries to become minimally invasive. This requires a smaller incision (3 to 5 inches) and results in less tissue [2]. This, in turn, leads to less pain in recovery and decreased recovery time. However, only a small percentage of surgeons are trained to perform this method. Traditional knee replacement surgery requires an 8 to 12 inch incision as well as an incision through tendon [2].

Recovery from total knee replacement requires an average hospital stay of 3 to 5 days. Walking support, such as crutches, canes or walkers, must be used until the patient is able to support their full body weight again. Most patients are able to walk comfortably with minimal assistance after a 6-week timeframe. Physical therapy can be initiated as soon as a few hours post surgery and can last for more than 3 months [4, 5]. Fig. 2 below shows a sketch of an implanted knee joint next to a normal knee joint.

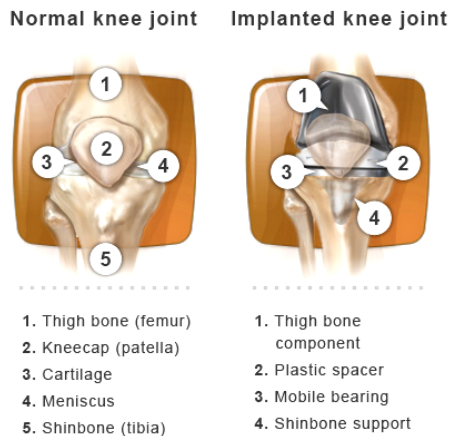


Figure 2: Anatomy of the normal knee joint and an implanted knee joint. [DePuy]

It must be noted that even with the best surgeon, the best possible alignment of the knee joint and careful choice of the TKR product, TKRs have a lifespan of up to 20 years. Besides infection, the main roots of implant failure are aseptic loosening and osteolysis due to excessive wear, which depends on the articular surface design, the surface finish, joint kinematics, joint loads, and locking mechanisms placed on the tibial tray. Therefore, it is essential to examine both

the mechanical loading conditions imposed on the knee replacement and the material properties of the implant to gain a better understanding of why it may fail and what can be done to avoid failure. Deformation and wear are important considerations because both are dependent on pressures on the surfaces of the sliding components in the knee joint.

4. Mechanical Analysis

4.1 Biomaterial Properties

Mechanical and material properties of cartilage in the knee are hard to quantify because of measurement difficulties and insufficient sampling. Tissues are hard to grip without damaging, and external factors can lead to inaccurate or faulty measurements, especially when dealing with biomaterials *ex vivo* [6].

Tensile modulus of articular cartilage in the knee has been measured in the range of 3.1-5 MPa in high weight bearing areas and 5.4-10.1 MPa in low weight bearing areas of the femoral condyle [7]. With this said, a more accurate characterization of cartilage is that of compression because loading on the knee during walking and standing is compressive. Compressive modulus for articular cartilage has been measured anywhere from 0.1 to 2 MPa and can vary significantly, even within a single joint [6].

4.2 Contact and Loading

4.2.1 Joint Loading

It has been estimated that femoro-patellar contact forces can range from 300 to 2000 N during normal walking. This translates to a compressive stress of 2-4 MPa on the contact surface [6]. When considering joint loading on the knee, it is important to note that load on the knee joint is rarely constant for an extending period of time. Proper loading analysis must consider spatial dimensions, position of the joint, and muscle groups most active in loading activity. The walk cycle is broken into four phases: stance, swing, heel strike, and toe off. For most of the walk cycle, one leg is in swing phase and one is in stance [6]. The leg in stance phase is weight bearing and in contact with the ground. The walking cycle becomes more complex when considering the five separate motions involved: pelvic rotation, pelvic tilt, knee flexion, ankle flexion, and toe flexion. These five motions result in a center of gravity path that oscillates left to right and up and down creating a figure 8 motion [6].

Maximum load on the knee occurs during the heel strike and just before toe off phases of the walk cycle, where it reaches about 1500 N [7]. Sliding velocity in the knee varies with load and increases as load on the knee decreases. Forces in the knee are highly dependent on the position of the tibia, as a 1-degree change in angle moves the knee by 10mm [7].

Joint force can be calculated with 2-D or 3-D analysis and static or dynamic analysis of horizontal force balance, vertical force balance, and moment balance in the joint. A 3D analysis of the knee in a stair climbing motion has been reviewed and is included in Appendix A. This analysis yielded a resultant joint force for stair ascent of 2.44W and for stair descent 3.21W. During walking, this resultant joint force ranges from 2.7- 4.3W [7].

Alternative analyses have been conducted to assess stability and load bearing characteristics of implants independent of the knee joint [8]. Tests used in these experiments measured displacements and rotations under applied loads and torques.

4.2.2 Surface Contact

Because the femur and tibia have the freedom to move somewhat independently of one another, there is not a simple solution for contact between the two surfaces. Fig. 3 below illustrates three possible orientations of the femoral surface on the tibial surface and compares shear forces for each position.

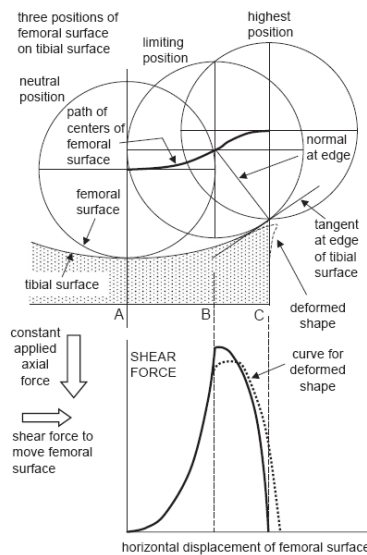


Figure 3: Tibio-femoral Surface Contact

Recent advances in interventional MRI have allowed for imaging of the internal anatomy of the knee joint and tibio-femoral contact regions. The posterior femoral condyles have been shown to

have close to circular surfaces in the sagittal plane, and these points have been used as reference for femoral condylar position relative to the tibia [9].

5. Materials Analysis

The next consideration that is just as important as the understanding of the loading conditions to which the knee joint is subjected is the choice of materials for TKRs. Ideally, components of a TKR must exhibit biocompatibility, increased wear and corrosion resistance, adequate strength that can sustain the cyclic loading in the knee, and suitable modulus to prevent bone resorption [10]. Dearnley provides a detailed review of different metallic, ceramic, and surface-treated metals used for joint replacements. The metallic materials include a variety of titanium and cobalt alloys as well as austenitic stainless steel and ceramic materials consist of alumina (Al_2O_3) and zirconia (ZrO_2). Surface engineered materials are those that combine the bulk properties of the metallic materials to the surface properties of a ceramic. These metallic, ceramic and surface-engineered materials are mainly used for the femoral and tibial components. To replace the damaged cartilage, ultra-high molecular weight polyethylene (UHMWPE) is used.

With regards to biocompatibility, there is not really one perfectly biocompatible material. Rather there are some materials that are considered more physiologically tolerable than others. That is, a material is biocompatible if it does not elicit an immune response in the duration that the material remains inside the body. Two main issues when performing biocompatibility tests include the physiological tolerance of surrounding tissues to the implant as well as the implant's reaction to surrounding body fluids, and the compatibility of wear debris when they remain in the body for an extended period of time [11]. Generally, the materials mentioned above have proven biocompatible and current manufacturers of TKRs have declared that their products, which are combinations of the mentioned materials, can remain in the body for up to 20 years.

To ensure that selected biomaterials meet the mechanical, tribological and biological demands *in vivo*, agencies such as the International Organization for Standardization (ISO) have established standards for biomaterials used for load bearing applications. For metallic articulating surfaces, a surface roughness (R_a) = 0.05 μm is required, and minimum tensile strengths of 860-930 MPa, 725-1275 MPa, and 850-1200 MPa are expected for titanium alloys, cobalt alloys, and austenitic stainless steel, respectively. For ceramic surfaces, R_a better than 0.02 μm is required with elastic moduli of 380 GPa for alumina ceramic implants and 152-220 GPa

for zirconia implants. Compressive strengths for these ceramic implants must also be in the order of 10^3 MPa [12].

For the femoral and tibial metallic components, it is essential that the materials not be too stiff. Bone grows with adequate mechanical stimulation, and if the material is too stiff, then the bone experiences reduced tensile and/or compressive loads. This results in reduced bone density and is known as stress shielding. As for the surfaces of these components, femoral components are typically designed with a highly polished surface as it serves to be the main articulating surface along with the UHMWPE tibial insert. A polished surface helps reduce friction by minimizing adhesion between the surfaces as well as minimizes both normal and shear stresses on the contacting surface. Increased adhesion can cause adhesive wear, and if normal and shear stresses reach high enough values, materials detach from the bulk in the form of debris particles, which then act as third-body particles that can lead to abrasive wear during tibio-femoral articulation. In fact, these are the main wear modes observed in the articulating surface, with most of the wear occurring on the medial compartment of the tibial plate [13, 14].

Another major source of wear in the TKR has been reported in an area previously considered to connect non-articulating surfaces: the tibial tray, and the tibial insert. For a fixed bearing TKR, the tibial insert is snap-fit into the tray and the focus was given to the main articulating surfaces. However, evidence from several studies [15, 16, 17, 18] suggests that care must also be taken when considering material and surface properties of these two surfaces. Micromotion caused by both the macromotion of the knee and improper fit of the UHMWPE insert on the tray lead to what is known as backside wear which is the wear at the interface between the bottom side of the polymer insert and the top side of the baseplate [15]. It was reported by McEwan, et al that backside wear may contribute up to 30% of the total wear of the polyethylene insert. Although articulation may be small compared to that of the femoral component and upper side of the insert, the contact area at this interface is larger compared to the main articulating surfaces and so will be subjected to friction and increased levels of cross shear. In this type of wear, a smooth surface will not necessarily produce the best result as it may allow for more sliding articulation between the two surfaces. Jayabalan reported backside wear in 3 total knee designs and found that the tibial tray that provides a full peripheral capture of the insert in order to limit motion in all directions had the least amount of backside wear. Therefore, a smooth upper tibial tray surface can benefit from reduced wear given that the tray provides adequate restraint to the insert, thus preventing micromotion.

Several materials have been tried and tested for TKRs. Zirconium-based implants replaced alumina due to their improved fracture resistance and hardness, and also due to its manufacturing ability to produce oxides which assists in controlling oxidative wear that can lead to delamination. In fact, the only system that uses ceramic technology for knee replacements in the US are those surfaces treated with zirconia ceramics [19]. In metals, titanium alloys are preferred to cobalt alloys and stainless steel due to their lower modulus, better corrosion resistance properties, and better biocompatibility. Titanium alloys, however, are prone to produce oxide layers and so several titanium alloys are being tested to optimize the properties that will be best suited for joint replacements [10]. Besides UHMWPE, several other polymers have been tested and these include polytetrafluoroethylene (PTFE also known as Teflon), polyacetal, high-density polyethylene, polyesters and carbon-reinforced UHMWPE. PTFE was generally inert and had a low coefficient of friction. However, it failed within a couple of years due to low resistance to creep and inferior abrasive wear properties. Polyacetal showed higher yield strength and was easier to manufacture than UHMWPE, but it only lasted 5 years due to high rates of failure. High-density polyethylene was also tried, but UHMWPE was found to be the better material [20]. Today, the research focus is on improving the degree of cross-linking in UHMWPE which was found to improve wear rates, but decreases the material's strength [19]. Another type of materials being tested are PVA-H hydrogels, which due to their high water content, provide reduced friction and reduced surface degradation of the opposing surface as compared to UHMWPE [21].

6. Conclusion

The knee joint is a complex system of bones, cartilage, tendons and other soft tissue, that, in a healthy state, work together to provide mobility and support to the body. In severe cases of osteoarthritis, TKRs are required to restore the full functioning of the knee joint. In this paper, the natural state of the knee joint was described and mechanical analysis was performed to better understand how wear occurs in the joint. Material properties were then examined to see how different combinations of metals, ceramic and/or polymers work together to mimic the natural motion of the knee while, not only supporting the loading conditions imposed during walking, but also minimizing wear between articulating surfaces in order to prolong the life of the knee implant. In considering what makes the best implant, it is therefore important to consider both the mechanical integrity of the implant as well as its material and surface properties.

7. References

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Appendix A

The following is a 3D Analysis of the Knee during a stair climbing motion:

R: ground reaction force

Q: quadriceps force

L: ilio-tibial band

V and H: joint forces perpendicular and parallel to the tibial surface

Vertical force balance, Sagittal plane

$$R + L\cos(\theta) + Q\cos(2\beta) + H\sin(\alpha) - V\cos(\alpha) = 0$$

Horizontal force balance, Sagittal plane

$$L\sin(\theta) + V\sin(\alpha) - H\cos(\alpha) - Q\cos(\beta) = 0$$

Moment Balance, Sagittal Plane

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

Moment Balance, frontal plane

$$8Q\cos(\gamma) + 47L\cos(\theta) - 42R = 0$$